NBS Special Publication 642

Construction Materials for Coal Conversion

Performance and Properties Data

Prepared For:
U.S. Department of Energy
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Prepared By:
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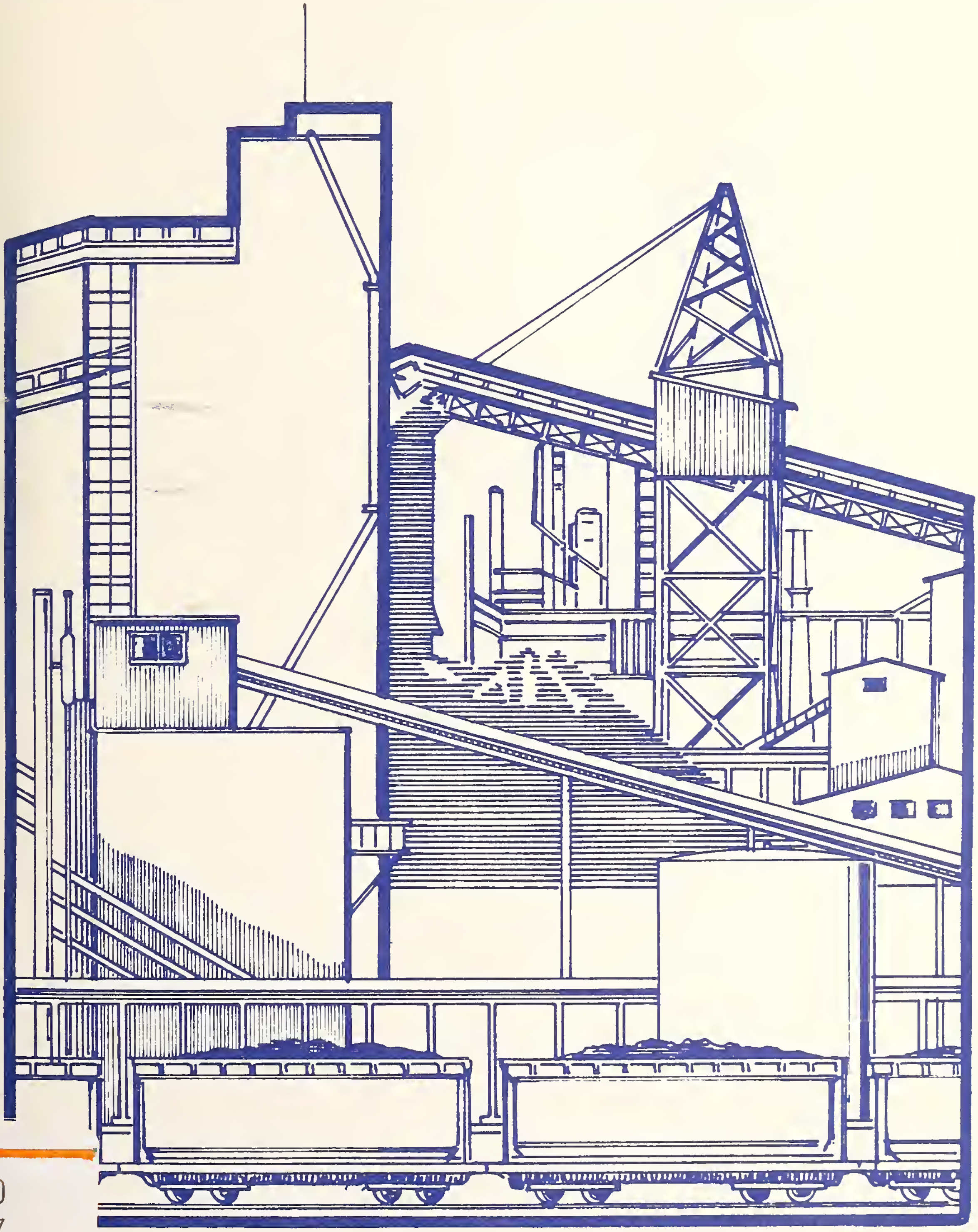

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INTRODUCTION

Background

Construction Materials for Coal Conversion--Performance and Properties Data, a reference book for the fossil fuel industry, is a result of the combined effort of the two data centers which constitute the NBS/DoE Fossil Energy Materials and Components Performance and Properties Data System. This System was established at the National Bureau of Standards under the sponsorship of the Department of Energy and its predecessor, the Energy Research and Development Administration.

The first of the data centers is the Materials and Components Plant Performance Data Center, established in 1976 as the Failure Information Center. NBS was given the responsibility for collecting, abstracting, and disseminating information about operating events and materials and components failure analyses submitted by coal conversion pilot plant personnel and failure analyses laboratories under a voluntary information and data exchange program. The second of the data centers at NBS is the Materials Properties Data Center, established to collect, abstract, and disseminate construction materials properties and testing performance data. Emphasis is placed on the results of work by materials research contractors to the Department of Energy, but the compilation effort is not to be limited to those data sources.

Data compiled by the two data centers have been tabulated and summarized for inclusion in this book. At present, the book is focused on coal gasification, that form of coal conversion for which there is the largest amount of available information in the library of the data centers. It is anticipated that future issues will add more material in areas of interest such as coal liquefaction, direct combustion, etc. Some small amounts of applicable data are already included in Section B.

The looseleaf format is designed to permit data to be added and revised easily. This first issue will be expanded and updated with new sections and with additional data gathered since the cutoff dates of the abstracting effort. The cutoff dates vary with each project reviewed since the reports on hand at the time the data were abstracted and the book tables prepared varied for each project. Portions of the book remain incomplete either because no data were readily available in the source documents which were applicable to the component area or because the data were limited, and it was felt that definitive statements and recommendations would be premature. Future issues of pages for this book will remedy that deficiency as the data base is expanded by inclusion of more data from present sources and from additional information sources. Although portions of this book are incomplete at this time, it was felt that the data contained in this issue would be of sufficient interest and use to the fossil energy community to warrant publication.

Organization of the Book

The book is divided into six major parts with the following headings--

A. Materials Considerations and Performance Data
B. Materials Testing and Research Results
C. Properties of Candidate Materials
D. Properties of Experimental Materials
E. References
F. Index

Part A deals with materials needs and materials data for coal gasification plants by component area. It is anticipated that the user, in looking for information, will be interested in data for materials in a specific application. The major headings and subheadings for component area sections in Part A are:

1. Coal Handling and Preparation Equipment, including;
    - Conveying Equipment
    - Grinding and Crushing Equipment
    - Drying Equipment
    - Fines Control Equipment
    - Coal Pretreatment Equipment

2. Vessels (includes reactors, devolatilizers, lockhoppers, etc.)
    - Pressure-Containing Shell
    - Refractory Linings and Components--Dry-Bottom Vessels
    - Refractory Linings and Components--Slagging Vessels
    - Metal Internal Components

3. Gas Clean-Up Equipment
    - Solids Separation Equipment
        - Scrubbers
        - Cyclones
    - Cooling-Down Systems
        - Quench Systems
        - Heat Exchangers
    - Gas Removal Systems (carbon dioxide, sulfur compounds, etc.)

4. Water-Gas Shift Equipment

5. Methanation Equipment

6. Compressors

7. Piping
    - Gas Lines
    - Solids Transfer Lines
    - Slurry Lines
    - Liquids Lines

8. Pumps
    - Slurry Pumps
    - Liquids Pumps

9. Valves
   - Gas Valves
   - Liquids Valves
   - Slurry and Solids Valves

Each component area title above is a heading for the following three subsections--

1. Operating Requirements

These paragraphs are brief discussions outlining the major problems of that component area which must be considered in choosing suitable materials of construction.

2. Performance Data

There are three possible divisions of this subsection which may appear for each component area.

2.1 Plant Experience

Under this heading, there will be tables of data taken from the files of the Materials and Components Plant Performance Data Base with discussion of the data. The quality and completeness of the original information from which these tables were prepared is highly variable, and this fact must be taken into account in making use of the data.

2.2 Component Test and Development

For some component areas there is a subsection with this heading containing data obtained either by testing prototypes or off-the-shelf components on test stands, or in constructing and testing portions of or models of components. Such data are not available for all component areas and this subsection does not appear at all for most component areas. The data are taken from the Materials Properties Data Base.

2.3 Materials Evaluation

These subsections contain summaries and discussions of data tables appearing in Part B of this book which are pertinent to the component area under consideration. The tables in Part B present the results of testing and research programs utilizing small sample specimens rather than actual component pieces. Section B.0, the introduction to Part B, contains a full explanation of its contents. Since much of the data in Part B are applicable to more than one component area, it was decided to place them together in one section. The data are, therefore, simply summarized and discussed in these "Materials Evaluation" subsections.

The units used in the text, tables, and graphs in these subsections correspond to those used in the individual reports under discussion. The compilers did not convert all data to a common system of units. It is recognized that a common system of units is highly desirable, and that mixed units result in a wide variation in reporting of data causing possible confusion and requiring the user to exercise great care. Conversion of all the data in the book to a common system of units, however, would have been a very costly effort.

It should be pointed out that most of the testing programs utilized specimens of commercially available materials. These samples should be considered as representatives of various classes of materials; the inclusion of brand names merely serves to identify and help characterize the materials. The designation of brand names should not be construed as an endorsement of any product or manufacturer. The materials are usually given the designation the authors of the original reports assigned although this practice causes some inconsistency in the book. This inconsistency is especially noted for alloys for which the designations given may or may not follow any one of the standard systems such as AISI, ASTM, or ANSI.

Much of the laboratory testing for which the data are discussed in this subsection was performed utilizing a "typical" or "simulated" coal gasification atmosphere. The composition was given as 18 percent CO, 12 percent CO_2, 24 percent H_2, five percent CH_4, one percent NH_3, with varying amounts of H_2S (0.1 to 1.5 percent), and the balance H_2O. In many reports it is clearly indicated that the above was an input composition, and equilibrium compositions at operating temperature and pressure were often given too. Some reports indicated that the above composition was the equilibrium one and others did not make any clear indication at all. The compilers have included the composition in the footnotes to tables as given in the reports.

3. Candidate Materials

These subsections, absent in this issue of the book, will discuss materials which may be given consideration for use in the given component area. The discussion will be based on the information in the "Performance Data" sections, as outlined above. It was felt that recommendations for candidate materials based on the present information was premature without further consideration of the data.

Part B, "Materials Testing and Research Results", contains data from the Materials Properties Data Base. The testing and research results have been arranged in four major categories: Corrosion effects, chemical reactions, and phase changes; Erosion, erosion/corrosion, and abrasion effects; Mechanical properties testing; and Physical properties testing.

Parts C and D will contain handbook-type data for materials which will be named in Part A under the headings "Candidate Materials" in future issues. Where such data are available, Parts C and D will give information under these headings for alloys: alloy designations, composition, general applicability, available forms, density, melting range, specific heat, thermal expansion, thermal conductivity, emissivity, microstructure, phase stability, chemical stability (corrosion, diffusion, carburization, oxidation, H_2 embrittlement, etc.), stress-strain data (elasticity, plasticity, yield strength, ultimate tensile strength, elongation, reduction in area, Poisson's ratio, compressive strength, etc.), hardness, impact resistance, fatigue properties, fracture toughness, fatigue crack growth rate, creep and stress-rupture data, and fabrication characteristics (compatibility with other metals, surface preparation, welding procedures). For refractories, the headings will be: ASTM performance group, generic designation, brand name(s), composition, mixing and curing characteristics, density, porosity and pore size, permeability, phase and chemical stability, erosion resistance, abrasion resistance, spalling, cracking, compressive strength, bending strength (modulus of rupture), fracture properties, elastic modulus, Poisson's ratio, shear modulus, creep, specific heat, thermal conductivity, and thermal expansion.

Part E consists of complete references for the material contained in other sections of the book. References for data have been identified by numbers in square brackets which follow the titles of tables or graphs in Part B or appearing elsewhere in the text or tables of Part A. Most of the references given in this first issue of the book are to reports of contractors to the Department of Energy and its predecessor agencies. See B.0, the Introduction to Part B, for fuller information about the handling of the references.

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NOTICE ABOUT USE OF THE BOOK IN LOOSELEAF FORM

These pages are three-hole punched to fit any standard ring binder. The binding permits easy removal of the pages for insertion and use in such a binder.

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* See individual sections for detailed tables of contents.

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A.1.1.1 OPERATING REQUIREMENTS

Coal conveying equipment includes screw feeders, conveyors, chutes, hoppers, and screens. The usual operating environment will be one of relatively low temperature (∿ 250 °F [394 K]) and atmospheric pressure. Some feeders to pretreater or reactor vessels may encounter significantly higher temperatures near the vessels which could require special material considerations.

The major materials problem is expected to be wear due, primarily, to abrasion. Some corrosion problems may occur in handling wet coal and will be aggravated by the presence of coal impurities such as sulfur and chlorine. Galvanic corrosion is also a possibility. To minimize condensation corrosion during shutdowns, provisions for draining pipes, flumes, and tanks are desirable.

Current coal and other solids handling processes can be expected to provide an appropriate materials technology basis to minimize the wear and corrosion problems for coal conveying equipment. Hard alloy liners and wear-resistant materials can counter abrasive effects and appropriate stainless steel liners should be adequate protection for the corrosion problems.

A.1.1.2.2 MATERIALS EVALUATION

INTRODUCTION-- Material used in coal handling situations can be in wrought or cast product forms. Either form is suitable as long as the material has adequate wear resistance and resistance to aqueous and galvanic corrosion. Results from analysis of the CO_2 acceptor plant [18] show that 25 percent of the failures in the coal handling area occurred in the conveying equipment. Wear results from the action of abrasive coal particles on exposed metal surfaces, whereas corrosion results from the acids formed when coal particles are exposed to water. Materials which are wear resistant include medium-carbon steels, low-alloy steels, cobalt-base alloys, and cast irons. (Note: The medium-carbon steels are not as weldable as the low-carbon steels.) Corrosion resistant materials include stainless steels, especially those in the 300 series. Fortunately, operating temperatures in most coal handling situations do not usually exceed 250 °F, so that most alloys are metallurgically stable.

WEAR RESISTANCE of some steels can be estimated from measurements of hardness and Charpy data. An approximate rule of thumb for estimating wear resistance is that if hardness is between 50-60 HR_c and Charpy energy is in the 20-30 ft-lb range, the steel will stand up in most coal handling situations. Hardness and Charpy data for several commercial and developmental steels appear in Sections B.3.1.53, .55, .57, .58, .62, and .63. Properties of one developmental steel which shows an excellent combination of hardness and Charpy energy are listed in B.3.1.58. A remelted commercial 4340 steel alloyed with aluminum and chromium shows moderately good combinations of hardness and Charpy energies (see Section B.3.1.60). For this alloy, isothermal transformation above Ms (start of martensite transformation) results in good Charpy energies coupled with moderately good hardness level, whereas isothermal transformation below Ms results in good hardnesses coupled with moderately good Charpy energies. Heat treatment via isothermal transformation may or may not result in an optimum combination of hardness and Charpy energy for a given steel. For example, the base alloy in Section B.3.1.55 showed a moderately good response to one isothermal transformation treatment, but a poor response to another. Moreover, the response to each isothermal transformation treatment was poorer than the response to a conventional oil quench and tempering treatment.

Another method for estimating the wear resistance of steels and other materials is through the use of one wear test or another. There are many wear tests, some of which may give rather ambiguous and even contradictory results on the same material. The approach to overcoming these difficulties is to use one wear test method on several materials and rank their performance according to that test method alone. This has been done for several experimental steels listed in Sections B.2.1.40, B.2.1.41, and B.2.1.43. The test method used was pin-on-disc. For martensitic steels, bainitic steels, matrix steels, modified ultra-high-strength steels, some experimental Cr-Si-Mo steels, and some commercial steels, wear factors range between 0.48 and 0.70. Experimental matrix steels listed in B.2.1.43 showed the best wear resistance. For steels subjected to varying tempering temperatures between 200-650 °C wear resistance was generally better at the higher tempering temperatures. Heat treatment of bainitic steels (see B.2.1.41) influenced wear resistance.

For example, isothermal transformation above Ms gave better wear resistance than isothermal transformation below Ms or oil quenching, at least for tempering temperatures below 500 °C. However, above 500 °C, the method of heat treatment had practically no influence on wear resistance. A cryogenic quench after isothermal transformation above Ms, presumably to promote transformation of retained austenite, did not have a favorable influence on wear resistance. Some steels were tested for wear resistance in a Jaw Crusher Apparatus (see B.2.1.43). The five steels tested by this method showed about the same wear resistance, the maximum difference in resistance being about seven percent.

ABRASIVE WEAR has been evaluated for ten alloys (Sections B.2.1.27-.34). These wear tests involved rubber wheel abrasive wear and grinding wheel abrasive wear. The materials tested included four Ni-Hard 4 irons (consisting of austenite decomposition product, retained austenite, and carbides), and six cobalt-base superalloys. Conclusions drawn from the wear tests appear in B.2.1.34 for the Ni-Hard 4 irons and in B.2.1.33 for the cobalt-base superalloys.

In general, these conclusions relate to aspects of the test method more than to the materials' wear resistance. Section B.2.1.31 illustrates how the test method influences the outcome of a test for orientation dependence of wear resistance for A532-Types II and III. The rubber wheel abrasive test shows no strong orientation dependence of wear for these alloys, whereas the gouging abrasive wheel test does. Despite ambiguities and uncertainties inherent in wear test methods, some points are clear. For example, Sections B.2.1.31 and B.2.1.32 show persuasively that wear resistance of A532-Types II and III increases as hardness increases. Section B.2.1.29 shows that this is also true for some cobalt-base superalloys. Furthermore, Section B.2.1.30 shows that wear resistance is sensitive to carbide volume fractions in some cobalt-base superalloys and shows a minimum at about 50 volume percent carbide. The amount of retained austenite in Ni-Hard 4 irons (A532-Type I) influences wear resistance, as shown in Sections B.2.1.27 and B.2.1.28 for several different test methods.

A.1.2.1 OPERATING REQUIREMENTS

The various gasification processes have specific size requirements for the coal feed. The necessary crushing and grinding equipment normally operates at relatively low temperatures (∿ 250 °F [394 K]) and atmospheric pressure. Wear from abrasion represents the major materials problem. This problem can be minimized by appropriate technology transfer from current solids handling processes. Materials with improved combinations of hardness and toughness at lower cost are desirable.

A.1.2.2.2 MATERIALS EVALUATION

The materials considerations which must be taken into account for grinding and crushing equipment are comparable to those for conveying equipment. Minimizing abrasive wear from coal particles is the main problem to deal with. For example, results from analysis of the CO_2 Acceptor Plant [18] show that 25 percent of the failures in the coal handling area occurred in the crushing equipment. The discussion of wear resistance of materials in the section on Conveying Equipment (A.1.1.2.2) applies equally well to this section on Grinding and Crushing Equipment, and it is recommended that the material in section A.1.1.2.2 be reviewed for the materials considerations which apply to grinding and crushing equipment.

A.1.3.1 OPERATING REQUIREMENTS

Drying equipment ranges from dewatering screens to thermal driers. Hence, the environment may range from ambient conditions up to air temperatures of 750 °F (672 K) and atmospheric pressures. Wear and corrosion problems common to general coal handling equipment will occur and are expected to be manageable through appropriate technology transfer from existing solids handling systems.

A.1.4.1 OPERATING REQUIREMENTS

Equipment used for fines control includes cyclones, wet scrubbers, bag houses, electrostatic precipitators, etc. Temperature and pressure conditions are generally mild. Problems from erosion, abrasion, and corrosion should be manageable by technology transfer from presently existing and well-developed fines control systems.

A.1.5.1 OPERATING REQUIREMENTS

Some gasification processes require the pretreatment of caking coals to prevent caking. This pretreatment is done by the mild oxidation of the caking coals in the presence of oxygen or air at 750 °F (672 K) to 850 °F (727 K) and atmospheric pressures. The equipment used consists of simple vessels of refractory-lined carbon steel with the refractory functioning, presumably, primarily to reduce the heat loss since the environmental conditions are not very severe. No major material problems are anticipated in this section.

Other pretreatment, depending on the process, may include slurrying, pressurizing of coal/slurry feeds, preheating of feed stock, etc. Major problem areas can be expected to include transport lines, valves, pumps, and metal internals of heat exchangers (if reaction product gas is used as a source of heat). These items are all considered in separate sections of this book.

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A.2 Vessels

* Sections included in this issue.

* Sections included in this issue.

A.2.1.1 OPERATING REQUIREMENTS

The major pressure-containing vessels are lockhoppers and gasifiers. The huge size of some of these vessels will create new problems in fabrication and welding techniques.

Environmental conditions will vary greatly depending on the process (pressures from 100-1,600 psi, temperatures up to 3,000 °F [1,922 K]) and the vessel function or location in the process stream. For example, feed lockhoppers will have to withstand the maximum pressures and pressure fluctuations, but temperatures in them should not exceed 800 °F and the gaseous atmosphere can be controlled to minimize corrosion. Within the gasifiers, the environment will be most severe--maximum temperatures, highly erosive and potentially corrosive. Basic design assumes the welded steel shell will be protected by an internal refractory lining. However, since such linings can crack and spall, the possible effects on the steel shell of exposure to process conditions must be considered.

Potential material problems from chemical attack include reactions with acidic condensates, hydrogen, and sulfur compounds through lining cracks. Complete lining deterioration through erosion and spalling would expose the shell to extreme thermal conditions and direct erosive wear as well as the hot corrosive gases. Physical influences of temperature, time, stress, temperature and pressure cycling may create or exacerbate such problems as creep fatigue, thermal fatigue, and stress-corrosion cracking. In general, most of these problems will be minimal if an intact refractory lining can be maintained in these vessels.

A.2.1.2.2 MATERIALS EVALUATION

INTRODUCTION--Large reaction pressure vessels in the petrochemical and nuclear industries are almost always constructed of steel. Among the candidate materials for pressure vessels, steel has the most attractive combination of cost, stiffness, strength, fatigue resistance, and toughness. The data base established for pressure vessel steels in these two industries can be considered as a good starting point for design considerations about pressure vessels in coal conversion systems. Although pressure vessel technology in general is well established and codes are in effect for construction of pressure vessels, special consideration must be given to vessels for second generation commercial coal gasification systems because of the proposed vessel size. The largest vessels considered by designers so far are already three to four times larger than any pressure vessels that have been fabricated previously. A typical large pressure vessel currently manufactured might be 100 feet long and 14 feet in diameter. Some proposed designs for specific processes would require vessels of double that length, others would require diameter increases up to four times the above.

One need at this stage in the development of coal conversion pressure vessels is to assess the available data base on pressure vessel steels used in the petrochemical and nuclear industries. For a recent assessment of the technology for pressure vessels for second generation coal gasification systems, see Canonico et al. [42]. This ORNL report covers such considerations as design, materials compatibility, materials properties, fabrication, and nondestructive testing.

The mechanical properties of interest include: strength, toughness, stress rupture, and fatigue, including creep fatigue, thermal fatigue, and corrosion fatigue. Of primary interest is the initial quality of the steel and the susceptibility of the steel to unfavorable changes in metallurgical structure during service. Steel making technology today is such that excellent quality steel can be supplied if the best level of effort is made. At the high service temperature of coal conversion pressure vessels; e.g., 800 to 3000 °F, metallurgical changes can occur which degrade the as-received mechanical properties. Temper embrittlement, which results in reduced toughness, is one example.

Some laboratory studies have been conducted on the mechanical properties of pressure vessel steels in the DoE-sponsored programs for gasifier and reaction pressure vessels for coal conversion systems. Five commercial steels were studied and are listed in Table A.2.1.2.2a. A number of developmental alloy steels, made from modifications of the commercial steels, have also been evaluated. Results of the mechanical properties studied appear in Sections B.3.1.11, B.3.1.12, B.3.1.41-.50, and B.3.1.64-.77. The focus of these studies has been principally on tensile properties and toughness. A small amount of environmental fatigue data have been obtained. The amount of fracture mechanics data is very limited, and there is clearly a need for an intensification of efforts to obtain fracture-mechanics-type data for toughness and fatigue properties. Very little data have been reported on the susceptibility of pressure vessel steels in coal conversion use to temper embrittlement or hydrogen embrittlement, and there is a need to obtain more data of this type also. Temper embrittlement is a diffusion problem that can occur at operating temperatures, whereas hydrogen embrittlement is more likely to occur during cool downs as a result of supersaturation.

Commercial Pressure Vessel Steels Investigated for Gasifier and Reaction Pressure Vessels for Coal Conversion Systems

Steel [43]	Chemistry Highlights (Heat Analysis, Wt. %)	Heat Treatment	Ultimate Tensile Strength ksi	Ultimate Tensile Strength MPa	Yield Strength ksi	Yield Strength MPa	Section B Number & Reference
ASTM A 387-79b Pressure Vessel Plates, Alloys Steel, Chromium-Molybdenum	Grade 22-"2 1/4 Cr-1 Mo" C: 0.15 max, Mn: 0.30 to 0.60, P: 0.035 max, S: 0.035 max, Cr: 2.00 to 2.50, Mo: 0.90 to 1.10	Class 1 Annealed	60 to 85	415 to 585	30 minimum	228 minimum	B.3.1.41, .43, .44, .46, .47, .50 [35]
		Class 2 Normalized and Tempered or Accelerated Cooled and Tempered	75 to 100	515 to 690	45 minimum	310 minimum	B.3.1.64, .71, [40] B.3.1.11, .12 [29]
ASTM A 508-80a Quenched and Tempered Vacuum-Treated Carbon & Alloy Steel Forgings for Pressure Vessels	5 Strength Classes Specified [43] C: 0.23 max to 0.35 max, Mn: 0.20 to 1.50, P: 0.020 max to 0.025 max, S: 0.020 max to 0.025 max, V: 0.03 max to 0.08 max, Cr: 0.25 max to 2.00, Mo: 0.10 max to 0.70	Liquid Quenched and Tempered	70 to 140*	485 to 965*	36 to 100*	250 to 690*	B.3.1.65, .71 [40]
			*Strength range over all classes is tabulated.				
ASTM A 533-80 Pressure Vessel Plates, Alloy Steel, Quenched & Tempered, Manganese-Molybdenum & Manganese-Molybdenum-Nickel	Type B C: 0.25 max, Mn: 1.15 to 1.50, P: 0.035 max, S: 0.040 max, Mo: 0.45 to 0.60, Ni: 0.40 to 0.70 (Residual elements--Cu, P, S, and V are controlled for nuclear applications.)	Water Quenched and Tempered	80 to 125*	550 to 860*	50 to 83*	345 to 570*	B.3.1.65, .66, .71, .72 [40]
			*Strength range over all classes is tabulated.				
ASTM A 542-79 Pressure Vessel Plates, Alloy Steel, Quenched & Tempered, Chromium-Molybdenum	4 Strength Classes Specified [43] C: 0.15 max, Mn: 0.30 to 0.60, P: 0.035 max, S: 0.035 max, Cr: 2.00 to 2.50, Mo: 0.90 to 1.10	Liquid Quenched and Tempered	105 to 135*	724 to 930*	60 to 100*	415 to 690*	B.3.1.66, .68, .69 [40]
			*Strength range over all classes is tabulated.				
ASTM A 543-79a Pressure Vessel Plates, Alloy Steel, Quenched & Tempered, Nickel-Chromium-Molybdenum	3 Strength Classes Specified [43] C: 0.23 max, Mn: 0.40 max, P: 0.020 max, S: 0.020 max, Ni: 2.25 to 3.25, Cr: 1.20 to 2.00, Mo: 0.45 to 0.60, V: 0.03 max	Liquid Quenched and Tempered	105 to 135*	724 to 930*	70 to 100*	485 to 690*	B.3.1.42, .45, .48, .49 [35] B.3.1.68, .75 [40]
			*Strength range over all classes is tabulated.				

Table A.2.1.2.2a

LABORATORY STUDIES OF COMMERCIAL PRESSURE VESSEL STEELS have been made on the following ASTM designations: A387-Grade 22, A508, A533-Type B, A542, and A543. In general, the studies did not involve exposure to typical coal gasification atmospheres. Rather, material in the as-mill-processed condition was heat treated, then tested and evaluated for tensile properties, fracture toughness, and fatigue properties. Performance of these five commercial steels is described below.

A387-Grade 22: "2-1/4 Cr--1 Mo"--Results of tensile tests appear in Sections B.3.1.41, B.3.1.43, and B.3.1.47. Results of fracture toughness tests appear in Sections B.3.1.44, B.3.1.46, and B.3.1.50. Fatigue test results appear in Sections B.3.1.11 and B.3.1.12. Increasing austenitizing temperature from 1700 to 1900 °F has the favorable effects of improving yield and tensile strengths, and toughness. Ductility seems unaffected by an increase in austenitizing temperature from 1700 to 1900 °F. The austenitizing temperature seems to have a stronger effect on tensile properties than do any post-quench heat treatments. However, post-quench heat treatments seem to have a very strong and favorable influence on Charpy impact properties (see B.3.1.44). For example, tempering results in a significant improvement over the as-quenched toughness. Furthermore, post-tempering stress relief and aging treatments result in another ten percent improvement in toughness. Highlights of standard Charpy impact toughness data appear in Section B.3.1.50. Upper shelf energies are in the neighborhood of 80-90 ft-lbs and transition temperatures are near or slightly below 50 °F. Some precracked Charpy slow bend test results have been converted to fracture toughness data, as shown in Section B.3.1.46. At temperatures above -100 °F, the fracture toughness estimated from slow bend tests on tempered A387 is between 100-200 ksi$\sqrt{\text{in}}$, regardless of austenitizing temperature. Stress relief and stress relief plus aging treatments lead to increases in fracture toughness of 15 to 20 percent. In tests to simulate the cooling rates which occur in commercial heat treating that results in through-thickness gradients in thick plate, it was found that tensile properties and toughness of surface specimens were better than tensile properties and toughness of greater-thickness specimens.

A542: "2-1/4 Cr--1 Mo"--This type of steel has practically the same chemistry as A387-Grade 22. However, A542 receives a different heat treatment; i.e., either liquid or spray quenched as compared to annealed or normalized and tempered for A387-Grade 22. Hardness (Section B.3.1.66) and toughness (B.3.1.68, B.3.1.69) data have been reported on A542 steel. A plot of Vickers hardness vs. tempering temperature (Section B.3.1.66) peaks at 600 °C in a test simulating eight-inch thick plate at the quarter-thickness position. A similar test simulating 12-inch thick plate at the quarter-thickness position showed a continuous decrease in Vickers hardness vs. tempering temperature (Section B.3.1.66) between 575 and 675 °C.

The Charpy impact energy on the upper shelf for both the eight-inch and 12-inch simulations was between 75 and 80 ft-lbs, and the transition temperature of the 12-inch simulation at -20 °C was 40 centigrade degrees below the transition temperature of the eight-inch simulation (see B.3.1.68). Results in Section B.3.1.69 are comparable. The upper shelf energies in these simulations are somewhat less than the upper shelf energies reported for A387-Grade 22 steel (see B.3.1.50). The transition temperatures are roughly comparable.

Fatigue crack growth kinetics of 2-1/4 Cr--1 Mo steel were evaluated in various environments and over a range of temperatures and pressures. The test environments were: vacuum, dehumidified argon, water vapor, dehumidified hydrogen and hydrogen sulfide. Temperatures ranged between 295 and 477 K. Pressure varied between 0.1 and 5.0 torr in some tests. Results appear in B.3.1.11 and B.3.1.12. These figures show that crack growth rate was in the range 10^{-7} to 10^{-5} inches per cycle for $20<\Delta K<70$. Increasing frequency from five to 10 Hz increased crack growth rate slightly. Crack growth rate increased with increase in stress intensity factor range. At fixed value of stress intensity factor range, crack growth rate generally decreased with increase in temperature. Hydrogen sulfide atmospheres caused fastest crack growth rates, and rates increased with increasing hydrogen sulfide pressure. Dehumidified hydrogen caused the second fastest crack growth rates. Water vapor, dehumidified argon, and vacuum tests resulted in comparable crack growth rates at $\Delta K \geq 50 \mathrm{MPa\text{-}m}^{\frac{1}{2}}$.

<u>A508: "Carbon and Alloy Steel"</u>--Results of tensile tests and Charpy impact tests on A508 steel appear in Sections B.3.1.65 and B.3.1.71, respectively. The tensile data show that reheat treatment can result in a 12 to 20 percent increase in yield and tensile strengths with an attendant 20 percent reduction in ductility. The Charpy data were obtained on a quenched and tempered and stress relieved 14-inch thick plate at the mid-thickness position. They indicate a 135 to 140 ft-lb upper shelf and a transition temperature of about 10 °C. This upper shelf energy is considerably higher than that shown by the other commercial steels investigated, except for A533-Type B, which showed a 200 ft-lb upper shelf energy (see B.3.1.72).

<u>A533-Type B: "Quenched and Tempered Alloy Steel, Mn-Mo-Ni"</u>--Results of tensile tests, hardness tests, and Charpy impact tests have been obtained on A533-Type B steel. The tensile test results (Section B.3.1.65) show that reheat treatment can result in a noticeable increase in yield and tensile strengths with an attendant reduction in ductility. Tests on plates heat treated to simulate eight and 12-inch plate quarter-thickness properties show higher yield and tensile strengths than commercial and reheat treated six-inch thick plate showed; however, ductilities were comparable. Plates of eight, nine, and 12-inch thickness all have about the same strengths and ductilities, and all are comparable with the strengths and ductilities of six-inch thick commercial plates.

Plots of Vickers hardness vs. tempering temperature (Section B.3.1.66) in tests which simulated the quarter-thickness positions for eight and 12-inch thick plates showed a rather level response between 575 and 650 °C, then a precipitous drop between 650 and 700 °C.

Charpy test results appear in Sections B.3.1.71 and B.3.1.72. Upper shelf energies range between 100 and 200 ft-lbs and transition temperatures range between 15 and 45 °C. Best impact properties were shown by a commercially prepared 12-inch thick, spray quenched plate (quarter-thickness).

A543-Class 1: "Quenched and Tempered Alloy Steel, Ni-Cr-Mo"--Results of tensile tests and Charpy impact tests have been obtained on A543-Class 1 steel. Tensile test results (Sections B.3.1.45 and B.3.1.49) show that there is no strong dependence of strength on orientation of the plate or depth within the plate. However, there was a slight decrease in ductility between surface and center. It was found that stress relief results in a slight reduction of strength, but has no strong influence on ductility.

Charpy impact properties for A543-Class 1 steel are reported in Sections B.3.1.42, B.3.1.48, B.3.1.68, and B.3.1.75. Included in these results are Charpy impact energy and transition temperatures, fracture appearance transition temperatures, and some estimates of fracture toughness from precracked Charpy tests. Effects of heat treatment on toughness, including embrittling heat treatments, have been investigated. Upper shelf energies range from 67 to 140 ft-lbs. Lowest upper shelf energies occurred for test specimens taken from the mid-thickness of the plate and from as-received commercial test specimens. Remelted material showed improved toughness over as-received commercial material (see B.3.1.75). Transition temperatures ranged from -50 to +10 °C. Estimated values of fracture toughness ranged from 35 to 208 ksi$\sqrt{\text{in}}$.

LABORATORY STUDIES OF EXPERIMENTAL PRESSURE VESSEL STEELS have been carried out. About 30 experimental compositions were studied. Tensile properties, toughness, and hardness were measured as a function of composition and/or heat treatment. Many of these compositions represent slight variations of standard ASTM specifications for pressure vessel steels, as noted in Table A.2.1.2.2b. This table indicates that the compositional variations of A533B involved silicon, chromium, and manganese, individually or in various combinations, up to concentrations of one percent. The same is true for A542, except that the compositional variations included nickel and molybdenum. Additions of boron and nitrogen were made to A543, in amounts of 0.005 and 0.015, respectively (see B.3.1.75). The carbon steel base was alloyed with chromium, molybdenum, tungsten, manganese, nickel, and vanadium, individually or in various combinations, at concentrations of up to three percent (see Sections B.3.1.67 and B.3.1.76). Heat treatment of all these experimental alloys involved quenching and tempering. Some heat treatments to intentionally promote temper embrittlement were carried out on some compositional variations of A542 and A543.

COMPOSITIONAL VARIATIONS OF A533B--Tensile data (section B.3.1.65) and Charpy data (Sections B.3.1.71 and B.3.1.72) have been obtained on A533B alloyed with silicon, chromium, or manganese. Results indicate that silicon additions of one to two percent increase strength and upper shelf energy, but shift the transition temperature upwards from 0 °C towards 50 to 150 °C. Chromium plus manganese additions increase strength and upper shelf energies and, furthermore, do not have an unfavorable effect on the transition temperature. The same is true for chromium plus manganese plus silicon additions.

COMPOSITIONAL VARIATIONS OF A542--Tensile data (Section B.3.1.64) and Charpy data (Sections B.3.1.68-.70, B.3.1.74) have been obtained on A542 alloyed with chromium, molybdenum, manganese, silicon, and nickel. The influence of alloying additions on the tensile properties of A542 is mixed. Some additions and combinations of additions increase strength, whereas others tend to decrease strength. Nickel and molybdenum seem to cause the largest

Experimental Pressure Vessel Steels Investigated for Gasifier and Reaction Pressure Vessels for Coal Conversion Systems

Base Steel	Chemistry Highlights (Heat Analysis, Wt.%)	Heat Treatment	Section B Number and Reference
A533B [43]	A533B base, plus: Si, Cr, Mn (in concentrations up to 1%) individually, or in various combinations	Quenched and Tempered	B.3.1.65, .71, .72 [40]
A542 [43]	A542 base, plus: Cr, Mo, Mn, Si, Ni, in concentrations up to 1%) individually, or in various combinations	Quenched and Tempered (Some Embrittling Heat Treatments)	B.3.1.64, .68, .69, .70, .73, .74 [40]
A543 [43]	A543 base, plus: 0.005 B, 0.015 N individually	Quenched and Tempered (Some Embrittling Heat Treatments)	B.3.1.75 [40]
Carbon steel	Carbon steel base (0.1 to 0.15% C, 0.5Mn) plus Cr, Mo, Mn, Ni, V, W (in concentrations up to 3%) individually, or in various combinations	Quenched and Tempered	B.3.1.67, .76 [40]

Table A.2.1.2.2b

increases in strength. Nickel and manganese additions significantly increase the upper shelf energy and, simultaneously, lower the transition temperature. Chromium and molybdenum also increase the upper shelf energy but do not increase the transition temperature. There is a tendency for all alloys to show a downward shift in upper shelf energy on changing from eight-inch to 12-inch thick plate. A summary of some Charpy properties for several experimental alloys based on A542 appears in Section B.3.1.70. Results of a temper embrittlement study appearing in Section B.3.1.74 show that A542 steel alloyed with one percent manganese alone and 0.5 percent manganese plus 0.5 percent nickel exhibits a slight decrease in upper shelf energy and a significant upwards shift in transition temperature.

COMPOSITIONAL VARIATIONS OF A543--Charpy data (Section B.3.1.75) have been obtained on A543 alloyed with 0.005 percent boron and with 0.015 percent nitrogen. Heat treatments were carried out to intentionally promote embrittlement. Prolonged aging of the base A543 material at 483 °C resulted in a significant upward shift in the transition temperature and a 25 percent decrease in the upper shelf energy. Remelting the A543 material did not improve the response to the embrittlement treatment, but did significantly improve the Charpy properties of the unembrittled remelted material. Remelted A543 alloys containing 0.005 percent boron or 0.015 percent nitrogen exhibited good Charpy properties in the unembrittled state but poorer Charpy properties after an embrittlement heat treatment. Upper shelf energies of the embrittled, remelted material with and without boron or nitrogen were higher than for the embrittled as-received A543.

COMPOSITIONAL VARIATIONS OF CARBON STEEL--Hardness data (Section B.3.1.67) were obtained on carbon steel alloyed with chromium, molybdenum, or tungsten. Only the molybdenum steel showed a peak in the hardness vs. temperature tempering curve, suggesting a tendency toward embrittlement at around 650 °C. Tensile properties of some 0.1 and 0.2 percent carbon steels alloyed with vanadium or nickel have been determined for various heat treatments (see B.3.1.76). Yield strength ranged from 55 to 172 ksi and ultimate tensile strength from 85 to 190 ksi. Heat treatments included total decomposition through the upper or lower transformation C-curves, and ausaging, followed by quenching. The ausaged/quenched product usually had the higher strength and lower ductility. Total decomposition products through the upper transformation C-curve usually had lower strengths than bainite formed through the lower transformation regime. The nickel-containing alloys were usually stronger.

A.2.2.1 OPERATING REQUIREMENTS

Refractory linings are used for thermal insulation and improved erosion resistance. These linings in gasifier vessels must cope with the most severe conditions of the gasification process. In dry-bottom (i.e. non-slagging) processes, the maximum temperatures are limited by the ash-slagging temperatures of coals. Slagging temperatures are composition dependent and range from 2,000 °F to ∿2,900 °F. In actual non-slagging processes being proposed temperatures range from 800 °F (∿700 K) to 2,400 °F (∿1,590 K) and pressures range from 100 to 1,000 psi. In all gasifiers, there will be entrained solids of coal, char, ash and, in some processes, dolomite. Gaseous components may include H_2, CO, CO_2, H_2O, H_2S, N_2, NH_3, CH_4, organic sulfur compounds, chlorides, hydrocarbons, organic acids, and at lower temperatures, tar and oils. These constituents create both an erosive and corrosive environment.

Possible problems could arise from phase changes or reactions within the refractory material at elevated temperatures or pressures as well as reactions between the refractory and components of the gasification atmosphere, primarily with steam, hydrogen, and carbon monoxide. Thermal and mechanical stresses may be substantial, especially during start-up and shut-down procedures. Coping with these problems will require a careful blend of material selection, design considerations, and close control of process conditions. Most likely, a multiple-layered refractory will be necessary, i.e. a dense concrete or brick layer exposed to the process conditions backed up by an insulating porous layer to protect the metal pressure shell from excessive temperatures. Unfortunately, operating conditions in gasifiers are sufficiently different from other severe industrial processes, such as blast furnaces and petrochemical facilities, that substantial technology transfer is uncertain.

A.2.2.2.1 PLANT EXPERIENCE

Information concerning the performance of refractories in actual use in coal gasification plants is limited to data gathered from only two pilot plants. The usual operation of a pilot plant subjects the refractories to the shock of many more temperature and pressure cycles than would normal commercial scale operation so that good performance on a pilot scale should indicate better commercial use performance.

Minimal information is available for insulating refractories. Phase changes which occurred during operation in one pilot plant for one aluminosilicate insulating castable are given in Section A.2.2.2.1.1. Comparison of the compounds present initially in the refractory with those found in used material taken from around a sample port adjacent to the steel vessel shell where the temperature was about 95 °C (200 °F) indicates marked changes. The initial material contains, in order of apparent abundance, first the calcium aluminate bonding phases, anorthite ($CaAl_2Si_2O_8$) and gehlenite ($Ca_2Al_2SiO_7$) and simple calcium aluminate ($CaAl_2O_4$), followed by the aggregate materials, quartz (SiO_2) and mullite ($Al_6Si_2O_{13}$). The exposed refractory contains none of the bonding phases of the original material, all of the calcium present being in the form of calcium carbonate, indicating exposure to and reaction with carbon dioxide under conditions which permitted decomposition of the bonding phases. The silica present in the original bonding phases exists largely as cristobalite in the exposed material, and the mullite and quartz aggregate of the original material seem relatively unaffected. Some gibbsite (hydrated alumina) has also formed. The sample was described as very friable, which is consistent with the breakdown of the strong bonding phases and the lack of formation of new strong bonding phases. Such changes may not be serious for the insulating refractory in a vessel provided the hard-faced inner portion of the refractory lining remains intact. If, however, the hard-faced liner should fail, permitting reactive process gases to penetrate to the insulation, the degraded insulation would no longer provide protection from chemical and thermal attack to the metal shell.

More information is available for performance of hard-faced refractories from one coal gasification pilot plant. The pilot plant operation involved circulation of char or lignite with limestone to take up excess carbon dioxide. At the time plant operation was ended, samples of the refractory lining of the gasifier were taken. Two different calcium-aluminate-bonded medium-alumina refractories had been in use, an abrasion-resistant castable in the lower "boot" section (and as vapor stops at several heights) and a dense castable in the rest of the vessel. A full description of the sampling and analysis of the refractory is contained in Dobbyn et al. [18]. Visual examination of the refractory revealed cracking, but all cracks were tight and the lining offered good protection to the vessel shell. Some minor chipping and spalling had occurred along crack edges in the lower fluidized-bed portion of the vessel, but none along cracks in the upper vessel region (freeboard). General erosion was so slight that original casting marks were still visible on the refractory surface. Core samples were drilled from the lower part of the vessel, but the refractory in the upper portion proved so hard that it was only possible to obtain chips.

Physical properties of the samples were measured: apparent porosity, water absorption, apparent specific gravity, and bulk density (see Section

A.2.2.2.1.5). Eight samples of each material were chosen randomly from the core specimens. The data, summarized below, show that the uniformity of the installed refractory was good and that no one portion of the refractory was affected by exposure more than another.

Refractory	Property	Avg. Value for 8 Samples	Max. Percent Deviation From Avg.
Abrasion-Resistant Castable	Apparent Porosity	30.17 %	4.6
	Water Absorption	15.30 %	6.6
	Apparent Spec. Gravity	2.820	0.8
	Bulk Density	1974 kg/m^3	1.6
Dense Castable	Apparent Porosity	30.35 %	3.8
	Water Absorption	15.42 %	5.4
	Apparent Spec. Gravity	2.826	0.4
	Bulk Density	1968 kg/m^3	1.6

X-ray diffraction studies of laboratory-prepared, fired refractory showed that the major constituents were the mullite and cristobalite aggregate compounds with calcium aluminate bonding phases. Examination of the refractory from the vessel lining (see A.2.2.2.1.2) indicated a number of reactions had taken place during the operation of the gasifier. The amount of bonding phases in proportion to aggregate materials had increased markedly. The original calcium aluminates, $CaAl_2O_4$ and $CaAl_4O_7$, had reacted with the silica in the presence of the steam in the gasifier atmosphere to form anorthite ($CaAl_2Si_2O_8$), a strong bonding phase. In some samples, the anorthite apparently was the most abundant compound. Gehlenite ($Ca_2Al_2SiO_7$), a good bonding phase, also formed and some of the calcium in the circulating lime may have been involved in this reaction. Appreciable amounts of nepheline, $(Na,K)_2Al_2Si_2O_8$, were also formed, the alkali probably being supplied by the lignite which was circulated during the second half of the operation of the plant. Nepheline is also a good bonding phase. In general, these bonding phases were better crystallized and more abundant in samples taken from the hot face of the refractory than in samples deeper in the refractory cores.

Changes in the compressive strength and erosion resistance of the refractories are consistent with the enhancement of the bonding phases. Comparison of the compressive strength of the liner refractories with that of laboratory-prepared, fired samples indicates large increases due to exposure in the gasifier atmosphere (see A.2.2.2.1.3). The exposed samples showed wide-ranging percent increases in strength for both refractories.

Refractory	Increase in Strength of Exposed Samples
Abrasion-Resistant Castable	24, 40, 42, 70, 100, 131, 175, 186 %
Dense Castable	82, 95, 99, 127, 182 %

Erosion losses of samples subjected to SiC abrasive (see A.2.2.2.1.4) indicate increased erosion resistance for exposed material compared with control specimens (laboratory-prepared and fired). Material loss of the exposed samples was generally considerably less than the control samples.

Refractory	Increase in Erosion Resistance of Exposed Samples
Abrasion-Resistant Castable	25, 37, 44, 46, 56, 60, 68 %
Dense Castable	46, 57, 59, 62, 64, 72 %

In one pilot plant environment, two medium-alumina refractories performed well and the properties were apparently enhanced due to chemical reactions which occurred in the hydrothermal gasifier atmosphere.

CHANGES IN CHEMICAL PHASES[a] IN LIGHTWEIGHT INSULATING CASTABLE REFRACTORY IN GASIFIER PILOT PLANT USE[b][23]

Premixed Lightweight Insulating Castable Dried Basis			Castable Sample from Gasifier[b]
Chemical Analysis		Phases Present[a,c]	Phases Present[a]
Al_2O_3	38.4%	Anorthite (CAS_2)	Cristobalite (SiO_2)
SiO_2	31.2%	Gehlenite (C_2AS)	Calcite ($CaCO_3$)
CaO	22.4%	CA	Mullite (A_3S_2)
Fe_2O_3	4.8%	α-Quartz (SiO_2)	α-Quartz (SiO_2)
TiO_2	1.5%	Mullite (A_3S_2)	Gibbsite (AH_3)
MgO	0.5%	CA_2	
Na_2O & K_2O	0.2%		
loss on ignition	0.8%		

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[a] As determined by x-ray diffraction; listed in order of abundance; A = Al_2O_3, C = CaO, H = H_2O, S = SiO_2.

[b] Refractory sample taken from around a gas sample port, adjacent to the outer steel shell of the gasifier at Morgantown Energy Research Center; normal temperature at that location is 95 °C (∿200 °F); sample was very friable.

[c] There are also trace amounts of unidentified phase(s); cristobalite, probably present, is masked by other phases.

PHASES[a] PRESENT IN THE GASIFIER REFRACTORY LINING[b] OF A GASIFICATION PILOT PLANT[c] [18]

MATERIAL Sample Location[d]	Phases Present[a] Hot End[d]	 Cold End[d]
ABRASION-RESISTANT CASTABLE[b]		
Control Specimen[e]	A_3S_2, S_c, CA, CA_2.	
Bottom-of-bed, east	A_3S_2, CAS_2(T), S_c, α-A, C_2AS, CA(trace).	A_3S_2, S_c, CAS_2(T), α-A, C_2AS, CA(trace). Similar to hot face.
Bottom-of-bed, south	CAS_2(T), A_3S_2, S_c, C_2AS, CA(trace). CAS_2(T) well crystallized.	CAS_2(T), A_3S_2, S_c, C_2AS, CA and CA_2(trace). Similar to hot face, CAS_2(T) well crystallized.
Bottom-of-bed, west	A_3S_2, S_c, CAS_2(T), α-A, C_2AS, CA(trace).	A_3S_2, S_c, CAS_2(T), α-A, C_2AS, CA(trace). CAS_2 less well crystallized than at hot face.
Bottom-of-bed, north (crust on surface)	A_3S_2, CAS_2(T), S_c, (Na,K)$_2AS_2$[g], C_2AS(trace). Core surface blackened.	
Bottom-of-bed, north (material below surface)	A_3S_2, S_c, CAS_2(T), α-A, CA(trace). CAS_2 moderately well crystallized.	A_3S_2, S_c, CAS_2(T), α-A, CA(trace). Similar to hot face, CAS_2 moderately well crystallized
Mid-bed, east	A_3S_2, S_c, CAS_2(T), α-A, (Na,K)$_2AS_2$[g], CAS_2(H), CA(trace).	A_3S_2, S_c, CAS_2(T), α-A, CAS_2(H), CA. Both forms of CAS_2 poorly crystallized.
Mid-bed, north	A_3S_2, CAS_2(T), S_c, (Na,K)$_2AS_2$[g], α-A, CA(trace).	A_3S_2, S_c, CAS_2(T), CAS_2(H), α-A, CA(trace). Both forms of CAS_2 poorly crystallized.
Bed-freeboard interface[f]	CAS_2(T), A_3S_2, S_c, α-A, (Na,K)$_2AS_2$[g], C_2AS.	
DENSE CALCINED FLINT CLAY CASTABLE[b]		
Control Specimen[e]	A_3S_2, S_c, CA, CA_2.	
Mid-bed, south	A_3S_2, CAS_2(T), S_c, C_2AS, (Na,K)$_2AS_2$[g], CA, CAS_2(H)(trace).	A_3S_2, S_c, CAS_2(T), CAS_2(H), CA. CAS_2(T) less well crystallized than at hot face.
Mid-bed, west	(Na,K)$_2AS_2$[g], C_2AS, A_3S_2, CAS_2(T), S_c(trace).	A_3S_2, S_c, CAS_2(T), CAS_2(H), CA, C_2AS. Both forms of CAS_2 poorly crystallized.
Mid-bed, north	CAS_2(T), A_3S_2, C_2AS, (Na,K)$_2AS_2$[g], S_c.	A_3S_2, S_c, CAS_2(H), CAS_2(T), CA. CAS_2(T) poorly crystallized.
Mid-bed, northeast	A_3S_2, CAS_2(T), C_2AS, (Na,K)$_2AS_2$[g], S_c, CA, α-A. Sample includes black crust.	A_3S_2, S_c, CAS_2(T), CAS_2(H), CA. Both forms of CAS_2 poorly crystallized.
Upper bed[f]	A_3S_2, CAS_2(T), S_c, C_2AS, CA, CA_2.	
Bed-freeboard interface[f]	CAS_2(T), A_3S_2, S_c, (Na,K)$_2AS_2$[g], C_2AS, CA_2(trace).	
Mid-freeboard[f]	A_3S_2, CAS_2(T), S_c, (Na,K)$_2AS_2$[g], C_2AS, CA_2(trace).	
Top-of-freeboard[f]	CAS_2(T), A_3S_2, (Na,K)$_2AS_2$[g], S_c, α-A, C_2AS. Small sample, difficult to crush.	

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[a] Phases determined by x-ray diffraction; compounds listed in apparent order of abundance, silicate formulae are idealized; cement notation use, A = Al_2O_3, C = CaO, S = SiO_2, S_c = cristobalite, H = hexagonal, T = triclinic, trace = $\leq 0.3\%$.

[b] Lining hot face consisted of a 6-in layer of an abrasion-resistant castable (~37% SiO_2, 57% Al_2O_3, 6% CaO; Lo-Abrade, A. P. Green) in the lower "boot" section of the vessel and the same material was used as vapor stops at several heights; the rest of the vessel had a hot face lining of a dense calcined flint clay castable (~40% SiO_2, 50% Al_2O_3, 10% CaO; KS-4V, A. P. Green).

[c] Conoco Lignite Gasification Pilot Plant, CO_2 Acceptor Process, was in operation about five and one-half years; the time the system operated fully at temperature (1500-1600°F) and pressure (150 psig) was about 3/4 year; the number of pressure cycles to which the refractory was subjected was at least 175, the number of temperature cycles at least 123, the number of runs 72; gaseous environment varied widely from run to run but steam was one of the major reactants to which the refractory was subjected; in approximately one half of the runs char was used, in the latter half lignite was used.

[d] Core samples were drilled with a two-inch, water-cooled diamond core drill; samples were from various locations within the portion of the vessel occupied by the char(lignite)-dolomite fluidized bed; the compass point designations were a convenient way to keep track of samples; core samples could not be taken from the upper levels because of the extreme hardness of the material, only small chips could be obtained from the hot face surface; hot end designates the portion of a core close to the hot face surface; cold end designates the portion of a core adjacent to the underlying insulating refractory or, in the case of cores taken from vapor stops, adjacent to the metal shell of the vessel.

[e] Control specimens are laboratory-prepared and fired to 900°C for 16 hr.

[f] Chip samples only, not from cores.

[g] Nepheline, $(Na_{1.5}K_{0.5})Al_2Si_2O_8$ (idealized formula).

COMPRESSIVE STRENGTH DATA[a] FOR THE GASIFIER REFRACTORY LINING[b] OF A GASIFICATION PILOT PLANT[c] [18]

MATERIAL	Sample Location[d]	Compressive Strength[a] MPA	(psi)	Density kg/m³
ABRASION-RESISTANT CASTABLE[b]				
	Control Specimens[e]	41.5	(6,024)	2120.5
	Bottom-of-bed, east, cold end	118.8	(17,238)	2100
	hot end	114.3	(16,584)	2057
	Bottom-of-bed, south, cold end	51.4	(7,460)	
	hot end	58.8	(8,579)	1934.5
	Mid-bed, east, cold end	57.9	(8,406)	2015
	hot end	83.0	(12,040)	1996
	Mid-bed, north, cold end	70.4	(10,205)	1979
	hot end	95.8	(13,897)	2028.8
DENSE CALCINED FLINT CLAY CASTABLE[b]				
	Control Specimens[e]	21.5	(3,114)	2042.2
	Mid-bed, south, cold end	48.7	(7,069)	1925
	hot end	42.8	(6,216)	1920.5
	Mid-bed, north, cold end	42.0	(6,116)	1915
	hot end	60.6	(8,796)	1909
	Mid-bed, west, hot end	39.2	(5,682)	1931.7

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[a] Compressive strength was tested on a commercial compression machine; samples were 1 in x 0.5 in x 0.5 in, cut by diamond sawing and diamond surface grinding; direction of compression was along the long dimension of the sample; crosshead speed was 0.1 cm/min; each value is an average of two samples from the same end of the core.

[b] Lining hot face consisted of a 6-in layer of an abrasion resistance castable (∿37% SiO_2, 57% Al_2O_3, 6% CaO; Lo-Abrade, A. P. Green) in the lower "boot" section of the vessel and the same material was used as vapor stops at several heights; the rest of the vessel had a hot face lining of a dense calcined flint clay castable (∿40% SiO_2, 50% Al_2O_3, 10% CaO; KS-4V, A. P. Green).

[c] Conoco Lignite Gasification Pilot Plant, CO_2 Acceptor Process, was in operation about five and one-half years; the time the system operated fully at temperature (1500-1600°F) and pressure (150 psig) was about 3/4 year; the number of pressure cycles to which the refractory was subjected was at least 175, the number of temperature cycles at least 123, the number of runs 72; gaseous environment varied widely from run to run but steam was one of the major reactants to which the refractory was subjected; in approximately one half of the runs char was used, in the latter half lignite was used.

[d] Core samples were drilled with a two-inch, water-cooled diamond core drill which yielded a core 1 3/4 inches in diameter; samples were from various locations within the portion of the vessel occupied by the char(lignite)-dolomite fluidized bed; core samples could not be taken from higher levels because of the extreme hardness of the material in the upper regions; the compass point designations were a convenient way to keep track of samples; hot end designates the portion of a core close to the hot face surface; cold end designates the portion of a core adjacent to the underlying insulating refractory or, in the case of cores taken from vapor stops, adjacent to the metal shell of the vessel.

[e] Control specimens are laboratory-prepared and fired to 900°C for 16 hr.

EROSION DATA[a] FOR THE GASIFIER REFRACTORY LINING[b] OF A GASIFICATION PILOT PLANT[c] [18]

MATERIAL Sample Location[d]	Erosion[a] kg/kg abrasive	Density kg/m^3
ABRASION-RESISTANT CASTABLE[b]		
Control specimen[e]	1.03×10^{-2}	2100.8
Control specimen[e]	9.36×10^{-3}	2115
Bottom-of-bed, east, cold end	4.49×10^{-3}	2112
hot end	5.50×10^{-3}	2081.1
Bottom-of-bed, south, hot end	6.67×10^{-3}	1921.1
Bottom-of-bed, north, hot end	2.42×10^{-3}	2079
Mid-bed, east, hot end	5.88×10^{-3}	1957.9
Mid-bed, north, cold end	3.63×10^{-3}	1967.7
hot end	4.37×10^{-3}	2051
DENSE CALCINED FLINT CLAY CASTABLE[b]		
Control specimen[e]	1.07×10^{-2}	2043
Control specimen[e]	1.02×10^{-2}	2035
Mid-bed, south, cold end	7.51×10^{-3}	1899
hot end	6.52×10^{-3}	1970.9
Mid-bed, north, cold end	4.87×10^{-3}	1980.5
hot end	6.18×10^{-3}	1925.5
Mid-bed, north-east, hot end	5.98×10^{-3}	1934
Mid-bed, west, hot end	6.71×10^{-3}	1934

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[a] Erosion samples were 0.5 in x 0.5 in x 0.5 in, cut by diamond sawing and diamond surface grinding; samples were subjected to erosion by 100 mesh SiC, at 30 psig, ambient temperature, 90° angle of impingement, 400 grams of abrasive per sample.

[b] Lining hot face consisted of a 6-in layer of an abrasion resistant castable (∿37% SiO_2, 57% Al_2O_3, 6% CaO; Lo-Abrade, A. P. Green) in the lower "boot" section of the vessel and the same material was used as vapor stops at several heights; the rest of the vessel had a hot face lining of a dense calcined flint clay castable (∿40% SiO_2, 50% Al_2O_3, 10% CaO; KS-4V, A. P. Green).

[c] Conoco Lignite Gasification Pilot Plant, CO_2 Acceptor Process, was in operation about five and one-half years; the time the system operated fully at temperature (1500-1600°F) and pressure (150 psig) was about 3/4 year; the number of pressure cycles to which the refractory was subjected was at least 175, the number of temperature cycles at least 123, the number of runs 72; gaseous environment varied widely from run to run but steam was one of the major reactants to which the refractory was subjected; in approximately one half of the runs char was used, in the latter half lignite was used

[d] Core samples were drilled with a 2-in, water-cooled diamond core drill which yielded a core 1-3/4 inches in diameter; samples were from various locations within the portion of the vessel occupied by the char(lignite)-dolomite fluidized bed; the compass point designations were a convenient way to keep track of samples; core samples could not be taken from higher levels because of the extreme hardness of the material in the upper region; hot end designates the portion of a core close to the hot face surface; cold end designates the portion of a core adjacent to the underlying insulating refractory or, in the case of cores taken from vapor stops, adjacent to the metal shell of the vessel.

[e] Control specimens are laboratory-prepared and fired to 900 °C for 16 hr.

POROSITY AND DENSITY[a] FOR SAMPLES OF THE GASIFIER REFRACTORY LINING[b] OF A GASIFICATION PILOT PLANT[c] [18]

MATERIAL Sample No.[d]	Apparent Porosity[a] %	Water Absorption[a] %	Apparent Specific Gravity[a] x 1000	Bulk Density[e] kg/m^3
ABRASION-RESISTANT CASTABLE[b]				
1	31.578	16.295	2832	1938
2	30.481	15.485	2832	1968
3	30.057	15.224	2823	1974
4	30.465	15.511	2825	1964
5	30.069	15.369	2798	1956
6	29.718	14.987	2821	1983
7	29.446	14.811	2818	1988
8	29.238	14.688	2813	1991
DENSE CALCINED FLINT CLAY CASTABLE[b]				
1	31.001	15.928	2821	1946
2	30.543	15.495	2838	1971
3	30.584	15.613	2822	1959
4	30.150	15.279	2825	1973
5	29.192	14.596	2825	2000
6	30.124	15.269	2823	1973
7	30.678	15.684	2822	1956
8	30.498	15.514	2828	1966

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[a] Apparent porosity, water absorption, and specific gravity were all measured according to ASTM C20-70.

[b] Lining hot face consisted of a 6-in layer of an abrasion resistant castable (∿37% SiO_2, 57% Al_2O_3, 6% CaO; Lo-Abrade, A. P. Green) in the lower "boot" section of the vessel and the same material was used as vapor stops at several heights; the rest of the vessel had a hot face lining of a dense calcined flint clay castable (∿40% SiO_2, 50% Al_2O_3, 10% CaO; KS-4V, A. P. Green).

[c] Conoco Lignite Gasification Pilot Plant, CO_2 Acceptor Process, was in operation about five and one-half years; the time the system operated fully at temperature (1500-1600 °F) and pressure (150 psig) was about 3/4 year; the number of pressure cycles to which the refractory was subjected was at least 175, the number of temperature cycles at least 123, the number of runs 72; gaseous environment varied widely from run to run but steam was one of the major reactants to which the refractory was subjected; in approximately one half of the runs char was used, in the latter half lignite was used.

[d] Core samples were drilled with a 2-in, water-cooled diamond core drill which yielded a core 1-3/4 inches in diameter; samples were from various locations within the portion of the vessel occupied by the char(lignite)-dolomite fluidized bed; core samples could not be taken from higher levels because of the extreme hardness of the material in the upper regions; samples were prepared from both the hot face end of the cores and from the cold end adjacent to underlying insulation or the vessel shell; the samples are in random order since there was little difference in the values from location to location.

[e] Bulk density was determined from the measured dimensions and weight of samples.

A.2.2.2.2 COMPONENT TEST AND DEVELOPMENT

Since it is vital to maintain the integrity of a refractory lining and therewith the capability of the refractory to protect the covered metal from chemical attack and thermal effects, it is important to use proper installation techniques to minimize the effect of thermal shock causing cracking and spalling. Experimental work has been done with small cast panels and test pressure vessels to determine the effect of anchor types and spacing, installation techniques, firing rates, and temperature on crack patterns and sizes and on shrinkage.

In one set of tests, small (15 in. x 18 in.) panels were prepared with 12-inch thick refractory (Section A.2.2.2.2.1). Various anchor types were used, with various firing schedules, and the crack patterns formed were observed. The 12-inch refractory layer consisted of about seven inches of 50 percent alumina lightweight commercial insulating castable and about five inches of 90 percent alumina dense generic castable for most of the tests; one test panel consisted of 12 inches of 50 percent alumina dense generic castable. Most of the firing schedules utilized heating rates of 100 °F/hour; but, in two tests using faster rates (260 °F/hour and 480 °F/hour), the panels spalled explosively. In general, the longer the holding times at low temperature and the slower the heating and cooling rates, the fewer and smaller were the cracks which formed.

A second set of tests (see A.2.2.2.2.2) was performed using a test pressure vessel of seven-foot overall height, four-foot working height, and an inner diameter of five feet, which was heated internally and pressurized with steam. The vessel was lined a number of times and the refractories subjected to various patterns of heating and cooling cycles. The linings were examined visually after each cycle and cores were also taken and examined. Crack widths were measured and crack patterns observed. The same refractories were used as had been used in the small panel tests, a 7.5-inch thick 50 percent alumina insulating layer, a 4.5-inch thick layer of the 90 percent and 50 percent alumina dense castables, plus one test which included a 56 percent alumina refractory. Just as had occurred in the panel tests, a high heating rate after a relatively short holding period at lower temperatures caused explosive cracking and spalling. Because the crack pattern was found to be related to the pattern of the anchors and because many cracks propagated through the hard-face layer to the insulation, sometimes to the shell, the rest of the tests were done with linings installed in such a way that bonding barriers between refractory and anchors and between refractory layers existed. These barriers, materials which are destroyed during firing, were a thin layer of ceramic paper fiber or plastic film between the layers of dense and insulating refractory, ceramic paper, plastic film, or a coating of silicone grease between the vessel shell and the insulating refractory, and a thin wrap of masking tape or asphalt-based tape around the anchors. From the tabulation in A.2.2.2.2.2, the following general conclusions may be drawn. Placement of a bonding barrier between the dense and insulating layers of the lining is an effective method of preventing propagation of cracks through the interface. Although cracking patterns frequently follow anchor spacings, coating the anchors does reduce this relationship and much finer and fewer cracks result. Coating the metal shell also provides for fewer cracks in the insulation layer. For both the high- and medium-alumina refractories, installation with bonding barriers improved performance with respect to crack formation and propagation. As the linings were heat cycled, there was no appreciable increase in crack formation during second or even third heating cycles, even when the vessel was steam pressurized as part of the cycle.

Core samples of these test refractory linings were not only examined visually, but some physical and mechanical property measurements were also made. Density measurements were made by immersion, volume, and mercury porosity techniques. The values reported in Section A.2.2.2.2.4 are averages of ten (in some cases, five) samples from each location, each from separate drill cores. Measurements include values for both hot face and cold ends of the cores. Examination of the data shows that there is no real difference in refractory densities attributable to the heat treatment or the location of the samples or the test method, compared with the densities for laboratory-prepared specimens (controls). The following table demonstrates this fact for the dense castables; the insulating castable data has greater scatter, but the average is in good agreement.

Refractory	Density of Controls	Firing Temp. of Controls	Average All Core Samples, Tests & Methods	Maximum Difference Average & Core	Difference Core Avg. & Controls
90% castable	166 kg/m^3	2000 °F	177 kg/m^3	2.3%	6.6%
50% castable	136	1850	140	3.9	2.9
50% insulation	85	1500	85	19.	0.

The porosity data show much greater scatter but no obvious trends to indicate changes due to exposure to the thermal or pressure cycling. Unfortunately, as-cast or fired porosity data are not available.

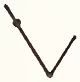
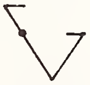
Cold crushing strength tests (see A.2.2.2.2.5) and diametral compression tests yielding splitting tensile strength data (see A.2.2.2.2.3) were performed on samples taken from the cores of the liner to determine the effect of thermal cycling on the refractory strength. The data are not extensive, but examination of these results given in the Table A.2.2.2.2a indicates possible trends. As is to be expected, higher temperatures tend to increase strength. Although the data are sparse, there is an indication that the presence of steam somewhat weakens the 90 percent alumina dense castable but strengthens the 50 percent alumina dense castable to a marked extent. The insulating refractory seems not to be affected in a consistent way, probably because penetration of steam completely through the dense hard-face layer of the lining is minimal, and even the effect of temperature is not consistent. These data, indicating an effect of steam, are consistent with the information included in Sections A.2.2.2.1 and A.2.2.2.3.

Refractory	Maximum Exposure Temperature	Splitting Tensile Strength	Cold Crushing Strength
90% dense castable (hot face values)	1200 °F	985 psi	8004 psi
	2000	1870	13160
	1950	1880	15672
	1850 + steam	1563	9939
50% dense castable (hot face values)	1200	260	2964
	1200 + steam	638	
	1850 + steam	715	
	1850 + steam	879	5732
50% insulating castable (interface values with 90% hard face)	800	200	1750
	1500	220	1293
	1500	340	2081
	1400 + steam	230	1341
50% insulating castable (interface values with 50% hard face)	800	270	2248
	1200 + steam	401	
	1400 + steam	558	2228

Table A.2.2.2.2a

PANEL CASTING[a] AND TESTING SUMMARY[26]

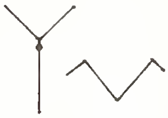
EFFECT OF FIRING AND HEAT CYCLING ON CRACK FORMATION AND SPALLING

Panel Composition	Anchors	Comments on Mixing and Casting Procedure	Firing Schedule[b]	Crack Pattern
Insulation: 50% Al_2O_3 lightweight castable,[c] 26% casting water 7 in thick Hardface: 90+% Al_2O_3 dense generic castable,[d] 10.3% casting water 5 in thick	None	Lightweight Dense Mixer 4 ft^3 4 ft^3 Batch size 75 lb 175 lb H_2O/pour temp. -/- -/- Ball-in-hand - sticky Vibration table concrete vib. Other - insulation plastic covered and cured 60 hrs. Dense troweled lightly and plastic covered overnight. Six day (70°F) cure outside of mold. 4 ft^3 mortar mixer stalled on both components. Some settling in insulation from table vibration.	16 hrs at 400°, 100°/hr to 1000°, 3 hrs at 1000°, 100°/hr at 1800° T_{max}, Cooled at 100°/hr	Many small interconnected cracks on hot face. Propagated from 1 to 5 in into dense component.
Insulation: 50% Al_2O_3 lightweight castable,[c] 26% casting water 7 in thick Hardface: 90+% Al_2O_3 dense,[d] generic castable 10.3% casting water 5 in thick	Standard Y uncoated 6 in spacing	Mixer 4 ft^3 4 ft^3 Batch size 100 lb 175 lb H_2O/pour temp. -/- -/- Ball-in-hand good wet, sticky Vibration concrete vib. in & outside mold. Other - Motor hp. increased on mixer. OK for insulation but mixer stalled with dense material. Concrete vibrator worked well against mold. 3 day cure in mold plastic covered at ∿70°F.	16 hrs at 400°, 100°/hr to 1000°, 3 hrs at 1000° 100°/hr to 2000° T_{max}, Cooled at 100°/hr	Many small interconnected cracks on hot face. Propagated from 1 to 5 in into dense component. Other cracks at interface and in insulator.
Insulation: 50% Al_2O_3 lightweight castable,[c] 26% casting water 7 in thick Hardface: 90+% Al_2O_3 dense generic castable,[d] 9.3% casting water 5 in thick	Standard Y wax coated 6 in spacing	Mixer 4 ft^3 4 ft^3 Batch size 75 lb 2-75 lb H_2O/pour temp. -/- -/- Ball-in-hand good wet to good Vibration concrete vib. in and outside mold. Other - Dense material cast in 2 parts. Mixer OK. Concrete vib. only good when placed against mold. Six day cure in mold plastic covered at 70°F.	18 hrs at 300°, 100°/hr to 1800°, 12 hrs at 1800° T_{max}, Cooled at 100°/hr	Separation between panel and base plate. Almost no visible cracks in hot face. Few cracks in insulator perpendicular to base plate.
Insulation: 50% Al_2O_3 lightweight castable,[c] 20% casting water 7 in thick Hardface: 90+% Al_2O_3 dense generic castable,[d] 9.3% casting water 5 in thick	6-V type with straight legs 6 in spacing uncoated 	Mixer 4 ft^3 4 ft^3 Batch size 100 lb 2-100 lb H_2O/pour temp. -/- -/- Ball-in-hand good good Vibration concrete vib. in and outside mold. Other - Dense surface troweled smooth to identify cracks. Cast surface covered with wet blotter paper & plastic. Cured 4 days at 65°F.	16 hrs at 200°, 100°/hr to 700°, 260°/hr to 770° when panel spalled explosively. Many small pieces from front 2 in of dense material. Panel blown out of furnace door. Firebrick baffle used to distribute heat.	Spalled explosively at 770°F
Insulation: 50% Al_2O_3 lightweight castable,[c] 21% casting water 7.5 in thick Hardface: 90+% Al_2O_3 dense generic castable,[d] 9.3% casting water 4.5 in thick	6-V type with leg ends bent inward 6 in spacing uncoated 	Mixer 4 ft^3 4 ft^3 Batch size 100 lb 2-100 lb H_2O/pour temp. 84°/78°F 86°/79°F Ball-in-hand good good Vibration concrete vib. in & outside mold. Other - Warm H_2O caused fast set in both components. Surface wire brushed when cast. Wrapped in Kaowool to maintain hydration temp. Panel wt. - 284 lb	13 hrs at 200°, 480°/hr to 1000° when panel spalled explosively. Hot face spalled into 4 large pieces with anchors imbedded and threads stripped. (Controller malfunction)	Spalled explosively at 1000°F

(Table Continued)

PANEL CASTING[a] AND TESTING SUMMARY[26]

(Table Continued)

Panel Composition	Anchors	Comments on Mixing and Casting Procedure	Firing Schedule[b]	Crack Pattern
Insulation: 50% Al_2O_3 lightweight castable,[c] 21% casting water 7.5 in thick Hardface: 90+% Al_2O_3 dense generic castable,[d] 9.3% casting water 4.5 in thick	3-Y type 1-V type set in insulator 8½ in x 8½ in x 12 in spacing 	Lightweight / Dense Mixer: 4 ft^3 / 4 ft^3 Batch size: 100 lb / 2-100 lb H_2O/pour temp.: -/70°F / -/70°F Ball-in-hand: good / good Vibration: concrete vib. in & outside mold. Other - surface wire brushed when cast. Cool H_2O temp. gave better mixing & working time. Wrapped in plastic & Kaowool. Panel wt - 284 lb	22 hrs at 170°, 26 hrs at 450°, 100°/hr to 1000°, 14 hrs at 1000°, 125°/hr to 2000°, 3 hrs at 2000°, Cooled at 100°/hr. 10% H_2O loss after firing.	Random and interconnected network of shallow cracks on hot face with some extending from anchor/refractory interface.
Insulation: 50% Al_2O_3 lightweight castable,[c] 21% casting water 7.5 in thick Hardface: Modified 90+% Al_2O_3 dense generic castable,[e] 8.5% casting water 4.5 in thick	3-Y type 1-V type set in insulator 8½ in x 8½ in x 12 in spacing 	Mixer: 4 ft^3 / 12 ft^3 Batch size: 100 lb / 600 lb H_2O/pour temp.: 100°/78°F / -/73°F Ball-in-hand: poor, crumbly / excellent Vibration: concrete vib. in & outside mold. Other - insulation temp. = 58°. Hot H_2O resulted in 15 min set time. Insulation and dense material wrapped in plastic & Kaowool. Excellent mixing action with large mixer.	14 hrs at 100°, 22 hrs at 170°, 26 hrs at 450°, 100°/hr to 1000°, 3 hrs at 1000°, 100°/hr to 2000°, 4 hrs at 2000°, Cooled 100°/hr to 900°, 50°/hr to 500°.	Very few cracks on hot face. Those found are shallow and not interconnected.
Single component: 50% Al_2O_3 dense generic castable,[f] 10% casting water 12 in thick	3 anchors straight legs 7 in long 8½ in x 8½ in x 12 in spacing 	Mixer: 12 ft^3 Batch size: 550 lb H_2O/our temp.: 70°/70°F Ball-in-hand: fair Vibration: concrete vib. in & outside mold. Other - Used 5% ball mill fines plus 0.1% boric acid as hydration retarder. Wrapped in plastic & Kaowool. Stored with wet sponge. Panel wt. = 285 lb.	16 hrs at 180°, 16 hrs at 450°, 100°/hr to 1000°, 3 hrs at 1000°, 100°/hr to 2000°, 5 hrs at 2000°, Cooled 300°/hr to 1600°, 100°/hr to 1000°, 50°/hr to ambient temp.	Single crack across hot face. Several cracks parallel to and approximately 5 in from hot face.

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[a] Test panels were 15 in by 18 in by 12 in thick.

[b] All temperatures are °F.

[c] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

[d] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[e] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[f] Generic preparation: 75% calcined kaolin (70% 6 to -20 mesh, 5% ball milled fines, 50% less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

CRACKING AND SHRINKAGE OF REFRACTORIES SUBJECTED TO VARYING HEATING SCHEDULES^{a} AND ANCHOR CONFIGURATIONS IN A TEST PRESSURE VESSEL^{b}[26]

Lining Material^{c}	Anchor Configuration	Heating Schedule^{a}	Crack Width^{d} ver.	Crack Width^{d} hor.	% Shrinkage^{e} ver.	% Shrinkage^{e} hor.	Observations
90% Al$_2$O$_3$ generic castable^{f}	12 in vertical spacing, 18 in circumferential, V anchors	200°F for 16 hr, 400°F for 16 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 1200°F, cool at 50°F/hr to ambient.					Crack pattern seen to be related to anchor spacing; no cracks observed to have propagated from dense to insulation layer.
		400°F for 16 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 2000°F, 2000°F for 5 hr, cool at 50°F /hr to ambient.	up to 1/8 in				Cracks enlarged and new cracks formed; cracks continuous from dense layer through interface and insulation, many almost to shell; cracks intersect at anchor and/or refractory interface.
90% Al$_2$O$_3$ generic castable	12 in vertical spacing, 18 in circumferential, V anchors, coated with 0.020-0.030 in masking tape	200°F for 16 hr, 400°F for 16 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 1200°F, cool at 50°F/hr to ambient.	0.028	0.102	0.2	0.2	Little or no anchor/refractory bond, but anchors still affecting crack formation; crack patterns similar to above test; one 5 in diameter spalled area.
90% Al$_2$O$_3$ generic castable/ ceramic fiber paper 0.030 in thick placed between vessel shell and insulation, and between dense layer and insulation	No anchors	100°F/hr to 200°F, 200°F for 16 hr, 100°F/hr to 400°F, 400°F for 16 hr, cool at 50°F/hr or slower to ambient.	0.005	0.005	0.05	0.05	Numerous fine cracks on the hotface but no horizontal and vertical pattern as before.
		100°F/hr to 400°F, 400°F for 8 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 1200°F, cool at 50°F/hr or slower to ambient.	0.017	0.010	0.09	0.11	Increased cracking but still in random pattern; explosive cracking/ spalling at 800-1000°F due to high heating rate; caused 1/2-1 in wide crack around entire circumference of hotface; no cracks propagated through the interface.
		100°F/hr to 400°F, 400°F for 5 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 2000°F, 2000°F for 5 hr, cool at 50°F/hr or slower to ambient.	0.020	0.018	0.14	0.17	Little change in crack pattern from last heat; still no great degree of crack propagation through interface.
90% Al$_2$O$_3$ generic castable/ ceramic fiber paper 0.046 in thick placed between vessel shell and insulation, plastic film 0.004 in thick between dense layer and insulation	12 in vertical spacing, 30 in circumferential for standard Y anchors, 36 in circumferential for Longhorn Y anchors to anchor the insulation to the chell independently; most but not all anchors coated with 0.100 in thick asphalt-based tape^{g}	50°F/hr to 1000°F, 100°F/hr to 1200°F, cool at 50°F/hr or slower to ambient.	0.016	0.009	0.07	0.10	Fairly fine cracks, no propagation through interface; still related to anchor locations.
		50°F/hr to 1000°F, 100°F/hr to 1850°F, 1850°F for 10 hr at 120 psig steam, depressurize and cool at 50°F/hr or slower to ambient.	0.031	0.017 0.032^{k}	0.16	0.21 0.36^{k}	Only slight increase in cracking, pattern more random than in other tests with anchors.
50% Al$_2$O$_3$ commercial castable^{h}/ 0.004 in thick plastic film at vessel shell and between dense layer and insulation	same specifications as above but with all anchors coated with tape	50°F/hr to 1000°F, 100°F/hr to 1200°F, cool at 50°F/hr or slower to ambient.	0.007	0.005	0.04	0.04	Fewer and finer cracks than in previous tests at 1200°F, no gap at refractory interface.
		50°F/hr to 1000°F, 100°F/hr to 1850°F, hold 3 hr while pressurizing to 140 psig, 1850°F and 140 psig steam for 10 hr, depressurized and cool at 50°F or slower to ambient.	0.034	0.030 0.024^{k}	0.21	0.26 0.26^{k}	Less cracking than in tests with 90% alumina material.

(Table Continued)

CRACKING AND SHRINKAGE OF REFRACTORIES SUBJECTED TO VARYING HEATING SCHEDULES[a] AND ANCHOR CONFIGURATIONS IN A TEST PRESSURE VESSEL[b][26]

(Table Continued)

Lining Material[c]	Anchor Configuration	Heating Schedule[a]	Crack Width[d] ver.	Crack Width[d] hor.	% Shrinkage[e] ver.	% Shrinkage[e] hor.	Observations
50% Al_2O_3 commercial castable/ vessel shell was coated with silicone grease, 0.004 in thick plastic film between dense layer and insulation	average spacing between anchors 30 in, standard Y anchors, all anchors coated with 0.100 in thick asphalt-based tape[g]	50°F/hr to 1000°F, 100°F/hr to 1200°F, steam pressurizing from 350°F at 15 psig/hr, hold at 1200°F and 150 psig for 48 hr, depressurize and cool at 50°F/hr to ambient.	0.007	0.005	0.04	0.04	Less cracking than in previous linings; only very fine cracks in dense layer except one large one; cracks follow anchor spacing; very few cracks in insulation, cracks which propagated through the interface extended only few inches into insulation from dense layer.
		50°F/hr to 1000°F, 100°F/hr to 1850°F, steam pressurizing from 350°F at 15 psig/hr, hold at 1850°F and 150 psig for 35 hr, depressurize and cool at 50°F/hr to ambient.	0.004 0.020[k]	0.012	0.03 0.48[k]	0.07	Less cracking than in other linings tested at 1850 or 2000°F; most cracks did not propagate entirely through each component.
50% Al_2O_3 commercial castable with 4 wt% 310SS[i] fiber added/ vessel shell was coated with silicone grease, 0.004 in thick plastic film between dense layer and insulation.	average spacing between anchors 30 in, standard Y anchors, all anchors coated with 0.100 in thick asphalt-based tape[g]	50°F/hr to 1000°F, 100°F/hr to 1700°F, 1700°F for 10 hr, cool at 50°F/hr or slower to ambient.	0.012[j]		0.10[j]		Only very fine cracks on hotface, pattern of cracks similar to earlier tests running horizontally and vertically.
		50°F/hr to 1000°F, 100°F/hr to 1700°F, pressurize with air to 100 psig, hold at 1700°F and 100 psig for 10 hr, depressurize and cool at 50°F/hr or slower to ambient.	0.009[j]		0.095[j]		No additional cracking, cracks still very fine.
		100°F/hr to 1850°F, 1850°F for 10 hr, cool at 50°F/hr or slower to ambient.	0.012[j]		0.13[j]		No additional cracking, some cracks widened, but few visible to the naked eye; no propagation to the interface from the hotface; some fine cracks in the insulation but no propagation to shell.

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[a] Linings were subjected to the conditions given in the table, but were frequently cored and sampled, then patched before being subjected to the next test cycle.

[b] Test pressure vessel has an inner diameter of 5 ft, a 7-ft overall height with a 4-ft working height; vessel was heated internally.

[c] All linings had an insulation layer 7.5 in thick consisting of a commercial lightweight 50% Al_2O_3 insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories). The dense component named in the table was 4.5 in thick. For several tests bonding barriers were placed between the insulation and the vessel shell and at the interface between the two refractory layers.

[d] Crack widths given are average values. Cracks were measured at 90° intervals horizontally around the lining and at three 15 in intervals vertically. Units are inches.

[e] Linear shrinkage calculations assume summation of crack widths account for shrinkage in vertical and horizontal directions from the as-cast condition.

[f] DOE 90 generic preparation: 70% tabular alumina (T-61, Alcoa), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[g] Presstite, Virginia Chemicals.

[h] Coarse grain size, high strength 50% Al_2O_3 prototype castable (B&W 36C, Babcock & Wilcox).

[i] 1-in long fibers of 310 SS (Ribtec 310).

[j] Average of cracks in vertical and horizontal directions.

[k] Average of cracks in vertical and horizontal directions for the insulating component of the lining.

TENSILE STRENGTH DETERMINED BY DIAMETRAL COMPRESSION TESTING[a] OF REFRACTORY SAMPLES FROM LININGS[b] OF A TEST PRESSURE VESSEL[c] [26]

Lining No.	Heating Schedule	Lining Material[b]	Sample Location[d]	Tensile Strength[a] psi
1	First cycle: 200°F for 16 hr, 400°F for 16 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 1200°F, cool at 50°F/hr to ambient. Second cycle: 400°F for 16 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 2000°F, 2000°F for 5 hr, cool at 50°F/hr to ambient.	90% Al_2O_3 dense generic castable[e]	Hot Face	1870
		50% Al_2O_3 lightweight insulating castable[f]	Interface	220
2	200°F for 16 hr, 400°F for 16 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 1200°F, cool at 50°F/hr to ambient.	90% Al_2O_3 dense generic castable	Hot Face	985
		50% Al_2O_3 lightweight insulating castable	Interface	200
3	First cycle: 100°F/hr to 200°F, 200°F for 16 hr, 100°F/hr to 400°F, 400°F for 16 hr, cool at 50°F/hr or slower to ambient. Second cycle: 100°F/hr to 400°F, 400°F for 8 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 1200°F, cool at 50°F/hr or slower to ambient. Third cycle: 100°F/hr to 400°F, 400°F for 5 hr, 100°F/hr to 1000°F, 1000°F for 3 hr, 100°F/hr to 2000°F, 2000°F for 5 hr, cool at 50°F/hr or slower to ambient.	90% Al_2O_3 dense generic castable	Hot Face Interface	1880 1110
		50% Al_2O_3 lightweight insulating castable	Interface	340
4	First cycle: 50°F/hr to 1000°F, 100°F to 1200°F, cool at 50°F/hr or slower to ambient. Second cycle: 50°F/hr to 1000°F, 100°F/hr to 1850°F, 1850°F for 10 hr at 120 psig steam, depressurize and cool at 50°F/hr or slower to ambient.	90% Al_2O_3 dense generic castable	Hot Face Interface	1563 1185
		50% Al_2O_3 lightweight insulating castable	Interface Cold Face	230 255
5	First cycle: 50°F/hr to 1000°F, 100°F/hr to 1200°F, cool at 50°F/hr or slower to ambient.	50% Al_2O_3 commercial castable[g]	Hot Face Interface	260 305
		50% Al_2O_3 lightweight insulating castable	Interface Cold Face	270 250
	Second cycle: 50°F/hr to 1000°F, 100°F/hr to 1850°F, hold 3 hr while pressurizing to 140 psig, 1850°F and 140 psig steam for 10 hr, depressurize and cool at 50°F or slower to ambient.	50% Al_2O_3 commercial castable	Hot Face	715
6	First cycle: 50°F/hr to 1000°F, 100°F/hr to 1200°F, steam pressurizing from 350°F at 15 psig/hr, hold at 1200°F and 150 psig for 48 hr, depressurize and cool at 50°F/hr to ambient.	50% Al_2O_3 commercial castable	Hot Face (As-Cast) Interface (As-Cast)	638 (521) 515 (552)
		50% Al_2O_3 lightweight insulating castable	Interface (As-Cast) Cold Face (As-Cast)	401 (362) 370 (387)
	Second cycle: 50°F/hr to 1000°F, 100°F/hr to 1850°F, steam pressurizing from 350°F at 15 psig/hr, hold at 1850°F and 150 psig for 35 hr, depressurize and cool at 50°F/hr to ambient.	50% Al_2O_3 commercial castable	Hot Face Interface	879 781
		50% Al_2O_3 lightweight insulating castable	Interface Cold Face	558 333

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[a] Splitting tensile test designed around ASTM test C496-71 was used; specimens were 1-in thick cylinders, sectioned from 2-in diameter drill cores; specimens were compressed between 1/32-in aluminum sheets along a diameter direction to failure.

[b] Linings cast in test vessel consist of an insulation layer 7.5 in thick and a dense component 4.5 in thick.

[c] Test pressure vessel is 5 ft in inner diameter, 7 ft in overall height with a 4 ft working height; vessel heated internally.

[d] Samples were taken at different stages with respect to the heating cycles to which they were subjected. The first linings were core drilled only after all of the heating cycles were completed; later linings were core drilled after each cycle then patched for the next cycle. Also, samples examined in early linings were not from complete core depth as in later tests.

[e] DOE 90 generic preparation: 70% tabular alumina (T-61, Alcoa), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[f] Commercial lightweight 50% alumina insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

[g] Coarse grain size, high strength 50% alumina prototype castable (B&W 36C, Babcock & Wilcox).

EFFECT OF HEAT CYCLING[a] ON THE DENSITY AND POROSITY OF REFRACTORY FROM LININGS OF A TEST PRESSURE VESSEL[b] [26]

Lining Material	Sample Location[b]	Maximum Exposure[a] Temperature, °F	Density[d], lb/ft^3 Immersion	Density[d], lb/ft^3 Mercury	Density[d], lb/ft^3 Volume	Porosity[d], % Immersion	Porosity[d], % Mercury
90% Al_2O_3 dense generic castable[e]	Hot Face	2,000	173		177	17.1	17.4
	Interface	1,800	176		176	16.4	15.2
50% Al_2O_3 castable insulation[f]	Interface	1,500	80		81	36.6	21.8
	Cold Face	400	88		74	37.7	18.7
90% Al_2O_3 dense generic castable	Hot Face	1,200	181		175	15.2	9.5
	Interface	950	180.6		174	14.8	9.3
50% Al_2O_3 castable insulation	Interface	800	78.5		74.7	35.1	19.7
	Cold Face	210	78		74.8	32.4	24.0
90% Al_2O_3 dense generic castable	Hot Face	1,950	177	178.6	176	15.7	15.8
	Interface	1,650	176	178.0	174	16.8	16.2
50% Al_2O_3 castable insulation	Interface	1,500	85.6	89.7	82.9	36.2	43.8
	Cold Face	450	87.2	96.8	85.3	26.5	44.3
90% Al_2O_3 dense generic castable	Hot Face	1,800[h]	179	180	178.7	13.6	11.3
	Interface	1,600	179	180	178.8	14.2	14.1
50% Al_2O_3 castable insulation	Interface	1,400	76	74	77	39.6	28.2
	Cold Face	450	77.5	87.7	77.4	41.4	34.7
50% Al_2O_3 commercial castable[g]	Hot Face	1,200	141	143	135		12.8
	Interface	950	141	145	135		12.4
50% Al_2O_3 castable insulation	Interface	800	87	87	86.5		29.1
	Cold Face	210	86	88.5	85		34.2
50% Al_2O_3 commercial castable	Hot Face	1,800[h]		139	137		19.9
	Interface	1,600		139	136		18.9
50% Al_2O_3 castable insulation	Interface	1,400		86	83		36.5
	Cold Face	450		89	85		45.2
50% Al_2O_3 commercial castable	Hot Face	1,200[h]		144[i]	139[i]		14.5
	Interface	950		145.5[i]	139[i]		13
50% Al_2O_3 castable insulation	Interface	850		101.5[i]	90[i]		29
	Cold Face	350		98[i]	88[i]		30
50% Al_2O_3 commercial castable	Hot Face	1,850[h]		142[i]	139[i]		18
	Interface	1,550		141.5[i]	139[i]		18
50% Al_2O_3 castable insulation	Interface	1,400		98[i]	84.7[i]		31
	Cold Face	500		95.5[i]	88[i]		34

[a] The refractory linings were subjected to a variety of heating cycles with varying patterns of holding at various temperatures and some cycles with the vessel sealed and pressurized; temperatures listed are the maximum values reached by the samples during the heating cycles to which they were subjected.

[b] Test pressure vessel has an inner diameter of 5 ft, a 7-ft overall height with a 4-ft working height; vessel was heated internally. Linings consist of 7.5 in thick insulation layer and 4.5 in thick dense component.

[c] Samples were taken from drill cores; the designations indicate the distance of the sample from the hot face surface: Hot Face = 1/2 in, Interface (dense layer) = 4 in, Interface (insulation) = 5 in, Cold Face = 11 in.

[d] Densities and porosities were determined by immersion, volume, and mercury porosity techniques; density values are each the average of 10 samples from each location, each taken from separate drill cores, except for values marked with i which are the average of 5 samples; porosity values are the average of 2 samples. Sample densities may be compared with densities (volume, lb/ft^3) of laboratory samples: 90% Al_2O_3 material from cast bars, as cured 179, dried at 250 °F 175, fired to 2000 °F 166, fired to 1800 °F 165; 50% Al_2O_3 insulation, from bars corresponding to linings with 90% Al_2O_3 dense component, as cured 79.4, dried at 250 °F 76.0, fired to 1500 °F 85, fired to 400 °F 82; insulation for linings with 50% Al_2O_3 dense component, as cast values reported varied 86 to 100.2, dried at 250 °F from 84.6 to 89.2, fired to 1400 °F 85, fired to 500 °F 82; 50% Al_2O_3 dense component, as cast values reported varied 141 to 147.4, dried at 250 °F from 137.7 to 141.6, fired to 1850 °F 136, fired to 1550 °F 136.

[e] DOE 90 generic preparation: 70% tabular alumina (T-61, Alcoa), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[f] Commercial lightweight 50% Al_2O_3 insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

[g] Coarse grain size, high strength 50% Al_2O_3 prototype castable (B&W 36C, Babcock & Wilcox).

[h] The vessel was steam pressurized at 120-140 psig for these cycles.

[i] These values are the average of 5 samples, see footnote d.

COLD CRUSHING STRENGTHS[a] OF REFRACTORY FROM LININGS OF A TEST PRESSURE VESSEL[b][26]

Lining Material[b]	Sample Location[c]	Maximum Exposure[d] Temperature, °F	Cold Crushing Strength[a] psi
90% Al_2O_3 dense	Hot Face	2,000	13,160
generic castable[e]	Interface	1,800	11,787
50% Al_2O_3 castable	Interface	1,500	1,293
insulation[f]	Cold Face	400	1,778
90% Al_2O_3 dense	Hot Face	1,200	8,004
generic castable	Interface	950	9,439
50% Al_2O_3 castable	Interface	800	1,750
insulation	Cold Face	210	1,324
90% Al_2O_3 dense	Hot Face	1,950	15,672
generic castable	Interface	1,650	8,611
50% Al_2O_3 castable	Interface	1,500	2,081
insulation	Cold Face	450	2,413
90% Al_2O_3 dense	Hot Face	1,800[h]	9,939
generic castable	Interface	1,600	7,392
50% Al_2O_3 castable	Interface	1,400	1,341
insulation	Cold Face	450	1,563
50% Al_2O_3 commercial	Hot Face	1,200	2,964
castable[g]	Interface	950	2,575
50% Al_2O_3 castable	Interface	800	2,248
insulation	Cold Face	210	2,098
50% Al_2O_3 commercial	Hot Face	1,800[h]	5,732
castable	Interface	1,600	4,910
50% Al_2O_3 castable	Interface	1,400	2,228
insulation	Cold Face	450	2,332

[a] Each value is the average of the results of testing 5 samples from each location, each taken from separate drill cores. Values may be compared with hot crushing strength values for laboratory samples of the same materials: 90% Al_2O_3 castable, at 2000 °F, 8455 ±420 psi, at 1500 °F, 9130 ± 1480 psi; 50% Al_2O_3 castable insulation, at 1500 °F, 5330 ±430 psi, at 500 °F, 3490 ± 180 psi; 50% commercial castable, at temperatures between 950 °F and 1800 °F, values ranged around 3300 psi.

[b] Test pressure vessel has an inner diameter of 5 ft, a 7-ft overall height with a 4-ft working height; vessel was heated internally. Linings consist of 7.5 in thick insulation layer and 4.5 in thick dense component.

[c] Samples were taken from drill cores; the designations indicate the distance of the sample from the hot face surface: Hot face = 1/2 in, Interface (dense layer) = 4 in, Interface (insulation) = 5 in, Cold face = 11 in.

[d] Linings were subjected to a variety of heating cycles with varying patterns of holding at various temperatures and some cycles with the vessel sealed and pressurized; temperatures listed are the maximum values reached by the samples during the heating cycles to which they were subjected.

[e] DOE 90 generic preparation: 70% tabular alumina (T-61, Alcoa), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[f] Commercial lightweight 50% Al_2O_3 insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

[g] Coarse grain size, high strength 50% Al_2O_3 prototype castable (B&W 36C, Babcock & Wilson).

[h] The vessel was steam pressurized at 120-140 psig for these cycles.

A.2.2.2.3.1 CHEMICAL AND PHASE CHANGES

OVERVIEW

A knowledge of the chemical and physical changes in refractories in use in coal conversion vessels is necessary from two points of view: first, the formation of the initial refractory and second, the reaction of the refractory to its use environment. The formation of the initial refractory is normally dependent on a series of reactions which occur during its preparation and firing which may include hydration, dehydration, and formation of new chemical species through reaction of preexisting compounds. The reaction products, will ultimately determine the chemical, physical, and mechanical properties of the materials. In addition to the chemical composition, the physical attributes, i.e. aggregate size and size distribution, may play a significant role in defining the properties of a refractory. One further complication should be noted. The performance of any refractory material can be greatly influenced by the installation technique used.

During use, potential problem areas include chemical reaction of the refractory constituents with components of the gasification atmosphere to produce compounds with less desirable properties, i.e. lower melting point, less erosion resistance, lower mechanical strength, or having large volume changes. To a large extent the integrity, strength, and chemical and physical resistance is primarily dependent upon the formation and retention of strong bonding phases occurring in the cement portion as opposed to the aggregate of the refractory. The reactions and changes involving cement portions of refractory castables are found to be of particular importance. A knowledge, therefore, of cement bonding phases and their stability ranges is critical to the successful application of refractory linings.

LABORATORY TESTS

THE EFFECT OF CONSTITUENTS OF COAL GASIFICATION ATMOSPHERES on the mineral phases present in various refractories is tabulated in a number of subsections in B.1.2.

Eleven alumina refractories were examined for phases present after curing and drying, after firing to 1100 °C, and after exposure of fired samples to steam, to hydrogen, to carbon monoxide, and to a mixed gas environment like that given in section B.0 for various times at 1100 °C and 1000 psi (see B.1.2.5). The phases were identified by means of x-ray diffraction. The refractories tested had alumina contents ranging from 95 percent to 45 percent. Some were castables, both calcium aluminate bonded and phosphate bonded, and some were bricks. One of the test samples was neat calcium aluminate cement. The data are not complete for all refractories under all test conditions.

Hydrogen had little effect generally on high-alumina materials except for two brick refractories. One of the two observed component phases, β-alumina (β-$NaAl_{11}O_{17}$), disappeared after hydrogen exposure of these high-alumina bricks. The only effect observed due to CO exposure was the decrease in certain calcium aluminates ($CaAl_2O_4$, $CaAl_4O_7$, $CaAl_2O_{19}$, and $Ca_2Al_2SiO_7$) in the high- and medium-alumina calcium aluminate-bonded castables. One might expect weakened materials because of this loss since these compounds are bonding phases. Steam or the mixed gas, which is intended as a simulated coal gasification atmosphere, had a greater effect, especially with respect to medium-alumina (45 to 60 percent) calcium aluminate-bonded castables or brick refractories. High-alumina castables or brick showed less change. The major change in castables appeared with regard to bonding phases, the various calcium aluminate compounds. The calcium aluminates tended to disappear and another bonding phase, anorthite ($CaAl_2Si_2O_8$), to form. Neat calcium aluminate cement when tested only showed a slight increase in β-$NaAl_{11}O_{17}$ in steam. This same compound disappeared under steam exposure in the 99 percent and 90 percent alumina brick. The medium-alumina brick showed apparent conversion in steam of the α-cristobalite to tridymite.

THE EFFECT OF STEAM is shown more directly in a series of experiments which subjected alumina castable refractories to hydrothermal treatment (see B.1.2.6 and B.1.2.7). The hydrothermal treatment consisted of exposing samples to saturated steam in a pressure vessel at varying temperatures or at a single temperature followed by exposure to various test temperatures. The refractories were generic and commercial calcium aluminate-bonded castables, three of which were medium-alumina (50, 55.6 and 55 percent) and one high-alumina (95 percent). For medium-alumina castables the general trend as the temperature is raised is to observe fewer different constituent phases in the samples. The hydrothermal treatment reduces the number of phases also. For medium-alumina materials the phases which are consistently present upon exposure to heat and steam are mullite ($Al_6Si_2O_{13}$), cristobalite (SiO_2), and anorthite ($CaAl_2Si_2O_8$). Other phases, particularly hydrated phases, tend to disappear with temperature. The one high-alumina castable tested formed gibbsite ($Al_2O_3.3H_2O$) and boehmite ($Al_2O_3.H_2O$) at the lower temperatures and these disappeared at higher temperatures. A combination of steam and carbon dioxide was used as a test media for a 94.4 percent alumina generic castable bonded with calcium aluminate cement (see B.1.2.8). The refractory was exposed to 70% H_2O-30% CO_2 in a pressure vessel at temperatures up to 910 °C. X-ray diffraction analysis of the mineral phases showed the formation of hydrated phases $Al_2O_3.3H_2O$, $Ca_3Al_2O_6.6H_2O$, $Al_2O_3.H_2O$ as well as calcium carbonate and β-alumina (β-$NaAl_{11}O_{17}$). α-Alumina, $CaAl_4O_7$ and $CaAl_2O_4$ are the original constituents which remain present but in varying amounts.

Another series of experiments performed on a medium-alumina generic castable (55.6 percent alumina) (see B.1.2.9) showed that the same 70% H_2O-30% CO_2 composition at temperatures up to 910 °C increased the amount of the anorthite component of the refractory but no evidence of calcium carbonate was reported. Only trace amounts were found when the atmosphere was 50% H_2O-50% CO_2 and none was detected when the atmosphere was pure carbon dioxide.

THE EFFECT OF HEAT TREATMENT on the mineral phases of high- and medium-alumina castables is given in section B.1.2.10. The results of heating the refractories to 1350 °C is consistent with the pattern seen in the experiments with steam and various gases. The very high alumina (75 percent tabular alumina/25 percent calcium aluminate cement) castable is largely α-alumina with smaller amounts of $CaAl_2O_4$, $CaAl_2O_4.10H_2O$ and $Al_2O_3.3H_2O$. These small amounts of hydrated phases appear at low temperatures (ambient to 200 °C) and disappear at higher temperatures. At the higher temperatures $CaAl_4O_7$ and $CaAl_{12}O_{19}$ appear. The medium-alumina refractories (75 percent mullite aggregate with calcium aluminate cement) maintain a fairly consistent composition with regard to major constituents, mullite, cristobalite, $CaAl_2O_4$, $CaAl_4O_7$, etc. over the lower temperature ranges with anorthite appearing at 800 °C and becoming a major constituent at 1200 °C. The two refractories made with calcined kaolin aggregate did show formation of appreciable amounts of anorthite at 1200 and 1350 °C. A 50 percent alumina insulating castable showed traces of anorthite formation at 1200 °C. The heat stability of phases in these same refractories was studied by differential thermal analysis and the results appear in section B.1.2.11. It is apparent that the data in B.1.2.11, all showing changes between 250-300 °C, are consistent with the dehydration of the hydrated calcium aluminates above 200 °C as indicated by the x-ray diffraction data in B.1.2.10.

THE MINERAL PHASES OF NEAT CALCIUM ALUMINATE CEMENT as affected by steam was studied in a pressure vessel so constructed that specimens could be examined in situ by energy dispersive x-ray diffraction (see B.1.2.12). Temperature was varied from 25 °C to 1000 °C and pressure from ambient to 1130 psig for time periods from 1 to 46 hours. The initial compounds, $CaAl_2O_4$, $CaAl_4O_7$ and α-alumina, are diminished in proportion as hydrated aluminas and calcium aluminates are formed. These hydrated compounds remain the major phases up to about 400 °C when boehmite ($Al_2O_3.H_2O$) begins to dissociate. At and above 500 °C there is no evidence for the existence of any hydrated compounds. The major constituent of the cement at 600 °C and above is $CaAl_4O_7$ with a very small amount of α-Al_2O_3. In other experiments samples of five neat calcium aluminate cements were exposed to simulated coal gasification atmospheres and then examined by x-ray diffraction and differential thermal analysis and thermogravimetric analysis (see B.1.2.20). One cement was the same high-purity (79 percent alumina, 18 percent calcia) cement tested and reported in B.1.2.12. The initial materials, primarily alumina and $CaAl_2O_4$, formed boehmite and calcite in the simulated coal gasification atmosphere (see B.0) at 500 °C and 500 psi pressure. The exposure periods were 10, 20, and 30 days. Exposures to the coal gasification atmosphere for the same periods of time at 1000 °C and 1000 psi produced no boehmite as shown by the x-ray diffraction and the differential thermal and thermogravimetric analyses. Two other cements, both 72 percent alumina and ∿25 percent calcia, tested the same way showed similar compounds formed with the addition of $CaAl_4O_7$ as an important phase which was not found in the higher alumina cement. Two medium-alumina cements were tested, both containing some titania, one 58 percent alumina + titania with 33 percent calcia and one 44 percent alumina + titania with 36 percent calcia. For these cements alumina was not generally present, the major constituent phases being $CaAl_2O_4$, $CaAl_4O_7$, and $Ca_2Al_2SiO_7$. The data show boehmite formation at the lower temperatures and a lack of boehmite at the higher temperatures.

TESTING IN COAL GASIFICATION ATMOSPHERE was also performed on seven high-alumina (91 to 95 percent) castables and four medium-alumina (54 to 59 percent) castables under the same conditions as the testing of the neat calcium aluminate cements (see B.1.2.17 and B.1.2.18). In addition to the coal gasification atmosphere, some tests were done in steam-carbon monoxide atmospheres at 465 psi and 390, 500, and 1000 °F for 10 day periods. The effects of exposure were studied using the same methods as with the neat cements. The results for all the high-alumina dense castables were essentially the same. The initial material consisted of alumina. Boehmite and calcite formed as major constituents in addition to the alumina as the materials were exposed to the coal gasification atmosphere at 500 °C and 500 psi, or at 447 °C and 1000 psi. Tests in steam-carbon monoxide at 465 psi and 500 °C and below also showed alumina, boehmite and calcite as major constituents. Just as with the neat cements the boehmite was not found after exposure to these atmospheres when the temperature was 1000 °C. In the medium-alumina dense and lightweight insulating castables, boehmite was not found under any conditions except in minor and trace quantities by means of x-ray diffraction. The differential thermal and thermogravimetric analyses showed amounts of boehmite comparable to those found in the high-alumina castables. Cycling tests (see B.1.2.21) were run specifically to determine the effect of steam-saturated vapor and liquid exposure to temperature-pressure cycling on the phases present in seven alumina castables, especially with regard to boehmite formation and decomposition. The test atmospheres included steam alone and steam-saturated coal gasification gases. The cycling tests included exposure to the test atmosphere for five days followed by firing at 1000 °C in air for 18 hours. The dense castables included 93 percent alumina, 87 percent alumina, 64 percent alumina-28 percent silica, and 58 percent alumina-30 percent silica and the data for these show that the boehmite which forms at temperatures at or below 500 °C is decomposed by the firing at 1000 °C. Other calcium aluminates do not persist with this treatment. The x-ray data show mostly alumina with calcite as a minor phase present for the high-aluminas, and mullite as the major phase and some alumina and calcite present for the medium-aluminas. The three insulating low-aluminas tested also show an absence of boehmite, but the data are sparse for two of these materials.

THE EFFECT OF EXPOSURE TO ALKALI ON THE ALKALI CONTENT of some refractories was tested. Nine refractories were exposed to alkali-gas, and alkaline solution-alkali gas. These refractories included two high-alumina calcium aluminate-bonded dense castables (one commercial product and one generic preparation), three medium-alumina calcium aluminate-bonded dense castables (all commercial products), one dense high-alumina phosphate-bonded castable (commercial), one high-alumina phosphate-bonded ramming mix (commercial), and one medium-alumina calcium aluminate-bonded insulating castable, and one medium-alumina fired brick (commercial). The results of a variety of exposures to alkali are given in B.1.2.4 expressed as Na_2O-K_2O content of exposed samples in weight percent. Not all samples were tested in all of the various exposures. Table A.2.2.2.3.1a summarizes the data. It is readily seen that appreciable amounts of alkali are taken up by the refractories even if only the minimum values are considered. The exposure methods included exposure only to alkali vapor as well as soaking in alkali solutions. The effect of the increase of alkali content on the mechanical properties of the refractories is discussed in A.2.2.2.3.4.

THE EFFECT OF A "HIGH-BTU" GAS MIXTURE (21.7% H_2, 17.0% CO, 11.6% CO_2 4.7% CH_4, and 45% H_2O) ON THE SILICA CONTENT of a 55 percent alumina castable at 980 °C and 1000 psi for 250 hours was studied (see B.1.2.2). The refractory, a dense alumina-fireclay calcine aggregate with calcium aluminate cement, was exposed in the form of bars, powder, and crushed material and the silica content measured for intervals of exposure of 50 hours. Exposure of the bar samples to

Refractory and Cement	Alkali Content in Weight Percent					
	Prefined Samples		Minimum for All Exposures		Maximum for All Exposures	
	K_2O	Na_2O	K_2O	Na_2O	K_2O	Na_2O
Dense 95% tabular Al_2O_3 castable (Castolast G) high-purity calcium aluminate (CA-25)	0.008	0.018	0.24	0.33	2.40	1.4
Dense 90% tabular Al_2O_3 castable (Generic Preparation) high-purity calcium aluminate (CA-25)	0.01	0.20	0.24	0.22	1.5	1.5
Dense 55% Al_2O_3 fire clay calcine castable (Lo-Abrade) high-purity calcium aluminate (CA-25)	0.54	0.28	1.4	0.51	5.00	2.0
Dense 45% Al_2O_3 fire clay calcine castable (H.S. Brikcast BF) medium-purity calcium aluminate (Refcon)	0.12	0.06	0.82	0.30	3.3	2.0
Dense 45% Al_2O_3 fire clay calcine castable (B & W Kaocrete D) low-purity calcium aluminate (Secar 50)	0.26	0.04	1.8	0.52	3.5	2.0
Dense 90% tabular Al_2O_3 castable (Resco Cast AA-22) phosphate	0.008	0.07	0.70	0.33	2.4	1.1
Lightweight 50% Al_2O_3 insulating castable pyrophyllite aggregate (Lite-cast 75-28) high-purity calcium aluminate (CA-25)	---	---	3.00	1.20	6.00	2.70
90% tabular Al_2O_3 ramming mix (Brikram 90R) phosphate bond	0.02	0.15	1.1	0.53	2.20	1.10
45% Al_2O_3 fired super duty brick, clay aggregate (KX-99)	---	---	1.30	0.29	2.10	0.65

Table A.2.2.2.3.1a (see text for legend) gas with a calculated superficial velocity of 0.04 ft/min for varying times resulted in no significant change in silica content (about 1 weight percent). Exposure of powder resulted in a slight increase in silica content (maximum of 4 weight percent). Scanty test data for crushed samples exposed to gas with a calculated superficial velocity of 1.4 ft/min indicated a possible decrease in silica content (maximum of 6 percent). It should be noted that the data are limited but do not indicate serious silica loss under the test conditions.

THE EFFECT OF DIFFERENT ENVIRONMENTS ON A HIGH-ALUMINA PHOSPHATE-BONDED REFRACTORY was tested (Section B.1.2.3). The refractory, a 90 percent alumina ramming mix, was analyzed for P_2O_5 content by wet chemical methods after the test exposures. There was an increase in phosphorus oxide content (compared with cured but unexposed samples) after air-firing at 1100 °C for 24 and 250 hours, after exposure to steam at 1100 °C and 1000 psi for 250 hours, after exposure to CO at 1100 °C and 1000 psi for 125 hours, and after exposure to carbon dioxide at 1100 °C and 800 psi for 250 hours. Samples exposed to a simulated coal gasification environment (see B.0) at 1000 °C and 1000 psi for 160 hours showed no significant change in phosphorus oxide content. The P_2O_5 content of a sample exposed to H_2 at 1100 °C and 1000 psi for 250 hours was drastically reduced from 2.97 wt percent to 0.03 wt percent. There was apparently no loss of strength (see footnote, B.1.2.3) due to this loss of binder. Three high-alumina phosphate-bonded ramming mixes were subjected to a simulated coal gasification atmosphere at 500 °C and 500 psi and at 1000 °C and 1000 psi. The exposure times for both sets of conditions were periods of 10, 20, and 30 days (see B.1.2.19). X-ray diffraction analyses of the exposed materials compared with analyses of air-fired samples showed no major changes due to exposure. The basic components given are alumina and forms of aluminum phosphate. The exposures to the coal gasification atmosphere seem to enhance the crystallinity of the berlinite form of aluminum phosphate for at least two of the materials since the berlinite is listed as increasing from trace amounts to minor or major phases after exposure. It is difficult to say how much of this effect is due just to the increased temperature. The exposures seem to have little other compositional effect on these refractories. One of these ramming mixes (90 percent alumina) is included in section B.1.2.5 in which the effect of various gaseous exposures on mineral phases was investigated by x-ray diffraction. In B.1.2.5 the phases are listed as alumina, with quartz and cristobalite, and no aluminum phosphate which should be present is mentioned. It should be pointed out that aluminum phosphate occurs in forms which are structural analogs of the various forms of silica, i.e. quartz, cristobalite, and tridymite. The x-ray diffraction peaks of the various forms of silica and aluminum phosphate are extremely close together and mask each other. This masking effect probably is the reason that no aluminum phosphate is mentioned in section B.1.2.5 and no silica forms are mentioned in B.1.2.19 although small amounts were probably present.

THE EFFECT OF CO ON IRON-CONTAINING REFRACTORIES was investigated since iron may be present as an impurity in many refractories and it has been implicated in carbon monoxide disintegration of refractories. Generic preparations of three types of refractory were tested: 90 percent alumina and 50 percent alumina castables, both calcium aluminate-bonded, and a 90 percent alumina phosphate-bonded ramming mix (see B.1.2.13). The refractories were doped with varying amounts of iron, 0.5, 1.0, and

2.0 weight percent. Samples were exposed at 500 °C for 100 hours, to carbon monoxide at 600 psi and 200 psi, to 80% CO-20% H_2O at 200 psi and 500 psi, and to a simulated coal gasification atmosphere (14% CO, 5% CO_2, 45% H_2, 17% H_2O, 17% CH_4, 0.1% H_2S) at atmospheric pressure. Exposures to CO and CO-H_2O caused complete or partial disintegration of Fe-doped samples whereas undoped samples were not seriously affected except for the 50 percent alumina material which showed serious degradation in CO at 600 psi. Exposure to the mixed gases of the coal gasification atmosphere did not seem to affect doped or undoped samples at all.

SILICON CARBIDE AND SIALON REFRACTORIES have been tested for the effect of the mixed gas environment on the compounds present in these materials (see B.1.2.1). The SiC, whether oxynitride-, silicate-, or direct-bonded, completely disintegrated after 1000 hour exposure to 24% H_2, 18% CO, 12% CO_2, 5% CH_4, 1% H_2S, 2% NH_3, and 38% H_2O at 980 °C and 1000 psi. The breakdown of the material is due to formation of SiO_2 (as cristobalite with traces of quartz). The sialon samples remained intact but an outer layer of mullite and cristobalite formed which indicates some chemical effect of the gases on the material. Whether this outer layer indicates the beginning of disintegration or a protective layer is not known. Further testing is necessary since the data are limited.

PILOT PLANT TESTING

THE EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS is shown in section B.1.2.16. Specimens of various refractories were placed on test racks in a total of eight locations within five pilot plants. Not all refractories were tested in all locations, and for some plants there was only one exposure, for others two or three exposures. Rotating rod abrasion testing of exposed specimens was performed at ambient temperature and at 1400 °F and the results compared with abrasion tests performed on unexposed samples. The data are expressed as volume loss of material and depth of penetration of the test rod. The tests are not meant as a measure of abrasion or erosion resistance but as a measure of changes which may have occurred in the bonding of the refractories as a result of exposure in the plant. The full conditions to which the samples were exposed are not available. Exposure times, when given, are approximate, as are the concentrations of the chemical constituents of the atmospheres, the temperatures, and the pressures. During plant operation these variables would have fluctuated widely and the extent and duration of these fluctuations is unknown. Not all specimens were subjected to abrasion testing at 1400 °F. Evaluation of the numerical data is difficult since percentage differences for exposed vs. unexposed data do not seem equally reliable for all cases and multiplicate samples were not tested. The results for separate exposures in the same location differ widely for many of the materials. Table A.2.2.2.3.1b contains a qualitative summary of the data in B.1.2.16 and constitutes an attempt to indicate materials which should be tested further and those which may not be worth testing further. In the light of all of the uncertainties outlined above, the data must be viewed with caution.

The symbols used in Table A.2.2.2.3.1b carry the following meaning:

nt	the material was not tested in that location
-	the percent change in data between unexposed and exposed samples is less than or about equal to 50 percent in either direction

Results of Refractory Coupon Testing in Pilot Plant Locations

Refractories	Synthane 1	Synthane 2	CO_2 Acceptor 1	CO_2 Acceptor 2	Bi-Gas	Battelle 1	Battelle 2	HYGAS
CASTABLES, CALCIUM ALUMINATE-BONDED								
90+% Al_2O_3 dense (Purolite 30)	W	nt	W	W	nt	nt	nt	nt
90+% Al_2O_3 dense (Greencast-97)	nt	nt	W	W	nt	nt	nt	W
90+% Al_2O_3 light (Greencast-97L)	-	-	-	W	nt	nt	nt	nt
90% Al_2O_3 dense (Castolast G)	W	-	W	W	nt	nt	nt	W
60% Al_2O_3 dense (Mizzou Castable)	B	B	-	W	nt	nt	?	B
60% Al_2O_3 dense (Super Brikcast A)	B	B	B	-	B	nt	nt	B
55% Al_2O_3 lightweight insulating (Litecast 75-28)	W	-	W	W	W	nt	nt	W
52% Al_2O_3 light (Litecast 80)	W	nt	W	W	nt	nt	nt	nt
PHOSPHATE-BONDED REFRACTORIES								
90% Al_2O_3 dense castable (Resco Cast AA-22)	-	-	W	W	W	W	W	nt
90% Al_2O_3 ramming mix (Brikram 90)	-	W	-	B	-	B	B	-
73% Al_2O_3 dense ramming mix (Blu Ram)	-	nt	nt	nt	nt	nt	nt	nt
73% Al_2O_3 dense ramming mix (Blu Ram H.S.)	-	nt	nt	nt	nt	nt	nt	nt
60% Al_2O_3 ramming mix (Wasp #60)	-	-	W	B	nt	nt	nt	nt
85% Al_2O_3 dense fired brick (Chemal 85 B)	W	-	W	W	-	-	nt	-
85% Al_2O_3 fired brick (Altex 85-B)	W	W	-	-	nt	nt	nt	W
80+% Al_2O_3 fired brick (Alumex P-8)	W	-	B	-	nt	-	nt	W
ALUMINA BRICKS								
99+% Al_2O_3 self-bonded dense fired (H-W Corundum)	-	-	W	W	nt	nt	nt	-
99+% Al_2O_3 self-bonded fused-cast dense (Monofrax A)	B	B	-	B	nt	nt	nt	nt
98+% Al_2O_3 self-bonded light insulating fired (Alfrax B 101)	W	-	W	W	nt	nt	nt	-
90+% Al_2O_3 self-bonded dense fired (Kricor)	-	-	-	-	nt	nt	nt	-
77% Al_2O_3 vitreous bond light insulating fired (B&W Insalcor)	W	-	W	W	nt	nt	nt	W
70% Al_2O_3 vitreous bond fired (Mul-8)	-	-	-	-	nt	-	nt	B
70% Al_2O_3 vitreous bond fired (Hi Lumite 70 D)	W	-	W	-	nt	nt	nt	-
70% Al_2O_3 vitreous bond dense fired (Alumex 70-HD)	nt	nt	-	-	-	nt	nt	-
60% Al_2O_3 tar-impregnated fired (Ufala TI)	-	-	-	-	-	nt	-	nt
45-50% Al_2O_3 vitreous bond high-fired superduty (KX-99)	-	-	-	-	nt	nt	-	-
MISCELLANEOUS BRICKS								
SiC silicon nitride-bonded dense fired (Refrax 20)	W	W	W	B	nt	nt	nt	nt
SiC silicon oxynitride-bonded (Crystolon 63)	W	W	W	B	nt	nt	nt	nt
SiC clay-bonded	nt	nt	nt	nt	nt	?	?	nt
Alumina-zirconia-silica fused-cast	W	nt	nt	nt	nt	nt	nt	nt
Zirconium silicate vitreous bond	nt	-	W	nt	nt	nt	nt	nt
90% Alumina-10% chromia solid solution fired (CS 612)	nt	nt	-	-	nt	nt	nt	nt

Table A.2.2.2.3.1b (see text for legend)

W	worse--the percent change in data between unexposed and exposed specimens is greater than 50 percent and indicates a weakening of the refractory bond after exposure
B	better--the percent change in data between unexposed and exposed specimens is greater than 50 percent and indicates a strengthening of the refractory bond after exposure
?	data are incomplete--data given only for the unexposed sample or only for the exposed sample

The criteria used in the assignment of these symbols are completely arbitrary. Some trends may be seen in examining Table A.2.2.2.3.1b. Among the dense alumina castables the 60 percent alumina showed more promising performance than the 90 percent alumina. The medium-alumina light castables do not perform well but if used as insulating layers covered with dense castable these materials would not be expected to face the same conditions as the denser materials. The phosphate-bonded materials, whether castable, ramming mix, or brick, showed erratic performance and need further testing for specific applications. Alumina bricks of varying alumina content were tested. No trends are easily observed based on alumina content or brick type except that in general the insulating bricks showed poorer performance. In general, the medium-alumina castables and the alumina bricks showed the best overall performance of the categories of materials tested. SiC bricks received insufficient testing and in general performed very poorly where tested. The other bricks listed, two zirconium-containing and one alumina-chromia, underwent so little testing that no conclusions are possible.

A.2.2.2.3.2 EROSION

OVERVIEW

Erosion occurs in various parts of coal conversion systems as abrasive particles of coal, ash, char, or dolomite are driven by fluid pressures against surface scales and metal or refractory surfaces. Some variables which affect erosion include: type of erodent, erodent particle velocity, shape and hardness, angle of impingement, temperature of material impacted, and condition (including hardness) of impacted material surface. Each of these variables is important in determining the rate at which an erosion process takes place. It is important that any testing methodology which is used to evaluate and rank material performance take into account all of these variables. Highlights of this testing methodology include the following:

1. Erosion weight loss shows a mixed dependence on angle of impingement. In considering the effect of impingement angle on erosion, the character of the materials being subjected to the erosion must be considered, whether ductile (most metallic materials) or brittle (ceramic materials). For ductile (metallic) materials, weight loss shows a peak in the angular range 10-20°, usually followed by a systematic decrease as impingement angle approaches 90°. For brittle (ceramic) materials, the maximum erosion occurs at 90°. Examples of such performance are the data in Sections B.2.1.11 and B.2.1.14, which show erosion data typical of that for ductile materials, and Sections B.2.2.10 and B.2.2.13 (data at 25 °C), which show data typical of brittle materials. (Some variations of brittle materials behavior are to be seen at high temperatures because of phase changes in the refractories.)

2. Erosion weight loss is dependent upon the type of erodent. The rate of erosion tends to decrease as the hardness of the erodent decreases. Since char, ash, and coal particles are not as hard as silicon carbide or aluminum oxide, test results from the latter erodents will be conservative relative to a coal conversion environment.

3. Erosion weight loss increases with increasing erodent velocity in the range 10 to 100 m/s. Data in B.2.1.5, B.2.1.13, B.2.2.7, B.2.2.11, and B.2.2.12, show the trend for both ductile and brittle materials. Some of the erosion data included in this book have been normalized by dividing the weight of sample lost by the weight of erodent used. Generally, a greater amount of erodent creates a greater material loss although when very large amounts of erodent are involved there is not a corresponding increased erosion effect, probably because erodent particles are acting against each other. Section B.2.2.8 contains data showing an initial decrease in erosion at larger particle flux and then the approach of a steady state.

4. Erosion weight loss increases with increasing particle size in the range five to 50 μm. Particle size and erosion are generally directly proportional. In Sections B.2.1.9 and B.2.1.13 there are data showing increased material loss with increased particle size.

5. Erosion weight loss depends upon the temperature of the material impacted, and may increase or decrease with increasing temperature, depending upon the material. Data for alloys in Sections B.2.1.5, B.2.1.9, B.2.1.10, B.2.1.11, and B.2.1.12 do not indicate a definite trend. Conflicting

results are also indicated for refractory materials in B.2.2.8, B.2.2.11, B.2.2.12, and B.2.2.13. Although data in B.2.2.8 and B.2.2.13 show increased erosion loss with increasing temperature, the results in B.2.2.11 and B.2.2.12 are conflicting. For both alloys and refractories, the results seem more dependent on the response of individual materials to increased temperature in terms of possible changes in the properties rather than a direct effect of temperature as a parameter on the phenomenon of erosion.

6. Erosion weight loss depends upon the hardness of the material impacted and tends to decrease slightly as the material hardness increases.

LABORATORY TESTS

THE EROSION OF CASTABLE REFRACTORIES was studied using 150 µm SiC particles at several particle velocities and temperatures. The SiC particles are much harder and, therefore, subject the test materials to more severe erosion than the char and ash in a coal gasifier. Investigators [22] have found that erosion of castables occurs primarily within the cement matrix until enough of the matrix has been eroded away from the harder aggregate particles to permit dislodging of the aggregate particles by the erodent.

THE EFFECT OF IMPINGEMENT ANGLE AND TEMPERATURE is to be seen in B.2.2.10 and B.2.2.13. A high-alumina (95 percent) calcium aluminate-bonded commercial castable was subjected to erosion at varying impingement angles at 25 °C and 1000 °C (see B.2.2.13). The curve of material loss vs. angle at 25 °C for 28 m/s particle velocity fits the pattern expected for the erosion of a brittle material; i.e., less material loss at low angles and a maximum loss at 90°. At 1000 °C and 39 m/s particle velocity the behavior is similar to that expected of ductile materials with a maximum material loss at low angles, evidence that there is plastic flow of the cement matrix occurring at high temperatures. The investigators [22] found small pieces of the SiC erodent embedded in the surface of the matrix and aggregate at the high temperature, also a behavior typical of ductile materials. Three other castable refractories were similarly tested at 25 °C and 1000 °C, but the particle velocities were more than twice that used for the tests just described, 72 m/s at 25 °C and 93 m/s at 1000 °C (see B.2.2.10). Two of the castables tested were calcium aluminate-bonded generic preparations, one high-alumina (∿ 95 percent), and one medium-alumina (∿ 56 percent). The third material was a high-alumina (∿ 90 percent) phosphate-bonded commercial castable. The low temperature performance for all three castables is similar to that discussed in the previous tests, in general lower material loss occurring at low angles, greater loss occurring at high angles. The behavior at 1000 °C for the three castables shown in B.2.2.10 differs considerably from that of the castable shown in B.2.2.13. The investigators [22] ascribed the difference in performance to the higher particle velocities used in the tests in B.2.2.10. Although the erosion at the higher temperatures occurred by a ductile flow mechanism, the higher particle velocities caused deep channels and steps to form. The presence of these channels and steps effectively resulted in a 90° exposure angle for all impingement angles used. The erosion loss curves, therefore, do not resemble those normally found for ductile materials, the loss at the higher particle velocities being less sensitive to the angle than the losses at lower velocities. The low-temperature tests do not show greatly increased material loss as the impingement angle increases.

THE EFFECT OF PARTICLE VELOCITY AND TEMPERATURE can be seen in Section B.2.2.12, where erosion data are shown for various particle velocities and several temperatures for tests at 90° impingement angles. For the high-alumina castables studied, the material loss increased with increasing particle velocity for any given temperature. For a given velocity, the material loss is lower the higher the temperature, apparently due to the higher ductility at high temperatures discussed above with regard to B.2.2.10 and B.2.2.13. The 90° impingement angle is that angle for which the erosion loss is a minimum for ductile materials.

THE EFFECT OF HYDROTHERMAL TREATMENT ON EROSION RESISTANCE OF CASTABLES is shown in B.2.2.7, B.2.2.9, B.2.2.11, and B.2.2.17. Test samples of castable refractories were treated by sealing the samples in pressure chambers with water and heating to various temperatures and pressures for varying periods of time. Erosion testing at ambient temperatures using the SiC erodent was then performed on these samples. A commercial 95 percent alumina castable bonded with calcium aluminate was subjected to erosion testing after hydrothermal treatment at two different temperatures (B.2.2.7). Samples treated at 210 °C showed improved erosion resistance compared to untreated specimens, but samples treated at 510 °C showed decreased erosion resistance. Erosion data for the same castable as well as a commercial 55 percent alumina calcium aluminate-bonded castable are given in B.2.2.9 where the erosion loss is plotted against the temperature of the treatment. The erosion behavior for the high- and medium-alumina castables is markedly different. The high-alumina shows an initial improvement in erosion resistance with treatment up to about 200 °C. Treatment above about 350 °C changes the refractory so that the loss of material upon erosion testing has increased about ten times. This drastic change in erosion resistance is apparently due to the formation of hydrated aluminas and hydrated calcium aluminates and their subsequent decomposition (see A.2.2.2.3.1). The formation of the hydrated compounds apparently strengthens the cement matrix initially but the decomposition with no other suitable bonding phases being formed weakens the matrix considerably. The medium-alumina refractory, however, show little change in erosion resistance, that little change which does occur being an improvement in erosion resistance. This improvement is in accord with the formation of strong bonding phases upon exposure to hydrothermal conditions which is discussed in A.2.2.2.3.1 (see also A.2.2.2.2.1 and A.2.2.2.2.2). Similar hydrothermal treatment was given to two calcium aluminate-bonded medium-alumina generic castables (one 50 percent alumina, one 56 percent alumina) which were erosion tested with SiC at 25 °C and 1000 °C (see B.2.2.11). The data clearly show that for both of these medium-alumina castables, also, the hydrothermal treatment has increased the erosion resistance, whether the erosion tests are conducted at 25 °C or 1000 °C.

THE EFFECT OF EXPOSURE TO VARIOUS ATMOSPHERES AT HIGH TEMPERATURE AND PRESSURE ON THE EROSION RESISTANCE of a variety of refractory materials has been studied. The material loss was measured in accordance with ASTM standard test method C-704-72. After curing and drying, the refractories were fired in air for 250 hours at 1100 °C and the erosion loss of the fired materials measured. Air-fired samples were then exposed to the different atmospheres and the erosion resistance tested. The atmospheres were steam, hydrogen, carbon monoxide, carbon dioxide, and a mixed gas simulating a coal gasification environment: 24 percent hydrogen, 18 percent carbon monoxide, 12 percent carbon dioxide, five percent methane, two percent ammonia, one percent hydrogen sulfide, and 38 percent steam. The full results are given in B.2.2.14 and B.2.2.15 and are summarized qualitatively in Table A.2.2.2.3.2a. Not every refractory was tested under all conditions.

The hydrogen and the simulated coal gasification atmospheres had no serious effect on the erosion resistance of the refractories tested. Only the insulating castable seemed unfavorably affected by the carbon monoxide and the 45 percent alumina dense castable unfavorably affected by the carbon dioxide. The steam exposure had the greatest effect, and that was an enhancement of the erosion resistance of the medium-aluminas (the two calcium aluminate-bonded castables, the dense 55 percent alumina and the lightweight 50 percent alumina castables, and the 45 percent alumina brick).

THE EFFECT OF ADDITION OF CERAMIC FIBER on the erosion resistance of a high-alumina castable is shown in Section B.2.2.16. Various quantities of ceramic fibers (either Al_2O_3-B_2O_3-SiO_2 or Al_2O_3-SiO_2) were added to the castable with varying amounts of water. The effect of varying the amount of water added without fiber was also studied since more water was needed to add the fibers to the castable mixture. Some samples were prepared with wetting agents added to the mix to reduce the amount of water required. Samples prepared with lower amounts of water (ten percent or less) had better erosion resistance than samples with higher water content. If the water content is not more than ten percent, small amounts (one or two percent) of ceramic fiber may improve the erosion resistance but higher fiber content, even with only about ten percent water, seems to lower the erosion resistance.

EROSION TESTING was conducted on a number of materials to screen those which might be considered for valve use but which also might be considered as useful in linings, or parts of linings, or as small internal component parts, such as nozzles, etc. The materials were subjected to erosive attack by alumina for three minutes at impingement angles of 20° and 90° at 20 °C and at an angle of 90° at 700 °C. Not all materials were tested under all three conditions so that there are gaps in the data, as will be seen readily by glancing at any of the part B sections listed in this text. When only one test at one angle is performed, it is not possible to have a true picture of the erosion resistance of the material. The results in terms of sample loss were compared to erosion loss of samples of a cobalt-based alloy, Stellite 6B, arbitrarily chosen as a standard and tested with each set of samples. The data consist of Relative Erosion Factors (REF), values less than one indicating a more erosion resistant material than Stellite 6B, values greater than one indicating a less erosion resistant material. The reported values are the mean of five tests on a material. Although the tests permit a ranking of materials with respect to erosion resistance, it must be borne in mind that the test conditions are not comparable to those seen by the linings or other components in coal gasifiers or other vessels in the plants. The alumina erodent used is much harder than the coal, char, and ash particles to which the materials are subjected in plants, and the tests did not include any of the gaseous chemical constituents of gasifiers. Also, discussion of performance of materials at 20 °C is not of very meaningful value if the prospective material use is in vessels operating at high temperatures and pressures (see operating requirements). Therefore, the high-temperature test results are more important although there are data for only 90° impingement angle, the angle at which brittle materials (refractories) are less erosion resistant.

Meaningful Change in Erosion Resistance After
Exposure as Compared to Air Fired Values
(+ greater resistance/- poorer resistance)

Refractory	Steam	H_2	CO	CO_2	Mixed Gas
Dense 95% Al_2O_3 castable, calcium aluminate bond (Castolast G)	none	none	none	none	none
Dense 55% Al_2O_3 castable, calcium aluminate bond (Lo-Abrade)	+	none	none	none	
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond (Litecast 75-28)	+	none	-	none	none
Dense 45% Al_2O_3 castable, calcium aluminate bond (H.S. Brikcast BF)				-	none
90% Al_2O_3 ramming mix, phosphate bond (Brikram 90R)	none	none	none	none	none
Dense 90% Al_2O_3 castable, phosphate bond (Resco Cast AA-22)				none	none
Calcium aluminate neat cement (78% Al_2O_3) (CA-25)	none	none	none	none	none
99% Al_2O_3 brick (99AD)	none	none	none	none	none
90% Al_2O_3 brick (Arco-90)	none	none	none	none	none
60% Al_2O_3 tar-impregnated brick (Ufala TI)	none	none	none	none	none
45% Al_2O_3 fired super duty brick (KX-99)	+	none	none	none	none

Table 2.2.2.3.2a

Any discussion or ranking of materials using the high temperature data must be tempered by the fact that the 700 °C (1292 °F) test temperature is much lower than prospective gasifier operating temperatures, and the performance at the operating temperatures may be rather different.

REFRACTORY MATERIALS, EITHER ALUMINA OR ALUMINA-BASED, were tested (see B.2.2.1 and B.2.2.2). The data generally show the usual performance of brittle materials in that the 90° impingement angle data indicates a greater loss of material than the 20° angle data. Exceptions to this trend are a low alumina sialon (13 percent Al_2O_3, 87 percent Si_3N_4), an alumina-titanium carbide sample, and experimental compositions of alumina with varying amounts of MgO, TiB_2, and WC. These Al_2O_3-TiB_2-MgO-WC materials and the Al_2O_3-TiC material all had REF values less than 0.4 for 90° angles at both 20 °C and 700 °C. The sialon materials were much less erosion resistant than the standard. None of the rest of the alumina materials tested showed any outstanding erosion resistance, most of them being much poorer than the Stellite 6B standard. Only a densified alumina had REF values around 0.5 for the 90° impingement angle.

SILICON CARBIDE REFRACTORIES of varying types were erosion tested (B.2.2.3). The 29 different materials from commercial sources included 22 different SiC preparations, including hot-pressed, pressed and sintered, and recrystallized materials. There were also two silicon carbides which were silica bonded, two with silicon nitride-silica bond, and one with silicon nitride bond. One material contained ZrB_2 and another had ZrB_2 and graphite. The erosion performance with regard to impingement angle was, as expected, typical of brittle materials, with less erosion for the 20° angle and greater for the 90° angle of attack. The effect of temperature was mixed, 15 materials having less resistance at 700 °C than at 20 °C, four samples showing little or no effect, and four samples having increased resistance.

The plain SiC materials in general had good erosion resistance relative to the standard but with some very wide differences. Most of the plain samples had REF values less than one at both temperatures and both angles of impingement. The performance of SiC with either SiO_2 bond or Si_3N_4 bond was variable depending on the particular specimen but since the complete characterization of the various specimens is not given the reasons for the variability are unknown. SiC with ZrB_2 had good performance but that material with graphite added had very poor erosion resistance. Those samples which had REF values less than 0.5 for 90° impingement angles at both 20 °C and 700 °C are listed below.

Material	REF	
	20 °C	700 °C
SiC, hot-pressed	0.12	0.44
SiC, recrystallized (HD 430)	0.40	0.38
SiC, 98 percent dense	0.05	0.02
SiC (SDIP-1-3)	0.47	0.43
SiC (SDIP-1-4)	0.44	0.43
SiC-Si_3N_4, hot-pressed	0.20	0.42

Other materials showed good erosion resistance at 20 °C, but no data are available for 700 °C.

FOURTEEN CARBONITRIDES were tested at 20 °C and 700 °C at 90° impingement angle (see B.2.2.4). These were mostly experimental compositions having from 85 to 97 percent (Ti, Cr) or (Ti, Mo) carbonitrides and varying percentages of Ni and Mo. None of them showed an REF lower than 0.5, and in general their performance is not significantly better than Stellite 6B. Pressed and sintered TiCN and both pressed and sintered and cast MoTiCN yielded REF values close to one.

SILICON NITRIDE REFRACTORIES (see B.2.2.5) were also tested at both temperatures and both impingement angles. Those which showed good erosion resistance at the 90° angle are listed.

Material	REF	
	20 °C	700 °C
Si_3N_4, hot-pressed	0.18	0.57
Si_3N_4, hot-pressed	0.40	0.12

Reaction-bonded Si_3N_4 had a relative erosion factor of about six for all test conditions. None of the sialon materials (Si_3N_4-Al_2O_3) tested had good erosion resistance, nor did a Si_3N_4-SiC-SiO_2 refractory which had factors close to one.

MISCELLANEOUS MATERIALS were tested and the full results given in B.2.2.6. Those with better erosion resistance than the standard are listed below for the 90° impingement angle.

Material	REF	
	20 °C	700 °C
B_4C, hot-pressed	0.38	0.21
B_4C, hot-pressed	0	0.38
TiC-Al_2O_3, pressed and sintered	0.19	0.30
Cubic BN	0	0

Materials which had poor erosion resistance compared with the standard are TiC with Ni or Ni-Mo binder and several $MgAl_2O_4$-based materials, all hot-pressed with varying amounts of MgO.

Many of the above materials which showed poor erosion resistance because they are brittle in nature and were tested using a 90° impingement angle may perform satisfactorily in design situations in which erodent material impinges on the material surface at low angles.

A.2.2.2.3.3 EROSION/CORROSION

OVERVIEW

Erosion/corrosion occurs where hot gas corrosion and abrasive particle impingement can take place simultaneously. Chemical reaction is influenced by gas composition, refractory composition, temperature, and pressure. Some variables which affect erosion include: type of erodent; erodent particle velocity; shape and hardness of erodent; angle of impingement; temperature of material impacted; condition (including hardness) of impacted material surfaces. Each of these variables is important in determining the rate at which an erosion process takes place. Although erosion may not be a critical problem for the gasifier lining generally, erosion/corrosion can be especially harmful to components of coal conversion plants because of the cyclic nature of the processes. Chemical reactions may take place forming a layer which can be eroded away to present fresh surface to the hot corrosive gases which in time can form more of the new compound(s) which can erode away until the design function can no longer be fulfilled.

LABORATORY TESTS

EROSION/CORROSION EFFECTS ON REFRACTORIES under coal gasification conditions have been studied in a testing program for screening candidate materials (see B.2.2.18). Test samples were subjected to erosion at a 90° impingement angle in a simulated coal gasification atmosphere with 1% H_2S (see Section B.0) at 1800 °F for 100 hours under both atmospheric and 1000 psi pressures using coarse (-20+24 mesh) FMC char at a particle velocity of 100 ft/s. The average corrosion loss of the refractories (in mils) for the one side of the samples exposed to both erosion and corrosion was calculated from thickness measurements of uneroded areas. The maximum erosion/corrosion (Max E/C) loss (in mils) was calculated for the one side exposed to both erosion and corrosion from thickness measurements made in eroded areas and pits. In Section B.2.2.18 both average corrosion and maximum erosion/corrosion have been reported with visual observations. Ten different refractory materials were tested and the results are summarized below for the 2 in x 2 in x 3/4 in bar samples. Values are for one specimen per test.

Only the crudest ranking of the materials is possible on the basis of the very limited data. As might be expected, the better performance is exhibited by brick and dense castables and the poorest performance by the one insulating castable tested. In plant use it is not to be expected that insulating materials would be subject to erosion/corrosion effects. The only parameter which varied was the pressure, and there is a definite trend for most of the refractories showing an adverse effect of increased pressure.

Refractory	Max E/C, in mils	
	1 atmosphere	1000 psi
90% Al_2O_3 castable, calcium aluminate bond (Castolast G)	7.8	2.5
60% Al_2O_3 castable, calcium aluminate bond (Super Brikcast A)	34.4	23.6
54% Al_2O_3 castable, insulating, calcium aluminate bond (Litecast 75-28)	243.8	246.7

85% Al_2O_3 brick, phosphate bond (Chemal 85 B)	17.6	55.6
90% Al_2O_3 brick, self-bond (Kricor)	5.4	26.6
77% Al_2O_3 insulating brick, vitreous bond (B&W Insalcor)	7.0	49.2
70% Al_2O_3 brick, mullite (Alumex 70-HD)	13.9	45.7
60% Al_2O_3 brick, pitch impregnated (Ufala TI)	3.4	15.3
45% Al_2O_3 superduty fire brick (KX-99)	5.2	27.8
90% Al_2O_3-10% Cr_2O_3 brick (Ruby)	5.0	14.0

Another set of refractories was tested (see B.2.2.19) with the same char (FMC), temperature 1800 °F (980 °C), particle velocity 125 ft/s (39 m/s), pressure 35 psi (240 MPa), and the gas composition as in the previous tests. The weight change after 50 and 100 hours of testing was noted. The table below gives the total weight change for 100 hours. In all cases, the bulk of the change had occurred during the first 50 hour period (see B.2.2.19).

Refractory	Weight Change, g (±0.0005 g) for 100 h	% change
98% Al_2O_3 fused cast brick (Monofrax A2)	-0.001	0.001
99+% Al_2O_3 fused cast brick (Monofrax A1)	+0.029	0.03
90+% Al_2O_3 dense castable (Castolast G)	-0.476	0.05
90% Al_2O_3/10% Cr_2O_3 solid solution fired brick (CS 612)	-0.065	0.06
~70% Si_2ON_2, ~20% Si_3N_4, ~10% SiC brick (SION)	+2.901	4.2
90% Al_2O_3 phosphate bond ramming mix (Brikram 90)	-0.059	0.04
90+% Al_2O_3 phosphate bonded castable (Resco Cast AA-22)	-0.370	0.4
72% Al_2O_3, 23% SiO_2 brick (Alumex 70)	-0.500	0.7
62% Al_2O_3 castable (AR 400)	-1.479	1.9

55% Al_2O_3 fire clay aggregate gunning mix (Lo-Abrade GR)	-1.075	1.7
50% Al_2O_3 fused cast brick (Monofrax R)	+0.048	0.04
~57% Al_2O_3 castable (Fraxcast ES)	-4.606 (No visible erosion. Experimental error is suspected to account for weight loss.)	6.2
46% Al_2O_3, 40% SiO_2 castable (B&W Kaocrete HS)	-2.327	4.0
79% SiC, ~18% Si_3N_4 bonded, dense fired brick (Refrax 20)	+1.852	2.0
73% SiC, 14% Al_2O_3, ~10% SiO_2 brick (Siltec)	+0.078	0.1

The weight loss data of these tests do not permit ranking of materials according to performance although all materials show only moderate or no attack. In general, the fused cast bricks and dense castables show smaller material loss. The two SiC-based bricks and the sialon brick all gained weight, possibly due to oxidation of some of the SiC and Si_3N_4 according to the investigators [33].

A.2.2.2.3.4 MECHANICAL PROPERTIES

OVERVIEW

In most gasification processes the gasifier is planned to be a refractory lined steel vessel with the steel providing most of the load-bearing and pressure-resisting strength. An intact refractory lining is necessary to insulate and protect the steel shell from the high temperature erosive and corrosive gasification environment. A thorough knowledge of the various mechanical properties, such as tensile and compressive strengths, modulus of elasticity, creep, and crack resistance of the refractories, is needed to choose appropriate materials and construction designs for linings which will safely and reliably perform this protective function. Information on these properties at the operating conditions of various gasification processes and the response of the refractory to cycling between ambient and operating conditions is particularly important since there can be significant differences between room temperature and high temperature measurements.

LABORATORY TESTS

HIGH TEMPERATURE MEASUREMENTS OF SEVERAL MECHANICAL PROPERTIES of some alumina castables and ramming mixes have been made as part of a study on monolithic refractory concrete linings. Data on hot compressive strength (B.3.2.42 and B.3.2.50), hot modulus of rupture (B.3.2.43 and B.3.2.51), hot modulus of elasticity (B.3.2.44 and B.3.2.49), and fracture energy (B.3.2.39) are given for 50 and 90 percent alumina generic dense castables and a commercial 50 percent alumina insulating castable. The compositions listed as "modified" have been coarsened by reducing the amount of the finest aggregate fraction (- 325 mesh) with a corresponding increase in the amount of the intermediate and coarse fractions. These modified castables showed improvement in the mixing, casting, and working time characteristics relative to the original standard mixes. For all of the measured properties, the modified 90 percent generic composition seems to be slightly better than the standard 90 percent generic composition. While the room temperature values of these properties for the 90 percent compositions tend to be significantly higher than comparable values for the 50 percent generic composition, they fall rapidly within a temperature rise of a few hundred degrees F. From 500 to 1800 °F, there is relatively little difference in the property values of the 90 percent and 50 percent castable compositions, and there generally seems to be a region toward the higher part of this temperature range where the 50 percent composition has the advantage. For fracture energy (i.e., resistance to crack growth) (B.3.2.39), the 50 percent composition appears to be significantly better than the 90 percent composition over this whole temperature range. Beyond 1800 °F, the mechanical properties of the 50 percent composition deteriorate rapidly, and the 90 percent composition would become the more advantageous material at the highest temperature investigated (2000 °F). The insulating castable was the weakest material in all categories and, indeed, could not be tested beyond 1500 °F because of insufficient strength at higher temperatures.

The crushing strength of two generic (45 percent and 90 percent alumina compositions) and one high-alumina commercial phosphate-bonded ramming mixes is given in B.3.2.37. Of the three, the 45 percent alumina composition shows the best higher temperature strength, but none appears to have any advantages over the dense castable refractories.

A very limited amount of creep data is given in B.3.2.38, B.3.2.40, and B.3.2.41. The data suggest that a top temperature limit of 1800 °F should not be exceeded for any of the materials if creep problems are to be avoided. In B.3.2.38, the data of the 50 percent alumina insulating castable and the modified 90 percent alumina dense castable suggest that any excess water in the mix is detrimental to the creep resistance of the material. A prototype coarse grain 50 percent alumina castable appears to have improved creep resistance over the standard generic 50 percent alumina castable. No further conclusions on creep resistance seem to be warranted from the small number of data points available at the present time.

<u>THE EFFECT OF EXPOSURE TO VARIOUS GASEOUS ENVIRONMENTS AT ELEVATED TEMPERATURES ON THE COMPRESSIVE STRENGTH AND MODULUS OF RUPTURE</u> of eleven commercial refractories is given in B.3.2.11, B.3.2.17, B.3.2.18, B.3.2.19, and B.3.2.21. A summary of the results is given in Table A.2.2.2.3.4a in the form of the ratio of the strength after exposure to the strength of a comparable air fired sample. The precise conditions and gaseous compositions are given in the footnotes to the original sections. The most obvious effect is shown by the dense intermediate-alumina castables in the presence of steam or steam-containing gases. Insulating intermediate-alumina castables show some strength improvement in the same steam-containing environments, but it is less marked. The difference in the low-Btu gas and high-Btu gas exposures for the 55 percent alumina dense castable is most likely due to the difference in steam content (12 percent vs. 38 percent). The effect on the compressive strength of a dense intermediate-alumina castable by exposure to a 45 percent steam--55 percent high-Btu gas is given in B.3.2.9. The strengthening effect is seen to be completed in the first few hours and then remains essentially constant at the higher strength level (independent of time of exposure). Additional confirmation of the strengthening effect of exposure to a high-Btu gas containing a substantial proportion of steam (36 percent) on intermediate-alumina dense castables is seen in Section B.3.2.8. The two dense castables show increases in compressive strength by a factor greater than two, while the insulating castable and the spinel ramming mix show a much smaller effect.

The strengthening effect on the hot modulus of rupture for intermediate-alumina dense castables from exposure to steam containing high-Btu gas may be influenced by the purity of calcium aluminate cement used. Data in B.3.2.13 suggests a greater increase in the hot modulus of rupture (relative to air fired values) after exposure to a high-Btu atmosphere for an intermediate-alumina dense castable using intermediate-purity calcium aluminate cement compared to one using a similar high-purity cement. Different castables were used so it is not proven that the difference in cements is the primary source of the variation in hot modulus of rupture values. Unfortunately, this point does not seem to have been pursued further in this project.

Ratio of Compressive Strength (CS) and Modulus of Rupture (MOR) After Exposure to Various Gases to That of Air-Fired Values at Same Time and Temperature

	Steam		H_2		CO		CO_2		Low-Btu Gas	High-Btu Gas
DENSE CASTABLES										
Calcium aluminate bond	CS	MOR	CS	MOR	CS	MOR	CS	MOR	CS	CS
95% Al_2O_3 (Castolast G)	0.9	0.4	0.7	0.8	1.3	NT[a]	0.8	1.0	1.0	0.8
55% Al_2O_3 (Lo-Abrade)	3.5	3.1	1.3	1.0	1.4	NT	1.5	1.3	1.3	3.3
45% Al_2O_3 (H.S. Brikcast BF)	3.5	NT	NT	NT	NT	NT	0.8	0.8	2.3	2.6
Phosphate bond										
90% Al_2O_3 (Resco Cast AA-22)	0.7	NT	NT	NT	NT	NT	1.1	1.1	0.8	0.7
RAMMING MIX										
Phosphate Bond										
90% Al_2O_3 (Brikram 90R)	0.9	0.9	0.9	1.2	1.0	NT	0.9	1.0	0.8	1.0
INSULATING CASTABLES										
Calcium aluminate bond										
50% Al_2O_3 (Litecast 75-28)	1.6	2.2	1.6	1.4	NT	NT	0.9	1.0	1.9	1.3
CALCIUM ALUMINATE NEAT CEMENT										
78% Al_2O_3 (CA-25)	1.2	1.5	0.8	0.8	NT	NT	1.0	0.8	0.9	1.0
BRICK										
99% Al_2O_3 (99AD)	NT	0.8	1.4	1.2	1.3	NT	1.2	0.9	NT	NT
90% Al_2O_3 (Arco-90)	1.0	1.2	1.0	1.0	1.1	NT	0.9	1.0	1.4	0.8
60% Al_2O_3-tar impregnated (Ufala TI)	NT	1.4	0.5	0.9	1.0	NT	0.9	1.0	NT	NT
45% Al_2O_3 (KX-99)	1.7	1.6	0.6	1.1	1.1	NT	1.1	1.0	0.9	1.7

[a] NT = not tested

Table A.2.2.2.3.4a

The effect of similar exposures to steam and steam-containing high-Btu gas on the compressive strengths of chromia containing refractories (for possible slagging gasifier use) is given in B.3.2.20. Only two of the tested materials show meaningful changes. A high-iron containing ramming mix (Kemram) shows a substantial loss of strength after exposure in both atmospheres and a silicon carbide based brick (Refrax 20) disintegrated in both atmospheres. None of the other refractories exhibited substantial strength changes between air-fired and atmosphere-exposed conditions.

The influence of alkali exposure on the compressive strength and hot modulus of rupture of a variety of refractories has been investigated in screening tests. All of the materials were initially fired in air at 980 °C for 24 hours and then subjected to various treatments. In B.3.2.16 are given the compressive strength measurements of eleven refractories after additional treatments of firing in a high-Btu gas (no alkali), firing in the same gas containing alkali gas, and soaking in a strong alkali solution followed by either air firing or firing in the high-Btu alkali-containing atmosphere. All of these firings were for 200 hours at 980 °C. Six of the original eleven materials were measured for hot modulus of rupture values (B.3.2.12) after soaking in two strengths of alkali solutions followed by firing in either air or a high-Btu gas for 250 hours at 980 °C. The amount of alkali absorbed after the various treatments has been reported in B.1.2.4. It is clear that the soaking treatment introduced more alkali into the refractory than the vapor phase exposure and that the intermediate-alumina refractories absorb more alkali than the comparable high-alumina refractories. The amount of alkali picked up in soaking is independent of firing in air or firing in alkali-gas containing atmospheres. The presence of alkali appears to improve the compressive strength of high-alumina compounds (with the possible exception of the phosphate-bonded castable, Resco Cast AA-22) and to lower the strength of intermediate-alumina castables. Intermediate-alumina brick and ramming mixes are unchanged in strength. The hot modulus of rupture data of B.3.2.12 is too sparse to draw any definite conclusions. Generally, there is little difference between the air-fired and the high-Btu values for all the materials. There are no strictly comparable MOR values for these materials after exposure to an alkali-free environment which can be used as a reference base. However, since the normal trend for intermediate-alumina castables is a substantial increase in both MOR and compressive strength after exposure to steam-containing gases, the data can be interpreted as supporting a deleterious effect by alkali on the strength behavior of such castables. Much more data on similar materials plus longer exposure times are needed to establish the effect of alkali exposure on the strength of refractories.

The effect of various additives on the strength of some castables has been investigated in some preliminary experiments. Steel fiber reinforcement of five castables (three commercial, two generic) shows no significant effect on the compressive strength behavior (B.3.2.22). The strength values and the changes of strength on firing in gasification atmospheres of the reinforced castables are quite comparable to those of similar unreinforced refractories. Addition of ceramic fibers (B.3.2.28) does not appear to be of any benefit in increasing the modulus of rupture of a high-alumina castable. Excessive water in the mix is detrimental to the modulus of rupture (B.3.2.28) and crushing strength (B.3.2.23 and B.3.2.24) for such castables. The addition of a plasticizer (polyvinyl alcohol--B.3.2.24) also lowered the crushing strength. Attempts to add small amounts of silica to a generic high-alumina (B.3.2.23), presumably with the hope of getting the strengthening effects found for steam exposure of intermediate-aluminas, did not produce any improvement. Overall, although these were all preliminary experiments, it would appear that the use of additives is not a helpful technique to improve the strength of castable refractories.

THE EFFECT OF RELATIVELY LOW TEMPERATURE STEAM/CO AND STEAM/CGA (COAL GASIFICATION ATMOSPHERE) EXPOSURES ON THE MODULUS OF RUPTURE (MOR) of various refractories has been investigated. The project was intended to explore possible changes and reactions of refractory linings at the cold face (∿ 250 °C [482 °F]) of gasifiers where conditions may be below the dew point of the atmosphere. These same materials under the same exposure conditions have also been examined for changes in density, porosity, and phases (see Sections A.2.2.2.3.1 and A.2.2.2.3.5). In Section B.3.2.57, values of MOR are given after 20 days exposure to three ratios of a CO/saturated steam atmosphere at temperatures of 400-532 °F. Section B.3.2.58 shows the MOR values after 60 days exposure in an unsaturated (with respect to steam) simulated coal gasification atmosphere (CGA) at 700 °F and in a comparable saturated CGA at 447 °F. The percentage change in MOR relative to controls air-fired at 1000 °F for samples common to both of these exposures has been listed in Table A.2.2.2.3.4b in the hope that any trends would be more obvious. The 1000 °F fired control (rather than the 500 °F air-fired value) was chosen so that the phosphate bonded ramming mixes could be included and rationalized on the basis that for most of these materials, there was very little difference in the MOR values of air-fired samples at 500 or 1000 °F. With this limited set of data, it is difficult to draw firm conclusions, but some trends seem to be indicated. In steam saturated atmospheres, the carbon monoxide-to-steam ratio does not appear to have much effect for any of the materials. The dense high-alumina castables using calcium aluminate cements show a marked increase in strength in saturated steam but not in the unsaturated atmospheres. The intermediate-alumina castables generally show a marked increase in their MOR when exposed to a steam saturated atmosphere, although the Cer-Lite #75 seems to be an anomaly. There are insufficient data points from the unsaturated exposures to warrant any comments at this time. The phosphate-bonded ramming mixes show a marked deterioration in MOR upon exposure to the steam saturated conditions. In the phase change analysis (Section A.2.2.2.3.1), the saturated exposures of calcium aluminate-bonded castables led to formation of appreciable amounts of boehmite ($Al_2O_3 \cdot H_2O$) and some calcite ($CaCO_3$). These compounds arise from the reaction of the calcium aluminate cement with the steam, CO, and CO_2 and improve the bonding in the castables which is consistent with the observation of higher MOR values after exposure relative to the air fired values.

The indication that water vapor is the major reactant of the atmosphere and that boehmite formation is the major cause of improved MOR

Percent Change[a] In Modulus of Rupture of Refractories Exposed to Various Atmospheres

	CO/H_2O Atmospheres with Ratios of			Coal Gasification Atmospheres	
	0.1	1.0	3.0	Unsaturated	Saturated
DENSE CASTABLES					
94% Alumina, Greencast-94	NT[b]	NT	NT	-35	+48 (+71)
93% Alumina, UMR-1 (generic)	+112 (+110)[c]	+32 (+115)	+51 (+63)	-20	+110 (+136)
91% Alumina, UMR-2 (generic)	+27 (+160)	+10 (+108)	+7 (+12)	-13	+99 (+34)
91% Alumina, UMR-3 (generic)	NT	NT	NT	+17	NT
87% Alumina, UMR-4 (generic)	+64 (+17)	+109 (+140)	-5 (+108)	NT	NT
57% Alumina, RC-3	+222 (+185)	+232 (+179)	+192 (+157)	+156	+156 (+206)
50% Alumina, UMR-5 (generic)	+190 (+22)	+154 (+187)	+204 (+135)	NT	+177 (NT)
INSULATING CASTABLES					
54% Alumina, Cer-Lite #75	-48 (-73)	+31 (+27)	+17 (+53)	+12	-49 (+43)
46% Alumina, Litecast 60-25	+148 (+148)	+376 (+319)	+274 (+381)	NT	+143 (NT)
35% Alumina, VSL-50	+20 (+70)	+200 (+320)	+180 (+290)	NT	NT
RAMMING MIXES, PHOSPHATE BONDED					
96% Alumina, Greenpak-90P	-77 (-73)	-52 (-53)	-56 (-62)	NT	-60 (NT)
90% Alumina, Brikram-90R	NT	NT	NT	NT	-40 (NT)

[a] Relative to MOR of air fired (1000 °F, 18 h) samples.

[b] NT = not tested.

[c] Values in parentheses are for samples immersed in liquid water.

Table A.2.2.2.3.4b

values in calcium aluminate-bonded dense castables is reinforced by the data given in Sections B.3.2.55 and B.3.2.56. Generally, the highest MOR values are for samples exposed to steam saturated atmospheres at temperatures from 400-500 °F. The reactions are fairly rapid since exposures beyond ten days show no trend of increasing MOR. Exposures at 1000 °F show decreased MOR values which is consistent with the decomposition of boehmite expected at that temperature. Phosphate-bonded ramming mixes (B.3.2.55) again show a marked reduction in the modulus of rupture when exposured to steam saturated conditions at 400-500 °F. The addition of one percent of H_2S to the atmosphere does not appear to have any effect on any of the tested refractories. Repeated cycling between saturated exposures at 465 °F and air firing at 1000 °F (B.3.2.56) does not indicate any progressive changes in the modulus of rupture of calcium aluminate-bonded castables. Any significant changes generally occur in the first cycle, and then the modulus of rupture remains essentially constant after subsequent cycles. The major results from this project on the choice of refractories for cold wall conditions would seem to be (1) phosphate-bonded refractories should not be used, (2) either high or medium alumina calcium aluminate-bonded dense castables can be used with probably a preference for the medium alumina refractories on the basis of cost plus their improved strength on higher temperature exposures.

CARBON MONOXIDE DISINTEGRATION of iron and iron oxide doped refractories as indicated by compressive strength measurements has been investigated on three generic compositions: a 50+ wt.% alumina castable, a 90+ wt.% alumina castable, and a 90+ wt.% alumina phosphate-bonded ramming mix (B.3.2.52 and B.3.2.54). The objectives of the project were to (1) establish whether CO disintegration is likely to occur in refractories used in coal gasifiers, and (2) define the conditions in which it could be a serious problem. Primary variables were dopant levels, gas compositions, and pressure. The project was not completed at the cutoff date for this publication, so all conclusions must be considered tentative at this time.

The data in B.3.2.54 are the complete results of testing at ambient pressures of 100 hour exposures at 500 °C. All samples were prefired for five hours in air at 1100 °C. Strength tests on samples which were prefired but not exposed to the test gas environments showed that the variations in strength of undoped samples after exposure to various gas compositions are due to differences in raw materials, preparation techniques, and/or environmental conditions at the time of preparation and not due to the effects of the gas exposure. Therefore, in B.3.2.54, comparison of the actual strengths as a function of dopant level is valid only within a given feed gas composition. The ratio of the strengths of the doped to undoped materials is the proper indicator for comparison between different gas exposures.

In general, the two castables behave in a similar fashion for a given exposure condition with the 50+ percent castable usually showing a greater deterioration in strength than the 90+ percent castable for a given Fe concentration. Neither castable appears to be sensitive to the presence of Fe_2O_3. After exposure to pure CO and several of the gas mixtures, the strength of the ramming mix doped with the higher levels of Fe_2O_3 is substantially reduced relative to the strength of the undoped material. The presence of metallic iron as a dopant degrades the strength of the ramming mix in pure CO exposures but not to the same extent as it does for the castables.

An attempt to depict the effect of the gaseous impurities has been made in Table A.2.2.2.3.4c where a strength index is listed for each dopant against the gas compositions used. This strength index is defined as the weighted average of the ratios of doped to undoped strengths for a given gaseous environment, where the average is taken over all levels of doping. In general, the addition of all of the various gases has some retarding effect on the strength losses relative to pure CO exposures caused by metallic iron doping of the castables. The retarding effect is fairly small at the five percent CO_2 and 0.2 percent H_2S levels for the 50 percent castable but appears to be more substantial at the higher concentrations of these gases. The addition of NH_3 to the gaseous environment has some retarding effect on the strength loss which does not seem to be sensitive to varying NH_3 concentration. The addition of 20 percent H_2O or 20 percent H_2 appears to improve the strength of the doped materials relative to the undoped materials, but this improvement disappears upon increasing the concentration of these gases to 40 percent.

The effect of the various gases on the ramming mix is frequently quite different than on the castables. With the exception of H_2S, the various gas additives have the same effect on the ramming mix, whether the dopant is Fe or Fe_2O_3. At the five percent CO_2 level, the strength index increases, but at 15 percent CO_2, it is at or below the level shown in pure CO. Addition of NH_3 to the gas environment has little effect. The addition of H_2S has a markedly different effect depending on whether the dopant is Fe or Fe_2O_3. For the Fe doped material, H_2S has no retarding effect at the 0.2 percent level but does have a strong effect at the 0.8 percent level. The Fe_2O_3 doped material shows a continuing decrease of the strength index as the H_2S concentration increases. The addition of H_2O or H_2 at the 20 percent level improves the strength index relative to the 100 percent CO exposure, but this improvement remains the same at 40 percent concentration levels for these gases.

Preliminary data for higher pressure exposures are given in B.3.2.52. These materials were exposed to pure CO at 600 psi and 500 °C for 100 hours. All of the samples doped with metallic iron at the 0.5 percent level were completely destroyed under these conditions. This should be contrasted with the data from B.3.2.54, where the same materials retained over 50 percent of the undoped strength at atmospheric pressure exposure. The Fe_2O_3 doped materials were not affected by the higher pressure exposure in terms of retained strength.

These results indicate that pressure is an extremely important variable and that metallic iron is the most serious contaminant in the problem of carbon monoxide disintegration of refractories. Whether or not the problem is serious in coal gasification atmospheres with their lower CO concentrations has not yet been answered, but such testing is anticipated for later stages of this project.

Effect of Gas Composition on Strength Index of Doped Alumina Refractories Exposed to CO-Containing Atmospheres

Gas Composition	DOE 90 Generic Castable doped with		DOE 50 Generic Castable doped with		DOE Generic Ramming Mix doped with	
	Fe	Fe_2O_3	Fe	Fe_2O_3	Fe	Fe_2O_3
100% CO	0.336	1.254	0.197	0.994	0.650	0.885
95% CO-5% CO_2	0.971	1.365	0.287	1.143	1.032	1.160
85% CO-15% CO_2	1.074	1.015	1.217	1.136	0.656	0.751
99.8% CO-0.2% NH_3	0.637	0.939	0.508	1.072	0.554	0.802
99.2% CO-0.8% NH_3	0.855	1.226	0.486	1.363	0.610	0.950
99.8% CO-0.2% H_2S	0.892	1.168	0.253	1.076	0.654	0.693
99.2% CO-0.8% H_2S	0.972	1.064	0.818	1.020	1.487	0.442
80% CO-20% H_2O	1.418	2.024	1.282	1.362	1.004	1.302
60% CO-40% H_2O	0.953	1.170	0.854	0.850	0.985	1.424
80% CO-20% H_2	1.540	1.721	1.953	2.051	0.929	1.067
60% CO-40% H_2	1.205	1.179	0.978	1.008	0.976	0.999

Table A.2.2.2.3.4c (see text for explanation)

REFRACTORY STRENGTH AFTER HYDROTHERMAL TREATMENT was tested since steam is a major reactant with the component compounds in refractories (see Section A.2.2.2.3.1). The hydrothermal treatment consisted of sealing refractory specimens in a pressure chamber with water, raising the temperature to produce high-pressure steam, and holding for a set period of time. In some tests, the amount of water varied, in others the temperature, and in others the time of exposure. Refractories tested included high- and medium-alumina castables, both commercial and generic calcium aluminate-bonded preparations, and a high-alumina phosphate-bonded generic castable. Flexural strength was tested at ambient temperature by four-point bending after exposure and compared with control specimens which did not receive hydrothermal treatment. In one series of experiments, the effect of varying amounts of water at 510 °C was studied using a high- and a medium-alumina castable, both commercial materials. Different batches of both were tested as well as specimens which were only dried and specimens which were both dried and fired. The flexural strength after the various exposures is compared (see B.3.2.1) with the strength of untreated control samples, as well as samples treated in the pressure chamber with no water added, and samples merely soaked in water at ambient temperature for five hours. Firing or water soaking had relatively little effect on the strength of the high-alumina castable whether fired or merely dried. Heat treatment in the pressure chamber with no water present had little effect on fired specimens, but dried specimens dropped in flexural strength by a factor of about 3.5. The hydrothermal treatment had a drastic effect in reducing the strength of the high-alumina material. The medium-alumina castable showed a marked drop in strength of the fired materials as compared with the dried samples. Exposure to water, whether by soaking at ambient temperature or by the hydrothermal treatment, produced samples with strengths only slightly less than that of the dried samples.

The effect of temperatures of hydrothermal treatment from 10 to 510 °C on the high-alumina castable is seen in B.3.2.4. Whether the samples were merely dried or also pre-fired before the hydrothermal treatment did not affect the results significantly. The major change in strength was caused by the hydrothermal treatment above 310 °C. The strength was reduced dramatically. Included in B.3.2.4 are the results of tests performed after hydrothermal exposure and refiring in air to various temperatures. Refiring restores only some of the strength to the castable; the strength values of the untreated control samples are much greater.

Neat calcium aluminate cement was cast into samples, exposed to hydrothermal treatment at varying temperatures, and the flexural strength tested. The results given in B.3.2.5 show that for both dried and fired samples, the changes in the cement phase which lower the strength occur between 310 and 400 °C. These results are in agreement with the work on the high-alumina castable. Tests on sintered alumina were done to see the effect of the treatment on the aggregate (see B.3.2.6). There is a degradation of strength related to the density (or porosity), but there was no phase change detected by x-ray diffraction analysis. Tests were also run using a generic medium-alumina castable, calcium aluminate-bonded. Results given in B.3.2.2 for fired samples show that there are no drastic differences in flexural strength for specimens subjected to hydrothermal treatment at various temperatures as had occurred for high-alumina material tested the same way (see B.3.2.4). There are data given also in B.3.2.2 for a generic high-alumina phosphate-bonded refractory. Although the data are scanty, there seems not to be any large effect of hydrothermal treatment on the strength. There is only a relatively small drop in strength for the 310 to 400 °C region, which is a critical region for the calcium aluminate-bonded high-alumina refractory. Data reported for a commercial medium-alumina castable, calcium aluminate-bonded, tested after hydrothermal treatment for varying periods of time (see B.3.2.3) show that the refractory strength is not diminished by the treatment and some samples show somewhat increased strength after treatment at 510 °C. Comparison of strength data for commercial high- and medium-alumina castables after hydrothermal treatment (see B.3.2.6) shows directly the degradation of the strength of the igh-alumina refractory in the 310 to 400 °C region compared with the elatively unaffected strength of the medium-alumina material.

Generic preparations of high- and medium-alumina calcium aluminate-onded castables were strength tested after two modes of hydrothermal reatment, both different from the procedures used with the fixed volume ressure chamber utilized in the rest of the treatments (see B.3.2.7). n the first mode, the test vessel was heated to the final test temperaure and then steam was introduced to bring the vessel to operating ressure. Under these conditions, both the high- and medium-alumina astables showed no diminishment of flexural strength and both showed ome increase over the strength of control samples. In the second mode, ater was introduced to the test vessel and during heating the pressure nd temperature followed the saturated vapor curve. When the operating ressure (1000 psi) was reached, steam was vented to maintain that ressure as heating was continued to the test temperature. Under this econd mode, the medium-alumina refractory showed a constant increase in trength with the increased temperature. The high-alumina showed a drop n strength at about 410 °C, comparable to the results of the other sets f data, although at higher temperatures under these conditions the trength increases and at 910 °C the strength is close to that found for he first mode of operation. The second mode more closely approximates ctual plant heat-up procedures. In Section B.3.2.47, data appear for xposures of medium-alumina generic castable to carbon dioxide, steam, nd carbon dioxide-steam mixtures; in B.3.2.48, there are data for imilar exposures of a high-alumina generic castable. These data show he degradation in strength caused by exposure to steam in the lower emperature range (here 410 and 510 °C). At higher temperature (910 °C), owever, the strength was not degraded, but even enhanced. The data lso show that exposure to a steam-carbon dioxide mixture or a simulated oal gasification atmosphere at even a temperature as low at 510 °C did ot appreciably affect the strength. The procedures for these exposures re similar to the first mode described above in that the test chamber as heated containing argon at ambient pressure and temperature equilirium was reached before any gases were put into the chamber.

One set of experiments was conducted testing the hot flexural trength of two medium-alumina generic preparations both before and fter hydrothermal treatment. The temperature range of treatment and ot strength testing was 610 to 1310 °C. Over the entire temperature ange, the hydrothermally treated specimens showed increased hot flexral strength compared to the hot strength of dried untreated samples (see B.3.2.14).

The differences in behavior of the high- and medium-alumina refractories is due to the chemical changes discussed in A.2.2.2.3.1 (see also .2.2.2.1 and A.2.2.2.2). High-alumina refractories suffer degradation in strength in the region 300-400 °C because the calcium aluminate onding phases break down as hydration occurs and hydrated alumina (boehmite, $Al_2O_3 \cdot H_2O$) and calcium aluminate hydrates form. As the alcium aluminate hydrates crystallize, they do not form good bonding hases. The boehmite does perform as a bonding phase initially, but at igher temperatures, it breaks down. These hydration-dehydration reactions account for the loss of flexural strength of the high-alumina refractory in the temperature region 300-400 °C. Although calcium aluminate bonding phases do seem to reform at higher temperatures, the original strength of the refractory is not restored. In contrast, medium-alumina refractories undergo reactions such that silica from the aggregate and calcium aluminate from the cement produce anorthite ($CaSi_2Al_2O_8$) which forms a strong continuous structure so that the refractory strength is enhanced.

THERMAL EFFECTS ON THE BEHAVIOR AND STRENGTH of nine commercial high-alumina refractories were investigated as part of a project to develop appropriate test methods for measuring these properties at ambient and elevated temperatures (∿ 2000 °F). Section B.3.2.10 covers the modulus of rupture at room temperature, before and after thermal shock, and at 2000 °F. Section B.3.2.15 lists the ambient and 2000 °F values of crushing strength plus the room temperature measurements for shear strength and mechanical shock. For the same materials, visual observations are given as to their condition after thermal shock (B.3.2.31) and the effect of thermal cycling on sample lengths is given in B.3.2.30. There are no trends observable based on composition. As might be expected, the strength values at high temperatures are generally lower than the room temperature values. The thermal shock treatment provided the lowest MOR values and the poorest reproducibility of measurements. Length changes on cycling between ambient temperatures and 2000 °F appear to be very minor relative to the fired condition. No further conclusions can be drawn from this limited set of data.

FRACTURE CHARACTERISTICS OF REFRACTORY CONCRETES AS A FUNCTION OF TEMPERATURE were measured in one project with the intention of providing data for the engineering design of refractory liners. The project was not completed at the time of publication, so no final conclusions can be drawn. At our cutoff time for data assembly, four materials had been measured: two intermediate-alumina dense castables (same aggregate but with two brands of calcium aluminate cement), one high-alumina generic dense castable utilizing a calcium aluminate cement, and one intermediate-alumina insulating castable, also with calcium aluminate cement. Measurements of the flexural strength (MOR), Young's modulus, fracture toughness, work of fracture, and the fracture surface energy made at room temperature (after firing at various temperatures) and at elevated temperatures up to 1200 °C are given in Sections B.3.2.32 through B.3.2.36. These same materials were also examined for phase changes after firing at various temperatures (Sections A.2.2.2.3.1 and B.1.2.10). For some of the properties measured, a vague correlation with the phase changes can be imagined, but the amount of data is insufficient to draw any definitive conclusions. Generally, the phase changes break into three regions: (1) from room temperature to ∿ 300 °C, formation of hydrated calcium aluminate bonding; (2) from ∿ 300 °C to 800 or 1000 °C, disappearance of hydrated bonding phases with no new bonding phases; and (3) 1000 °C and up, formation of anorthite in silica containing cements and higher alumina calcium aluminates as bonding phases. The insulating castable follows this pattern but has additional iron-containing compounds which may be contributing to its usually more complicated behavior. For most of the properties and most of the materials, the values measured at temperature are not greatly

.fferent from the corresponding room temperature values in the low and :dium temperature range (i.e., up to 800-1000 °C). In this temperature inge, the values measured at elevated temperature are usually lower than ie room temperature values, but the trends are very roughly parallel .th the possible exception of the insulating castable which has a more mplicated behavior pattern, especially on the fracture toughness and :acture surface energy measurements. At the highest temperatures · 1200 °C), the flexural strength and elasticity measurements at room :mperature and elevated temperature seem to be diverging rapidly for the :nse castables. Unfortunately, the reality of this apparent trend, iile physically reasonable because most materials can be expected to :come weaker at high temperatures, is not proven by the data. This)parent high temperature trend comes primarily from the single data)int of room temperature measurements after firing at 1350 °C, whereas ie high temperature measurements stopped at 1200 °C. Much more data on variety of materials is needed before a consistent interpretation of iese kind of fracture measurements can be made.

SLOW CRACK GROWTH IN CASTABLE REFRACTORIES occurs over a wide range : temperatures and is a possible failure mode of reactor vessel mono- .thic linings. Some studies have been made on a high- and a medium- .umina castable refractory investigating the mechanism of and the effect : temperature on crack growth in these materials. Initial data were)tained on a commercial 95 percent alumina calcium aluminate- bonded istable using the as-received material (see B.3.2.25). Controlled :acture in which the velocity can be measured properly was not obtained .th this material. The range of particle sizes of the as-received ;gregate with respect to total cast sample size was too large and iterfered with directed propagation of the crack. The calcium .uminate cement is the weaker phase with respect to crack propagation.)r these two reasons, it was necessary to use castable with a higher :ment-to-aggregate ratio by using only aggregate particles smaller than l4 Tyler mesh from the castable mix. Such test samples were cast and :ack propagation data were obtained at 610, 810, 1010, and 1210 °C (see .3.2.25). Crack velocity data are plotted against the stress-intensity ictor, K_I. The stress-intensity factor is defined as a measure of the :ress-field intensity near the tip of the crack; it is directly propor- ional to the applied load and depends on specimen geometry. The effect : temperature on the relationship between crack velocity and the stress itensity for this material is seen readily in B.3.2.25. At 610 °C the :ack velocity increases rapidly at high stress with only small in- :eases in the stress intensity factor. The slope of the line is a :asure of crack growth, the inverse of the slope being related to crack :owth susceptibility; the larger the slope, the less susceptible to :acking. At 610 °C the crack growth at low stress is minutely slow, .though at high stress the crack velocity increases so rapidly with nall increases in stress that failure occurs very rapidly. At higher :mperatures (810 and 1010 °C), the data show a region developing and :panding in which the crack velocity is not increasing rapidly but iich includes a larger range of the stress-intensity factor, involving)wer stresses. At 1210 °C, the relatively slow crack growth region)vers the entire range of the data, even to the lowest stress-intensity ictor included. While crack growth does not increase as rapidly at

1210 °C with increased stress as it does at lower temperatures, such growth still has an appreciable velocity at low stress. The high-temperature region then presents a potential for failure of such refractory. (It should be noted that the two regions of large and small slope were not observed in the as-cast material at 1010 °C. Only one region of large slope occurs, indicating the possible importance of cement to aggregate ratio on this region of slow crack growth.) The investigators [23] have provided an example to illustrate the problems of the high-temperature region. Using the data in B.3.2.25, they have calculated the time for a one mm crack subjected to a constant tensile stress of one MNm^{-2} (one MPa, 145 psi) to grow to such a size in a refractory component that catastrophic failure occurs. At 610 °C it would take 10^{25} years for such failure due to cracking to take place, but at 1210 °C the same one mm crack would grow to critical size after 20 minutes.

The effect of firing temperature was studied as part of the crack growth testing of a commercial 55 percent alumina calcium aluminate-bonded castable. Samples were fired to 1010 °C or to 1410 °C. Specimens fired to the lower temperature were tested at 610, 810, and 1010 °C. The crack velocity vs. stress-intensity factor data are given in B.3.2.26. There is little diference in the crack growth behavior for these samples at the three test temperatures, the slopes for all three sets of data being large. In contrast to the tests of the high-alumina castable with small particle aggregate, there is apparently no second region of crack growth, just as was true for the test on the cast-as-received high-alumina materials. Specimens of the medium-alumina castable fired at 1410 °C were tested at 1010, 1110, and 1210 °C (see B.3.2.26). The tests at 1010 °C for samples fired at the two firing temperatures show similar crack growth behavior in terms of the crack susceptibility (almost equal slopes) although the stress corresponding to a given crack velocity is much higher for the specimens fired at the higher temperature. The fracture toughness has increased by a factor of two, that is, for a crack to grow at a given velocity the stress must be approximately doubled. The data for tests at 1010, 1110, and 1210 °C show that even though the samples were fired to 1410 °C there is an increase in the crack susceptibility (the slope decreases in value) as the test temperature increases. This behavior is similar to that of the high-alumina material (increased cracking susceptibility with temperature) but without the presence of the two distinct regions of data exhibited by the high-alumina castable.

SILICON CARBIDE AND SIALON REFRACTORIES have been examined in connection with use in heat exchanger tubing. Compressive strength data are given in Sections B.3.2.45 and B.3.2.46. Extruded tubes were radially loaded, so as to prevent point loading, at ambient temperatures and at 1500, 1700, 1900, 2300, and 2500 °F. The effect of temperature on the flexural strength of several silicon-containing refractories is shown in B.3.2.53. All the materials tested but one showed a decrease in flexural strength at about 1371 °C (2500 °F). The one material which did not decrease in flexural strength up to 1700 °C is a sintered α-SiC. The variation of both compressive and flexural strength with temperature appears fairly constant within experimental error, falling off at temperatures beyond those commonly expected to exist in most gasification processes (2500 °F).

A.2.2.2.3.5 PHYSICAL PROPERTIES

OVERVIEW

Those properties which receive the greatest attention in this section are weight, dimensions, density, and porosity. Weight and dimensional changes may be indicators of chemical reactions occurring in the refractory. They are important in that major differences in them after installation of refractory material in a vessel may produce changes, such as cracks, which would undermine the integrity and protective ability of the materials as a vessel liner. Changes in density and porosity might affect corrosion and/or erosion resistance in affecting the kinetics of any chemical reactions taking place. Thermal conductivity is directly affected by porosity, the better insulators having higher porosity. Higher porosity usually provides better resistance to thermal shock effects. A disadvantage to high porosity is the reduced strength and generally lower corrosion resistance.

LABORATORY TESTS

THE EFFECT OF EXPOSURE TO VARIOUS ATMOSPHERES AT HIGH TEMPERATURE AND PRESSURE on the bulk density has been studied. The measurements of bulk density (and some apparent porosity measurements) were made in accordance with ASTM C20-73. After curing and drying, the refractories were fired in air for 250 hours at 1100 °C and the properties measured. Air-fired samples were then exposed to the different atmospheres and the properties remeasured. The atmospheres were steam, hydrogen, carbon monoxide, carbon dioxide, and a mixed gas simulating a coal gasification environment: 24% H_2, 18% CO, 12% CO_2, 5% CH_4, 2% NH_3, 1% H_2S, and 38% H_2O. The full data with test conditions are given in B.4.2.1-.3 and are summarized below. Not all refractories were tested under all conditions.

Percent Change in Bulk Density after Exposure Compared with Air Firing

Refractory	Steam	H2	CO	CO_2	Mixed Gas at 1000 °C	Mixed Gas at 760 °C
CALCIUM ALUMINATE-BONDED CASTABLES						
Dense 95% Al_2O_3 (Castolast G)	+3.7	+0.6	+1.8	-1.2	+1.2	-2.7
Dense 90% Al_2O_3 (DOE Generic)						-2.2
Dense 55% Al_2O_3 (Lo-Abrade)	+2.3	+0.8	+2.3	-2.3	-3.0	-5.8
Lightweight 50% Al_2O_3 insulating (Litecast 75-28)	-5.8	+1.2	+1.2	-2.3	+2.3	-2.4
Dense 45% Al_2O_3 (B&W Kaocrete D)						-1.0
Dense 45% Al_2O_3 (H.S Brikcast BF)				-0.8	-0.8	+0.2
PHOSPHATE-BONDED REFRACTORIES						
90% Al_2O_3 ramming mix (Brikram 90R)	-2.7	-3.2	+1.6	-1.1	-2.1	-1.2
Dense 90% Al_2O_3 castable (Resco Cast AA-22)				0	-0.6	-8.7
60% Al_2O_3 ramming mix (HW 23-75)						-4.5
CALCIUM ALUMINATE CEMENT						
Neat 78% Al_2O_3 cement (CA-25)	+2.7	+2.7	+1.8	-2.6	-4.4	-5.4
BRICKS						
99% Al_2O_3 (99AD)	+1.6	+1.0	+2.6	-1.0	0	
90% Al_2O_3 (Arco-90)	-0.5	0	+0.5	-0.5	+1.6	+0.1
60% Al_2O_3 tar-impregnated (Ufala TI)	-3.1	-0.6	+2.5	-1.8	-0.6	
45% Al_2O_3 superduty (KX-99)	-1.4	0	+1.4	-0.7	-0.7	-1.0

It can be seen from the preceding table that the bulk density is affected very little by the test exposures. There are no obvious trends indicating susceptibility of a group of refractories to particular atmospheres as measured by density.

Measurements of apparent porosity were made of air-fired samples before and after exposure to the mixed gas atmosphere at 760 °C. These data are given in the following tabulation.

Percent Change in Apparent Porosity after Exposure Compared with Air Firing

Refractory	Mixed Gas at 760 °C
CALCIUM ALUMINATE BONDED CASTABLES	
Dense 95% Al_2O_3 (Castolast G)	- 2.3
Dense 90% Al_2O_3 (DOE Generic Preparation)	+ 2.7
Dense 55% Al_2O_3 (Lo-Abrade)	-16.8
Lightweight 50% Al_2O_3 insulating (Litecast 75-28)	- 8.5
Dense 45% Al_2O_3 (B&W Kaocrete D)	-13.4
Dense 45% Al_2O_3 (H.S. Brikcast BF)	-23.2
PHOSPHATE-BONDED REFRACTORIES	
90% Al_2O_3 ramming mix (Brikram 90R)	- 5.0
Dense 90% Al_2O_3 castable (Resco Cast AA-22)	-15.9
60% Al_2O_3 ramming mix (HW 23-75)	-13.3
CALCIUM ALUMINATE CEMENT	
Neat 78% Al_2O_3 cement (CA-25)	- 1.7
BRICKS	
90% Al_2O_3 (Arco-90)	-19.1
45% Al_2O_3 superduty (KX-99)	- 4.6

The medium-alumina dense castables, the phosphate-bonded high-alumina castable and medium-alumina ramming mix, and the high-alumina brick showed decreases in apparent porosity in excess of ten percent. It is difficult to relate this loss of apparent porosity with chemical and phase changes occurring in these refractories under these environmental conditions (see A.2.2.2.3.1). There is no measure of the effect of this decreased porosity on the performance of the materials in actual use.

<u>THE EFFECT OF SIMULATED COAL GASIFICATION ATMOSPHERE ON CASTABLES TO WHICH STEEL FIBER WAS ADDED</u> for reinforcement was studied (see B.4.2.4). Two weight percent of various steel fibers were added to three castables as the samples were prepared. The bulk density and porosity were tested after air-firing at 980 °C for 250 hours and after exposure to a coal gasification environment at 980 °C and 1000 psi for 250 hours. The change in properties is summarized below.

Refractory	Fiber	Percent Change in Bulk Density	Percent Change in Apparent Porosity
Dense 95% Al_2O_3 castable, calcium aluminate bonded (Castolast G)	430 SS	-2.3	-16.7
	446 SS	0	- 8.3
	446 SS, coated	-1.1	- 9.1
	310 SS, coated	0	- 7.7
Dense 90% Al_2O_3 castable, calcium aluminate bonded (DOE Generic Preparation)	430 SS	-1.1	- 9.5
	446 SS	-1.1	- 8.5
	446 SS, coated	-0.4	- 7.4
	310 SS, coated	+0.7	- 1.9
Dense 45% Al_2O_3 castable, calcium aluminate bonded (H.S. Brikcast BF)	430 SS	+0.9	-15.0
	446 SS	+1.4	-10.2
	446 SS, coated	+1.4	- 8.9
	310 SS, coated	+1.9	-12.1

The data show that the presence of the fibers had no real effect on the response of the refractories to the coal gas exposure as measured by the bulk density changes. The apparent porosity decreased in all cases, but the effect of the fibers is unclear.

THE EFFECT OF HEAT TREATMENT AND VARIOUS GASEOUS ENVIRONMENTS on eleven castables, seven high-alumina and two medium-alumina dense castables, and two medium-alumina insulating castables, all calcium aluminate bonded, and three ramming mixes was studied. Samples were exposed in a simulated coal gasification atmosphere with no H_2S included for periods of 10, 20, and 30 days, at 500 °F and 500 psi, and at 1000 °F and 1000 psi. They were also exposed in the coal gasification atmosphere with one percent H_2S at 1000 °F and 1000 psi and in a 52.5 percent carbon monoxide--47.5 percent steam environment for ten days at 500 °F and 1000 °F at 465 psi. The materials were also exposed to these atmospheres under steam-saturated conditions. Measurements were made to determine weight and dimensional changes of the samples (see B.4.2.7 for full test conditions and data; values are averages for seven samples except for saturated conditions where two samples were tested). The weight and dimensional changes were minimal, the largest percent weight change which occurred being that for the difference between values for the air-dried samples and air-fired control samples of the castables. A glance at B.4.2.7 will show that the maximum weight change was 5.2 percent, and the maximum dimensional change was 1.2 percent for all treatments, including the air firing of the control samples. The change in weight was generally a weight loss, and the change in dimensions generally a shrinkage.

FIVE NEAT CALCIUM ALUMINATE CEMENTS were exposed to the same set of test conditions as the above refractories, and the weight and dimensional changes examined (see B.4.2.9). Data are given for the weight change experienced by the initially dry powders exposed to the various atmospheres and appreciable weight gains were found, a not unexpected result. Various chemical reactions are expected upon mixing these powders with water, a major constituent of all the test atmospheres. Of more practical interest are the percent weight and percent dimensional changes experienced by the neat cement samples prepared by hydrating, casting, and drying. No data are given for air firing of these samples. The percent changes for the neat cements are somewhat greater than were the changes occurring for the calcium aluminate-bonded castables. For weight changes, the maximum weight gain was 16.5 percent and maximum loss was 8.0 percent. For the dimensional changes, the maximum shrinkage was 3.1 percent and the maximum expansion was 4.6 percent. Firm trends are difficult to find in the data because the data divide somewhat equally between positive and negative percent changes, as opposed to the castables which generally showed weight loss and shrinkage. This difference may be due to the presence of the aggregate in the castables. There is some indication that weight and dimensional gains correspond somewhat to the formation of hydrated compounds at lower temperatures and in atmospheres with higher water content and that the weight losses and shrinkage occur at higher temperatures. See A.2.2.2.3.1 and B.1.2.20 for the chemical changes which occurred in these tests.

The same eleven castables mentioned above were also examined for changes in density and porosity after the above exposures (see Section B.4.2.8). Table A.2.2.2.3.5a contains a summary of the percent changes in density and apparent porosity occurring after the various exposures which are reported in B.4.2.8. These data are average values of seven samples except in saturated conditions where two samples were exposed. All changes are with respect to values found for control samples air-fired at 1000 °F for 18 hours. The conditions of the exposures listed in Table A.2.2.2.3.5a have the following meaning:

CGA = coal gasification atmosphere: 18% CO, 12% CO_2, 24% H_2, 41% H_2O, 5% CH_4

CGA No. 1: 500 °F, 500 psi, for 30 days

CGA No. 2: 1000 °F, 1000 psi, for 30 days

CGA with 40% H_2O and 1% H_2S: 1000 °F, 1000 psi, for 30 days

CGA with 40% H_2O and 1% H_2S, steam saturated: 447 °F, 1000 psi, for 30 days

47.5% H_2O/52.5% CO No. 1: 500 °F, 465 psi, for ten days

47.5% H_2O/52.5% CO No. 2: 1000 °F, 465 psi, for ten days

47.5% H_2O/52.5% CO, steam saturated: 390 °F, 465 psi, for ten days

Changes in density for the dense castables were almost always increases, the maximum value being +7.2 percent for the high-alumina refractories and +5.9 percent for the medium-aluminas. The insulating castables showed smaller changes, the maximum value being +3.4 percent. The density changes for the ramming mixes were about evenly divided between increases and decreases with a maximum value of +4.1 percent. There are no obvious trends.

	DENSE CASTABLES						
Exposures*	94% Alumina Greencast-94	93% Alumina Kao-Tab 93	90-95% Alumina Castolast G	90-95% Alumina Purotab	93% Alumina UMR-1 Generic	91% Alumina UMR-2 Generic	91% Alumina UMR-3 Generic
CGA No. 1	+ 5.2	+ 1.5	+ 5.1	+ 4.3	+ 2.6	+ 6.3	+ 7.2
CGA No. 2	+ 3.0	- 0.8	+ 4.0	+ 3.2	+ 1.9	+ 2.8	+ 3.8
CGA, H_2O saturated	+ 4.5	- 2.3	not tested	+ 5.8	+ 2.6	not tested	+ 3.8
CGA with H_2S	not tested	not tested	not tested	not tested	+ 3.7	+ 3.2	not tested
CGA with H_2S, H_2O saturated	not tested	not tested	not tested	not tested	+ 1.9	+ 2.4	not tested
H_2O/CO No. 1	not tested	+ 3.1	+ 5.5	not tested	+ 2.2	+ 7.1	not tested
H_2O/CO No. 2	+ 6.0	- 1.2	+ 3.6	not tested	+ 1.9	+ 2.4	not tested
H_2O/CO, H_2O saturated	+ 4.1	- 1.9	+ 4.7	Not tested	+ 1.5	+ 3.6	not tested

	DENSE CASTABLES		INSULATING CASTABLES		RAMMING MIXES		
	54-57% Alumina Lo-Abrade	57% Alumina RC-3	59% Alumina Kast-O-Lite 30	54% Alumina Cer-Lite #75	96% Alumina Greenpak-90P	96% Alumina 90 Ram H.S.	90% Alumina Brikram 90R
CGA No. 1	+ 2.7	+ 4.1	+ 2.7	- 1.3	+ 0.7	+ 0.7	- 0.7
CGA No. 2	- 0.4	+ 1.8	+ 2.1	- 0.6	0	+ 1.4	+ 1.4
CGA, H_2O saturated	- 0.9	- 2.7	- 0.7	0	+ 0.3	+ 0.7	- 1.0
CGA with H_2S	not tested	+ 1.4	not tested	0	- 2.7	not tested	not tested
CGA with H_2S, H_2O saturated	not tested	+ 2.3	not tested	+ 3.2	- 1.7	not tested	not tested
H_2O/CO No. 1	+ 2.7	+ 5.9	+ 3.4	+ 0.6	- 2.7	+ 0.7	+ 4.1
H_2O/CO No. 2	+ 0.4	+ 1.4	+ 2.1	0	- 1.7	- 0.7	+ 2.7
H_2O/CO, H_2O saturated	- 0.9	+ 4.5	+ 0.7	- 1.3	- 2.7	- 1.0	+ 2.0

Percent Change in Apparent Porosity Due to Various Exposures of Refractories as Compared with Air Firing

	DENSE CASTABLES						
Exposures*	94% Alumina Greencast-94	93% Alumina Kao-Tab 93	90-95% Alumina Castolast G	90-95% Alumina Purotab	93% Alumina UMR-1 Generic	91% Alumina UMR-2 Generic	91% Alumina UMR-3 Generic
CGA No. 1	-20	-14	- 5.0	-18	- 8.7	-21	-13
CGA No. 2	- 4.0	0	+ 5.0	- 4.5	+13	- 3.6	+ 3.2
CGA, H_2O saturated	-48	+ 3.6	not tested	-73	-52	not tested	- 9.7
CGA with H_2S	not tested	not tested	not tested	not tested	0	- 3.6	not tested
CGA with H_2S, H_2O saturated	not tested	not tested	not tested	not tested	-35	-36	not tested
H_2O/CO No. 1	not tested	-18	-15	-18	- 4.3	-25	not tested
H_2O/CO No. 2	-20	- 3.6	+ 5.0	- 4.5	+ 4.3	- 7.1	not tested
H_2O/CO, H_2O saturated	-80	- 3.6	-80	-82	-78	-75	not tested

	DENSE CASTABLES		INSULATING CASTABLES		RAMMING MIXES		
	54-57% Alumina Lo-Abrade	57% Alumina RC-3	59% Alumina Kast-O-Lite 30	54% Alumina Cer-Lite #75	96% Alumina Greenpak-90P	96% Alumina 90 Ram H.S.	90% Alumina Brikram 90R
CGA No. 1	-10	-13	- 2.0	+ 4.8	+ 5.9	0	+ 5.9
CGA No. 2	+ 5.0	- 4.3	+ 6.1	+24	+ 5.9	- 5.0	- 5.9
CGA, H_2O saturated	-40	- 4.3	+10	+24	+24	+ 5.0	+24
CGA with H_2S	not tested	- 4.3	not tested	+21	+18	not tested	not tested
CGA with H_2S, H_2O saturated	not tested	-26	not tested	+ 7.1	+24	not tested	not tested
H_2O/CO No. 1	- 5.0	-26	0	+ 7.1	+53	0	-18
H_2O/CO No. 2	0	0	+ 4.1	+12	+12	0	-12
H_2O/CO, H_2O saturated	-10	-52	+ 4.1	+14	+24	+ 5.0	0

*See text for details of exposure conditions.

Table A.2.2.2.3.5a

Changes in apparent porosity varied greatly. For the dense castables, the porosity tended to decrease in almost all cases. There is a trend for a larger change in porosity (always a decrease) at lower temperatures and pressures for like atmospheres (compare data for CGA No. 1 and No. 2 and H_2O/CO No. 1 and No. 2). The changes for the higher temperatures and pressures (No. 2 exposures) are all either much smaller decreases in porosity or increases. There is some indication that for similar atmospheres, saturated steam conditions frequently decrease the porosity by large percentages (50-80 percent), with some exceptions. These data are consistent with the results discussed in A.2.2.2.3.1, indicating boehmite ($Al_2O_3 \cdot H_2O$) formation at lower temperatures and higher water concentrations which would reduce the apparent porosity due to the boehmite filling the pores. The apparent porosity of the insulating castables tended to increase upon exposure as did one of the ramming mixes. There are no consistent trends obvious for the three ramming mixes tested. The largest decreases in porosity of the intermediate-alumina dense castables is rather less than the largest decrease of the high-alumina castables. The tendency of the insulating castables to exhibit increased porosity upon exposure would enhance the insulating capability but could be detrimental if it indicated a breakdown of the integrity of the material (see A.2.2.2.1).

PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION of alumina castables was studied in a series of experiments. Seven castables, four dense ones containing alumina in percentages ranging from 93 to 58, and three insulating ones containing 54 to 35 percent alumina were subjected to the same coal gasification atmosphere (CGA) with H_2S used in the tests of B.4.2.8 in a steam generator providing 85 percent steam saturation of the atmosphere. After this exposure, the samples were air-fired. The cycles, which caused boehmite to form in the saturated atmosphere and then decompose upon being air fired, were repeated with measurements being repeated after each cycle on seven samples to determine changes in weight, dimensions, density, and porosity. Tests were also run in a steam-saturated coal gasification atmosphere with H_2S and in just a steam-saturated atmosphere. Samples were exposed both in the vapor phase and the liquid phase to determine the effect of condensation which might occur in a coal gasifier during changes in temperature and/or pressure. The percent weight change and percent dimensional change measured after these exposures are given in Section B.4.2.10 along with the details of the test conditions. The changes are not of great magnitude, especially for the dense castables. The results of exposure in the liquid phase are not significantly different from the values for exposure in the vapor phase. The relatively consistent values found for the cycling experiments indicate little effect on the weight or dimensions of the complete cycling process. The insulating castables also show relatively little change in the weight or dimensions. The largest weight change was produced by the exposure in liquid during the test in the coal gasification atmosphere with H_2S, a gain of 9.1 percent in weight. The dimensions were essentially unaffected.

For density and porosity changes for this last series of tests, see Section B.4.2.11. Table A.2.2.2.3.5b summarizes the density changes found for the refractories in this series of tests. The percent changes are with respect to the density of air-fired control samples of the materials. The densities of the dense castables seem relatively unaffected with the percent changes being generally small. The insulating castables, especially the two lower alumina refractories, showed appreciably greater density changes in the exposures which apparently permitted large amounts of water to be retained by the sample. The cycling tests indicated that reactions had occurred which had increased the density.

Percent Change in Density after Vapor-Liquid Exposure and Cyclic Exposures

		Dense Castables			
		93% Alumina	87% Alumina	64% Alumina	58% Alumina
Exposures*		UMR-1 Generic	UMR-4 Generic	UMR-8 Generic	UMR-5 Generic
Saturated steam	vapor	+ 0.8	- 0.4	- 2.1	- 1.9
	liquid	+ 0.4	- 0.8	- 1.3	- 1.9
CGA with H_2S, saturated	vapor	+ 1.1	+ 3.9	+ 1.3	- 1.7
	liquid	+ 2.6	not tested	+ 1.3	not tested
CGA with H_2S, saturated		+ 0.08	+ 5.1	+ 2.5	+ 3.4
followed by air firing		- 2.3	+ 1.2	+ 0.8	+ 0.8
Above CGA-air firing	cycle 1	+ 1.1	+ 2.0	+ 1.7	+ 0.4
	cycle 2	+ 1.1	+ 3.1	+ 1.3	+ 0.4
	cycle 3	+ 1.5	+ 3.1	+ 1.7	0
	cycle 4	+ 0.8	+ 3.5	+ 1.7	+ 0.4
	cycle 5	+ 1.1	+ 3.1	+ 2.1	+ 0.8

		Insulating Castables		
		54% Alumina	47% Alumina	35% Alumina
		Cer-Lite #75	Litecast 60-25	VSL-50
Saturated steam	vapor	- 5.2	0	- 4.4
	liquid	- 3.9	- 1.8	- 5.5
CGA with H_2S, saturated	vapor	+ 2.6	+ 6.2	+ 7.7
	liquid	+ 9.8	not tested	+26
CGA with H_2S, saturated		+ 3.3	+13	+16
followed by air firing		+ 0.1	+ 9.7	+ 5.5
Above CGA-air firing	cycle 1	+ 2.0	+ 7.1	+ 7.7
	cycle 2	+ 1.3	+ 7.1	+ 6.7
	cycle 3	+ 2.0	+ 8.0	+ 8.8
	cycle 4	+ 2.0	+ 9.7	+ 8.8
	cycle 5	- 0.7	+ 8.8	+ 7.7

Table A.2.2.2.3.5b (see text for details of exposure conditions)

Table A.2.2.2.3.5c summarizes the changes in apparent porosity as compared to values for air-fired control samples. Correlating the porosity changes with the density changes is a bit difficult since some very large porosity changes have occurred with minimal density changes and vice versa. In general, the dense castables seemed to experience a large loss in apparent porosity upon exposure to the saturated test atmospheres with the relatively little change in density discussed above. The chemical or physical changes caused by the test atmospheres are filling the pores of the refractories. The formation of hydrated aluminas (especially boehmite) as discussed in A.2.2.2.3.1 is certainly occurring at the 447 °F saturated test temperature. The insulating castables tend to show an increase in porosity and generally of a lower magnitude than the changes in the dense castables. Only one, the 54 percent alumina castable, exhibited any appreciable loss in porosity and that occurred both in the vapor and the liquid phases of the steam-saturated coal gasification atmosphere test. The boehmite formation-degradation cycling tests indicated that the dense castables retained some loss of porosity compared with air-fired materials upon continued cycling. This retention seems fairly constant if wide limits are accepted in some cases. Although the formation of boehmite seems to cause moderately large porosity loss as the pores are filled with the compound, and the air-firing definitely causes its loss, the porosity does not return quite to the level of the air-fired but otherwise unexposed material.

Percent Change in Apparent Porosity after Vapor-Liquid Exposure and Cyclic Exposure

		Dense Castables			
		93% Alumina	87% Alumina	64% Alumina	58% Alumina
Exposures*		UMR-1 Generic	UMR-4 Generic	UMR-8 Generic	UMR-5 Generic
Saturated steam	vapor	-32	- 5.6	-33	-10
	liquid	-28	- 5.6	-24	-14
CGA with H_2S, saturated	vapor	-61	-86	-49	-34
	liquid	- 7.9	not tested	-48	not tested
CGA with H_2S, saturated		-23	-51	-42	-34
followed by air firing		- 5.7	-25	-19	-15
Above CGA-air firing	cycle 1	- 1.9	- 8.1	- 8.0	- 5.3
	cycle 2	- 3.4	- 9.3	- 4.5	- 5.3
	cycle 3	- 1.9	- 9.3	-12	- 6.3
	cycle 4	0	- 9.6	- 5.0	- 5.3
	cycle 5	- 4.2	- 8.9	- 2.5	- 6.3

		Insulating Castables		
		54% Alumina	47% Alumina	35% Alumina
		Cer-Lite #75	Litecast 60-25	VSL-50
Saturated steam	vapor	+14	+ 6.3	+ 6.7
	liquid	+15	+ 9.9	+ 1.6
CGA with H_2S, saturated	vapor	-15	+ 3.9	+ 1.3
	liquid	-46	not tested	- 8.3
CGA with H_2S, saturated		- 3.5	- 4.6	- 5.4
followed by air firing		- 1.7	- 0.9	+ 2.5
Above CGA-air firing	cycle 1	+ 5.7	+ 3.7	+ 2.2
	cycle 2	+ 4.6	+ 2.4	+ 2.5
	cycle 3	+ 4.8	- 0.6	- 0.3
	cycle 4	+ 7.4	+ 2.9	+ 1.4
	cycle 5	+11	- 4.6	+ 1.3

Table A.2.2.2.3.5c (see text for details of exposure conditions)

The cycling of the insulating refractory appears to cause small increases in porosity generally. The exception is the 54 percent alumina castable which shows some trend toward increasing porosity with cycling. If the increase in porosity of the insulating castables does not coincide with a severe degradation of the material, then the insulating ability is merely enhanced by use. If the increased porosity is indeed caused by breakdown of bonding phases (see discussion in A.2.2.2.1 and A.2.2.2.3.1), then the change in this property may indicate the degree of degradation, and finding refractories exhibiting small changes will be desirable.

THE EFFECT OF VARYING CARBON MONOXIDE-STEAM CONCENTRATIONS was studied in a series of tests since these are the apparently most important reactants in the coal gasification atmospheres at lower temperatures and pressures. A variety of refractories, dense high- and intermediate-alumina castables, insulating castables, and ramming mixes were tested. One series of tests exposed samples to gas which contained CO/steam in ratios of 0.1, 1.0, and 3.0 with one vol. percent H_2S. The tests were run for 20 days at temperatures and pressures providing these component ratios and also under conditions which exposed samples to both vapor and liquid phases in a vessel in which the CO/steam atmosphere was steam saturated. Section B.4.2.13 shows the weight changes which occurred (data are averages for seven samples exposed in vapor, two samples exposed in liquid). Values in parentheses are for samples exposed under liquid. The changes, either losses or gains, are not generally meaningful for any of the refractories under any of the conditions. Even the weight losses or gains experienced by samples immersed in liquid did not exceed 9.5 percent. Tests were also performed in steam-saturated CO/H_2O atmospheres with no H_2S added but with the same CO/H_2O ratios of 0.1, 1.0, and 3.0 and samples were exposed both in the vapor (seven of each) and under liquid (two of each) in the steam generator. Density and porosity results for these tests are given in B.4.2.12 (data in parentheses are for samples immersed in liquid). These density and porosity changes compared to values for air-fired control samples are summarized in Table A.2.2.2.3.5d. The density changes were generally greater for the samples immersed in liquid, but these were not large for the dense castables or the ramming mix tested, the maximum loss for any castable in any test being 5.6 percent, the maximum gain 4.7 percent. The density changes occurring in vapor and liquid exposures tended to be higher for the insulating castables, but the behavior seems erratic with respect to gain or loss and CO/H_2O ratio, or vapor or liquid exposure. The porosity changes for most of the dense castables consisted largely of appreciable losses in porosity in the vapor phases of the 0.1 and 1.0 CO/H_2O atmosphere. Only the 93 percent alumina and the 87 percent alumina generic materials showed appreciable differences in behavior between vapor- and liquid-exposed samples. The tests run in atmospheres of $CO/H_2O = 3.0$ tended to show larger differences between vapor and liquid exposures for the dense castables. The insulating castables tended to show increases in porosity but differences between exposure to liquid as opposed to vapor phases do not seem meaningful.

THE EFFECT ON WEIGHT, DENSITY, AND POROSITY OF STEAM-SATURATED COAL GASIFICATION ENVIRONMENTS was also studied (see B.4.2.14). The density and porosity data are also summarized in Table A.2.2.2.3.5d. Examination of the data for liquid exposures (values given in parentheses) shows a large effect of decreasing porosity for some dense castables, but the densities are relatively unaffected.

Percent Change in Density of Refractories Exposed to Various Atmospheres

Refractory	CO/H$_2$O Atmospheres with Ratios of			Coal Gasification Atmospheres	
	0.1	1.0	3.0	Unsaturated	Saturated
DENSE CASTABLES, Calcium Aluminate Bonded					
94% Alumina, Greencast-94	not tested	not tested	not tested	+1.9	+0.7(+1.9)
93% Alumina, UMR-1 (Generic)	+3.0(+3.4)	-1.5(-0.4)	+0.4(-5.6)	+3.0	+5.0(+11)
91% Alumina, UMR-2 (Generic)	+5.2(+4.4)	-0.4(+1.2)	+3.6(-5.6)	+2.4	+0.8(+3.2)
91% Alumina, UMR-3 (Generic)	not tested	not tested	not tested	-9.0	0(+7.7)
87% Alumina, UMR-4 (Generic)	+2.4(+4.7)	-0.8(+2.0)	+1.6(-3.1)	not tested	not tested
57% Alumina, RC-3	+2.3(+3.6)	+5.0(+2.3)	+3.6(-2.7)	+5.0	+3.2(+7.7)
50% Alumina, UMR-5 (Generic)	+0.8(+1.7)	+0.4(+0.4)	+3.2(-1.7)	not tested	-1.3
INSULATING CASTABLES, Calcium Aluminate Bonded					
54% Alumina, Cer-Lite #75	-1.9(-1.9)	+1.2(+9.1)	-0.6(-1.9)	-1.9	0(+16)
46% Alumina, Litecast 60-25	+5.3(+16)	+9.7(+18)	+8.0(+0.9)	not tested	+5.3
35% Alumina, VSL-50	-4.4(+3.3)	-6.7(0)	-1.1(-3.3)	not tested	not tested
RAMMING MIXES, Phosphate Bonded					
96% Alumina, Greenpak-90P	-3.7(-3.7)	-2.7(+0.7)	-3.7(-2.4)	not tested	-2.0
90% Alumina, Brikram 90R	not tested	not tested	not tested	not tested	-4.1

Percent Change in Apparent Porosity of Refractories Exposed to Various Atmospheres

Refractory	CO/H$_2$O Atmospheres with Ratios of			Coal Gasification Atmospheres	
	0.1	1.0	3.0	Unsaturated	Saturated
DENSE CASTABLES, Calcium Aluminate Bonded					
94% Alumina, Greencast-94	not tested	not tested	not tested	+4.0	-8.0(-28)
93% Alumina, UMR-1 (Generic)	-43(-43)	+13(-29)	-4.3(+13)	+17	-8.7(-74)
91% Alumina, UMR-2 (Generic)	-46(-50)	-21(-21)	-21(+18)	-3.4	-18(-14)
91% Alumina, UMR-3 (Generic)	not tested	not tested	not tested	0	+3.2(-23)
87% Alumina, UMR-4 (Generic)	-30(-37)	-3.7(-19)	-15(+3.7)	not tested	not tested
57% Alumina, RC-3	-26(-30)	-22(-13)	-61(-4.3)	-13	-17(-43)
50% Alumina, UMR-5 (Generic)	-16(-26)	-11(-16)	-32(-5.3)	not tested	-11
INSULATING CASTABLES, Calcium Aluminate Bonded					
54% Alumina, Cer-Lite #75	+24(+24)	+21(-17)	+21(+24)	+24	+19(-12)
46% Alumina, Litecast 60-25	+3.7(-5.6)	+5.6(-17)	+3.7(+11)	not tested	+5.6
35% Alumina, VSL-50	+7.9(+1.6)	+11(+70)	+70(+9.5)	not tested	not tested
RAMMING MIXES, Phosphate Bonded					
96% Alumina, Greenpak-90P	+35(+29)	+24(+12)	+29(+29)	not tested	+24
90% Alumina, Brikram 90R	not tested	not tested	not tested	not tested	+29

Table A.2.2.2.3.5d (see text for details of exposure conditions)

ILOT PLANT TESTING

THE EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS n physical properties of a variety of refractories is given in Section .4.2.6. Specimens of the refractories were placed on test racks in a total f eight locations within five pilot plants. Not all refractories were tested n all locations; for some plants there was only one exposure, in other plants there were two or three exposures. The full conditions to which the samples were exposed are not available. Exposure times, when given, are approximate as are the concentrations of the chemical constituents of the atmospheres, the temperatures, and the pressures. During plant operation, these variables could have fluctuated widely, and the extent and duration of these fluctuations is unknown. Evaluation of the numerical data is difficult since percentage differences for data for exposed and unexposed samples do not seem sufficiently reliable for all of the data and multiplicate samples were not tested. The results for separate exposures in the same location differ for many of the materials. In the light of all of the uncertainties given above, the data must be viewed with caution. Four measurements were made, the percent weight change, the apparent porosity, the apparent specific gravity, and the bulk density. The porosity, specific gravity, and density were measured by liquid immersion in kerosene using the ASTM C20-46 method.

Table A.2.2.2.3.5e contains a qualitative summary of the data in B.4.2.6 for sample weight change. The symbols used in the figure have the following meaning:

nt	The material was not tested in that location.
-	The change in weight between unexposed and exposed samples is less than or about equal to five percent in either direction.
I	Increased--the gain in weight is greater than five percent.
D	Decreased--the loss in weight is greater than five percent.

The use of these symbols and the criteria used in assigning them are completely arbitrary. It can be seem readily from Table A.2.2.2.3.5e that the weight change for most samples was trivial. Only a few showed as much change as ten percent and only one refractory had a change appreciably greater than ten percent (a 60 percent alumina dense castable, 38.5 percent change). This lack of major weight change is consistent with the laboratory data reported above.

Qualitative data summaries for apparent porosity, apparent specific gravity, and bulk density appear in Tables A.2.2.2.3.5f, g, and h, respectively. The following meaning attaches to the symbols:

nt	Not tested.
-	The change in data between unexposed and exposed samples is less than or about equal to ten percent.
I	Increased--the increased value of the data between unexposed and exposed samples is greater than ten percent.
D	Decreased--the decreased value of the data between unexposed and exposed samples is greater than ten percent.

Percent Weight Change of Refractory Coupons Due to Exposures in Pilot Plant Locations

Refractories	Synthane		CO_2 Acceptor		Bi-Gas	Battelle		HYGAS
	1	2	1	2		1	2	
CASTABLES, CALCIUM ALUMINATE-BONDED								
90+% Al_2O_3 dense (Purolite 30)	-	nt	-	D	nt	nt	nt	nt
90+% Al_2O_3 dense (Greencast-97)	nt	nt	-	-	nt	nt	nt	-
90+% Al_2O_3 light (Greencast-97L)	-	-	-	-	nt	nt	nt	nt
90% Al_2O_3 dense (Castolast G)	D	D	-	-	nt	nt	nt	-
60% Al_2O_3 dense (Mizzou Castable)	-	-	-	-	nt	D	D	-
60% Al_2O_3 dense (Super Brikcast A)	-	-	-	-	D	nt	nt	-
55% Al_2O_3 lightweight insulating (Litecast 75-28)	D	-	-	-	D	nt	nt	-
52% Al_2O_3 light (Litecast 80)	-	nt	-cr	-	nt	nt	nt	nt
PHOSPHATE-BONDED REFRACTORIES								
90% Al_2O_3 dense castable (Resco Cast AA-22)	-	-	-	-	-	-	-	nt
88% Al_2O_3 mortar (Chemal 111)	-	nt	nt	nt	nt	nt	nt	nt
90% Al_2O_3 ramming mix (Brikram 90)	-	-	-cr	-	nt	-	-	-
73% Al_2O_3 dense ramming mix (Blu Ram)	-	nt	nt	nt	nt	nt	nt	nt
73% Al_2O_3 dense ramming mix (Blu Ram H.S.)	-	nt	nt	nt	nt	nt	nt	nt
60% Al_2O_3 ramming mix (Wasp #60)	-	-	-f	-	nt	nt	nt	nt
85% Al_2O_3 dense fired brick (Chemal 85 B)	-	-	-	-	-	-	nt	-
85% Al_2O_3 fired brick (Altex 85-B)	-	-	-	-	nt	nt	nt	-
80+% Al_2O_3 fired brick (Alumex P-8)	-	-	-	-	nt	-	nt	-
ALUMINA BRICKS								
99+% Al_2O_3 self-bonded dense fired (H-W Corundum)	-	-	-	-	nt	nt	nt	-
99+% Al_2O_3 self-bonded fused-cast dense (Monofrax A)	-	-	-	-	nt	nt	nt	nt
98+% Al_2O_3 self-bonded light insulating fired (Alfrax B 101)	-	-	-	I	nt	nt	nt	-
90+% Al_2O_3 self-bonded dense fired (Kricor)	-	-	-	-	nt	nt	nt	-
77% Al_2O_3 vitreous bond light insulating fired (B&W Insalcor)	-	-	D	I	nt	nt	nt	-
70% Al_2O_3 vitreous bond fired (Mul-8)	-	-	-	-	nt	-	nt	-
70% Al_2O_3 vitreous bond fired (Hi Lumite 70 D)	-	-	-	-	nt	nt	nt	-
70% Al_2O_3 vitreous bond dense fired (Alumex 70-HD)	nt	nt	-	-	-	nt	nt	-
60% Al_2O_3 tar-impregnated fired (Ufala TI)	-	-	D	-	nt	nt	D	-
45-50% Al_2O_3 vitreous bond high-fired superduty (KX-99)	-	-	-	-	nt	nt	-	-
MISCELLANEOUS BRICKS								
SiC silicon nitride-bonded dense fired (Refrax 20)	-	-	-c	-	nt	nt	nt	nt
SiC silicon oxynitride-bonded (Crystolon 63)	-	-	D	-	nt	nt	nt	nt
SiC clay-bonded	nt	nt	nt	nt	nt	-	-	nt
Alumina-zirconia-silica fused cast	-	nt	nt	nt	nt	nt	nt	nt
Zirconium silicate vitreous bond	nt	-	-	nt	nt	nt	nt	nt
90% Alumina-10% chromia solid solution fired (CS 612)	nt	nt	-	-	nt	nt	nt	nt

Table A.2.2.2.3.5e (see text for definition of symbols)

c	One of the coupons from one of the plant exposures corroded.
cr	One of the coupons from one or more of the plant exposures cracked.
f	One of the coupons from one or more of the plant exposures fractured.
dis	The coupon disintegrated during exposure.

Where both I and D appear, there are conflicting values for different exposures of the same refractory in the same plant. The order I,D or D,I merely indicates which has the greater numerical value. Where there is more than one exposure, the qualitative rating is based on the worst result, the greatest difference for exposed vs. unexposed values. The criteria used in the assignment of these symbols are completely arbitrary.

Table A.2.2.2.3.5f indicates that the apparent porosity generally increased more than ten percent for most of the refractories for most of the tests. A large number also show changes of less than ten percent. The number of large decreases in porosity noted in the figure is very small. Whether the increase in apparent porosity for so many of the materials is disadvantageous or not is difficult to assess. It is obvious that the bricks generally experienced an increase in porosity upon exposure. Extremely large increases were measured for fused cast materials which had developed a network of hairline cracks due to thermal shock. Trends in this set of data are difficult to correlate with data discussed in section A.2.2.2.3.1 and summarized in Table A.2.2.2.3.1a for the same series of pilot plant exposures. Favorable performance with respect to the stability of the bonding phase as discussed in A.2.2.2.3.1 seems to have little relationship with any change or lack of change of the apparent porosity of the material or indeed of the specific gravity (Table A.2.2.2.3.5g) or of the bulk density (Table A.2.2.2.3.5h). For most of the refractories tested, the changes of these two properties, specific gravity and bulk density, were less than ten percent.

SILICON CARBIDE AND SIALON REFRACTORIES were among those refractories tested in the above described pilot plant exposures, and the data appear in the tables summarizing the data. Silicon nitride-bonded and oxynitride-bonded silicon carbides exhibited moderate to large increases in porosity with decreases in the specific gravity and bulk density for the gasifier exposures. Data for exposure in the dolomite regenerator shows a large decrease in porosity, with some decrease in specific gravity and increase in density.

IN GENERAL, DENSITY AND POROSITY, ALONG WITH WEIGHT AND DIMENSIONAL CHANGE do not seem to be very sensitive measures of the effect of various atmospheres and reactants on the performance of refractories for coal gasification use. Mechanical properties (see A.2.2.2.3.4) form more important criteria for choosing various refractories for different uses.

THERMAL CONDUCTIVITY data are given for three high-alumina dense castables, two generic preparations, and one commercial material. The data (see B.4.2.5) are consistent with the material with the lower bulk density having the lower thermal conductivity, as is to be expected. The one generic material with the lower density and lower thermal conductivity is unusual in that the aggregate portion of the refractory consists of sintered calcium aluminate cement. This material also shows the least change in thermal conductivity over the temperature range tested (ambient to 2500 °F).

Percent Apparent Porosity Change of Refractory Coupons Due to Exposures in Pilot Plant Locations

Refractories	Synthane		CO_2 Acceptor		Bi-Gas	Battelle		HYGAS
	1	2	1	2		1	2	
CASTABLES, CALCIUM ALUMINATE-BONDED								
90+% Al_2O_3 dense (Purolite 30)	dis	nt	I	I	nt	nt	nt	nt
90+% Al_2O_3 dense (Greencast-97)	nt	nt	-	D	nt	nt	nt	-
90+% Al_2O_3 light (Greencast-97L)	-	I	D,I	I,D	nt	nt	nt	nt
90% Al_2O_3 dense (Castolast G)	-	-	D,I	I,D	nt	nt	nt	-
60% Al_2O_3 dense (Mizzou Castable)	-	-	D,I	-	nt	-	D	D
60% Al_2O_3 dense (Super Brikcast A)	-	-	-	-	-	nt	nt	D
55% Al_2O_3 lightweight insulating (Litecast 75-28)	I	I	I	I	I	nt	nt	I
52% Al_2O_3 light (Litecast 80)	D	nt	Icr	I	nt	nt	nt	nt
PHOSPHATE-BONDED REFRACTORIES								
90% Al_2O_3 dense castable (Resco Cast AA-22)	I	D	-	I	-	-	-	nt
90% Al_2O_3 ramming mix (Brikram 90)	I	D	Dcr	D,I	nt	-	-	I,D
73% Al_2O_3 dense ramming mix (Blu Ram)	I	nt	nt	nt	nt	nt	nt	nt
73% Al_2O_3 dense ramming mix (Blu Ram H.S.)	-	nt	nt	nt	nt	nt	nt	nt
60% Al_2O_3 ramming mix (Wasp #60)	I	I	Icr	I,D	nt	nt	nt	nt
85% Al_2O_3 dense fired brick (Chemal 85 B)	I	I	-	I	-	-	nt	I
85% Al_2O_3 fired brick (Altex 85-B)	I	I	I	I	nt	nt	nt	I
80+% Al_2O_3 fired brick (Alumex P-8)	I	I	I	I	nt	-	nt	I
ALUMINA BRICKS								
99+% Al_2O_3 self-bonded dense fired (H-W Corundum)	-	-	D,I	I	nt	nt	nt	-
99+% Al_2O_3 self-bonded fused-cast dense (Monofrax A)	I	I	I,D	I,D	nt	nt	nt	nt
98+% Al_2O_3 self-bonded light insulating fired (Alfrax B 101)	-	-	-	D	nt	nt	nt	-
90+% Al_2O_3 self-bonded dense fired (Kricor)	I	-	-	-	nt	nt	nt	-
77% Al_2O_3 vitreous bond light insulating fired (B&W Insalcor)	I	I	I	I	nt	nt	nt	I
70% Al_2O_3 vitreous bond fired (Mul-8)	I	-	I	-	nt	-	nt	I
70% Al_2O_3 vitreous bond fired (Hi Lumite 70 D)	-	I	I	D,I	nt	nt	nt	D,I
70% Al_2O_3 vitreous bond dense fired (Alumex 70-HD)	nt	nt	nt	-	-	nt	nt	-
60% Al_2O_3 tar-impregnated fired (Ufala TI)	I	-	I	I	nt	nt	I	I
45-50% Al_2O_3 vitreous bond high-fired superduty (KX-99)	I	I	I	-	nt	nt	-	I
MISCELLANEOUS BRICKS								
SiC silicon nitride-bonded dense fired (Refrax 20)	I	I	I	D	nt	nt	nt	nt
SiC silicon oxynitride-bonded (Crystolon 63)	I	I	I	D	nt	nt	nt	nt
SiC clay-bonded	nt	nt	nt	nt	nt	-	D	nt
Alumina-zirconia-silica fused cast	I	nt	nt	nt	nt	nt	nt	nt
Zirconium silicate vitreous bond	nt	-	-	nt	nt	nt	nt	nt
90% Alumina-10% chromia solid solution fired (CS 612)	nt	nt	-	-	nt	nt	nt	nt

Table A.2.2.2.3.5f (see text for definition of symbols)

Percent Specific Gravity Change of Refractory Coupons Due to Exposures in Pilot Plant Locations

Refractories	Synthane		CO_2 Acceptor		Bi-Gas	Battelle		HYGAS
	1	2	1	2		1	2	
CASTABLES, CALCIUM ALUMINATE-BONDED								
90+% Al_2O_3 dense (Purolite 30)	dis	nt	I	I	nt	nt	nt	nt
90+% Al_2O_3 dense (Greencast-97)	nt	nt	-	-	nt	nt	nt	-
90+% Al_2O_3 light (Greencast-97L)	I	I	I,D	I,D	nt	nt	nt	nt
90% Al_2O_3 dense (Castolast G)	-	-	-	-	nt	nt	nt	-
60% Al_2O_3 dense (Mizzou Castable)	-	-	-	-	nt	-	-	-
60% Al_2O_3 dense (Super Brikcast A)	-	-	-	-	-	nt	nt	-
55% Al_2O_3 lightweight insulating (Litecast 75-28)	I	I	I	I	I	nt	nt	D
52% Al_2O_3 light (Litecast 80)	I	nt	Icr	I	nt	nt	nt	nt
PHOSPHATE-BONDED REFRACTORIES								
90% Al_2O_3 dense castable (Resco Cast AA-22)	D,I	-	-	-	-	-	-	nt
90% Al_2O_3 ramming mix (Brikram 90)	-	-	-cr	D	nt	-	-	-
73% Al_2O_3 dense ramming mix (Blu Ram)	-	nt	nt	nt	nt	nt	nt	nt
73% Al_2O_3 dense ramming mix (Blu Ram H.S.)	-	nt	nt	nt	nt	nt	nt	nt
60% Al_2O_3 ramming mix (Wasp #60)	-	-	-cr	-cr	nt	nt	nt	nt
85% Al_2O_3 dense fired brick (Chemal 85 B)	-	-	-	-	-	-	nt	-
85% Al_2O_3 fired brick (Altex 85-B)	-	-	-	-	nt	nt	nt	-
80+% Al_2O_3 fired brick (Alumex P-8)	-	-	-	-	nt	-	nt	-
ALUMINA BRICKS								
99+% Al_2O_3 self-bonded dense fired (H-W Corundum)	-	-	-	-	nt	nt	nt	-
99+% Al_2O_3 self-bonded fused-cast dense (Monofrax A)	-	-	-	-	nt	nt	nt	nt
98+% Al_2O_3 self-bonded light insulating fired (Alfrax B 101)	D	-	D,I	D	nt	nt	nt	-
90+% Al_2O_3 self-bonded dense fired (Kricor)	-	-	-	-	nt	nt	nt	-
77% Al_2O_3 vitreous bond light insulating fired (B&W Insalcor)	D	I	I	I	nt	nt	nt	D
70% Al_2O_3 vitreous bond fired (Mul-8)	-	-	-	-	nt	-	nt	-
70% Al_2O_3 vitreous bond fired (Hi Lumite 70 D)	-	-	I	D,I	nt	nt	nt	-
70% Al_2O_3 vitreous bond dense fired (Alumex 70-HD)	nt	nt	-	-	-	nt	nt	-
60% Al_2O_3 tar-impregnated fired (Ufala TI)	-	-	-	-	nt	nt	I	-
45-50% Al_2O_3 vitreous bond high-fired superduty (KX-99)	-	-	-	-	nt	nt	-	-
MISCELLANEOUS BRICKS								
SiC silicon nitride-bonded dense fired (Refrax 20)	-	D	D	-	nt	nt	nt	nt
SiC silicon oxynitride-bonded (Crystolon 63)	-	-	-	-	nt	nt	nt	nt
SiC clay-bonded	nt	nt	nt	nt	nt	-	-	nt
Alumina-zirconia-silica fused-cast	-	nt	nt	nt	nt	nt	nt	nt
Zirconium silicate vitreous bond	nt	-	-	nt	nt	nt	nt	nt
90% Alumina-10% chromia solid solution fired (CS 612)	nt	nt	-	-	nt	nt	nt	nt

Table A.2.2.2.3.5g (see text for definition of symbols)

Percent Bulk Density Change of Refractory Coupons Due to Exposures in Pilot Plant Locations

Refractories	Synthane 1	Synthane 2	CO_2 Acceptor 1	CO_2 Acceptor 2	Bi-Gas	Battelle 1	Battelle 2	HYGAS
CASTABLES, CALCIUM ALUMINATE-BONDED								
90+% Al_2O_3 dense (Purolite 30)	dis	nt	-	-	nt	nt	nt	nt
90+% Al_2O_3 dense (Greencast-97)	nt	nt	-	-	nt	nt	nt	-
90+% Al_2O_3 light (Greencast-97L)	-	-	I	-	nt	nt	nt	nt
90% Al_2O_3 dense (Castolast G)	-	-	-	-	nt	nt	nt	-
60% Al_2O_3 dense (Mizzou Castable)	-	-	-	-	nt	-	-	-
60% Al_2O_3 dense (Super Brikcast A)	-	-	-	-	-	nt	nt	-
55% Al_2O_3 lightweight insulating (Litecast 75-28)	D	-	-	I	D	nt	nt	D
52% Al_2O_3 light (Litecast 80)	-	nt	-cr	-	nt	nt	nt	nt
PHOSPHATE-BONDED REFRACTORIES								
90% Al_2O_3 dense castable (Resco Cast AA-22)	D	-	-	-	-	-	-	nt
90% Al_2O_3 ramming mix (Brikram 90)	-	-	-cr	-	nt	-	-	-
73% Al_2O_3 dense ramming mix (Blu Ram)	-	nt	nt	nt	nt	nt	nt	nt
73% Al_2O_3 dense ramming mix (Blu Ram H.S.)	-	nt	nt	nt	nt	nt	nt	nt
60% Al_2O_3 ramming mix (Wasp #60)	D	-	Dcr	Dcr	nt	nt	nt	nt
85% Al_2O_3 dense fired brick (Chemal 85 B)	-	-	-	-	-	-	nt	-
85% Al_2O_3 fired brick (Altex 85-B)	-	-	-	-	nt	nt	nt	-
80+% Al_2O_3 fired brick (Alumex P-8)	-	-	-	-	nt	-	nt	-
ALUMINA BRICKS								
99+% Al_2O_3 self-bonded dense fired (H-W Corundum)	-	-	-	-	nt	nt	nt	-
99+% Al_2O_3 self-bonded fused-cast dense (Monofrax A)	-	-	-	-	nt	nt	nt	nt
98+% Al_2O_3 self-bonded light insulating fired (Alfrax B 101)	-	-	-	-	nt	nt	nt	-
90+% Al_2O_3 self-bonded dense fired (Kricor)	-	-	-	-	nt	nt	nt	-
77% Al_2O_3 vitreous bond light insulating fired (B&W Insalcor)	D	-	D	D	nt	nt	nt	D
70% Al_2O_3 vitreous bond fired (Mul-8)	-	-	-	-	nt	-	nt	-
70% Al_2O_3 vitreous bond fired (Hi Lumite 70 D)	-	-	I	I,D	nt	nt	nt	-
70% Al_2O_3 vitreous bond dense fired (Alumex 70-HD)	nt	nt	-	-	-	nt	nt	-
60% Al_2O_3 tar-impregnated fired (Ufala TI)	-	-	-	-	nt	nt	-	-
45-50% Al_2O_3 vitreous bond high-fired superduty (KX-99)	-	-	-	-	nt	nt	-	-
MISCELLANEOUS BRICKS								
SiC silicon nitride-bonded dense fired (Refrax 20)	D	D	D	-	nt	nt	nt	nt
SiC silicon oxynitride-bonded (Crystolon 63)	-	D	-	-	nt	nt	nt	nt
SiC clay-bonded	nt	nt	nt	nt	nt	-	-	nt
Alumina-zirconia-silica fused-cast	-	nt	nt	nt	nt	nt	nt	nt
Zirconium silicate vitreous bond	nt	-	-	nt	nt	nt	nt	nt
90% Alumina-10% chromia solid solution fired (CS 612)	nt	nt	-	-	nt	nt	nt	nt

Table A.2.2.2.3.5h (see text for definition of symbols)

A.2.3.1 OPERATING REQUIREMENTS

All of the problems of erosion and corrosion noted in the previous section for non-slagging vessels (A.2.2.1) exist for slagging vessels and are intensified in a portion of the gasifier by higher temperature requirements (up to 3,200 °F [2,033 K]) and the presence of liquid slag which is very corrosive. Resistance to slag corrosion would be the major criterion for material selection in the hottest portion of slagging gasifiers. Slag compositions vary greatly for different coals with Western coals generally more acidic and Eastern coals more basic. This suggests that a single refractory composition is unlikely to be equally effective against all slags and, once a choice is made, a specific plant will be limited in the type of coal it can handle. The corrosive effects of liquid slag can be substantially reduced by cold wall designs which remove enough heat to freeze a protective layer of slag on the walls. A substantial materials technology exists from coal combustors and blast furnaces, but differences in operating conditions suggest that technology transfer will not be straightforward.

A.2.3.2.2.1 SLAG CORROSION

THE RELATIVE CORROSION RESISTANCE of thirty-six different refractories exposed to varying slag composition at ~1500 °C for 200 or 500 hours was determined by measuring the maximum depth of material removed from the original hot face of the specimen (see B.1.2.14). Of 15 materials exposed for 200 hours (see B.1.2.14 for slag composition), two Al_2O_3-CaO castable refractories (B & W Kao-Tab CS and Purotab), one phosphate-bonded alumina castable (Kao Phos 30), and one chrome-iron- alumina-magnesia ramming mix (Kemram) suffered the greatest material loss from the moving slag, >20 mm depth of material removal. A Cr_2O_3-MgO-Fe_2O_3 fused cast brick (Monofrax E) suffered no apparent material loss in this environment and an alumina fused cast brick (Monofrax A2) had little loss. In two groups of materials exposed to two different (more basic) slag compositions (see B.1.2.14) for 500 hours, the Cr_2O_3-MgO-Fe_2O_3 fused cast brick (Monofrax E), chrome-iron-alumina-magnesia bricks (Dibond 50, GR-200, Guidon, Krilex 621, Nucon 60) and two alumina-chromia bricks (CS-612, Ruby) suffered the least material removal from the moving slag. Silicon carbide, sialon, silicon nitride containing bricks and most alumina-containing bricks or castable had moderate to large material losses. An Al_2O_3-SiO_2-P_2O_5 brick (Chemal 85B) suffered large material removal in the less basic slag for 200 hours but appeared to perform well when exposed to the more basic slag for 500 hours.

A total of 31 materials were exposed to slag attack for periods of 500 or 1000 hours during which time the original slag compositions varied somewhat. The bricks were water cooled, thus producing a temperature gradient (see B.1.2.15). A Cr_2O_3-Al_2O_3-Fe_2O_3 ramming mix (Kemram), an Al_2O_3-Cr_2O_3 ramming mix (Shamrock 888), and a medium alumina Al_2O_3-Cr_2O_3 brick (LT5) suffered the least material removal during 500 hour tests in less basic slags. The same materials were not exposed for longer times or to a more basic slag for comparison. Two Cr_2O_3-MgO-Fe_2O_3 fused cast bricks (Monofrax E and Monofrax K-3) performed well when exposed for 1000 hours. Another Al_2O_3-Cr_2O_3 brick [852Z (Serv-M)] performed very well during 500 hours exposure to an even more basic slag as did chrome-iron-alumina-magnesia bricks (Guidon, Krilex 911, and Corhart RFG). The bricks based on silicon carbide showed better performance in the tests with water cooling for 500 hours but were poor in the 1000 hour test.

It should be noted that the test conditions effectively expose a brick wall composed of many kinds of bricks to a slag liquid. Local variations in slag composition due to dissolution of some bricks may influence the performance of neighboring bricks. Therefore, these tests do not simulate the behavior of a single composition wall in a slagging environment.

A.2.3.2.2.2 COMPRESSIVE STRENGTH

THE EFFECT OF STEAM AND A SIMULATED COAL GASIFICATION ATMOSPHERE ($25\%H_2$, $13\%CO_2$, 21%CO, $5\%CH_4$, $36\%H_2O$) [vs. air-fired] ON THE COMPRESSIVE STRENGTH of several refractories considered for possible use in slagging vessels is tabulated in B.3.2.20. One material, $73SiC\text{-}21Si_3N_4\text{-}3Al_2O_3\text{-}3SiO_2$ sintered brick, disintegrated when exposed to steam and to the coal gas. For a chemically bonded ramming plastic ($40Cr_2O_3\text{-}23Fe_2O_3\text{-}21Al_2O_3\text{-}$ 10MgO) the compressive strength after exposure to steam (980 °C, 250 hr, 1000 psi) decreased 60 percent from that for air-fired (980 °C, 250 hr) and after exposure to the gas (980 °C, 250 hr, 1000 psi) decreased 40 percent from that for air-fired. Three of these materials (medium alumina with varying compositions) increased slightly in compressive strength following both exposure conditions. The behavior of other materials tested was variable with only slight changes in compressive strength. These test results have limited value for actually determining which materials to use for lining slagging vessels because the tests have been performed in the coal gasification environment with no slag present. However, they are useful for initial screening purposes to select materials for further testing.

For a discussion of corrosion/erosion and mineralogical changes caused by the reactor atmosphere and high temperature and high pressure effects on mechanical and physical properties, see Section A.2.2.2.3, Materials Evaluation for Dry-Bottom Vessels.

A.2.4.1 OPERATING REQUIREMENTS

Gasifier vessel metal internals include components such as pressure and temperature probes, solids transfer line nozzles, gas distributor plates and tubes, dip legs, cyclones, valves and their support structures, and refractory anchors. Although some operating conditions in blast furnaces, coke oven gas producers, and petrochemical processes are similar, the coal gasifier environment is sufficiently different that materials experience with these other processes is not directly transferable. High temperature and pressure (up to 3,000 °F and 1,500 psig), erosion by solid particulates in turbulent flow, and corrosion (oxidation, carburization, sulfidation, hydrogen embrittlement and temper embrittlement), the introduction of new reactions at higher temperatures, and the ever-present possibility of melting metal internals in process excursions are the conditions in which such structures must perform during operation of the gasifier. In addition, all metal internal components are exposed to typical low temperature corrosion mechanisms (e.g., pitting, galvanic-, crevice-, stress-, condensation-corrosion) during shutdown periods.

Corrosion of a material depends not only on the material and its environment, but also on the internal structure of the material (secondary phases, residual stresses, voids, inclusions, dissolved gases, composition) and the nature of its service. The internal components need to be made of materials with the best combination of high-temperature mechanical properties and corrosion resistance in the coal gasification atmosphere to minimize costly time-consuming shutdowns.

A.2.4.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 12 different THERMOWELLS (A.2.4.2.1.1). Eight different materials were used for these thermowells. The materials included Hastelloy C-276, Hastelloy X, Incoloy 800, RA 330, three austenitic stainless steels - 304, 310, and 316, and one ferritic stainless steel - 446. Reported service temperatures ranged from 800 to 2300 °F.

Reaction to sulfur was the most frequently reported cause of failure. The three Hastelloy X thermowells as well as the RA 330 and one of the 310 stainless steel thermowells failed because of reaction with sulfur. Three failures - one 310 stainless steel, one 316 stainless steel and one 446 stainless steel - were due to overheating. The Incoloy 800 and the 304 stainless steel failures were due to stress corrosion cracking. In addition, the 304 stainless steel suffered chloride attack. The Hastelloy C-276 failed due to pitting of the outer surface, possibly from clinker formation.

For those thermowells for which service times were reported, one which was fabricated from 310 stainless steel and exposed to a coal gas/CO_2/steam/coal char environment at 1600-1800 °F had the longest service life (1.5 years). The 310 stainless steel thermowell exposed to a fluidized bed environment at temperatures in excess of 2100 °F had the shortest reported service life.

PLANT EXPERIENCE for five CYCLONES has been reported (A.2.4.2.1.2). The materials of fabrication included Incoloy 800, 310 stainless steel, 310 stainless steel lined with RA 330 and faced with a cobalt-base hard coating, and 316 stainless steel. Operating temperatures ranged from 550 to 1700-1800 °F

Erosion appeared to be the predominant cause of failure. Such was the case for the cyclones made of Incoloy 800, unlined 310 stainless steel, and 316 stainless steel. The Incoloy 800 and the unlined 310 stainless steel both suffered perforation. For the cyclone fabricated from 310 stainless steel lined with RA 330, the liner suffered surface roughening, wall thinning, gouging and perforation. The cyclone made of 310 stainless steel lined with RA 330 and faced with a cobalt-base hard coating suffered severe attack and wall perforation at the fusion line of a weld. Cracking and surface scale were also noted.

The 316 stainless steel material exposed to product gas and char at a relatively low temperature of 550 °F had the longest service life (6214 hours). The cobalt-base hard coating on the RA 330 lined 310 stainless steel subjected to a product gas/char/ash environment at a relatively high temperature of 1692 °F failed in the shortest time - 32 hours. Unlined 310 stainless steel and the 310 stainless steel lined with RA 330 without the cobalt-base coating had longer service lives (20 days and 288 hours, respectively) than the cobalt-base hard coating on the RA 330 lined 310 stainless steel under the same environmental conditions and temperatures.

A.2.4 Metal Internal Components
A.2.4.2 Performance Data
A.2.4.2.1 Plant Experience

THERMOWELL IN-SERVICE PERFORMANCE[5]

Material	Location	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Hastelloy C-276	Gasifier	Synthane	~500 hr	Fluidized bed	1500-1600	N.A.	Outer surface pitted possibly caused by clinker formation.
Hastelloy X	Gasifier (bench scale)	CO_2 Acceptor	90-150 hr	$N_2/CO_2/H_2O/H_2S$	1400-1900	150	Severe corrosion caused by reaction of sulfur with Hastelloy X. (bench scale test)
Hastelloy X	Regenerator (bench scale)	CO_2 Acceptor	N.A.	Dolomite/recycle gas/ Air	1900	150	Failed by high temperature sulfur corrosion. (bench scale test)
Hastelloy X	Gasifier	Westinghouse	1000 hr	Product gas	1800	240	Hole in thermowell caused by high temperature sulfur corrosion.
Incoloy 800	N.A.	Westinghouse	700 hr	Recycle gas	N.A.	N.A.	Cracks formed in weld HAZ probably caused by stress corrosion cracking.
RA 330	Ash agglomerating gasifier	Hygas	120-1200 hr	Coal/product gas/steam	1950	N.A.	Thermowells were breaking off in service from high temperature sulfur corrosion.
304 S.S.	High pressure separator	Project Lignite	N.A.	Lignite/ solvent	N.A.	N.A.	General pitting and transgranular cracking resulted from chloride attack and stress corrosion cracking.
310 S.S.	Coal pretreatment vessel	Hygas	N.A.	Process gas	>800	N.A.	Failed from severe oxidation and sulfidation which led to melting near the tip.
310 S.S.	Ash agglomerating gasifier	Hygas	61 hr	Fluidized bed	>2100	N.A.	Erosion/corrosion failure caused by overheating of thermowell by several hundred degrees.
310 S.S.	Thermal oxidizer	Synthane	1.5 yrs	Coal gas/CO_2/ steam/coal char	1600-1800	N.A.	Thermowell burned off to a length of 7" from original 18". Cause unknown.
316 S.S.	Coal pretreater	Hygas	~200 hr	Coal/gas	>1625	N.A.	Overheating led to an oxidation failure of the thermowell
446 S.S.	Ash agglomerating gasifier	Battelle, Columbus	~400 hr	Bauxite/coal	2300	N.A.	Degradation and cracking probably caused by overheating of fluidized bed.

CYCLONE IN-SERVICE PERFORMANCE[5]

Material	Description	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Incoloy 800	Gasifier cyclone	Synthane	∿1000 hr	Product gas/ char/coal dust	800	600	General erosion pattern with a hole in the cone section.
310 S.S.	Low BTU internal cyclone	Hygas	∿20 days	Product gas/ char/ash	1700-1800	N.A.	General erosion and perforation of inner wall.
310 S.S. lined with RA 330	Low BTU internal cyclone	Hygas	288 hr	Product gas/ char/ash	1477-1700	N.A.	Liner had surface roughening, wall thinning, gouging, and perforations.
310 S.S. Lined with RA 330 and faced with a cobalt-base hard coating	Low BTU internal cyclone	Hygas	32 hr	Product gas/ char/ash	1692	N.A.	Severe attack and wall perforation occurred at fusion line of weld. Cracking and surface scale occurred.
316 S.S.	Product gas cyclone	CO_2 Acceptor	6214 hr	Product gas/ char	550	150-190	Cyclone shell failed from erosion damage at point of char and gas impingement.

A.2.4.2.2.1 CORROSION

HOT GAS CORROSION-OVERVIEW

Structural materials in a coal conversion system may react chemically with components of the gas atmosphere. The metal internal components face some of the most severe hot gas corrosion conditions...temperatures to 2000 °F; pressures to 1000 psi; abrasive particles at high velocities. Reactive gases in the coal conversion atmosphere include H_2S, SO_2, SO_3, H_2, O_2, H_2O, CO, CO_2, and CH_4. The tendency towards chemical reaction depends upon temperature, pressure, time of exposure, the partial pressure of each gas, the metallurgical structure of the material and its stress state.

Reactions may lead to sulfidation, oxidation, or carburization of the materials of construction. Sulfide reactions seem to be the most frequent and the most harmful. (See Sections B.1.1.38-41, B.1.1.43, B.1.1.66, B.1.1.75-83, and B.1.1.91-99 for data on sulfidation.) Sulfide formation can take place at the surface or internally following diffusion. Some stainless steels are susceptible to sulfidation attack.

Usually oxidation occurs before sulfidation. However, oxygen partial pressures are quite low, e.g., 10^{-16} atm, and extensive oxidation does not occur. When adherent oxides form a continuous, non- porous layer, the resulting protective film can be beneficial. (See Sections B.1.1.66, B.1.1.75-83, and B.1.1.91-99 for data on oxidation.) Carburization of structural materials results from reaction with CO and CO_2 and in the worst case can result in complete disintegration of the material. Fortunately, carburization does not occur very frequently. Average gas atmosphere compositions are not always useful in predicting reactions because local concentrations may differ significantly from average compositions. For example, sulfur diffusion inward through a porous oxide scale at high temperatures may result in internal sulfidation. Furthermore, in some steels it is thought that gradual chromium depletion by internal sulfide formation can result in breakdown of a protective, adherent scale.

It has long been known that hydrogen can embrittle structural metals. Water vapor is one source of hydrogen in a coal conversion atmosphere. However, there is very little evidence for embrittlement of the internal components of coal conversion systems which operate at elevated temperatures. Reaction of hydrogen with carbon in steel to form methane sometimes happens, and the resulting internal voids are known to promote embrittlement.

Some colorful names have been coined to describe hot gas corrosion processes. "Metal dusting," involving local carburization and powdering of the metal, is one. "Green rot," which occurs on nickel-iron-chromium alloys in carbon-containing atmospheres, is another. It describes the appearance of the affected surface following attack.

HOT GAS CORROSION-SOME FUNDAMENTALS

SOUND METAL LOSS VS. TIME is shown schematically for a constant temperature static test in Figure A.2.4.2.2.1a, where weight loss is used to represent sound metal loss. Of the two cases (linear or parabolic) shown, the parabolic behavior is most desirable for it represents the formation of an adherent, non-porous surface scale. The slope of the parabolic curve in

Figure A.2.4.2.2.1a gives the rate of sound metal loss. Figure A.2.4.2.2.1b shows that the rate of sound metal loss is very high during the initial stage of testing, but decreases as the test proceeds. Moreover, Figure A.2.4.2.2.1 shows that there is a critical time which roughly divides the high rate regio (hereafter called Stage I) and the low rate region (hereafter called Stage II). This critical time is expected to vary for each material and with the composition of the gas atmosphere.

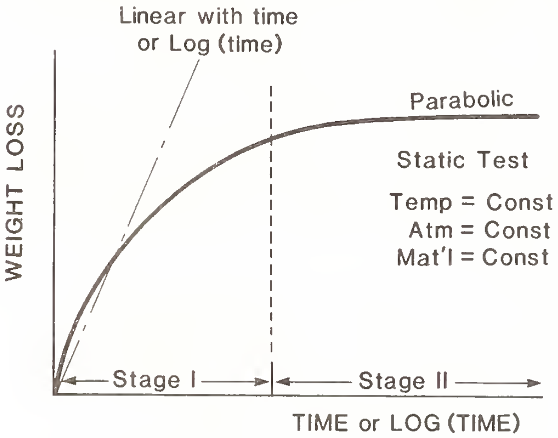


Figure A.2.4.2.2.1a

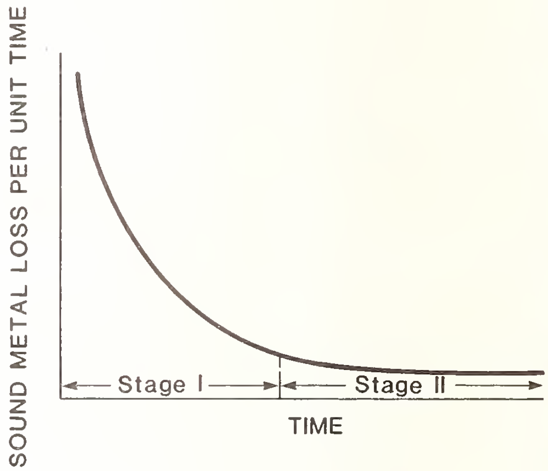


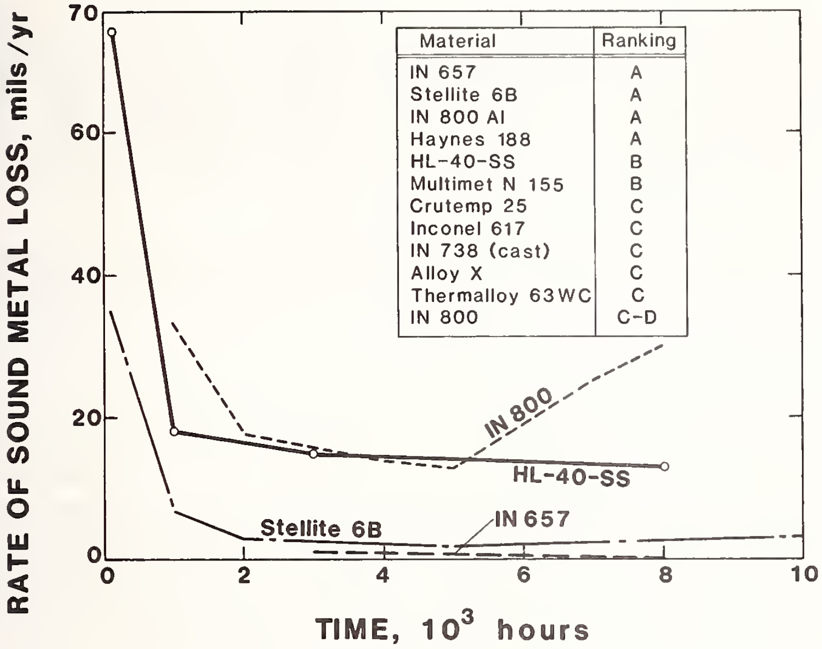
Figure A.2.4.2.2.1b

Some actual test results on several alloys appear in Figure A.2.4.2.2.1c The data were plotted from Sections B.1.1.17 and B.1.1.18. Despite much scatter in these data, one trend is clear, namely, that Stage I is completed for all the alloys investigated in about 1000 - 3000 hours. Another feature evident in Figure A.2.4.2.2.1c is that long term static corrosion behavior ca be ranked from Stage II data. For example, IN 657, Stellite 6B, and HL-40 show the least sound metal loss in a 10,000 hour test.

Figure A.2.4.2.2.1c shows that the ranking order of materials in Stage I is generally preserved into Stage II. This feature suggests that at least fo these alloys, extrapolation of Stage I rankings are valid for Stage II. An important reservation about Stage I data is that it gives rates of sound metal loss which are substantially higher than long term test results would show. Thus, linear extrapolation of Stage I test results to an average annual rate will overestimate the rate. Design based on Stage I extrapolations will be extremely conservative unless breakaway corrosion occurs.

THE TEMPERATURE DEPENDENCE of hot gas corrosion rates is of interest. Results from four commercial alloys listed in Sections B.1.1.17 and B.1.1.18 appear in Figure A.2.4.2.2.1d. Each alloy shows a very weak temperature dependence below about 1500 °F. Corrosion rates increase dramatically above about 1500 °F. Similar behavior is shown in Section B.1.1.6 for four other alloys, including Type 310 stainless steel.

HYDROGEN SULFIDE is one of the most reactive species in hot gas corrosion. Concentrations of hydrogen sulfide in the gas atmosphere may range



Material	Ranking
IN 657	A
Stellite 6B	A
IN 800 Al	A
Haynes 188	A
HL-40-SS	B
Multimet N 155	B
Crutemp 25	C
Inconel 617	C
IN 738 (cast)	C
Alloy X	C
Thermalloy 63WC	C
IN 800	C-D

Figure A.2.4.2.2.1c

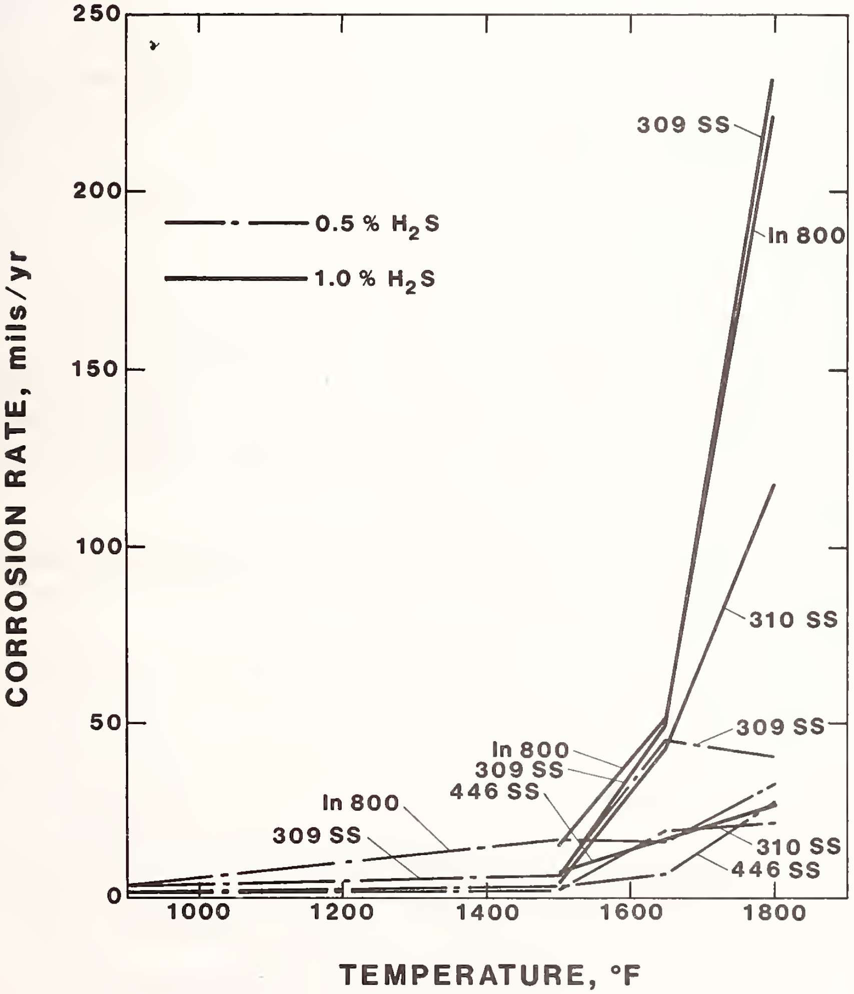


Figure A.2.4.2.2.1d

up to 2.5 percent. The rate of sound metal loss for most alloys seems relative independent of hydrogen sulfide concentrations at 1500 °F. However, the rate increases dramatically with increasing temperature. For example, at 1800 °F it is about 3 to 5 times as high as at 1500 °F for H_2S concentrations between 0.1 and 1.0 percent. Significant increases in rate have been observed at 1800 °F for IN 800 and Types 309 and 310 stainless steels when hydrogen sulfide concentration increases from 0.5 to 1.0 percent.

THE PRESSURE DEPENDENCE of hot gas corrosion rates is also of interest. Data in Sections B.1.1.6 show a tendency toward a decrease in corrosion rate with increasing pressure.

LABORATORY TESTS

PERFORMANCE DATA have been obtained in laboratory tests on about fifty metal alloys. In addition to numerous commercial alloys, a few experimental alloys were tested. Also, a few weld metals were tested. The following types of performance were evaluated: hot (900-1800 °F) gas corrosion rates in various coal gasification atmospheres for exposure times between 100 and 10,000 hours; changes in mechanical properties resulting from exposure to various coal gasification atmospheres; changes in internal metallurgical structure during exposure to various coal gasification atmospheres. In addition, some corrosion scale was analyzed following exposure.

Corrosion test specimens were sectioned after exposure and the depth of corrosion was determined on polished surfaces. Total sound metal loss was defined as the sum of the scale thickness and the depth of penetration via diffusion. The rate of sound metal loss in mils per year was determined from a linear extrapolation of the depth of corrosion which occurred in exposure times ranging from 100 to 10,000 hours. It is presented in various tables and figures as the annual corrosion rate. Test specimen size was often 1 x 1 x 1/4 inches.

In almost all cases, the laboratory test results reported below were obtained on a single specimen. Because the overall reproducibility of test results is in the medium range (see below, REPRODUCIBILITY OF CORROSION TEST RESULTS), the laboratory test results reported in this volume are more useful for representing overall trends in groups of alloys than for representing the exact corrosion behavior of a given alloy. In fact, it is misleading to regard the test result from one specimen as an exact representation of the corrosion behavior of that material.

In some instances, it has been possible to rank the hot gas corrosion performance of the alloys studied in the laboratory. The ranking system that was used in these instances is as follows:

A. Practically complete resistance. The alloy is the best of materials within its class.
B. Good resistance. May replace materials given A rating to secure some other advantage.
C. Adequate resistance under favorable conditions. Limited tolerance beyond design conditions.
D. Sufficient resistance if adequate precautions are taken to reduce effect of corrosive conditions, as by coatings, cathodic protection, redesign, etc., or where appearance is not important and appreciable corrosion may be provided for or tolerated.
E. Poor resistance. Used only if no better material is available.

REPRODUCIBILITY OF CORROSION TEST RESULTS was determined on two independent sets of Type 309 stainless steel. The gas atmosphere consisted of 0.5 or 1.0% H_2S, 31%H_2, 17%CO, 15%CO_2, 3%CH_4, 1%NH_3 and balance H_2O. Exposures were at 1800 °F for 1000 hours at 1000 psi. Data appear in Section B.1.1.19. Results are tabulated below:

Number of Specimens	H_2S	Percentage Difference In Averages Of Each Set	Reproducibility of Range (G-good, F-fair, P-poor)	Overall Reproducibility (G-good, M-medium, P-poor)
2 sets of 32 each	0.5%	10%	F	M
2 sets of 6 each	1.0%	12%	F	M

Reproducibility tests were also carried out on five other alloys under the same test conditions. A summary of the results, including results on the Type 309 stainless steel, appears below:

Reproducibility of Corrosion Test Results on Six Metal Alloys

Alloy	0.5% H_2S	1% H_2S	Range of Results (M-medium, B-broad, N-narrow)	Overall Reproducibility (G-good, M-medium, P-poor)
309SS	32 specimens		B	M
	32 specimens		B	M
314SS	6 specimens		N	G
446SS	6 specimens		N	G
Inconel 601	6 specimens		M	M
Incoloy 800	6 specimens		B	P
Inconel 671	6 specimens		N	M
309SS		6 specimens	B	M
		6 specimens	B	M
314SS		6 specimens	M	M
446SS		6 specimens	M	P
Inconel 601		6 specimens	N	G
Incoloy 800		6 specimens	B	P
Inconel 671		6 specimens	N	G

Reproducibility of corrosion behavior sometimes depended on H_2S content. For example, at 0.5 percent H_2S, Type 314 stainless steel showed excellent reproducibility. On the other hand, Incoloy 800 showed the worst reproducibility at both hydrogen sulfide levels. Some factors which influence reproducibility include: nonuniformities in the metallurgical structure of the metal, possible oversights in the experimental data taking, and possible fluctuations in the experimental conditions during exposure.

RANKING OF CORROSION RATES of about fifty alloys in a simulated coal gasification atmosphere (Section B.1.1.17) appears in the histograms which follow. The histogram form of presentation allows for rapid identification of those alloys which show the most favorable corrosion rates. For example, those alloys with the lowest corrosion rates appear towards the left in each figure. The horizontal scale of each histogram has been adjusted so that the majority of the results in each of the twenty data sets can be reasonably represented in the histogram. Those data points that did not fall within the scale selected for some data sets, e.g., Data Set Xa, appear in the tabulation accompanying the figure. The guideline cited above applies, namely, that design estimates based on tests of less than 1000 - 3000 hours duration will be extremely conservative. An index to the histograms appears below.

Data Set	Exposure Time (Hours)	Temperature (°F)	%H_2S	Number of Specimens*
I	1000	900°	0.5	16
II	100	1250	1.5	16
III	1000	1500	0.1	16
IV	1000	1500	0.5	12
V	1000	1500	1.0	15
VI	100	1500	1.5	16
VIIa	5000	1650	0.5	11
VIIb	1000	1650	0.5	7
VIIIa	10000	1650	1.0	6
VIIIb	6000	1650	1.0	7
IX	1000	1800	0	28
Xa	1000	1800	0.1	46
Xb	100	1800	0.1	8
XIa	10000	1800	0.5	7
XIb	8000	1800	0.5	8
XIc	5000	1800	0.5	8
XId	1000	1800	0.5	17
XIIa	5000	1800	1.0	8
XIIb	3000	1800	1.0	7
XIIc	1000	1800	1.0	31

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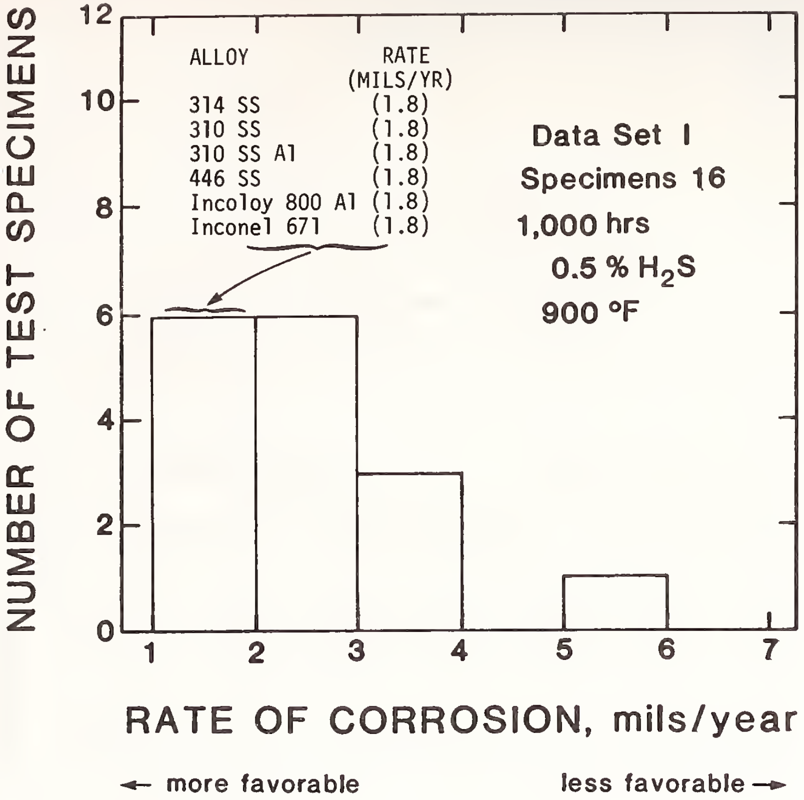
*In most cases, test results were obtained on a single test specimen of each alloy.



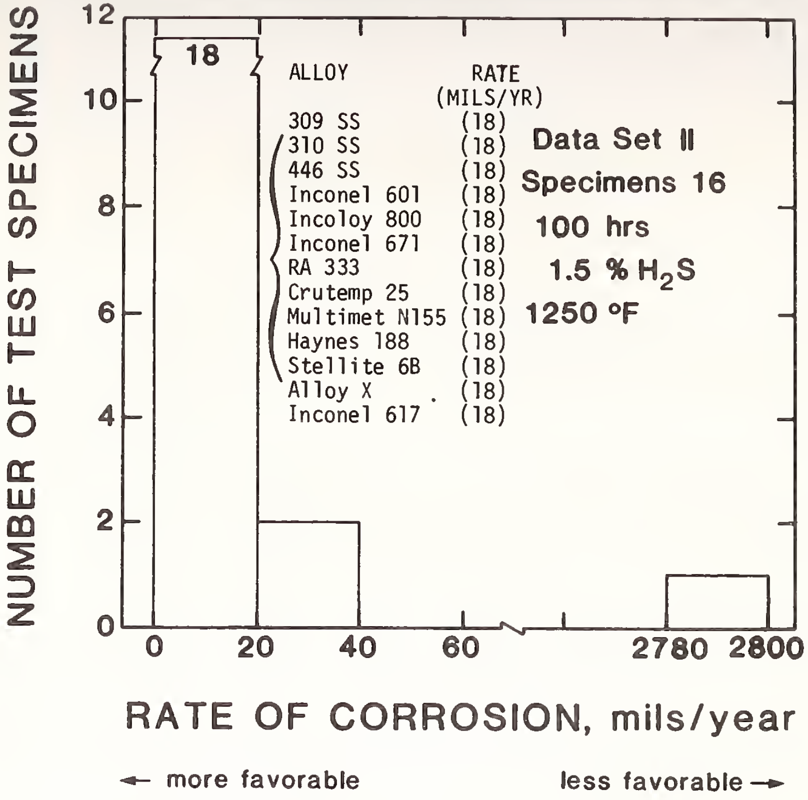
Comments:

Highest corrosion rate: 5.3 mils/yr

Lowest corrosion rate: 1.8 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
302 SS	5.3
309 SS	3.5
Incoloy 800	3.5
Incoloy 800 Cr	3.5



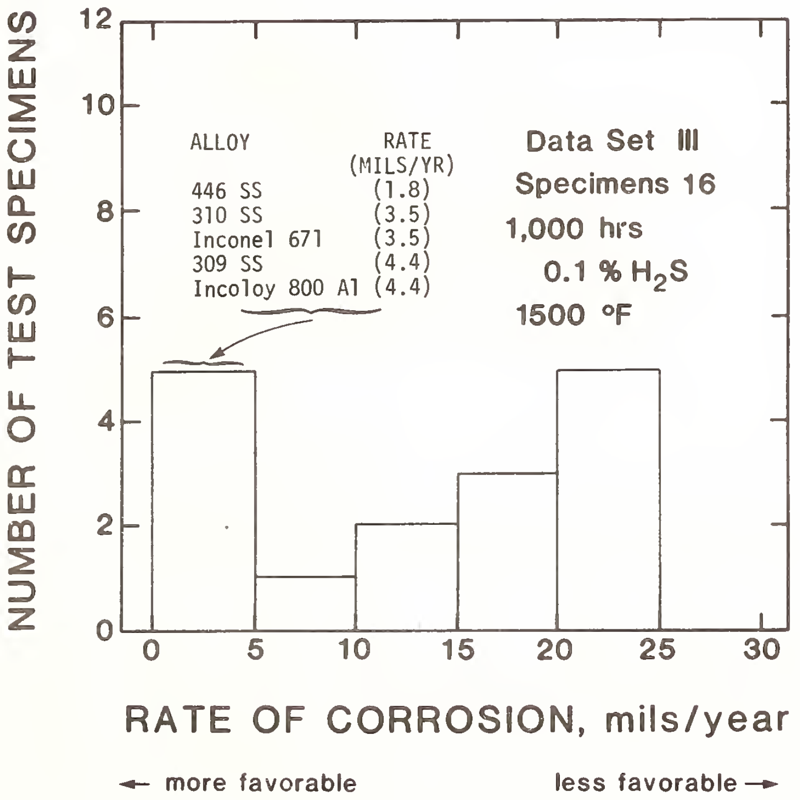
Comments:

Highest corrosion rate: 2799 mils/yr

Lowest corrosion rate: 18 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
Inconel 600	2799
304 SS	35
316 SS	35



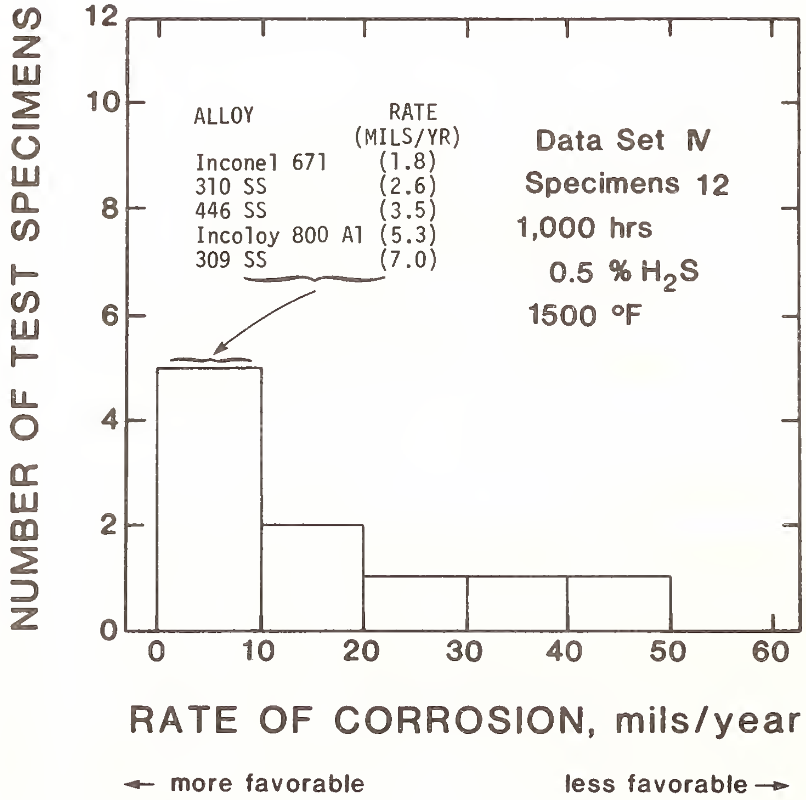
Comments :

Highest corrosion rate : 25 mils/yr

Lowest corrosion rate : 1.8 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Inconel 601	25
Incoloy 800	25
Incoloy 800 Cr	25
310 SS Cr	25
316 SS	21



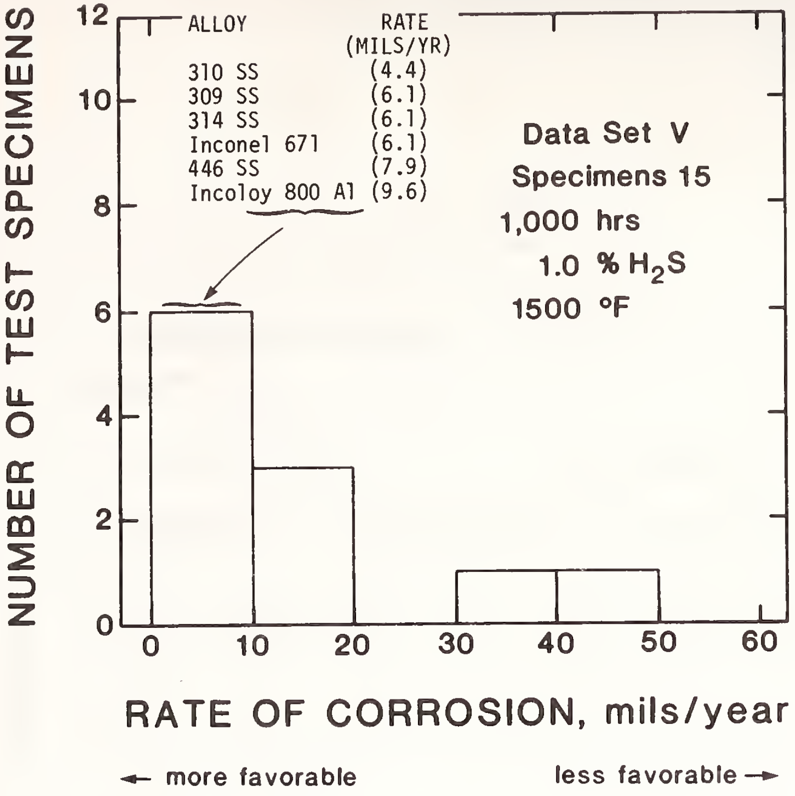
Comments :

Highest corrosion rate : Complete corrosion

Lowest corrosion rate : 1.8 mils/ yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Inconel 600	Complete corrosion
Inconel 601	Complete corrosion
304 SS	46



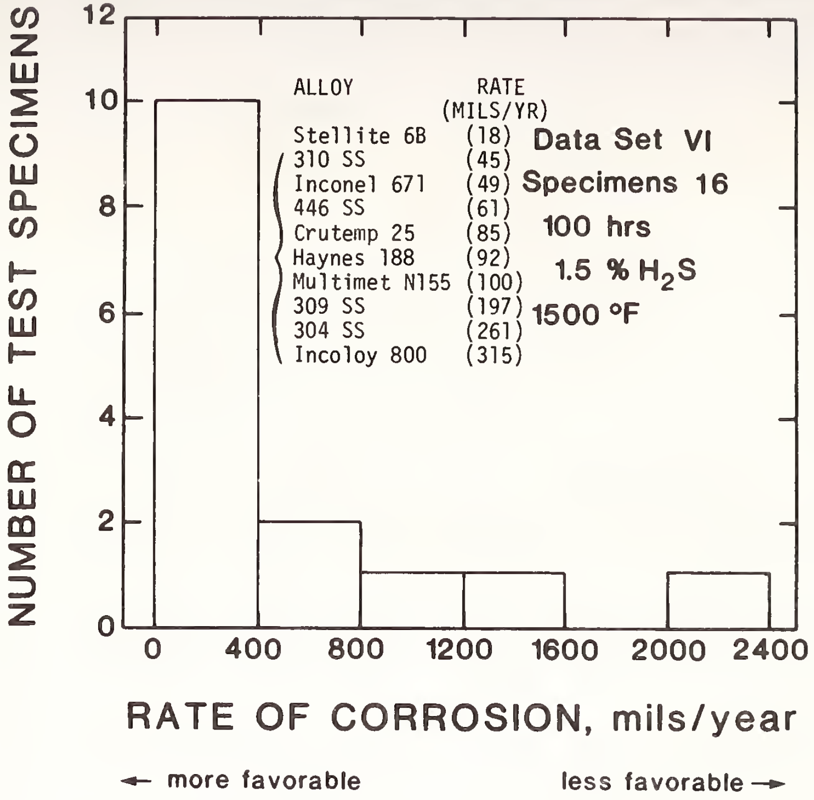
Comments:

Highest corrosion rate: 658 mils/yr

Lowest corrosion rate: 4.4 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
Inconel 601	658
Incoloy 800 Cr	138
310 SS Cr	111
302 SS	102



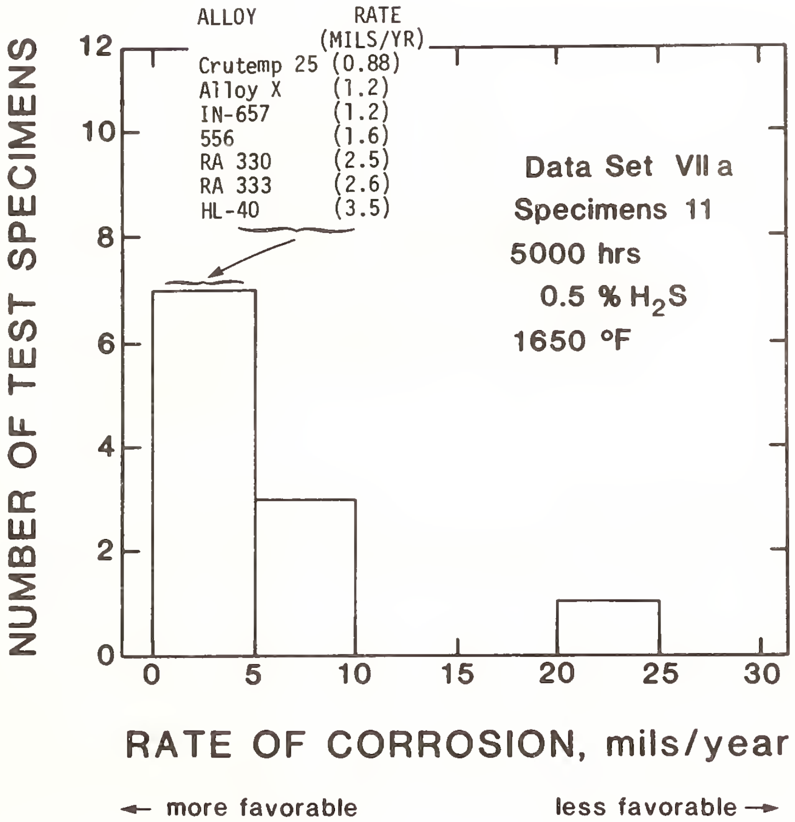
Comments:

Highest corrosion rate: Complete corrosion

Lowest corrosion rate: 18 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
Inconel 600	Complete corrosion
RA 333	2314
Inconel 617	1606
Inconel 601	853



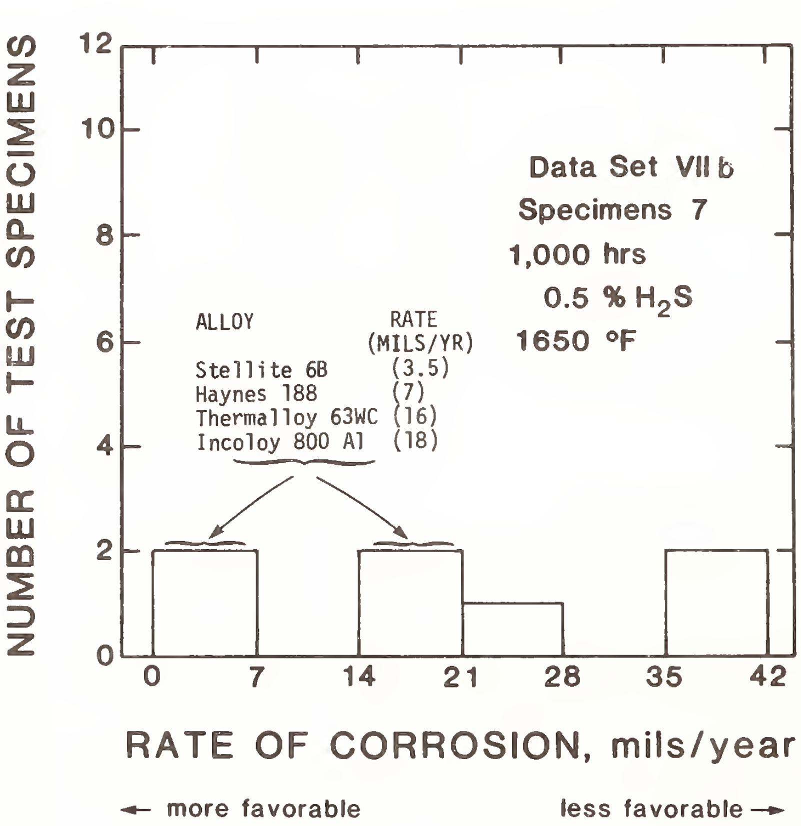
Comments:

Highest corrosion rate: 23 mils/yr

Lowest corrosion rate: 0.88 mils/ yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
310 SS	23
IN-793 (cast)	10
Incoloy 800	6.7
446 SS	6.5



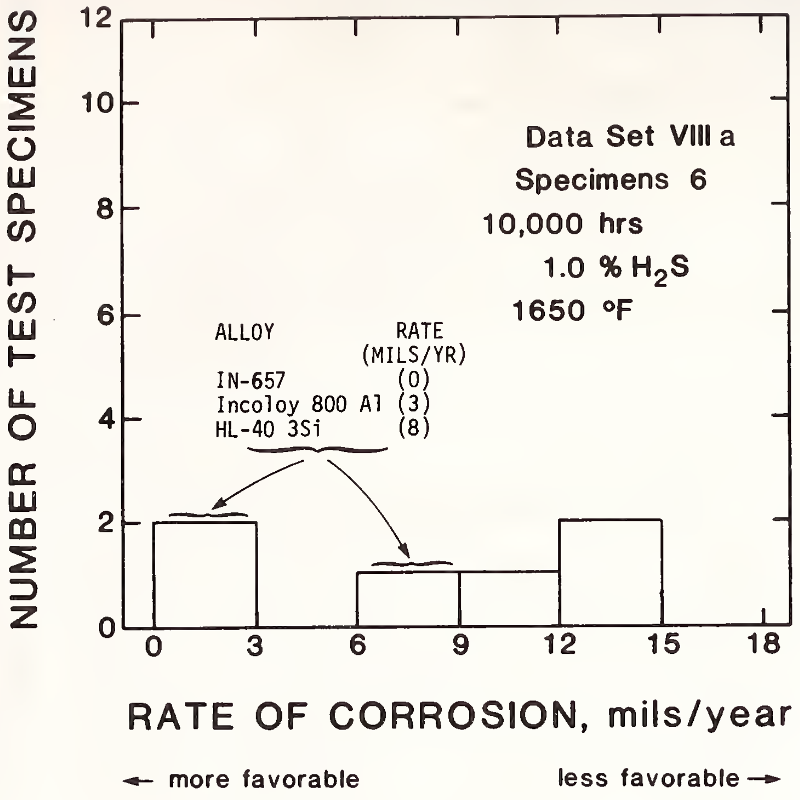
Comments:

Highest corrosion rate: 40 mils/yr

Lowest corrosion rate: 3.5 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
310 SS Al	40
Inconel 617	36
Sanicro 32X	22



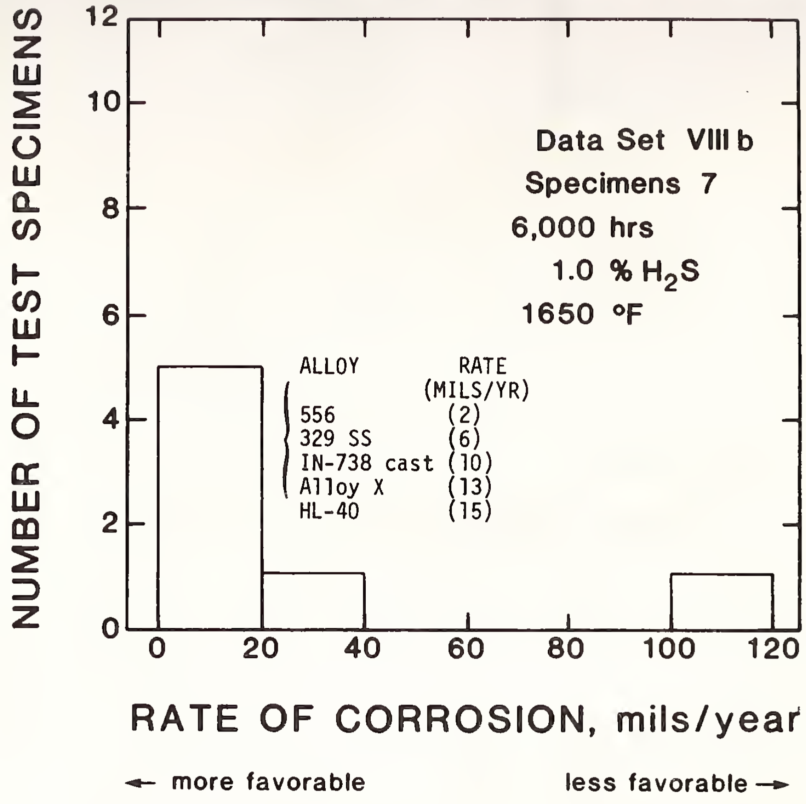
Comments :

Highest corrosion rate : 15 mils/yr

Lowest corrosion rate : 0 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Incoloy 800	15
310 SS	13
310 SS Al	11



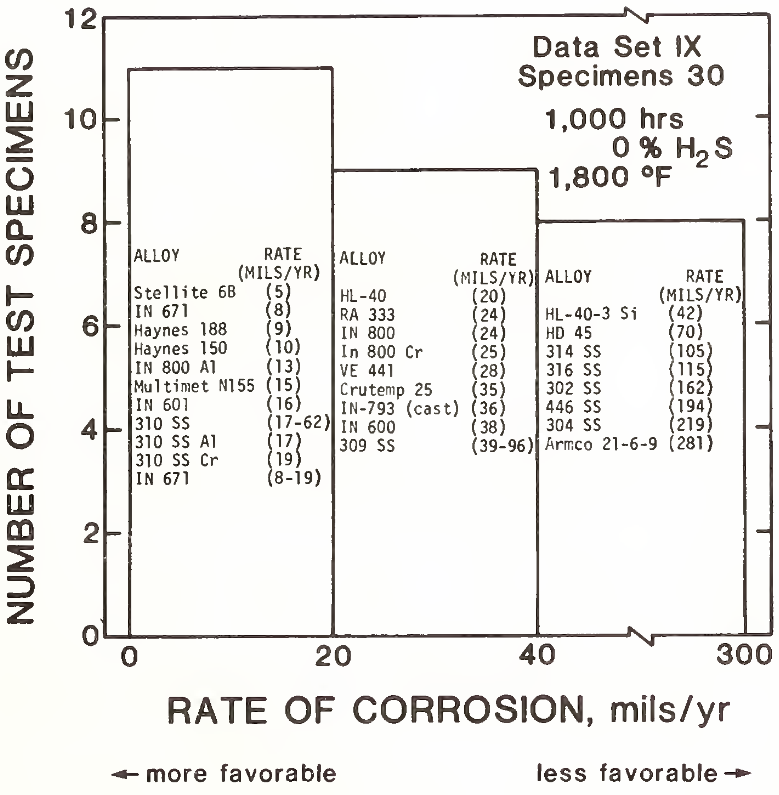
Comments :

Highest corrosion rate :

Lowest corrosion rate :

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Thermalloy 63WC .	110
HK-40	25



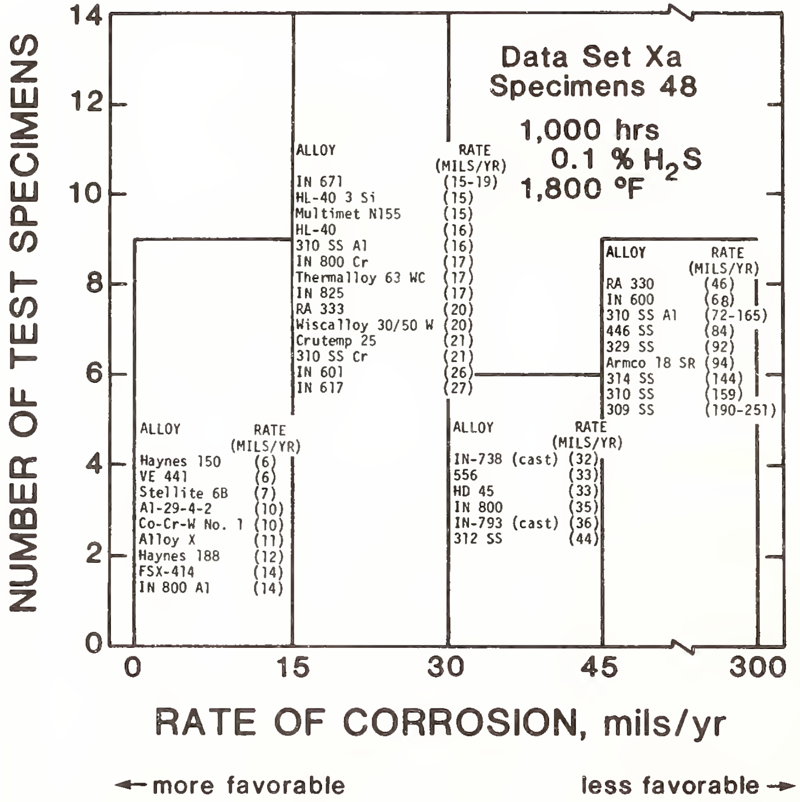
Comments:

Highest corrosion rate : Complete corrosion

Lowest corrosion rate: 5 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
HC-250	Complete corrosion
Armco 21-6-9	281
304 SS	219
446 SS	194
302 SS	162



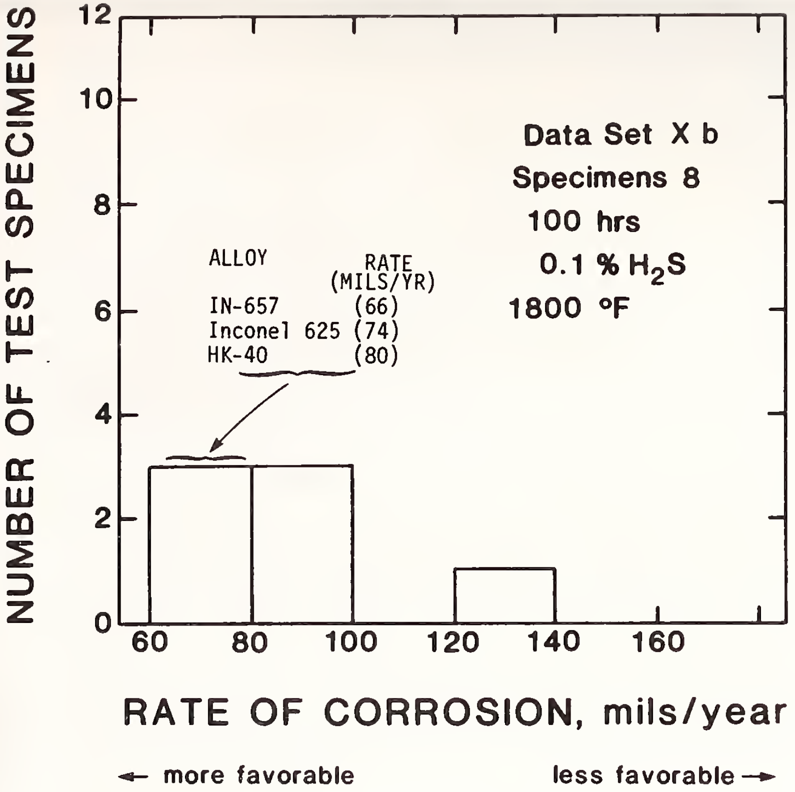
Comments :

Highest corrosion rate : 593 mils/yr

Lowest corrosion rate : 6 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Al Ex-20	593
304 SS	549
Armco 21-6-9	519
316 SS	480
302 SS	380
HC-250 SS	360



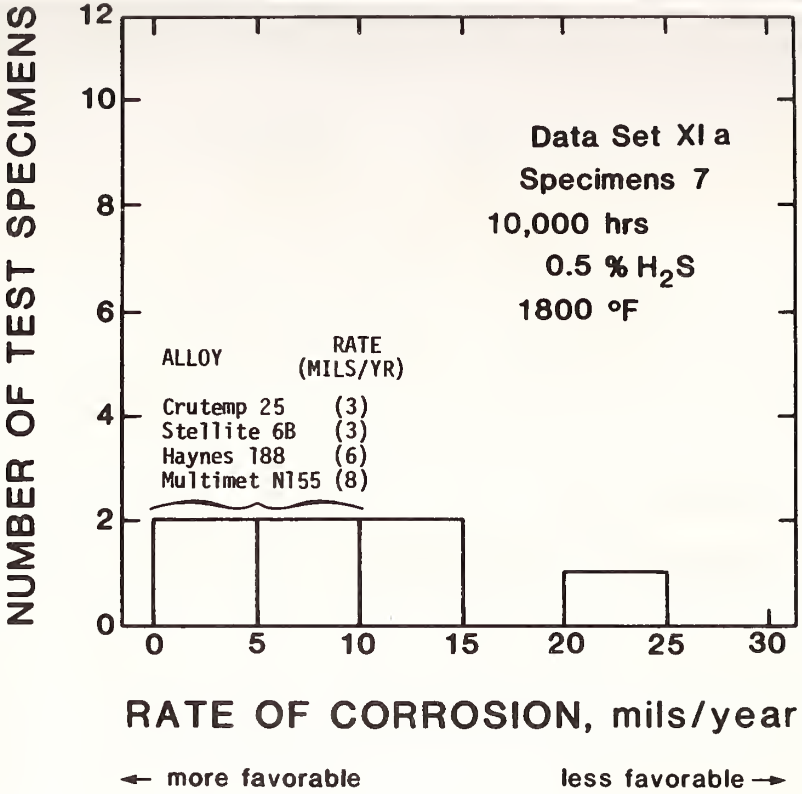
Comments:

Highest corrosion rate: 405 mils/yr

Lowest corrosion rate: 66 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
HK-40 3Si	405
Thermalloy 63W	130



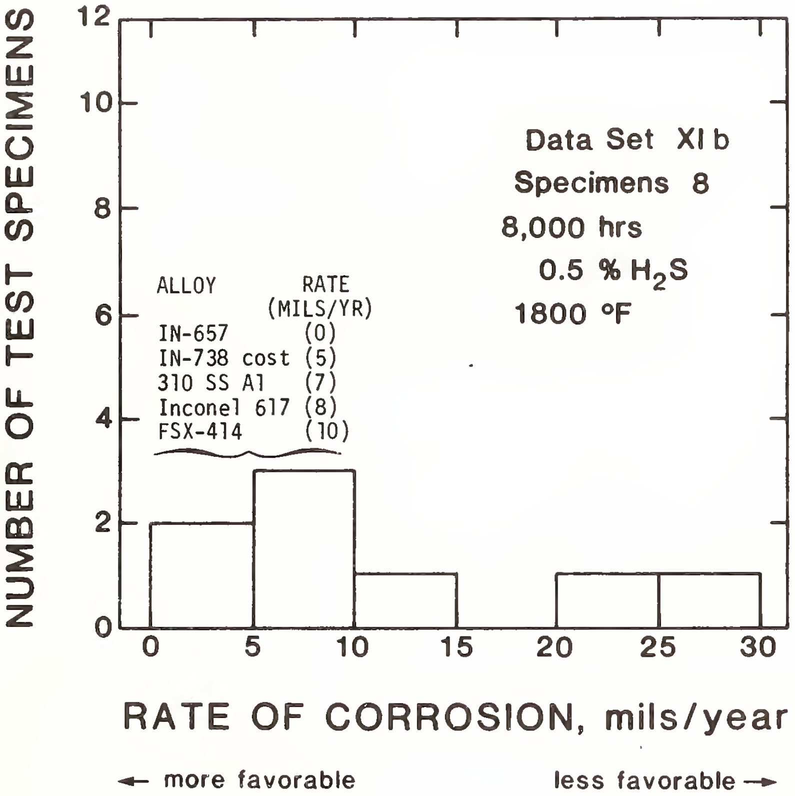
Comments:

Highest corrosion rate: 21 mils/yr

Lowest corrosion rate: 3 mils/yr

Least favorable corrosion rate:

Alloy	Rate, mils/yr
HK-40	21
Thermalloy 63 WC	14
Alloy X	13



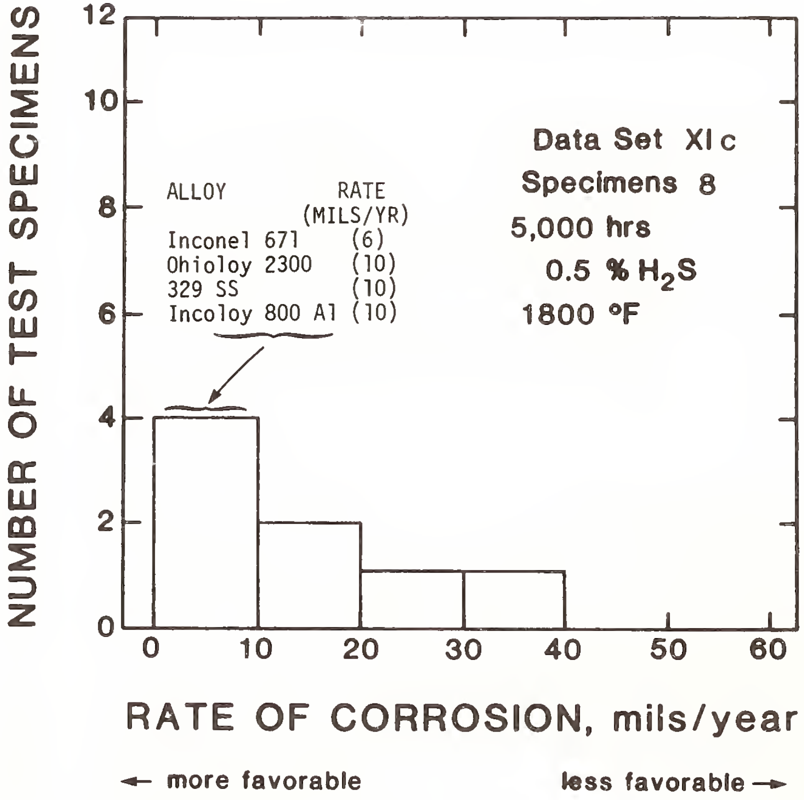
Comments :

Highest corrosion rate : 30 mils/yr

Lowest corrosion rate : 0 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Incoloy 800	30
Sanicro 32X	25
HL-40	13



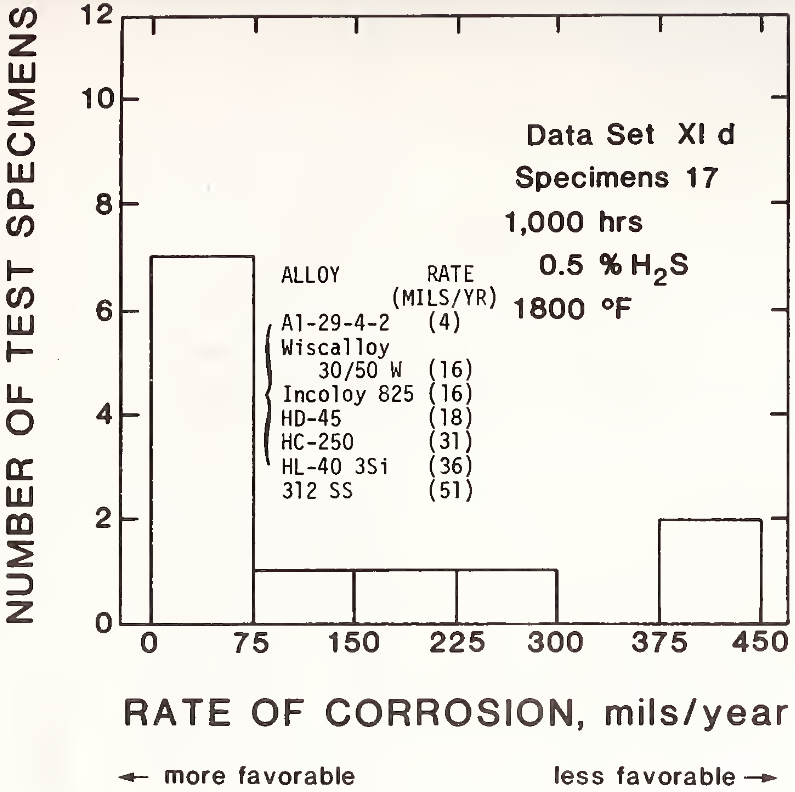
Comments :

Highest corrosion rate : 162 mils/yr

Lowest corrosion rate : 10 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
310 SS	162
309 SS	109
Fe-31Cr-36Ni	40



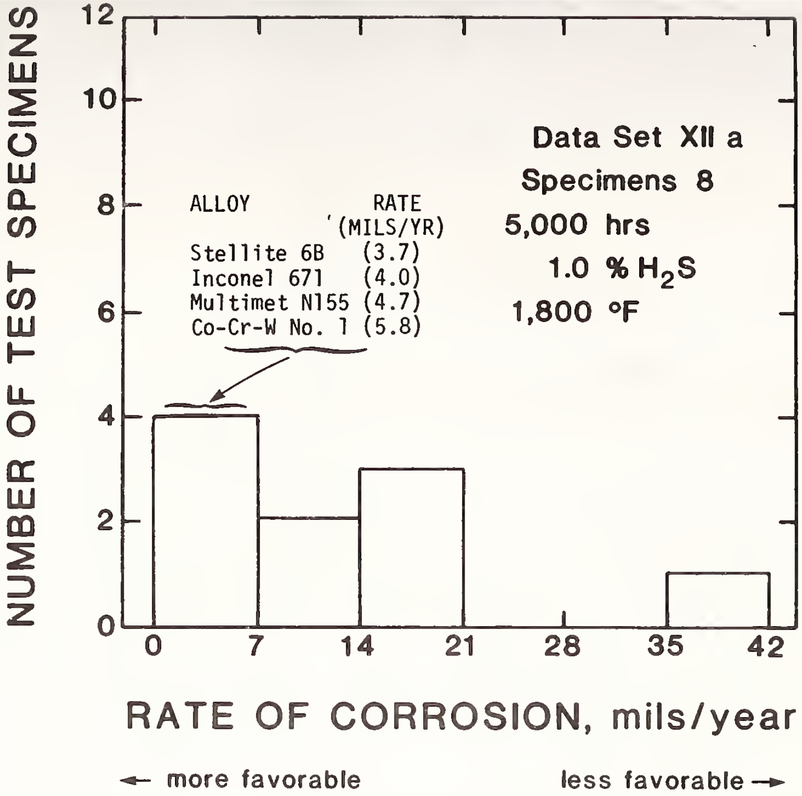
Comments:

Highest corrosion rate : Corroded completely

Lowest corrosion rate : 4 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
VE 441	Corroded completely
Al Ex-20	
Al-16-5-Y	
LM-1866 (low HF)	
253 MA	



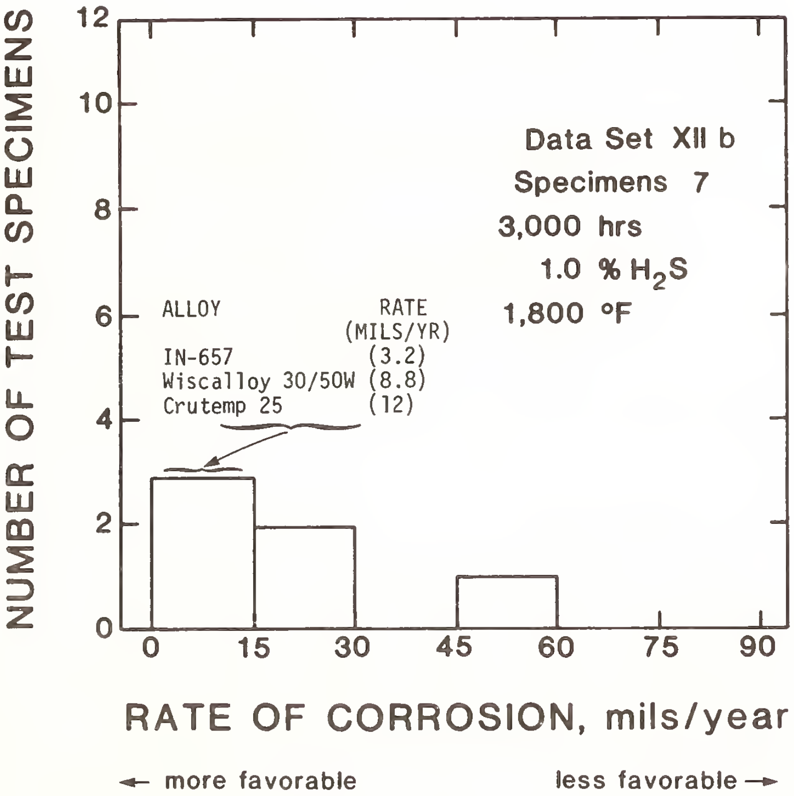
Comments:

Highest corrosion rate : 36 mils/yr

Lowest corrosion rate : 3.7 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Thermalloy 63 WC	36
Inconel 671	20
Inconel 671	16
HL-40	15



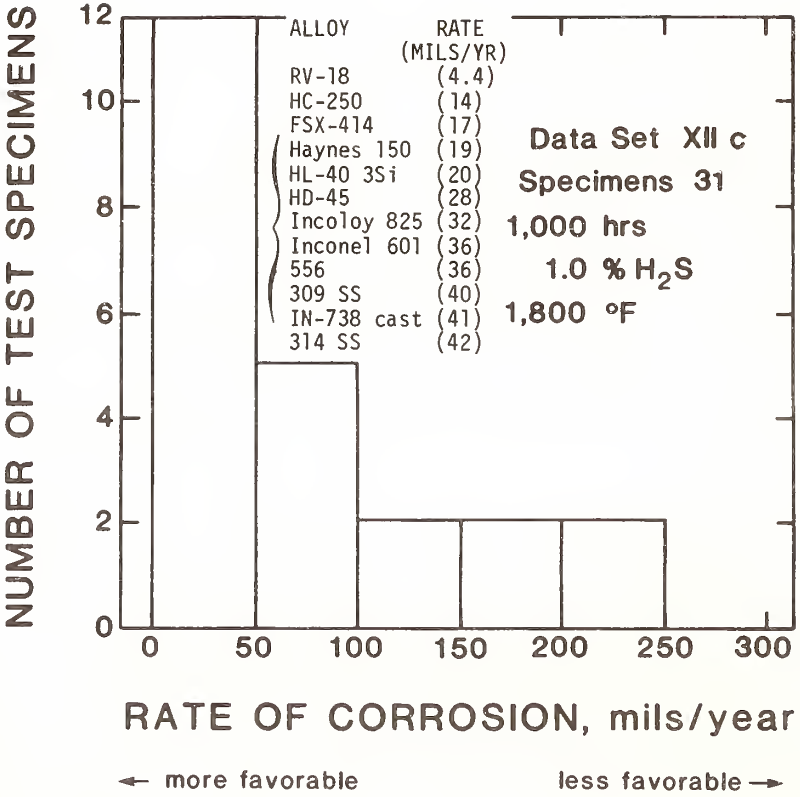
Comments :

Highest corrosion rate : 110 mils/yr

Lowest corrosion rate : 3.2 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
Inconel 617	110
310 SS Al	52



Comments :

Highest corrosion rate : Corroded completely

Lowest corrosion rate : 4.4 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
302 SS	Corroded completely
304 SS	
316 SS	
Inconel 600	
IN-793 cast	
VE 441	
AL EX-20	
Armco 18 SR	
RA 330	976
309 SS	583
Incoloy 800 Cr	389

EFFECTS OF TEMPERATURE AND PRESSURE on the corrosion loss of seven alloys ere measured in simulated coal gasification atmospheres containing upwards of percent hydrogen sulfide and 2 percent water vapor (see B.1.1.1 and B.1.1.6). he temperatures were 1382, 1600, and 1800 °F. Pressures were 34, 68, and 102 tmospheres. Exposure time was usually 1000 hours. Corrosion effect was easured as depth of penetration, determined by optical microscopy. These esults show that in general the influence of temperature at fixed pressure is o increase the corrosion loss. This point is also illustrated in Figure .2.4.2.2.1d for some other alloys. The results do not show any clear trend or the influence of pressure on corrosion loss at fixed temperature. In some ests, increased pressure resulted in increased corrosion loss, and in others, ncreased pressure resulted in decreased corrosion loss. In only two cases ere conditions such that there was total loss of a test specimen.

The kinetics of penetration, as shown in depth vs. time curves for the even alloys tested appear in Section B.1.1.2. During 1000 hours exposure, lloys GE 1541, GE 1541 (preoxidized), and Incoloy 800 showed the least depth f penetration, whereas type 310 stainless steel and alloy 18-18-2 showed the reatest depth of penetration. The kinetics of penetration for 18-18-2 were eculiar, in that depth of penetration at 1382 °F was often greater than at igher temperatures.

Some metallographic observations of scale formation and subscale penetration characteristics for four of the seven alloys appear in Section B.1.1.3. here seemed to be no distinctive response in the corrosion characteristics ith various combinations of temperature, pressure, and coal gasification tmosphere. No pronounced evidence of carburization was detected. In eneral, spalling sulfide scales and adherent oxide scales formed at the urface. Electron microprobe analysis of corrosion scale on Incoloy 800 see B.1.1.4) showed a porous outer sulfide scale containing iron and nickel, nd a subscale zone containing chromium.

CORROSION RATES FOR SAMPLES IN CONTACT WITH SOLIDS were measured on nine lloys to determine their corrosion rates during simultaneous exposure to a as atmosphere and a solid which is a possible slag former for 100 hours. ests were run at 1800 °F and 1000 psi. In most cases, test results were btained on a single test specimen of each alloy. The atmosphere was:

Equilibrium Atmosphere Composition, Volume %

H_2	H_2S	CO	CO_2	CH_4	NH_3	H_2O
31	1	17	15	3	1	bal.

Four different solids were used in the tests in this single atmosphere: estern Kentucky Char, Husky Char, CaO and SiO_2.

Test specimens were 1 x 1 x 1/4 inches. Two holes 1/4 inch in diameter ere drilled in each specimen. One hole was hand-packed with one of the solid aterials, and the other hole was left empty to serve as an experimental lank. After exposure, the specimens were wire-brushed and the extent of orrosion was determined metallographically. Test data appear in Section .1.1.23.

Results appear in Figure A.2.4.2.2.1e. Only two of the nine metal alloys showed moderately good resistance to the CaO, Types 309 and 446 stainless steels. All alloys but Type 310 stainless steel, Inconel 601 and Incoloy 800 showed good resistance to the Western Kentucky Char. Five alloys showed good resistance to the Husky Char. Alloys RA 333 and Type 446 stainless steel showed the poorest resistance to the Husky Char. Most alloys showed their best corrosion resistance when exposed to SiO_2.

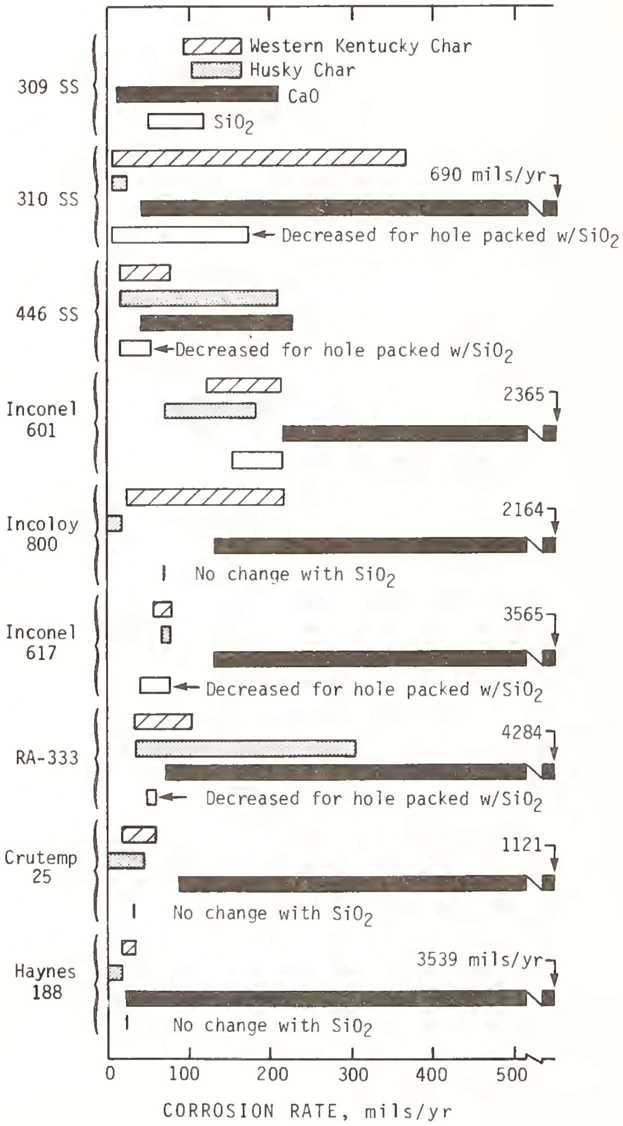


Figure A.2.4.2.2.1e

EFFECTS OF VARIABLE WATER VAPOR CONTENT on hot gas corrosion rates were termined on sixteen alloys. Tests were run at 1800 °F and 1000 psi. In st cases, test results were obtained on a single test specimen of each loy. Exposures were for 100 hours at two water vapor contents: 20 percent d 40 percent. The exit gas composition of each atmosphere was as follows:

Exit Gas Composition, Volume %

H_2O	H_2	H_2S	CO	CO_2	CH_4	NH_3
20.0	40.0	1.0	17.6	16.8	4.0	1.0
40.0	20.0	1.0	18.0	12.0	4.5	1.0

st data appear in Section B.1.1.20.

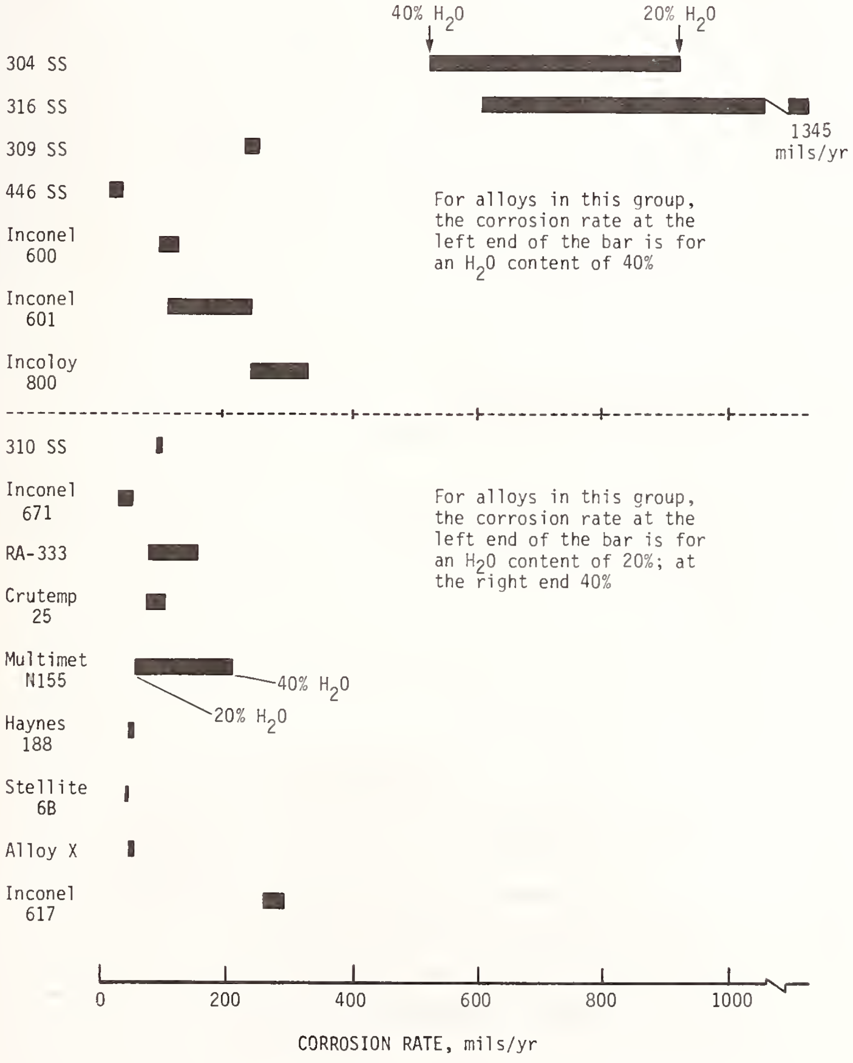


Figure A.2.4.2.2.1f

Results appear in Figure A.2.4.2.2.1f. The effect of water vapor is variable. For seven alloys, the corrosion rate decreases for an increase in water vapor from 20 percent to 40 percent (upper portion of the figure). The corrosion rate increases for the other nine alloys (lower portion of the figure). Seven of the 16 alloys showed corrosion rates of less than 100 mils per year, irrespective of water content. Nine of the 16 alloys showed very little sensitivity to the change in water content. The greatest sensitivity was exhibited by Types 304 and 316 stainless steels. These alloys both showed very poor corrosion resistance in these atmospheres, with resistance improving as water content increased from 20 percent to 40 percent. Good resistance irrespective of water content was shown by: Stellite 6B, Haynes 188, Alloy X, Type 446 stainless steel, Inconel 671, Crutemp 25, Type 310 stainless steel, and Inconel 600.

CORROSION RATES IN A LOW-BTU ATMOSPHERE were measured on eighteen alloys. Tests were run at 1800 °F and 400 psi for 1000 hours. In most cases, test results were obtained on a single test specimen of each alloy. The equilibrium atmosphere compositions were as follows:

Equilibrium Atmosphere Composition, Volume %

H_2S	H_2O	H_2	CO	CO_2	CH_4	N_2
0.5	8	12	20	8	4	47
1.0	8	12	20	8	4	47

Test data appear in Section B.1.1.21.

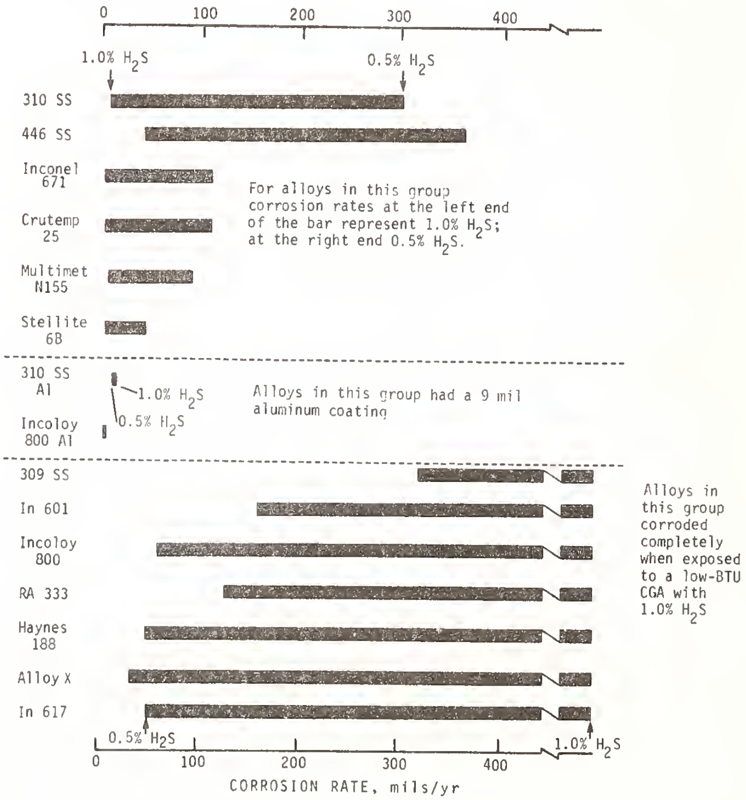


Figure A.2.4.2.2.1g

Results appear in Figure A.2.4.2.2.1g. The effect of hydrogen sulfide content on corrosion rates in the low-Btu atmosphere is variable. Six alloys showed a decrease in corrosion rate with an increase in hydrogen sulfide from 0.5 to 1.0 percent. Two alloys showed a faint increase, and seven alloys dramatically increased in corrosion rate to the point where they were completely corroded in the 1000 hour test.

The lowest corrosion rates regardless of hydrogen sulfide concentration, were shown by aluminized 310 SS and aluminized Incoloy 800. Stellite 6B, Multimet N155, Crutemp 25, and Inconel 671 showed low corrosion rates at 0.5 and 1.0 percent hydrogen sulfide. Moderate to poor corrosion resistance in 0.5 percent hydrogen sulfide was characteristic of Types 309, 310, and 446 stainless steels, IN 601 and RA 333. All specimens in the lower half of Figure A.2.4.2.2.1g corroded completely in 1.0 percent hydrogen sulfide during the 1000 hour exposure.

Three alloys corroded completely at both 0.5 and 1.0 percent hydrogen sulfide: Types 304 and 316 stainless steels and Inconel 600.

Two specimens of alloy LM-1866 were tested at 1.0 percent hydrogen sulfide only. Their average corrosion rate was 300 mils per year.

CORROSION RATES IN A DOLOMITE REGENERATOR ATMOSPHERE were measured on sixteen alloys. Tests were run at 1850 °F and 150 psi for 100 and 1000 hours. In most cases, test results were obtained on a single test specimen of each alloy. The gas atmosphere in these laboratory tests simulated that in the dolomite regenerator of the CO_2 Acceptor Process pilot plant.

Atmosphere Composition, Volume %

H_2	CO	CO_2	N_2	SO_2
1.05	1.2	30.4	67.4	0.13

Test data appear in Section B.1.1.22.

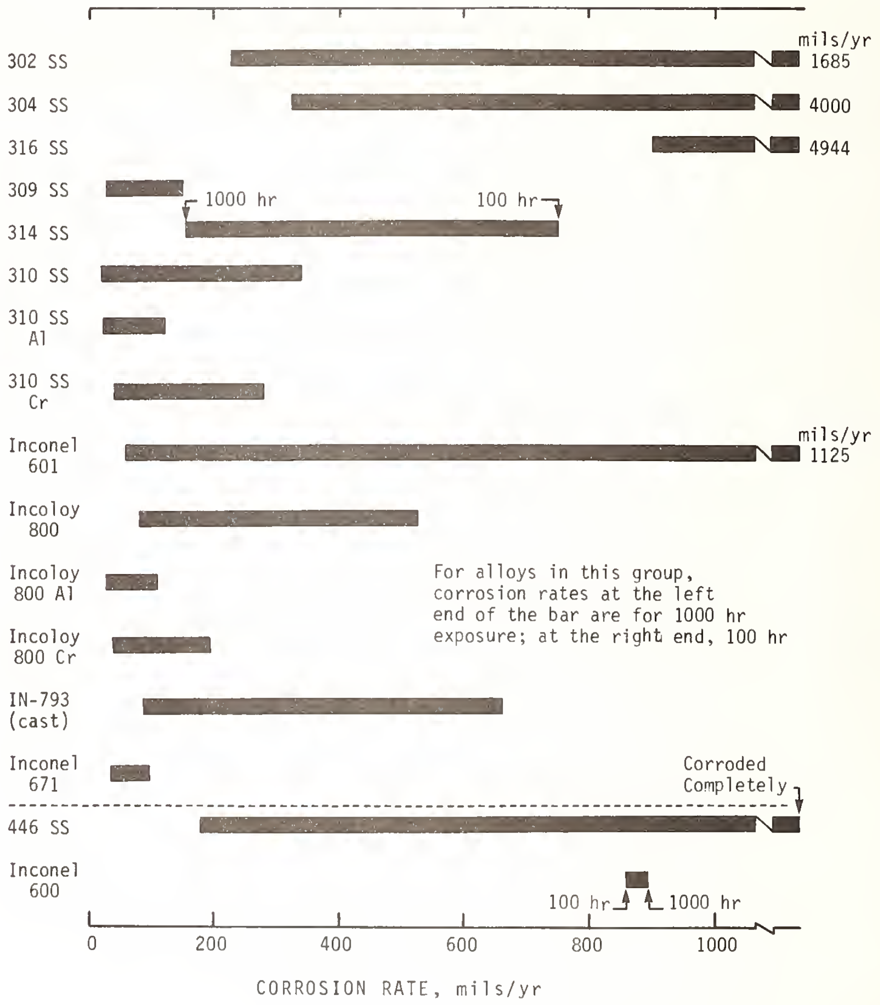


Figure A.2.4.2.2.1h

Results appear in Figure A.2.4.2.2.1h. Fifteen alloys showed decreasing corrosion rates with increased exposure time. IN 600 showed a slightly increasing corrosion rate with increased exposure time. The highest corrosion rates were exhibited by three stainless steels: Types 316, 304, and 302. The lowest corrosion rates were shown by: IN 671, Incoloy 800 (Al), Type 310 stainless steel (Al), Type 309 stainless steel and Incoloy 800 (Cr). Type 446 stainless steel corroded completely. Aluminum coatings and chromium coatings improved the hot gas corrosion resistance of Incoloy 800 and Type 310 stainless steel. The aluminum coating resulted in slightly better corrosion resistance in the 1000 hour tests. It should be noted that, based on the agreement of dual measurements on single specimens, any one value of metal loss must be considered to have a large error (up to a factor of 10) associated with it.

HYDROGEN SULFIDE effects on hot gas corrosion rates of sixteen alloys ve been measured at H_2S concentrations up to 1.0 percent in typical coal nversion atmospheres. Typical tests were run at 1000 psi at temperatures of 00 °F and 1800 °F. In most cases, test results were obtained on a single st specimen of each alloy. Exposure time was 1000 hours. The equilibrium s composition of each atmosphere was as follows:

Equilibrium Gas Composition, Volume %

Temperature	H_2S	CO	CO_2	H_2	CH_4	NH_3	H_2O
1500 °F	0-1.0	11	19	23	9	1	balance
1800 °F	0-1.0	17	15	31	3	1	balance

ulated test data appear in Sections B.1.1.17 and B.1.1.18.

Results at 1500 and 1800 °F appear in Figures A.2.4.2.2.1i and j, respec-vely. The influence of temperature on corrosion rate is significant. For mple, the corrosion rate of Type 309 stainless steel increases dramatically temperatures increase from 1500 to 1800 °F. In general, corrosion rates crease by a factor of 3 to 5 as temperature increases from 1500 (Figure i) 1800 °F (Figure j). Most of the alloys tested show a rather weak dependence corrosion rate on hydrogen sulfide concentration. Types 309 and 316 inless steels show strong increases in corrosion rate as hydrogen sulfide centration increases to 1.0 percent. A few alloys show a decrease in rosion rate with increasing hydrogen sulfide concentration, such as IN 800 1500 °F and HD 45 stainless steel at 1800 °F. The best performance at 0 °F was shown by alloy X, Co-Cr-W No. 1, IN 671 and Crutemp 25 for the ge of hydrogen sulfide between 0 and 1.0 percent. Types 309, 310, and 446 inless steels and IN 671 showed the best performance at 1500 °F over the ge of hydrogen sulfide concentrations.

THE PERFORMANCE OF WELDED JOINTS in the hot gas environment of a l conversion plant is of major interest. Some laboratory tests were to evaluate performance. Tests were run at 1800 °F and 1000 psi. most cases, test results were obtained on a single test specimen of h alloy. Exposure time was 1000 hours. The atmosphere was:

Equilibrium Gas Composition, Volume %

H_2	H_2S	CO	CO_2	CH_4	NH_3	H_2O
31	0.5	17	15	3	1	balance

The base metal was IN 800H. Seven weld metals were tested. Two ferent weld metals were used for the root and cover passes of a gle weld to expedite the hot gas corrosion tests. Test data appear Section B.1.1.24.

Results appear in Table A.2.4.2.2.1a, where the average and maximum ual rates of sound metal loss are tabulated for duplicate tests. Often the imum rate is comparable to the average rate. Sometimes, the maximum rate tly exceeds the average rate. Reasons for this include: non-uniformities the metallurgical structure of the metal, possible oversights in the erimental data taking, and possible fluctuations in experimental conditions ing exposure. The rankings given in the figure show that RA 333 weld metal

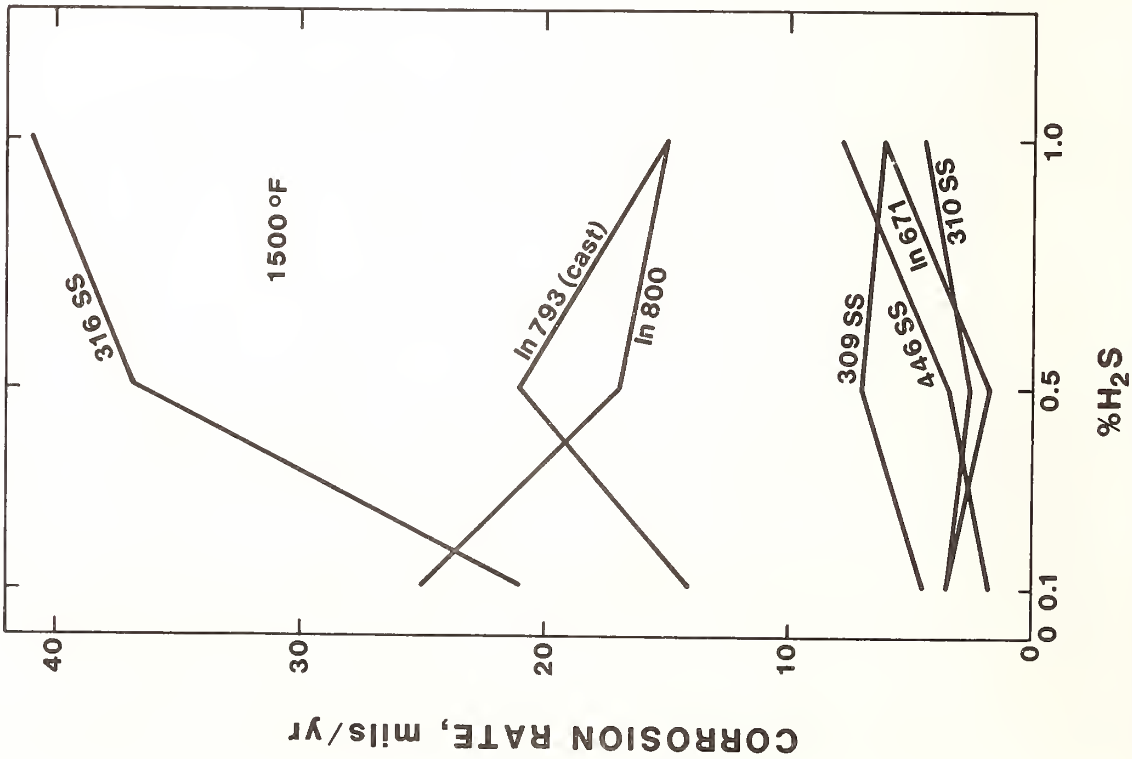


Figure A.2.4.2.2.1i

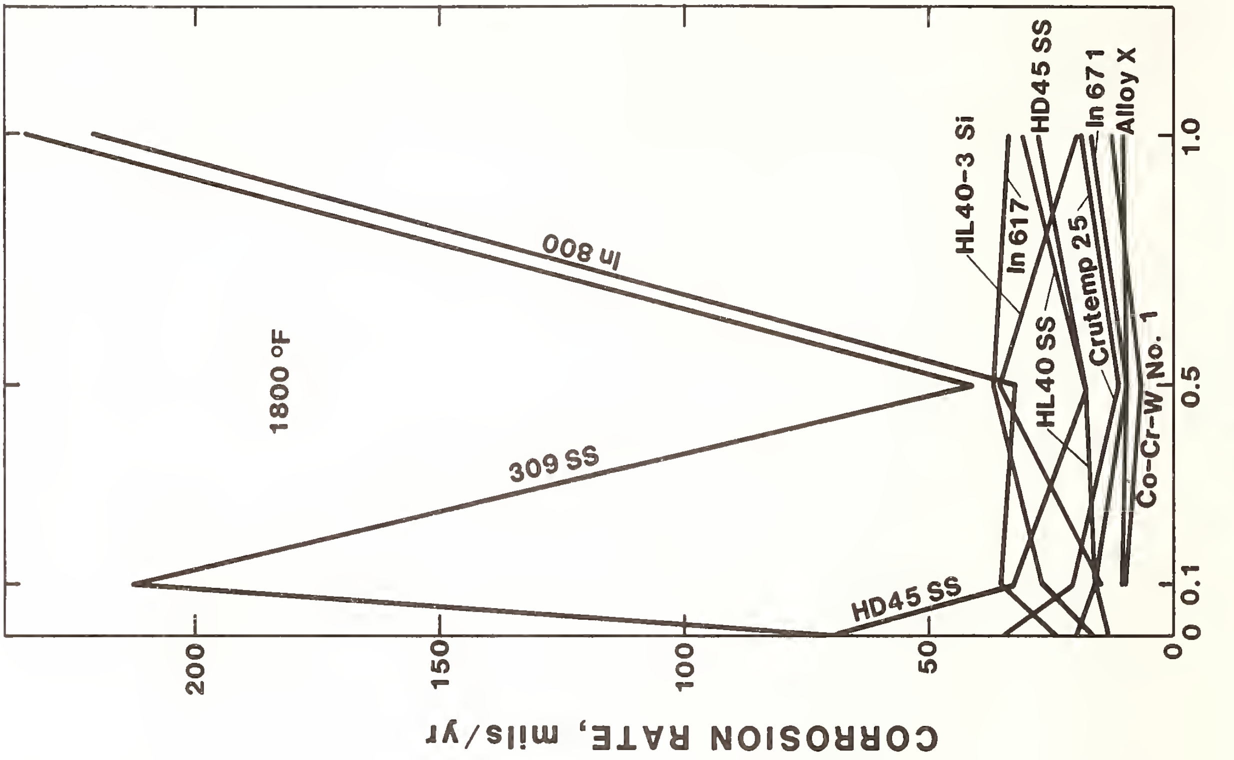


Figure A.2.4.2.2.1j

Specimen Number	HAZ Cover Area	WELD-COVER (Gas-Tungsten Arc Weld)				Ranking	HAZ Root Area	WELD-ROOT (Shielded Metal Arc Weld)				Ranking
	IN 800H	RA-330-04-15	RA-333-80-16	Metrode 50Cr-50Ni	IN 617		IN 800H	RA-330-04	RA-333	IN 72	IN 617	
1a	Av. 21 Max 276	Av. 14 Max 440				C	Av. 23 Max ---	Av. 23 Max 131				C-
1b	Av. 18 Max 73	Av. 19 Max 228					Av. 18 Max ---	Av. 25 Max 198				
2a	Av. 14 Max ---		Av. 11 Max 607			B	Av. 14 Max ---		Av. 8.8 Max 18			A-
2b	Av. 14 Max 19		Av. 18 Max 38				Av. 16 Max ---		Av. 5.3 Max 69			
3a	Av. 23 Max 107			Av. 5.3 Max 23		B-	Av. 25 Max 85			Av. 30 Max ---		C-
3b	Av. 21 Max 123			Av. 3.5 Max 41			Av. 23 Max 388			Av. 7.0 Max 39		
4a	Av. 21 Max ---				Av. 14 Max ---	C	Av. 21 Max ---				Av. 25 Max ---	C-
4b	Av. 25 Max 77				Av. 23 Max 465		Av. 23 Max ---				Av. 21 Max ---	

Specimen Number	BASE METAL Cover Area	WELD-COVER (Gas-Tungsten Arc Weld)				Ranking	BASE METAL Root Area	WELD-ROOT (Shielded Metal Arc Weld)				Ranking
	IN 800H	RA-330-04-15	RA-333-80-16	Metrode 50CR-50Ni	IN 617		IN 800H	RA-330-04	RA-333	IN 72	IN 617	
1a	Av. 21 Max 74	Av. 14 Max 440				C	Av. 14 Max 23	Av. 23 Max 131				C
1b	Av. 19 Max 69	Av. 19 Max 228					Av. 19 Max 19	Av. 25 Max 198				
2a	Av. 14 Max 21		Av. 11 Max 607			B-	Av. 11 Max 80		Av. 8.8 Max 18			A-
2b	Av. 25 Max 32		Av. 18 Max 38				Av. 11 Max 30		Av. 5.3 Max 69			
3a	Av. 25 Max 52			Av. 5.3 Max 23		B-	Av. 19 Max ---			Av. 30 Max ---		C
3b	Av. 25 Max ---			Av. 3.5 Max 41			Av. 21 Max 64			Av. 7.0 Max 39		
4a	Av. 18 Max ---				Av. 14 Max ---	B	Av. 19 Max ---				Av. 25 Max ---	C-
4b	Av. 16 Max 26				Av. 23 Max 465		Av. 26 Max ---				Av. 21 Max ---	

*Rankings:
A, practically complete resistance, or the alloy is the best of materials within its class.
B, good resistance. May replace materials given A rating to secure some other advantage.
C, adequate resistance under favorable conditions, which should be investigated beforehand.
D, sufficient resistance if adequate precautions are taken to reduce effect of corrosive conditions, as by coatings, cathodic protection, redesign, etc., or where appearance is not important and appreciable corrosion may be provided for or tolerated.
E, poor resistance; used only if no better material is available.

Table A.2.4.2.2.1a

gives the lowest rate of sound metal loss. The lowest resistance of weld metal to hot gas corrosion was shown by IN 72 and IN 617.

Some laboratory experiments were started to evaluate the hot gas corrosion of IN 657 and IN 800H (aluminized) with two weld metals. However, insufficient data were obtained to carry out complete evaluations.

Other tests involving corrosion of welded and unwelded alloys were carried out at 1000 °C in a special gas mixture for 100 hours. In most cases, test results were obtained on a single test specimen of each alloy. The gas composition in volume per cent was: H_2O-30; H_2S-1; H_2-30; Ar-balance. The five alloys tested are listed in Section B.1.1.29.

Results of metallographic examination are listed in B.1.1.29 and show that the welded and unwelded specimens of the same alloy behaved similarly. For example, specimens of type 310 stainless steel (high purity) alloyed with 2 and 3 percent titanium formed an adherent oxide about 12-16 μm thick and exhibited internal oxidation to a depth of 22 to 36 μm. Similar behavior was shown by a Ni-30Cr-4Ti alloy, although the scale thickness and depth of penetration was considerably greater. Ni-30Cr alloyed with 3 or 4 percent aluminum developed a spall-prone oxide. Scale thickness was 3-6 μm, but depth of internal oxidation was not reported. The alloy containing 3 percent aluminum exhibited some weld surface cracking.

CHAR CORROSION REACTIONS have been studied for about eleven alloys in contact with chars containing 0.9 and 2.7 percent sulfur. (See Sections B.1.1.54-65.) In general, unprotected alloys showed significant weight gains accompanying the formation of sulfides and oxides. Sulfides formed initially, then oxides formed if the char was not replenished. There was no evidence of significant carburization for any of the alloys, despite the high carburization potential of the char. More reaction tended to occur with the finer char particle sizes. A protective alloy coating and pre-oxidation coatings tended to reduce the rate of char corrosion reactions.

The alloys tested for reaction with char included type 310 stainless steel, Inconel 671, Incoloy 800, Hastelloy X, Haynes 188, Ni-10Cr-5Al, Incoloy MA 956, GE 1541, Fe-13Al, Ni-10Cr-5Al and Fe-24Cr. Tests were conducted with two chars: FMC-High Volatile Bituminous, W. Kentucky Colonial Mine (2.7 percent sulfur) and Husky, N. Dakota Lignite (0.9 percent sulfur). Exposures were mostly at 1800 °F with the test specimens embedded in char in ceramic or graphite boats in an argon atmosphere. Exposure times were usually 96 hours. In most cases, test results were obtained on a single test specimen of each alloy. Weight gains reported are conservative, since some of the char adhered tightly to the test specimens and could not be brushed off easily afterward.

A detailed description of the performance of most of the alloys studied is given in Section B.1.1.62. Generally, good performance was shown by Hastelloy X and Haynes 188. Type 310 stainless steel, Inconel 671 and Incoloy 800 showed poorer performance. An increase in temperature from 1600 to 1800 °F significantly increased the char corrosion rates for type 310 stainless steel and Inconel 671 (see B.1.1.58). Kinetic studies showed that Fe-Cr-Al-Y alloys are not very resistant to corrosion reactions with char (see B.1.1.60). Very good resistance was shown by Incoloy 800 when coated with Cr-Al-Hf, although some spalling occurred. Pre-oxidation in air or argon saturated with water vapor tended to be beneficial in reducing corrosion actions for GE 1541 and Incoloy MA 956 (see B.1.1.65). Pre-oxidation did t seem to be beneficial for Hastelloy X, Inconel 671, Incoloy 800 or 310 ainless steel (compare B.1.1.54 and B.1.1.64). For some alloys, particularly 1541 and Inconel 671, increased pre-oxidation time reduced the char corsion weight gain.

CYCLIC EXPOSURE TO COAL GASIFICATION ATMOSPHERES can result in loss of a otective scale due to differences in the coefficients of thermal expansion scale and the base metal. Fifteen iron alloys were evaluated for corrosion havior characteristic of cyclic exposure to a coal gasification environment. e composition of the alloys tested and the results obtained appear in ctions B.1.1.68 through B.1.1.73. Alloying elements were chromium-aluminum-lybdenum, with silicon and/or hafnium in some cases. Commercial and experintal alloys were tested. In most cases, test results were obtained on a ngle test specimen of each alloy. Twelve alloys were vacuum induction lted and seven were arc melted using a nonconsumable electrode. The comsition of the coal gasification atmosphere was the same for all tests and is sted in each table. Hydrogen sulfide concentration was 1 percent. Temrature and pressure were 1800 °F and 1 atmosphere respectively. Cycling volved repeated exposure at temperature for 100 hours and cooling to room mperature in less than a minute. Total exposure times were 800 to 1000 urs.

All alloys tested tended to show a weight gain. This was due to formaon of a scale of unidentified chemical composition. The largest weight gain s 7.57 mg/cm^2. Most alloys showed a weight gain in the range 0.5 to 3 /cm^2. In many cases, the weight gain did not always increase continuously th time. Sometimes it showed a downturn, which may have been due to loss of ale during handling or from differences in the thermal expansion coeffients of the scale and the base metal.

There was no significant effect of melting practice, either nonconsumable ectrode arc melting or vacuum induction melting, on the corrosion resistance the alloys during cyclic exposure.

Two alloys were given surface conditioning treatments to evaluate fects of surface condition on corrosion resistance. One alloy was Cr-5Al-2Mo-1Hf-balance Fe, and the other was 17Cr-3Si-2Mo-balance Fe. rface conditioning generally improved the corrosion resistance of the first loy (see B.1.1.71). A pre-oxidized surface showed the least corrosion. In e case of the second alloy, the surface conditioning did not seem beneficial ee B.1.1.73).

Another series of cyclic tests was carried out on twenty-four alloys sted at 1800 °F in air. Two specimens each of the commercial and experintal alloys were tested. Cycling involved repeated exposure for 100 hours llowed by cooling to room temperature. Total exposure times ranged from 500 1000 hours. Test data appear in Section B.1.1.38.

Type 304 stainless steel showed a large and consistently increasing ight loss with each cycle, indicating a loss of scale due to spalling. Most her alloys showed a weight gain of 0.1 to 2 mg/cm^2 in the first 3 or 4 cles, indicating an adherent scale. About seven alloys showed an initial ight gain, followed by a loss. The remaining alloys showed a consistent ight gain. In some cases, the specimens of a given alloy pair did not show similar behavior, indicating that reproducibility is sometimes a matter of concern. In other cases, the specimens showed remarkably similar behavior.

EFFECT OF A POTENTIALLY CARBURIZING ATMOSPHERE was evaluated for five alloys in a coal gasification atmosphere. Tests were run at temperatures between 1330 and 1808 °F at 68 atmospheres pressure for 80 hours. The alloys tested included 18-18-2, Incoloy 800, 310 stainless steel, Inconel 671 and GE 1541. In most cases, test results were obtained on a single test specimen of each alloy. The input gas composition was:

Input Gas Composition, moles

H_2S	CO	CO_2	H_2	CH_4	H_2O
0.010	0.2014	0.1151	0.2014	0.300	0.172

Tabulated test data appear in Section B.1.1.5.

The results listed in B.1.1.5 indicate that temperature has a significant effect on the alloy response. In general, each alloy formed an adherent continuous protective scale at temperatures around 1300-1400 °F and internal sulfidation especially along grain boundaries at temperatures around 1600-1800 °F. There was no evidence of carburization reported for any alloy. Pre-oxidation of the GE 1541 seemed to prevent sulfide reactions and apparently formed adherent protective scales and grain boundary precipitates.

SCALE FORMATION is a surface phenomenon which occurs as a result of chemical reaction between components of the gas atmosphere and the structural metals. Scales may be adherent or loose, continuous or discontinuous. When adherent scales form a continuous, non-porous layer, the resulting protective film can be beneficial. Spalling scale is undesirable. Scales formed in coal conversion atmospheres tend to be sulfides or oxides. Sulfide reactions seem to occur most frequently. This is because the partial pressure of sulfur or sulfur compounds in a gas atmosphere is usually 10^5 to 10^{10} times higher than the partial pressure of oxygen.

Both sulfidation reactions and oxidation reactions can occur internally following diffusion as well as at the surface. Internal reactions result in products which are often termed sub-scale. Internal chemical reactions are complex and can involve reaction between an inward diffusing species, e.g., oxygen or sulfur, and alloying elements of the structural metal, e.g., aluminum, titanium, chromium, manganese, silicon, nickel, iron, etc. Often, internal sulfidation or oxidation reaction products show up as precipitates along grain boundaries.

In tests on about 14 commercial and experimental alloys (see B.1.1.30) exposed for 48 to 124 hours to a simulated coal gasification atmosphere containing 1 percent hydrogen sulfide and a variable water content, a decrease in water content from 15 to 6 volume percent resulted in an increase from two to six in the number of specimens which were totally destroyed. Type 310 stainless steel specimens showed especially poor corrosion resistance at all water contents. Of those alloys that survived, scale thickness ranged from 8 to 24 µm, with sub-scale corrosion penetrating to depths of 50 µm. The scale was usually in the form of an adherent oxide, although Inconel 671 formed nodular sulfides regardless of water content. Scale thickness tended to decrease with decreasing water content, although there seemed to be no correlation between sub-scale corrosion depth and water content. Sub-scale corrosion tended to be mostly in the form of grain boundary oxides.

In tests on twenty-five commercial and experimental alloys (see B.1.1.32) exposed for 100 hours to a simulated coal gasification atmosphere containing 1 percent hydrogen sulfide and 40 percent water vapor, twenty alloys formed an adherent oxide, whereas some form of internal sulfur attack occurred in nine alloys. Thirteen alloys showed only oxygen attack in the form of an adherent oxide and a grain boundary oxide. No alloy was totally destroyed. The best performance was shown by Fe-25Cr-20Ni, 233 MS, 233 M, 233 S, Incoloy 825 and Inconel 617. Poor performance was exhibited by Inconel 690, Incoloy 800 and Ni-30Cr. In 310 stainless steel, the tendency is to form surface scale of iron and manganese sulfides and sub-surface precipitates of chromium oxide and sulfide. The presence of titanium in any alloy results in formation of sub-surface titanium oxide. Nickel-based alloys tend to form chromium sulfide and oxide precipitates.

Thirteen commercial and experimental alloys (Section B.1.1.35) which were exposed cyclically in 100 hour increments to a typical coal gasification atmosphere containing 1 percent hydrogen sulfide and 40 percent water vapor tended to form adherent oxide scales and grain boundary oxides in tests which ran for two or three cycles. Eight alloys developed internal sulfides as well as grain boundary oxides. Only Type 310 stainless steel formed a spalling oxide and exhibited internal sulfidation. It may be that the relatively high water vapor content helped to form an adherent oxide which promoted resistance to spalling during thermal cycling as well as prevented internal sulfidation.

In tests on Type 310 stainless steel alloyed with 3 percent titanium (see Sections B.1.1.40 and B.1.1.53), it was found that surface oxide scale was adherent and developed to a thickness of 20 μm in 500 hours exposure to a typical coal gasification atmosphere containing 40 percent water vapor. Furthermore, internal oxide penetrated to a depth of about 20 μm, whereas a layer of $(Cr,Ti)_2O_3$ developed below that. The 3 percent titanium addition to the Type 310 stainless steel more than doubled the oxide thickness for a given exposure time.

In tests on eight alloys exposed at 1800 °F for 100 hours to a gas atmosphere containing 41 percent argon, 16 percent water vapor and a partial pressure of oxygen of 2.4×10^{-16} atm (see B.1.1.41), it was found that six alloys developed adherent oxide scales and two developed spalling oxides. Oxide thickness ranged from 6 to 20 μm, and the depth of penetration of internal oxidation was 5 to 30 μm. The protective oxide layers were composed of Cr_2O_3, with some Ti, Al or Mn incorporated in the oxide.

These alloy specimens were pre-oxidized at 1800 to 2300 °F in air or argon saturated with water vapor for 8 to 16 hours, then exposed to 0.1 atm sulfur vapor at 1000 °C (see B.1.1.66). The effect of pre-oxidation was beneficial for Incoloy MA 956 and Fe-24Cr, but was not beneficial for Fe-13Al.

Type 310 stainless steel and Incoloy 800 were tested at 1800 °F for 19-24 hours in an atmosphere in which the P_{H_2O}/P_{H_2} ratio was varied (see B.1.1.83.) As log P_{H_2O}/P_{H_2} increased from -0.341 to +0.249, the reaction of the Type 310 stainless steel changed from formation of a liquid sulfide on the surface (which spalled upon cooling) to the development of a surface oxide and internal oxidation with no sulfidation occurring. The Incoloy 800 showed the same changes for the same change in log P_{H_2O}/P_{H_2} ratio.

ALLOY DEVELOPMENT PROGRAMS represent an important source of information for making selections of new structural materials for coal conversion plants. One goal of an alloy development program for materials for metal internal components is to produce materials with adequate tensile properties coupled with good corrosion resistance. Corrosion resistance results from promoting the development of continuous adherent surface films, usually oxides, which inhibit the inward diffusion of sulfur and subsequent sulfur compound formation The formation of continuous adherent protective oxide films on many structural alloys seems to be encouraged by the presence of at least 20 percent water vapor in the gas atmosphere at temperatures of 1800 °F.

A comprehensive alloy development program was carried out which investigated over one hundred alloys (see Sections B.1.1.12, B.1.1.74-82, B.1.1.92-96, B.1.1.98 and B.1.1.99) to determine the effect of composition and minor alloying additions on sulfidation resistance. Hot gas corrosion tests were carried out in simulated coal gasification atmospheres containing from 1 to 1.5 percent hydrogen sulfide and about 40 percent water vapor. Exposure times ranged from about 25 to 500 hours. Temperature and pressure were 1800 °F and 1 atmosphere, respectively.

The alloy systems investigated were mainly iron-based, but a few were chromium-based and nickel-based. The iron-based systems investigated were:

iron-chromium
iron-aluminum
iron-chromium-silicon
iron-chromium-aluminum
iron-chromium-aluminum-silicon
iron-chromium-aluminum-manganese
iron-chromium-aluminum-molybdenum

About 80 different iron-based alloy compositions were examined. Only about six chromium-based alloy systems were investigated, and the same is true for the nickel-based alloy systems. The minor alloying elements included Y, La, Hf, Ti and Zr in amounts up to 1 percent.

The corrosion performance variables studied included the weight change and the corrosion products which formed. In many cases, the alloy specimens were completely destroyed. Categories of corrosion products which formed included: sulfide slags, internal sulfidation, sulfide case, spalled oxide, adherent oxide.

The iron-based alloy systems which were investigated are classified according to alloy composition and concentration in Table A.2.4.2.2.1b. The coal gasification atmosphere had a nominal composition of 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 0.5-1 H_2S, and 39.5-40 H_2O. The equilibrated atmosphere also contained some minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, and CS. Where "nominally reactive" gas is given, the test atmosphere was 50 H_2, 15 H_2O, 20 CO, 6 CO_2, 7 CH_4, 1.5 H_2S, 1 NH_3. Tests in air were cyclical exposures, 120 heating and cooling cycles in 100 hours. Performance is evaluated in terms of the type of deterioration which was observed and is specified as adherent oxide, spalled oxide, sulfide slag, etc. Formation of an adherent oxide is regarded as the best

:formance, since sulfide penetration can lead to disintegration and
entually to total destruction. Exposures were at 1800 °F for most of
e tests for times usually between 24 and 100 hours, although a few 500 and
)0 hour exposures were made. Some exposures involved thermal cycling
:ween 1800 °F and ambient temperatures once each hour to provide a severe
st of the adherence of scale. Most of these cycling tests were in air
though a few were conducted with a reactive gas. A comparison of the
:formance of each alloy can be made simply by reference to appropriate
umns in Table A.2.4.2.2.1b.

Some mechanical properties of some of these iron-based alloy systems
e measured (Sections B.3.1.35 through .38, B.3.1.52). The Charpy impact
a indicate upper shelf energies in the range 20 to 80 ft-lb with
nsition temperatures in the neighborhood of 60 °C. A recrystallization
eriment on one alloy, Fe-18Cr-6Al-1Mo-0.6Hf, demonstrated that almost
cold work anneals out at about 1800 °F.

Surface condition effects on corrosion resistance of six alloys were
estigated (see Sections B.1.1.76 and B.1.1.78). Exposure was in a simulated
l gasification atmosphere for 96 hours at 1 atmosphere pressure. For
n-chromium-aluminum-silicon alloys, the greatest weight gain was for grit
sted surfaces which also formed adherent oxides and the least weight gain
for 120 grit polished surfaces which formed spalling oxides. For iron-
omium-aluminum-molybdenum-hafnium alloys, the least weight gain was for
nished alloys and the greatest weight gain was for 120 grit polished
oys.

OT PLANT TESTING

EXPOSURE IN GAS PHASE LOCATIONS IN PILOT PLANTS has produced data
commercial and experimental alloys which show how these alloys behave in a
l coal gasification atmosphere. Forty alloys were exposed in ten different
-phase locations at the following pilot plants: HyGas, Synthane, CO_2
ceptor and Bi-Gas. These exposures are unique because they represent the
st test data which demonstrate the performance of the structural alloys in
eal coal gasification environment. Temperatures ranged from 900 to 1700 °F.
osure times were between 181 and 2909 hours. These times are for the hours
plant was operating under coal gasification conditions; standby time is
included, nor are the standby conditions specified which affect the alloy
:formance. Depth of penetration and total sound metal loss, as determined
m metallographic and gravimetric analysis, respectively, were used to
scribe the extent of corrosion. Test results appear in Section B.1.1.27.

Table A.2.4.2.2.1c shows the results. The performance of each
loy in each plant location can be determined from the appropriate row
column in the table. The key to the figure is as follows. The
:formance of the alloys is expressed as a letter code based on arbitrarily
sen limits for the corrosion rates:

<5 mils/yr, excellent, e;
5-50 mils/yr, satisfactory, s;
>50 mils/yr, unsatisfactory, u.

e locations in the pilot plant where the specimens were exposed are
en using the following code:

Sulfidation-Oxidation Behavior of Experimental and Commercial Alloys

					Results						
Alloy Groups	Test Temp. °F	Equilibrated	Not Equilibrated	Test Time h	Adherent Oxide	Adherent Sulfide	Spalling Oxide	Internal Sulfide	Sulfide Slag	Destroyed	Comments
Tests in Coal Gasification Atmosphere (see text)											
Fe-Al alloys											
-5,8,10,12,15Al	1800		X	24						X	
-5,8,10,12Al	1800		X	100						X	Nominally reactive gas (see text).
-12Al	1800		X	24				X	X		Specimen preoxidized.
Fe-Cr alloys											
-15Cr	1800	X	X	24 & 96						X	
-20Cr	1800		X	25					X		
Fe-Al-Cr alloys											
-1Al-15Cr	1800	X	X	24						X	
-1Al-19Cr	1800	X		25	X						
-2Al-10,12.5,15Cr	1800		X	24						X	
-2Al-10Cr	1800	X		24						X	
-2Al-12.5Cr	1800	X		24	X				X	X	
-2Al-15Cr	1800	X		24 & 96	X						
-2Al-18Cr	1800		X	24	X						
-2Al-18Cr	1550		X	50					X		
-2,6Al-18Cr	1800		X	24	X						
-3Al-10,12.5,13Cr	1800		X	24						X	
-3Al-12.5Cr	1800	X		24	X				X		
-3Al-13Cr	1800	X		96			X				
-3Al-15,17Cr	1800		X	24	X						
-3Al-17Cr	1800		X	24			X				
-3Al-17Cr	1550		X	50					X		
-4Al-10,12.5,14Cr	1800		X	24						X	
-4Al-10Cr	1800		X	24			X		X	X	
-4Al-12.5,14,15Cr	1800	X		96			X				
-4Al-14Cr	1800	X		96	X						
-4Al-14Cr	1800	X	X	24			X				
-4Al-18Cr	1800		X	24 & 96			X				Conditions irregular in 96 h tests
-4Al-18Cr	1550		X	50	X						
-4.5Al-16Cr	1800		X	24 & 96			X				Conditions irregular in 96 h tests
-4.5Al-16Cr	1800		X	500			X				
-4.5Al-16Cr	1550		X	50	X						
-6Al-5,7.5Cr	1800		X	24						X	
-6Al-7.5Cr	1800		X	24			X		X	X	
-6Al-7.5,10Cr	1800	X		24			X				
-6Al-10Cr	1800		X	24	X		X		X		
-6Al-12.5Cr	1800	X	X	24			X				
-6Al-15,18Cr	1800		X	24			X				
-6Al-15Cr	1800	X		96			X				
-6Al-18Cr	1800		X	500			X				
-6Al-18Cr	1550		X	50	X						
-5,8Al-8Cr	1800		X	24						X	
-8Al-8Cr	1800	X		24			X		X		
-8Al-9Cr	1800	X	X	24			X				
-8,10Al-10Cr	1800		X	24			X				
-8,10Al-10Cr	1800	X		24						X	
-8,10Al-15Cr	1800	X	X	24			X				
-10Al-5Cr	1800		X	24						X	
-10Al-8Cr	1800		X	24			X				
-10Al-9Cr	1800	X	X	24			X				
Fe-Al-Cr-Mn alloys											
-4.5Al-16Cr-0.75Mn	1800		X	96	X		X				Conditions irregular in 96 h tests.
-4.5Al-16Cr-1.5Mn	1800	X		24			X				
-8,10Al-5Cr-1Mn	1800		X	24						X	
-8Al-5Cr-1.5Mn	1800		X	47						X	
-8Al-5Cr-2.5Mn	1800		X	24 & 60			X			X	
-8,10Al-10Cr-1.5Mn	1800		X	24			X				
-8,10Al-10Cr-2.5Mn	1800	X		24						X	
-8Al-10Cr-1,1.5,2.5Mn	1800		X	24			X				
-8Al-10Cr-5Mn	1800		X	47			X				
-8Al-10Cr-20Mn	1800		X	24			X				Preoxidized and unpreoxidized tests
-8Al-10Cr-20Mn	1800	X		24				X	X		
-8Al-15Cr-1Mn	1800		X	24			X				
-8,10,12Al-5,10Cr-2.5Mn	1800	X		96						X	Preoxidized specimen.
-8,10,12Al-5,10Cr-2.5Mn	1650	X		24				X	X		

(Continued)

Table A.2.4.2.2.1b

Sulfidation-Oxidation Behavior of Experimental and Commercial Alloys, Continued

Alloy Groups	Test Temp. °F	Equili- brated	Not Equili- brated	Test Time h	Results						Comments
					Adherent Oxide	Adherent Sulfide	Spalling Oxide	Internal Sulfide	Sulfide Slag	De- stroyed	
Fe-Al-Cr-Mn alloys continued											
-10Al-2.5Cr-5Mn	1800		X	47						X	
-10,12Al-5Cr-2.5Mn	1800		X	24						X	
-10Al-5Cr-5Mn	1800		X	24 & 60			X				
-10Al-5,10,15Cr-5Mn	1800	X		96						X	Preoxidized specimen.
-10Al-5,10,15Cr-5Mn	1650	X		24				X	X		
-10Al-5,10,15Cr-30Mn	1800		X	24				X	X		
-10Al-10Cr-1,1.5Mn	1800		X	24			X				
-10Al-10Cr-1.5Mn	1800	X		24			X				
-10Al-10Cr-2.5,5Mn	1800		X	24 & 60			X				
-10Al-10,15Cr-5Mn	1800	X		24						X	
-10Al-15Cr-1.5,2.5Mn	1800		X	24			X				
-10Al-15Cr-1.5Mn	1800		X	47						X	
-10Al-15Cr-1.5Mn	1800	X		24			X				
-10Al-15Cr-5Mn	1800		X	24 & 60			X				
-12Al-10Cr-2.5Mn	1800		X	24 & 60			X		X		
Fe-Al-Cr + other elements											
-4Al-14,18Cr-0.5Y	1800	X		24			X				
-4.5Al-16Cr-0.5Hf	1800	X		24			X				
-4.5Al-16Cr-0.5Hf	1800		X	24	X						
-4.5Al-16Cr-0.5Hf	1550		X	50	X						
-4.5Al-16Cr-2,4Mo-0.5Y	1800	X		24			X				
-4.5Al-16Cr-0.5Y	1800	X		24 & 96	X						Second 24 h test gave spalling oxide.
-4.5Al-16Cr-0.5Y	1800		X	24	X						
-4.5Al-16Cr-0.5Y	1550		X	50	X						
-4.5Al-16Cr-0.5Y	1800		X	1000	X						Both steady state & cyclic exposure.
-5Al-16Cr-1Hf-2Mo	1800		X	1000	X						Both steady state & cyclic exposure.
-5Al-18Cr-0.5,1Hf	1800		X	100			X				
-5Al-18Cr-1Hf	1800		X	100	X						
-5Al-18Cr-0.5Hf-1Mo	1800		X	100	X						Preoxidized specimen.
-5Al-18Cr-0.5Hf-1Mo	1800		X	100			X				
-5Al-18Cr-1Hf-1Mo	1800		X	100	X		X				
-5Al-18Cr-1Hf-2Mo	1800		X	1000	X						Cyclical exposure.
-5Al-18Cr-1Hf-2Mo	1800		X	494	X	X					Sample burnished & acid pickled.
-5Al-20Cr-0.5Hf-1Mo	1800		X	100			X				Preoxidized specimen.
-5Al-20Cr-0.5Hf-1Mo	1800		X	100			X				
-5Al-20Cr-1Hf-1Mo	1800		X	100			X				
-6Al-18Cr-0.5,1Hf	1800		X	100			X				
-6Al-18Cr-0.5Hf-1Mo	1800		X	100			X				
-6Al-18Cr-0.5Hf-1Mo	1800		X	100	X						Preoxidized specimen.
-6Al-18Cr-1Hf-1Mo	1800		X	100			X				Preoxidized specimen.
-6Al-19Cr-1Hf-1Mo	1800		X	100	X						
-6Al-19Cr-1Hf-2Mo	1800		X	494	X	X					Sample burnished & acid pickled.
-6Al-20Cr-0.5,1Hf	1800		X	100			X				
-6Al-20Cr-0.5Hf-1Mo	1800		X	100			X				
-6Al-20Cr-1Hf-1Mo	1800		X	100			X				Preoxidized specimen.
-8Al-10Cr-0.5Y	1800	X		24			X				
-8Al-10Cr-0.5Y	1800		X	24	X						
Fe-Al-Cr-Mn + other elements											
-4.5Al-16Cr-0.75,1.5Mn-0.5,1Si	1800		X	96	X		X				Conditions irregular during test.
-4.5Al-16Cr-0.75Mn-0.5Si	1800		X	24			X				
-4.5Al-16Cr-0.75Mn-0.5Si	1550		X	50	X						
-8Al-10Cr-20Mn-3,6,9Mo	1800	X		24				X	X		
-8Al-10Cr-20Mn-2Ta	1800	X		24				X	X		
-8Al-10Cr-20Mn-0.5Y	1800	X		24				X	X		
Fe-Al-Cr-Si alloys											
-1Al-18Cr-1Si	1800		X	25	X						
-4,6Al-16,18Cr-0.5Si	1800		X	96			X				As-rolled specimen.
-4,6Al-16,18Cr-0.5Si	1800		X	96	X						Mill scaled removed from specimen.
-4,6Al-16,18Cr-0.5Si	1800		X	96			X				Scale & underlying metal polished off.
-4.5Al-16Cr-0.25,0.5,1Si	1800		X	96			X				Conditions irregular during test.
-4.5Al-16Cr-0.5Si	1800		X	500			X				
-4.5,6Al-16,18Cr-0.5,1Si	1800		X	24			X				
-4.5Al-16Cr-1Si	1550		X	50	X						
-6Al-18Cr-0.5,1Si	1550		X	50	X						
-6Al-18Cr-0.5Si	1800		X	500			X				
-6Al-18Cr-0.5,1,2Si	1800		X	25			X				
-2Al-18Cr-1Si-0.4Ti	1800	X	X	24	X						
-2Al-18Cr-1Si-0.4Ti	1800	X		96	X						

(Continued)

Table A.2.4.2.2.1b

Sulfidation-Oxidation Behavior of Experimental and Commercial Alloys, Continued

Alloy Groups	Test Temp. °F	Equili- brated	Not Equili- brated	Test Time h	Results Adherent Oxide	Adherent Sulfide	Spalling Oxide	Internal Sulfide	Sulfide Slag	De- stroyed	Comments
Fe-Al-Mn alloys											
-3Al-2Mn	1800		X	24						X	
-5Al-10,20,30Mn	1800		X	24						X	
-5Al-20Mn	1800		X	100						X	Nominally reactive gas (see text).
-5Al-3Mn	1800		X	100				X	X		Nominally reactive gas.
-6Al-30Mn	1800		X	100						X	Nominally reactive gas.
-6,7Al-30,35Mn	1800		X	24						X	
-7Al-30,35,40Mn	1800		X	100				X	X		Nominally reactive gas.
-7Al-40Mn	1800		X	24						X	
-8Al-10,20,30,35Mn	1800		X	24						X	
-8Al-10Mn	1800		X	100						X	Nominally reactive gas.
-8Al-20,30,35Mn	1800		X	100				X	X		Nominally reactive gas.
-8Al-20Mn	1800		X	24			X	X			Nominally reactive gas; samples p oxidized.
-9Al-30Mn	1800		X	24						X	
-9Al-30Mn	1800		X	24				X	X		Nominally reactive gas; samples p oxidized.
-9Al-30Mn	1800		X	100				X	X		Nominally reactive gas.
-10Al-5,10,20,30Mn	1800		X	24						X	
-10Al-5,10,20Mn	1800		X	100						X	Nominally reactive gas.
-10Al-5,10Mn	1800		X	24				X	X		Nominally reactive gas; samples p oxidized.
-10Al-20,30Mn	1800		X	24			X	X			Nominally reactive gas; samples p oxidized.
-12Al-2.5,5Mn	1800		X	24						X	
-12Al-2.5,5Mn	1800		X	100						X	Nominally reactive gas.
-12Al-2.5,5Mn	1800		X	24				X	X		Nominally reactive gas; samples p oxidized.
-15Al-5,10Mn	1800		X	24						X	
-15Al-5Mn	1800		X	100				X	X		Nominally reactive gas.
-15Al-10Mn	1800		X	100						X	Nominally reactive gas.
Fe-Al-Mn-C(N) alloys											
-5Al-20Mn-0.2,0.4N	1800		X	24						X	
-5Al-20Mn-1C	1800		X	24						X	
-7Al-20Mn-0.75,1C	1800		X	24						X	
-7Al-30Mn-0,75,1C	1800		X	24						X	
-8Al-10Mn-0.75C	1800		X	24						X	
-8Al-20Mn-0.75,1,1.2C	1800		X	24						X	
-8Al-25Mn-1.2C	1800		X	24						X	
-8Al-30Mn-0.5,0.75,1C	1800		X	24						X	
-8Al-35Mn-0.75,1C	1800		X	24						X	
-8Al-40Mn-0.75C	1800		X	24				X	X		
Fe-Cr-Si alloys											
-17Cr-3Si	1800		X	24			X				
-17Cr-3Si	1550		X	50	X						
-17Cr-3Si	1800		X	1000			X				
-18Cr-2Si	1800		X	25			X				
-19Cr-1Si	1800		X	25			X				
Fe-Cr-Si + other elements											
-17Cr-3Si-1Hf-1Mo	1800		X	1000			X				Both steady state & cyclic expos
-17Cr-3Si-2Mo	1800		X	1000					X		Steady state exposure.
-17Cr-3Si-2Mo	1800		X	1000			X				Cyclical exposure.
Cr alloys											
Cr	1800		X	60	X						
Cr-2Fe	1800		X	60	X						
Cr-2Mn	1800		X	60	X						
Cr-0.5La	1800		X	24	X						
Cr-0.5Y	1800		X	24	X						
Mo alloy											
Mo-0.5Ti-0.1Zr	1800	X		96		X					

(Continued)

Table A.2.4.2.2.1b

Sulfidation-Oxidation Behavior of Experimental and Commercial Alloys, Continued

y Groups	Test Temp. °F	Equili-brated	Not Equili-brated	Test Time h	Results Adherent Oxide	Adherent Sulfide	Spalling Oxide	Internal Sulfide	Sulfide Slag	De-stroyed	Comments
ercial alloys											
9 SS	1800	X	X	24	X						
9 SS	1800	X		96	X						
6 SS	1800	X	X	24	X						
6 SS	1800	X		96	X						
mco 18SR	1800	X	X	24	X						
mco 18SR	1800	X		96	X						
0 SS	1800	X	X	24			X				Sulfide slag in a 2nd unequil. test.
0 SS	1800	X		96	X						
0 SS	1550		X	50					X		
0 SS	1800		X	1000	X						Steady state exposure.
0 SS	1800		X	1000			X	X			Cyclical exposure.
i-46Cr	1800		X	1000	X						Steady state exposure.
i-46Cr	1800		X	1000	X			X			Cyclical test; also internal oxide.
ncoloy 800	1800		X	24	X						
ncoloy 800	1800	X		24 & 96			X				
nconel 600	1800	X	X	24	X				X		
nconel 600	1800	X		96	X						
nconel 657	1800	X	X	24	X				X		
nconel 657	1800	X		96	X						
nconel 671	1800	X	X	24	X				X		Spalling oxide in a 2nd unequil. test.
nconel 671	1550		X	50	X						
aynes 188	1800	X	X	24			X				
aynes 188	1800	X		96	X				X		
04 SS	1800	X	X	24					X		
14 SS	1800	X	X	24			X				
A 333	1800	X	X	24					X		

-Tests in Air, Cyclical Exposure (see text)-

oy Groups	Test Temp. °F	No. of Cycles	Results, as above						Comments
Al alloys									
5,8,10,12,15Al	1800	120			X				
Al-Cr alloys									
8Al-10Cr	1800	120	X						
Al-Cr-Mn alloys									
-8Al-5,10Cr-1Mn	1800	120			X				
-8Al-5,10Cr-2.5Mn	1800	120	X						
-8Al-10Cr-20Mn	1800	120	X						
-10Al-5,10,15Cr-1Mn	1800	120			X				
-10Al-5,10Cr-2.5,5,30Mn	1800	120	X						
-10Al-15Cr-5,30Mn	1800	120	X						
-12Al-5,10Cr-2.5Mn	1800	120	X						
-Al-Cr-Mn + other elements									
-8Al-10Cr-20Mn-3,6,9Mo	1800	120			X				
-8Al-10Cr-20Mn-2Ta	1800	120			X				
-8Al-10Cr-20Mn-0.5Y	1800	120	X						
-Al-Mn alloys									
-3Al-2Mn	1800	120			X				
-5Al-10,20,30Mn	1800	120			X				
-6Al-30,35Mn	1800	120			X				
-7Al-30,35,40Mn	1800	120			X				
-8Al-10,20Mn	1800	120	X						
-8Al-30,35Mn	1800	120			X				
-9Al-30Mn	1800	120	X						
-10Al-5,10,20,30Mn	1800	120	X						
-12Al-2.5,5Mn	1800	120	X						
-15Al-5Mn	1800	120	X						
-15Al-10Mn	1800	120			X				
-Al-Mn-C(N) alloys									
-5Al-20Mn-0.2,0.4N	1800	50			X				
-5Al-20Mn-1C	1800	50			X				
-7Al-20Mn-0.75,1C	1800	120			X				
-7Al-30Mn-0.75,1C	1800	50			X				
-8Al-10Mn-0.75C	1800	120			X				
-8Al-20Mn-0.75,1,1.2C	1800	120			X				
-8Al-25Mn-1.2C	1800	120			X				
-8Al-30Mn-0.5,0.75,1C	1800	75 or 50			X				
-8Al-35Mn-0.75,1C	1800	50			X				
-8Al-40Mn-0.75C	1800	25			X				

Table A.2.4.2.2.1b

Ranking of Corrosion Performance of Alloys Exposed to Gas Phase Locations in Coal Gasification Pilot Plants

	Gasification Plant and Test Location									
	HYGAS					SYNTHANE		CO_2 ACCEPTOR		BIGA
Alloys	H-1	H-2	H-3	H-4	H-5	S-1	S-2	C-1	C-2	B-1
304 SS	e	s		s-e	e	u-e	u-s	s-e	u	
309 SS	e-s	s-e	e			u-e	u-s	s-3	u	u
310 SS	e	e	e					s-e	u	s
310 SS (Al)	s	s	s					u	u	u
310 SS (Cr)								e-s	s-u	
314 SS									u	s
316 SS	s	s				u-s	u-s			
321 SS	s	s				u-s	u-s			
410 SS				s-e	e-s					
430 SS	s	e		e		s	u-s			
446 SS	s	e	e						s-u	s
HK-40 SS									u	
HL-40 SS									u	
HC-250									u	
Armco 21-6-9	s	s				u-s	u-s	s	u	
Armco 22-13-5	e	e				u-s	u-s	s-e	u	s
IN-793	s	e	e					s	u	u
Carbon steel (A515)				s-e	s					
Carbon steel (Al)				s-e	e-s					
Crutemp 25									u	
Monel 400				u						
Inconel 600	u	u				u	u			
Inconel 601	s	u-e	e-s			u-s	u-s			
Inconel 671	s	e	e-s					e	u	u
Incoloy 800	e-s	s-e	e-s	e		u-e	u-s	s-e	u	u
Incoloy 800 (Al)	s	s	s					s	u	u
Incoloy 800 (Cr)								s	u	
Incoloy 825	s					s-e	u-e	e-s	u	
RA 330									u	u
RA 333	e-s					s-e	u-e		u	s
Alloy X	e					s-e	u-s	s	u	
Haynes 150									u	
Haynes 188									u	
Titanium				e						
Welded U-Bends										
304 SS	s			s	s					
309 SS	s									
316 SS				s	s					
Inconel 600	u									
Incoloy 800	s			s	s					
Incoloy 825	s									

Table A.2.4.2.2.1c (see text for key)

H-1, steam-oxygen gasifier fluidized bed;
H-2, low-temperature first-stage reactor;
H-3, high-temperature second-stage reactor;
H-4, hydrogasifier upper reactor off-gas;
H-5, coal pretreater off-gas, neutral gas;

S-1, gasifier fluidized bed, reducing gas;
S-2, gasifier off-gas, reducing gas;

C-1, gasifier off-gas;
C-2, dolomite regenerator off-gas;

B-1, gasifier off-gas.

It is seen that performance is variable, depending upon location.

COATINGS FOR CORROSION PROTECTION

Refractory and alloy coatings on several substrates have been tested to determine their effectiveness in providing corrosion protection to alloys in a coal gasification atmosphere (see B.1.3.1). Many coatings might provide corrosion protection if it is possible to overcome the common problems of materials compatibility, which weaken the bond and cause spalling. The substrate and coating must be chemically compatible so that they are either inert or, if diffusion occurs, the diffusion process should enhance the protective action of the coating and not weaken the bond between coating and substrate. The substrate alloys tested were 1020 cold-rolled steel, 304, 310, and 316 stainless steels, Incoloy 800, and SA 285. The refractory coating materials were alumina, calcium-oxide-stabilized zirconia, magnesia-alumina, magnesia-zirconia, and chromium carbide with additions of Ni-Cr and Ni-Al. The alloy coatings were Co-Cr-Al and Tribaloy 800. Three diffusion coatings were tested, boron, chromium, and chromium-aluminum. Not all coating and substrate combinations were tested.

The gaseous environment was that indicated as the simulated coal gasification atmosphere in section B.0, the temperature was 980 °C, and the pressure atmospheric. Exposure times were short, 100 hours with a few tests for 500 hours. The general results observed were the following:

Coating	Performance
Al_2O_3	resisted or retarded corrosion; coatings on stainless steel generally spalled on cooling
ZrO_2	resisted corrosion including three samples tested 500 hours
$MgO \cdot ZrO_2$	resisted corrosion but with some spalling during cooling
$MgO \cdot Al_2O_3$	resisted corrosion but spalled during cooling

Tribaloy 800	resisted or retarded corrosion (100 hr tests)
CoCrAl	resisted corrosion in 100 hour tests only
Cr_3C_2(Ni-Al)	resisted corrosion up to 100 hr but corroded by 500 hr
Cr_3C_2(Ni-Cr)	not generally resistant
diffusion coatings (B, Cr, Cr+Al)	all corroded

The 1020 steel substrate formed some type of molten sulfide eutectic under the test conditions.

The results are not conclusive in the light of the relatively short exposure times but indicate the usefulness of further testing and the need to overcome the problem of spalling of refractory coatings. It should be noted that these tests did not subject the samples to thermal cycling. In an attempt to investigate coating systems which would overcome the spalling problem caused largely by thermal expansion mismatch between the refractory coatings and the alloy substrates, a wide variety of coated samples were prepared with a number of different bond coats and intermediate layers. These samples were subjected to thermal shock testing (see B.3.3.1) to see if the layered coating structures would resist spalling. Most combinations lasted very few cycles without spalling. Testing of some combinations was discontinued when no spalling was observed after a number of cycles. The highest ranking of these are:

Coating System	Substrate	No. of Cycles
MgO·ZrO_2 with a bond coat of CoCrAl(Y)	304SS, 310SS and Incoloy 800	8
CoCrAl (no intermediate or bond coat layers)	304SS, 310SS, and Incoloy 800	7

Other systems were tested for more cycles (up to 14) but these did show spalling with the increased thermal shock.

A.2.4.2.2.2 EROSION

OVERVIEW

Erosion occurs in various parts of coal conversion systems as abrasive particles of coal, ash, char, or dolomite are driven by fluid pressures against surface scales and metal or refractory surfaces. Some variables which affect erosion include: type of erodent, erodent particle velocity, shape and hardness, angle of impingement, temperature of material impacted, condition (including hardness) of impacted material surface. Each of these variables is important in determining the rate at which an erosion process takes place. It is important that any testing methodology which is used to evaluate and rank material performance takes into account all of these variables. Attention to each of these testing variables has been considered in the testing methodology which is reported in Sections B.2.1.4-.14 and B.2.1.21-.22. Highlights of this testing methodology include the following:

1. Erosion weight loss shows a mixed dependence on angle of impingement. In considering the effect of impingement angle on erosion, the character of the materials being subjected to the erosion must be considered, whether ductile (most metallic materials) or brittle (ceramic materials). For ductile (metallic) materials, weight loss shows a peak in the angular range 10-20°, usually followed by a systematic decrease as impingement angle approaches 90°. For brittle (ceramic) materials, the maximum erosion occurs at 90°. Examples of such performance are the data in Sections B.2.1.11 and B.2.1.14, which show erosion data typical of that for ductile materials, and Sections B.2.2.10 and B.2.2.13 (data at 25 °C), which show data typical of brittle materials. (Some variations of brittle materials behavior are to be seen at high temperatures because of phase changes in the refractories.)
2. Erosion weight loss is dependent upon the type of erodent. The rate of erosion tends to decrease as the hardness of the erodent decreases. Since char, ash, and coal particles are not as hard as silicon carbide or aluminum oxide, test results from the latter erodents will be conservative relative to a coal conversion environment.
3. Erosion weight loss increases with increasing erodent velocity in the range 10 to 100 m/s. Data in B.2.1.5, B.2.1.13, B.2.2.7, B.2.2.11, B.2.2.12, show the trend for both ductile and brittle materials. Some of the erosion data included in this book have been normalized by dividing the weight of sample lost by the weight of erodent used. Generally, a greater amount of erodent creates a greater material loss although when very large amounts of erodent are involved there is not a corresponding increased erosion effect, probably because erodent particles are acting against each other. Section B.2.2.8 contains data showing an initial decrease in erosion at larger particle flux and then the approach of a steady state.
4. Erosion weight loss increases with increasing particle size in the range five to 50 μm. Particle size and erosion are generally directly proportional. In Sections B.2.1.9 and B.2.1.13 there are ata showing increased material loss with increased particle size.

5. Erosion weight loss depends upon the temperature of the material impacted, and may increase or decrease with increasing temperature, depending upon the material. Data for alloys in sections B.2.1.5, B.2.1.9, B.2.1.10, B.2.1.11, and B.2.1.12 do not indicate a definite trend. Conflicting results are also indicated for refractory materials in B.2.2.8, B.2.2.11, B.2.2.12, and B.2.2.13. Although data in B.2.2.8 and B.2.2.13 show increased erosion loss with increasing temperature, the results in B.2.2.11 and B.2.2.12 are conflicting. For both alloys and refractories, the results seem more dependent on the response of individual materials to increased temperature in terms of possible changes in the properties rather than a direct effect of temperature as a parameter on the phenomenon of erosion.

6. Erosion weight loss depends upon the hardness of the material impacted and tends to decrease slightly as the material hardness increases.

LABORATORY TESTS

EROSION TESTING was conducted on a large number of materials. The materials were subjected to erosive attack by alumina for three minutes at impingement angles of 20° and 90° at 20 °C and at an angle of 90° at 700 °C. Not all materials were tested under all three conditions so that there are gaps in the data, as will be seen readily by glancing at any of the Part B sections listed in this text. When only one test at one angle is performed, it is not possible to have a true picture of the erosion resistance of the material. The results in terms of sample loss were compared to erosion loss of samples of a cobalt-based alloy, Stellite 6B, arbitrarily chosen as a standard and tested with each set of samples. The data consist of Relative Erosion Factors (REF), values less than one indicating a more erosion resistant material than Stellite 6B, values greater than one indicating a less erosion resistant material. The reported values are the mean of five tests on a material. Although the tests permit a ranking of materials with respect to erosion resistance, it must be borne in mind that the test conditions are not comparable to those seen by components in coal gasification plants. The alumina erodent used is much harder than the coal, char, and ash particles to which gasifier internals are subjected in the plants and the tests did not include any of the gaseous chemical constituents to be found with the char and ash particles. Also, discussion of performance of materials at 20 °C is not of very significant value if the prospective material use is in gasifier vessels at high temperatures and pressures (see operating requirements). Therefore, the high-temperature test results are more important although there are data only for the 90° impingement angle, the angle at which ductile materials (alloys) are generally more erosion resistant and brittle materials (refractories) less erosion resistant. Any discussion or ranking of materials using the high-temperature data must be tempered by the fact that the 700 °C (1292 °F) test temperature is much lower than many prospective gasifier operating temperatures, and the performance at the higher operating temperature may be rather different. Further data are required for definitive choices to be made.

EROSION TESTING OF METALS AND ALLOYS was performed on fifteen alloys, including mild steel, tool steel, several stainless steels and superalloys

(B.2.1.1). The same tests were performed on twenty-three materials which included tungsten, molybdenum, and tantalum, seven cobalt-based alloys, two titanium alloys, high nickel-chromium alloys, and miscellaneous alloys (B.2.1.2).

The effect of high temperature on the erosion results are mixed. Nineteen materials for which there are both 20 °C and 700 °C data exhibited increased erosion resistance, while six showed less resistance and five appeared little affected by temperature. The effect of angle of impingement for the various steels and the superalloys is generally what is expected for ductile materials, a greater material loss (less erosion resistance) at lower angle. For the cobalt-based alloys, tungsten and molybdenum, the performance is more like that expected of brittle materials in that they are less erosion resistant at the higher angle. The following list of materials are less than, approximately, or equally erosion resistant with respect to the Stellite 6B standard at both test angles at 20 °C:

Aluminized 304 SS
316 SS
Incoloy 800 and 800H
HK-40
RA 330
HC-250
Graph air tool steel
Mild steel
Ti-6Al-4V
RA 333
Inconel 671
00025 copper alloy
SPA (proprietary alloy)

The following materials show greater erosion resistance than the standard at both angles at 20 °C:

Tungsten, plain and with diffused boron
Molybdenum, plain and with diffused boron
Mo with Ti, Zr, C, and diffused boron
Tantalum
Tantalum nitride
Tungsten alloy, 90W-10 (Ni, Cu, Fe)

At the higher temperature (700 °C), twenty of the samples tested exhibit erosion resistance better than the standard material and these are ranked below.

Relative Erosion Factor	Material
0-0.20	Wrought Tungsten, Molybdenum alloy with diffused B
0.21-0.40	Molybdenum with diffused B
0.41-0.60	Tungsten with diffused B, Ti-6Al-4V, Titanium alloy Beta III, Tungsten alloy 90W-10 (Ni, Cu, Fe), 316 SS, Incoloy 800 and 800H

0.61-0.80	RA 333, Inconel 600 and 671, 304 SS, 430 SS, HK-40, RA 330

Any judgment of the value of these numbers and the ranking of materials must be tempered by the fact that these data are for 90° impingement angle, that angle for which ductile materials are expected to be most erosion resistant.

Those materials which are very little better than, approximately equal to, or worse than the standard at 700 °C are listed below.

Relative Erosion Factor	Material
0.81-1.00	Stellite 3, Haynes 188, Haynes 25, SPA (proprietary alloy)
1.01-1.20	Stellite 6K, Haynes 93, 25 Cr iron
1.21-1.40	Wrought Molybdenum, Stellite 31 with diffused B, Stellite 6 with diffused B
1.41-1.61	Stellite 3, HC-250, HR-37

WELD OVERLAYS were erosion tested (see B.2.1.3), but data are present only for 90° impingement angle at 20 °C. There were six cobalt-based weld alloys, four iron-based chromium alloys, one nickel-based and three composite weld alloys. All were only equal to or worse than the standard.

EROSION RESISTANCE was measured for eleven materials and is reported in Sections B.2.1.4-.14 and B.2.1.21-.22. At 25 °C and an impingement angle of 90°, Type 310 stainless steel erodes at a slightly lower rate than does Type 304 stainless steel (compare B.2.1.14 and B.2.1.21). At 25 °C, Type 304 erodes about twice as fast as Type 310 for all angles of impingement. At angles above 30° and for increased temperature above 25 °C, Type 310 erodes faster than the 25 °C rate, whereas Type 304 erodes more slowly. A chrome plate on steel tended to erode more slowly than Types 304 and 310 at 25 °C and at 500 °C (see B.2.1.5). The chrome plate on steel tends to erode more slowly than Types 304 and 310 and Inconel 671, for impingement angles of 10 to 90°. The erosion rate for 250 MS tends to decrease slightly as hardness increases from HR_c 37 to HR_c 52. For a variety of test conditions, Inconel 671 showed better erosion resistance than any of the other ten materials tested. Chromium metal showed slightly better than average resistance to erosion, whereas chromium plate on steel consistently showed much better than average erosion resistance.

A.2.4.2.2.3 EROSION/CORROSION

OVERVIEW

Erosion/corrosion occurs where hot gas corrosion and abrasive particle impingement can take place simultaneously. Hot gas corrosion in a coal conversion system usually involves reactions with sulfur or oxygen which may produce spalling oxides or sulfide scales. Reaction is influenced by gas composition, alloy composition, temperature, and pressure. Some variables which affect erosion include: type of erodent; erodent particle velocity; shape and hardness; angle of impingement; temperature of material impacted; condition (including hardness) of impacted material surfaces. Each of these variables is important in determining the rate at which an erosion process takes place. Erosion/corrosion can be especially harmful to components of coal conversion plants because of the cyclic nature of the processes. Once a scale is formed, it can be eroded away to present fresh surface to the hot corrosive gases which in time can form more scale which can erode away until the design function can no longer be fulfilled. Erosion/corrosion can be minimized by alloy selection which reduces the rate of hot gas corrosion and simultaneously reduces the rate of erosion. This means selecting non-reactive, hard alloys.

LABORATORY TESTS

EROSION/CORROSION EFFECTS on alloys under coal gasification conditions have been studied in a testing program to provide data for screening candidate materials and to investigate the parameters affecting the performance of the materials (see B.2.1.23-26). Test samples were subjected to erosion at a 45° impingement angle in a simulated coal gasification atmosphere (see Section B.0) except for two tests run in nitrogen. The variable parameters were temperature, pressure, H_2S concentration, particle velocity, particle size, and erodent. The particle size was -20 + 40 mesh for all erodents except in one test where a finer mesh was used. Specimens were measured by micrometer before and after exposure. The average corrosion loss of alloy (in mils) for the one side of the sample exposed to both erosion and corrosion was calculated from thickness measurements of uneroded areas. The maximum erosion/corrosion (Max E/C) loss (in mils) was calculated for the one side exposed to both erosion and corrosion from thickness measurements made in eroded areas and pits. In Sections B.2.1.23-26, both average corrosion and maximum erosion/corrosion losses have been reported with visual observations. For the following discussion, only the maximum erosion/corrosion loss is given. Values are for one specimen per test; some alloys were included in more than one test with the same conditions for reference purposes. The tests were all of rather short duration, 50 or 100 hours, one factor to keep in mind in examining the data.

REPRODUCIBILITY of the erosion/corrosion testing may be judged by looking at data for multiple samples run in the same test or in different tests under the same conditions. The following table lists multiple values of Max E/C in various tests for which the conditions were the same for any given test number. There are not multiplicate data for all the alloys tested.

Alloy	Max E/C, mils						
Test	1	2	3	4	5	6	7
Incoloy 800	130.1	39.7	50.9	27.4		74.1	12.8
	118.2	1.2	201.3	68.8		31.2	1.5
	1.0	0.7		44.4			7.6
	165.5			4.4			
Inconel 601	1.0	33.9		15.8			
	31.6	4.1		26.3			
310 SS	1.7	15.6		12.1			
	9.1	0.6		12.2			
	14.5			13.0			
Inconel 671	0.9	0.9	7.6	3.9	1.2	0.9	1.2
	0.9	0.8	1.1	0.8	1.3	1.7	1.1
	0.9	0.8		1.5			1.2
	1.1			8.2			
446 SS	5.6			18.6			
	11.9			10.4			
	1.2			15.9			
Haynes 188	0.5	17.1		2.5			
	0.7	1.1		1.5			
	0.2			0.7			
Incoloy 800 (Al)		4.5					
		0.8					
310 SS (Al)		3.6					
		0.5					
RA 333		22.9					
		1.2					
LM-1866		1.1					
		0.8					
Crutemp 25		9.7					
		0.8					
CoCrW No. 1		0.7					
		0.2					

It is obvious that there is an extremely wide disagreement between multiplicate values for some materials and good agreement for others. The data may be used to indicate trends but the numbers do not represent reliable values for material loss from erosion/corrosion effects. Some conclusions may be drawn as to the effect of varying the test conditions, but the poor reproducibility of the results for some of the alloys must be kept in mind.

THE EFFECT OF INCREASING TEMPERATURE on the loss of material due to erosion/corrosion should be indicated in the comparison of data from sets of tests in which the only parameter varied was the temperature. The following tables compare the Max E/C values for several sets of tests.

Test Conditions: pressure 1000 psi, particle velocity 100 ft/s, 50 hours, 1.0 percent H_2S, erodent coarse FMC char.

Alloy	Max E/C, mils		
	1500 °F	1650 °F	1800 °F
Incoloy 800	39.7, 1.2, 0.7	10.8	50.9, 201.3
Incoloy 800 (Al)	4.5, 0.8	5.4	1.1
Inconel 601	33.9, 4.1	53.3	36.2
310 SS	15.6, 0.6	2.0	25.3
310 SS (Al)	3.6, 0.5	0.7	2.9
RA 333	22.9, 1.2	11.0	14.9
LM-1866	1.1, 0.8	2.6	9.1
446 SS	10.7, 0.9	1.9	20.6
Inconel 671	0.9, 0.8, 0.8	3.8	7.6, 1.1
Crutemp 25	9.7, 0.8	5.5	23.9
Haynes 188	17.4, 1.1	49.8	75.7
Stellite 6B	0.2		1.1
Wiscalloy 30/50W	0.1		17.7
HK-40	1.3		1.8
Alloy X	0.6		122.8
Sanicro 32X	0.4		72.2
Multimet N155	0.7		147.6
Haynes 150	0.2		127.3
Thermalloy 63WC	0.8		52.3

Test Conditions: 1000 psi, gas velocity 10 ft/s, 100 hours, 1.0 percent H_2S, no solid erodent

Test Conditions: 1000 psi, gas velocity 100 ft/s, 100 hours, 1.0 percent H_2S, no solid erodent

Alloy	Max E/C, mils		Max E/C, mils	
	1650 °F	1800 °F	1650 °F	1800 °F
Incoloy 800	1.3	16.9	28.4	45.6
Incoloy 800 (Al)	1.4	0.8	1.4	1.3
Inconel 601	2.9	13.1	8.4	27.6
310 SS	1.9	1.9	8.7	8.0
310 SS (Al)	0.7	1.5	1.6	2.8
RA 333	29.1	12.9	23.3	56.6
LM-1866	1.0	2.9	0.6	23.0
446 SS	1.4	1.2	0.6	18.8
Inconel 671	10.4	0.6	28.7	2.1
Crutemp 25	1.2	1.6	19.5	6.1
Haynes 188	11.5	6.9	25.0	27.5

Test Conditions: atm pressure, particle velocity 100 ft/s, 100 hours, 1.0 percent H_2S, coarse Husky char

Test Conditions: 1000 psi, particle velocity 100 ft/s, 50 hours, 1.0 percent H_2S, coarse Husky char

Alloy	Max E/C, mils		Max E/C, mils	
	1650 °F	1800 °F	1650 °F	1800 °F
Incoloy 800	74.1,31.2	0.8,48.3	12.8,1.5,7.6	31.9
Incoloy 800 (Al)	0.5	3.5	3.1	1.5
Inconel 601	2.4	6.7	137.6	37.9
310 SS	1.8	0.7	2.4	10.7
310 SS (Al)	1.1	2.4	1.5	3.1
RA 333	0.8	2.3	63.5	46.6
LM-1866	0.2	3.3	1.1	13.9
446 SS	1.3	1.1	2.0	17.8
Inconel 671	0.9,1.7	0.6,0.8	1.2,1.1,1.2	72.4
Crutemp 25	1.2	0.3	3.8	27.1
Haynes 188	0.9	0.5	13.4	9.8

The normal expectation for the effect of increasing temperature on erosion/corrosion is to see a greater loss of material. The data show an increase in only about one half of the above cases, the rest of the data indicating either little change or a definite decrease in material loss. Since there is only one test of one sample for most of the results and the reproducibility is apparently quite poor for a number of the alloys, it is possible that further extensive testing might indicate a more definite trend but the present data are inconclusive.

PRESSURE EFFECTS can be seen in the comparison of tests made at atmospheric pressure and at 1000 psi with all other variable parameters kept constant.

Test Conditions: 1800 °F, gas velocity 100 ft/s, 100 hours, 1.0 percent H_2S, no erodent used

Test Conditions: 1800 °F, particle velocity 50 ft/s, 50 hours, 1.0 percent H_2S, coarse Husky char

Alloy	Max E/C, mils		Max E/C, mils	
	1 atmosphere	1000 psi	1 atmosphere	1000 psi
Incoloy 800	0.5	5.8	0.3	155.6
Incoloy 800 (Al)	1.2	1.5	0.6	1.6
Inconel 601	0.7	24.7	0.7	0.7
310 SS	0.6	1.7	0.7	10.5
310 SS (Al)	0.5	2.9	3.0	4.0

RA 333	0.4	26.7	0.7	5.1
LM-1866	0.5	1.4	0.4	3.5
446 SS	0.5	5.3	0.9	10.9
Inconel 671	0.7	1.9	1.0	7.8
Crutemp 25	0.7	3.7	0.5	9.7
Haynes 188	0.7	9.7	0.7	1.0

Although the degree of change in the amount of material lost is highly variable, it is apparent that there is definitely an adverse effect due to the increased pressure.

THE EFFECT OF VARIED HYDROGEN SULFIDE CONCENTRATION in the coal gasification atmosphere is not unequivocally defined by the data in the following tables.

Test Conditions: 1800 °F, 1 atmosphere, 100 ft/s, 100 hours, coarse FMS char

Test Conditions: 1800 °F, 1000 psi, 100 ft/s, 50 hours, coarse FMC char

Alloy	Max E/C, mils		Max E/C, mils	
	0.5% H_2S	1.0% H_2S	0.1% H_2S	1.0% H_2S
Incoloy 800	98.1	27.4,68.8,44.4,4.4	62.3	50.9, 201.3
Incoloy 800 (Al)	1.5	3.6	3.6	1.1
Inconel 601	1.8	15.8, 26.3	169.5	36.2
310 SS	1.9	12.1, 12.2, 13.0	8.1	25.3
310 SS (Al)	2.0	1.5	3.6	2.9
RA 333	0.6	5.7	8.1	14.9
LM-1866	5.6	14.4	0.8	9.1
446 SS	1.3	18.6, 10.4, 15.9	9.1	20.6
Inconel 671	0.7	3.9, 0.8, 1.5, 8.2	1.1	7.6, 1.1
Crutemp 25	0.9	10.9	64.4	23.9
Haynes 188	1.2	2.5, 1.2, 0.7	2.0	75.7

Test Conditions: 1800 °F, 1 atmosphere, particle velocity 100 ft/s, 50 hours, dolomite erodent

Test Conditions: 1800 °F, 1 atmosphere, particle velocity 100 ft/s, 50 hours, alumina erodent

Alloy	Max E/C, mils		Max E/C, mils	
	0.1% H_2S	1.0% H_2S	0.5% H_2S	1.0% H_2S
Incoloy 800	0.8	0.6	15.0	1.7
Incoloy 800 (Al)	0.8	0.6	0.8	5.4
Inconel 601	0.3	0.5	7.7	2.2
310 SS	0.3	0.5	20.2	0.8
310 SS (Al)	1.2	1.0	1.5	1.9

RA 333	0.4	0.5	11.4	1.2
LM-1866	0.1	0.7	1.8	2.9
446 SS	0.4	0.6	1.7	2.2
Inconel 671	0.8	0.8	3.0	1.6
Crutemp 25	0.3	0.6	16.0	1.9
Haynes 188	0.4	0.6	1.2	1.0
CoCrW No. 1			0.2	1.6

The results for the above tests are mixed, the nature of the erodent and the specific alloy influencing the trends. For the tests with char as the erodent, the data appear to indicate a general increase of erosion/corrosion degradation with increasing H_2S concentration. There are anomalies in the data corresponding to similar anomalous behavior found in the hot gas corrosion tests (see Section A.2.4.2.2.1). The tests with dolomite erodent in the coal gasification atmosphere indicate no real effect of varying the H_2S concentration, whereas testing under the same conditions with alumina erodent show mixed behavior, a large number of alloys having a marked decrease in material loss at the higher H_2S concentration.

THE RESULT OF INCREASING PARTICLE VELOCITY is generally, as expected, the increase of material loss. As is the case with all of the tests, there are anomalies, some of which may be explained on the basis of the apparent poor reproducibility for some alloys. A number of tests were performed which permit examination of the effect of particle velocity, all other variables being held constant.

Test Conditions: 1800 °F, 1 atmosphere, 50 hours, 1.0 percent H_2S, alumina erodent.

Alloy	Max E/C, mils			
	50 ft/s	100 ft/s	160 ft/s	200 ft/s
Incoloy 800	5.8	1.7	46.8	84.1
Incoloy 800 (Al)	8.9	5.4	1.3	49.6
Inconel 601	0.7	2.2	33.6	77.2
310 SS	2.5	0.8	38.8	57.0
310 SS (Al)	1.3	1.9	1.2	43.6
RA 333	7.6	1.2	51.4	60.2
LM-1866	1.3	2.9	4.4	12.3
446 SS	1.5	2.2	5.2	33.4
Inconel 671	0.5	1.6	1.7	24.0
Crutemp 25	14.0	1.9	43.3	141.4
Haynes 188	1.2	1.0	11.3	82.5

	est Conditions: 1800 °F, 1 atosphere, 100 hours, 1.0 percent $_2$S, coarse FMC char		Test Conditions: 1800 °F, 1000 psi, 50 hours, 1.0 percent H_2S, coarse FMC char	
lloy	Max E/C, mils		Max E/C, mils	
	50 ft/s	100 ft/s	50 ft/s	100 ft/s
ncoloy 800	2.3	27.4, 68.8, 44.4, 4.4	33.6	50.9, 201.3
ncoloy 800 (Al)	5.6	3.6	1.9	1.1
nconel 601	12.1	15.8, 26.3	135.1	36.2
10 SS	6.8	12.1, 12.2, 13.0	5.0	25.3
10 SS (Al)	2.6	1.5	1.3	2.9
A 333	19.4	5.7	90.4	14.9
M-1866	2.7	14.4	16.9	9.1
46 SS	3.9	18.6, 10.4, 15.9	7.3	20.6
nconel 671	0.5	3.9, 0.8, 1.5, 8.2	2.5	7.6, 1.1
rutemp 25	2.3	10.9	1.7	23.9
aynes 188	7.9	2.5, 1.5, 0.7	106.0	75.7

	Test Conditions: 1650 °F, 1000 psi, 100 hours, 1.0 percent H_2S, no solid erodent		Test Conditions: 1800 °F, 1000 psi, 100 hours, 1.0 percent H_2S, no solid erodent	
Alloy	Max E/C, mils		Max E/C, mils	
	10 ft/s	100 ft/s	10 ft/s	100 ft/s
Incoloy 800	1.3	28.4	16.9	45.6
Incoloy 800 (Al)	1.4	1.4	0.8	1.3
Inconel 601	2.9	8.4	13.1	27.6
310 SS	1.9	8.7	1.9	8.0
310 SS (Al)	0.7	1.6	1.5	2.8
RA 333	29.1	23.3	12.9	56.6
LM-1866	1.0	0.6	2.9	23.0
446 SS	1.4	0.6	1.2	18.8
Inconel 671	10.4	28.7	0.6	2.1
Crutemp 25	1.2	19.5	1.6	6.1
Haynes 188	11.5	25.0	6.9	27.5

Test Conditions: 1800 °F, 1 atmosphere, 50 hours, 1.0 percent H_2S, coarse Husky char

Test Conditions: 1800 °F, 1000 psi, 50 hours, 1.0 percent H_2S, coarse Husky char

Alloy	Max E/C, mils		Max E/C, mils	
	50 ft/s	100 ft/s	50 ft/s	100 ft/s
Incoloy 800	0.3	0.6	155.6	31.9
Incoloy 800 (Al)	0.6	3.5	1.6	1.5
Inconel 601	0.7	0.6	0.7	37.9
310 SS	0.7	0.5	10.5	10.7
310 SS (Al)	3.0	0.9	4.0	3.1
RA 333	0.7	0.4	5.1	46.6
LM-1866	0.4	1.7	3.5	13.9
446 SS	0.9	0.8	10.9	17.8
Inconel 671	1.0	1.3	7.8	72.4
Crutemp 25	0.5	1.2	9.7	27.1
Haynes 188	0.7	0.6	1.0	9.8

Examination of the above data does bear out the expected increase of erosion/corrosion loss with increasing particle velocity for most of the materials tested.

TESTING FOR THE EFFECT OF PARTICLE SIZE using coarse (-20 + 40 mesh, 840 to 420 µm) and fine (-100 + 140 mesh, 149 to 105 µm) FMC char indicated that there is little overall difference in the data for the two tests.

Test Conditions: 1800 °F, 1 atmosphere, particle velocity 100 ft/s, 100 hours, 1.0 percent H_2S, FMC char.

Alloy	Max E/C, mils	
	Coarse	Fine
Incoloy 800	27.4, 68.8, 44.4, 4.4	25.6
Incoloy 800 (Al)	3.6	5.6
Inconel 601	15.8, 26.3	5.7
310 SS	12.1, 12.2, 13.0	14.8
310 SS (Al)	1.5	4.6
RA 333	5.7	13.3
LM-1866	14.4	16.8
446 SS	18.6, 10.4, 15.9	15.5
Inconel 671	3.9, 0.8, 1.5, 8.2	7.0
Crutemp 25	10.9	11.9
Haynes 188	2.5, 1.5, 0.7	5.3

The results are mixed and there is no reliable trend to indicate a efinite effect of particle size.

<u>THE PARTICULAR ERODENT MATERIAL</u> might be expected to affect the rosion/corrosion metal loss. Various materials, Husky char, FMC char, lumina, and dolomite were used as erodents. Some testing was done ithout adding solid erodent to see the effect of the impinging gas tream by itself.

est Conditions: 1800 °F, 1 atmosphere, gas or particle velocity 00 ft/s, 100 hours, 1.0 percent H_2S.

lloy	Max E/C, mils		
	No Erodent	Husky Char	FMC Char
ncoloy 800	0.5	0.8, 48.3	27.4, 68.8, 44.4, 4.4
ncoloy 800 (Al)	1.2	3.5	3.6
nconel 601	0.7	6.7	15.8, 26.3
10 SS	0.6	0.7	12.1, 12.2, 13.0
10 SS (Al)	0.5	2.4	1.5
A 333	0.4	2.3	5.7
M-1866	0.5	3.3	14.4
46 SS	0.5	1.1	18.6, 10.4, 15.9
nconel 671	0.7	1.2, 1.3	3.9, 0.8, 1.5, 8.2
rutemp 25	0.7	0.7	10.9
aynes 188	0.7	0.8	2.5, 1.5, 0.7

est Conditions: 1800 °F, 1 at- osphere, particle velocity 100 t/s, 50 hours, 1.0 percent H_2S

Test Conditions: 1800 °F, 1 atmosphere, particle velocity 50 ft/s, 50 hours, 1.0 percent H_2S

lloy	Max E/C, mils			Max E/C, mils	
	Alumina	Dolomite	Husky Char	Alumina	Husky Char
ncoloy 800	1.7	0.6	0.6	5.8	0.3
ncoloy 800 (Al)	5.4	0.6	3.5	8.9	0.6
nconel 601	2.2	0.5	0.6	0.7	0.7
10 SS	0.8	0.5	0.5	2.5	0.7
10 SS (Al)	1.9	1.0	0.9	1.3	3.0
A 333	1.2	0.5	0.4	7.6	0.7
M-1866	2.9	0.7	1.7	1.3	0.4
46 SS	2.2	0.6	0.8	1.5	0.9
nconel 671	1.6	0.8	1.3	0.5	1.0
rutemp 25	1.9	0.6	1.2	14.0	0.5
aynes 188	1.0	0.6	0.6	1.2	0.7

<u>Test Conditions</u>: 1650 °F, 1 atmosphere, particle velocity 100 ft/s, 100 hours, 1.0 percent H_2S

<u>Test Conditions</u>: 1650 °F, 1000 psi, particle velocity 100 ft/s, 50 hours, 1.0 percent H_2S

Alloy	Max E/C, mils		Max E/C, mils	
	Husky char	FMC char	Husky char	FMC char
Incoloy 800	74.1, 31.2	130.1, 118.2, 1.0, 165.5	12.8, 1.5, 7.6	10.8
Incoloy 800 (Al)	0.5	0.9	3.1	5.4
Inconel 601	2.4	1.0, 31.6	137.6	53.3
310 SS	1.8	1.7, 9.1, 14.5	2.4	2.0
310 SS (Al)	1.1	1.2	1.5	0.7
RA 333	0.8	0.5	63.5	11.0
LM-1866	0.2	7.0	1.1	2.6
446 SS	1.3	5.6, 11.9, 1.2	2.0	1.9
Inconel 671	0.9, 1.7	0.9, 0.9, 0.9, 1.1	1.2, 1.1, 1.2	3.8
Crutemp 25	1.2	0.6	3.8	5.5
Haynes 188	0.9	0.5, 0.7, 0.2	13.4	49.8
Stellite 6B	0.8	0.6		
Wiscalloy 30/50W	0.7	3.0		
HK-40 SS	0.8	6.2		
Alloy X	5.8	22.6		
Sanicro 32X	4.0	113.8		
Multimet N155	21.3	3.2		
Haynes 150	3.0	0.7		
Supertherm T63WC	0.8	4.7		
HL-40 SS	2.5	4.0		
329 SS	2.0	1.6		

<u>Test Conditions</u>: 1800 °F, 1000 psi, particle velocity 50 ft/s, 50 hours, 1.0 percent H_2S

<u>Test Conditions</u>: 1800 °F, 1000 psi, particle velocity 100 ft/s, 50 hours, 1.0 percent H_2S

Alloy	Max E/C, mils		Max E/C, mils	
	Husky char	FMC char	Husky char	FMC char
Incoloy 800	155.6	33.6	31.9	50.9,201.3
Incoloy 800 (Al)	1.6	1.9	1.5	1.1
Inconel 601	0.7	135.1	37.9	36.2
310 SS	10.5	5.0	10.7	25.3
310 SS (Al)	4.0	1.3	3.1	2.9
RA 333	5.1	90.4	46.6	14.9
LM-1866	3.5	16.9	13.9	9.1
446 SS	10.9	7.3	17.8	20.6
Inconel 671	7.8	2.5	72.4	7.6, 1.1
Crutemp 25	9.7	1.7	27.1	23.9
Haynes 188	1.0	106.0	9.8	75.7

Some trends may be seen in the above data. An obvious, and expect- l, result is that the least erosion/corrosion occurs when the impinging s carries no solid erodent as compared with tests in which char is esent. Also to be expected is that the larger metal loss occurs when umina is used as an erodent as compared with either dolomite or char, nce alumina, commonly used as abrasive, is much harder than the other o materials. In comparing the results for the two different chars, e situation is not clear cut. In some tests the FMC char appears to use greater metal loss but examination of all the tests does not yield definitive result. Compare Section B.1.1.58, in which data appear for me of these same alloys in tests conducted in coal gasification mospheres in which the alloys were in static contact with the same two ars used in these erosion/corrosion tests. The FMC char, with a igher sulfur content, had a much greater corrosive effect than did the sky.

EFFECT OF PREOXIDATION ON EROSION/CORROSION RESISTANCE was tested n coal gasification atmospheres without an erodent in the impinging gas tream (B.2.1.25). Eleven alloys were tested. Variable test conditions ere the same for untreated and preoxidized samples (1800 °F, 1000 psi, mpinging gas stream 100 ft/s, 1.0 percent H_2S, and 100 hr duration). reoxidation treatment consisted of exposure to the coal gasification tmosphere for 24 hours with no H_2S present. For three of the alloys, luminized Incoloy 800, aluminized 310 SS, and Inconel 671, there was no eal change in the average corrosion values (all less than one mil) or ax E/C values (all less than three mils) for samples exposed and nexposed to preoxidation conditions. The difference was marked for the ther eight alloys as given in the following table.

lloy	Max E/C, mils		Average Corrosion, mils	
	Unoxidized	Preoxidized	Unoxidized	Preoxidized
ncoloy 800	45.6	5.8	17.6	0.8
nconel 601	27.6	24.7	8.7	1.7
10 SS	8.0	1.7	0.5	0.7
A 333	56.6	26.7	29.6	3.7
M-1866	23.0	1.4	1.1	0.4
46 SS	18.8	5.3	1.3	0.3
rutemp 25	6.1	3.7	1.1	0.7
aynes 188	27.5	9.7	1.0	2.7

The corrosion losses tabulated above indicate that pre-oxidation in n atmosphere containing water vapor is generally beneficial in reducing he amount of corrosion loss for hot gas corrosion as well as for rosion/corrosion. The formation of a continuous adherent protective xide film seems to occur when at least 30 ± 10 percent water vapor is in the atmosphere regardless of the hydrogen sulfide content (see Section A.2.4.2.2.1, subsections on SCALE FORMATION and ALLOY DEVELOPMENT). This suggests that the corrosion losses tabulated above would be much higher if water vapor were not present in the impinging gas stream.

The same beneficial effect of water vapor is demonstrated in a set of tests in which the atmosphere contained no simulated coal gasification components but which consisted of nitrogen or nitrogen with 40 percent water (B.2.1.23). The tests were run at 1800 °F and atmospheric pressure, coarse FMC char was the erodent at a velocity of 100 ft/s for 100 hours.

Alloy	Max E/C, mils		Ave. Corr., mils	
	N_2	N_2 + 40% H_2O	N_2	N_2 + 40% H_2O
Incoloy 800	3.2	0.9	0.7	0.5
Incoloy 800 (Al)	2.1	1.1	0.2	0.7
Inconel 601	1.3	6.9	0.3	0.4
310 SS	1.1	0.3	0.2	---
310 SS (Al)	5.1	2.8	0.7	0.9
RA 333	1.7	1.0	0.7	0.5
LM-1866	3.5	0.4	1.5	0.2
446 SS	3.0	4.3	1.5	3.7
Inconel 671	1.6	1.2	0.6	0.7
Crutemp 25	1.1	0.6	0.1	0.3
Haynes 188	1.8	0.5	0.4	---

Although Inconel 601 and 446 SS show greater metal loss in the atmosphere with water vapor and the data for the average corrosion for all the alloys are not unequivocal, it would appear in the light of the discussion of Section A.2.4.2.2.1 that one may place a favorable interpretation on the trend of the above data with respect to the presence of water vapor.

There is no way to make an estimate of the effect of time of exposure since there are no pairs of tests in which the only varied parameter was the test time.

RANKING OF THE ALLOYS WITH RESPECT TO EROSION/CORROSION RESISTANCE is not straightforward with the existing data. The lack of multiplicate data for all the alloys, the poor reproducibility apparent for at least some alloys, the lack of clear-cut trends for the effect of most of the variables, and the variability of the response of the alloys to changes in the test conditions make any ranking a very arbitrary procedure. A ranking of sorts may be obtained by examining alloys in terms of consistency of performance in all tests. The following table ranks the alloys using the data from all the tests, under all the conditions, by listing the number of tests in which the Max E/C values fell above or below a given, arbitrarily chosen, value. It must be kept in mind that the variables in these tests are mixed, including the test time which was either 50 or 100 hours.

loy	Number of Test Values in Max E/C Range		Total Number of Test Values
	0-5.9 mils	> 6.0 mils	
nconel 671	38	8	46
ncoloy 800 (Al)	32	2	34
10 SS (Al)	30	4	34
-1866	26	8	34
46 SS	26	12	38
aynes 188	24	14	38
rutemp	22	12	34
10 SS	22	16	38
333	16	18	34
nconel 601	16	20	36
ncoloy 800	19	27	46

The alloys listed above are those which were tested in all of the ests. The following table gives those alloys which had received mini- al testing during the time period of the tests covered in this book.

lloy	Number of Test Values in Max E/C Range		Total Number of Test Values
	0-5.9 mils	> 6.0 mils	
oCrW No. 1	11	0	11
tellite 6B	8	0	8
aynes 150	7	1	8
upertherm T63WC	6	2	8
L-40	5	0	5
29 SS	5	0	5
K-40	5	2	7
iscalloy 30/50W	5	2	7
ultimet N155	5	3	8
anicro 32X	4	4	8
lloy X	4	4	8

The "ranking" in the two preceding tables must be viewed with xtreme caution. Further testing must be carried out, and the reasons and perhaps solutions) sought for the poor reproducibility of results or some alloys. The above order in which the alloys are listed may be hanged dramatically by further testing.

COATINGS FOR EROSION/CORROSION PROTECTION are being investigated. efractory coatings on several substrates have been tested to determine heir effectiveness in providing erosion/corrosion protection to alloys nder coal gasification conditions (see B.2.3.2 and B.2.3.3). The simulated coal gasification conditions provided a gas composition close to that given in Section B.0, the test temperature was 980 °C and the pressure was 240 kPa. FMC char was the erodent with a particle velocity of 39 m/s. Maximum time for the tests was 100 hours with shorter runs of 17, 33, and 50 hours. The coatings were alumina, chromia, alumina-chromia, CaO-stabilized zirconia, and magnesium zirconate. The alloy substrates were 304 and 310 stainless steels and Incoloy 800. Each sample had a base coat of NiCrAl. After exposure, samples were examined visually, by weighing to determine the weight loss due to erosion, and microscopically to determine coating thickness. The only coating which survived the runs was the magnesium zirconate, which showed no weight loss, no coating failure, retained coating even on the eroded sample face, and exhibited only the beginning of spalling after 100 hours on the 304 SS samples. The samples with zirconia coatings lost less weight but did not exhibit better performance or hold up any better than the other coatings, all of which failed, lost weight, and spalled.

A.2.4.2.2.4 MECHANICAL PROPERTIES

OVERVIEW

The mechanical properties of structural materials which are of interest for metal internal components include stress rupture and creep properties, tensile properties, low-cycle fatigue, hardness, and impact properties. Mechanical properties at 1200-1800 °F are especially of interest, since metal internal components operate at service temperatures in this range. Under conditions of hot gas corrosion, it is possible that degradation of the load bearing capacity of an alloy could result from surface scaling and pitting and/or internal chemical reactions following inward diffusion of components of the gas atmosphere. Moreover, prolonged times at high temperatures could result in changes in the metallurgical structure of an alloy through diffusion processes which could promote embrittlement that, in turn, reduces tensile ductility, stress rupture and creep life, fatigue life, and impact toughness. It is expected that the influence of a coal conversion environment on mechanical properties would vary from alloy to alloy and with the conditions of exposure. The alloys of interest for metal internal components include those with good resistance to hot gas corrosion and good elevated temperature mechanical properties.

LABORATORY TESTS

UNIAXIAL AND BIAXIAL STRESS RUPTURE TESTS were carried out on ten alloys to determine the rupture life. Data from uniaxial tests appear in Sections B.3.1.13-.14, and rankings appear in Section B.3.1.15. The rankings show that Stellite 6B supports the highest stress for a 1000-hour stress rupture life test. The next most favorable materials for 1000-hour stress rupture lives are Haynes 188 and HK-40 SS. Data from biaxial tests on five alloys appear in Section B.3.1.25, and the analysis of performance appears in B.3.1.26. The analysis of performance is presented graphically in terms of a rupture parameter, which equals the absolute temperature multiplied by a constant plus the log of the rupture time. Best performance is shown by Incoloy 800H and 800H Al. The effect of exposure to a coal gasification atmosphere was to reduce the biaxial stress rupture life for the five alloys investigated.

LOW-CYCLE FATIGUE DATA were measured on three alloys at 1500 and 1800 °F (see B.3.1.16). The alloys studied were 310 stainless steel, Incoloy 800H and INCO 657. Results in section B.3.1.16 show that at both temperatures, the number of cycles to failure decreases with increasing tensile stress holding time for 310 stainless and Incoloy 800H. The data for INCO 657 do not show this same trend. These alloys were not exposed to a coal gasification atmosphere.

UNIAXIAL TENSILE PROPERTIES of several alloys have been measured after exposure to a coal gasification atmosphere. Structural metal, welded alloys, and weld overlays have been evaluated. Structural metal data appear in Sections B.3.1.9-.12, B.3.1.22-.24, B.3.1.27, and B.3.1.31. Data on welded alloys appear in Section B.3.1.13, and data on weld overlays appear in Sections B.3.1.1-.7.

Results of elevated temperature tests on 18-18-2, Incoloy 800, 310 stainless steel, and Inconel 671 after exposure to two different coal gasification atmospheres appear in Sections B.3.1.9-.10 and in Figures

A.2.4.2.2.4a through e. Included in these figures for comparison is a reference value from unexposed specimens tested under the same conditions.

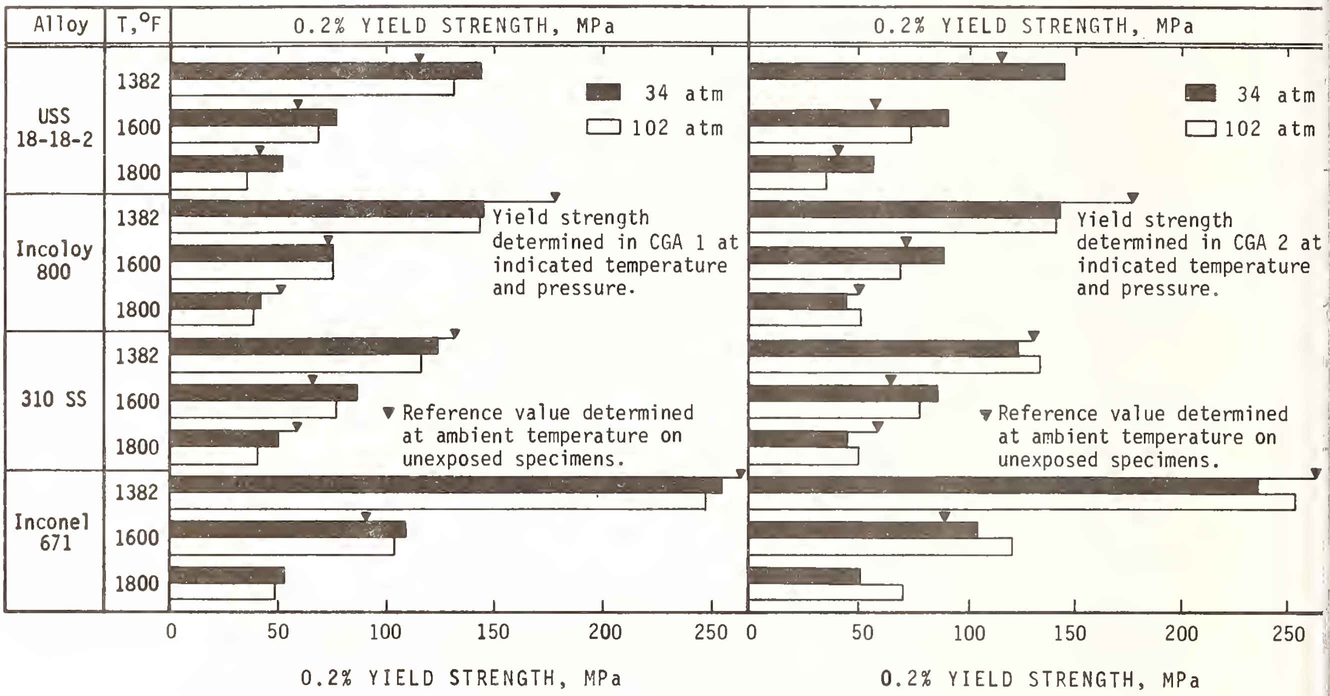


Figure A.2.4.2.2.4a

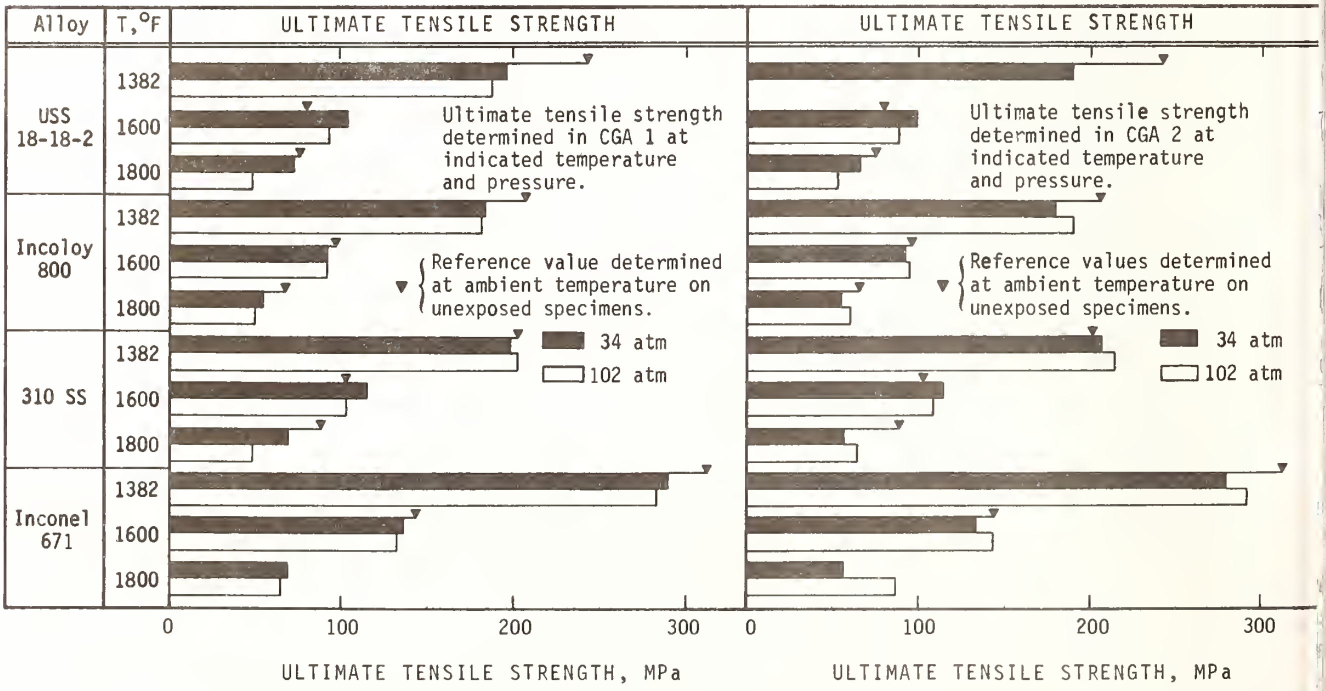


Figure A.2.4.2.2.4b

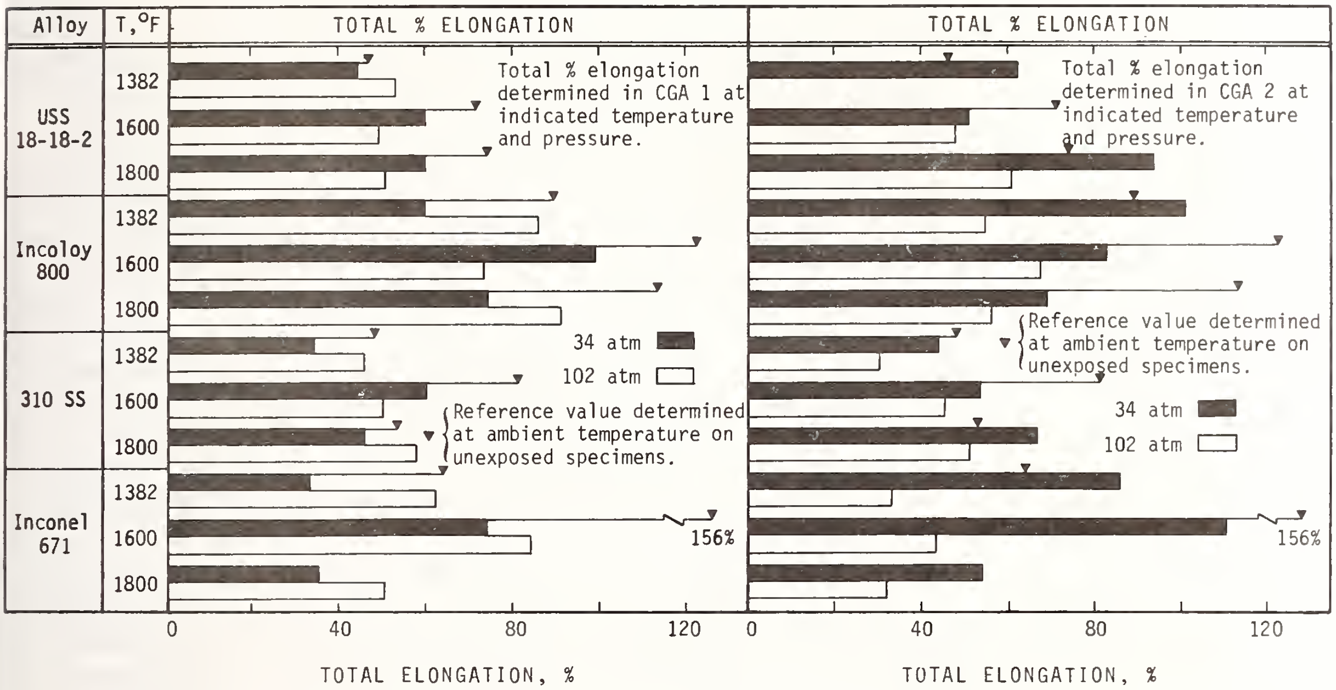


Figure A.2.4.2.2.4c

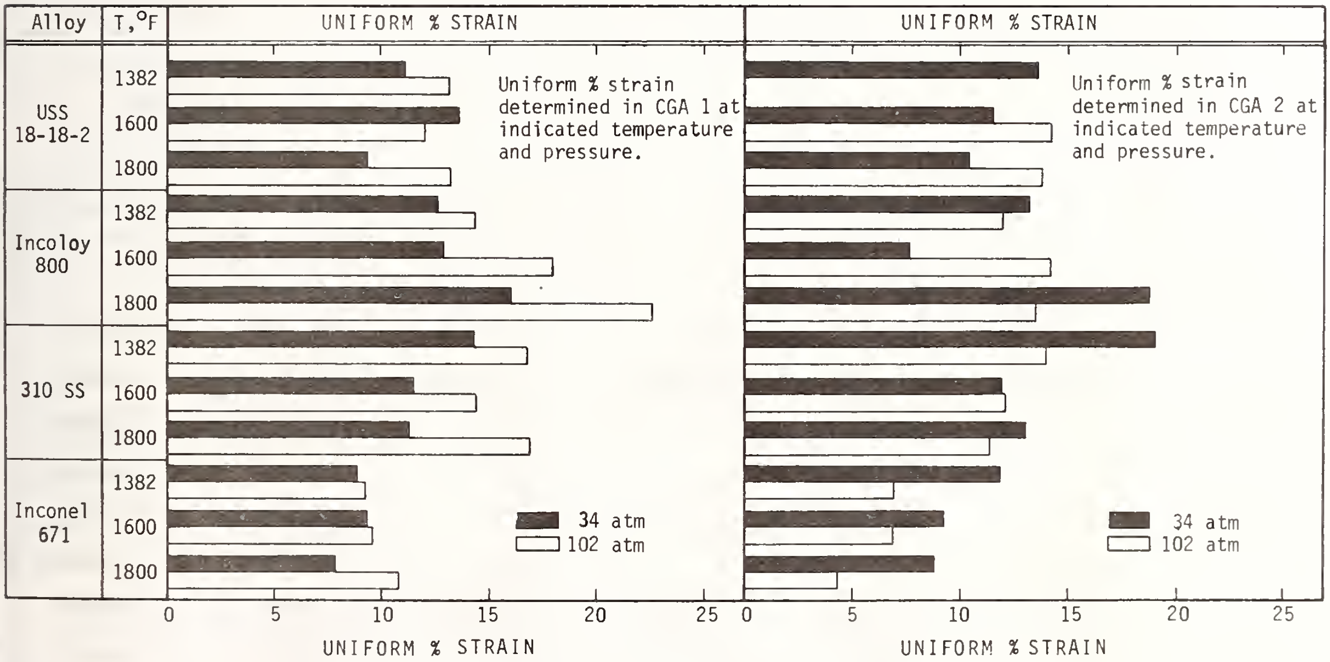


Figure A.2.4.2.2.4d

In general, these results show that a 100-hour exposure to the coal gasification atmospheres does not significantly affect the stability of the tensile properties of the four alloys tested. Property changes are small but, nevertheless, noticeable. Properties showed both increases and decreases. In general, elongation changed more than strength. For example, the maximum change in total elongation was a 50 percent decrease, whereas the maximum change in yield strength was a 30 percent increase. Most of the observed changes in tensile properties were smaller, e.g., ± 10 percent. Figures A.2.4.2.2.4a and b show that the yield and tensile strength of each alloy decreased with increasing temperature. The elongation, Figures A.2.4.2.2.4c and d, shows a mixed response to increasing temperature for all four alloys. In some cases, it increased and, in others, it decreased. These results are the same as for unexposed specimens tested in vacuum (see B.3.1.8), indicating that exposure to typical coal gasification atmospheres for 100 hours does not have a major effect on the temperature dependence of tensile properties for these alloys.

Figures A.2.4.2.2.4a and b show that effects of the pressure of the coal gasification atmospheres, 500 vs. 1500 psi, on the observed strength changes, were small. Strength-change differences between the 500 and 1500 psi tests were about ± 10 percent. Elongation-change differences between the 500 and 1500 psi tests were somewhat larger, i.e., about ± 20 percent.

Some 1000-hour aging treatments in vacuum were carried out at 1382, 1600 and 1800 °F on some untreated test specimens to facilitate a comparison of tensile property changes due to aging and to typical coal gasification atmospheres (see B.3.1.10). Exposure times were 1000 hours in vacuum and in the coal gasification atmospheres. Two coal gasification atmospheres were used at pressures of 500 and 1500 psi. The gas compositions for each combination of pressure and temperature appear in section B.3.1.10. Hydrogen sulfide ranged between one and two percent, and was closer to one percent for atmosphere number 2. Specimen design conformed to ASTM Designation E8. Specimens were pulled to fracture

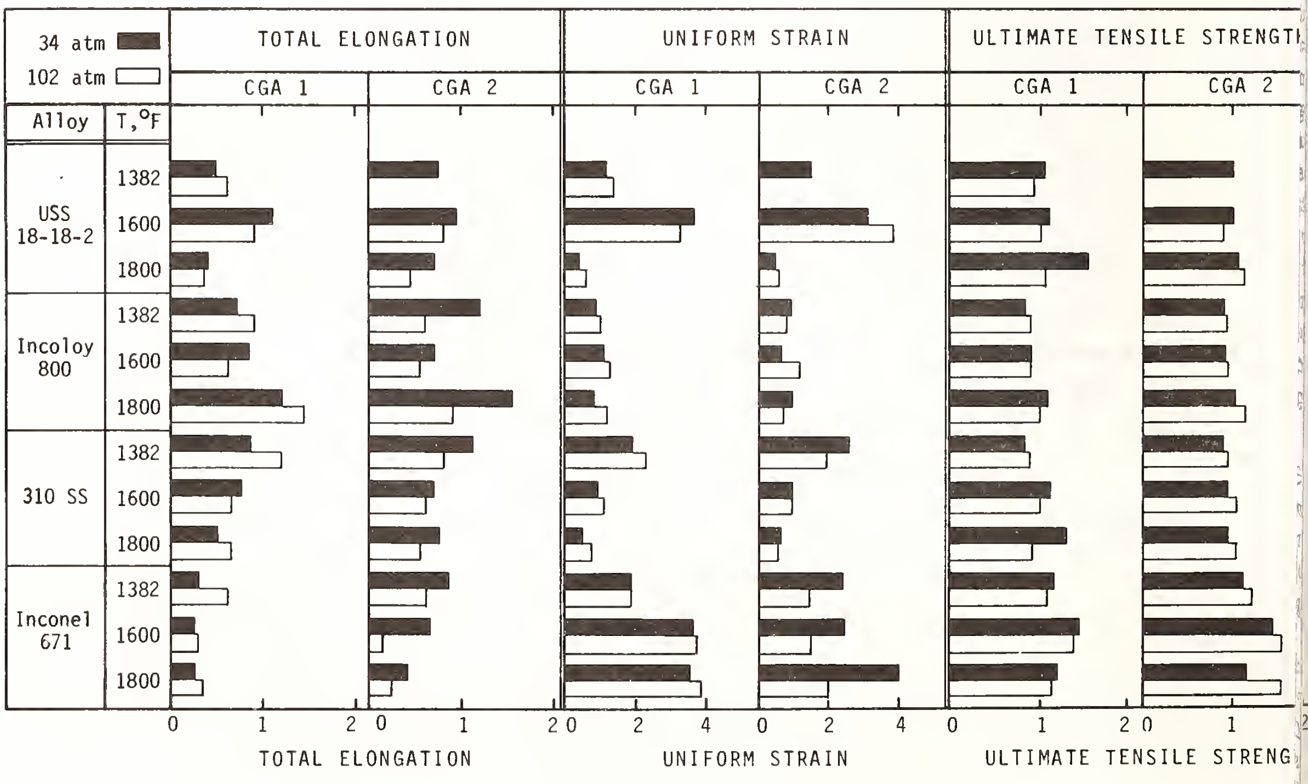


Figure A.2.4.2.2.4e

under dry flowing argon in a constant cross-head speed testing machine. Properties measured were ultimate tensile strength, uniform strain, and total elongation.

Test results appear in Figure A.2.4.2.2.4e. The ratio of the property of the exposed specimen to the property of the aged specimen has been plotted. Values greater than one indicate an increase in the property of the exposed specimen relative to the aged specimen, and vice-versa. In general, the ratio for uniform strain showed a greater change with exposure than did the ratios for total elongation and tensile strength. Inconel 671 and 18-18-2 showed the largest increases in the ratio for uniform strain, with the largest ratio being 4.9. About half the tests for uniform strain showed a decrease in the ratio, with the lowest ratio being 0.4.

<u>WELDED ALLOYS</u> were tested to determine tensile properties of welds at various temperatures after a 1000-hour exposure at elevated temperature to air or a coal gasification atmosphere (Section B.3.1.8). Fractures occurred in base metal more often than in weld metal, which prevented accurate determination of how environmental effects influence the tensile properties of weld metal. The alloys tested were: Incoloy 800H, Incoloy 800H Al, 310 stainless steel, RA 333, Haynes 188, and INCO 657. In the two cases where fracture occurred in the weld metal, Incoloy 800H Al showed good strength and ductility, and Haynes 188 showed excellent strength and ductility. The strength and ductility of Haynes 188 remained at a high level following a 1000-hour exposure to a coal gasification atmosphere. Tensile properties of the base metals appear in Section B.3.1.21 for comparison.

<u>WELD OVERLAYS</u> were tested to determine room temperature tensile properties of the overlay after a 1000-hour exposure to a coal gasification atmosphere at 1800 °F. Results appear in Sections B.3.1.1-.3. As a rule, yield strength, tensile strength, and elongation decreased significantly following exposure. This was so for both single and double overlays. R139 filler metal deposited on 310 stainless showed the least loss in elongation. Another good performer was Inconel filler metal 72 on 310 stainless steel. Hardness tests (see B.3.1.4) were also carried out on the exposed overlay specimens after exposure. Hardness showed mixed changes following exposure. Room temperature bend tests carried out on overlays of Inconel filler metal 72, R139 filler metal, and ER 309 showed that tensile elongation in the outer fibers ranged between 14 and 28 percent for each filler. None of these overlays was exposed to a coal gasification atmosphere.

<u>SOME TENSILE DATA ON UNEXPOSED ALLOYS</u> are included in Sections B.3.1.32-.34 and B.3.1.39. Although test specimen material was not exposed to a coal gasification atmosphere, the tests were carried out in air at temperatures comparable with the operating temperatures of metal internal components, 1500 and 1800 °F. Results in Section B.3.1.32 show a good combination of strength and ductility for Ni-30Cr-4Ti and Nimonic 81. In Section B.3.1.39, which lists tensile properties of seven experimental chromium-aluminum-silicon alloys, good combinations of strength and ductility at room temperature were shown by 18Cr-6Al-0.5Si-bal iron and 16Cr-4Al-0.5Si-4Mo-bal iron. However, these alloys and most others listed in Section B.3.1.39 lost most of their strength at 1600 and 1800 °F.

SOME SLOW STRAIN RATE TENSILE TESTS were carried out on Incoloy 800, Inconel 671, and 310, 310S, 347, 309, and 446 stainless steels which were exposed to oxidizing/sulfidizing and oxidizing/sulfidizing/carburizing coal gasification atmospheres at temperatures up to 1100 °F. Data appear in Sections B.3.1.22-.24, B.3.1.27, and B.3.1.31. In some cases, e.g., 310 stainless steel at 450 °C, changing atmosphere did not affect elongation to failure significantly, whereas in others it did, e.g., 446 stainless steel at 600 °C. This generalization is also true for changing temperature between 450 and 600 °C. In no case did elongation drop below eight percent. The largest elongations were in the range 40 to 60 percent. Ultimate tensile strengths ranged from 63 to 82 ksi for these materials. In some tests, cracking occurred, which was directly attributable to the reactive environment; in other tests, cracking occurred without an assist from the environment. A tabulation of tensile properties as affected by the coal gasification atmosphere appears in Section B.3.1.31. Type 446 stainless steel showed the most significant change in elongation due to variation in environment.

HARDNESS DATA were measured on six alloys to determine the effect on Rockwell hardness of a 1000 hour exposure at 1200, 1500, and 1800 °F to a coal gasification atmosphere (see B.3.1.18). Hardness was measured for base metal and weld metal. The results show a trend toward a slight increase in hardness following exposure to a coal gasification atmosphere. In another series of hardness tests to determine the effect of exposure to char on hardness of eleven alloys (see B.3.1.17), there was no effect within the reproducibility of the measurement.

CHARPY IMPACT ENERGIES were measured on six alloys to determine the effect of a 1000 hour exposure at 1200, 1500, and 1800 °F on the Charpy impact energy. Measurements were made on base metal and weld metal (Sections B.3.1.19-.20). The results show a significant decrease in Charpy energies for all six alloys. Despite a significant decrease, Incoloy 800H and 310 stainless steel base metals retained a significant level of Charpy impact energy, 117.3 and 74 ft-lbs., respectively. Charpy impact energy for the weld metals was significantly lower, in the range one to 38 ft-lbs.

ABLE OF CONTENTS

Sections included in this issue.

.3.1.1 OPERATING REQUIREMENTS

Product gases leave the gasifier at high temperatures and pressures, o to 1,800 °F (1,255 K) and 1,500 psi depending on the process. They will ontain some or all of the potentially corrosive and erosive constituents numerated in Section A.2.2.1. Removal of solid materials is necessary o minimize their erosive effects in downstream components and to comply ith air pollution standards.

Hot gas clean-up generally utilizes cyclones for solids separation t or near the product gas temperature and pressure. Present technology as not been established for such conditions. Possible problem areas nclude erosion, deposition and high temperature corrosion (carburizing, ulfidizing, hydrogen reaction, or temper embrittlement) for metal omponents in the gasifier overhead lines and cyclones. Refractory inings may reduce these problems if they can take the stresses without xcessive cracking and spalling.

Cold gas clean-up is a more advance technology than the hot gas rocedure. The product gas is first passed through a heat exchanger for hermal efficiency and its temperature reduced to about 600 °F (589 K). he solids and much of the chemical impurities are then removed in a wet crubber system (water quench system) (see Section A.3.2.1).

A.3.1.2.1.2 MATERIALS EVALUATION

The operating conditions for some cyclones may be comparable to those for metal internal components. Materials must stand up to hot gas corrosion, particulate erosion and erosion/hot gas corrosion. Data on materials suitable for application under these conditions appear in Section A.2.4.2.2.

.3.2.1 OPERATING REQUIREMENTS

Removal of the erosive particles and corrosive chemical impurities from he product gas is necessary to prolong the lifetime of downstream components nd to meet air pollution standards. Cold gas clean-up generally involves eat recovery through a heat exchanger followed by a water scrubber quench.

The erosive and corrosive product gas stream (described in Section A.2.2.1) ould enter the heat exchanger at temperatures and pressures approximating the asifier exit conditions and leave at temperatures in the 600-800 °F range 589-699 K). The major problems will be erosion and hot corrosion as denoted n Section A.3.1.1. Wet corrosion should not be a problem except during hutdown periods. High alloy steels or cladding will probably be necessary or the heat exchanger tubes, but the lifetimes of materials under gasification onditions has not been established by industrial experience.

Within the quench system, entering gas temperatures of ~600 °F (589 K) nd exiting gas temperatures of 240-450 °F (389-505 K) at process pressures up to 1,200 psi) are anticipated. Circulating quench water may attain emperatures up to 450 °F (505 K) at process pressures. The quench operation emoves solid particles, tars and oils. It will, also, substantially reduce he amount of many gaseous impurities in the gas stream. The resulting queous stream, called sour water, is an acidic liquid whose corrosive behavior s aggravated by erosive circulating solids. Exact composition of the scrubber luids depends on the process and the coal feed, but potential corrosive ontributors include H_2S, CO_2, HCN, NH_3, phenols, organic acids, and chlorides.

Potential material problems include erosion, aqueous corrosion, stress orrosion, pitting, weld cracking, hydrogen embrittlement, etc. High pressure ill accelerate any stress-corrosion problems. Possible solutions include hemical neutralization of sour water or possible use of corrosion inhibitors. esistant cladding may be adequate for many of the processes. Pilot plant xperience of the CO_2 acceptor process has shown 316 SS cladding to be adequate n the water stripper, but long term experience is lacking.

3.2.2.1.2 MATERIALS EVALUATION

ERVIEW

The major problem in quench systems is corrosion by the complex aqueous lutions formed by quenching the gas streams produced at various stages of e coal gasification process. General testing of materials for quench system rrosion resistance is difficult because of the large number of variables volved. The solution composition and pH depend on the specific process, the ecific quench step in the process, and any fluctuations in process contions which alter the gas composition. In addition, varying temperature and essure in the quench vessel must be considered for the effects on the lution composition, pH, and the corrosion kinetics. A testing program to udy completely the effect of all possible variables would be formidable. me testing has been done to examine the performance of several alloys in rms of general corrosion, pitting, and stress corrosion cracking (see ctions B.1.1.100-.109).

BORATORY TESTS

Alloy coupons were subjected to testing in complex aqueous solutions in toclaves in order to simulate the quench steps of a variety of coal gasifition pilot plants. A volume of liquid was added to the vessel to approxitely half the vessel capacity and, for a given test, specified impurities re added to the liquid in amounts based on the total weight of the liquid. st coupons were inserted, the autoclave purged with nitrogen, the temperure and pressure raised to the test values, and after equilibrium was ached, gases were introduced and circulated. A constant flow of new gas was intained and condensate was automatically fed back to the vessel. This test ocedure was followed for all of the tests described below except for those belled "dynamic". The dynamic test procedure included provision for a ntinuous liquid input and periodic discharge to obtain a flow through the st vessel. Corrosion rates were determined from coupon weight loss. Since e data are based on few samples (only one specimen in tests reported in 1.1.1000, and .107, two specimens in B.1.1.105, .108, .109, and three ecimens in B.1.1.102, .103, .104) the corrosion rates reported must be ewed with caution.

TWENTY-THREE ALLOYS WERE SUBJECTED TO 50-HOUR LABORATORY TESTS in aqueous d gaseous environments designed to simulate quench conditions of a variety coal conversion pilot plants (see Section B.1.1.100). The objective was to velop a data base to serve as the basis for ranking corrosion resistance.

Tests were carried out in twelve different sets of environmental conditions d compositions. Temperature and pressure ranges were as follows:

vironment	Temperature Range(°F)	Pressure Range (psig)
ueous	120 - 462	95 - 1210
seous	200 - 950	100 - 1215

e pH of the twelve environments ranged from 2.9 to 9.7. These environments ntained varying concentrations of coal-conversion-atmosphere components as llows:

ENVIRONMENTAL CONDITIONS AND COMPOSITIONS FOR 50-HOUR LABORATORY TESTS OF TWENTY-THREE ALLOYS

Chemical Composition
(mole percent unless otherwise specified)

Temperature and Pressure

Data Set	pH Range	Toluene (Vol. %)	Phenol (ppm)	HCN (ppm)	Chloride (ppm)	H_2S	CO_2	NH_3	H_2	CO	CH_4	N_2	H_2O (Vol. %)	LIQUID (psig)	LIQUID (°F)	GAS (psig)	GAS °F
1A	7.6 - 9.7	23	1000	500	3000	0.2	15	0.3	17	10	7	-	27	1000	200	1000	600
1B	9.2 - 10.6	same	0	100	same												
2A	3.9 - 9.4	3	700	200	3000	0.8	18	0.45	22	19	15	-	20	1210	400	1210	400
2B	7.5 - 8.5	NIL	same	same	100												
3A	6.5 - 9.2	NIL	100	100	3000	0.02	3.2	0.52	56	15	10	0.18	15	126	120	131	200
3B	7.5 - 8.5	NIL	NIL	NIL	100												
4A	3.8 - 3.9	NIL	NIL	200	3000	0.34	7	NIL	15	26	10	0.5	42	1200	462	1215	597
4B	2.9 - 4.2	NIL	NIL	NIL	100												
5A	7.2 - 9.0	0.04	6000	10	3000	1.1	21	0.6	19	9	13	0.1	36	1200	462	1210	950
5B	7.9 - 9.0	same	1000	NIL	100												
6A	4.7 - 7.0	NIL	100	100	3000	0.35	5	0.002	48	27	5	0.5	14	95	230	100	500
6B	4.3 - 7.0	NIL	NIL	NIL	100												

Table A.3.2.2.1.2a

ponent	Concentration Range
	0.02 - 1.1 mole percent
	5 - 21 mole percent
	0.002 - 0.6 mole percent
	9 - 27 mole percent
	5 - 15 mole percent
	0.1 - 0.5 mole percent
	14 - 42 volume percent
uene	NIL - 23 volume percent
	NIL - 500 parts per million
enol	NIL - 600 parts per million
oride	100 -3000 parts per million

etailed tabulation of the twelve sets of environmental conditions and positions appears in Table A.3.2.2.1.2a. It might be expected that the le ranges of environmental conditions and compositions would have some luence on the rankings of the twenty-three alloys tested. Surprisingly, e rankings were not very sensitive to environmental conditions and compositions. However, the corrosion rates were. Maximum and minimum corrosion tes appear in Section B.1.1.101. A comprehensive analysis of the more tailed data in Section B.1.1.100 leads to the following ranking of the rrosion resistance of all twenty-three alloys, regardless of environmental nditions and compositions:

od Corrosion sistance	Intermediate Corrosion Resistance	Poor Corrosion Resistance
stelloy C	304 stainless steel	Aluminum 1100
stelloy G	316 stainless steel	Cast iron
nco 22-13-5	18-18-2	Carbon steel
9 stainless steel	Aluminum 6061	Ni-Resist
Cb-3	18-2	Ni-Resist (Cu)
-1		410 stainless steel
tanium		430 stainless steel
coloy 800		Monel 400
coloy 825		Aluminum bronze

The highest corrosion rates were between 100 and 500 mils per year, ereas the lowest were less than 1 mil per year. In general, if an alloy owed good resistance to an aqueous environment, it also showed good resistance a gaseous environment, and vice-versa. For some alloys the aqueous environ- nt caused the highest corrosion rate, whereas for other alloys, the gaseous vironment caused the highest rate. Alloys with high chromium content, i.e., -30 percent, usually showed good corrosion resistance. Austenitic stainless eels (304, 316) showed better corrosion resistance than the Type 400 stainless eels (410, 430). Aluminum 1100 and Aluminum 6061 showed pronounced suscep- bility to pitting in aqueous environments.

Within the twelve sets of environmental conditions and compositions pearing in the tabulation below, it was found that the highest corrosion tes were associated with Sets 4A, 4B, 5A, and 5B. Sets 4A and 4B had the st acid pH and the highest liquid temperatures, whereas Sets 5A and 5B had e highest H_2S concentrations. Sets 5A and 5B also had the highest gas temperature. These conditions of very acid pH values, high temperatures and high H_2S concentration would tend to promote the observed high corrosion rates. The lowest corrosion rates were associated with Set 1B, which had the most basic pH and a relatively low liquid temperature. Decreases in the concentration of HCN and phenol between Sets 1A and 1B may have decreased the corrosion rates from those of Set 1A to those in Set 1B. Corrosion rates seemed relatively insensitive to changes in chloride concentration between 100 and 3000 ppm for all data sets.

THE EFFECT OF AMMONIA AND WATER CONTENT was tested on four alloys subjected to static (gas flow only, no liquid flow) laboratory tests in simulated quench environments (Section B.1.1.102). Exposures were at temperatures between 250 and 462°F and pressures between 150 and 1210 psia for 150 hours. The corrosive environment contained 1.1 percent H_2S and 3000 ppm chloride. Water content varied between 5 and 79.3 percent, ammonia was either 0.1 or 0.6 percent and pH varied between 4.5 and 8.6. Types 304 and 316 austenitic stainless steels showed the best aqueous corrosion resistance, with a slight increase in rate from around 0.1 to about 2 mils per year as temperature increased from 250 to 462°F. Gaseous corrosion rates for these two alloys were slightly less, but showed the same temperature dependence. Aqueous corrosion rates for carbon steel were usually the highest and ranged between 2 and 29.6 mils per year. Type 410 martensitic stainless steel showed comparabl aqueous corrosion rates which ranged between 1.4 and 29 mils per year. In general, the gaseous corrosion rates for all four alloys were less than the aqueous corrosion rates. Furthermore, there seemed to be no clearcut correlation between corrosion rate, and ammonia or water content (B.1.1.102). There were slight improvements from the use of two inhibitors, one oil-soluble and one water-soluble, for these four alloys (B.1.1.103).

ABOUT TWENTY ALLOYS WERE SUBJECTED TO FOUR SIMULATED AQUEOUS AND GASEOUS QUENCH ENVIRONMENTS IN STATIC LABORATORY TESTS (Section B.1.1.108). Exposures were for 400 hours at temperatures of either 240, 380, or 495°F. The simulate environments represented the quench conditions in the following pilot plants: 1) CO_2 Acceptor Process, 2) BI-GAS, 3) Synthane and 4) HYGAS. Aqueous and gaseous corrosion rates served as the basis for ranking corrosion resistance. As with the data in Section B.1.1.100, the rankings were not very sensitive to the differences in environments. A comprehensive analysis of the data in Section B.1.1.108 resulted in the following ranking of the corrosion resistanc of the alloys, regardless of the pilot plant process:

Good Corrosion Resistance	Intermediate Corrosion Resistance	Poor Corrosion Resistance
Hastelloy C	304 stainless steel	Cast iron
Hastelloy G	316 stainless steel	Carbon steel
Armco 22-13-5	18-18-2	Ni-Resist
329 stainless steel	Aluminum 6061	Ni-Resist (Cu)
20Cb-3	18-2	Monel 400
26-1	Aluminum 1100	Aluminum bronze
Titanium	410 stainless steel	
Incoloy 800	430 stainless steel	
Incoloy 825		

These rankings are comparable to those found for the data in B.1.1.100, where the test temperatures ranged between 120-462°F and the test time was 50 hours. Usually, the corrosion rates determined in the varied quench environments listed in B.1.1.100 (50-hour tests) were considerably higher than the corrosion rates determined in the simulated pilot plant quench environments cited in B.1.1.108 (400-hour tests).

The highest rates in Section B.1.1.108, approximately 50 to 200 mils per year, were exhibited by Monel 400 and Aluminum bronze in the BI-GAS process. Those listed above under the heading of Good Corrosion Resistance showed corrosion rates of less than 1 mil per year for all four pilot plant processes. In general, if an alloy showed good resistance to an aqueous environment, it also showed good resistance to a gaseous environment, and vice-versa, regardless of the pilot plant process. For some alloys, the aqueous environment caused the highest corrosion rate, whereas for other alloys, the gaseous environment caused the highest rate. Alloys with high chromium content, i.e., greater than 15 percent, usually showed good corrosion resistance.

As a rule, cast iron, carbon steel and Type 430 stainless steel showed better corrosion resistance in the quench environment of the Synthane and HYGAS processes than in the BI-GAS and CO_2 Acceptor processes. Furthermore, 8-2, 18-18-2, and Type 316 stainless steels have better corrosion resistance in the quench environment of the CO_2 Acceptor process than in the quench environments of the other three processes.

Usually, pit depth for all materials tested in all four process quench environments did not exceed 2 mils. The austenitic stainless steels and other materials listed under the heading of Good Corrosion Resistance in the table above showed high resistance to pitting. Cast iron, carbon steel, and Ni-Resist (Cu) showed the poorest resistance to pitting. Cast iron showed good pitting resistance in the simulated quench environment of the Synthane process.

<u>FOUR ALLOYS WERE SUBJECTED TO DYNAMIC (INCLUDES GAS AND LIQUID FLOWTHROUGH) LABORATORY TESTS IN AQUEOUS AND GASEOUS ENVIRONMENTS</u> designed to simulate the quench environments in the CO_2 Acceptor Process, the HYGAS plant, and the BI-GAS and Synthane plants (see B.1.1.107). Types 304, 316, and 329 austenitic stainless steels showed the best aqueous and gaseous corrosion resistance. Carbon steel showed poorer resistance. Environments characteristic of the HYGAS, BI-GAS and Synthane processes caused higher corrosion rates than environments characteristic of the CO_2 Acceptor process. In general, corrosion rates increased with increasing temperature, and corrosion rates were higher for aqueous corrosion than for gaseous corrosion. In no case did corrosion rates exceed 40 mils per year.

<u>STATIC (GAS FLOW ONLY, NO LIQUID FLOW) AND DYNAMIC (BOTH GAS AND LIQUID FLOW) LABORATORY TESTS IN AQUEOUS AND GASEOUS ENVIRONMENTS</u> were performed (Sections B.1.1.104 - B.1.1.106). Exposures were at 1210 psig and 462°F for times of either 50 or 150 hours. The corrosive environments contained CO_2, CO, H_2S, HCN, phenol and chloride, in varying proportions. The environments also contained fixed concentrations of: H_2O (40%), NH_3 (0.6%), N_2-balance. Types 304 and 316 austenitic stainless steels showed the best corrosion resistance, whereas carbon steel and Type 410 martensitic stainless steel showed poorer resistance. This performance was true in both the static and dynamic environments, regardless of the composition of the environments. Type

329 austenitic stainless steel showed good resistance to the dynamic environments. It was not tested in static environments. For the 150-hour tests, it turned out that some times the static corrosion rates exceeded the dynamic rates and other times the opposite occurred. In general, aqueous corrosion rates exceeded gaseous corrosion rates. In no case did corrosion rates exceed 100 mils per year.

FOUR ALLOYS WERE SUBJECTED TO STATIC LABORATORY TESTS IN AQUEOUS AND GASEOUS QUENCH ENVIRONMENTS designed to simulate variations in the constituents of a "standard " environment (Section B.1.1.109). Results in the standard environment (HYGAS) served as the basis for comparison with results in test environments with slight variations in composition. Exposure times were either 150, 500, 1000, or 5000 hours at temperatures of 150, 250, 300, 350 or 380°F (temperature of standard environment). Types 304, 316, and 329 austenitic stainless steels showed the best aqueous corrosion resistance, with corrosion rates in the range 0.1 to 0.9 mils per year. There were no significant influences of environmental changes on corrosion rates for these alloys. Carbon steel showed the poorest corrosion resistance, with rates varying from 4 to 32.5 mils per year. In general, the gaseous corrosion rates for all four alloys were less than the aqueous corrosion rates. Corrosion rates tended to be higher at the higher test temperatures.

PILOT PLANT TESTING

Alloy coupons were exposed to quench conditions in a variety of locations in several coal gasification pilot plants (B.1.1.28). Duplicate specimens were exposed and both gravimetric and metallographic analyses were performed to determine the extent of corrosion. Full exposure conditions, i.e., concentration of chemical constituents, fluctuations of temperature and pressure, are not known and therefore the corrosion rates reported here must be interpreted cautiously.

ALLOYS TESTED IN THE COAL PRETREATER WATER QUENCH SYSTEM OF THE HYGAS PLANT faced an environment of water, methane, oxygen, carbon monoxide and nitrogen at temperatures around 150 °F. Nine alloys tested (see B.1.1.28, p. 1) in this environment at temperatures of 70 and 158 °F indicate that 18-18-2 stainless steel and Titanium 50A alloy show the lowest corrosion rates. Carbon steel and cast iron show the highest corrosion rates. The corrosion rates of six alloys increased by a factor of seven with an increase in temperature from 70 to 158 °F. However, the corrosion rates of two alloys, 18-18-2 and Titanium 50A, remained very low. Welded U-bend test specimens of carbon steel, and Types 304, 18-18-1, and 329 stainless steels did not show signs of stress corrosion or cracking during exposure at either temperature.

MATERIALS WERE TESTED IN THE COAL PRETREATER QUENCH TOWER (OFF GAS) OF THE HYGAS PLANT in an environment of neutral gas, H_2O, O_2, CO, CH_4 and N_2. Four alloys were tested during pilot plant exposures at 140 °F/0.4 psig/1719 hours and 174 °F/1 atm/1790 hours (see p.3, B.1.1.28). At both temperatures, Types 304 and 316 stainless steels showed the lowest corrosion rates (0.1 mils per year or less) and carbon steel showed the highest at 36.9 mils per year. Type 410 stainless steel corroded ten times faster than the other two stainless steels, at about 1 to 1.25 mils per year. The average annual corrosion rates of these four alloys did not change significantly with a change in temperature etween 140 and 174 °F. Welded U-bend test specimens of the carbon teel and Types 304 and 316 stainless steel did not show stress corrosion racks during either exposure.

THE PRODUCT GAS PREQUENCH TOWER OF THE HYGAS PLANT provided an nvironment of H_2O, char fines, ash and process condensate at temperatures rom about 170 to 205 °F. Nine alloys were exposed in pilot plant tests t 171 °F for about 300 hours at operational conditions (see p. 2, .1.1.28). Results showed extremely low corrosion rates (0.1 mil per ear or less) for Types 304 and 18-18-2 stainless steels and for Titanium 0A alloy. For the same conditions, Ni-Resist, Ni-Resist (Cu), carbon teel and cast iron showed much higher corrosion rates, from 13.5 to 2 mils per year. In tests at 205 °F for 1150 hours exposure, these ankings remained about the same. Surprisingly, the average annual orrosion rates decreased significantly in the higher temperature tests. elded U-bend test specimens of Types 304, 329 and 18-18-2 stainless teels did not show stress corrosion cracks during either exposure.

IN THE QUENCH SEPARATOR TOWER OF THE HYGAS PLANT structural materials aced an environment of H_2O, char fines, ash and process condensate. Tests ere carried out in the oil phase and the gas phase. Four alloys were tested uring pilot plant exposures in the oil phase at 140 °F/990 psi/1150 hours operating) and 120 °F/650 psi/2010 hours (standby) (see B.1.1.28, p.3). ype 304 stainless steel showed the lowest average annual corrosion rate, .02 mils per year, whereas carbon steel showed the highest corrosion rate, 3 mils per year. Type 430 stainless steel showed a corrosion rate of .75 mils per year, which is about 40 times greater than that of Type 304. he average annual corrosion rate for Type 410 stainless steel was about mils per year. Welded U-bend test specimens of carbon steel tested in the il phase showed no signs of stress corrosion cracks.

These four alloys were tested in the gas phase of the quench separator ower at 95 °F/949 psig/2909 hours, and each showed about a tenfold increase n average annual corrosion rate, although the ranking remained the same as in he oil phase exposure.

MATERIALS IN THE QUENCH TOWER FOR OFF GAS OF THE HYGAS PLANT were ubjected to an environment of product gas and water at temperatures round 100 °F (see p. 4, B.1.1.28). Of three alloys tested during ilot plant exposures at 900-1100 psi, Type 304 stainless steel showed he lowest rate of corrosion at less than 0.1 mil per year, and carbon teel showed the greatest rate at about 77 mils per year. The corrosion ate of Type 410 stainless steel was intermediate at 5.6 mils per year. elded U-bend test specimens of Type 304 and carbon steel showed no igns of stress corrosion cracks during exposure.

IN THE GAS WASHER/LIQUID PHASE OF THE BI-GAS PLANT structural lloys were exposed to water, plus H_2S, CH_4, CO_2, CO, H_2, and N_2 as well s particulates such as ash and char. Temperatures were around 450 °F. f six alloys tested (see B.1.1.28, p. 5), Types 304 and 316 stainless teels and Incoloy 825 showed corrosion rates of less than 1 mil per ear. The rate for Type 405 stainless steel was 2.5 mils per year, hereas Monel 400 and carbon steel showed considerably higher rates. elded U-bend test specimens of Types 304, 316, and 405 stainless steel howed no signs of stress corrosion cracking during exposure.

MATERIALS TESTED IN THE VENT GAS WASHER/LIQUID PHASE OF THE BI-GAS PLANT were exposed to water, plus char, ash, and condensate at about 225 °F. Of three alloys tested (see p. 5, B.1.1.28), Types 304 and 405 stainless steel showed corrosion rates of less than 1 mil per year, whereas carbon steel deteriorated at the rate of 43.6 mils per year. Welded U-bend test specimens of carbon steel, and Types 316 and 405 stainless steel showed no signs of stress corrosion cracking during exposure.

ALLOY SAMPLES PLACED IN THE RECYCLE GAS WASHER/LIQUID PHASE OF THE BI-GAS PLANT were exposed to water plus coal fines at 130 °F. Of six alloys tested (see p. 5, B.1.1.28), three showed corrosion rates of less than 1 mil per year: Types 304 and 316 stainless steel and 20Cb-3Fe-33Ni-19Cr. However, carbon steel, Monel 400 and 2¼ Cr-1Mo showed substantially higher rates. Welded U-bend test specimens of Types 304 and 316 stainless steel showed no signs of stress corrosion cracking.

IN THE CYCLONE OVERFLOW TANK/LIQUID PHASE OF THE BI-GAS PLANT structural materials were exposed to coal fines and water at 65-75 °F. Of five alloys tested (see B.1.1.28, p. 5), three showed corrosion rates of less than 1 mil per year: Types 304 and 316 stainless steel and 20Cb-3Fe-33Ni-19Cr. The rate for Monel 400 was 3.3 mils per year, and the rate for carbon steel was 54.0 mils per year. Welded U-bend test specimens of Types 304 and 316 stainless steel showed no signs of stress corrosion cracking during exposure.

THE VAPOR PHASE SIDE OF THE SCRUBBER SURGE TANK OF THE SYNTHANE PLANT provided an environment of reducing gas, H_2O, CO_2, H_2, H_2O, ash and char, as well as mist from condensate at temperatures from 385 to 445 °F. Ten alloys were exposed in pilot plant tests at 385 °F/600 psig/592 hours and 445 °F/600 psi/618 hours (see p. 6, B.1.1.28). The 385 °F test results showed the lowest corrosion rates for Incoloy 800 and Types 304 and 316 stainless steels. Low rates were also characteristic of alloy Titanium 50A (0.2 mils per year), Inconel 600 (0.8 mils per year) and 430 stainless steel (1.5 mils per year). Monel 400 showed the highest rate (206 mils per year), with Type 410 stainless steel showing the fourth highest rate (4.1 mils per year). Carbon steel showed the second highest rate (56.1 mils per year). Aluminizing the carbon steel reduced the rate to 5.6 mils per year. The 445 °F test results showed about the same ranking, with an increased corrosion rate for most of the alloys. As in the 385 °F tests, aluminizing the carbon steel reduced the corrosion rate significantly. In general, corrosion rates of the ten alloys tested on the vapor phase side of the scrubber surge tank were not significantly different from the rates on the liquid phase side. Welded U-bend test specimens of Type 304 stainless steel and Incoloy 800 did not show signs of stress corrosion cracking at either test temperature.

THE LIQUID PHASE SIDE OF THE SCRUBBER SURGE TANK OF THE SYNTHANE PLANT provided an environment of H_2O, condensate, ash, char and tar at temperatures around 385 °F. Ten alloys were exposed in pilot plant tests at 600 psig for 592 hours (see B.1.1.28, p. 7). Lowest corrosion rates were shown by Types 304 and 316 stainless steel and alloy Titanium 50A in the range, 0.09 - 0.3 mils per year. Rates

:ween 1.4 and 404 mils per year were shown by Inconel 600 and Types) and 430 stainless steels. Monel 400 and carbon steel showed the ghest corrosion rates, about 53.5 mils per year. Aluminizing the :bon steel reduced the rate to 5.4 mils per year. In general, cor- sion rates of the ten alloys tested for conditions in the liquid phase le of the scrubber surge tank were not significantly different from : rates on the vapor phase side. Welded U-bend test specimens of oe 304 stainless steel and Incoloy 800 did not show signs of stress :rosion cracking during exposure.

STRUCTURAL ALLOYS PLACED IN THE DECANTER SPLASH ZONE OF THE SYNTHANE \NT were subjected to an environment of HO, condensates, ash, char, l tar at temperatures around 190 to 220 °F. Four alloys were exposed pilot plant tests at 220 °F/<5 psig/592 hours and at 190 °F/5 psi/ 3 hours (see p. 7, B.1.1.28). Types 430 and 304 stainless steels owed the lowest corrosion rates at both temperatures, less than 1 mil : year. The average rate for Type 410 stainless steel was 1.6 mils : year. Carbon steel had the highest corrosion rates, 43.7 and .1 mils per year at 220 and 190 °F, respectively. Welded U-bend test ecimens of carbon steel and Type 304 stainless steel showed no signs stress corrosion cracking during exposure at either temperature.

IN THE DECANTER/SOLID-LIQUID ZONE OF THE SYNTHANE PLANT alloys were oosed to an environment of H_2O, condensate, ash, char, tar, and other lids at temperatures around 190-220 °F. Four alloys were exposed in lot plant tests at 190 °F/5 psig/618 hours and at 220 °F/<5 psig/592 ırs (see p. 8, B.1.1.28). Corrosion rates of Type 410, 430, and 304 ainless steel were less than 1 mil per year. Carbon steel showed the ghest rate, 19.2 mils per year. Welded U-bend test specimens of carbon eel and Type 304 stainless steel showed no signs of stress corrosion acking during exposure.

EIGHT ALLOYS WERE EXPOSED IN PILOT PLANT TESTS IN THE GASIFIER ENCH TOWER OF THE CO_2 ACCEPTOR PLANT at 120 °F/145 psig (see), B.1.1.28). Six alloys showed average annual corrosion rates which :e less than 1 mil per year, with Incoloy 825 and Type 316 stainless eel showing the lowest rates. Carbon steel showed the highest rate, .3 mils per year, and Type 410 stainless steel showed the second ghest corrosion rate, 8.5 mils per year.

THE REGENERATOR QUENCH TOWER OF THE CO_2 ACCEPTOR PLANT operated at) °F when two sets of twelve alloys were exposed in pilot plant tests : 1710 and 2990 hours at pressures around 130-135 psig (see B.1.1.28, 10). In each set, seven alloys showed average annual corrosion rates less than 1 mil per year. Lowest rates were shown by Incoloy 825, oes 304 and 316 stainless steels, Iron-14Ni-21Cr and Titanium 50A loy. Highest rates were shown by Ni-Resist (Cu), carbon steel, cast on, Aluminum bronze and Ni-Resist, with the highest rate being 59.5 mils : year. An increase in test time from 1710 to 2990 hours led to a ostantial reduction in the average annual corrosion rate for most of the loys. Pilot plant tests were run for 2161 hours at 130 °F on five of e alloys with higher corrosion rates and two of the alloys with lower rrosion rates. The ranking of corrosion rates in these tests remained e same as in the other tests. Welded U-bend test specimens of carbon steel and Type 304 stainless steel showed no signs of stress corrosion cracking during exposure.

Alloys were also exposed to aqueous corrosion conditions in portions of the pilot plants which did not involve gas quench operations. Data gathered from exposures in these other locations is included here since these tests involved the same alloys and provide complementary information about the corrosion resistance of the alloys.

MATERIALS EXPOSED IN THE GASIFIER SLAG QUENCH SYSTEM OF THE BI-GAS PLANT faced a water-saturated vapor phase at about 470 °F and a liquid phase associated with char and ash at about 70 °F. The pressure at each stage was about 750 psig. Good resistance to corrosion in the vapor and liquid phases at 470 and 70 °F, respectively, was shown by five of the seven alloys tested (see p. 4, B.1.1.28). Corrosion rates of less than one mil per year were characteristic of Types 304, 316, 329, and 405 stainless steels, and of an Iron-26Cr-1Mo alloy. Carbon steel and 2¼ Cr-1 Mo showed corrosion rates around 20-22 mils per year in the vapor phase and rates of 56-80 mils per year in the liquid phase. Welded U-bend test specimens of Types 304 and 329 stainless steel and of an Iron-26Cr-1Mo alloy showed no stress corrosion cracking in either the vapor or liquid phases.

IN THE GASIFIER CHAR COOLER/VAPOR PHASE OF THE SYNTHANE PLANT alloys were subjected to an environment of water and char at temperatures of 600 to 900 °F. Three alloys were exposed in pilot plant tests at 800°F/600 psig/417 hours and 600-900 °F/600 psig/592 hours (see p. 8, B.1.1.28). At 800 °F, the average annual corrosion rates of Types 410 and 304 stainless steel were 10.5 and 2.35 mils per year, respectively, and the rate for carbon steel was much higher, about 73.5 mils per year. In tests at 600-900 °F, the rate for carbon steel was substantially higher, whereas the rate for Type 410 and 304 stainless steels decreased significantly. Welded U-bend test specimens of carbon steel and Type 304 stainless steel showed no signs of stress corrosion cracking during exposure.

ALLOYS TESTED IN THE CHAR/SLURRY MIX TANK OF THE HYGAS PLANT were exposed to an environment of water, char and ash (see B.1.1.28, p. 4). Of three alloys tested in this environment during pilot plant exposures at 95 °F/890 psi/1350 hours (operation) and 880 °F/730 psi/1760 hours (standby), Type 304 stainless steel showed the lowest corrosion rate at 0.045 mils per year and carbon steel showed the highest at about 17.9 mils per year. The corrosion rate of Type 410 stainless steel was intermediate at 0.9 mils per year. Each alloy showed about a tenfold increase in average annual corrosion rate for an exposure of 135 °F/907 psig/2909 hours, and the ranking remained the same as the 95 °F-880 °F ranking.

MATERIALS EXPOSED IN THE FEED SLURRY MIX VESSEL OF THE HYGAS PLANT were subjected to an environment of treated coal fines plus toluene. Three alloys were tested in this environment during pilot plant exposures at 180 °F/1 atm/228 hours and 85 °F/3 psi/1150 hours (see p. 2, B.1.1.28). In the 180 °F tests, Type 304 stainless steel showed the lowest average annual corrosion rate, 0.045 mils/year, and carbon steel showed the highest corrosion rate, 17.3 mils/year. The rate for Type 410 stainless steel was intermediate at 0.24 mils/year. The average annual corrosion rate decreased considerably for all three in the 85 °F tests, yet the ranking remained the same.

A.3.3.1 OPERATING REQUIREMENTS

Most of the proposed gasification procedures require additional processing of the quenched product gas stream in order to produce pipeline quality (i.e., high Btu) gas. Typically this would consist of a water-gas shift reaction to produce the desired H_2 to CO ratio, acid gas (H_2S, CO_2) removal, and finally a catalytic methanation step.

Sulfur-containing gas removal is necessary to avoid catalyst poisoning while CO_2 removal reduces the volume of gas going through the methanator and improves the reaction efficiency. Gas purification is a frequently encountered process in the petroleum refining and petrochemical industry. It is usually done by passing the gas through an absorbing column. Process conditions may range from 110-240 °F and 500-1,500 psi, depending on the specific process and absorbent used. Direct technology transfer should be possible without any severe materials problems.

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A.6.1 OPERATING REQUIREMENTS

Compressors in coal gasification processes are used for air streams and recycled product gas streams. In general, temperatures (ambient to a few hundred degrees F) and pressures (to 2,000 psi) to which these components are exposed are comparable to existing industrial applications. It is anticipated that technology transfer from existing applications will be adequate for most of these components although the possible long term corrosive effects of the recycled product stream has not been established.

A.6.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE for seven COMPRESSORS has been reported (Section A.6.2.1. The compressor components that failed were different for each of the seven compressors and were fabricated from several different materials including aluminum, cast iron, 304 stainless steel, 416 stainless steel and Teflon steel. Reported operating temperatures ranged from 32 to 219 °F.

Reasons for failure were varied. Compressors containing aluminum wheels suffered corrosion and/or erosion of these wheels which led to an imbalance causing bearing damage. One failure was due to improper material substitution (304 stainless steel for Incoloy X-750) for valve springs and one was due to abuse resulting in a crack between the water jacket and cylinder bore caused by freezing of residual cooling water. Other failures were due to a broken valve disk (cause unknown) and from oil pump plungers failing to operate on startup.

Two failures, one in 416 stainless steel and one in Teflon steel, were possibly due to high moisture contents in the systems. The 416 stainless steel had suffered pitting corrosion and fractures from stress corrosion cracking.

Because of the variation in components, materials, environments and cause of failure, no definitive conclusions can be drawn based on the limited data available in regard to compressor plant experience.

COMPRESSOR IN-SERVICE PERFORMANCE[5]

Material	Compressor/ Components	Plant/ Process	Service Life	Atmosphere	Temp. °F	Press. PSIG	Failure Mode
Aluminum	Process air compressor K-701 A/B (wheels and bearings)	Battelle, Columbus	5000 hr	Air	Ambient	N.A.	Corrosion and/or erosion of wheels caused an imbalance which damaged the bearing.
Cast Iron	Recycle make gas booster compressor	Battelle, Columbus	N.A.	Process gas/ cooling water	<32	N.A.	Crack occurred between the water jacket and cylinder bore possibly caused by freezing of residual cooling water.
Cast Iron	Duplex recycle compressor (oil injection pump plungers)	Clean Coke	N.A.	Oil	N.A.	N.A.	Plungers on oil pumps failed on startup after oil injection pumps were extensively rebuilt
Cast Iron	Inert gas compressor (valve disc)	Battelle, Columbus	3000 hr	Inert gas	Ambient	N.A.	Broken valve disc. Cause unknown.
304 S.S. Inconel X-750	Hydrogen compressor (helical coil springs from a two-way pressure valve)	SRC (Wilsonville)	21 hr	Hydrogen/ nitrogen	77-190	N.A.	Improper material substitution (304 S.S. for Inconel X-750) led to eventual failure of valve springs and a total plant shutdown.
416 S.S.	Three stage reciprocating (valve assembly leaf springs)	Hygas	∼42 hr	$H_2/CO/CO_2/$ H_2O	75-219	1050	Several springs fractured, others suffered pitting corrosion. Possible causes are moisture in the gas, preload on springs too high, stress corrosion cracking.
Teflon Steel	Inert gas compressor (piston ring, shaft)	Synthane	6 mos	Recycle $CO_2/$ H_2O	N.A.	N.A.	Teflon piston ring wear has accelerated possibly due in part to increased moisture in CO_2. Most of shaft wear of 0.008" max. occurred in initial operation and was due to internal rust and contamination.

A.6.2.2 MATERIALS EVALUATION

The operating conditions for compressors involve "cool gas" corrosion, as compared to hot gas corrosion. Data on materials suitable for application in cool gas corrosion environments can be found by looking selectively at the low temperature data in Section A.2.4.2.2.

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A.7.1.1 OPERATING REQUIREMENTS

In general, piping environments will be determined by their location and function in the process stream. Gas feed lines (steam, air, H_2, etc.) containing no erosive particulates will be at moderate temperatures (up to 1,000 °F [811 K]) and pressures up to 1,500 psi. Materials technology transfer from hydrogen, ammonia, and steam-generating facilities should be adequate for these lines.

However, gas lines associated with gasifier product gas containing particulates will have the same conditions as gasifier internals, i.e., temperatures up to 1,800 °F (1,255 K) and pressures up to 1,500 psi. Metal corrosion problems may include carburization (CO, CO_2, and CH_4), sulfidation (H_2S, COS), and oxidation. Erosive damage, especially at bends, will be superimposed on and probably aggravate any corrosion effects. Refractory linings in either multilayer castable form or pre-fired shapes will almost certainly be necessary to provide reasonable lifetimes for these parts.

A.7.1.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE for more than 60 GAS PIPING components has been reported (see A.7.1.2.1.1). The gas piping was manufactured from a variety of materials including carbon-molybdenum steels, carbon steels, Incoloy 800, Inconel 600, Inconel 601, Inconel 702, RA 330, Monel, austenitic stainless steels 304, 310, 316, and 321, martensitic stainless steels 410 and 416, and ferritic stainless steel 446. Reported operating temperatures ranged from ambient to 1700-1900 °F.

The common causes of failure were corrosion and stress corrosion cracking which accounted for approximately half of the gas piping failures reported. Six of the 12 carbon steel failures reported were due to corrosion. The longest service life reported for these six was 3 years in a CO_2 environment (temperature of operation not available), whereas the shortest reported service life was 56 days in a steam/fluidized bed environment at 800 °F. There were no reported failures of carbon steel piping due to stress corrosion cracking.

Corrosion was the cause of failure in six of the 17 cases reported for Incoloy 800. Sulfidation and carburization were responsible for the corrosion in three instances and metal dusting was listed for two. In one case, Incoloy 800 piping in a recycle gas environment suffered high temperature pitting. Adding 50-60% steam to the recycle gas appeared to alleviate the problem. The longest service life reported for these six failures was up to 1500 hours in an inert gas/air/recycle gas environment at a temperature of 1500 °F. The shortest reported service life was 150 hours at 550-1220 °F in a low sulfur environment.

Five of the Incoloy 800 failures were due to stress corrosion cracking. The longest service life reported among these four was 2 years at a temperature of 525 °F in a recycle gas environment, whereas the shortest service life reported was 200 hours at 1700-1900 °F in product gas.

The one Inconel 600 failure and the one Inconel 702 failure reported both were due to sulfidation corrosion. One of the three 321 stainless steel failures was due to corrosion.

All of the 304 stainless steel failures reported for which a cause was given (4 of 7) failed due to stress corrosion cracking near welds. Environments included process gas, steam, and flue gas/steam/oxygen. Temperatures ranged from 460 to 850 °F. Of the ten reported 316 stainless steel components, three failed due to stress corrosion cracking and one failed due to sulfidation corrosion.

Erosion was the cause of failure for the only one (out of three) carbon-molybdenum steel pipeline failure for which a cause is given. One of the carbon steel failures and one of the Incoloy 800 failures were also due to erosion.

There were a number of failures at welds or at heat affected zones associated with welds for which the cause either was not stated or was due to abuse or misuse. These included one carbon-molybdenum steel failure, three carbon steel failures, three Incoloy 800 failures, two 304 stainless steel failures and one 316 stainless steel failure.

One failure each in 310 stainless steel and 321 stainless steel were thought to be due to thermal cycling and one failure in 316 stainless steel was due to thermal shock.

There were two reported failures due to differential thermal expansion of dissimilar materials. One of these systems was comprised of 316, 410, and 416 stainless steels and the other was comprised of 316 stainless steel and Incoloy 800.

One of the 316 stainless steel failures was caused by an explosion and there were several other failures of various materials due to abuse.

For all of the systems reported, the longest service life was three years for carbon steel in a CO_2 environment (temperature of operation not stated). The shortest service life reported (except for failure due to abuse) was 61.5 hours for Inconel 702 at 1500 °F in an inert gas/air/recycle gas environment.

PLANT EXPERIENCE has been reported for 10 BELLOWS made from three different materials - Incoloy 800, and 304 and 321 stainless steels (Section A.7.1.2.1.2). Reported operating temperatures ranged from 120 to 1650 °F. Corrosion and stress corrosion cracking are the two most frequent causes of failure reported in these limited data.

Failure of one of the Incoloy 800 bellows was due to oxidation and intergranular attack. The cause of failure of the other two Incoloy 800 bellows was not stated.

Four of the five 304 stainless steel bellows failures reported were due to stress corrosion cracking from chlorides. The fifth 304 stainless steel failure was due to pitting corrosion caused by moist deposits and chlorides.

There were two reported failures of bellows made of 321 stainless steel. One failure was from the burnout of an oxygen line in the burner and the second was from pitting corrosion caused by improper drainage.

The longest service life reported was 9 months for Incoloy 800 at 1650 °F in an environment consisting of $H_2/H_2O/CO_2/CH_4/C$. The shortest service life reported was 31 days for 304 stainless steel at 300 °F in a recycle gas/air/-steam environment.

GAS PIPING IN-SERVICE PERFORMANCE [5]

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
C-Mo steel (A335 Gr. P21)	Elbow attached to letdown valve PCV-338	4 in ID Schedule 40	Synthane	N.A.	Steam	760	700	Pipe ballooned increasing in size from 4.44" OD to 4.60" OD. Cause unknown.
C-Mo steel	Elbow socket weld fitting on char cooler letdown line	1 in (P2110E2B)	Synthane	6 mos.	99% steam/ char/various gases	650-900	600	Erosion damage led to a leak at weld fitting.
C-Mo steel	Weld zone in high pressure steam line	1.5 in (HS2403E2B)	Synthane	N.A.	Steam	700	1000	Leak occurred at a weld zone. Cause unknown.
Carbon steel (SA106 Gr. B)	Pretreater reactor cooling bundle	N.A.	Hygas	30 days	Steam/fluidized bed	800	N.A.	Circumferential fracture in HAZ of one tube caused by overcooling of the tube.
Carbon steel (SA106 Gr. B)	Pretreater reactor cooling bundle	N.A.	Hygas	56 days	Steam/fluidized bed	800	N.A.	Two tubes had small ruptures, several tubes were bent, corrosion deposits on outer surface of bundle.
Carbon steel (A234 Type WPB)	Elbow fitting on outlet of separator condenser C-A801	4 in, 90° long radius, schedule 40 elbow (Line 81-4AB)	Cresap	N.A.	Ammonia/sulfur oxide/hydrogen sulfide/off-gas condensates	110	4	0.5 in diameter hole corroded through outside radius of elbow.
Carbon steel (A2A)	Elbow located downstream of valve PCV-266	4 in Elbow	Synthane	1 week	Steam/char fines	N.A.	N.A.	Hole eroded in elbow.
Carbon steel	Elbow on CO_2 high pressure line	3 in Elbow 600 lb, schedule 80 (CG3106D2A)	Synthane	2 yrs.	CO_2	N.A.	1000	0.5 in diameter hole corroded through inside radius of elbow.
Carbon steel	Elbow on CO_2 high pressure line	1.5 in Elbow (CG2101)	Synthane	N.A.	CO_2/inert gas	80	1000	Elbow developed a leak during operation.
Carbon steel	Pipe located downstream of orifice flange FE-308A	3 in pipe (CG3110D2A)	Synthane	3 yrs.	CO_2	N.A.	1000	Radiography revealed pitting that extended 50-60 percent of wall thickness.
Carbon steel (A106 Gr. B)	Pipe connecting to gasifier vessel C115	1 in pipe Schedule 40	Westinghouse	30 mos.	Recycle gas	600	N.A.	Failed by erosion near the weld at the gasifier.
Carbon steel (A178)	Tube segments from a 100 HP boiler heat exchanger	2 in 12 gauge	Pittsburgh Energy Technology Center	1000 hrs	Steam/flue gas	350	N.A.	Steam-side corrosion consisted of pitting and heavy scale on pipe exteriors. Flue gas corrosion occurred as a 3 mil scale that formed on interior walls.
Carbon steel (A106)	Pipe in gasifier steam superheater outlet line, B-207	1 1/2 in Schedule 40	CO_2 Acceptor	391 days	Steam	600	350	Pipe ruptured near 45° welded fitting.
Carbon steel (SA106 Gr. B)	Pipe weld in hydrogen addition line Line 5.1	3 in Schedule 80	Hygas	Nominal new weld	Hydrogen/methane	100	(1000 psia)	Cracking in weld and base metal extending through 75% of wall thickness.
Carbon steel	Pipe/elbow weld on high pressure CO_2 line, CG3107	3 in	Synthane	Nominal	CO_2/inert gas	N.A.	600	Leak developed at a pipe/elbow joint in the HAZ.
Incoloy 800	Weld in downcomer pipe, C110	N.A.	Westinghouse	600 hrs	Devolatilized product gas	N.A.	N.A.	Possibly stress corrosion cracking in weld.
Incoloy 800	Elbows on fines feed line	N.A.	Westinghouse	200 hrs	Recycle gas/ coke breeze	1200	240	Erosion damage by coke fines. Recurring problem.
Incoloy 800	Pipe/elbow connection	2 in	Westinghouse	800 hrs	Moist product gas	Ambient	N.A.	Crack in HAZ of pipe/elbow connection.
Incoloy 800	Pipe/flange connection in 2nd stage gasifier. Line 322	N.A.	Hygas	(1 1/2-2 yrs) (intermittent)	Synthesis gas/ char	1500	N.A.	Circumferential crack in HAZ of pipe/flange weld.
Incoloy 800	Piping in recycle gas line	N.A.	CO_2 Acceptor	N.A.	Recycle gas/ H_2S	N.A.	N.A.	Metal deposits formed in line from attack by H_2S.

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE[5], Continued

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
Incoloy 800	Pipe/flange connection to heater, F114. RGS-25	1 in	Westinghouse	2 yrs	Recycle gas	525	N.A.	Cracking in HAZ near weld. Possibly stress corrosion cracking.
Incoloy 800	Pipe weld area	4 in	Westinghouse	700 hrs	Recycle gas	N.A.	N.A.	Stress corrosion cracking in weld HAZ.
Incoloy 800	Pipe weld area in dolomite feed line to devolatilizer	4 in	Westinghouse	500 hrs	Recycle gas	Ambient	N.A.	Circumferential cracking in weld HAZ.
Incoloy 800	Heater tubes from recycle gas heater	N.A.	Clean coke	300 hrs	Recycle gas	1700	N.A.	Tubes failed by pitting, melting, and longitudinal splits caused by high temperature "metal dusting" corrosion.
Incoloy 800	Heater tube from the gasifier recycle gas heater 8-201-IA	N.A.	CO_2 Acceptor	1100 hrs	Steam/low S gas (<0.03%)/ high S gas (>0.03%)	1000-1600	150	Pipe experienced severe corrosion by carburization, sulfidation, and oxidation.
Incoloy 800	Heater tubes from gasifier recycle gas heaters B-201-IA, B-201-IIA, B-201-IIIA	1 5/8 - 2 in	CO_2 Acceptor	150 hrs	Low S gas	550-1220	150	150 hours after installation of a sulfur removal system 16 sections of tubing were examined. The insides of the tubes were severely pitted by "metal dusting" corrosion.
Incoloy 800	Heater tubes from acceptor lift gas heater, B-205	N.A.	CO_2 Acceptor	1699 hrs	Flue gas	1400	150	Severe scaling on pipe interiors led to termination of a run. Cause unknown.
Incoloy 800	Furnace coil in "A" pass of acceptor lift gas heater, B-205	N.A.	CO_2 Acceptor	N.A.	Inert gas/ air/recycle gas	1500	150	A 9 ft. 9 in. section of coil was replaced due to thinning from a combination of carburization and sulfidation.
Incoloy 800 RA 330	Furnace coil in "A" pass of acceptor lift gas heater, B-205	N.A.	CO_2 Acceptor	338-1500 hrs	Inert gas/ air/recycle gas	1500	150	Tubing greatly thinned from a combination of carburization and sulfidation.
Incoloy 800	Heater tube from recycle gas heater, B-201-1A	N.A.	CO_2 Acceptor	510 hrs with steam	Recycle gas/ steam	1400-1600	150	Piping was experiencing high temperature pitting corrosion. 50-60% steam was added to recycle gas and seemed to cure the problem.
Incoloy 800	Saddle between C111 entry elbow and CO_2 line	2 in	Westinghouse	800 hrs	Process gas	Ambient	220	Stress corrosion cracking in HAZ of saddle.
Incoloy 800	Pipe weld on pipe union on cyclone C119	N.A.	Westinghouse	200 hrs	Product gas	1700-1900	220	360° circumferential in central pipe weld of union caused by stress corrosion cracking.

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE [5], Continued

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
Inconel 600	Purge pipe BB-1 located inside gasifier	7/8 in 1/4 in wall thickness	Synthane	114-350 hrs	Steam (Interior)	800-1500	600	Pits were discovered on OD with depths up to 50% of wall thickness. Caused by sulfidation.
Inconel 601	Pipe from secondary Air Preheater Line	N.A.	Pittsburgh Energy Technology Center	~32 hr	Air with 25% oxygen	>2100	N.A.	Controller malfunction led to overheating and melting of the pipe.
Inconel 702	Furnace Coil from Acceptor Life Gas Heater B-205	N.A.	CO_2 Acceptor	61.5 hrs	Inert gas/ Air/Recycle gas	1500	150	Coil failed due to three holes in three different tube passes. Severe corrosion from sulfidation and carburization.
Monel	Reduction fitting on Line CX-9106	1 1/2 x 3/4 in Schedule 80	BCR BI-GAS	1 Year	Oxygen/Nitrogen	100	1600	Complete separation occurred at the 1 1/2 in diameter section at the point of transition caused by an explosion in the vicinity of the vent valve.
304 S.S.	Neck flange weld on Gasifier Inlet Line	4 in 900 lb R.F. Schedule 40	Synthane	~1000 hrs	Flue gas/ steam/oxygen	750	600	Cracking occurred at ID of neck flange weld probably due to stress corrosion cracking.
304 S.S.	Neck flange weld on Oxygen orifice Flange FI 203(FR-203)	N.A.	Synthane	2 Years	Oxygen	N.A.	1000	Leak occurred at edge of weld in HAZ, pitting in neck of flange. Cause unknown.
304 S.S.	Pipe from steam transport line.	4 in	Hygas	~2 Years	Steam	460	500	Five sections of pipe developed leaking cracks near welds caused by stress corrosion cracking.
304 S.S.	Pipe from Heat Up Line LI 2103 E2K	4 in Schedule 40 4" LI 2103 E2K	Synthane	2 Years	Fuel Oil/ LP Gas/ Steam/ CO_2/Coal gases/O_2/Air	800	600	2" Horizontal Crack occurred during operation. Cause unknown.
304 S.S.	Pipe from Heat Up Line L 2103 E2K	4 in	Synthane	N.A.	Fuel Oil/ LP Gas/ Steam/ CO_2/Coal gases/ O_2/Air	800	600	2" Crack parallel to the weld. Cause unknown.
304 S.S.	Pipe from Gasifier Relief Vent Line GG-4105-FG	3 in	BCR BI-GAS	~6 months	Process Gas	850	700	Circumferential Crack near elbow weld from stress corrosion cracking.
304 S.S.	Pipe from Gasifier Relief Vent Line GG-4105-FJ	3 in Schedule 80	BCR BI-GAS	~8 months	Process Gas	800	750	Brittle type Crack near a weld, possibly from stress corrosion cracking.
310 S.S.	Ring from regenerator Air distributor	4 in Schedule 40	CO_2 Acceptor	2200 hr	Air/flue gas	1830	150	Ring was partially melted from excessive heat from a process upset
310 S.S.	Pipe used as the inlet to line CD-206	6 in with .250 wall thickness	CO_2 Acceptor	2200 hr	Flue gas	1830	150	Tube was badly distorted probably from thermal cycling.
310 S.S.	Air distributor ring and pipe liner from dolomite transfer line nozzle	N.A.	CO_2 Acceptor	1400 hr	Air/flue gas	2300	150	Inner pipe lining fell on regenerator air distribution ring leading to excessive heat which melted the ring.
316 S.S. 410 S.S. 416 S.S.	High pressure fittings in the hydrogeneration PDU	316 SS Body 410 SS Gland nut 416 SS Collar	Clean Coke	N.A.	Hydrogen	700	N.A.	Leaks developed during operations; believed to be the result of differential expansion of dissimilar metals.
316 S.S. Incoloy 800	Pipe/flange joint at the interchanger shell outlet	316 SS Flange Incoloy 800 Piping	Clean Coke	3600 hr	Recycle gas	500-1200	165	Crack occurred between the flange and pipe; believe to be caused by differential expansion of dissimilar metals.

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE[5], Continued

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
316 S.S.	Pipe/elbow joint in the interchanger bypass line	2 in Schedule 40	Clean Coke	3600 hr	Recycle process gas	700-800	165	Circumferential crack that originated at root of the butt-weld joint; caused by a poor weld.
316 S.S.	Pipe from oxygen line OG 2102 E 3L	1 1/2 in	Synthane	N.A.	Oxygen/steam	N.A.	600-1000	A leaking valve allowed steam to enter the line, leading to a pinhole leak and a crack on the I.D.
316 S.S.	Pipe from gas sampling system No. 6411	1/4 in with 0.049 wall thickness	Hygas	∿4 mos	Producer gas	400	500	Cracks found which originated at OD bends; caused by chloride stress corrosion cracking.
316 S.S.	Heat exchanger tubes from fluidized bed combustor	1/2 in NPS Schedule 160	Morgantown Energy Technology Center	100 hr	Air	∿2000	N.A.	Tubes failed by melting due to high temperature sulfidation caused by excessive SO_2 and low oxygen pressure in the fluidized bed.
316 S.S.	Pipe in preheater line from the gas entrained feed system	N.A.	Synthane	N.A.	Gas	N.A.	N.A.	Chloride stress corrosion cracking occurred, originating at the ID. Also, general corrosion and pitting of ID.
316 S.S.	Instrument tubing used on impulse lines	1/2 in x 0.049 wall thickness	Hygas	2 mos.	Steam/oxygen	600	1200	Failed from mixed transgranular and intergranular cracking typical of chloride stress corrosion cracking.
316 S.S.	Supply tubing and fitting on line to slag tap burner POK-127-C-17050	1/2 in x 0.049 wall thickness	BCR BI-GAS	4 mos.	Triethy/aluminum/nitrogen	Amb-100	800	Moisture in the nitrogen combined with the triethyl/aluminum and exploded, rupturing the tubing.
316 S.S.	Welded tee fitting on spent char carrier line	N.A.	Hygas	N.A.	Steam/gas	550-1600	1000	Cracks found on internal surface of fitting, possibly caused by thermal shock.
321 S.S.	Furnace tube from lift gas furnace	1 5/8 in OD 0.109 wall thickness	CO_2 Acceptor	N.A.	Flue gas	900	150	Tube suffered nearly 50% loss of wall thickness from oxidation.
321 S.S.	Water jacketed pipe from gasifier overhead line	4 in	CO_2 Acceptor	∿8800 hr	Product gas	1525	150	Hole and a crack found on inside of pipe; possibly caused from strains associated with repeated thermal cycling.
321 S.S.	2 tubes from gasifier recycle gas heater B-201-IIIB	1 5/8 in OD x 0.109 wall thickness	CO_2 Acceptor	∿12,500 hrs	Steam/air/recycle gas	700-800	150	One tube cracked at a weld and the other had several longitudinal cracks in base metal. Failures believed to be corrosion related.
446 S.S.	Welded reducer between pipe and flange	4 in x 3 in reducer	Hygas	6 mos	Flue gas	1500	15	Stress corrosion cracking that originated at weld.
Alonized R.A. 330	Tubing coil from acceptor lift gas heater B-205	N.A.	CO_2 Acceptor	3929 hr	Inert gas/air/recycle gas	500-1500	150	Circumferential cracking found in lower section of coil, possibly due to stress corrosion cracking.

BELLOWS IN-SERVICE PERFORMANCE[5]

Material	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Incoloy 800	Hygas	9 mos	$H_2/H_2O/CO_2/CH_4/C$	1650	N.A.	Failed at an external convolution of the bellows from oxidation and intergranular attack.
Incoloy 800	Hygas	8 mos	$H_2O/H_2/CH_4/CO/CO_2/N_2$	650	N.A.	Leaked gas during start up pressure test - cause unknown.
Incoloy 800	Hygas	2 yrs	$H_2O/H_2/CH_4/CO/CO_2/N_2$/coal products	120-1200	N.A.	Bellows perforated, cracks found in end nipple.
304 S.S.	CO_2 Acceptor	N.A.	Recycle gas/ nitrogen	N.A.	150	Pitting corrosion initiated at ID caused by moist deposits and chlorides.
304 S.S.	CO_2 Acceptor	N.A.	Recycle gas/ nitrogen	N.A.	150	Circumferential cracking in bellows caused by chloride stress corrosion cracking.
304 S.S.	CO_2 Acceptor	31 days	Recycle gas/ air/steam	300	150	Transgranular cracking caused by chloride stress corrosion cracking.
304 S.S.	CO_2 Acceptor	∿4000 hr	$H_2/CH_4/CO_2/CO$	N.A.	150	Crack occurred at a convolution of the bellows probably from chloride stress corrosion cracking.
304 S.S.	CO_2 Acceptor	N.A.	Gasifier recycle gas	200	150	Crack occurred at first convolution of the bellows caused by chloride stress corrosion cracking.
321 S.S.	Hygas	3 mos	Exterior, hydrogen Interior, nitrogen	<200	Differential pressure <40 psi	Holes in bellows and loss of ductility believed to be caused by burnout of oxygen line in burner.
321 S.S.	Clean Coke	N.A.	Oil/0.8% H_2O/ 247 PPM chloride	450	N.A.	Pitting corrosion on inside led to a leak caused by improper drainage during shutdowns.

A.7.1.2.2 MATERIALS EVALUATION

The operating conditions for many gas lines are comparable to those for metal internal components. Materials must stand up to hot gas corrosion, particulate erosion and erosion/hot gas corrosion. Data for materials suitable for application under these conditions appear in Section A.2.4.2.2.

.7.2.1 OPERATING REQUIREMENTS

Solids transfer lines moving mixtures of coal, char, ash, and sometimes olomite connect various stages of the gasifier. Environments vary greatly ut in the worst cases may be as severe as that faced by gasifier internals temperatures up to 1,800 °F [1,255 K] and pressures up to 1,500 psi). nvironmental corrosion effects will be aggravated by erosive wear from bulk olids movement. Material problems will be similar to those anticipated for he gasifier internals (Section A.2.4.1) and product gas lines (Section .7.1.1). Refractory-lined pipes will probably be required for the most evere conditions.

A.7.2.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 16 SOLIDS PIPING systems (see A.7.2.2.1.1). Materials utilized included carbon-molybdenum steel, Incoloy 800, Incoloy 800 coated with nickel aluminide, Incoloy 800 coated with Stellite 12, Incoloy 800 coated with 75% chromium carbide/25% nichrome, alumina (Al_2O_3), and 304, 310, 316 and 446 stainless steels. Operating temperatures ranged from 400 to 1450 °F.

The one carbon molybdenum steel pipe subjected to a char/steam/coal gas environment failed due to a combination of erosion and corrosion. Five of the seven Incoloy 800 pipelines as well as the three coated Incoloy 800 pipelines all failed due to erosion. The probable cause of failure of one of the Incoloy 800 pipes was stress corrosion cracking. The other Incoloy 800 failure was due to an explosion.

The one alumina failure reported was due to erosion, caused by an excessive lift gas flow. The one 304 stainless steel failure and the one 316 stainless steel failure were also due to erosion.

Failure of the one reported 310 stainless steel pipe was caused by sulfur corrosion and thermal cycling. Stress corrosion cracking was the cause of failure of the one reported 446 stainless steel pipe.

Based on the reported data, erosion was clearly the most frequent cause of failure in the solids piping systems.

The longest service life reported was two years for Incoloy 800 at 400 °F in a char/recycle gas environment. The shortest service life reported was thirty hours, again for Incoloy 800, but at 1200 °F in a dolomite/recycle gas environment.

SOLIDS PIPING IN-SERVICE PERFORMANCE [5]

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
C-Mo Steel	Pipe welded to a 1 in 1500 lb sock-o-let in char transfer line, 1 P2112 E2B	1 in Schedule 80	Synthane	N.A.	Char/steam/ coal gases	N.A.	600	A hole occurred at edge of weld due to erosion/ corrosion.
Incoloy 800	Elbow on fines feed line, C102B	N.A.	Westing-house	100 hr	Coke breeze/ recycle gas	1200	240	Hole eroded in elbow.
Incoloy 800	Piping in spent acceptor lift line CD-208	4 in ID x 3/16 in wall thickness	CO_2 Acceptor	630 hr	Dolomite/re-cycle gas	1450	150	A hole was eroded in the inner liner close to lower slip joint due to misalignment of the slip joint.
Incoloy 800	Piping in spent acceptor lift line, CD-208	4 in ID x 3/16 in wall thickness	CO_2 Acceptor	N.A.	Dolomite/re-cycle gas	1350	150	Line exploded during attempt to clear a plug using forced air.
Incoloy 800	Piping in char recycle gas line, Dolomite diverter	1 in Schedule 40	Westing-house	30 hr	Dolomite/re-cycle gas	1200	240	Hole eroded in "Y" branch caused by impact of dolomite
Incoloy 800	Pipe below 4 in x 1 in reducer on line C-103B	1in pipe	Westing-house	120 hr	Coke breeze/ recycle gas	400	220	Hole eroded in wall by fines impingement.
Incoloy 800	Spool piece be-low C-103B	N.A.	Westing-house	2 yrs	Char/recycle gas	400	220	Pinhole leak and hairline cracks - possibly stress corrosion cracking.
Incoloy 800	Tee on char feed line near C-105B	4 in Tee	Westing-house	200 hr	Coke breeze/ recycle gas	500	200	Hole eroded in tee by fines impact.
Incoloy 800 coated with nickel aluminide	Transition cones of slip joint	4 in ID x 3/16 in wall thickness	CO_2 Acceptor	184 hr	Dolomite/re-cycle gas	1450	150	Erosion damage to transition cones.
Incoloy 800 coated with Stellite 12	Transition cones of slip joint	4 in ID x 3/16 in wall thickness	CO_2 Acceptor	835 hr	Dolomite/re-cycle gas	1450	150	Erosion damage to transition cones.
Incoloy 800 coated with 75% chromium carbide/25% nichrome	Transition cones of slip joint	4 in ID x 3/16 in wall thickness	CO_2 Acceptor	110 hr	Dolomite/re-cycle gas	1450	150	Erosion damage to transition cones.
Tabular Al_2O_3 castable	Refractory lined spool piece at bottom of riser leg	5 in-thick liner within 14 in ID pipe	Battelle, Columbus	∿200 hr	Mulcoa (cal-cined bauxite)/ lift gas	Ambient	N.A.	Spool piece refractory erosion caused by excessive lift gas flow.
304 S.S.	Tee in char transfer line P2112	1 in Pipe	Synthane	3 mos	Coal char/ steam/coal gas/ CO_2/N_2	400	600	Coal char erosion of line tee.
310 S.S.	Inner liner of outlet from re-generator line	6 in pipe with 0.250 wall thick-ness	CO_2 Acceptor	850 hr	Dolomite/flue gas	1830	150	Inner lining broke off and fell into vessel. Failed by sulfur corrosion and thermal cycling.
316 S.S.	Elbow from coal feed line, above nozzle 118	2 in/45° pipe elbow	Synthane	9 mos	Coal/oxygen/ steam/coal gas	N.A.	600	Hole eroded in elbow from coal particle impingement.
446 S.S.	Pipe in solids transfer line of hydrogasifier	N.A.	Hygas	N.A.	Process solids/gas	1500	1500	Circumferential cracking and complete fractures in welds and parent metal, possibly caused by stress corrosion cracking.

A.7.2.2.2 MATERIALS EVALUATION

The operating conditions for some solids transfer lines may be comparable to those for metal internal components. Materials must stand up to hot gas corrosion, particulate erosion and erosion/hot gas corrosion. Data on material suitable for application under these conditions appear in Section A.2.4.2.2.

.7.3.1 OPERATING REQUIREMENTS

Some gasification processes utilize coal feed in a slurry form in which he carrier fluid may be water or a hydrocarbon liquid. Other slurry lines ay be from a slag quench tank or a water quench scrubber tower. The latter ines will have the same corrosion problems as the originating vessels. All lurry lines will have potential erosion damage superimposed on the corrosion roblems since the velocity must be great enough for turbulent flow to aintain particles in suspension. Temperatures can range from 200-1,000 °F 366-811 K) and pressures up to 1,000 psi in slurry lines.

Carbon steel is probably adequate for low temperature applications. igher temperature feed lines and the more acid slurry lines will need, at east, stainless steel lining for corrosion resistance. Hard-face inserts for rosion resistance should be used wherever flow perturbations occur such as oints, elbows, and valves.

A.7.3.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for nine SLURRY PIPING systems (see A.7.3.2.1.1). Materials used in these systems included carbon steel, 300 series (austenitic) stainless steels and a 200 series (austenitic) stainless steel with a hard chromium coating. Reported temperatures of operation ranged from 60 to 800 °F and pressures ranged from 600 to 1500 psig.

Three of the four reported carbon steel failures were due to erosion. The other carbon steel failure was due to poor quality control.

All three reported 316 stainless steel failures were due to stress corrosion cracking. Conditions of usage were similar for these three piping systems. For the other 300 series stainless steel (consisting of four nozzles and the 200 series stainless steel, failure occurred due to erosion.

Except for the 316 stainless steel failures and the one carbon steel failure due to poor quality control, erosion was the predominant cause of failure, although stress corrosion cracking was a significant problem.

Service lives for the slurry piping were relatively short. The longest reported service life was 5 months for carbon steel in a water/1-20% char environment at 300 °F. The shortest service life was 50 hours for 316 stainless steel in an oil/lignite environment at 1500 °F.

SLURRY PIPING IN-SERVICE PERFORMANCE

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
Carbon Steel (A-53)	Piping Cross from slurry mixing vessel to pressure letdown valves	1 in IPS ASTM A-53 Schedule 160	Hygas	∿100 thermal cycles	Water/10% char	300	1000	Severe erosion by coal char.
Carbon Steel	Elbow on discharge line of pump GA-207	N.A.	Synthane	∿5 mos	Water/1-20% char	300	800	About 25% of elbow eroded away
Carbon Steel (D2A)	4 way cross on char transport line	1 in Schedule 80	Synthane	N.A.	Water/char fines	200-300	600	Leak at outlet weld of the cross. Pipe thinning on both sides of cross.
Carbon Steel	Heat exchanger tube/tube sheet interface in coal slurry Preheater	N.A.	BCR BI-GAS	3 weeks	Coal Slurry	60-457	1175	Leakage at rolled interface of tube/ tube sheet. Poor quality control.
S.S. (300 series)	4 spray tower Tar slurry nozzles, E-A-801 Line 81-360	1/2 in Diameter spray orifice	Cresap	N.A.	10% Tar Slurry solids	300	N.A.	All nozzles had plugging problems. One nozzle had through-wall leaks and severe erosion damage.
S.S. (200 series) Gullite coating (Hard Chromium)	Carbonizer internal spray nozzle D-A801 Line 81-159 CPH	1/4 in Diameter orifice	Cresap	N.A.	4-27% solids concentration	600	N.A.	Hole eroded through the nozzle body opposite flow inlet.
316 S.S.	Preheater Coil #1, 9 9/16 in diameter and 95 ft long	9/16 in OD x 0.250 wall thickness	Project Lignite	400 hr	Oil/Lignite	800	1500	Coil fractured at bottom near inlet from chloride stress corrosion cracking
316 S.S.	Preheater coil #2; 9 9/16 in diameter and 95 ft long	9/16 in x 0.250 wall thickness	Project Lignite	250 hr	Oil/Lignite	800	1500	Coil fractured near bottom from chloride stress corrosion cracking
316 S.S.	Preheater coal #3; 9 9/16 in diameter and 95 ft long	9/16 in x 0.250 wall thickness	Project Lignite	50 hr	Oil/Lignite	800	1500	Coil fractured near inlet from chloride stress corrosion cracking.

A.7.3.2.2 MATERIALS EVALUATION

The operating conditions for slurry lines involve exposure to particulate erosion and corrosive aqueous fluids at moderate to elevated temperatures. Data on materials which are resistive to particulate erosion over a range of temperatures appear in Section A.2.4.2.2. Data on materials which are resistive to aqueous corrosion over a range of temperatures appear in Section A.3.2.2.1.2.

.7.4.1 OPERATING REQUIREMENTS

Pure liquids lines other than cooling water lines are rare in the asification process. Lines carrying ash or slag in quench water from ne gasifier and lines from the product gas quench carry a significant articulate burden. Such lines are more appropriately considered as lurry lines (Section A.7.3) because of the substantial erosive damage otential.

Corrosion problems for piping will be dependent on their function and enerally will be the same as for the process vessel they serve, e.g. sour ater piping will need the same materials as the scrubber quench tank.

A.7.4.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 21 LIQUID PIPING systems (see A.7.4.2.1.1). Materials used for the piping included brass, carbon-molybdenum steel, carbon steel, Hastelloy G, Incoloy 800, and 304, 310, 316 and 316L stainless steels. Reported temperatures of operation ranged from 130 to 2000

The one admiralty brass failure reported was due to corrosion by nitric oxides. The other brass (alloy not identified) failure was caused by a poor weld. Failure of the one carbon-molybdenum steel pipe was due to the formatio of deposits on the inside of the piping in a heat exchanger which reduced heat transfer allowing the pipe to overheat.

Two of the seven carbon steel pipes failed due to corrosion and two failed due to a combination of corrosion and fatigue. One carbon steel failure was due to fatigue, one was due to erosion, and one was from unknown causes.

Stress corrosion cracking was clearly the predominant cause of failure for the superalloys and the stainless steels. The one Hastelloy G failure and the one Incoloy 800 failure were both due to stress corrosion cracking. Two of the three 304 stainless steel failures were due to stress corrosion crackin one from chlorides and the other from an improper heat treatment. The third 304 stainless steel failure was due to a crack in the heat affected zone associated with a weld.

The one 310 stainless steel failure reported was due to corrosion. One 316 stainless steel pipe failed due to erosion and another failed from stress corrosion cracking. A 316 stainless steel elbow welded to a 304 stainless steel flange, and another 316 component with Kaylo insulation both failed fron stress corrosion cracking. The one 316L stainless steel failure reported was due to a combination of erosion and corrosion.

The longest service life reported was 47 months for carbon-molybdenum steel in water at 600 °F with a pressure of 1500 psig. It should be noted that similar components under the same conditions failed in only two months. The shortest service life reported was 36 hours for 304 stainless steel exposed to molten carbonate at 950 °F.

LIQUID PIPING IN-SERVICE PERFORMANCE [5]

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
Admiralty Brass	Cooler tubes in Inert Gas Compressor After-cooler	N.A.	CO_2 Acceptor	N.A.	Water/nitric oxides	N.A.	200	Corrosion caused by the forming of nitric oxides under pressure in the presence of water.
Brass	Pipe in oil cooling bundle from the recycle compressor, K-501	N.A.	Battelle, Columbus	N.A.	Water	N.A.	N.A.	Tube ruptured due to a poor weld.
C-1/2 Mo Steel	U-tube heat exchanger from the Secondary Reformer Effluent Waste Heat Boiler	N.A.	Exxon Ammonia Plant, Netherlands	2-47 months	Water	600	1500	Many tubes have failed because deposits form on inside, insulating the metal walls, leading to above-design temperatures on exterior walls.
Carbon Steel	Threaded pipe adaptor CGR-30-1/4	1/4 in NPS	Westing-house	2 Years	Glycol	130	100	Fatigue failure.
Carbon Steel	Condenser tubing from Raw Gas Quench Cooler	3/4 in x 0.095 wall thickness	Hygas	1 Year	Raw gas condensate/ Ammonia	N.A.	N.A.	Pitting corrosion on interior caused by acidic nature of gas condensate.
Carbon Steel	Pipe elbow transporting water from Quench Tower to a Heat Exchanger	4 in IPS ASTM A-53-A ORB Schedule 120 Pipe butt welded to 4 in IPS ASTM A-234 Grade WPA Schedule 120 pipe	Hygas	N.A.	Water/10% caustic soda	200	1050	A crack was discovered by radiographic inspection. Cause of failure unknown.
Carbon Steel (D2A)	Inlet elbow to venturi Recycle Water Scrubber Pump, GA-207	6 in x 3 in reduction elbow	Synthane	3 Years	Water/char fines/Dissolved gases	N.A.	600	Elbow suffered erosion and corrosion damage from process fluid.
Carbon Steel	Heat exchanger tubes used in Syngas Compressor intercoolers and Synloop water coolers	N.A.	Exxon Ammonia Plant, Netherlands	2-6 Years	Water	N.A.	N.A.	The cooling bundles have been replaced several times over a 6 year period because of pitting corrosion caused by the poor quality of cooling water.
Carbon Steel	Pipe from waste water line	1/2 in Schedule 80	Westing-house	18 months	Chlorinated Coal tar liquid	N.A.	N.A.	Pipe failed at root of thread by corrosion fatigue.
Carbon Steel	Pipe from waste water line	1 in Schedule 40	Westing-house	18 mos.	Coal Tar Liquid	180	N.A.	Pipe failed at root of thread by corrosion fatique.
Hastelloy G	Cooling coil located at upper edge of slag taphole	1/4 in	Grand Forks Energy Technology Center	~54 hrs	Water	130-499	450	Many coils have failed in this application (S.S. and titanium). This coil failed by stress corrosion cracking.
Incoloy 800	Forged reducer butt welder to a carbon steel gasifier nozzle	3 in x 1 1/2 in	Synthane	N.A.	Aqueous condensate/ CO_2/CO/H_2S/ tars	400	N.A.	Stress corrosion cracking in the HAZ between the reducer and the nozzle lining.
304 S.S.	Entrant nozzles to Scrubber Pump Tank.	2 in Schedule 40	Carbonate, Atomics International	36-66 hrs	Molten Carbonate	950	N.A.	Circumferential cracking in HAZ of pipe-to-tank weld.
304 S.S	Tubes from a reboiler bundle	U-bends	Exxon Ammonia Plant, Netherlands	1-24 mos.	Promoted hot Carbonate solution	N.A.	N.A.	Stress corrosion cracking in U-bend area cause by an improper heat treatment.
304 S.S.	Piping from Purge Lines, FT-668 and LGR-3115, used to purge sight glasses.	1/2 in x 0.045 wall thickness	Hygas	6 mos.	Water	200	1200	Multiple circumferential cracks occurred caused by chloride stress corrosion cracking.

(Table Continued)

LIQUID PIPING IN-SERVICE PERFORMANCE [5], Continued

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
310 S.S.	2 Pipe Sections used as heat exchangers in a fluidized bed.	1/4 in Schedule 40	Morgantown Energy Technology Center	160 hrs	Water	200-2000	N.A.	Tubes suffered severe corrosion damage primarily due to being heated to 2000°F before cooling water was introduced.
316 S.S.	Six bayonet-type cooling tubes used in a fluidized bed.	0.125 in wall thickness	Battelle, Columbus	1100 hrs	Water	212	N.A.	Tubes failed from erosion damage.
316 S.S. 304 S.S	316 S.S. elbow welded to a 304 S.S. Flange	1 in Schedule 80	Synthane	N.A.	Water	500	1700	Circumferential crack in weld caused by stress corrosion cracking.
316 S.S. Kaylo Insulation	Pipe from purge Line LT-342	1/2 in x 0.049 wall thickness	Hygas	N.A.	Water/chlorides from insulation	300	1300	Leaking cracks found on OD at tube bends due to chloride stress corrosion cracking.
316 S.S.	Pipe from high pressure water line LT-477	1/2 in x 0.049 wall thickness	Hygas	N.A.	Water	300	1350	Leaking cracks occurred which were caused by chloride stress corrosion cracking.
316L S.S.	Pipe and elbows from cooling coil	3/4 in x 0.048 wall thickness	Exxon Mini Plant Linden, NJ	60 hrs	Combustor gas CO_2, SO_2, O_2	1500-1850 (Ext. gas temp)	N.A.	Severe erosion/corrosion on elbow exterior surfaces

7.4.2.2 MATERIALS EVALUATION

The operating conditions for liquids lines involve exposure to corrosive ueous fluids over a range of temperatures. Data on materials which are sistive to aqueous corrosion over a range of temperatures appear in ction A.3.2.2.1.2.

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8 Pumps

Sections included in this issue.

8.1.1 OPERATING REQUIREMENTS

Slurry pumps face the same corrosive and erosive conditions and oblems as the slurry lines (Section A.7.3.1). It is questionable ether presently available slurry pumps are adequate for reliable rvice in a commercial-sized gasification plant. Considerable developnt in both design and materials for this component is still needed. osion-resistant materials such as cemented tungsten carbides in the rm of easily replaceable inserts may be needed in many applications.

A.8.1.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 21 SLURRY PUMPS or SLURRY PUMP COMPONENTS (Section A.8.1.2.1.1). A variety of materials was involved includi cast iron, nichrome, cast steel, ceramic, Chempro 2000 and 620A, chromium steels, Ni-Hard, 410 stainless steel, 410 stainless steel with a Stellite overlay, Worthite 20 stainless steel, Stellite 6 on carbon steel and on 13% chromium steel, Teflon, carbon, tungsten carbide on stainless steel and on carbon steel, and Viton. Reported operating temperatures ranged from ambient to 750 °F.

The two cast iron failures and all four of the reported cast steel failures were due to erosion or a combination of erosion and corrosion. One of these failures was an impeller where failure was attributed to improper material selection which led to erosion/corrosion. The one nichrome impeller failure reported was also attributed to erosion.

One of the reported ceramic failures was a seal. The other two ceramic failures were coatings that flaked and peeled from the carbon steel substrate due to a combination of differential thermal expansion, poor bond strength, and low ductility.

Chempro 2000 and 620A packing failures in a solvent/diatomaceous earth environment led to the conclusion that these pumps were not suited to the application.

The 11-13% chromium steel, the Ni-Hard, and the Worthite 20 stainless steel components all failed due to erosion. The one reported failure of a 410 stainless steel component with a Stellite overlay was attributed to wear of the overlay. A Stellite 6 coating on carbon steel and on 13% chromium steel flaked off the casing, head and impeller.

Many Teflon seals and carbon washers in pumps were reported to have failed in use.

Tungsten carbide on carbon steel and on a stainless steel failed when the tungsten carbide peeled off, possibly due to differential thermal expansion.

Viton rings failed by oil and coal particle attack and a Viton stator suffered erosion damage.

The longest reported service life for a slurry pump or slurry pump component was 1422 hours at 200 °F in an oily water/char/tar environment. The shortest reported service life was 2.3 hours for the Chempro 2000-Chempro 620A seal failure. The operating temperature for this seal was 465 °F and the environment consisted of solvent and diatomaceous earth.

SLURRY PUMP IN-SERVICE PERFORMANCE [5]

Material	Description/ Component	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Cast Iron	Amime pump (Impeller)	CRESAP	N.A.	Lean MEA solution (14-22%)/4% CO_2	130	150(max)	Erosion/corrosion damage to impeller. Improper material selection.
Cast Iron Nichrome	Coal slurry pump (casing, impeller)	SRC (Wilsonville)	1.5 mos	Oil/coal	N.A.	N.A.	Cast iron casing and back plates lost significant amounts of material to erosion. Nichrome impeller suffered erosion damage.
Cast Steel	Filtration feed pump (casing)	SRC (Wilsonville)	750 hr	Oil/coal	600	150	Failure from erosion/corrosion of casing.
Cast Steel	Slurry recycle pump (casing)	SRC (Ft. Lewis)	N.A.	Slurry recycle stripper bottoms	750	50	Erosion damage to casing and pinhole leak in casing.
Cast Steel	Flare K.O. drum pump (casing)	Synthane	450 hr	Oily water/ char/tar	200	N.A.	Erosion of pump casing.
Cast Steel	Flare K.O. drum pump (casing, head)	Synthane	1422 hr	Oily water/ char/tar	200	N.A.	Erosion of casing and head.
Ceramic	Slurry circulating pump (seal)	Project Lignite	N.A.	Toluene/coal	N.A.	N.A.	Ceramic seal failed releasing toluene slurry and causing line pluggage.
Ceramic (PTI-54) on carbon steel	Primary hydroclone feed pump (coating)	CRESAP	N.A.	6 wt% slurry	100 (max)	650 (max)	Coating flaked and peeled at wear ring areas, impeller eye, and inside shrouds from differential thermal expansion, poor bond strength, and lack of ductility of coating.
Ceramic (PTI-54) on carbon steel	Primary hydroclone feed pump (coating)	CRESAP	N.A.	3 wt% alurry	100 (max)	650 (max)	Coating stripped off 80% of casing, head, impeller eye, and shrouds. Same reasons as above.
Chempro 2000 Chempro 620A (Packing)	Filtration precoat pump (packing)	SRC (Ft. Lewis)	2.3 hr	Solvent/ diatomaceous earth	485	165	Pumpa suffered packing leak problems. Conclusion was that theae pumps were unsuited for this application.
11-13% Chrome Steel	Tar quench pump (casing, head, impeller)	CRESAP	195 hr	Char slurry, 3-50% solida	100 (max)	625 (Max)	Erosion of casing, head, and impeller from char slurry and high operating speeds (3600 RPM).
Ni-Hard	Char slurry pump (casing)	Synthane	300-1200 hrs	Char slurry	Ambient	N.A.	Erosion damage to casing of two pumps.
410 S.S.	Coal slurry pump (valves, seats)	BCR BI-GAS	170-561 hrs	Coal slurry, 23-35 wt%	75-100	850	Valves and seats pitted and corroded.
410 S.S. Stellite overlay	Positive displacement pump (seats)	SRC (Wilsonville)	6-10 weeks	Oil/coal	Ambient	N.A.	Stellite seats were failing from wear problems.
Worthite 20 S.S.	Coal slurry pump (suction head)	SRC (Wilsonville)	∿2 mos	Oil/coal	176	40	Erosion damage to suction head.
Stellite 6 coating on carbon steel and 13% chrome steel	Extract disposal pump (casing, head, impeller)	CRESAP	N.A.	Water/2% granular coal material	100 (max)	8000	Coating on casing, head, and impeller flaked off.
Teflon Carbon	Filtration and fractionation pumpa (seals, washers)	SRC (Ft. Lewis)	N.A.	Oil/coal	N.A.	N.A.	30 different pumps have had a total of 79 failures. 12 pumps with John Crane 9B double seals accounted for 59 of the failures. Carbon washers and teflon seals were problems.
Tungsten Carbide on 12% chrome ateel	Coal slurry pump	SRC (Ft. Lewis)	30 days	Oil/coal	N.A.	N.A.	Erosion/corrosion failures have occurred in a circulating heater section and in hot slurry pumps.
Tungsten Carbide on carbon steel and stainless steel	Primary hydroclone feed pump (coating)	CRESAP	N.A.	6 wt% slurry	100 (max)	650 (max)	Recurring problem of peeling coating possibly from differential thermal expansion.
Viton	H.P. slurry pump (seals)	Hygas	<4 days	Oil/coal 45% solids (max)	N.A.	N.A.	Viton rings were destroyed by the attack of the oil and coal particles.
Viton	Slurry charge pump (stator)	Project Lignite	N.A.	Oil/coal	N.A.	N.A.	The Viton stator experienced erosion damage leading to a drop in discharge pressure.

A.8.1.2.2 MATERIALS EVALUATION

The operating conditions for slurry pumps involve exposure to particulate erosion and corrosive aqueous fluids over a range of temperatures. Data on materials which are resistive to particulate erosion over a range of temperatures appear in Section A.2.4.2.2. Data on materials which are resistive to aqueous corrosion over a range of temperatures appear in Section A.3.2.2.1.2.

.8.2.1 OPERATING REQUIREMENTS

Pumps for liquid streams will face the same corrosive problems as the iping lines (Section A.7.4) and their environment will be dependent on their unction. The most severe environment will be in quench water lines from the asifier and the product gas quench which carry a significant particulate urden. For such applications the pumps should be considered in the same ontext as slurry pumps.

A.8.2.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for eleven LIQUID PUMPS AND PUMP COMPONENT groups manufactured from various materials including Babbitt's metal, carbon, carbon steel, cast iron, cast steel, plastic and stainless steel (see A.8.2.2.1.1). Reported operating temperatures ranged from less than 32 to 300 °F.

At least six of the groups of failures were caused by misuse or abuse. These included the one Babbitt's metal failure where insufficient cooling water led to melting of the bearings, a carbon steel pump casing failure due to misalignment, a carbon steel shaft failure due to overload and vibration, two cast iron bearing housing failures caused by freezing of the cooling water jackets, a plastic pump casing failure due to stress on the pipe, and an oversize stainless steel shaft that led to excessive noise during operation.

In one system, a water leak resulted from a worn carbon pipe seal after 2000 hours of service. One carbon steel pump housing failed after 125 hours due to corrosion and another failed due to a combination of erosion and corrosion of the casing and head (service life not stated).

One carbon steel shaft and one cast steel bearing housing developed cracks from unknown or unstated causes.

There are insufficient data to draw any definitive conclusions regarding liquid pumps.

A.8.2 Liquids Pumps
A.8.2.2 Performance Data
A.8.2.2.1 Plant Experience

LIQUID PUMP IN-SERVICE PERFORMANCE [5]

Material	Description/ Component	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Babbitt's metal (48 Pb, 40 Sn, 10 Sb , 2 Cu)	H.P. boiler feed water pump (bearings, gears)	Synthane	N.A.	Water	200	30 in 1300 out	Insufficient cooling water led to melting of babbitt bearings and damage to gears.
Carbon	Cooling water pump (seals)	Battelle, Columbus	2000 hr	Water	Ambient	N.A.	Pipe seal worn which led to water leak.
Carbon Steel	Scrubber recycle water pump (casing)	Synthane	125 hr	Water/air/ char fines	300	600 in 740 out	Corrosion damage to the dome of the case and through the bolt holes.
Carbon Steel	Scrubber recycle water pump (casing)	Synthane	4 hr	Water/air/ char fines	300	600 in 740 out	Misalignment during installation led to a leaking, circumferential crack in the case.
Carbon Steel	H.P. boiler feed water pump (shaft)	Synthane	2 yrs	Water	200	30 in 1300 out	Shaft replaced because of crack near one end.
Carbon Steel	Solvent quench pump (casing, head)	CRESAP	N.A.	Solvent/0.3-1% H_2O/0.5-1.6% solids/sour gas	100-250	720 (max)	Erosion/corrosion of casing and head.
Carbon Steel	Quench water re-circulating pump (shaft)	Hygas	<4 days	Water/5% solids	150	N.A.	Pump shaft cracked near one end apparently due to overload and vibration.
Cast Iron	Scrubber recycle water pump (bearing housings)	Synthane	2 yrs	Water/air/ char fines	<32	600 in 740 out	Cooling water jackets froze and cracked the bearing housings on 2 pumps.
Cast Steel	Scrubber recycle water pump (bearing housing)	Synthane	3 mos	Water/air/ char fines	300	600 in 740 out	Crack in bearing housing. Cause unknown.
Plastic	Inhibitor pump (casing)	Battelle, Columbus	2000 hr	Water/ Inhibitor compound	Ambient	N.A.	Pump body broke at pipe fitting due to stress on the pipe.
Stainless Steel	Scrubber recycle water pump (shaft)	Synthane	1 hr	Water/air/ char fines	300	600 in 740 out	New shaft was oversized leading to a rapping noise during operation.

A.8.2.2.2 MATERIALS EVALUATION

The operating conditions for liquids pumps involve exposure to particulate erosion and corrosive aqueous fluids over a range of temperatures. Data on materials which are resistive to particulate erosion over a range of temperatures appear in Section A.2.4.2.2. Data on materials which are resistive to aqueous corrosion over a range of temperatures appear in Section A.3.2.2.1.2.

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A.9.1.1 OPERATING REQUIREMENTS

Gas stream valves to control the flow of air, combustion gases, and product gases are required in all gasification processes. These valves must withstand rapidly changing pressures, intermittent high flow rates, and, in some cases, high temperatures (up to 2,000 °F [1,366 K]) and high pressures (up to 1,500 psi). Materials technology transfer appears to be available for purely gaseous environments from high pressure chemical processes. The most severe environment exists for the product gas which contains potentially corrosive compounds plus an erosive particulate burden which seems to be the most serious problem. Valves for this environment should be considered in the context of solids transfer valves (Section A.9.3).

A.9.1.2.2 MATERIALS EVALUATION

The operating conditions for gas valves involve exposure to particulate erosion and hot corrosive gases over a range of temperatures. Data on materials which are resistive to particulate erosion and hot corrosive gases over a range of temperature appear in Section A.2.4.2.2. Data on resistance to erosion for candidate valve materials appear in Section A.9.3.

A.9.2.1 OPERATING REQUIREMENTS

Valves on all-liquids lines will need the same corrosion resistance requirements as the lines themselves with the added requirement of good thermal and mechanical shock resistance. Materials technology transfer from chemical and petroleum industries should be adequate for this application. However, if the liquid carries a significant particulate burden, the erosive problem will be quite serious and these valves should be considered in the context of slurry valves (Section A.9.3).

A.9.2.2.2 MATERIALS EVALUATION

The operating conditions for liquids valves involves exposure to aqueous corrosion over a range of temperatures and to thermal and mechanical shock. Data on materials which are resistive to aqueous corrosion over a range of temperatures appear in Section A.3.2.2.1.2. Data on resistance to thermal and mechanical shock of candidate valve materials appear in Section A.9.3.

A.9.3.1 OPERATING REQUIREMENTS

The operating requirements for valves used in solids transfer vary among the several coal gasification processes. High temperature, high pressure, cyclic loading, and wear and erosion are typical of service conditions. Requirements depend on location of the valve within a process. In general, however, solids valves may be classified into four types, depending primarily on temperature of service; this classification is summarized below.

DESIGN OPERATING TEMPERATURES[3]

Maximum Bulk Media Temperature	Maximum Interface Temperature
Type I - 350 °F	350 °F
Type II - 600 °F*	850 °F
Type III - 2000 °F	850 °F
Type IV - 600 °F (slurry & slag discharge)	600 °F

*The valve temperature may reach 850 °F on initial heat-up under maximum pressure but without coal.

In addition to the ability to withstand the above temperatures, and to operate at pressures from atmospheric to 1,600 psig, the materials of construction and the design must be combined to meet expected lifetimes of 30,000 cycles while exposed to highly erosive streams containing corrosive gases and liquids. Abrasive wear associated with unlubricated materials contact often occurs, even in the presence of purging, and often leads to more serious erosive failure. Materials compatibility is an important requirement in order to minimize contact welding, spalling of surface coatings, and thermal distortion. Clogging of valves by adhering solids or tarry substances can prevent complete closure. The leak of gas-borne particles through the gap can result in erosion.

A.9.3.2.1 PLANT EXPERIENCE

Plant experience has been reported for 20 different solids valves. Fifteen different materials were in these valves. Service temperatures ranged from 180 to 1,450 °F. Twelve valves were removed from service due to wear and erosion. These valves were made of a wide variety of materials-- carbon steel, 316 stainless steel, Kennametal K701, Stellite 6, Teflon, Coors 999 ceramic and Stellite coated on 316 stainless steel. The material which lasted the longest under the most severe service conditions was Stellite 6 in the Synthane Plant (1.5 years/300 °F/600 psi/char-water-gas). Carbon steel also lasted well. The ceramic showed the shortest life at four days.

A 3-inch pinch valve of rubber was removed due to abuse by overload. A poor weld between shaft and butterfly led to failure and removal of a valve made of RA 330 and Haynes 25 in service at 1,450 °F. An Incoloy 800 valve was removed after 9 months of service at 1,456 °F, but could have remained in service longer if misalignment had not caused severe erosion.

Inappropriate design leading to valve body distortion resulted in removal of three Type 316 stainless steel valves from service. Manufacturing defects overlooked by quality control resulted in two valves--one 440 stainless steel and one 316 stainless steel--being removed from service.

In some plant operations, there were indications that solids became lodged at the valve seats and prevented complete closure. The continuing leak of gas-borne particulates through the gap was identified as a source of considerable erosion in some cases. A method for removing solids buildup on mating surfaces could minimize this source of valve erosion.

SOLIDS VALVES IN-SERVICE PERFORMANCE[5]

im Material	Valve Type (Plant ID)	Process	Service Life	Environment	Temp. °F	Pressure PSIG	Failure Mode
6 SS ite Iron	6-in Full Port Ball (0612)	METC	297 cycles	Ash	900	125	Wear: scoring on ball, wear on seat
6 SS ellite 6	10-in Full Bore Ball (1005)	METC	257 cycles	Coal	250	300(max)	Quality control: cracks in ball from a manufacturing defect
16 SS	(HV-719)	Westinghouse	200 hours	Coke breeze/ recycle gas	500	200	Design: valve body distorted by impingement of fines particles
16 SS	(HV-718)	Westinghouse	200 hours	Coke breeze/ recycle gas	500	200	Design: valve body distorted by impingement of fines particles
16 SS	(HV-1106)	Westinghouse	200 hours	Coke breeze/ recycle gas	500	200	Design: valve body distorted by impingement of fines particles
S sleeve eramic seat	Letdown (LCV-405)	Synthane	2 months	Coal char	---	1000	Erosion
40C SS	2-in Ball (XCV-26)	Synthane	∿200 cycles	Coal/CO_2	300	160	Quality control: surface defects and poor design led to failure of the stem
tellite on 16 SS	Level control (LCV-201)	Synthane	1 month	Coal char fines in water	180-300	600	Erosion
A 330 aynes 25	High-temperature Butterfly (LCV-2002)	CO_2 Acceptor	1200 hours	Char/inert gas	1450	---	Fabrication: poor weld, butterfly came off shaft
ncoloy 800	High-temperature Gate (XCV-2010)	CO_2 Acceptor	∿9 months	Dolomite/recycle gas	1450	150	Erosion: pipe liner was misaligned during installation leading to erosion of valve in line
eflon arbon steel	6,10,12-in Ball (3 valves)	METC	100-200 hours	Coal/ash/gas/ air/steam	200-700	---	Wear: gouging and abrasion of seats
arbon steel	1-in, 800-lb Globe	Cresap	2400 hours	Carbonizer tar slurry, 3-28% solids	300	---	Erosion: hole in bonnet/ body and internals eroded
arbon steel	Plug (XV-271)	Synthane	1 year	Water/coal dust/coal char	300	600	Erosion: plug surface
Carbon steel	Gate (in venturi scrubber bypass)	Synthane	6 months	Char/water/ steam/CO_2/ coal gas	---	---	Erosion: severe, body and gate
Kennametal K701 (WC with Co-Cr binder)	Pressure letdown (on product oil line)	Synthoil	915 hours	Product oil with 5-6% solids	257	4000	Erosion: plug tip, stem seat eroded/braze joint cracked
Coors 999 ceramic	Coors Willis Choke (LCV-405A)	Synthane	4 days	Char/water/ dissolved gases	---	---	Erosion: holes in trim and downstream sleeve
Stellite 6	Letdown to flare (PCV-2205)	Synthane	1.5 years	Char/water/ gas	300	600	Erosion: 100% erosion of trim/body unusable
SS Carbon steel	Letdown (PCV-266)	Synthane	37 hours	Char/water/ gas	800	600	Erosion: 50% erosion of trim/groove in downstream pipe
Rubber	3-in Pinch (Series B3)	Bigas	6 months	Coal slurry	Ambient	---	Misuse, overstressing: tear in rubber sleeve from over-tightening hand wheel

A.9.3.2.2 COMPONENT TEST AND DEVELOPMENT

Seat leakage test results (A.9.3.2.2.1) were obtained for 11 Lockhopper valve types, the components of which included 16 material combinations. Valve design operating pressures varied from 200 psig to 1200 psig (13.8 bars to 82.7 bars). Operating temperatures varied from 37.8 °C (100 °F) to 454 °C (850 °F). Leak rates per number of cycles were determined in 3 different test categories for the various valve types and material combinations: an acceptance test, a static test, and a dynamic test.

A typical range of values for leak rate per number of cycles is shown in the following table for those valves which performed satisfactorily.

LEAK RATE, m^3/min. (ft.^{3}/min.)/CYCLES

ACCEPTANCE TEST	STATIC TEST	DYNAMIC TEST
0.0008 (0.030)/0 to 0.1123 (4.0)/0	0.0001 (0.005)/300 to 0.0730 (2.6)/370	0.0618 (2.2)/3970

Valve types in the satisfactory category were a: (1) 6 in Rotary Gate; (2) 6 in Knife Gate, (3) 6 in Y-Globe; (4) 8 in Hybrid Ball; (5) 6 in Hybrid Swing; and (6) 6 in Ball. Respective component materials combinations for these were: (1) Colmonoy #5 on 440C SS with Stellite 6 on 440C SS; (2) 440A SS, R_c 50 to 52, with Stellite 6 on 304 SS; (3) 440 SS with PTFE asbestos fiber ring seals with 440 SS, R_c 55; (4) Stellite 6 on 316 SS with Stellite 6 on 316 SS (5) Stellite 6 on carbon steel with Stellite 6 on 316 SS; and (6) Stellite 6 on 316 SS with cast Stellite 6.

Typical materials combinations for valves whose performance was not considered to be satisfactory because of galling and, in some cases, in combination with other failures such as valve stem failure, were: (1) 440 SS, R_c 58, with Stellite 6 on 316 SS; and (2) Kamog on cast Stellite 6 and Tribaloy 700.

Materials combinations of valves that failed due to external leakage problems or erratic performance (i.e. wide scatter in leakage rates) were: (1) Teflon (PTFE)-coated cast iron with cast iron integral with the body; (2) Colmony #5 on 440C SS with cast Stellite 6; (3) 304 SS with Thermalloy 400 on 304 SS; and (4) WC coating on 316 SS with Stellite 6 on 316 SS.

The Acceptance Test was used to determine conformance with the purchase agreement on leakage and dimensional requirements. Eleven valve types representing fifteen component material combinations were evaluated in this test. Of these tests, satisfactory performance resulted for 6 valve types.

The Static Test was designed to determine the initial leak rate, operating force or torque, response time, and the effects of dry cycling on these parameters. Valves were tested with air or inert gas at ambient temperatures and manufacturers rated operating temperatures. Pressures varied according to ANSI class. The same eleven valve types representing fifteen component material combinations used in the Acceptance Test were also evaluted under this test.

In the Dynamic Test the valve was required to handle solid materials at ambient temperatures only. Only two dynamic tests were performed on two different valve types representing two materials combinations. Of these, only one valve resulted in satisfactory performance. The short table above lists a range of acceptable leak rates for each of these tests.

Design operating pressure for those valves which performed satisfactorily ranged from 300 to 1000 psig (20.7 to 68.9 bars). Design operating temperature ranged from 149 °C (300 °F) to 454 °C (850 °F).

There were a wide range of failure types for those valves which did not perform satisfactorily. Five valves were deleted from the test program. Severe galling of the valve seat and ball; erratic performance, severe chipping and spalling of the coating; unsatisfactory operation at design conditions and valve stem failure were typical failure types for these valves. External leakage and sleeve failures for three of the valves resulted in reworking the valve but no further testing.

One of the valves locked up during dynamic tests which resulted in the valve cracking. The valve was reworked, but there was no report of further testing.

In Section A.9.3.2.2.2 are the results of seat-visor tests for twenty-two materials combinations. Nine different materials were involved. Sixteen tests were carried out in a prototype valve test fixture and six tests were carried out in a seating materials test fixture at 70 °F. Six tests were run at temperatures between 800 and 1050 °F---the other 16 were run at 70 °F. These 70 °F test results have use for ranking materials for performance at 70 °F, but results of these 16 tests are of minimal value in evaluating material performance for a typical solids valve under conditions where temperatures range from 350-850 °F. The number of cycles ranged from 22 to greater than 10,000.

Of the six high-temperature tests the materials which remained in excellent condition after severe testing included: Inconel 718 inlaid with Stellite 1016 or Stellite 6, and uncoated Inconel 718. Boron carbide performed well in some tests but poorly in others. The performance of boron carbide did not seem to be related to temperature.

Of the sixteen 70 °F tests, the materials which remained in excellent condition after severe testing included: boron carbide, Stellite 6B, silicon nitride, and TiCN coated on Ti-6Al-4V. Twelve of the 16 tests involved a TiCN coating on the seat (two tests) or the visor substrate (ten tests). The TiCN coating performed well on a Ti-6Al-4V substrate, but spoiled and cracked on an Inconel 718 or titanium substrate. Borided TY502 tended to chip in one test out of the two conducted with it as a seat material. Among the 16 tests at 70 °F, there were three test malfunctions, including one test with significant misalignment, which invalidated those test results.

LOCKHOPPER VALVES--SEAT LEAKAGE TEST RESULTS[4]

Trim Material	Valve Type	VALVE DESIGN OPERATING PARAMETERS Pressure Bars(psig)	Temperature °C(°F)	LEAK RATE[a]/NO. OF CYCLES Acceptance Test[b]	Static Test[c]	Dynamic Test[d]	Comments
Disc: Colmonoy #5 on 440C SS Seat: Stellite 6 on 440C SS	6 in Rotary gate ANSI Class 250	21.3(310)	149(300)	0.1123(4.0)/0	0.0730(2.6)/370	0.0618(2.2)/3970	Valve performance through 3600 dynamic cycles very good/no degradation
Ball: 440C SS, R_c 58 Seat: Stellite 6 on 316 SS	6 in Modified Ball, ANSI Class 600	82.7(1200)	37.8(100)	0.0003(0.01)/0	0.1685(6.0+)/250	---	Valve stem failure/seat galled/deleted from test program
Ball: 440C SS, R_c 58 Seat: Stellite 6 on 316 SS	6 in Modified Ball, ANSI Class 600	82.7(1200)	37.8(100)	0.0003(0.01)/0	0.1685(6.0+)/250	---	Severe galling of seat and ball/deleted from test program
EPR elastomer[e]/cord composite tube	6 in Pinch, ANSI Class 250	13.8(200)	65.6(150)	0.0618(2.2)/0	0.0309(1.1)/206	---	Sleeve failure/ valve refurbished but untested
EPR elastomer[e]/cord composite tube	6 in Pinch, ANSI Class 250	13.8(200)	65.6(150)	0.0253(0.9)/0	0.0421(1.5)/116	---	Incipient sleeve failure/ valve refurbished but untested
Plug: Teflon(PTFE)-coated cast iron Seat: Cast iron integral with the body	6 in Lubricated Plug, ANSI Class 250	20.7(300)	132.2(270)	0.0674(2.4)/0	0.0815(2.9)/261	---	Erratic performance/wide scatter of leakage rates as function of amount of lubricant present/test discontinued
Ball: CrO(LC-4)-coated 316 SS Seat: CrO(LC-4)-coated 316 SS	6 in Ball, ANSI Class 300	48.9(710)	260(500)	0.0506(1.8)/0	0.0871(3.1)/376	0.2809(10.0+)/1076	Coating spalled and chipped severely/test discontinued
Disc: Colmony #5 on 440C SS Seat: Cast Stellite 6	6 in Rotary Gate ANSI Class 600	41.4(600)	316(600)	0.0000(0.0)/0	0.0024(0.085)681	---	Problems with external leakage of valve at center body gasket
Disc: Stellite 6 on carbon steel Seat: Stellite 6 on carbon steel	6 in Rotary Gate ANSI Class 300	20.7(300)	316(600)	---	---	---	Deleted from test program/ failed to operate satisfactorily at design conditions
Disc: Stellite 6 on 316 SS Seat: Stellite 6 on 316 SS	6 in Hybrid Ball ANSI Class 600	41.4(600)	316(600)	0.0104(0.370)/0	---	---	External leakage from stuffing boxes/minor seat galling/valve reworked
Gate: 440A SS, R_c 50 to 52 Seat: Stellite 6 on 304 SS	6 in Knife Gate ANSI Class 600	41.4(600)	316(600)	0.0180(0.64)/0	0.0073(0.26)/287	---	Performance was beyond expectations
Disc: Stellite 1 on carbon steel(A 217) Seat: Stellite 6 on 310 SS	6 in Double Disc Gate, ANSI Class 900	68.9(1000)	316(600)	0.0025(0.09)/0	0.0039(0.14)/335	---	Valve locked up during dynamic tests/cracking found in stellite hardfacing/ valve reworked

(Table Continued)

LOCKHOPPER VALVES--SEAT LEAKAGE TEST RESULTS[4], Table Continued

Trim Material	Valve Type	VALVE DESIGN OPERATING PARAMETERS Pressure Bars(psig)	Temperature °C(°F)	LEAK RATE[a]/NO. OF CYCLES Acceptance Test[b]	Static Test[c]	Dynamic Test[d]	Comments
Plug: 440C SS with PTFE-asbestosfiber ring seals Seat: 440C SS, R_c 55	6 in Y-Globe ANSI Class 600	41.4(600)	316(600)	0.0011(0.04)/0	0.0001(0.005)/300	---	Performance satisfactory to date
Plug: 304 SS Seat: Thermalloy 400 on 304 SS	6 in Hybrid Swing Check, ANSI Class 600	41.4(600)	315(600)	0.0039(0.140)/0	---	---	Problems with external leakage at center body flange/valve reworked
Ball: Stellite 6 on 316 SS Seat: Stellite 6 on 316 SS	8 in Hybrid Ball ANSI Class 600	41.4(600)	315(600)	0.0899(3.2)/0	0.0011(0.04)/390	---	Performance satisfactory to date
Disc: Stellite 6 on carbon steel Seat: Stellite 6 on 316 SS	6 in Hybrid Swing Check, ANSI Class 900	68.9(1000)	149(300)	0.0008(0.030)/0	0.0008(0.030)/245	---	Performance satisfactory to date
Ball: Stellite 6 on 316 SS Seat: Cast Stellite 6	6 in Ball, ANSI Class 300	20.7(300)	454(850)	0.0098(0.350)/0	0.0044(0.155)/279	---	Performance satisfactory to date
Ball: Kamog[f] on cast stellite 6 Seat: Tribaloy 700	6 in Ball, ANSI Class 600	41.4(600)	316(600)	0.0008(0.028)/0	---	---	Seat galling in 600°F tests/valve reworked
Ball: WC coating on 316 SS Seat: Stellite 6 on 316 SS	6 in Ball, ANSI Class 600	41.4(600)	316(600)	0.0000(0.000)/0	---	---	External leakage problem with stuffing boxes/valve reworked
Wedge: Carbon steel Seat: Cast Stellite 6	6 in Wedge Gate ANSI Class 600	41.4(600)	316(600)	0.0000(0.000)/0	---	---	
Ball: Colmonoy #6 on carbon steel(4130) Seat: Cast Stoody #1, R_c 50-56	6 in Ball, ANSI Class 600	41.4(600)	316(600)	---	---	---	
Gate: Stellite 6 on A 487 Seat: Stellite 6 on A 182	6 in Expanding Wedge Gate, ANSI Class 600	41.4(600)	316(600)	---	---	---	

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[a] Leak rate units are m^3/min (ft^3/min).

[b] This test consists of inspections, operation, and leakage tests to determine compliance with dimensional and leakage requirements of the purchase agreement.

[c] This test is designed to determine the initial leak rate, operating force or torque, response time, and the effects of dry cycling on these parameters. Valves are tested with air or inert gas at ambient temperatures and at manufacturers' rated operating temperatures. Pressures vary according to ANSI Clas based on ANSI B16.34-1977 for Materials Group 1.1.

[d] This test is similar to the Static Test, but the valve is required to handle solid materials at ambient temperatures only.

[e] Ethylenediene propylene monomer.

[f] Kamog is a proprietary coating of Kamyr, Inc.

SEAT-VISOR MATERIALS TEST[a] RESULTS[6]

Seat Material	Visor Material	Test Conditions	Results
Boron carbide, square[b]	Stellite 6B, square[b]	3900 lbs load, 70°F, Husky char abrasive, specimens mounted eccentrically	Seat sample damaged by the impact of leading edge of visor sample just above the center of seat sample. Stellite 6B showed no significant wear after 5000 cycles testing with fluidized char.
Ti-6Al-4V, CVD[c] TiCN coating, square[b]	Boron carbide, square[b]	3900 lbs load, 70°F, Husky char abrasive, samples not misaligned	Visor sample undamaged; seat sample deformed by the impact of visor sample edge at midpoint of seat sample; deformation led to cracking of TiCN coating.
Ti-6Al-4V, CVD[c] TiCN coating, square[b]	Boron carbide, square[b]	3900 lbs load, 70°F, Husky char abrasive, fixture modified to give samples full area contact	No damage to samples; char trapped between test samples was crushed and compacted, preventing possible damage to seat and visor samples.
Tungsten carbide, TiCN coating, square[b]	Boron carbide, square[b]	3900 lbs load, 70°F, 8-100 mesh silica sand abrasive, 2500 cycles	Both samples badly damaged; one corner of seat sample broken off; entire surface of visor sample badly gouged; cause was significant misalignment of samples.
Silicon nitride, reaction bonded, 1/2" radius cylinder segment[b]	Ti-6Al-4V, TiCN coat, square[b]	500 lbs/linear inch load, fluidized sand abrasive, 70°F, 30,000 cycles	No damage; minimal surface wear on seat sample; no wear on surface of TiCN coating.
Silicon nitride, reaction bonded, 1/2" radius cylinder segment[b]	Ti-6Al-4V, TiCN coat, square[b]	6000 lbs/linear inch load, fluidized sand abrasive, 70°F, 1800 cycles	Seat sample cracked at the contact area and showed some surface wear.
Boron carbide	Inconel 718, CVD[c] TiCN coating	70°F, 70-1300 psig inlet pressure, 12 cycles 100-3000 ft-lbs torque to close valve	At inlet pressure of 70 psig, leakage rate was 0.9 scfm, at 1300 psig rate was 58.5 scfm; test discontinued because of high rate; upon disassembly the seat was found fractured (ca. 16 places).
Boron carbide	Inconel 718, CVD[c] TiCN coating	70°F, 250-500 psig inlet pressure, 2000 ft-lbs torque, no cycling	Pressure, psig — Leakage, scfm 500 — 1.2 250 — 0.7 500 — 1.8 750 — 3.75 500 — 8.3 Test discontinued; boron carbide seat found fractured; TiCN coating on visor had small cracks.
Borided TY502 (5% Cr-1/2% Mo)	Inconel 718 (uncoated)	70°F, 20-1600 psig inlet pressure, 180 cycles	Pressure psig — Leakage, scfm: initial — after 180 cycles 20 — 0.06 — 0.07 50 — 0.10 — 0.15 100 — 0.18 — 0.80 500 — 0.60 — 1.3 1000 — 1.0 — 1.5 1600 — 1.1 — 2.0 Test discontinued; small chips found in the boride coating of the seat; material discarded as a candidate seat material.
Boron carbide (shrink fit into Inconel 718 retainer)	Inconel 718, CVD[c] TiCN coating	70°F, 20-1600 psig inlet pressure, 500 cycles, seating load cycled 0, 830, 1600 lbs, then 2070 lbs	During cycling, 0-1600 lbs seating load, 20-100 psig, leakage ranged 0.12-0.35 scfm; at 0 lbs and 1600 psig, leakage was 0.006 scfm; after 500 cycles leakage was 0.003 scfm at 1600 psig and load of 2070 lbs; boron carbide seat was in excellent condition; visor showed small indentation in the seating area due to plastic deformation at high load.
Borided TY502 (5% Cr-1/2% Mo)	Titanium, TiCN coating (received with seating surface distorted 0.015 in)	70°F, 20-1600 psig inlet pressure, 30 cycles	Pressure psig — Leakage, scfm: initial — after 30 cycles 20 — 7.0 — 1.0 50 — 10.6 — 1.2 100 — 1.8 — 0.3 500 — 2.8 — 1.2 1000 — 3.3 — 1.8 1600 — 3.1 — 2.0 High initial leakage, 10.6 scfm at 50 psig, was due to distortion of viscr; leakage rates improved after cycling apparently due to smoothing of TiCN coat during cycling, coat was initially rough.
Boron carbide	Inconel 718, TiCN coating	850°F, 14.7 psig inlet pressure, 93 cycles	TiCN coating on visor spalled; boron carbide seat in good condition.
Boron carbide	Titanium, TiCN coating	70°F, 1600 psig inlet pressure, 117 cycles	Leakage before cycling, 0.37 scfh, after cycling, 0.44 scfh; increased leakage due to further deterioration of the TiCN coat on visor; boron carbide seat in good condition.

(Table Continued)

SEAT-VISOR MATERIALS TEST[a] RESULTS[6], continued

Seat Material	Visor Material	Test Conditions	Results
Boron carbide (shrink fit into 17-4PH SS retainer)	Titanium, TiCN coating (same visor as above reworked)	70°F, 20-1600 psig inlet pressure, 50 cycles	Leakage after 2 cycles, 0.003 scfm, after 50 cycles, 0.003 scfm; no degradation; TiCN coating showed spalling.
Boron carbide (free standing in Inconel 718 retainer)	Titanium, TiCN coating	70°F, 250-1600 psig inlet pressure, 156 cycles	Leakage at 1600 psig and 156 cycles, 350 scim; boron carbide seat in excellent condition; TiCN coating of visor showed evidence of spalling at seating surface; TiCN spalling cannot be eliminated, coating abandoned.
Boron carbide (shrink fit into Inconel 718 retainer)	Inconel 718 (uncoated), spherical	1050°F, 1600 psig inlet pressure, 95 cycles	Test terminated due to excessive leakage of the closure gasket of the test fixture; seat was in excellent condition, visor showed seating marks.
Boron carbide (shrink fit into Inconel 718 retainer)	Inconel 718 (uncoated), spherical	800°F, 1600 psig inlet pressure, 22 cycles	Leakage at 800°F after 22 cycles, 0.9 sccm; at 1000°F the actuating mechanism froze locking the visor in the closed position; leakage was excessive; boron carbide seat found shattered, visor was severely scored.
Boron carbide (shrink fit into Inconel 718 retainer, seat distorted about 0.001 in)	Boron carbide (shrink fit into Inconel 718 visor)	70°F, 1600 psig inlet pressure, no cycling, leak checked only, load on boron carbide inserts was radial[d] type	At 1600 psig, leakage was 65 scim; noise was heard; pressure was released at about 200 psig/minute; visor insert was found fractured, wedging action of the 30° seat combined with the sudden release of stored energy in the distorted visor caused the failure.
Boron carbide (shrink fit into Inconel 718 retainer)	Boron carbide (shrink fit into Inconel 718 visor)	1030°F, 1600 psig inlet pressure, 277 cycles, load on boron carbide inserts was compressive[d]	Leakage at 750 psig was >2000 scim, testing was discontinued; seat insert was found sheared; visor insert was in good condition.
Inconel 718 inlaid with Stellite 1016	Inconel 718 inlaid with Stellite 6	500°F, 1600 psig inlet pressure, >10,000 cycles, load on materials was radial[d]	No leakage after 30 cycles at 70°F and 1600 psig; no leakage after 75 cycles at 280°F and 1600 psig; no leakage after 860 cycles at 285°F and 1600 psig; no leakage at 955 cycles with temperature gradually increased to 500°F; no significant leakage after 10,000 cycles; seat and visor in excellent condition.
Boron carbide (shrink fit into Inconel 718 retainer)	Inconel 718 with Stellite 1016 overlay	950°F, 1600 psig inlet pressure, 9855 cycles, including 2 thermal cycles, load on materials was radial[d]	Leakage averaged <0.6 scfm measured at pressure differentials ranging from 20 to 1600 psig; highest leakages occurred at pressure differential of 200 psig averaging 0.810 scfm; wear characteristics indicate that 30,000 cycles of use should be achievable. Leakage rates initially increased after the first thermal cycle, but repeated cycling caused a decline in the leakage rates to values approaching the rates prior to cycling. Visual examination after 7700 cycles showed some evidence of wear on the boron carbide seat but there was no significant increase in wear after the 9855 cycles, indicating there is an initial wear-in process.
Silicon nitride (shrink fit into Incoloy 903 retainer)	Boron carbide (shrink fit into Inconel 718 visor)	70°F, 1600 psig inlet pressure, 7 cycles, load on materials was compressive[d]	Boron carbide visor insert failed in shear as predicted; silicon nitride seat material in excellent condition.

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[a] Tests were conducted in a prototype valve test fixture which has provisions for heating the valve, cycling, pressure application, passing small amounts of coal, seat purging, and operation in an inverted position. Heat is applied by conduction through the interface flanges and by convection. A small amount of coal is put through, dropped into valve when closed but before pressurization to simulate one of the most severe operating conditions--a high pressure difference across the valve with abrasive particles present. Leakage tests for external leakage: the outlet port is capped, the valve opened, and the inlet pressurized; the time for the pressure to drop from 1600 psig to 100 psig is measured. Leakage test for internal leakage: the valve inlet is pressurized with the valve closed; a flow meter at the valve outlet measures flow as the pressure increases in steps, 20, 50, 100, 500, 1000, 1500, and 1600 psig. Torque tests: with pressure on the valve, and at 1600 psig torque versus rotation data are obtained for complete opening and closing cycles. All tests reported above were conducted in this equipment except the first six, see next footnote.

[b] These tests were conducted in a seating materials test fixture which constantly subjects the material samples to a continually fluidized abrasive while the samples are separated and brought together by a pneumatic actuator. Square samples used are 1/2" x 1/2" by 1/8" thick. When the moving sample (visor) contacts the stationary sample (seat) the samples are subjected to a large controllable force.

[c] CVD = chemical vapor deposition.

[d] The radial type load on the materials provided a combination of pure compression and hoop tension; the compressive load provided pure compression.

A.9.3.2.3 MATERIALS EVALUATION

EROSION--OVERVIEW

The performance of materials when subjected to erosive conditions is dependent on a number of variables. In considering the effect of impingement angle on erosion, the character of the materials being subjected to erosion must be considered, whether ductile (most metallic materials) or brittle (ceramic materials).

For ductile materials the more serious erosion occurs at low impingement angles, for brittle materials the maximum erosion occurs at 90°. Examples of such performance are given in Sections B.2.1.11 and B.2.1.14, which show erosion data typical of that for ductile materials, and in Sections B.2.2.10 and B.2.2.13 (data at 25 °C), which show data typical of brittle materials. (Some variations of brittle materials behavior are to be seen at high temperatures because of phase changes in the refractories.)

Increasing the particle velocity increases the erosion of a material, more material being lost at higher velocity. Data in B.2.1.5, B.2.1.13, B.2.2.7, B.2.2.11, B.2.2.12, show the trend for both ductile and brittle materials. Some of the erosion data included in this book has been normalized by dividing the weight of sample lost by the weight of erodent used. Generally, a greater amount of erodent creates a greater material loss although when very large amounts of erodent are involved there is not a corresponding increased erosion effect, probably because erodent particles are acting against each other. Section B.2.2.8 contains data showing a decrease in erosion at larger particle flux.

Particle size and erosion are generally directly proportional. In Sections B.2.1.9 and B.2.1.13 there are data showing increased material loss with increased particle size. The effect of temperature is unclear. Data for alloys in Sections B.2.1.5, B.2.1.9, B.2.1.10, B.2.1.11, and B.2.1.12 do not indicate a definite trend. Conflicting results are also indicated for refractory materials in B.2.2.8, B.2.2.11, B.2.2.12, and B.2.2.13. Although data in B.2.2.8 and B.2.2.13 show increased erosion loss with increasing temperature, the results in B.2.2.11 and B.2.2.12 are conflicting. For both alloys and refractories the results seem more dependent on the response of individual materials to increased temperature in terms of possible changes in the properties rather than a direct effect of temperature as a parameter on the phenomenon of erosion.

EROSION-LABORATORY TESTS

EROSION TESTING was conducted on a large number of materials to screen those which might be considered for valve use. The materials were subjected to erosive attack by alumina for three minutes at impingement angles of 20° and 90° at 20 °C and at an angle of 90° at 700 °C. Not all materials were tested under all three conditions so that there are gaps in the data as will be seen readily by glancing at any of the Part B sections listed in this text. When only one test at one angle is performed it is not possible to have a true picture of the erosion resistance of the material. The results in terms of sample loss were compared to erosion loss of samples of a cobalt-based alloy, Stellite 6B, arbitrarily chosen as a standard, and tested with each set of samples. The data consist of Relative Erosion Factors (REF), values less than one indicating a more erosion resistant material than Stellite 6B, values greater than one indicating a less erosion resistant material. The reported values are the mean of five tests on a material. Although the tests permit a ranking of materials with respect to erosion resistance, it must be borne in mind that the test conditions are not comparable to those seen by valves in coal gasification plants. The alumina erodent used is much harder than the coal, char and ash particles to which valve materials are subjected in the plants and the tests did not include any of the gaseous chemical constituents to be found with the char and ash particles. Also, discussion of performance of materials at 20 °C is not of very significant value if the prospective material use is in valves operating at 350°-850 °F (see operating requirements) Therefore the high-temperature test results are more important although there are data only for 90° impingement angle, the angle at which ductile materials (alloys) are generally more erosion resistant and brittle materials (refractori less erosion resistant. Any discussion or ranking of materials using the high-temperature data must be tempered by the fact that the 700 °C (1292 °F) test temperature is much higher than the prospective valve operating temperatur and the performance at the lower operating temperatures may be rather different The 700 °C temperature may have caused microstructural or phase changes which would not occur in real plant use. Further data are required before definitive choices can be made.

<u>EROSION TESTING OF METALS AND ALLOYS</u> was performed on fifteen alloys including mild steel, tool steel, several stainless steels and superalloys (B.2.1.1). The same tests were performed on twenty-three materials which included tungsten, molybdenum, and tantalum, seven cobalt-based alloys, two titanium alloys, high nickel-chromium alloys, and miscellaneous alloys (B.2.1.2).

The effect of high temperature on the erosion results are mixed. Nineteen materials for which there are both 20 °C and 700 °C exhibited increased erosion resistance at the higher temperature, while six showed less resistance and five appeared little affected by temperature. The effect of angle of impingement for the various steels and the superalloys is generally what is expected for ductile materials, a greater material loss (less erosion resistance) at lower angle. For the cobalt-based alloys, tungsten and molybdenum, the performance is more like that expected of brittle materials in that they are less erosion resistant at the higher angle. The following list of materials are less than, approximately, or equally erosion resistant with respect to the Stellite 6B standard at both test angles at 20 °C:

Aluminized 304 SS
316 SS
Incoloy 800 and 800H
HK-40
RA 330
HC-250
Graph air tool steel
Mild steel
Ti-6Al-4V
RA 333
Inconel 671
00025 copper alloy
SPA (proprietary alloy)

The following materials show greater erosion resistance than the andard at both angles at 20 °C:

- Tungsten, plain and with diffused boron
- Molybdenum, plain and with diffused boron
- Mo with Ti, Zr, C, and diffused boron
- Tantalum
- Tantalum nitride
- Tungsten alloy, 90W-10 (Ni, Cu, Fe)

At the higher temperature (700 °C), twenty of the samples tested exhibit osion resistance better than the standard material and these are ranked low.

Relative Erosion Factor	Material
0-0.20	Wrought Tungsten, Molybdenum alloy with diffused B.
0.21-0.40	Molybdenum with diffused B
0.41-0.60	Tungsten with diffused B, Ti-6Al-4V, Titanium alloy Beta III, Tungsten alloy 90W-10 (Ni, Cu, Fe), 316 SS, Incoloy 800 and 800H
0.61-0.80	Ra 333, Inconel 600 and 671, 304 SS, 430 SS, HK-40, RA 330

Any judgment of the value of these numbers and the ranking of materials ust be tempered by the fact that these data are for 90° impingement angle, hat angle for which ductile materials are expected to be most erosion esistant.

Those materials which are very little better than, approximately equal o, or worse than the standard at 700 °C are listed below.

Relative Erosion Factor	Materials
0.81-1.00	Stellite 3, Haynes 188, Haynes 25, SPA (proprietary alloy)
1.01-1.20	Stellite 6K, Haynes 93, 25 Cr iron
1.21-1.40	Wrought Molybdenum, Stellite 31 with diffused B, Stellite 6 with diffused B
1.41-1.61	Stellite 3, HC-250, HR-37

WELD OVERLAYS were erosion tested (see B.2.1.3) but data are present nly for 90° impingement angle at 20 °C. There were six cobalt-based weld lloys, four iron-based chromium alloys, one nickel-based and three composite eld alloys. All were only equal to or worse than the standard.

SEVEN MARTENSITIC STEEL-BONDED CARBIDES were tested under conditions hich varied somewhat from those of all the other tests (Section B.2.1.15).

The impingement angle was 90° but there were three temperatures for testing, 20 °C, 350 °C, and 550 °C. Four of the samples were TiC in steels, two were TiC in (Fe, Ni, Cr, Mo) carbide, and one was an iron tungsten carbide material. The last sample was the only one exhibiting any better erosion resistance than the standard, the REF values being 0.73 at 20 °C, 0.86 at 350 °C, and 1.01 at 550 °C. All of the others had REFs greater than one.

TWENTY-FIVE TUNGSTEN CARBIDE commercially-supplied materials of various kinds (see B.2.1.16) were tested, eight with varied amounts of cobalt binder, six with undesignated binders, two with cobalt-chromium binder, one with nickel binder, six with a varying amount of other elements, one with diffused boron and one dispersion strengthened. There are few data values for 20 °C tests at 20° impingement angle. Those values which are included when compared with 20 °C, 90° angle data indicate that the erosion behavior is indeed that of brittle materials. Most of the materials are more erosion resistant than the standard to varying degrees.

The effect of the elevated temperature is either almost nil or there is a decrease in the erosion resistance. Those materials for which the effect is almost nil are a tungsten carbide with 1.5 percent Co binder, one with 5.8 percent Co, one with 6 percent Co-1 percent Cr, and one with a 7.8 percent unspecified binder. For the several materials listed below the temperature effect is either extreme and/or the change ranks the materials as less erosion resistant than the Stellite 6B standard.

Material	REF (20 °C-700 °C)
with 6% Co binder	0.38-1.53
with 6% Co binder	0.19-1.32
with 8.8% Co	0.78-1.03
with 11.5% binder (?)	0.57-0.84
with unknown bond	0.31-0.72
with diffused B	0.02-0.72

One material, with 25 percent unspecified binder, has REF values at one or above for both temperatures.

Those samples which had REF values below 0.5 for both temperatures are:

Material	REF	
	20 °C	700 °C
<1.5% Co binder	0.11	0.13
5.8% binder	0.43	0.50
6% Co binder	0.25	0.47
6% Co binder	0.23	0.36
6% Co binder	0.33	0.48
6% Co-1% Cr	0.26	0.25
6% Ni	0.32	0.46
7% Co	0.32	0.50
10% Co-4% Cr	0.25	0.47
7.8% binder	0.42	0.47

REFRACTORY MATERIALS, EITHER ALUMINA OR ALUMINA-BASED, were tested in the same way (see B.2.2.1 and B.2.2.2). The data generally show the ual performance of brittle materials in that the 90° impingement angle ta indicate a greater loss of material than the 20° angle data. Excep- ons to this trend are a low-alumina sialon (13 percent Al_2O_3-87 percent $_3N_4$), an alumina-titanium carbide sample, and experimental compositions of umina with varying amounts of MgO, TiB_2, and WC. These Al_2O_3-TiB_2-MgO-WC terials and the Al_2O_3-TiC material all had REF values less than 0.4 for 90° gles at both 20 °C and 700 °C. The sialon materials were much less erosion sistant than the standard. None of the rest of the alumina materials tested owed any outstanding erosion resistance, most of them being much poorer than e Stellite 6B standard. Only a densified alumina had REF values around 0.5 r the 90° impingement angle. Since the erodent was alumina further testing called for to ascertain the usefulness of the materials in actual use.

SILICON CARBIDE REFRACTORIES of varying types were erosion tested .2.2.3). The twenty-nine different materials from commercial sources cluded twenty-two different SiC preparations, including hot-pressed, essed and sintered, and recrystallized materials. There were also o SiC materials which were silica bonded, two with silicon nitride- lica bond, and one with silicon nitride bond. One material contained B_2 and another ZrB_2 and graphite. The erosion performance with regard impingement angle was, as expected, typical of brittle materials, with ss erosion for the 20° angle and greater for the 90° angle of attack. e effect of temperature was mixed, 15 materials having less resistance 700 °C than at 20 °C, four samples showing little or no effect, and ur samples having increased resistance.

The plain SiC materials (i.e., with no additives) in general had od erosion resistance relative to the standard but with some very ide differences. Most of the plain samples had REF values less than one both temperatures and both angles of impingement. The performance of iC with either SiO_2 bond or Si_3N_4 bond was variable depending on the articular specimen but since the complete characterization of the various pecimens is not given the reasons for the variability are unknown. SiC ith ZrB_2 had good performance but that material with graphite added had ery poor erosion resistance. Those samples which had REF values less than .5 for 90° impingement angles at both 20 °C and 700 °C are listed elow.

Material	REF	
	20 °C	700 °C
SiC, hot-pressed	0.12	0.44
SiC, recrystallized (HD 430)	0.40	0.38
SiC, 98% dense	0.05	0.02
SiC (SDIP-1-3)	0.47	0.43
SiC (SDIP-1-4)	0.44	0.43
$SiC-Si_3N_4$, hot-pressed	0.20	0.42

ther materials showed good erosion resistance at 20 °C but no data are vailable for 700 °C.

FOURTEEN CARBONITRIDES were tested at 20 °C and 700 °C at 90° impingement ngle (see B.2.2.4). These were mostly experimental compositions having from 5 to 97 percent (Ti,Cr) or (Ti,Mo) carbonitrides and varying percentages of i and Mo. None of them showed an REF lower than 0.5 and in general their performance is not significantly better than Stellite 6B. Pressed and sintered TiCN, and both pressed and sintered and cast MoTiCN were tested and showed REF values close to one.

SILICON NITRIDE REFRACTORIES (see B.2.2.5) were also tested at both temperatures and both impingement angles. Those which showed good erosion resistance at 90° angle are listed.

Material	REF	
	20 °C	700 °C
Si_3N_4, hot-pressed	0.18	0.57
Si_3N_4, hot-pressed	0.40	0.12

Reaction-bonded Si_3N_4 had a relative erosion factor of about six for all test conditions. None of the sialon materials (Si_3N_4-Al_2O_3) tested had good erosion resistance, nor did a Si_3N_4-SiC-SiO_2 refractory which had factors close to one.

MISCELLANEOUS MATERIALS were tested and the full results given in B.2.2.6. Those with better erosion resistance than the standard are listed below for 90° impingement angle.

Material	REF	
	20 °C	700 °C
B_4C, hot-pressed	0.38	0.21
B_4C, hot-pressed	0	0.38
TiC-Al_2O_3, pressed and sintered	0.19	0.30
Cubic BN	0	0

Materials which had poor erosion resistance compared with the standard are TiC with Ni or Ni-Mo binder, and several $MgAl_2O_4$-based materials, all hot-pressed with varying amounts of MgO.

Many of the above materials which showed poor erosion resistance because they are brittle in nature and were tested using a 90° impingement angle may perform satisfactorily in design situations in which erodent material impinges on the material surface at low angles.

COATINGS FOR EROSION PROTECTION were investigated by testing some twenty-five coating materials for erosion resistance (B.2.3.1). Substrates were variable, in some cases unknown. Testing was also performed on the pure coating. The materials were subjected to erosive attack by alumina for three minutes at impingement angles of 20° and 90° at 20 °C and at an angle of 90° at 700 °C. The results in terms of sample loss were compared to erosion loss of samples of Stellite 6B arbitrarily chosen as a standard tested with each set of samples. The data consist of Relative Erosion Factors, values less than one indicating a more erosion resistant material. The reported values are the mean of five tests on a material.

For twenty of the test samples the coating was readily penetrated and the indications were that the coating was too thin. Those coatings which had erosion resistance greater than Stellite 6B are ranked below.

Material	Relative Erosion Factor			Remarks
	20 °C		700 °C	
	20°	90°	90°	
B$_2$ electrodeposited on nickel	0	0	0	
B$_2$ electrodeposited on 310 SS	0	0	0	spalling occurred at 700 °C
B$_2$ sputtered on 410 SS	0	0	0	
B$_2$ (controlled nucleation thermochemical deposition, substrate not given)	0	0	0	some spalling on retesting at 20 °C after 700 °C
B$_2$ electrodeposited on Kovar	0	0	0	
C chemically vapor deposited pure coating	0.20	0.05	0	weight loss noted but no visible crater
C chem. vap. dep. on C converted to SiC	0.13	0.06	0	
iC chem. vap. dep. on SiC and graphite	0	0	0	
chem. vap. dep. pure coating		0.53	0.25	
chem. vap. dep. on mild steel		0.57	0.34	
chem. vap. dep. on mild steel		0.48	0.16	
iC on WC		0.31	0.72	

t is possible that some of the coatings which were readily penetrated by he alumina might survive erosion by char or ash which are much softer aterials.

BRASION-LABORATORY TESTS

ABRASION TESTING was performed by thrust washer wear testing for a arge number of materials (see B.2.1.17, B.2.1.18, B.2.1.19, and B.2.1.20). aterial loss was measured after rotating two washer samples against each ther under constant load and rotation rate for four minutes. In some ests the two washers were of the same material, in others the two ashers were different materials. An abrasive, alumina, fly ash, or oal was introduced between the washers for some of the tests but most ere run without abrasive. The measured material loss for two mild teel washer samples tested with alumina was used as the base line standard nd the testing results are reported as a factor showing the improvement ver the abrasion resistance of mild steel with alumina abrasive.

ABRASION TESTING OF A MATERIAL AGAINST ITSELF IN THRUST WASHER WEAR is reported in B.2.1.17 where the washer pairs were of the same materials. The performance of mild steel actually degraded to the same degree with no alumina abrasive and with abrasive, with heat and steam. Diffused boron, tungsten carbide and Tribaloy 800 coatings on mild steel improved performance by factors of 2 to 3.5 but this is a minimal effect. Among materials tested without alumina abrasive the following are materials which showed improvement factors over mild steel of at least ten.

Material	Improvement Factor (approximate)
LW-IN40 coating material	900
LC-4 coating material	150
316 SS with diffused B	100
440C SS with diffused B	70
Graph-air tool steel	45
HC-250	40
24% Cr white iron	20

With abrasive, only two materials had improvement factors greater than ten.

Material	Abrasive	Improvement Factor
Graph-air tool steel	-14 mesh coal	150
Graph-air tool steel	-14 mesh ash	50
Graph-air tool steel	alumina	25
24% Cr white iron	-14 mesh coal	65
24% Cr white iron	-14 mesh ash	35
24% Cr white iron	alumina	20

Materials which showed less than ten times the abrasion resistance of mild steel or equal to mild steel with or without abrasive used are 316 SS, AISI 4140 steel, Stellite 6 with and without diffused boron and SPA (a proprietary alloy).

ABRASION TESTING OF PAIRS OF DIFFERENT MATERIALS was performed in the same way with the material loss measured being the total loss for both material Several miscellaneous materials and a large number of cobalt- and iron-based and composite weld overlay alloys were tested against both 316 SS (see B.2.1.18 and 440C SS (see B.2.1.19) with no abrasive added. A few tests were performed with abrasive material present. The weld alloys were overlaid by two different methods, tungsten-inert gas overlay (Tig) and arc-welded overlay (Arc).

In tests of the weld overlays with 316 SS (B.2.1.18) only one overlay (40% Haynes 47-60% Stellite 954) with 316 SS showed an improvement factor over mild steel of ten or more ($\sim$12) with no abrasive. All other combinations were less than ten and the overlay method did not appear to make a great difference in those cases where both overlay methods were used for the same alloy. In tests of the overlays against 440C SS (B.2.1.19) a few values indicated that the weld overlay method may make a difference. The improvement over mild steel for the weld alloys paired with 440C SS were quite large in a number of cases.

terials Against 440C SS	Improvement Factor (approximate)
mp. 4E (Haynes 47-Stellite 954)	32
mp. 40E (Ni-based)	32
. 94 (Fe-based) Tig	29
. 94 (Fe-based) Arc	25
mp. 2 (WC-Stellite 6) Tig	24
mp. 2 (WC-Stellite 6) Arc	19
. 90 (Fe-based) Tig	21
. 1 (Co-based) Arc	13
16 (Co-based) Arc	12

. 90 Arc-welded, No. 21 Tig overlay, No. 1 Tig overlay, and 1016 Tig th 440C SS all had improvement factors of about seven.

Two chromium oxide coating materials were tested against 316 SS th no abrasive. One (LW-IN40)/316 SS combination had an improvement ctor over mild steel of 37 whereas another combination (LC-4/316 SS) d a factor of only 1.5. Graph-air tool steel tested with 316 SS had improvement factor over 20 when tested with no abrasive but only a ctor of ten when alumina and steam were introduced and the system bjected to externally applied heat (250 °C).

Several combinations of materials were tested without abrasive, th abrasive, and with abrasive and steam in the system, and externally plied heat. In the case of a soft material such as polytetrafluoroethylene ired with 316 SS the absence or presence of abrasive seems to make little fference in the performance of the pair but in the case of tool steel ith 316 SS), Stellite 6 (with 316 SS or 440C SS), and 24 percent chromium on (with 316 SS) the results were mixed. For the tool steel (with 316 SS) e presence of alumina cut the improvement factor back to nine from the value over 20 without abrasive. For the 24-percent-chromium iron there is a end indicating that the presence of abrasive (and also heat and steam) may rve to lubricate the abrading surfaces slightly since less material was lost d the improvement factor showed some increase. The same trend appears for ellite 6 with 440C SS with fly ash abrasive. For Stellite 6 with 316 SS the y ash appears to lower the material loss but alumina, heat, and steam have adverse effect. It is clear that further testing is required to find swers to the questions raised by the data.

Miscellaneous pairs of materials were tested, most of which showed large mprovement over mild steel factors when tested with no abrasive present.

Material Pairs	Improvement over mild steel
W-IN40/LC-4 chromium oxide coatings)	105
ool steel/LW-IN40	100
16 SS borided/Stellite 6 borided	44
ool steel/LC-4	31
40C SS borided/Stellite 6	26
16 SS borided/Stellite 6	14
40C SS borided/Stellite 6 borided	9

The above data are of limited use and further testing is required to help choose materials which will perform well in valves where two surfaces must meet and will probably trap solid particles between them and will also be subjected to temperatures and gaseous atmospheres which may affect the abrasion resistance.

NTRODUCTION

The purpose of Section B is twofold. The first is to present the data on hich the "Materials Evaluation" portions of Section A of this book are based. he second is to make available, in one place, the information generated by he wide variety of projects which are sponsored by the Department of Energy n the field of materials for fossil energy applications. The contents of his section, therefore, are summaries, in tabular or graphical form, of data ostracted from the reports of materials research contractors to the Department f Energy. Some tables and graphs have been generated by the compilers using he data given in the reports, others are reproduced from the reports with ittle or no modification. The units appearing in the tables or graphs are hose used by the authors of the various reports, the compilers not having onverted all data to a common system of units. Although this practice esults in a wide variation in the reporting of the data, and requires the ser to exercise great care in comparing data from table to table, conversion o a common system of units for all the data in Section B would have been a ery costly effort.

The original sources of the data are identified by the number in square rackets following the title of each table or other data summary. References o the source documents may be found by looking for that number in Section E, eferences. In order to condense the information and to bring related data ogether, data from more than one individual report may appear in a given ummary. The same data may appear in more than one of the source reports. he references, therefore, are to the series of reports for a given project nd, in some cases, to related publications by the same authors. It was onsidered unnecessary, and possibly confusing, to attempt to identify the pecific report(s) of a series from which a given data value was taken. Those eaders who wish to check the original reports would do well to examine the ntire series in any event. The coverage of the projects varies, depending on he reports on hand at the time the data were abstracted. Future issues of ages of this book will contain more data from these various projects.

The great majority of the programs generating the data which are presented n Section B have one or more of the following purposes:

. To expose materials to one or more conditions typical of a coal conversion process, to examine the performance of the materials, and to test the effect of exposure on the various properties. Materials have been exposed in laboratory vessels under simulated coal conversion conditions and also in various locations in coal conversion pilot plants.

. To develop materials with specific resistance to the effects of coal conversion conditions.

. To provide understanding of the basic phenomena affecting materials under the abusive conditions of coal conversion in order to provide criteria for development of materials and for design use of existing materials.

Most test exposures involved the use of small test specimens or coupons rather than very large samples or actual component pieces. In presenting the data we have attempted to include experimental details such as the test methods, sample size, and number of samples, to help the reader judge the value of the data for his application. The source documents are not all equally explicit about such details and the information is, therefore, often missing from our footnotes to tables and graphs. Conditions for the exposures are given much as they are given in the source documents, with some simplification and abbreviation. Laboratory conditions could be specified by the original authors but in the case of pilot plant exposures, the complete conditions with all fluctuations for the full time the samples were in pilot plant test locations were not available to the authors, and the conditions stated are necessarily incomplete. Much of the laboratory testing for which the data are discussed in this section was performed utilizing a "typical" or "simulated" coal gasification atmosphere. The composition was given as 18 percent CO, 12 percent CO_2, 24 percent H_2, five percent CH_4, one percent NH_3, with varying amounts of H_2S (0.1 to 1.5 percent), and the balance H_2O. In many reports, it is clearly indicated that the above was an input composition and equilibrium compositions at temperature and pressure were often given. Some reports indicated that the above composition was the equilibrium one and others did not make any clear indication at all. The compilers have included the composition in the footnotes to tables as given in the reports.

Sources of materials, preparations, thermomechanical histories, etc., are indicated if they were given in the original reports. Material identification follows that of the source reports for the most part. The materials are usually given the designation the authors of the original reports assigned although this practice causes some inconsistency in the book. This inconsistency is especially noted for alloys for which the designations given may or may not follow any one of the standard systems such as AISI, ASTM, or ANSI. In the ASTM system for designating alloys, the type or grade refer to an alloy manufactured by a specific producer.

Brand names and manufacturers, where included, are meant only as aids to identification of similar test samples from table to table, and inclusion of these is not intended either as an endorsement or recommendation of any brand name material or manufacturer, nor, conversely, is it intended to prejudice users against the use of any specific product.

The numerical data reported should be viewed with caution. Many of the tests were conducted to screen materials, and the numerical values cannot be considered definitive. Since in many tests the number of samples per material per test is few, often only one, no statistical significance attaches to the values. In most cases, complete characterization of the materials with preparative and thermomechanical history is lacking. The user, therefore, must bear in mind that the data should be used for guidance only and to support the "Materials Evaluations" portions of Section A of this book and are not suitable for inclusion in design calculations. Such use of the data is at the sole risk of the user, and no responsibility for such use can be taken either by the compilers of the data or by the sponsors of this compilation project.

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CORROSION LOSS[a] OF SOME ALLOYS UPON EXPOSURE TO SIMULATED COAL GASIFICATION ATMOSPHERES[b] [7]

	Depth of Corrosion Penetration (μm)											
	1382° F[b]				1600° F[b]				1800° F[b]			
Alloy[c]	Cont. Pen.	Surface Loss	Max. Pen.	Max. Metal Affected	Cont. Pen.	Surface Loss	Max. Pen.	Max. Metal Affected	Cont. Pen.	Surface Loss	Max. Pen.	Max. Metal Affected
Input gas, 1 atm., 77° F: CO 22.75, CO_2 30.20, H_2 25.47, H_2S 1.96, CH_4 19.61 (mol %)[d]												
RUN PRESSURE 34 ATM.												
USS 18-18-2	32	2	42	44	35	5	62	67	121	33	138	171
Incoloy 800	51	7	102	109	22	4	97	101	36	21	164	185
AISI 310	148	54	173	227	72	33	93	126	174	46	220	267
Inconel 671	13	8	80	88	33	7	73	80	48	57	172	229
RUN PRESSURE 102 ATM.												
USS 18-18-2	11	25	26	51	11	29	26	55	51	30	76	106
Incoloy 800	23	7	35	42	28	7	35	42	48	15	62	77
AISI 310	14	4	30	34	15	27	48	75	38	23	99	122
Inconel 671	10	2	12	14	18	8	22	30	45	42	113	155
Input gas, 1 atm., 77° F: CO 33.42, CO_2 19.15, H_2 33.42, H_2S 1.29, CH_4 12.85 (mol %)[e]												
RUN PRESSURE 34 ATM.												
USS 18-18-2	5	11	13	23	14	1	34	35	43	58	89	147
Incoloy 800	36	2	52	54	38	3	116	118	47	13	173	186
AISI 310	10	1	21	22	48	9	61	70	34	9	102	111
Inconel 671	12	9	24	33	16	7	51	58	17	29	126	155
Sandvik 253MA	10	9	21	30	13	9	52	59	44	25	117	141
RUN PRESSURE 102 ATM.												
USS 18-18-2	12	10	14	24	12	10	26	36	11	19	26	45
Incoloy 800	27	9	33	42	36	12	63	75	42	19	89	108
AISI 310	18	11	31	42	21	10	54	64	18	9	66	75
Inconel 671	31	9	52	61	82	20	94	115	49	9	82	91
Input gas, 1 atm., 298 K: CO 0.2014, CO_2 0.1151, H_2 0.2014, H_2O 0.172, H_2S 0.010, CH_4 0.300 (mole fraction)												
RUN PRESSURE 68 ATM.												
USS 18-18-2	306	201	370	571	58[f]	60[f]	77[f]	137[f]	--	--	--	--
Incoloy 800	32	49	120	169	40[f]	62[f]	178[f]	240[f]	26	16	286	302
AISI 310	74	42	95	137	84[f]	41[f]	226[f]	267[f]	22	13	184	197
Inconel 671	20	26	103	129	12	15	68	83	12	14	69	83
GE 1541	54	6	78	84	7[f]	17[f]	8[f]	25[f]	6	14	43	57
GE 1541 (ox)[g]	16	20	16	36	20[f]	14[f]	147[f]	160[f]	11	15	14	29

(Table Continued)

CORROSION LOSS[a] OF SOME ALLOYS UPON EXPOSURE TO SIMULATED COAL GASIFICATION ATMOSPHERES[b] [7]

(Table Continued)

Alloy[c]	Depth of Corrosion Penetration (μm)											
	1382° F[b]				1600° F[b]				1800° F[b]			
	Cont. Pen.	Surface Loss	Max. Pen.	Max. Metal Affected	Cont. Pen.	Surface Loss	Max. Pen.	Max. Metal Affected	Cont. Pen.	Surface Loss	Max. Pen.	Max. Metal Affected
Input gas, 1 atm., 77° F: CO 11.7, CO_2 15.4, H_2 12.9, H_2O 48.9, H_2S 1.0, CH_4 10.0 (mol %)[h]												
RUN PRESSURE 34 **ATM.**												
USS 18-18-2	56	47	66	113	completely corroded after 390 hours				completely corroded after 245 hours			
Incoloy 800	15	2	34	36	68	35	98	133	84	49	216	265
AISI 310	19	7	44	51	37	13	163	176	88	27(321)[i]	343	370(665)[i]
Inconel 671	9	6	18	24	29	35	133	162	70	61	465	526

[a] Corrosion effect measured in the following ways: Cont. Pen. = depth of continuous penetration, Surface Loss, Max. Pen. = depth of maximum penetration, Max. Metal Affected = maximum depth of affected metal (Surface Loss + Max. Pen.), all measured in μm; each value is the average of measurements on duplicate samples.

[b] **Specimens, as-machined condition, were exposed** for 1000 hours at the three temperatures given in the heading of the table and at the given pressures. Actual **temperatures** experienced by individual samples vary somewhat depending on sample location.

[c] Alloy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, 0.06 C, 0.296 others, balance Fe; Incoloy 800 (A.M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; AISI 310 SS (Rolled Alloys), 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe; Inconel 671 (Huntington Alloys), 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 0.02 Mn, 0.357 others; Sandvik 253 MA (Avesta Jernverks AB), 11 Ni, 21 Cr, 1.9 Si, 0.04 Ce, balance Fe; GE 1541 (General Electric), 15 Cr, 4 Al, 1 Y, balance Fe.

[d] Equilibrium compositions:

	At 34 atm.			At 102 atm.		
	1382° F	1600° F	1800° F	1382° F	1600° F	1800° F
CO	10.9	27.5	44.6	6.4	17.6	33.0
CO_2	18.9	12.9	6.3	20.7	16.9	11.1
H_2	16.0	25.8	34.3	10.2	17.3	25.2
H_2O	21.2	14.0	7.6	24.8	19.3	13.4
H_2S	1.6	1.5	1.5	1.7	1.6	1.6
CH_4	8.6	6.3	4.3	10.8	9.2	7.5
C	22.6	12.0	1.4	25.4	18.0	8.3

Note: Equilibrium atmospheres do contain dispersed solid carbon.

[e] Equilibrium compositions:

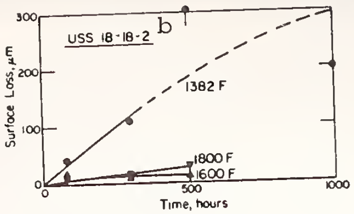
	At 34 atm.			At 102 atm.		
	1382° F	1600° F	1800° F	1382° F	1600° F	1800° F
CO	10.4	26.4	42.7	6.2	16.9	31.7
CO_2	17.9	12.1	5.9	19.5	15.9	10.5
H_2	16.3	26.1	34.7	10.3	17.6	25.5
H_2O	21.1	13.9	7.6	24.7	19.2	13.3
H_2S	1.2	1.1	1.1	1.2	1.2	1.1
CH_4	9.1	6.6	4.5	11.3	9.7	7.8
C	24.0	13.7	3.5	26.7	19.5	10.1

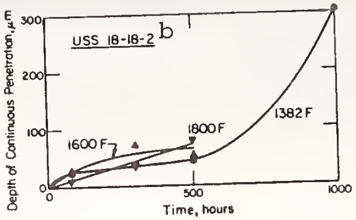
[f] These values are for 642 hours exposure.

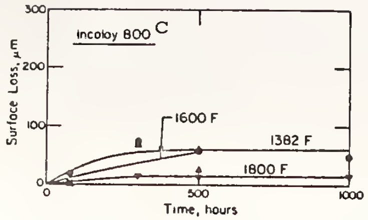
[g] These samples were pre-oxidized for 30 hours at 2100° F, 100 torr O_2.

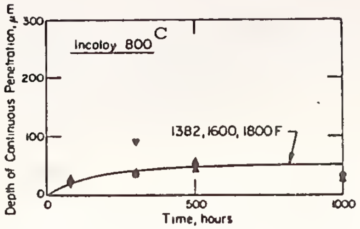
[h] Equilibrium compositions:

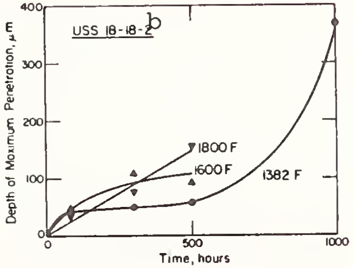
	1382° F	1600° F	1800° F
CO	8.796	15.542	19.068
CO_2	19.360	14.568	11.723
H_2	23.801	32.055	33.653
H_2O	39.806	34.816	34.319
H_2S	0.944	0.857	0.841
CH_4	7.282	2.149	0.396
COS	0.011	0.011	---

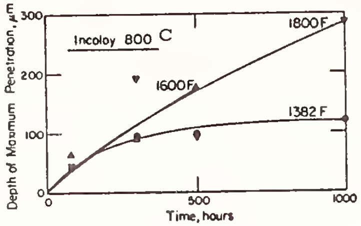


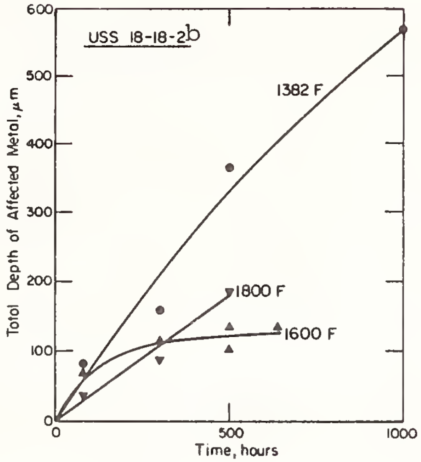


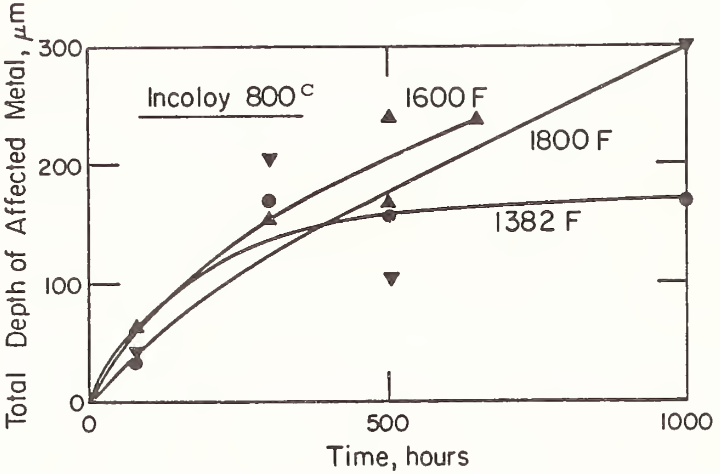












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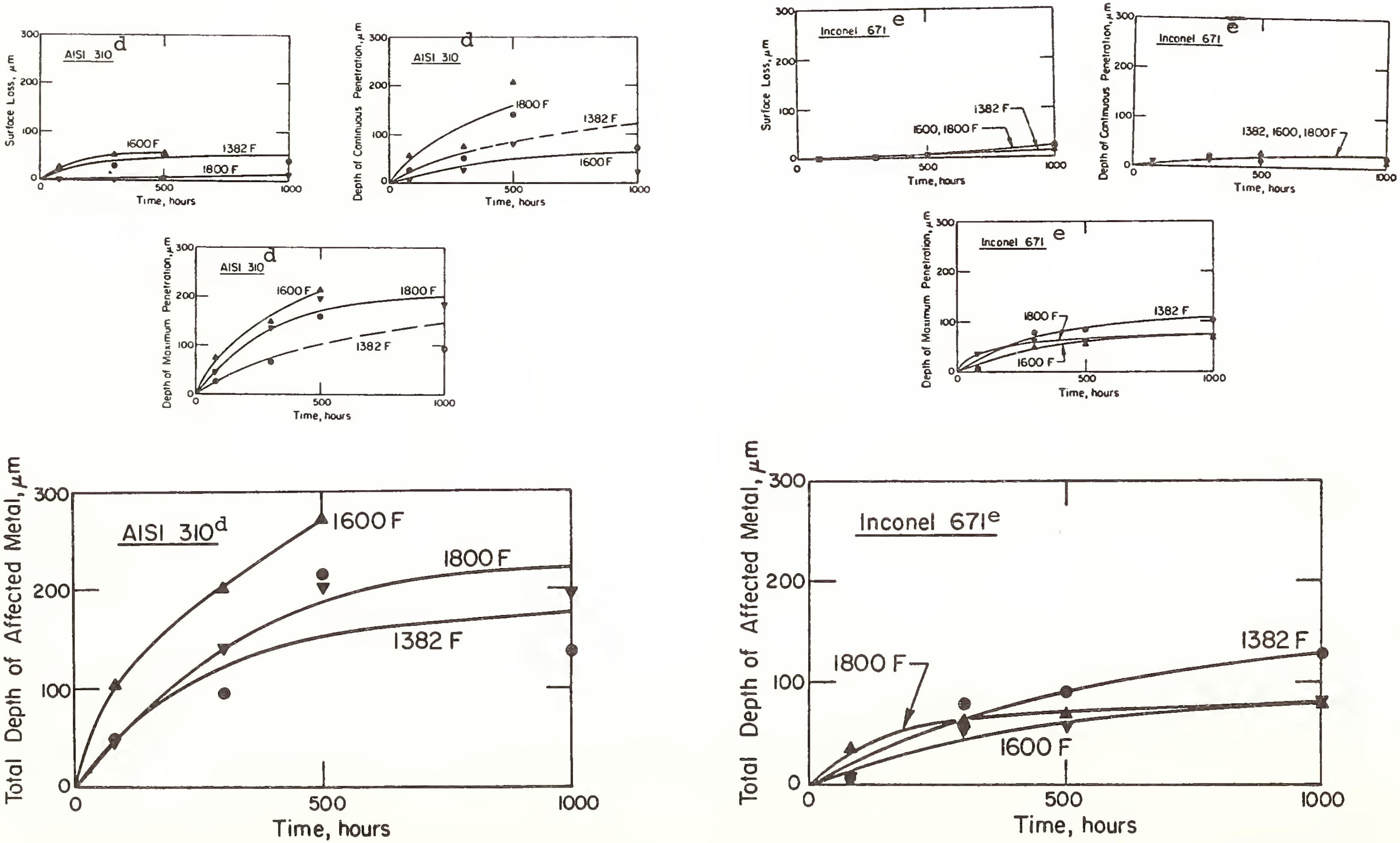
[a] Exposure was at 68 atm. Input gas composition (in moles) at 1 atm and 298 K: CO 0.2014, CO_2 0.1151, H_2 0.2014, H_2O 0.172, H_2S 0.010, CH_4 0.300.

[b] United States Steel 18-18-2: 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, 0.06 C, 0.296 others, balance Fe.

[c] Incoloy 800 (A.M. Castle): 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others.

(Data Continued)

CORROSION KINETICS FOR SEVERAL ALLOYS EXPOSED TO A SIMULATED COAL GASIFICATION ATMOSPHERE[a][7], Continued



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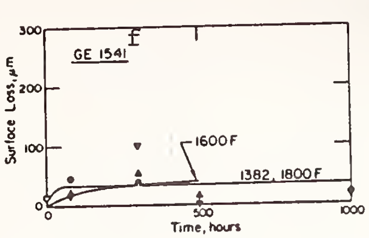
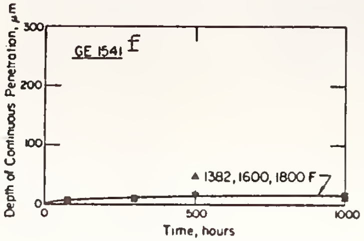
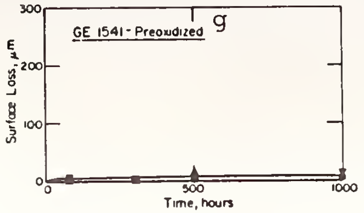
[d] AISI 310 SS (Rolled Alloys): 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe.

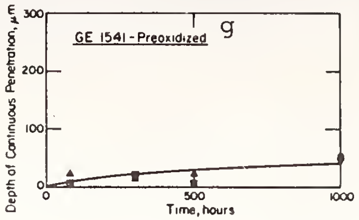
[e] Inconel 671 (Huntington Alloys): 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 0.02 Mn, 0.357 others.

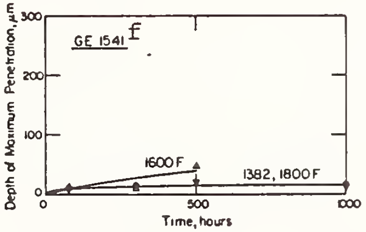
(Data Continued)

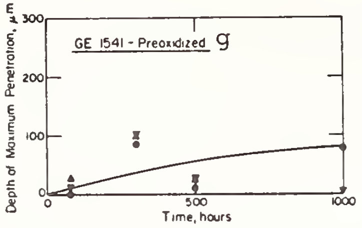


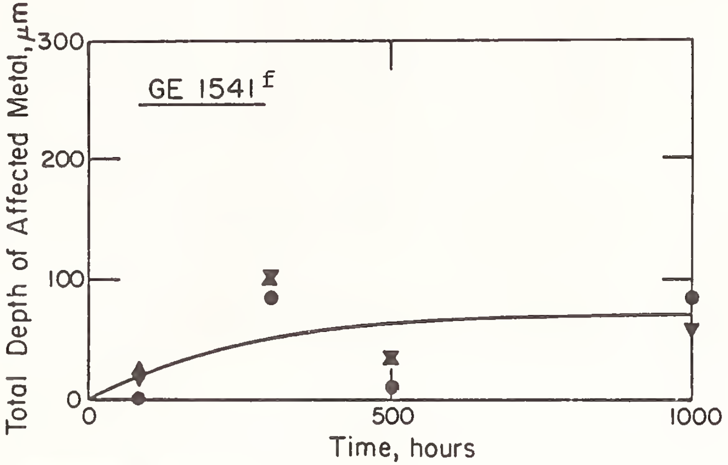


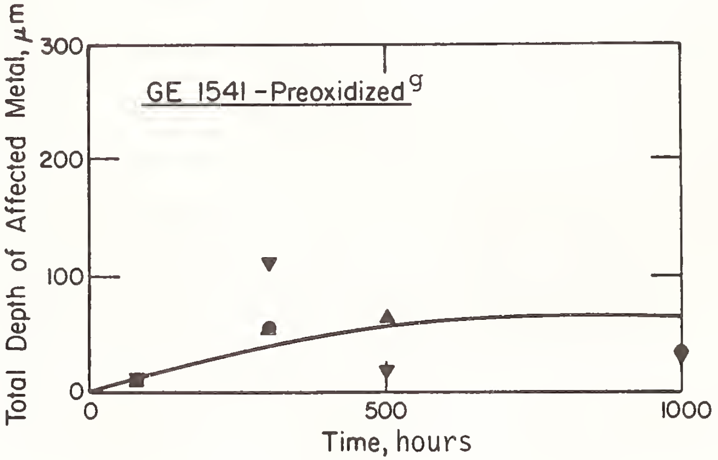












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[f] GE 1541 (General Electric): 15 Cr, 4 Al, 1 Y, balance Fe.

[g] GE 1541 pre-oxidized for 30 hours at 2100 °F, 100 torr O_2.

METALLOGRAPHIC CHARACTERIZATION[a] OF VARIOUS ALLOYS EXPOSED TO COAL GASIFICATION ATMOSPHERES[b] AT SEVERAL TEMPERATURES [7]

Temp.	Atmosphere No. 1[c]	Atmosphere No. 2[d]		Atmosphere No. 3[e]		Atmosphere No. 4[f]
	68 atm	34 atm	102 atm	34 atm	102 atm	34 atm
General Results	Voluminous sulfide scaling; corrosion penetration by sulfide or oxide; no general carburization; scales spalled excessively when autoclave opened.	At 1382° F voluminous tree-like scales, mostly Cr sulfides, minor Fe and Ni sulfide scales for all but 671; thin layer beneath scale rich in Cr but not S (Cr_2O_3-rich probably); penetration of alloys shallow except for 310.		Corrosive attack similar to that in Atmosphere 2, but sulfide/oxide attack less severe than in Atm. 2 at 1600 and 1800: internal precipitates have appearance of sulfides. (Sandvik 253 MA tested, had less surface attack than 18-18-2, less discontinuous penetration than other 3 alloys.)		Cr_2O_3-rich protective scale formed oxide subsurface precipitation, wi small amounts of sulfide.
ALLOY USS 18-18-2 [g]						
1382°F	Corroded fastest at 1382; rapid surface loss and corrosion penetration.	See general results.	Thick mottled gray deposit, essentially carbon; surface attacked through scale formation and sulfide penetration.		Thin oxide/sulfide scales formed; few small, discrete Cr-rich sulfide precipitates in alloy surface; some oxide penetration along grain boundaries intersecting metal/oxide surface.	
1600°F	Removed early; irregular corrosion pattern, metal-dusting type attack; slower corrosion than at 1382, rate similar to IN 800.	Cr_2O_3 outer scales formed with small islands of Cr, Fe, and Ni non-uniformly dispersed; penetration solely by Cr sulfides, along grain boundaries.	Same as at 1382°F.		Same as at 1382°F.	Complete conversi to sulfide scale; sample removed at 390 hours.
1800°F	Same as at 1600°F.	Same as at 1600 with some sulfide inclusion in the Cr_2O_3 external scales; some Ni-Fe sulfides at outer edge of scale; internal penetration greater, Cr sulfide precipitates at grain boundaries destroyed surface integrity.	Same as at 1382 with more extensive sulfide penetration.		Same as at 1382°F.	Same as as 1600, sample removed at 245 hours; scales apparently Cr_2O_3-rich, protective in nature.
ALLOY INCOLOY 800 [g]						
1382°F		Tree-like outgrowths in scale (carbon deposits); Cr-rich **carbide (not sulfide) innermost precipitates extended to 120 μ**; Cr sulfides precipitated to about 60 μ; Cr depletion to 200 μ, Cr level at alloy-scale interface falling to about 10%.	Almost continuous Cr-rich scale; scale penetrated by sulfide precipitates; thick gray carbon deposits.		Thin uniform oxide/sulfide scales; quite extensive grain boundary penetration by oxides; band of sulfides found deeper in alloy ahead of oxides, individual precipitates increasing in size and number with increasing temperature.	
1600°F	Removed early; irregular corrosion pattern, metal-dusting type attack.	Same as at 1382 but Cr depletion extended to about 130 μ, Cr level at alloy-scale interface falling to 12%.	Same as at 1382°F but with localized breakdown of Cr-rich scale by massive Fe- and Ni-rich sulfides.		Same as at 1382°F.	Sulfide scales w flaking off samp at 390 hours.
1800°F		Same as at 1382 but Cr depletion extended to 230 μ, Cr level at alloy-scale interface about 9%; Cr sulfides penetrated and partially destroyed surface integrity.	Cr-rich outer scale with localized breakdown by massive Fe- and Ni-rich sulfides.		Same as at 1382°F.	

(Table continued)

METALLOGRAPHIC CHARACTERIZATION[a] OF VARIOUS ALLOYS EXPOSED TO COAL GASIFICATION ATMOSPHERES[b] AT SEVERAL TEMPERATURES[7]

(Table continued)

	Atmosphere No. 1[c]	Atmosphere No. 2[d]		Atmosphere No. 3[e]		Atmosphere No. 4[f]
	68 atm	34 atm	102 atm	34 atm	102 atm	34 atm
310 SS[g]						
		See general results; penetration occurred along Cr carbide precipitates in grain boundaries.	Results similar to those for IN 800.		Surface extremely ragged, shallow penetrations of oxide/sulfide scale; band of Cr-rich sulfides formed in subjacent alloy at grain boundaries.	
	Removed early; irregular corrosion pattern, metal-dusting type attack.	See general results.	Results similar to those for IN 800.		Thin scale, better developed than at 1382, fewer islands of sulfide or Cr-depleted alloy; finger-like penetrations from base of scale down surface grain boundaries, beneath these in boundaries were Cr-rich sulfides.	Scales flaked off.
F		See results for IN 800; Cr sulfides penetrated and partially destroyed surface integrity.	Results similar to those for IN 800.		Scale appeared quite protective but metal/oxide interface was ragged and undercut by scale in places; fewer and smaller sulfide precipitates than at 1600.	Single sheet of thick sulfide scale spalled off at 245 hours; scales flaked off.
INCONEL 671[g]						
F	Best corrosion resistance of all alloys	See general results.	Little surface attack; only moderate sulfide penetration; some carbon deposition.		Heavily attacked; surface layers heavily sulfidized; some sulfide networks then oxidized driving S into alloy to form deep precipitates.	See general results.
F	Best corrosion resistance of all alloys.	Outer scale not analyze.	Same as at 1382°F.		Heaviest attack at this temperature, results as at 1382°F.	
F	Best corrosion resistance of all alloys.	See general results.	Sharp increase in both forms of attack; voluminous Ni-rich sulfides outside a thin "protective" Cr-rich scale; deep penetration of Cr-rich sulfides.		Complete layers of sulfide appeared protective, further penetration occurred only beneath breaks in layers.	

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section photomicrographs of polished and etched samples were taken of specimens 0.5 x 0.74 x C.1 in; some x-ray fluorescence and electron oprobe line scans also performed.

cimens in as-machined condition were exposed to various atmospheres for 1000 hours at the pressures indicated.

osition of atmosphere no. 1:

	Input, 1 atm, 298°K (mole fraction)
CO	0.2014
CO_2	0.1151
H_2	0.2014
H_2O	0.172
H_2S	0.010
CH_4	0.300

[d] Composition of atmosphere no. 2:

	Input, 1 atm, 77°F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	mol %	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
CO	22.75	10.9	27.5	44.6	6.4	17.6	33.0
CO_2	30.20	18.9	12.9	6.3	20.7	16.9	11.1
H_2	25.47	16.0	25.8	34.3	10.2	17.3	25.2
H_2O		21.2	14.0	7.6	24.8	19.3	13.4
H_2S	1.96	1.6	1.5	1.5	1.7	1.6	1.6
CH_4	19.61	8.6	6.3	4.3	10.8	9.2	7.5
C*		22.6	12.0	1.4	25.4	18.0	8.3

osition of atmosphere no. 3:

	Input, 1 atm, 77°F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	mol %	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
CO	33.42	10.4	26.4	42.7	6.2	16.9	31.7
CO_2	19.15	17.9	12.1	5.9	19.5	15.9	10.5
H_2	33.42	16.3	26.1	34.7	10.3	17.6	25.5
H_2O		21.1	13.9	7.6	24.7	19.2	13.3
H_2S	1.29	1.2	1.1	1.1	1.2	1.2	1.1
CH_4	12.85	9.1	6.6	4.5	11.3	9.7	7.8
C*		24.0	13.7	3.5	26.7	19.6	10.1

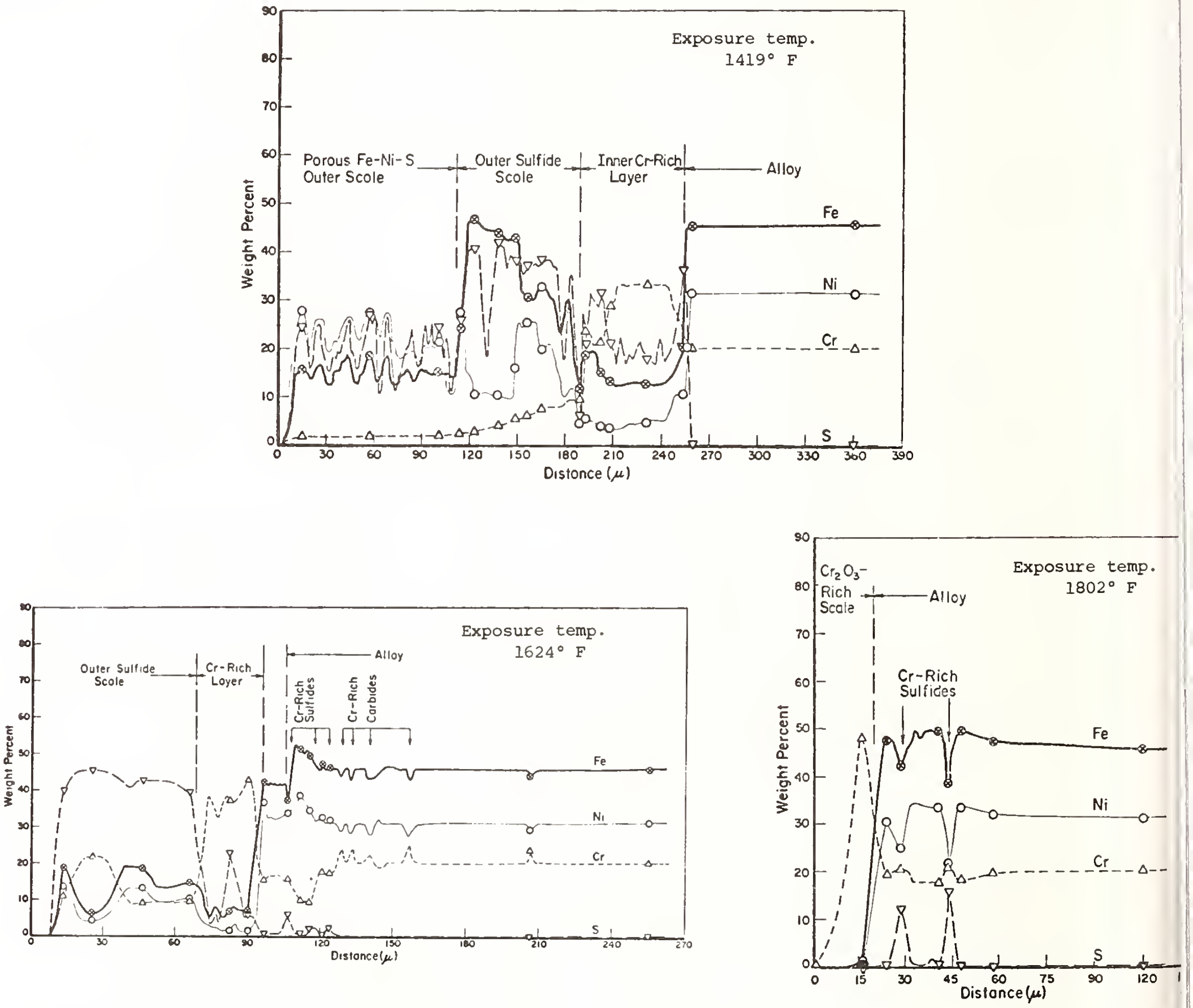
[f] Composition of atmosphere no. 4:

	Input, 1 atm, 77°F	Equilibrium at 34 atm		
	mol %	1382°F	1600°F	1800°F
CO	11.7	8.796	15.542	19.068
CO_2	15.4	19.360	14.568	11.723
H_2	12.9	23.801	32.055	33.653
H_2O	48.9	39.806	34.816	34.319
H_2S	1.0	0.944	0.857	0.841
CH_4	10.0	7.282	2.149	0.396
COS		0.011	0.011	---

oy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, 0.06 C, 0.296 others, balance Fe; ploy 800 (A.M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; AISI 310 SS (Rolled Alloys), 24.71 Cr, 02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe; Inconel 671 (Huntington Alloys), 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 2 Mn, 0.357 others.

*Note: Equilibrium atmospheres do contain dispersed solid carbon.

ANALYSIS[a] OF CORROSION SCALE FORMED ON INCOLOY 800[b] SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[c] AT SEVERAL TEMPERATURES[d] [7]



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[a] Analysis consists of electron-microprobe line scans across the scale which formed. Raw intensity data for Fe, Cr, and Ni were compared with chemical analysis data for the alloy; the data for S were compared to an FeS_2 sulfur standard; corrections were not made for absorption and fluorescence effects so sulfur levels, and to a lesser extent, Cr, levels are low.

[b] Incoloy 800 from A. M. Castle, heat HH7803A; composition in wt %: 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 0.04 C, 1.11 Mn, 0.41 Al, 0.41 Ti, 0.55 Cu, 0.004 S; specimens were exposed as machined.

[c] Coal gasification atmosphere (in moles at 1 atm and 298 K) = CO 0.2014, CO_2 0.1151, H_2 0.2014, H_2O 0.172, H_2S 0.010, CH_4 0.300; specimens were exposed for ~80 hours at 1000 psi.

[d] Temperature of exposure is indicated on each analysis.

EFFECT[a] OF A POTENTIALLY CARBURIZING ATMOSPHERE[b] ON SEVERAL ALLOYS AFTER 80 HOURS EXPOSURE[7]

Alloy[c]	Temp. °F	Results of Metallographic Examination
USS 18-18-2[d]	1330	Continuous outer sulfide scale layer; inner scale layer thick thick and continuous, little precipitation ahead of it; large cracks parallel to alloy surface observed in inner scale layer.
	1549	Massive, discontinuous sulfide layer outside original surface scale; subscale deeper and continuous, discrete sulfide particles only beneath areas of outer-inner scale.
	1808	Scale with outer and inner layers; large sulfide particles in matrix beneath scale.
Incoloy 800[d]	1419	Continuous sulfide outer scale and subscale on one side of specimen only; porous outer scale of small pieces of Fe-Ni-sulfide, thick inner solid scale of Fe-rich sulfide outer edge and Fe-Ni-rich sulfide inner edge; below this a Cr-rich sulfide layer enriched with S at innermost edge; no further S penetration and no Cr depletion beneath Cr-rich sulfide layer.
	1624	Sulfide outcrops outside protective scale; sulfide subscale has 3 bands, Fe-, Ni-, and Cr-rich; just below is Cr_2O_3-rich "protective" scale; alloy is Cr depleted in vicinity of Cr-rich particles; some carbides found, likely in original alloy, not formed during exposure; sulfidation likely along carbide network.
	1802	Single-layered, Cr-rich scale appears protective, some sulfide in matrix and surface grain boundaries; Cr-rich sulfide particles in alloy mainly at grain boundaries; Cr depletion beneath scale.
310 SS[d]	1419	Scale morphology similar to that at 1549 but with apparent Cr "healing layer" at base of subscale.
	1549	Heavy corrosion; continuous thick outer sulfide scale, continuous subscale, some penetration of grain boundaries; form of penetration did not resemble usual sulfide precipitates.
	1808	Protective scale with subjacent discrete sulfide globules on one side of specimen; more sulfidation attack on other side, numerous sulfides precipitated in alloy grain boundaries.
Inconel 671	All temps.	Protective scale; little sign of sulfide precipitates; at 1802°F greater amount of denudation of Cr-rich second phase than expected.
GE 1541 as received	1380	Protective scale; discontinuous sulfide nodules apparent on outside of scale, some evidence of development of subscale beneath largest sulfides.
	1549	Similar to 1380 with smaller nodules.
	1802	Thinner protective scale.
GE 1541 pre-oxidized[e]	All temps.	Adherent protective scales, no obvious sulfide penetration; some subscale and grain boundary precipitates, apparently oxide from pre-oxidation treatment.

---

[a] As-machined specimens were exposed to a coal gasification atmosphere at 68 atm for 80 hours and examined for corrosion.

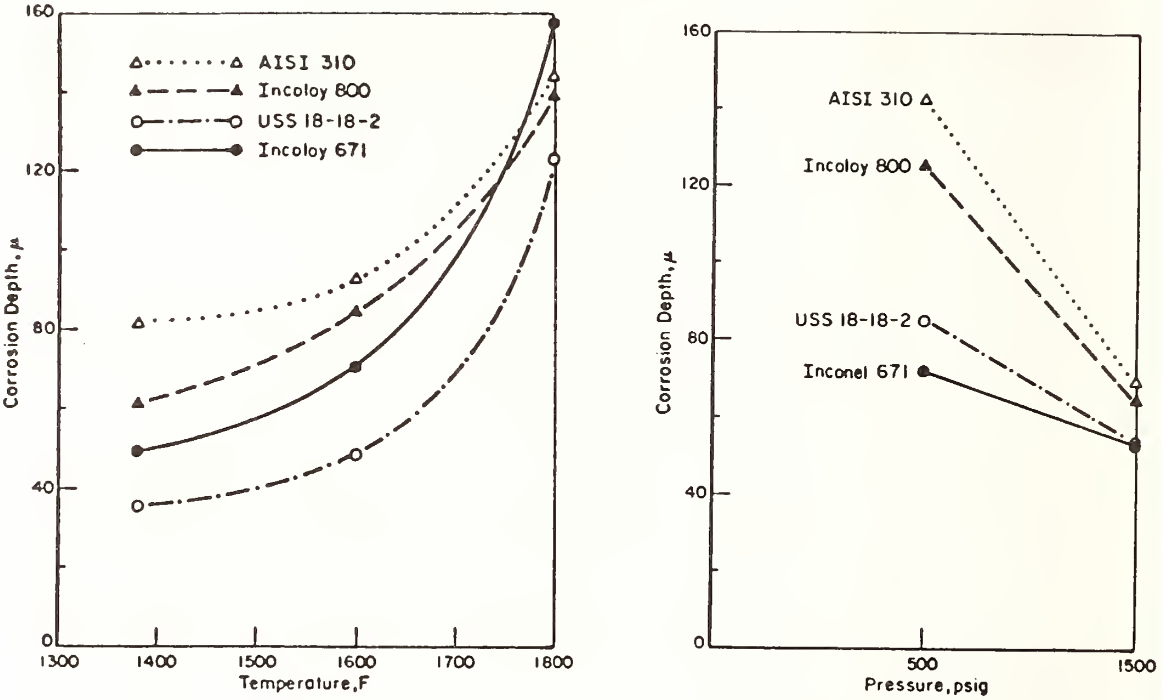
[b] Input gas composition at 1 atm and 298 K: CO 0.2014, CO_2 0.1151, H_2 0.2014, H_2O 0.172, H_2S 0.010, CH_4 0.300 (moles)

[c] Alloy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn,0.06 C, 0.296 others, balance Fe; Incoloy 800 (A. M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; AISI 310 SS (Rolled Alloys), 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe; Inconel 671 (Huntington Alloys), 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 0.02 Mn, 0.357 others; GE 1541 (General Electric), 15 Cr, 4 Al, 1 Y, balance Fe.

[d] Massive outer layers of sulfide spalled off when autoclave opened after exposure.

[e] These samples were pre-oxidized for 30 hours at 2100° F, 100 torr O_2.

EFFECT OF TEMPERATURE AND PRESSURE ON THE CORROSION PERFORMANCE[a] OF SOME ALLOYS[b] [7]



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[a] As-machined specimens were exposed for 1000 hours in the coal gasification atmospheres at the indicated temperatures and pressures. Gas compositions:

	Input, 1 atm, 77 °F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	mol %	1382 °F	1600 °F	1800 °F	1382 °F	1600 °F	1800 °F
CO	22.75	10.9	27.5	44.6	6.4	17.6	33.0
CO_2	30.20	18.9	12.9	6.3	20.7	16.9	11.1
H_2	25.47	16.0	25.8	34.3	10.2	17.3	25.2
H_2O		21.2	14.0	7.6	24.8	19.3	13.4
H_2S	1.96	1.6	1.5	1.5	1.7	1.6	1.6
CH_4	19.61	8.6	6.3	4.3	10.8	9.2	7.5
C		22.6	12.0	1.4	25.4	18.0	8.3
and							
CO	33.42	10.4	26.4	42.7	6.2	16.9	31.7
CO_2	19.15	17.9	12.1	5.9	19.5	15.9	10.5
H_2	33.42	16.3	26.1	34.7	10.3	17.6	25.5
H_2O		21.1	13.9	7.6	24.7	19.2	13.3
H_2S	1.29	1.2	1.1	1.1	1.2	1.2	1.1
CH_4	12.85	9.1	6.6	4.5	11.3	9.7	7.8
C		24.0	13.7	3.5	26.7	19.5	10.1

[b] Alloy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, 0.06 C, 0.296 other, balance Fe; Incoloy 800 (A.M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; AISI 310 SS (Rolled Alloys), 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe; Inconel 671 (Huntington Alloys), 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 0.02 Mn, 0.357 others.

OBSERVATIONS AFTER EXPOSURE[a] TO THE FLUE GASES OF FOUR COALS ON SEVERAL WELD/BASE METAL COMBINATIONS

Weld Composition		Weld Quality[b]	Coal Feedstock[c]	Exposure Conditions		Effect of Exposure	
Base Metals Joined	Weld Material			Avg. Temp. °F	Time Hrs.	Bonding	Attack[d]
316 SS/ Incoloy 800	Inconel 82 & Inconel 617		Subbitum. C	1000	3672	good	very little
		[Lack of penetration at root]	HV Bitum. A	1106	8081	good	very little
			HV Bitum. C	1202	4680	good	very little
		[Lack of penetration at root]	Lignite A	1244	4180	good	very little
Incoloy 800/ Inconel 617	Inconel 82 & Inconel 617	[Lack of penetration at root]	Subbitum. C	1280	7468	good	very little
		[Lack of penetration at root]	HV Bitum. A	994	3552	good	very little
Incoloy 800/ Inconel 617	Inconel 82	[Lack of penetration at root]	Subbitum. C	800	7368	good	very little
		[Lack of penetration at root]	HV Bitum. A	956	6478	good	very little
Inconel 617 clad on Incoloy 800/ Incoloy 800	Inconel 82	porosity and cold shuts, [lack of penetration at root]	HV Bitum. C	1230	4680	poor to clad	very little
		porosity and cold shuts, [crack at root]	Lignite A	1244	4180	poor to clad	very little
		porosity and cold shuts, [lack of penetration at root]	Subbitum. C	1240	3672	poor to clad	very little
		porosity and cold shuts, [lack of penetration at root]	HV Bitum. A	1122	8081	poor to clad	very little
Incoloy 800/ Haynes 188	Inconel 82	[lack of penetration at root]	Subbitum. C	800	7368	good	very little
		[lack of penetration at root]	HV Bitum. A	947	6478	good	very little

---

[a] Tests consisted of exposure of 28 pipe sections, 2 in O.D. x 1.5 in long, threaded into each other to form a probe. The exterior surface of the probe was exposed to combustion products and the interior surface temperature was controlled with air. The exposures were carried out in coal-fired commercial steam generators.

[b] Observations made on sections after exposure.

[c] Subbitum. C = Western subbituminous C coal, nominal HHV 7780, 24.5% ash, 0.4% sulfur and 7.2% moisture by weight; HV Bitum. A = Eastern bituminous high volatile A coal, nominal HHV 12280, 18% ash, 1% sulfur, and 0.4% moisture by weight; HV Bitum. C = Illinois No. 6 bituminous high volatile C coal, nominal HHV 10430, 10.7% ash, 3% sulfur and 15.9% moisture by weight; Lignite A = Texas Lignite A, nominal HHV 7010, 9.8% ash, 0.7% sulfur and 33.8% moisture by weight.

[d] Effect on weld surface.

FIRESIDE CORROSION MEASUREMENTS[a] ON HIGH-TEMPERATURE TUBES EXPOSED[b] IN AN ATMOSPHERIC FLUIDIZED-BED COMBUSTION FACILITY[c] [19]

MATERIAL Exposure Time, hr	Removal Time, hr[d]	Oxide Scale[e] Thickness, µm			Intergranular Corrosion Depth, µm			Depth, µm, of Sulfide Inclusions[f]		
		Ave.	Pooled S.D.	Max.	Ave.	Pooled S.D.	Max.	Ave.	Pooled S.D.	Max.
304 STAINLESS STEEL										
500	500	5.6	2.0	10.6	18.2	5.6	34.5	28.1	4.1	41.5
1000	3000	10.3	4.0	23.7	30.3	19.8	104.6	48.1	21.0	126.4
1500	4500	9.3	5.2	30.9	47.2	29.0	105.3	72.5	35.7	145.3
3000	4500	9.5	5.6	26.9	32.7	18.8	79.4	66.3	23.4	121.6
4000	4500	8.0	2.9	15.4	29.6	6.5	37.4	55.0	10.2	74.9
310 STAINLESS STEEL										
500	500	5.1	1.7	7.8	15.6	6.3	33.7	26.58	5.8	38.4
500	500	5.4	1.7	9.2	13.5	4.7	21.4	30.8	7.9	45.0
1000	1500	5.8	1.9	10.2	23.6	10.1	40.7	36.5	12.2	55.0
1500	1500	6.1	1.5	10.7	19.0	7.1	31.0	37.0	11.2	52.8
3000	4500	6.7	2.7	15.8	27.0	13.3	86.1	44.7	13.5	94.5
3000	4500	6.2	2.3	13.0	29.9	12.2	57.2	57.2	9.0	70.8
4500	4500	12.4	3.4	21.5	39.1	19.5	99.0	61.7	17.2	81.7
4500	4500	7.1	1.3	9.1	32.6	12.2	82.9	58.4	18.8	102.2
316 STAINLESS STEEL										
500	2000	5.4	2.1	11.5	13.5	8.1	29.7	19.0	8.7	48.2
1000	1500	10.4	4.8	28.0	31.0	12.4	48.9	47.7	11.1	73.5
1000	3000	11.2	4.6	32.9	34.3	17.8	100.3	46.5	20.3	119.3
1500	1500	8.5	1.6	12.4	25.4	8.0	50.1	47.0	8.4	62.1
1500	4500	9.6	2.9	14.1	59.7	23.9	111.3	78.0	24.0	137.8
3000	4500	16.9	9.7	46.7	31.9	16.8	68.1	47.0	19.5	87.7
4500	4500	11.3	3.8	22.6	33.1	11.1	60.7	60.0	11.4	92.8
4500	4500	12.3	4.0	22.6	37.7	15.6	89.0	62.2	14.6	104.6
One tube exposed for 3000 hr exhibited severe sulfidation-oxidation. Two tubes exposed for 4500 hr showed sulfidation attack at the refractory-tube interface at the hot end.										
INCOLOY 800H										
500	500	5.8	1.8	8.5	30.3	10.2	46.4	38.9	11.0	80.2
500	500	6.1	1.2	8.2	28.9	8.4	43.9	35.9	10.9	60.2
500	500	5.0	1.8	9.4	19.5	18.0	41.3	26.4	16.6	45.5
1000	1500	7.1	1.2	9.6	39.9	15.1	60.7	52.5	12.0	78.5
1500	1500	6.9	1.9	11.7	47.2	27.4	84.2	58.9	26.5	88.9
1500	2000	8.0	5.9	13.6	80.0	15.3	119.7	86.6	13.2	115.6
1500	4500	5.4	2.2	8.0	61.3	29.5	112.0	86.1	24.8	136.6
3000	4500	7.9	4.0	18.0	77.9	23.9	130.8	92.2	17.6	146.6
3000	4500	10.1	3.0	14.9	90.4	23.5	135.2	102.2	24.0	142.2
4500	4500	10.8	2.5	16.5	77.3	20.9	133.1	92.2	17.6	146.6
4500	4500	11.4	2.2	15.7	101.5	18.8	146.4	117.1	18.1	156.3
INCOLOY 800, aluminized										
310 STAINLESS STEEL, aluminized										
The outer layer cracked and spalled on both fireside and air side; aluminum diffusion zone appeared corrosion resistant but had been penetrated by sulfur; localized and random areas of the diffusion zone suffered mild sulfidation-oxidation attack; no meaningful measurements could be made since the original surface could not be identified.										

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[a] For each feature, values reported are averages of eight measurements taken around the circumference of the sample averaged with those of two to five additional samples from the same tube, the pooled standard deviation $\sqrt{\Sigma\sigma_i^2/m}$, for m specimens), and the greatest value among all measurements. Measurements were made using a digital measuring eyepiece and a metallograph at 320X magnification; measurements made at equally spaced points on the inner and outer circumferences of the polished cross sections; samples were rotated several degrees of arc at each location to find thickest scale or deepest discernable corrosion feature; locations with no scale or corrosion were not used.

[b] Exposures were at temperatures over the range 810-870 °C (1490-1600 °F). Composite tubes consisted of three alloys in 0.152 m (6 in) segments to form a tube 0.457 m (18 in) long and 12.7 mm (0.5 in) in outer diameter.

[c] Tests run in Fluidyne Engineering Co.'s 0.46 m x 0.46 m (18 in x 18 in) atmospheric fluidized-bed coal combustion facility; Illinois No. 6 coal (fixed carbon 43.10%, volatiles 32.94%, ash 13.55%, moisture 10.41%) burned with limestone as a sorbent for sulfur, flue gases had an average SO_2 level 250-400 ppm; system operated at 2-3% excess O_2; bed temperature ~870 °C (1600 °F); fluidizing velocity 1.2-1.8 m/s (4-6 ft/s).

[d] Time during 4500-h test at which sample was removed.

[e] Spalling probably occurred during exposure since variability in thickness is large and thickness does not increase with time; some samples show areas with no oxide scale probably due to spalling during final cooling; areas without scale were not used to compute thickness.

[f] Sulfide inclusions were discrete manganese-rich particles.

COMPARISON OF FIRESIDE AND AIR SIDE CORROSION OF ALLOYS TESTED[a] AS HIGH-TEMPERATURE HEAT EXCHANGER TUBES FOR ATMOSPHERIC FLUIDIZED-BED COMBUSTION[b] [19]

Material	Exposure Time, hr	Oxide Scale Thickness, μm			Intergranular Corrosion Depth, μm		
		Ave.[c]	S.D.[d]	Max.[e]	Ave.[c]	S.D.[d]	Max.[e]
			AIR SIDE				
304 SS	500	5.54	3.52	16.01	14.64	6.23	24.94
310 SS	500	4.25	0.97	6.36	13.30	3.87	28.84
	1500	5.26	1.00	7.64	17.01	6.74	40.66
316 SS	1500	5.97	0.86	7.42	25.69	8.03	40.56
Inconel 600	500[f]	4.04	0.75	5.68	12.68	3.04	20.65
Incoloy 800	500	5.53	1.53	10.10	42.85	5.31	55.62
	1500	7.19	1.32	10.44	49.17	9.29	83.41
			FIRESIDE				
304 SS	500	5.94	2.38	12.54	16.11	6.24	39.82
310 SS	500	4.74	1.17	6.76	13.08	5.45	30.76
	1500	6.49	1.83	12.78	15.73	5.92	32.47
316 SS	1500	7.51	2.51	10.80	41.64	8.26	55.44
Inconel 600	500[f]	3.96	0.81	4.13	14.09	3.88	20.96
Incoloy 800	500	5.64	1.49	8.94	34.54	10.77	63.89
	1500	7.42	1.33	9.64	30.91	12.13	65.91

COMMENTS:

310 SS - hotter end of tube shows a thin oxide layer under a thick $CaSO_4$ deposit on the outer surface, also minor intergranular corrosion; no evident sulfidation.
310 SS aluminized - outer surface coating separated completely from base metal, inner diffusion zone contains oxide particles, outer most layer is cracked and contains significant voids; inner surface coating less cracked but has delaminated because of almost continuous layer of voids; diffusion zone is intact, no sign of intergranular corrosion.
316 SS - relatively non uniform corrosion layer beneath $CaSO_4$ deposit on outer surface, slight intergranular corrosion; inner surface shows severe pitting oxidation.
Incoloy 800 - hotter end of tube shows surface oxidation on inner and outer surfaces, slight intergranular corrosion and grain boundary precipitate, also subsurface voids.
Incoloy 800 aluminized - outer layer extensively attacked, minor attack on inner surface; diffusion zone on both surfaces appears sound and little affected; no sulfidation attack.

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[a] Exposures were at temperatures over the range 810-870 °C (1490-1600°F). Composite tubes consisted of three alloys in 0.152 m (6 in) segments to form a tube 0.457 m (18 in) long and 12.7 mm (0.5 in) in outer diameter.

[b] Tests run in Fluidyne Engineering Co.'s 0.46 m x 0.46 m (18 in x 18 in) atmospheric fluidized-bed coal combustion facility; Illinois No. 6 coal (fixed carbon 43.10%, volatiles 32.94%, ash 13.55%, moisture 10.41%) burned with limestone as a sorbent for sulfur, flue gases had an average SO_2 level 250-400 ppm; system operated at 2-3% excess O_2; bed temperature ∿870 °C (1600 °F); fluidizing velocity 1.2-1.8 m/s (4-6 ft/s).

[c] Average of all measurements on material type; measurements were made using a digital measuring eyepiece and a metallograph at 320X magnification; measurements made at equally spaced points on the inner and outer circumference of the polished cross sections; samples were rotated several degrees of arc at each location to find thickest scale or deepest discernable corrosion feature; locations with no scale or corrosion were not used.

[d] Pooled Standard Deviation of all measurements.

[e] Maximum feature observed.

[f] All Inconel 600 samples removed from test shortly beyond 500 hr; material was subject to hot corrosion attack, apparently in bed areas where there was a low oxygen potential; a chromium sulfide corrosion front preceded a layer of nickel-rich, chromium-depleted matrix and voids; loose, porous chromium oxysulfide scale on original tube surface, adhering to this was a deposit of bed material cemented together by nickel sulfide which suggests the formation of a liquid corrosion product.

CORROSION OF ALLOYS TESTED AS LOW-TEMPERATURE HEAT EXCHANGER TUBING[a] IN ATMOSPHERIC FLUIDIZED-BED COMBUSTOR[b] [19]

MATERIAL Sample[c]	Exposure Time, h	Removal Time, h[d]	Fireside Measurements[e], µm Oxide Scale Thickness ave.	s.d.	max.	Intergranular Corrosion ave.	s.d.	max.	Airside Measurements[e], µ Oxide Scale Thickness ave.	s.d.	max.
2 1/4 Cr-1 Mo STEEL											
3A-1	500	2000	20	5	28	Intergranular corrosion or oxide finger penetration not significant within measuring limits.			20	10	30
-2			40	13	68				30	10	43
8B-1	500	2000	15	7	27				24	7	31
-2			28	9	47				40	7	48
3A-1	1000	3000	74	46	113				37	10	54
-2			82	41	152				54	14	76
8B-1	1000	3000	23	12	44				19	7	25
-2			31	4	34				40	4	45
8B-1	1500	4500	42	12	60				28	5	35
-2			37	7	45				27	9	36
-3			56	29	101				56	6	66
7D-1	3000	4500	91	48	166				68	18	95
-2			50	14	66				27	8	36
-3			58	30	110				31	8	43
304 STAINLESS STEEL											
3A-3	500	2000	4.0	1.4	4.6	9.0	5.3	18.6	Oxide scale too thin and spotty for meaningful measurement.		
-4[f]			5.0	1.3	6.5	0	0	0			
-5[f]			3.6	0.8	4.6	5.4	3.8	11.1			
-6			4.4	0.7	5.5	7.2	2.8	11.2			
8B-3	500	2000	6.0	0.8	6.8	4.6	0.8	5.7			
-4[f]			4.0	1.1	6.0	3.5	0.8	4.2			
-5[f]			6.4	1.2	8.3	5.2	1.6	7.4			
-6			3.5	1.0	5.7	4.1	2.0	6.9			
3A-3	1000	3000	3.7	0.8	4.7	6.1	2.1	9.5			
-4[f]			4.4	1.0	6.2	2.6	1.5	3.7			
-5[f]			4.4	0.4	4.9	6.8	2.1	10.8			
-6			4.7	0.9	6.3	7.7	3.8	10.7			
8B-3	1000	3000	5.2	1.9	7.3	9.9	2.9	14.9			
-4[f]			7.2	3.4	15.3	0	0	0			
-5[f]			5.3	1.2	7.0	7.5	1.1	8.9			
-6			6.1	1.2	7.9	11.8	8.0	19.6			
8B-4	1500	4500	6.2	1.8	10.4	7.5	2.4	10.4			
-5[f]			3.5	1.4	5.5	4.4	1.8	8.1			
-6[f]			5.6	1.3	7.3	4.1	2.1	7.1			
-7			4.5	0.5	5.2	4.0	2.1	7.9			
7D-4	3000	4500	5.7	1.2	7.0	6.9	2.7	13.0			
-5[f]			5.1	1.6	7.9	6.6	2.3	10.7			
-6[f]			5.6	2.2	9.8	9.6	3.8	15.4			
-7			6.4	3.3	14.2	9.9	3.9	16.0			

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[a] Composite tubes were made of 2 1/4 Cr-1 Mo steel for the inlet end and 304 SS for the outlet end of each low temperat heat exchanger tube; tubes are air cooled, 12.7 mm (0.5 in) outer diameter; temperature increases from ∿510 °C at inle to ∿590 °C at outlet end.

[b] Tests run in Fluidyne Engineering Co.'s 0.46 m x 0.46 m (18 x 18 in) atmospheric fluidized-bed coal combustion facility; Illinois No. 6 coal (fixed carbon 43.10%, volatiles 32.94%, ash 13.55%, moisture 10.41%) burned with limestone as a sorbent for sulfur, flue gases had an average SO_2 level 250-400 ppm; system operated at 2-3% excess O_2; bed temperature ∿870 °C (1600 °F); fluidizing velocity 1.2-1.8 m/s (4-6 ft/s).

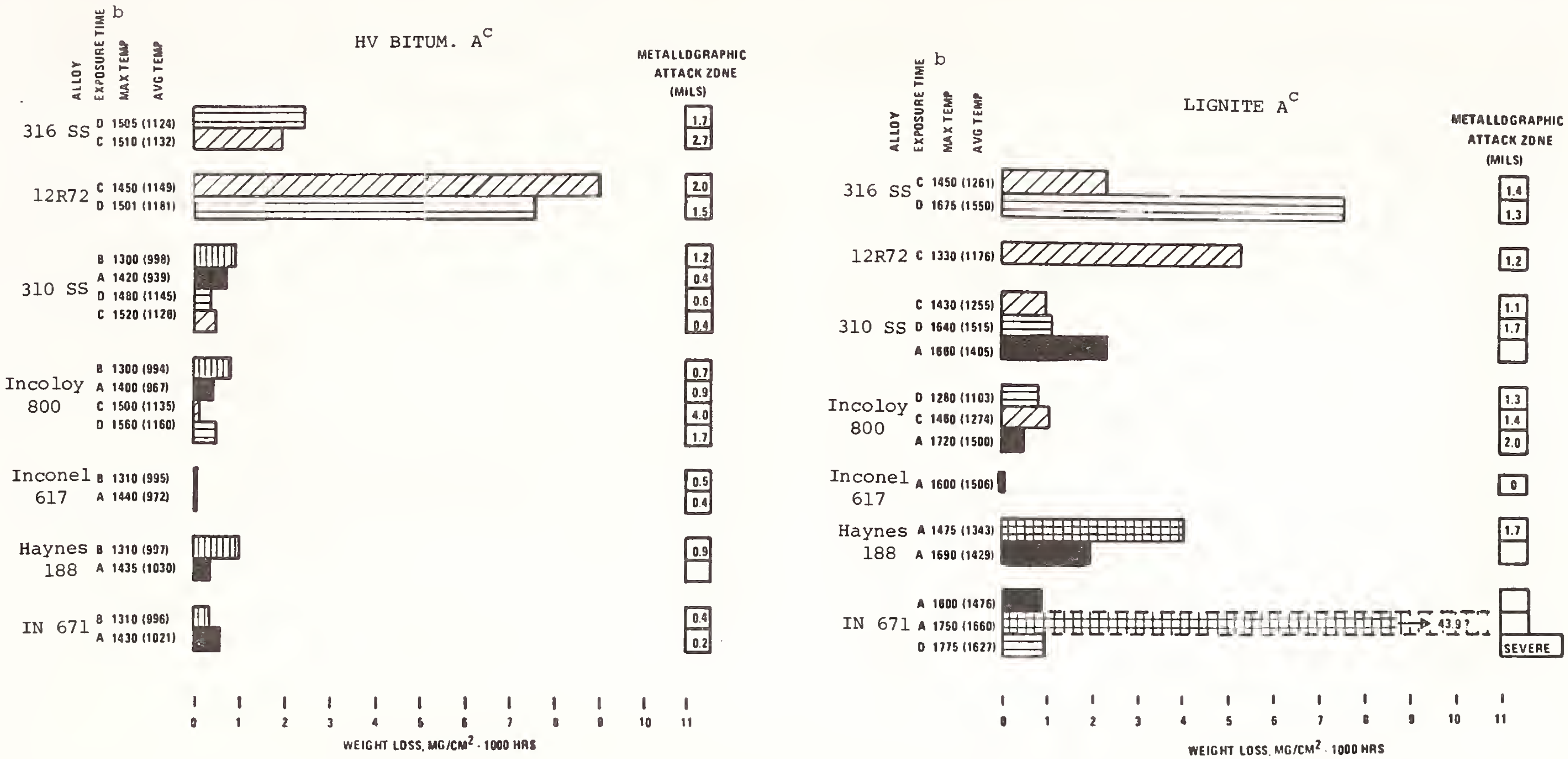
[c] The tube is designated by the row and column (number and letter) in the test bed; for each tube the sample number increases from the inlet end; temperature increases smoothly from ∿510 °C at the inlet to ∿590 °C at the outlet; midway between is the transition joint between the two test alloys.

[d] Time during 4500-h test at which sample was removed.

[e] For each feature the average of eight measurements taken around the circumference, the standard deviation of these measurements, and the greatest measurement are given; measurements were made using a digital measuring eyepiece and a metallograph at 320X magnification; measurements made at equally spaced points on the inner and outer circumferences of the polished cross sections; samples were rotated several degrees of arc at each location to find the thickest scale or deepest discernable corrosion feature; locations with no scale or corrosion were not used.

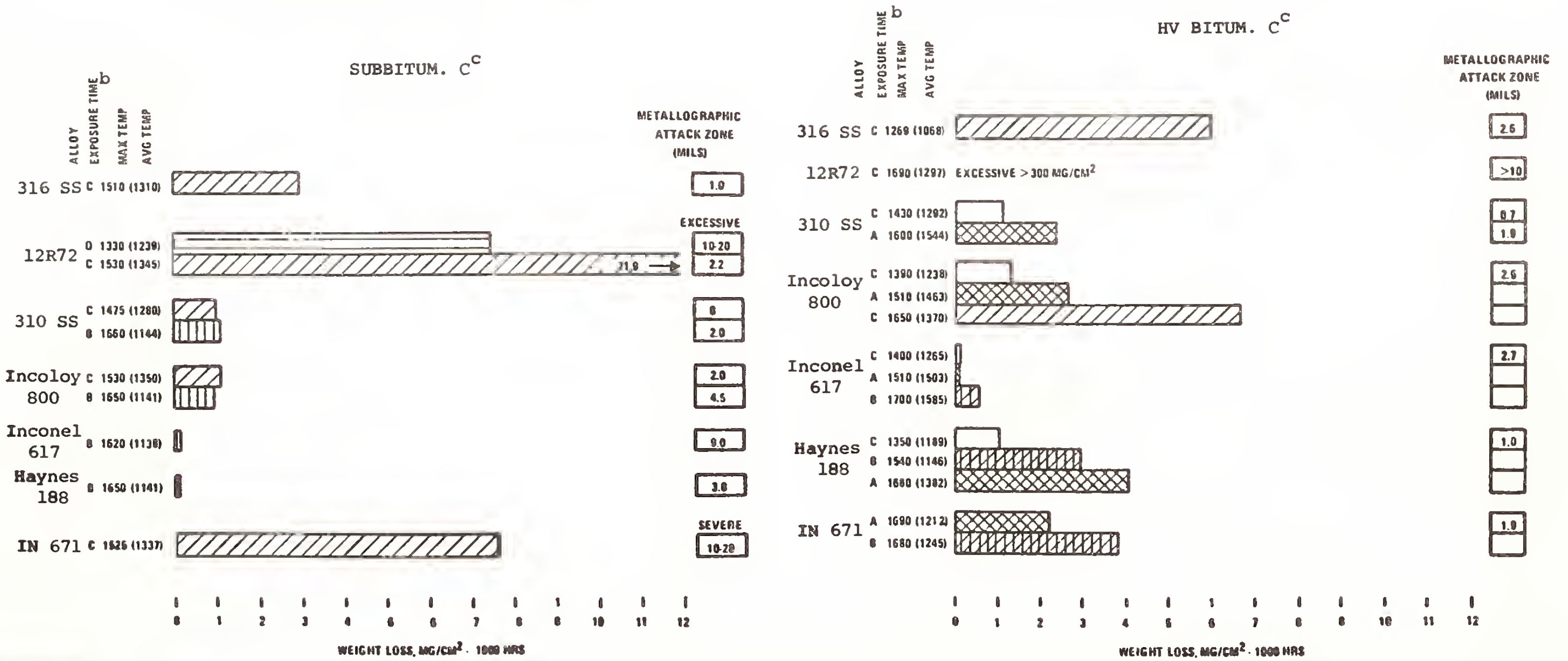
[f] Surface machine ground before exposure in combustion facility.

CORROSION OF SEVERAL ALLOYS EXPOSED TO FLUE GASES[a] IN COAL-FIRED COMMERCIAL STEAM GENERATORS[17]



(Data Continued)

CORROSION OF SEVERAL ALLOYS EXPOSED TO FLUE GASES[a] IN COAL-FIRED COMMERCIAL STEAM GENERATORS[17], Continued



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[a] Tests consisted of exposure of 28 pipe sections, 2 in OD x 1.5 in long, threaded into each other to form a probe. The exterior surface of the probe was exposed to combustion products and the interior surface temperature was controlled with air. Test temperatures in °F.

[b] Exposure times: A = 6478 hr, B = 3552 hr, C = 8081 hr, D = 3720 hr.

[c] Coal Feedstocks: HV Bitum. A = Eastern bituminous high volatile A coal, nominal HHV 12280, 18% ash, 1% sulfur, and 0.4% moisture by weight. Lignite A = Texas lignite A, nominal HHV 7010, 9.8% ash, 0.7% sulfur, and 33.8% moisture by weight. Subbitum. C = Western subbituminous C coal, nominal HHV 7780, 24.5% ash, 0.4% sulfur, and 7.2% moisture by weight. HV Bitum. C = Illinois no. 6 bituminous high volatile C coal, nominal HHV 10430, 10.7% ash, 3% sulfur, and 15.9% moisture by weight.

EFFECT OF COMPOSITION, ENVIRONMENT AND MINOR ALLOYING ADDITIONS ON SULFIDATION RESISTANCE[a] OF Fe-Cr-Al ALLOYS[b] IN SYNTHETIC COAL GASIFICATION ENVIRONMENTS[c] [34]

Alloy[b]	Weight Change (mg/cm^2)--Corrosion Products[d]					
	24 hr				96 hr	
	Not equilibrated[e]		Equilibrated[e]		Equilibrated[e]	
Fe-15Cr		D		D		
Fe-15Cr-1Al		D		D		
Fe-10Cr-2Al		D		D		
Fe-12.5Cr-2Al		D	+70.9	AO/SS		
Fe-15Cr-2Al		D				
Fe-15Cr-2Al		D	+1.2	AO	+0.03	AO
Fe-18Cr-2Al-1Si-0.4Ti[f]	+0.32	AO	+0.45	AO	+0.69	AO
Fe-10Cr-3Al		D				
Fe-12.5Cr-3Al		D	+2.3	AO/SS		
Fe-13Cr-3Al		D			-0.05	SO
Fe-14Cr-3Al		D			+0.17	AO
Fe-15Cr-3Al	+0.24	AO		D		
Fe-10Cr-4Al	 +4.29	D SS/SO				
Fe-12.5Cr-4Al		D			+0.43	SO
Fe-14Cr-4Al	+0.20	SO			+0.17	SO
Fe-14Cr-4Al-0.5Y			+1.9	SO		
Fe-15Cr-4Al			+0.49	SO	+0.42	SO
Fe-16Cr-4.5Al-0.5Y[g]	+0.69	AO	+0.39	AO	+0.49	AO
Fe-16Cr-4.5Al-0.5Y			+0.75	SO		
Fe-16Cr-4.5Al-1.5Mn			+9.41	SO		
Fe-16Cr-4.5Al-0.5Hf			+0.85	SO		
Fe-16Cr-4.5Al-2Mo-0.5Y			+0.61	SO		
Fe-16Cr-4.5Al-4Mo-0.5Y			+0.70	SO		
Fe-18Cr-4Al-0.5Y			+0.67	SO		
Fe-5Cr-6Al		D				
Fe-7.5Cr-6Al	 +3.48	D SS/SO				
Fe-10Cr-6Al	+6.57	SS/SO	+1.3	SO		
Fe-12.5Cr-6Al	-0.58	SO	+0.2	SO		
Fe-15Cr-6Al	nil -0.39	 SO			 +0.39	 SO
Fe-5Cr-8Al		D				
Fe-8Cr-8Al		D	-3.0	SO/SS		
Fe-9Cr-8Al	+0.14	SO	-1.8	SO		
Fe-10Cr-8Al	-0.10	SO		D		
Fe-10Cr-8Al-0.5Y	+0.47	AO	nil	SO		
Fe-10Cr-8Al-1.5Mn	-10.10	SO				
Fe-10Cr-8Al-1.5Mn-0.5Y	+0.33	SO	+0.71	SO		
Fe-10Cr-10Al	-0.47	SO		D		
Fe-10Cr-10Al-1.5Mn	+0.93	SO[h]	+12.8	SO		

(Table Continued)

EFFECT OF COMPOSITION, ENVIRONMENT AND MINOR ALLOYING ADDITIONS ON SULFIDATION RESISTANCE[a] OF Fe-Cr-Al ALLOYS[b] IN SYNTHETIC COAL GASIFICATION ENVIRONMENTS[c][34] - Continued

	Weight Change (mg/cm^2)--Corrosion Products[d]				
	24 hr				96 hr
Alloy[b]	Not equilibrated[e]		Equilibrated[e]		Equilibrated[e]
Fe-15Cr-8Al	-0.05	SO	-0.3	SO	
Fe-15Cr-10Al	-0.69 -0.55 -0.45	SO SO SO	-0.16	SO	
Fe-15Cr-10Al-1.5Mn	+7.90	SO[h]	-0.19	SO	
Fe-5Cr-10Al		D			
Fe-8Cr-10Al	-0.51	SO			
Fe-9Cr-10Al	-0.45	SO	-2.2	SO	

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[a] Tests for Sulfidation resistance in coal gasification atmosphere conducted at 1255 K (1800 °F) and 1 atm pressure; gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec.

[b] Alloys were arc melted and drop cast by the nonconsumable electrode process under argon at 1.5 atm. The cast structure was broken up by extrusion from 2000 °F and hot rolling from furnace temperature of 1600 °F (reduced 10% in thickness per pass and reheated between passes) to 0.1 in thick. Coupons were machined to 0.75 in x 0.25 in and rolled surfaces were ground flat and parallel (5 mils from each side).

[c] Nominal gas composition (mol %), not equilibrated: 24 H_2, 39 H_2O, 18 CO, 12 CO_2, 5 CH_4, 1 H_2S, 1 NH_3.

[d] AO - Adherent Oxide, SO - Spalled Oxide, SS - Sulfide Slag, D - Destroyed.

[e] To obtain equilibrated conditions, the inlet gas percolates through a heated bed of fine/coarse Al_2O_3 bubble grains fitted in the furnace tube to within 1-inch of the lowest sample on the specimen rack. Equilibrated gas also contains minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, CS.

[f] Armco 18SR.

[g] Alleghany-Ludlum Alloy-Y, developmental.

[h] 47 hr test.

RESULTS OF CORROSION TESTS[a] OF ALLOYS IN COAL-FIRED COMMERCIAL STEAM GENERATORS[17]

Material	Coal Feedstock	Temperature, °F Mean	Max	Exposure Hr	Total Weight Loss Mg/Cm^2	Weight Loss/ 1000 Hrs Mg/Cm^2	Penetration Mils
Haynes 188 (39Co, 22Cr, 22Ni, 14W, 2Fe)	H.V. Bitum. A[b]	997	1310	3552	3.4	1.0	+13 to 1.5
		930	1435	6478	2.7	0.4	+ 4 to .5
	Subbitum. C[c]	1141	1650	7368	<0.1	0.01	1
	H.V. Bitum. C[d]	1140	1540	1849	2.9	1.6	.5 to 1
		1184	1350	2940	3.3	1.1	+ .5 to 1
		1382	1680	2950	4.2	1.2	+ 2.5 to 2
	Lignite A[e]	1429	1690	620	1.2	1.9	+ 3.5 to + 1
		1343	1475	840	3.4	4.1	.5 to 1
Incoloy 800H (46Fe, 32Ni, 21Cr, 0.1C)	H.V. Bitum. A	994	1300	3552	2.87	0.8	+13 to + 8
		1160	1560	3720	1.9	0.5	+21.5 to + 3
		967	1400	6478	2.9	0.4	+ 8 to 1.5
		1135	1500	8081	2.0	0.2	+15 to .5
	Subbitum. C	1211	1310	3144	13.1	4.2	1
		1350	1530	3672	4.5	1.2	3 to 5
		1141	1650	7368	7.3	1.0	1 to 2
	H.V. Bitum. C	1238	1390	2940	3.9	1.3	+ 1 to 1
		1463	1510	2950	7.0	2.7	+ 1 to 1.5
		1370	1650	3672	24.6	6.7	+ 9 to 18
	Lignite A	1500	1720	620	0.3	0.5	+ 7.5 to + .9
		1274	1480	3214	4.0	1.2	+20 to 15
		1103	1280	3840	2.8	0.8	+ 4 to + 1
Inconel 617 (22Cr-54Ni-9Mo-12.5Co)	H.V. Bitum. A	995	1310	3552	0.21	0.06	+11 to .5
		912	1440	6478	0.17	0.03	+ 3.5 to 1.5
	Subbitum. C	1138	1620	7368		0.79	+ 7 to + 2
	H.V. Bitum. C	1230	1700	1849	1.1	0.60	+ 2 to 1.5
		1265	1400	2940	0.28	0.10	+ 2 to .5
		1503	1510	2950	0.18	0.06	+ 2 to 1.5
	Lignite A	1453	1700	620	3.7	5.9	+ 2.8 to + 1.2
		1506	1600	840	0	0	+ 2 to + 1
Sandvik 12R72 (15Cr, 15Ni, 1.2Mo, 0.4TiB)	H.V. Bitum. A	1181	1505	3720	28.3	7.6	1
		1149	1450	8081	72.4	9.0	+ 2 to 2.5
	Subbitum. C	1239	1330	3144	23.7	7.5	1
		1345	1530	3672	80.4	21.9	1 to 2
	Lignite A	1176	1330	3214	17.1	5.3	+ 3.5 to .5
310 S.S. (25Cr, 20Ni, 2Mn)	H.V. Bitum. A	998	1300	3552	3.1	0.9	+12 to 1
		1145	1480	3720	1.2	0.3	+ 9.5 to .5
		939	1420	6478	3.2	0.5	+ 3 to .5
		1128	1520	8081	3.3	0.4	+ 3.5 to + .5
	Subbitum. C	1249	1410	3144	6.5	2.1	1 to 5
		1280	1475	3672	4.0	1.1	+ 3 to 1
		1144	1660	7368	9.1	1.2	+ 8 to + 2
	H.V. Bitum. C	1292	1430	2940	3.3	1.1	.5
		1544	1600	2950	8.3	2.8	+ .5 to 1
		1350	1720	3672	38.0	10.3	+ .6 to 1
	Lignite A	1405	1680	620	1.5	2.4	+ 2.9 to + 1.5
		1588	1670	840	5.9	7.0	+ 1
		1255	1430	3214	3.2	1.0	+ 4 to + 1.5
		1515	1640	3840	4.7	1.2	+ 2.5 to 4
316 S.S. (16Cr, 13Ni, 2Mo)	H.V. Bitum. A	1124	1505	3720	9.3	2.5	+18 to + 2
		1132	1510	8081	16.4	2.0	+15 to 12
	Subbitum. C	1310	1510	3672	11.0	3.0	+ 2 to 2
	H.V. Bitum. C	1089	1260	3672	21.9	6.0	
	Lignite A	1261	1450	3214	7.5	2.3	+12 to + 1.5
		1550	1675	3840	29.3	7.6	+ 7 to + 2

(Table Continued)

RESULTS OF CORROSION TESTS[a] OF ALLOYS IN COAL-FIRED COMMERCIAL STEAM GENERATORS[17]

(Table Continued)

Material	Coal Feedstock	Temperature, °F		Exposure Hr	Total Weight Loss Mg/Cm^2	Weight Loss/ 1000 Hrs Mg/Cm^2	Penetration Mils
		Mean	Max				
Inconel 671 cladding on IN 800H base (51Cr-48Ni)	H.V. Bitum. A	996	1310	3552	1.2	0.3	+13 to 1.5
		921	1430	6478	4.2	0.6	+ 4 to .5
	Subbitum. C	1337	1525	3672	28.1	7.7	+ 3 to 3
	H.V. Bitum. C	1245	1680	1849	7.0	3.8	+ 8.5 to 1.5
		1212	1680	2950	6.3	2.2	.5 to 2
	Lignite A	1476	1600	620	0.5	0.8	+ 4.2 to + .1
		1660	1750	840	36.9	43.9	+ 1 to 3
		1627	1775	3840	3.4	0.9	+ 5 to 1
Titanium Nitride sprayed coating on IN 800H base	H.V. Bitum. A	919	1300	3552	25.3	7.1	5
		771	1250	6478	1.2	0.2	+ 6.5 to 5.5
	Subbitum. C	1270	1480	3672	19.5	5.3	2 to 6
	H.V. Bitum. C	1152	1500	3672	31.2	8.5	+11 to 14
	Lignite A	1280	1510	3214	25.7	8.0	+13 to 8
		1664	1790	3840	71.7	18.7	+ 4 to 6.5
Tungsten Carbide sprayed coating on IN 800H base	H.V. Bitum. A	1081	1381	3720	0.89	0.2	+ 4
		1142	1500	8081	24.1	3.0	+ 4.5 to 11
	H.V. Bitum. C	1377	1500	3672	34.5	9.4	+12.5 to 12.9
	Lignite A	1099	1260	3214	9.1	2.83	+ 7 to 13
Chromium/ 800H	H.V. Bitum. A	1167	1540	3720	10.9	3.0	+10 to + 7
		1063	1480	8081	27.6	3.4	+ .5 to 13
	Subbitum. C	1329	1520	3672	31.7	8.6	2 to 7

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[a] Tests consisted of exposure of 28 pipe sections, 2 in O.D. x 1.5 in long, threaded into each other to form a probe. The exterior surface of the probe was exposed to combustion products and the interior surface temperature was controlled with air.

[b] Eastern bituminous high volatile A coal, nominal HHV = 12280, 18% ash, 1% sulfur and 0.4% moisture by weight.

[c] Western subbituminous C coal, nominal HHV = 7780, 24.5% ash, 0.4% sulfur and 7.2% moisture by weight.

[d] Illinois no. 6 bituminous high volatile C coal, nominal HHV = 10430, 10.7% ash, 3% sulfur and 15.9% moisture by weight.

[e] Texas Lignite A, nominal HHV = 7010, 9.8% ash, 0.7% sulfur and 33.8% moisture by weight.

[Note: Mg/Cm^2 in the headings of the sixth and seventh columns of this table should read mg/cm^2.]

RESULTS OF EXPOSURE[a] OF MATERIALS TO SERVICE IN AN ATMOSPHERIC FLUIDIZED-BED COMBUSTION BOILER FACILITY[b] [20]

Material	Exposure Position[a]	Maximum Metal Temperature, °C (°F)		Exposure Time, hr	Results of Metallographic Examination
		Expected Mean Operating	Design Outer Surface		
SA-213-T2 1/2 Cr-1/2 Mo steel	Primary superheater (Cell A) heat exchanger bundles, lower pass	432 (810)	521 (970)	3	Exposed surface slightly roughened; discontinuous thin oxide scale, finely dispersed subsurface oxide specks; only one or two isolated adherent sulfate scale spots.
SA-213-T22 2 1/4 Cr- 1 Mo steel	Primary superheater (Cell A) heat exchanger bundles, upper pass	465 (868)	574 (1065)	3	Nonuniform duplex oxide layer with islands of unoxidized base metal; thin layer of deposited sulfate scale, lace-like subsurface oxidation.
	Finishing superheater (Cell B) heat exchanger bundles, upper pass	472 (881)	548 (1019)	115	Better developed oxide layer than in Cell A with only a few islands of unixidized base metal and slightly less subsurface oxidation; sulfate deposit layer separated from oxide layer in sample handling but without stripping oxide layer.
SA-213-TP304H	Finishing superheater (CellB) heat exchanger bundles, lower pass	553 (1028)	638 (1180)	115	Slightly roughened surface covered with relatively well-formed oxide scale; intergranular corrosion reached depth of 20 μm but tends to be localized; chromium carbide precipitates observed.
Inconel 601 21-25 Cr, 58-63 Ni, bal Fe	Primary superheater (Cell A) center row tube support ladders	899 (1650)		3	Very thin oxide scale on mill-finished sides, none on sheared edge; small area of sulfidation attack reaching a depth of ∿10 μm.
	Finishing superheater (Cell B) center row tube support ladders	899 (1650)		115	Extensive sulfidation attack on upper portions on one side only; opposite side often showed dense hot-cracked oxide layer with subsurface voids and oxides; lower portions of ladders had only a sprinkling of sulfide specks; sulfides detected on some sheared edges of lower ladders; cold-worked edge of a sample had recrystallized.
	Cell C center row tube support ladders	899 (1650)		264	On upper supports moderately deep intergranular corrosion, subsurface oxidation and voids, specks of sulfide, and oxide-under-sulfate scale layer; lower supports similar except for much less intergranular corrosion.

General results: All tube samples showed a discontinuous, thin sulfate deposit over the oxide scale, no indication of subsurface sulfide attack; support ladders showed strong subsurface sulfidation attack.

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[a] Materials were used either in heat exchanger tube bundles or as tube hanger ladders in cells of a multicell facility; total coal-firing hours for the cells were--Cell A 3, B 115, C 264, D 1500; the carbon burnup cell, D, contains no in-bed heat-exchanger surface and is the light-off cell; hot-bed material is transferred sequentially to the remaining cells for their ignition.

[b] Reevesville multicell atmospheric fluidized-bed combustion boiler facility (30 MWe).

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED[a] TO COMBUSTION PRODUCTS OF FOUR REGIONAL COALS[17]

Alloy	Coal Feedstock	Exposure Time (hr)	Temperature (°F)	OBSERVATIONS
Haynes 188	H.V. Bitum. A[b]	300	1425-1700	At 1425°F, continuous fine grain particles form; at 1617°F particles precipitated were observed in grain boundaries. At 1700°F fewer but larger precipitates were observed grain boundaries and matrix; width of depleted layer increased with increase in temperature. Chromium diffused to inner-most layer of scale. Nickel and cobalt constant in base metal.
		3552	973	Precipitation along grain boundaries and within grains.
		3552	993	Precipitation along grain boundaries, within grains and along two lines.
		6478	907	Similar to 973°F exposure.
	H.V. Bitum. C[c]	300	1500-1700	Grain boundary and matrix precipitation occurred.
		1849	700	Heavy precipitation within grains and along grains boundaries.
	Subbitum. C[d]	300	1575-1615	Grain boundary and matrix precipitation occurred.
		7368	700	Considerable intragranular carbide precipitation; little along grain boundaries.
		7368	1141	Precipitates mostly within grains.
		7368	1201	Precipitation mostly within grains.
		7368	1293	Precipitates mostly within grains. Grain structure coarse. Chromium depletion layer just below surface.
	Lignite A[e]	300	1710	Grain boundary and matrix precipitation occurred.
		840	1180	Intergranular precipitates and precipitates within grains.
		840	1343	Same as 1180°F exposure.
Incoloy 800	H.V. Bitum. A	300	1450-1600	No increase in grain size; oxides formed at 1600°F, Chromium depletion present at all temperatures, widest at 1600°F.
		3552	999	Slightly discontinuous precipitates in grain boundaries and twin lines. Carbides within grains.
		3720	1209	Slightly discontinuous precipitation along grain boundaries and twin lines.
		4180	1230	Slightly discontinuous carbide precipitation.
		6509	965	Discontinuous fine carbide precipitates along grain boundaries and twin lines.

(Table Continued)

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED[a] TO COMBUSTION PRODUCTS OF FOUR REGIONAL COALS[17]

(Table Continued)

Alloy	Coal Feedstock	Exposure Time (hr)	Temperature (°F)	OBSERVATIONS
Incoloy 800	H.V. Bitum. C	300	1190-1700°F	Structure essentially same as as-received.
		1480	1343	Carbides coarser than those resulting from 3144 and 3672 hr exposures.
		2350	1115	Few medium-sized carbides along grain boundaries and twin lines; boundaries evident to surface; possible partial anneal of structure during testing.
		2350	1463	Few medium sized carbides along grain boundaries and twin lines; boundaries poorly defined adjacent to surface, carbides sparse; possible partial anneal of structure during testing.
		4104	1281	Large discontinuous carbide along grain boundaries and twin lines; boundaries indistinct just below surface; possible anneal of structure during testing.
	Subbitum. C	300	1400-1575	Depletion occurred at 1400 and 1575°F; wider at 1575°F; Little structural change from as as-received.
		1480	1343	Carbides coarser than those resulting from 3144 and 3672 hr expsoures.
		3144	1277	Larger and discontinuous carbides compared to 3672 hr exposure.
		3672	1145	Carbide precipitates uniformly present along grain boundaries and twin lines.
		7468	1267	No carbides in grain boundaries or twin lines; boundaries poorly defined adjacent to surface; fine internal oxidation, possible annealing of structure during exposure.
	Lignite A	300	1493-1713°F	Depletion widest in 1713°F sample. Chromium depletion wider than in previous tests; structure essentially same as as-received.
		600	1001	Carbides continuous along grain boundaries and twin lines; duplex structure of large and small grains.
		4180	1230	Large discontinuous carbides along grain boundaries and twin lines.
		4680	1365	Discontinuous carbides along grain boundaries and twin lines; duplex structure of large and small grains; partial solution anneal of structure during testing.
Inconel 617	H.V. Bitum. A	300	1410-1625°F	Carbides coarsened at 1625°F; oxide or sub-scale formed in depleted layer at 1626°F. In depleted layer: Cr decreased, Ni elevated, Co constant.
		932	3552	Precipitates in grain boundaries; similar to 6478 hr exposure.
		994	3552	Similar to 6478 hr exposure.
		933	3552	Similar to 6478 hr exposure.
		956	6478	Precipitation continuous along grain boundaries with some within grains; cold work region still partially present.

(Table Continued)

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED[a] TO COMBUSTION PRODUCTS OF FOUR REGIONAL COALS[17]

(Table Continued)

Alloy	Coal Feedstock	Exposure Time (hr)	Temperature (°F)	OBSERVATIONS
Inconel 617	H.V. Bitum. C	300	1170-1570°F	Oxidation in cracks; depleted layer observed; structure essentially the same as as-received except for depleted layer formed.
		1261	2950	Fine precipitates in grains; large precipitates in grain boundaries.
		1211	3672	Very little precipitation in grains. Precipitates along slip lines; fine continuous precipitates along grain boundaries; cold work region still present.
	Subbitum. C	300	1500-1600°F	Depleted layer observed at both temperatures. Little change from as-received.
		700	7368	Precipitates small and almost continuous along grain boundaries; fine precipitates within grains.
		1138	7368	Large precipitates within grains. Fine precipitates near surface; large precipitates in boundaries.
		1188	7368	Fine precipitates at surface; precipitates in grain boundaries, and fine precipitates within grains to depth of 25 mils from surface.
		1280	7368	Large discontinuous precipitates within grains near surface; precipitates in grain boundaries.
	Lignite A	300	1580°F	Structure essentially the same as as-received except for depleted layer formed.
		953	600	Very little precipitation within grains except at surface; dense carbides along slip lines. Titanium carbides also present; cold work layer present.
12R72	H. V. Bitum. A	300	1150-1580	Carbide precipitates at all temperatures, some grain boundary oxidation at 1370°F, some Cr depletion at 1580°F
		4680	1477	Sensitization at surface, precipitates at grain boundaries
		7008	1125	Similar to 4680 hr exposure (above)
	H. V. Bitum. C	300	1160-1500	Little change from unexposed alloy
		4104	1302	Fine precipitates throughout, titanium carbides present, chromium depletion and nickel enrichment at surface
	Subbitum. C	300	1190-1460	Little change from unexposed alloy
		3144	1300	Fine precipitates throughout; titanium carbides present
		3672	1170	Similar to 3144 hr exposure (above)
	Lignite A	300	1080-1490	Little change from unexposed alloy
		4180	1249	Precipitates and titanium carbide throughout sample
		4680	1477	Similar to 4180 hr exposure (above)

(Table Continued)

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED[a] TO COMBUSTION PRODUCTS OF FOUR REGIONAL COALS[17]

(Table Continued)

Alloy	Coal Feedstock	Exposure Time (hr)	Temperature (°F)	OBSERVATIONS
316 SS	H. V. Bitum. A	300	1110-1340	Some oxidation along outer boundaries Grain boundary precipitation of carbides at all temperatures; carbides coarsened at higher temperatures
		3720	1195	Continuous, fine precipitates along grain boundaries and along slip lines at surface; cold work region present
		7008	1098	Continuous, coarse precipitates along grain boundaries; cold work region absent
	H. V. Bitum. C	300	1220-1340	Grain boundary precipitation of carbides at all temperatures; coarser carbides at higher temperatures
		3672	1310	Precipitates grew with exposure; smaller precipitates within grains
		4104	1264	Same as 3672 hr exposure
	Subbitum. C	300	1140-1330	Grain boundary precipitation of carbide at all temperatures; coarser carbides at higher temperatures
		3144	1258	Coarse precipitates at grain boundaries; fine precipitates within grains
		3672	1037	Uniform, fine precipitates along grain boundaries and twin lines
	Lignite A	4180	1258	Grain boundary precipitates, larger and more numerous than in longer exposure (below)
		4680	1290	Precipitates at grain boundaries; finer precipitates within grain
310 SS	H. V. Bitum. A	300	1000-1420	Grain boundary carbides prominent at higher temperatures; chromium depletion beneath scale
		3552	960	Grain boundary precipitates finer than 6504 hr sample (below)
		3770	1188	Grain boundary precipitates, finer than 6504 hr sample (below)
		6504	873	Considerable grain boundary precipitation, small precipitates within grains suggestive of prior grain boundaries
		7008	1089	Grain boundary precipitates, finer than 6504 hr sample (above)
	H. V. Bitum. C	300	1220-1520	Carbide precipitates; broken up and coarser at 1520°F. Chromium depletion under scale
		2905	1131	Large precipitates in grain boundaries and along twin lines; smaller precipitates within grains
		4104	1254	Coarser grain structure than 2905 hr exposure; precipitates along grain boundaries and twin lines
		7008	1301	Precipitates along grain boundaries and within grains; chromium depleted at surface.

(Table Continued)

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED^{a} TO COMBUSTION PRODUCTS OF FOUR REGIONAL COALS[17]
(Table Continued)

Alloy	Coal Feedstock	Exposure Time (hr)	Temperature (°F)	OBSERVATIONS
310 SS	Subbitum. C	300	1130-1605	Carbide precipitates at 1130°F, broke up and coarsened at 1605°F. Chromium depletion layer visible at 1130°F, less visible at 1605°F.
		3144	1344	Large precipitates intermittent along grain boundaries, fine precipitates within grains
		3672	1000	Grain size finer than other 310 SS samples; some precipitation along present grain boundaries, many within grains
		7368	800	Precipitation, mostly chromium carbides, within grains and along grain boundaries; finer sigma phase present
		7368	1215	No precipitation present; grain size large compared to as-received material
	Lignite A	300	1066-1418	Carbide precipitates, broken up and coarser at 1418°F
		4180	1272	Large precipitates in grain boundaries; considerable precipitation within grains
		4680	1215	Effects similar to 4180 hr exposure (above)
Inconel 671 clad on Incoloy 800	H.V. Bitum. A	300	1170-1700°F	Spheriodization of lamellar structure in clad occurred. Widening non-eutectic layer formed between interface and clad. At interface, single phase depleted layer gradually changes from that of two-phase clad. Depleted layer broadened, as test temperature increased. Layer is single phase.
		3552	1000	Chromium and nickel phaes homogeneously distributed in clad. Segregatives around inclusions in clad. Microstructure mostly lamellar inclusions contained Ca, Ti, Cr, Ni and Fe. Clad base interface was sound. Titanium carbides observed along interface.
		3553	1000	Similar to 1000°F, 3552 hr exposure.
		3720	1117	Similar to 1000°F, 3552 hr exposure.
		6478	974	Similar to 1000°F, 3552 hr exposure.
	Subbitum. C.	300	1160-1635°F	
		3672	1000	Finer dispersion of phases than as-received. Lamellar structure of gamma nickel and alpha chromium phases. Large chromium phases formed, adjacent to inclusions. Thin layer of fine precipitates in clad-base metal interface.
		3672	1337	Large gamma nickel phase, eutectic gamma nickel and alpha chromium phase finely dispersed. Phases larger near surface. Chromium rich phase adjacent to inclusions. Inclusions contained Ca, Ti, Cr, Ni and Fe. Thin layer of precipitates in clad-base metal interface. Titamium carbides in Incoloy base metal near interface.
		7368	1130	Similar to 1000°F, 3672 hr exposure. Difference: oversized inclusions and large Cr phases.
		7368	1162	Grossly affected by exposure. Phases largely segregated.

(Table Continued)

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED[a] TO COMBUSTION PRODUCTS OF FOUR REGIONAL COALS[17]

(Table Continued)

Alloy	Coal Feedstock	Exposure Time (hr)	Temperature (°F)	OBSERVATIONS
Inconel 671 clad on Incoloy 800	H.V. Bitum. C	300	1200-1700	
		2950	1342	Microstructure attack similar to 1350°F, 3144 hr exposure.
		3144	1230	Microstructure similar to 1160°F, 3672 hr exposure.
		3144	1350	Microstructure similar to 1160°F, 3672 hr exposure.
		3672	1160	Continuous nickel-rich phase with Cr-rich phase in globular and lamellar form; Cr-rich phase associated with inclusions. Five precipitates in clad-base metal interface.
	Lignite A	300	1093-1730	
		4180	1176	Fine dispersion of nickel and chromium phases; Cr phase near inclusions.
		4180	1236	More spheroidization than 1243°F, 4180 hr exposure; cracks in cladding.
		4180	1243	Microstructure similar to 1176°F, 4180 hr exposure.
		4680	1440	Microstructure similar to 1176°F, 4180 hr exposure.
WC Coating on Incoloy 800	H. V. Bitum. A	3720	1052	Signs of cold work region still present; precipitates in grains and along their boundaries.
		3720	1081	The cold work region was clearly evident and their was precipitation along the grain boundaries and within the grains.
	H. V. Bitum. C	300	1480 & 1600°F	Chromium depleted and nickel enriched in base metal adjacent to interface. Iron slightly depleted in base metal. Tungsten depleted.
		3672	1284	Precipitates coarser than 4104 hr, 1325°F exposure.
		4104	1325	Light precipitation throughout grains and boundaries.
	Subbitum. C	3144	1300	Base metal had large grain structure with fine precipitates along grain boundaries and within the grains.
		3672	1193	Attack not as severe as 1350 °F (below), heavy precipitation on slip planes at surface indicating cold work region still present. Grain size larger; less and finer precipitation when compared to 1350 °F exposure.
		3672	1350	Base metal had a relatively fine grain structure with precipitates along grain boundaries and within grains.
		7368	1130	The precipitates were much coarser than 3144 hr, 1300 °F exposure, particularly the precipitates within the grains.
	Lignite A	300	1200, 1400 and 1470 °F	Coating wastage as higher temperatures. Chromium depleted and nickel enriched in base metal. Chromium diffused through coating.

(Table Continued)

MICROSTRUCTURAL CHANGES IN ALLOYS EXPOSED[a] TO COMBUSTION PRODUCTS OF FOUR REGIONS COALS[17]

(Table Continued)

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[a] Exposure of alloys took place in coal-fired commercial steam generators; 28 pipe sections, 2 in O.D. x 1.5 in long, threaded into each other to form a probe were placed so that the exterior surface of the probe was exposed to combustion products and the interior surface was controlled with air.

[b] Eastern bituminous high volatile A coal, nominal HHV = 12280, 18% ash, 1% sulfur and 0.4% moisture by weight.

[c] Illinois no. 6 bituminous high volatile C coal, nominal HHV = 10430, 10.7% ash, 3% sulfur and 15.9% moisture by weight.

[d] Western subbituminous C coal, nominal HHV = 7780, 24.5% ash, 104% sulfur and 7.2% moisture by weight.

[e] Texas Lignite A, nominal HHV = 7010, 9.8% ash, 0.7% sulfur and 33.8% moisture by weight.

CARBURIZATION OF IRON AND NICKEL BASE ALLOYS[a] EXPOSED TO A BINARY CH_4-H_2 GAS ENVIRONMENT[b] AT 875°C[30]

Alloy[a]	Carbon[c] Activity	Exposure Time, h	Weight Gain per unit area mg/cm^2	Carbon Gain per unit area mg/cm^2
Inconel 600	0.151	100	d	-0.064
		500	0.248	0.240
		1000	1.37	1.090
	0.05	100	d	-0.066
		500	d	-0.002
		1000	0.014	0.093
	0.011	100	d	-0.064
		500	d	-0.056
		1000	d	-0.062
Inconel 625	0.151	100	0.186	0.188
		500	0.775	0.802
		1000	3.17	3.854
	0.05	100	0.135	-
		500	0.403	0.408
		1000	1.161	0.949
	0.011	100	0.124	0.094
		500	0.112	0.025
		1000	0.434	0.342
Incoloy 800	0.151	100	0.705	0.714
		500	4.266	4.104
		1000	7.102	9.054
	0.05	100	0.456	0.332
		500	1.508	1.721
		1000	3.398	3.314
	0.011	100	0.236	0.155
		500	0.662	0.543
		1000	1.479	1.435
Type 310 SS	0.151	100	1.414	1.700
		500	5.55	5.081
		1000	9.10	10.990
	0.05	100	0.684	0.636
		500	1.972	1.819
		1000	4.780	5.501
	0.011	100	0.335	0.324
		500	0.673	0.573
		1000	2.536	3.091

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[a] 50 mil - thick sheet specimens were exposed.

[b] relative compositions not specified.

[c] carbon activities were established by equilibrating high purity alloys of Fe - 18 wt % Cr - 8 wt % Ni and Fe - 8 wt % Ni in the CH_4-H_2 gas environment, analyzing the materials for carbon and then using reported data on the carbon activity - concentration relationship for these alloys.

[d] weight change was immeasurably small.

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13]

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c]		Exposure Time, hr[d]
		mils/yr	mm/yr	
Test Condition: CGA[a] with 0.5% H_2S, 900 °F				
302SS	Fe-9Ni-18Cr	5.3	0.13	1000
304SS	Fe-9Ni-19Cr	2.6	0.07	1000
316SS	Fe-14Ni-17Cr	2.6	0.07	1000
309SS	Fe-15Ni-23Cr	3.5	0.09	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	1.8	0.04	1000
310SS	Fe-20Ni-25Cr-2Mn	1.8	0.04	1000
310SS Al[e]		1.8	0.04	1000
310SS Cr[f]		2.6	0.07	1000
446SS	Fe-24Cr	1.8	0.04	1000
Inconel 600	7Fe-77Ni-16Cr	2.6	0.07	1000
Inconel 601	16Fe-60Ni-23Cr	2.6	0.07	1000
Incoloy 800	47Fe-31Ni-21Cr	3.5	0.09	1000
Incoloy 800 Al[e]		1.8	0.04	1000
Incoloy 800 Cr[f]		3.5	0.09	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	2.6	0.07	1000
Inconel 671	48Ni-50Cr	1.8	0.04	1000
Test Condition: CGA[a] with 1.5% H_2S, 1250 °F				
304SS	Fe-9Ni-19Cr	35	0.88	100
316SS	Fe-14Ni-17Cr	35	0.88	100
309SS	Fe-15Ni-23Cr	18	0.45	100
310SS	Fe-20Ni-25Cr-2Mn	18	0.45	100
446SS	Fe-24Cr	18	0.45	100
Inconel 600	7Fe-77Ni-16Cr	2799[g]	71[g]	100
Inconel 601	16Fe-60Ni-23Cr	18	0.45	100
Incoloy 800	47Fe-31Ni-21Cr	18	0.45	100
Inconel 671	48Ni-50Cr	18	0.45	100
RA 333	16Fe-45Ni-26Cr-4Mo	18	0.45	100
Crutemp 25	47Fe-25Ni-25Cr	18	0.45	100
Multimet N155	29Fe-20Ni-21Cr-20Co	18	0.45	100
Haynes 188	Co-23Ni-22Cr	18	0.45	100
Stellite 6B	3Ni-28Cr-57Co-5W	18	0.45	100
Alloy X	20Fe-45Ni-22Cr-9Mo	18	0.45	100
Inconel 617	54Ni-22Cr-13Co-9Mo	18	0.45	100

(Table Continued)

RROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued)

lloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c]		Exposure Time, hr[d]
		mils/yr	mm/yr	
Test Condition: CGA[a] with 0.1% H_2S, 1500 °F				
02SS	Fe-9Ni-18Cr	18	0.45	1000
04SS	Fe-9Ni-19Cr	16	0.40	1000
16SS	Fe-14Ni-17Cr	21	0.53	1000
09SS	Fe-15Ni-23Cr	4.4	0.11	1000
14SS	Fe-20Ni-24Cr-2Mn-2Si	5.3	0.13	1000
10SS	Fe-20Ni-25Cr-2Mn	3.5	0.09	1000
10SS Al[e]		13	0.33	1000
10SS Cr[f]		25	0.65	1000
46SS	Fe-24Cr	1.8	0.04	1000
nconel 600	7Fe-77Ni-16Cr	19	0.49	1000
nconel 601	16Fe-60Ni-23Cr	25	0.65	1000
ncoloy 800	47Fe-31Ni-21Cr	25	0.65	1000
ncoloy 800 Al[e]		4.4	0.11	1000
ncoloy 800 Cr[f]		25	0.65	1000
N-793 (cast)	43Fe-32Ni-21Cr-2Al	14	0.36	1000
nconel 671	48Ni-50Cr	3.5	0.09	1000
Test Condition: CGA[a] with 0.5% H_2S, 1500 °F				
04SS	Fe-9Ni-19Cr	46	1.2	1000
16SS	Fe-14Ni-17Cr	37	0.93	1000
09SS	Fe-15Ni-23Cr	7.0	0.18	1000
10SS	Fe-20Ni-25Cr-2Mn	2.6	0.07	1000
10SS Al[e]		11	0.27	1000
46SS	Fe-24Cr	3.5	0.09	1000
Inconel 600	7Fe-77Ni-16Cr	completely corroded		1000
Inconel 601	16Fe-60Ni-23Cr	completely corroded		1000
Incoloy 800	47Fe-31Ni-21Cr	17	0.42	1000
Incoloy 800 Al[e]		5.3	0.13	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	21	0.53	1000
Inconel 671	48Ni-50Cr	1.8	0.04	1000

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continue

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time, hr[d]
Test Condition: CGA[a] with 1.0% H_2S, 1500 °F				
302SS	Fe-9Ni-18Cr	102	2.6	1000
304SS	Fe-9Ni-19Cr	39	1.0	1000
316SS	Fe-14Ni-17Cr	41	1.0	1000
309SS	Fe-15Ni-23Cr	6.1	0.16	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	6.1	0.16	1000
310SS	Fe-20Ni-25Cr-2Mn	4.4	0.11	1000
310SS Al[e]		11	0.27	1000
310SS Cr[f]		111	2.8	1000
446SS	Fe-24Cr	7.9	0.20	1000
Inconel 601	16Fe-60Ni-23Cr	658	16.7	1000
Incoloy 800	47Fe-31Ni-21Cr	15	0.38	1000
Incoloy 800 Al[e]		9.6	0.24	1000
Incoloy 800 Cr[f]		138	3.5	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	15	0.38	1000
Inconel 671	48Ni-50Cr	6.1	0.16	1000
Test Condition: CGA[a] with 1.5% H_2S, 1500 °F				
304SS	Fe-9Ni-19Cr	261	6.6	100
316SS	Fe-14Ni-17Cr	402	10.2	100
309SS	Fe-15Ni-23Cr	197	5.0	100
310SS	Fe-20Ni-25Cr-2Mn	45	1.2	100
446SS	Fe-24Cr	61	1.5	100
Inconel 600	7Fe-77Ni-16Cr	completely corroded		100
Inconel 601	16Fe-60Ni-23Cr	853	22	100
Incoloy 800	47Fe-31Ni-21Cr	315	8.0	100
Inconel 671	48Ni-50Cr	49	1.2	100
RA 333	16Fe-45Ni-26Cr-4Mo	2314	59	100
Crutemp 25	47Fe-25Ni-25Cr	85	2.2	100
Multimet N155	29Fe-20Ni-21Cr-20Co	100	2.6	100
Haynes 188	Co-23Ni-22Cr	92	2.3	100
Stellite 6B	3Ni-28Cr-57Co-5W	18	0.45	100
Alloy X	20Fe-45Ni-22Cr-9Mo	428	11	100
Inconel 617	54Ni-22Cr-13Co-9Mo	1606	41	100

(Table Continued)

ORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued)

lloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time, hr[d]
Test Condition: CGA[a] with 0.5% H_2S, 1650 °F				
09SS	Fe-15Ni-23Cr	83	2.1	3000
10SS	Fe-20Ni-25Cr-2Mn	23	0.58	5000
10SS Al[e]		40	1.0	1000
46SS	Fe-24Cr	6.5	0.16	5000
ncoloy 800	47Fe-31Ni-21Cr	6.7	0.17	5000
ncoloy 800 Al[e]		18	0.47	1000
N-793 (cast)	43Fe-32Ni-21Cr-2Al	10	0.25	5000
L-40	47Fe-19Ni-31Cr	3.5	0.09	5000
A 333	16Fe-45Ni-26Cr-4Mo	2.6	0.07	5000
rutemp 25	47Fe-25Ni-25Cr	0.88	0.02	5000
aynes 188	Co-23Ni-22Cr	7.0	0.18	1000
tellite 6B	3Ni-28Cr-57Co-5W	3.5	0.09	1000
hermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	16	0.40	1000
lloy X	20Fe-45Ni-22Cr-9Mo	1.2	0.03	5000
anicro 32X	Fe-32Ni-22Cr-3W	22	0.56	1000
A 330	Fe-36Ni-19Cr	2.5	0.06	5000
IN-657	50Ni-48Cr	1.2	0.03	5000
56	Fe-20Ni-22Cr-20Co-3Mo	1.6	0.04	5000
Inconel 617	54Ni-22Cr-13Co-9Mo	36	0.91	1000
Test Condition: CGA[a] with 1.0% H_2S, 1650 °F				
309SS	Fe-15Ni-23Cr	50[h]	1.28[h]	1000
310SS	Fe-20Ni-25Cr-2Mn	13	0.33	10,000
310SS Al[e]		11	0.28	10,000
Incoloy 800	47Fe-31Ni-21Cr	15	0.38	10,000
Incoloy 800 Al[e]		3	0.08	10,000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	18	0.46	2000
Inconel 671	48Ni-50Cr	2	0.05	4000
HL-40	47Fe-19Ni-31Cr	15	0.38	6000
HL-40 3Si	46Fe-19Ni-31Cr-3Si	8	0.20	2000
RA 333	16Fe-45Ni-26Cr-4Mo	10	0.24	8000
Crutemp 25	47Fe-25Ni-25Cr	8	0.20	10,000
Multimet N155	29Fe-20Ni-21Cr-20Co	4	0.10	8000
Haynes 188	Co-23Ni-22Cr	38	0.96	4000

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time, hr[d]
- - - - - - - - Test Condition: CGA[a] with 1.0% H_2S, 1650 °F (continued) - - - - - - - -				
Stellite 6B	3Ni-28Cr-57Co-5W	1	0.02	9000
329SS	Fe-4Ni-27Cr	6	0.15	6000
Co-Cr-W No. 1	Co-30Cr-12W	1	0.02	9000
Thermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	110	2.8	6000
Wiscalloy 30/50W	Fe-49Ni-28Cr-4W	21	0.53	2000
Alloy X	20Fe-45Ni-22Cr-9Mo	13	0.33	6000
Sanicro 32X	Fe-32Ni-22Cr-3W	30	0.82	7000
HK-40	Fe-20Ni-28Cr	25	0.64	6000
RA 330	Fe-36Ni-19Cr	17	0.43	9000
IN-657	50Ni-48Cr	0	0	10,000
IN-738 (cast)	Ni-16Cr-8Co-3Al-3Ti	10	0.17	6000
556	Fe-20Ni-22Cr-20Co-3Mo	2	0.05	6000
LM-1866 (low Hf)	Fe-18Cr-5Al-1Mo-1Hf	23	0.58	5000
LM-1866 (high Hf)		27	0.69	7000
- - - - - - - - - - - Test Condition: CGA[a] with 0% H_2S, 1800 °F - - - - - - - - - - - - - -				
302SS	Fe-9Ni-18Cr	162	4.1	1000
304SS	Fe-9Ni-19Cr	219	5.6	1000
316SS	Fe-14Ni-17Cr	115	2.9	1000
309SS	Fe-15Ni-23Cr	39 96	1.0 2.4 }i	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	105	2.7	1000
310SS	Fe-20Ni-25Cr-2Mn	17 62	0.44 1.58 }i	1000
310SS Al[e]		17	0.42	1000
310SS Cr[f]		19	0.47	1000
446SS	Fe-24Cr	194	4.9	1000
Inconel 600	7Fe-77Ni-16Cr	38	0.97	1000
Inconel 601	16Fe-60Ni-23Cr	16	0.42	1000
Incoloy 800	47Fe-31Ni-21Cr	24	0.61	1000
Incoloy 800 Al[e]		13	0.33	1000
Incoloy 800 Cr[f]		25	0.63	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	36	0.91	1000
Inconel 671	48Ni-50Cr	19 8	0.48 0.20 }i	1000

(Table Continued)

RROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued)

loy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	mm/yr	Exposure Time, hr[d]
- - - - - - - - - Test Condition: CGA[a] with 0% H_2S, 1800 °F (continued) - - - - - - - - - -				
-250	68Fe-28Cr-3C	completely corroded		1000
-45	62Fe-5Ni-30Cr	70	1.8	1000
-40	47Fe-19Ni-31Cr	20	0.50	1000
-40 3Si	46Fe-19Ni-31Cr-3Si	42	1.1	1000
333	16Fe-45Ni-26Cr-4Mo	24	0.60	1000
utemp 25	47Fe-25Ni-25Cr	35	0.90	1000
ultimet N155	29Fe-20Ni-21Cr-20Co	15	0.38	1000
aynes 150	Co-18Fe-28Cr	10	0.25	1000
aynes 188	Co-23Ni-22Cr	9	0.24	1000
tellite 6B	3Ni-28Cr-57Co-5W	5	0.13	1000
E 441	82Fe-15Al-3Mo	28	0.70	1000
rmco 21-6-9	63Fe-9Ni-21Cr-8Mn	281	7.13	1000
- - - - - - - - - - - Test Condition: CGA[a] with 0.1% H_2S, 1800 °F - - - - - - - - - - - - -				
02SS	Fe-9Ni-18Cr	380	9.7	1000
04SS	Fe-9Ni-19Cr	549	14	1000
16SS	Fe-14Ni-17Cr	480	12	1000
09SS	Fe-15Ni-23Cr	197	5.0 }i	1000
		j{ 251	6.4	1000
		190	4.8	1000
14SS	Fe-20Ni-24Cr-2Mn-2Si	144	3.7	1000
10SS	Fe-20Ni-25Cr-2Mn	159	4.0	1000
10SS Al[e]		165	4.2	1000
		16	0.41 }i	
		j{ 100	2.5	
		72	1.8	
10SS Cr[f]		21	0.53	1000
46SS	Fe-24Cr	84	2.1	1000
nconel 600	7Fe-77Ni-16Cr	68	1.7	1000
nconel 601	16Fe-60Ni-23Cr	26	0.66	1000
ncoloy 800	47Fe-31Ni-21Cr	35	0.88	1000
Incoloy 800 Al[e]		14	0.36	1000
Incoloy 800 Cr[f]		17	0.44	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	36	0.92	1000

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	mm/yr	Exposure Time, hr[d]
- - - - - - - - - - Test Condition: CGA[a] with 0.1% H_2S, 1800 °F (continued) - - - - - - - -				
Inconel 671	48Ni-50Cr	15	0.38	1000
		16	0.42}i	
		j{17	0.44	
		19	0.48	
HC-250	68Fe-28Cr-3C	360	9.2	1000
HD-45	62Fe-5Ni-30Cr	33	0.84	1000
HL-40	47Fe-19Ni-31Cr	16	0.39	1000
HL-40 3Si	46Fe-19Ni-31Cr-3Si	15	0.37	1000
RA 333	16Fe-45Ni-26Cr-4Mo	20	0.50	1000
Crutemp 25	47Fe-25Ni-25Cr	21	0.53	1000
Multimet N155	29Fe-20Ni-21Cr-20Co	15	0.37	1000
Haynes 150	Co-18Fe-28Cr	6	0.15	1000
Haynes 188	Co-23Ni-22Cr	12	0.31	1000
Stellite 6B	3Ni-28Cr-57Co-5W	7	0.17	1000
VE 441	82Fe-15Al-3Mo	6	0.15	1000
Armco 21-6-9	63Fe-9Ni-21Cr-8Mn	519	13	1000
312SS	Fe-9Ni-31Cr	44	1.1	1000
329SS	Fe-4Ni-27Cr	92	2.3	100
AL 29-4-2	Fe-2Ni-30Cr-4Mo	10	0.24	1000
AL EX-20	Fe-3Ni-5Cr-10Al-20Mn	593	15	1000
Co-Cr-W No. 1	Co-30Cr-12W	10	0.25	1000
Thermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	17	0.42	1000
Wiscalloy 30/50 W	Fe-49Ni-28Cr-4W	20	0.51	1000
Armco 18SR	Fe-18Cr-2Al	94	2.4	1000
Armco 22-13-5	Fe-14Ni-21Cr-5Mn	299	7.6	1000
Alloy X	20Fe-45Ni-22Cr-9Mo	11	0.27	1000
Inconel 625	Ni-22Cr-9Mo-4Fe	74	1.9	100
Sanicro 32X	Fe-32Ni-22Cr-3W	100	2.6	100
Incoloy 825	28Fe-42Ni-22Cr	17	0.44	1000
FSX-414	Co-10Ni-29Cr-7W	14	0.35	1000
HK-40	Fe-20Ni-28Cr	80	2.0	100
HK-40 3Si	Fe-22Ni-26Cr	405	10	100
Thermalloy 63	Fe-36Ni-28Cr	99	2.5	100
Thermalloy 63W	Fe-36Ni-28Cr-5W	130	3.3	100

(Table Continued)

ORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued)

lloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	mm/yr	Exposure Time, hr[d]
- - - - - - - - - Test Condition: CGA[a] with 0.1% H_2S, 1800 °F (continued) - - - - - - - - -				
A 330	Fe-36Ni-19Cr	46	1.2	1000
N-657	50Ni-48Cr	66	1.7	100
N-738 (cast)	Ni-16Cr-8Co-3Al-3Ti	32	0.81	1000
56	Fe-20Ni-22Cr-20Co-3Mo	33	0.85	1000
nconel 617	54Ni-22Cr-13Co-9Mo	27	0.68	1000
- - - - - - - - - - - Test Condition: CGA[a] with 0.5% H_2S, 1800 °F - - - - - - - - - - - -				
09SS	Fe-15Ni-23Cr	109	2.8	5000
14SS	Fe-20Ni-24Cr-2Mn-2Si	24	0.62	4000
10SS	Fe-20Ni-25Cr-2Mn	162 17	4.1 }i 0.43	5000
10SS Al[e]		7	0.18	8000
46SS	Fe-24Cr	17	0.42	4000
ncoloy 800	47Fe-31Ni-21Cr	30	0.75	8000
ncoloy 800 Al[e]		10	0.26	5000
nconel 671	48Ni-50Cr	12 6	0.32 }i 0.15	5000
C-250	68Fe-28Cr-3C	31	0.78	1000
D-45	62Fe-5Ni-30Cr	18	0.46	1000
L-40	47Fe-19Ni-31Cr	13	0.32	8000
L-40 3Si	46Fe-19Ni-31Cr-3Si	36	0.92	1000
A 333	16Fe-45Ni-26Cr-4Mo	30	0.70	7000
rutemp 25	47Fe-25Ni-25Cr	3	0.08	10,000
ultimet N155	29Fe-20Ni-21Cr-20Co	8	0.21	10,000
aynes 150	Co-18Fe-28Cr	2	0.06	6000
aynes 188	Co-23Ni-22Cr	6	0.16	10,000
tellite 6B	3Ni-28Cr-57Co-5W	3	0.07	10,000
E 441	82Fe-15Al-3Mo	completely corroded		1000
rucible Ni	90Ni-3Cr-4Al	completely corroded		100
rmco 21-6-9	63Fe-9Ni-21Cr-8Mn	174	4.4	1000
12SS	Fe-9Ni-31Cr	51	1.3	1000
29SS	Fe-4Ni-27Cr	10	0.3	5000
L 29-4-2	Fe-2Ni-30Cr-4Mo	4	0.10	1000
L EX-20	Fe-3Ni-5Cr-10Al-20Mn	completely corroded		1000

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time, hr[d]
- - - - - - - - - - Test Condition: CGA[a] with 0.5% H_2S, 1800 °F (continued) - - - - - - - -				
Co-Cr-W No. 1	Co-30Cr-12W	2	0.04	7000
Thermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	14	0.34	10,000
Wiscalloy 30/50W	Fe-49Ni-28Cr-4W	16	0.42	1000
Armco 18SR	Fe-18Cr-2Al	447	11	1000
Armco 22-13-5	Fe-14Ni-21Cr-5Mn	139	3.5	1000
Alloy X	20Fe-45Ni-22Cr-9Mo	13	0.32	10,000
Sanicro 32X	Fe-32Ni-22Cr-3W	25	0.65	8000
Incoloy 825	28Fe-42Ni-22Cr	16	0.42	1000
FSX-414	Co-10Ni-29Cr-7W	10	0.1	8000
HK-40	Fe-20Ni-28Cr	21	0.53	10,000
RA 330	Fe-36Ni-19Cr	395	10	1000
IN-657	50Ni-48Cr	0	0	8000
IN-738 (cast)	Ni-16Cr-8Co-3Al-3Ti	5	0.12	8000
556	Fe-20Ni-22Cr-20Co-3Mo	112	2.9	2000
Inconel 617	54Ni-22Cr-13Co-9Mo	8	0.21	8000
AL-16-5-Y	Fe-16Cr-5Al	completely	corroded	1000
Fe-36Cr-36Ni	Fe-37Ni-37Cr	10	0.2	2000
Fe-31Cr-36Ni	Fe-36Ni-31Cr	40	1.0	5000
Fe-31Cr-28Ni	Fe-28Ni-31Cr	20	0.5	5000
Fe-31Cr-44Ni	Fe-44Ni-31Cr	30	0.6	5000
Ohioloy 2300	Fe-40Ni-30Cr-5Co-5W	10	0.2	5000
LM-1866 (Low Hf)	Fe-18Cr-5Al-1Mo-1Hf	completely	corroded	1000
LM-1866 (high Hf)		230	5.9	1000
IN-DS	43Fe-35Ni-18Cr	1330	34	278
253MA	Fe-11Ni-21Cr	completely	corroded	1000
- - - - - - - - - - - Test Condition: CGA[a] with 1.0% H_2S, 1800 °F - - - - - - - - - - - -				
302SS	Fe-9Ni-18Cr	completely	corroded	1000
304SS	Fe-9Ni-19Cr	completely	corroded	1000
316SS	Fe-14Ni-17Cr	completely	corroded	1000
309SS	Fe-15Ni-23Cr	583 j{40 79	15 }i 1.0 2.0	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	42	1.1	1000

(Table Continued)

RROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continued)

loy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time, hr[d]
- - - - - - - - - Test Condition: CGA[a] with 1.0% H_2S, 1800 °F (continued) - - - - - - - - -				
OSS	Fe-20Ni-25Cr-2Mn	164 j{ 134 55	4.2 }i 3.4 1.4	1000
OSS Al[e]		52	1.3	3000
OSS Cr[f]		223	5.7	1000
6SS	Fe-24Cr	18	0.47	2000
conel 600	7Fe-77Ni-16Cr	completely corroded		1000
conel 601	16Fe-60Ni-23Cr	36	0.91	1000
coloy 800	47Fe-31Ni-21Cr	221	5.6	1000
coloy 800 Al[e]		17	0.43	3000
coloy 800 Cr[f]		389	9.9	1000
-793 (cast)	43Fe-32Ni-21Cr-2Al	completely corroded		1000
conel 671	48Ni-50Cr	4.0 j{ 11 12 j{ 20 16	0.10 0.28 0.30 }i 0.51 0.40	5000
-250	68Fe-28Cr-3C	14	0.34	1000
-45	62Fe-5Ni-30Cr	28	0.72	1000
-40	47Fe-19Ni-31Cr	15	0.39	5000
-40 3Si	46Fe-19Ni-31Cr-3Si	20	0.51	1000
333	16Fe-45Ni-26Cr-4Mo	222	5.6	2000
utemp 25	47F -25Ni-25Cr	12	0.30	3000
ltimet N155	29Fe-20Ni-21Cr-20Co	4.7	0.12	5000
ynes 150	Co-18Fe-28Cr	19	0.47	1000
ynes 188	Co-23Ni-22Cr	92[h]	2.3[h]	2000
ellite 6B	3Ni-28Cr-57Co-5W	3.7	0.09	5000
441	82Fe-15Al-3Mo	completely corroded		1000
rucible Ni	90Ni-3Cr-4Al	completely corroded		100
mco 21-6-9	63Fe-9Ni-21Cr-8Mn	162	4.1	1000
12SS	Fe-9Ni-31Cr	72	1.8	1000
29SS	Fe-4Ni-27Cr	100	2.6	100
L 29-4-2	Fe-2Ni-30Cr-4Mo	54	1.4	1000
L EX-20	Fe-3Ni-5Cr-10Al-20Mn	completely corroded		1000

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13] (continue

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] mils/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time, hr[d]
- - - - Test Condition: CGA[a] with 1.0% H_2S, 1800 °F (continued) - - - -				
Co-Cr-W No. 1	Co-30Cr-12W	5.8	0.15	5000
Thermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	36	0.91	5000
Wiscalloy 30/50W	Fe-49Ni-28Cr-4W	8.8	0.22	3000
Armco 18SR	Fe-18Cr-2Al	completely corroded		1000
Armco 22-13-5	Fe-14Ni-21Cr-5Mn	126	3.2	1000
Alloy X	20Fe-45Ni-22Cr-9Mo	90[k]	2.3[k]	2000
Inconel 625	Ni-22Cr-9Mo-4Fe	82	2.1	100
Sanicro 32X	Fe-32Ni-22Cr-3W	97	2.5	100
Incoloy 825	28Fe-42Ni-22Cr	32	0.82	1000
FSX-414	Co-10Ni-29Cr-7W	17	0.43	1000
HK-40	Fe-20Ni-28Cr	138	3.5	100
HK-40 3Si	Fe-22Ni-26Cr	135	3.4	100
Thermalloy 63	Fe-36Ni-28Cr	92	2.3	100
Thermalloy 63W	Fe-36Ni-28Cr-5W	61	1.6	100
RA 330	Fe-36Ni-19Cr	976	25	1000
IN-657	50Ni-48Cr	3.2	0.08	3000
IN-738 (cast)	Ni-16Cr-8Co-3Al-3Ti	41 51	1.0 }i 1.3	1000
556	Fe-20Ni-22Cr-20Co-3Mo	36	0.92	1000
Inconel 617	54Ni-22Cr-13Co-9Mo	j{ 16 110	0.39[l] 2.8[m]	3000
RV-18	Fe-32Ni-35Cr-32Co	4.4	0.11	1000

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[a] CGA = coal gasification atmosphere; input composition (vol %), 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 0 to 1.0% H_2S, the balance H_2O. All tests run at 1000 psi. The equilibrium gas compositions at the test temperatures are:

Component	900° F	1500 °F	1650 °F	1800 °F
H_2	4	23	27	31
CO	5	11	14	17
CO_2	25	19	17	15
CH_4	19	9	6	3
NH_3	1	1	1	1
H_2S	0-1.0	0-1.0	0-1.0	0-1.0
H_2O	balance	balance	balance	balance

(Table Continued)

ROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a][13] (continued)

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pproximate compositions only.

lues are for one test specimen (1 in x 1 in x 1/4 in) exposed to the indicated conditions. though duplicate specimens were exposed, as a rule only one was sectioned, wire-brushed, d the depth of corrosion determined metallographically. Scale thickness, depth of ternal corrosion, and diffusion zone thickness were determined. Total sound metal loss the sum of scaling loss and depth of penetration. The reported rates are linearly trapolated from the metal loss data for the stated exposure times. See the following ables for a measure of the agreement of rates extrapolated from data for various exposure imes and for reproducibility of the data.

e exposure time give above is the maximum test time for which the alloy was subjected the stated conditions.

luminum coating ($\sim$9 mils) applied by Alon Processing, Inc. by a pack diffusion process Alonized).

hromium coating ($\sim$0.6 mils) applied by Alloy Surfaces, Inc.

xtensive metal-oxide scale with possible melting.

second specimen corroded completely.

alues for specimens from two different runs.

wo specimens were examined in this run.

wo other specimens completely corroded.

verall corrosion.

dge corrosion.

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a]

Alloy	Rate of Total Sound Metal Loss[b], mils/yr(mm/yr)									
Test Time, hr	100	1000	2000	3000	4000	5000	6000	7000	8000	10000
Test Condition: CGA[a] with 0.5% H_2S, 1650 °F										
309 SS		46(1.2)		83(2.1)						
310 SS		20(0.50)				23(0.58)				
446 SS		7.9(0.20)				6.5(0.16)				
Incoloy 800		12(0.31)				6.7(0.17)				
IN-793 (cast)		33(0.85)				10(0.25)				
HL-40		15(0.38)				3.5(0.09)				
RA 333		9.6(0.24)				2.6(0.07)				
Crutemp 25		7.0(0.18)				0.88(0.02)				
Alloy X		3.5(0.09)				1.2(0.03)				
RA 330		8.8(0.22)				2.5(0.06)				
IN-657		3.5(0.09)				1.2(0.03)				
556		4.4(0.11)				1.6(0.04)				
Test Condition: CGA[a] work 1.0% H_2S, 1650 °F										
310 SS		43(1.1)	6(0.15)		7(0.19)					13(0.33)
310 SS Al[c]		16(0.42)	8(0.22)		6(0.15)					11(0.28)
Incoloy 800		52(1.32)	25(0.63)		12(0.31)					15(0.38)
Incoloy 800 Al[c]		11(0.28)	6(0.16)		4(0.10)					3(0.08)
HL-40			12(0.03)	142(3.6)		19(0.48)	15(0.38)			
RA 333		11(0.28)	5(0.12)		3(0.08)				10(0.24)	
Crutemp 25		11(0.27)	5(0.12)		3(0.08)					8(0.20)
Haynes 188		3(0.08)	7(0.17)		38(0.96)					
329 SS			13(0.33)			8(0.20)	6(0.15)			
Wiscalloy 30/50W		311(7.9)	21(0.53)							
Alloy X			2(0.06)			17(0.43)	13(0.33)			
HK-40			25(0.63)			726(18)	25(0.64)			
IN-657		18(0.45)	3(0.07)		2(0.05)					0(0)
556			3(0.08)			10(0.25)	2(0.05)			
LM-1866					25(0.64)	23(0.58)				
Test Condition: CGA[a] with 0.1% H_2S, 1800 °F										
309 SS	394(10)	197(5.0) 251(6.4) 190(4.8)								
310 SS	242(6.1) 292(7.4)	159(4.0) 100(2.5) 72(1.8) 165(4.2)								
Inconel 671	62(1.6) 59(1.5)	16(0.42) 19(0.48) 17(0.44) 15(0.38)								
312 SS	135(3.4)	44(1.1)								
AL 29-4-2	37(0.95)	10(0.24)								
AL EX-20	917(23)	593(15)								
Co-Cr-W No. 1	57(1.5)	10(0.25)								
Thermalloy 63 WC	66(1.7)	17(0.42)								
Wiscalloy 30/50W	109(2.8)	20(0.51)								

(Table continued)

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a] [13]
(Table Continued)

Alloy	Rate of Total Sound Metal Loss[b], mils/yr(mm/yr)									
Test Time, hr	100	1000	2000	3000	4000	5000	6000	7000	8000	10000
Test Condition: CGA[a] with 0.1% H_2S, 1800 °F, continued										
Armco 18SR	102(2.6)	94(2.4)								
Armco 22-13-5	218(5.5)	299(7.6)								
Alloy X	64(1.6)	11(0.27)								
Incoloy 825	181(4.6)	17(0.44)								
FSX-414	125(3.2)	14(0.35)								
RA 330	335(8.5)	46(1.2)								
Inconel 617	279(7.1)	27(0.68)								
IN-738 (cast)	200(5.1)	32(0.81)								
556	298(7.6)	33(0.85)								
Test Condition: CGA[a] with 0.5% H_2S, 1800 °F										
309 SS	52(1.32)	50(1.3) 55(1.4) 19(0.48)	10(0.26) 257(6.5)[d]	181(4.6)	163(4.1)	109(2.8)				
314 SS		98(2.5)	77(2.0) 251(6.4)		24(0.62)					
310 SS		27(0.69) 17(0.43)	393(10) 167(4.3)			162(4.1)				
310 SS Al[c]				12(0.31)					7(0.18)	
446 SS		28(0.72)	28(0.71) 53(1.4)	30(0.77)	17(0.42)					
Incoloy 800		33(0.83)	18(0.46)	16(0.41)	14(0.35)	13(0.33)		25(0.63)	30(0.75)	
Incoloy 800 Al[c]		8(0.21)	8(0.20)	10(0.25)	13(0.32)	10(0.26)				
Inconel 671	35(0.88) 43(1.1) 18(0.47) 16(0.40)	15(0.37) 8(0.19) 6(0.15)	7(0.17) 9(0.23)	4(0.10)	9(0.23)	12(0.32) 6(0.15)				
HC-250	69(1.8)	31(0.78)								
HD-45	52(1.3)	18(0.46)								
HL-40	74(1.9)	18(0.46)		15(0.39)					13(0.32)	
HL-40 3Si	65(1.7)	36(0.92)								
RA 333	61(1.5)	16(0.40)	22(0.57)			55(1.4)		30(0.70)		
Crutemp 25	56(1.4)	11(0.29)	9(0.23) 45(1.1)			29(0.74)				3(0.08)
Multimet N155	43(1.1)	11(0.29)	19(0.47)			7(0.18)				8(0.21)
Haynes 150	43(1.1)	53(1.4)	5(0.13)				2(0.06)			
Haynes 188	43(1.1)	7(0.19)	5(0.12)			15(0.38)				6(0.16)
Stellite 6B	35(0.88)	7(0.18)	3(0.06)			2(0.06)				3(0.07)
VE 441	35(0.88)	Completely corroded								
Armco 21-6-9	199(5.1)	174(4.4)								
329 SS		30(0.7)		10(0.4)		10(0.3)				
Co-Cr-W No. 1		7(0.17)		1(0.03)				2(0.04)		
Thermalloy 63 WC		12(0.29)	12(0.31)			26(0.67)				14(0.34)
Alloy X		10(0.24)	7(0.18)			20(0.51)				13(0.32)
Sanicro 32 X				55(1.4)					25(0.65)	
FSX-414		8(0.21)		7(0.18)					10(0.1)	
HK-40			95(2.4)			39(0.99)				21(0.53)

(Table Continued)

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a]
(Table Continued)

Alloy	Rate of Total Sound Metal Loss[b], mils/yr(mm/yr)									
Test Time, hr	100	1000	2000	3000	4000	5000	6000	7000	8000	10000
Test Condition: CGA[a] with 0.5% H_2S, 1800 °F, continued										
IN-657				1(0.03)					0(0)	
IN-738 (cast)		55(1.4)		26(0.66)					5(0.12)	
556		46(1.2)	112(2.9)							
Inconel 617		37(0.95)		16(0.41)					8(0.21)	
Fe-36Cr-36 Ni		481(12)	10(0.2)							
Fe-31Cr-36 Ni		20(0.6)		60(1.6)		40(1.0)				
Fe-31Cr-28 Ni		20(0.6)		30(0.7)		20(0.5)				
Fe-31Cr-44 Ni		20(0.6)		40(1.0)		30(0.6)				
Ohioloy 2300		20(0.6)	10(0.2)			10(0.2)				
Test Condition: CGA[a] with 1.0% H_2S, 1800 °F										
302 SS	3872(98) 1174(30)	Completely corroded								
304 S	4030(102) 596(15)	Completely corroded								
316 SS	1104(28) 1647(42)	Completely Corroded								
309 SS	61(1.6) 272(6.9) 314(8.0) 261(6.6)	583(15) 40(1.0) 79(2.0)								
314 SS	70(1.8) 245(6.2)	42(1.1)								
310 SS	44(1.1) 237(6.0) 307(7.8) 211(5.4)	164(4.2) 134(3.4) 55(1.4)								
310 SS Al[c]	131(3.3) 131(3.3)	20(0.51)	79(2.0)[e]	52(1.3)						
446 SS	44(1.1) 18(0.45)	27(0.69)	18(0.47)							
Inconel 600	1235(31) 70(1.8)	Completely corroded								
Inconel 601	219(5.6) 105(2.7)	36(0.91)								
Incoloy 800	18(0.45) 412(11)	221(5.6)								
Incoloy 800 Al[c]	123(3.1) 79(2.0)	12(0.31)	138(3.5)[e]	17(0.43)						
IN-793 (cast)	2724(69) 420(11)	Completely corroded								
Inconel 671	96(2.4) 79(2.0) 95(2.4) 50(1.3)	22(0.56) 20(0.51) 16(0.40) 11(0.28)		2.3(0.06)		4.0(0.10)				
HC-250	43(1.1)	14(0.34)								
HD-45	61(1.5)	28(0.72)								
HL-40	70(1.8)	31(0.79)		21(0.53)		15(0.39)				
HL-40 3Si	74(1.9)	20(0.51)								
RA 333	52(1.3)	37(0.95)	222(5.6)							

(Table Continued)

PARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a][13]

(Table Continued)

oy	Rate of Total Sound Metal Loss[b], mils/yr(mm/yr)									
Test Time, hr	100	1000	2000	3000	4000	5000	6000	7000	8000	10000
Test Condition: CGA[a] with 1.0% H_2S, 1800 °F, continued										
temp 25	69(1.8)	19(0.49)		12(0.30)						
timet N155	43(1.1)	11(0.28)		19(0.47)		4.7(0.12)				
nes 150	35(0.88)	19(0.47)								
nes 188	43(1.1)	7(0.18)	92(2.3)[f]							
llite 6B	39(0.99)	19(0.49)		4.4(0.11)		3.7(0.09)				
441	18(0.45)	Completely corroded								
co 21-6-9	348(8.8)	162(4.1)								
	171(4.4)	72(1.8)								
29-4-2	53(1.4)	54(1.4)								
EX-20	245(6.2)	Completely corroded								
Cr-W No. 1	40(1.0)	13(0.34)		1.5(0.04)		5.8(0.15)				
rmalloy 63WC	71(1.8)	34(0.86) 24(0.62)		23(0.59)		36(0.91)				
calloy 30/50W	99(2.5)	20(0.50)	11(0.29)[e]	8.8(0.22)						
co 18SR	88(2.2)	Completely corroded								
co 22-13-5	253(6.4)	126(3.2)								
oy X	66(1.7)	11(0.27)	90(2.3)[g]							
oloy 825	92(2.3)	32(0.82)								
-414	78(2.0)	17(0.43)								
330	285(7.2)	976(25)								
-657	26(0.67)			3.2(0.08)						
-738 (cast)	194(4.9)	41(1.1) 51(1.3)								
	177(4.5)	36(0.92)								
onel 617	125(3.2)	34(0.87)		16(0.39)[h] 110(2.8)[i]						

GA = coal gasification atmosphere; input composition (vol %), 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 0 to 1.0 H_2S, the alance H_2O. All tests run at 1000 psi. The equilibrium gas compositions at the test temperatures are --

Component	1650 °F	1800 °F
H_2	27	31
CO	14	17
CO_2	17	15
CH_4	6	3
NH_3	1	1
H_2S	0-1.0	0-1.0
H_2O	balance	balance

alues are for one test specimen (1-in x 1-in x 1/4-in) exposed to the indicated conditions. Although duplicate ecimens were exposed, as a rule only one was sectioned, wire-brushed, and the depth of corrosion determined tallographically. Scale thickness, depth of internal corrosion, and diffusion zone thickness were determined. tal sound metal loss is the sum of scaling loss and depth of penetration. The reported rates are linearly trapolated from the metal loss data for the stated exposure time.

luminum coating (∼9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

pecimen reacted with an adjacent 446 SS specimen.

pecimen possibly contaminated.

ne specimen completely corroded.

wo specimens completely corroded.

verall corrosion.

dge corrosion.

TESTS FOR REPRODUCIBILITY OF CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO COAL GASIFICATION ATMOSPHERE[a] [13]

Alloy	Test Conditions	No. of Specimens	Average Rate of Total Sound Metal Loss[b] mils/yr	mm/yr	Range of Values of Rate of Loss
309 SS	32 specimens tested in CGA[a] with 0.5% H_2S, 1000 psi, 1800 °F, 1000 hr	32	31	0.80	22-47 (0.57-1.21)
309 SS	32 specimens tested in CGA[a] with 0.5% H_2S, 1000 psi, 1800 °F, 1000 hr	31	28	0.72	22-38 (0.55-0.95)
		1	134	3.4	
309 SS	6 specimens each tested in CGA[a] with 0.5% H_2S, 1000 psi, 1800 °F, 1000 hr	5	634	16	573-690 (15-17)
		1	375	9.5[d]	
314 SS		6	19	0.47	17-20 (0.42-0.52)
446 SS		6	25	0.64	20-34 (0.52-0.87)
Inconel 601		6	36	0.89	24-45 (0.60-1.1)
Incoloy 800		5	225	5.7	35-557 (0.89-14)
		1	Completely corroded		
Inconel 671		6	22	0.55	16-31 (0.40-0.78)
309 SS	6 specimens each tested in CGA[a] with 1% H_2S, 1000 psi, 1800 °F, 1000 hr	3	713	18	629-778 (16-20)
		1	136	3.4	
		2	Completely corroded		
314 SS		6	65	1.6	55-79 (1.4-2.0)
446 SS		5	31	0.77	24-44 (0.60-1.1)
		1	254	6.5	
Inconel 601		6	36	0.93	32-42 (0.82-1.1)
Incoloy 800		5	127	3.2	67-275 (1.7-7.0)
		1	703	18	
Inconel 671		6	22	0.55	18-28 (0.45-0.71)

---

[a] CGA = coal gasification atmosphere; input composition (vol %): $24H_2$, 18CO, $12CO_2$, $5CH_4$, $1NH_2$, 0.5% or 1.0% H_2S, balance H_2O. Equilibrium composition at 1800 °F: $31H_2$, 17CO, $15CO_2$, $3CH_4$, $1NH_3$, 0.5% or 1.0% H_2S, balance H_2O.

[b] After exposure the specimens (1 in x 1 in x 1/4 in) were sectioned, wire-brushed, and the depth of corrosion determined metallographically. Scale thickness, depth of internal corrosion, and diffusion zone thickness were determined. Total sound metal loss is the sum of scaling loss and depth of penetration. The reported rates are linearly extrapolated from the metal loss data for the stated exposure times.

[c] The number of specimens from the test batch included in calculating the average rate.

[d] Corrosion non-uniform; considerably greater corrosion on top half of sample.

CORROSIVE EFFECT OF VARIABLE WATER CONTENT OF COAL GASIFICATION ATMOSPHERE ON SOME ALLOYS[13]

	Rate of Total Sound Metal Loss[a], mils/yr (mm/yr)		
Alloy	CGA[b] with 0.5% H_2S, nominal 20% H_2O	CGA[c] with 1.0% H_2S, nominal 20% H_2O	CGA[d] with 1.0% H_2S, nominal 40% H_2O
304 SS	661 (17)	924 (23)	524 (13)
316 SS	484 (12)	1345 (34)	609 (15)
309 SS	240 (6.1)	255 (6.5)	238 (6.1)
310 SS	100 (2.6)	90 (2.3)	99 (2.5)
446 SS	19 (0.48)	36 (0.93)	18 (0.45)
Inconel 600	870 (22)	126 (3.2)	95 (2.4)
Inconel 601	27 (0.68)	242 (6.1)	108 (2.7)
Incoloy 800	235 (6.0)	331 (8.4)	239 (6.1)
Inconel 671	4 (0.11)	30 (0.75)	47 (1.2)
RA 333	22 (0.57)	81 (2.1)	159 (4.0)
Crutemp 25	45 (1.1)	74 (1.9)	100 (2.6)
Multimet N155	46 (1.2)	64 (1.6)	211 (5.4)
Haynes 188	16 (0.39)	47 (1.2)	50 (1.3)
Stellite 6B	6 (0.15)	40 (1.0)	42 (1.1)
Alloy X	5 (0.13)	43 (1.1)	52 (1.3)
Inconel 617	43 (1.1)	259 (6.6)	290 (7.4)

---

[a] Values are for one test specimen (1-in x 1-in x 1/4-in) exposed to the indicated conditions. Exposed specimens were sectioned, wire-brushed, and the depth of corrosion determined metallographically. Scale thickness, depth of internal corrosion, and diffusion zone thickness were determined. Total sound metal loss is the sum of scaling loss and depth of penetration. The reported rates are linearly extrapolated from the metal loss data for the stated exposure times.

[b] CGA = coal gasification atmosphere; inlet atmosphere (vol %), 30 H_2, 22 CO, 15 CO_2, 6 CH_4, 0.5 H_2S, 1 NH_3, balance H_2O (25.5); exit atmosphere, 41 H_2, 13 CO, 21 CO_2, 4 CH_4, 0.5 H_2S , 1 NH_3, balance H_2O (19.5); pressure 1000 psi, temperature 1800 °F, 1000 hr exposure.

[c] CGA = coal gasification atmosphere; inlet atmosphere (vol %), 30 H_2, 22 CO, 15 CO_2, 5.5 CH_4, 1.0 H_2S, 1 NH_3, balance H_2O (25.5); exit atmosphere, 40 H_2, 17.6 CO, 16.8 CO_2, 4 CH_4, 1.0 H_2S, 1 NH_3, balance H_2O (19.6); pressure 1000 psi, temperature 1800 °F, 100 hr exposure.

[d] CGA = coal gasification atmosphere; inlet atmosphere (vol %), 25 H_2, 18 CO, 12 CO_2, 4.5 CH_4, 1.0 H_2S, 1 NH_3, balance H_2O (38.5); exit atmosphere, 31.5 H_2O, 12 CO, 11.5 CO_2, 3 CH_4, 1.0 H_2S, 1 NH_3, balance H_2O (40); pressure 1000 psi, temperature 1800 °F, 100 hr exposure.

CORROSION BEHAVIOR OF SOME ALLOYS EXPOSED TO A LOW-BTU COAL GASIFICATION ATMOSPHERE[13]

	Rate of Total Sound Metal Loss[a], mils/yr (mm/yr)	
Alloy	Low Btu Gas,[b] 0.5% H_2S	Low Btu Gas,[c] 1.0% H_2S
304 SS	2 specimens completely corroded	2 specimens completely corroded
316 SS	2 specimens completely corroded	2 specimens completely corroded
309 SS	316 (8.0)	2 specimens completely corroded
310 SS	304 (7.7)	14 (0.35)
310 SS Al[d]	16 (0.40)	18 (0.46)
446 SS	362 (9.2)	46 (1.2)
Inconel 600	2 specimens completely corroded	2 specimens completely corroded
Inconel 601	159 (4.1)	2 specimens completely corroded
Incoloy 800	59 (1.5)	2 specimens completely corroded
Incoloy 800 Al[d]	8 (0.20)	9 (0.22)
Inconel 671	113 (2.9)	8 (0.21)
RA 333	123 (3.1)[e]	2 specimens completely corrode
Crutemp 25	113 (2.9)	8 (0.20)
Multimet N155	96 (2.4)	13 (0.32)
Haynes 188	47 (1.2)	2 specimens completely corrode
Stellite 6B	46 (1.2)	8 (0.20)
Alloy X	31 (0.80)	2 specimens completely corrode
Inconel 617	48 (1.2)	2 specimens completely corrode
LM-1866		89 (2.3)[f] 512 (13)[f]

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[a] Values are for one test coupon (1-in x 1-in x 1/4-in) exposed to the indicated conditions. Exposed specimens were sectioned, wire-brushed, and the depth of corrosion determined metallographically. Scale thickness, depth of internal corrosion, and diffusion zone thickness were determined. Total sound metal loss is the sum of scaling loss and depth of penetration. The reported rates are linearly extrapolated from the metal loss data for the stated exposure times.

[b] Low-Btu gas inlet composition (vol %): 1.7 H_2, 28.3 CO, 0.3 CO_2, 6.2 CH_4, 0.5 H_2S, 0.3 NH_3, 50.4 N_2, 12 H_2O; equilibrium atmosphere: 12 H_2, 20 CO, 8 CO_2, 4 CH_4, 0.5 H_2S, 47 N_2, 8 H_2O; 1800 °F, 400 psi, 1000 hr.

[c] Low-Btu gas inlet composition (vol %): 1.7 H_2, 28.3 CO, 0.3 CO_2, 6.2 CH_4, 1.0 H_2S 0.3 NH_3, 50.4 N_2, 12 H_2O; equilibrium atmosphere: 12 H_2, 20 CO, 8 CO_2, 4 CH_4, 1.0 H_2S, 47 N_2, 8 H_2O; 1800 °F, 400 psi, 1000 hr.

[d] Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

[e] One specimen completely corroded.

[f] Values for 2 specimens.

CORROSION BEHAVIOR OF ALLOYS SUBJECTED TO A DOLOMITE REGENERATOR ATMOSPHERE[a][13]

	Rate of Total Sound Metal Loss[b], mils/yr (mm/yr)	
loy	100 hr exposure	1000 hr exposure
2 SS	1685 (43)	219 (5.6)
4 SS	4000 (102)	313 (8.0)
5 SS	4944 (126)	891 (23)
9 SS	142 (3.6)	21 (0.53)
4 SS	86 (2.2)[c] 1399 (36)[c]	14 (0.35)
0 SS	332 (8.4)	13 (0.32)
0 SS Al[d]	112 (2.8)	13 (0.32)
0 SS Cr[e]	271 (6.9)	33 (0.84)
5 SS	169 (4.3)	completely corroded
conel 600	78 (2.0)[c] 1621 (42)[c]	885 (22)
conel 601	311 (7.9)[c] 1849 (47)[c]	51 (1.3)
coloy 800	251 (6.4)[c] 782 (20)[c]	71 (1.8)
coloy 800 Al[d]	104 (2.6)	17 (0.44)
coloy 800 Cr[e]	183 (4.6)	34 (0.86)
-793 (cast)	650 (17)	79 (2.0)
conel 671	88 (2.2)	25 (0.63)

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mosphere approximates that in the dolomite regenerator of the CO_2 Acceptor rocess pilot plant; composition in vol %, 67.4% N_2, 30.4% CO_2, 1.2% CO, .05% H_2, 0.13% SO_2; pressure 150 psi, temperature 1850 °F, exposure times s indicated.

alues are for one test specimen (1-in x 1-in x 1/4-in) exposed to the indicated onditions. Exposed specimens were sectioned, wire-brushed, and the depth of orrosion determined metallographically. Scale thickness, depth of internal orrosion, and diffusion zone thickness were determined. Total sound metal oss is the sum of scaling loss and depth of penetration. The reported rates re linearly extrapolated from the metal loss data for the given exposure times.

alues for two metallographic measurements made on the same specimen.

luminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion rocess (Alonized).

hromium coating (∿0.6 mils) applied by Alloy Surfaces, Inc.

RESULTS OF SLAGGING TEST EXPOSURES[a] OF SOME ALLOYS IN COAL GASIFICATION ATMOSPHERE[b][13]

	Rate of Total Sound Metal Loss[c], mils/yr (mm/yr)							
	Western Kentucky Char		Husky Char		CaO		SiO_2	
Alloy	blank hole[a]	packed hole[a]	blank hole[a]	packed hole[a]	blank hole[a]	packed hole[a]	blank hole[a]	packed hole[a]
309 SS	96 (2.4)	166 (4.2)	105 (4.0)	166 (4.2)	8.8 (0.22)	210 (5.3)	53 (1.3)	70 (1.8)
310 SS	8.8 (0.22)	368 (9.3)[d]	8.8 (0.22)	26 (0.67)	44 (1.1)	692 (18)	175 (4.5)	8.8 (0.22)
446 SS	18 (0.45)	79 (2.0)	18 (0.45)	210 (5.3)[d]	44 (1.1)	228 (5.8)	53 (1.3)	18 (0.45)
Inconel 601	123 (3.1)	219 (5.6)[d]	70 (1.8)	184 (4.7)	219 (5.6)	2365 (60)	158 (4.0)	219 (5.6)
Incoloy 800	26 (0.67)	219 (5.6)[d]	0 (0)	18 (0.45)	131 (3.3)	2164 (55)	70 (1.8)	70 (1.8)
Inconel 671	61 (1.6)	79 (2.0)	70 (1.8)	79 (2.0)	131 (3.3)	3565 (91)	79 (2.0)	44 (1.1)
RA 333	35 (0.89)	105 (4.0)	35 (0.89)	307 (7.8)[d]	70 (1.8)	4284 (109)	61 (1.6)	53 (1.3)
Crutemp 25	18 (0.45)	61 (1.6)	0 (0)	44 (1.1)	88 (2.2)	1121 (28)	35 (0.89)	35 (0.89)
Haynes 188	18 (0.45)	35 (0.89)	0 (0)	18 (0.45)	26 (0.67)	3539 (90)	26 (0.67)	26 (0.67)

[a] Specimens were 1-in x 1-in x 1/4-in. Two holes 1/4-in diameter and 3/16-in deep were drilled in each one. The slagging materials, char, CaO, and SiO_2 were hand compacted into one hole in each specimen, the second hole was considered the reference corrosion surface. Specimens were then exposed to a coal gasification atmosphere[b] at 1000 psi and 1800 °F for 100 hr.

[b] Coal gasification atmosphere inlet composition (vol %): 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, balance H_2O. Equilibrium composition at 1800 °F, 31 H_2, 17 CO, 15 CO_2, 3 CH_4, 1 NH_3, 1 H_2S, balance H_2O.

[c] Values are for one test specimen. Exposed specimens were sectioned, wire-brushed, and the depth of corrosion determined metallographically. Scale thickness, depth of internal corrosion, and diffusion zone thickness were determined. Total sound metal loss is the sum of scaling loss and depth of penetration. The reported rates are linearly extrapolated from the metal loss data for the 100 hr exposure time.

[d] Localized areas.

CORROSION BEHAVIOR OF WELDED ALLOYS EXPOSED TO COAL GASIFICATION ATMOSPHERE[a] [13]

lded Alloy[c]	Location		Rate of Total Sound Metal Loss[b], mils/yr			Comments
			Base Alloy	Weldment	Heat-Affected Zone	
se Incoloy 800H ot RA-330-04 ver RA-330-04-15	Cover	ave.[d]	21	14	21	Localized deep grain boundary corrosion in weldment at cover and root passes and in heat-affected zone at cover pass.
		max.[d]	74	440	276	
	Root	ave.	14	23	23	
		max.	23	131	--	
se Incoloy 800H ot RA-330-04 ver RA-330-04-15	Cover	ave.	19	19	18	Localized deep grain boundary corrosion in root and cover pass.
		max.	69	228	73	
	Root	ave.	19	25	18	
		max.	19	198	--	
se Incoloy 800H ot RA-333 **ver RA-333-70-16**	Cover	ave.	14	11	14	Localized deep corrosion in cover pass.
		max.	21	607	--	
	Root	ave.	11	8.8	14	
		max.	80	18	--	
se Incoloy 800H ot RA-333 ver RA-333-70-16	Cover	ave.	25	18	14	Localized moderate corrosion in one area, root pass.
		max.	32	38	19	
	Root	ave.	11	5.3	16	
		max.	30	69	--	
se Incoloy 800H ot Inconel 72 ver Metrode 50Cr-50Ni	Cover	ave.	25	5.3	23	Localized corrosion at heat-affected zone cover and root passes.
		max.	52	23	107	
	Root	ave.	19	30	25	
		max.	--	--	85	
se Incoloy 800H ot Inconel 72 ver Metrode 50Cr-50Ni	Cover	ave.	25	3.5	21	Localized deep corrosion root pass at heat-affected zone one side.
		max.	--	41	123	
	Root	ave.	21	7.0	23	
		max.	64	39	388	
se Incoloy 800H ot Inconel 617 ver Inconel 617	Cover	ave.	18	14	21	Minor scaling and internal corrosion.
		max.	--	--	--	
	Root	ave.	19	25	21	
		max.	--	--	--	
se Incoloy 800H oot Inconel 617 over Inconel 617	Cover	ave.	16	23	25	Localized deep grain boundary corrosion in weld bead with internal scaling.
		max.	26	465	77	
	Root	ave.	26	21	23	
			--	--	--	
ase IN-657[e] oot Inconel 72 over Metrode 50Cr-50Ni	Cover	ave.	--	3.5	--	Heavy casting porosity in parent metal; minor corrosion of weld bead.
		max.	196	--	--	
	Root	ave.	--	8.8	--	
		max.	778	--	--	

(Table Continued)

CORROSION BEHAVIOR OF WELDED ALLOYS EXPOSED TO COAL GASIFICATION ATMOSPHERE[a] [13] (continued)

			Rate of Total Sound Metal Loss[b], mils/yr			
Welded Alloy[c]	Location		Base Alloy	Weldment	Heat-Affected Zone	Comments
Base IN-657[e] Root Inconel 72 Cover Metrode 50Cr-50Ni	Cover	ave.	--	7.0	--	Heavy casting porosity in parent metal; minor corrosion of weld bead.
		max.	312	--	--	
	Root	ave.	--	5.3	--	
		max.	965	48	--	
Base Incoloy 800H Al[f] Root Inconel 72 Cover Metrode 50Cr-50Ni	Cover	ave.	--	12	19	Minor scaling and internal corrosion; localized corrosion in heat-affected zone at root pass.
		max.	--	46	--	
	Root	ave.	--	35	11	
		max.	--	45	303	
Base Incoloy 800H Al[f] Root Inconel 72 Cover Metrode 50Cr-50Ni	Cover	ave.	--	3.5	43	Minor scaling and inte corrosion; localized corrosion in heat-affe zone at cover pass.
		max.	--	5.3	282	
	Root	ave.	--	7.0	16	
		max.	--	--	--	

[a] Coal gasification atmosphere inlet composition (vol %): 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 0.5% H_2S, balance H_2O. At 1800 °F and 1000 psi, equilibrium gas composition is 31 H_2, 17 CO, 15 CO_2, 3 CH_4, 1 NH_3, 0.5 H_2S, balance H_2O.

[b] Values are for one test specimen exposed for 1000 hr. Total sound metal loss is the sum of scaling loss and depth of penetration. Scaling loss was determined from the metallographically visible scale on the specimen; in the absence of visible scales the loss was considered to be 0.2 mil. All corrosion determinations were based on one-side corrosion measurements. The rates of loss given in the table were linearly extrapolated from the total corrosion experienced by the specimens for a 1000 hr exposure. Rates are given in order to have values which may be compared with other data in this series of tests.

[c] Incoloy 800H specimens fabricated from 0.5 in plate. IN-657 specimens obtained from centrifugally cast tubing with 0.625 in wall thickness. Root pass was Gas Tungsten Arc welded, cover pass was Shielded Metallic Arc welded.

[d] Average and maximum values are given to indicate localized effects; if no localized effects were observable, maximum data are not listed.

[e] Specimens had deep shrinkage porosity in base metal. Surfaces in weld area were ground prior to welding. Shrinkage porosity precluded measurement of corrosion in the heat-affected zone; base metal corrosion depth represents the maximum depth of surface porosity.

[f] Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized). Corrosion depth of base metal could not be measured on these specimens because a 50Cr-50Ni weld overlay was applied to the base metal in the weld area. Corrosion of the base metal and heat-affected zone generally the same as the weldment except in localized areas.

QUALITATIVE EVALUATION OF THE EFFECTS OF MICROSTRUCTURAL CHARACTERISTICS ON THE WEAR RESISTANCE[a] OF COBALT BASE SUPERALLOYS[b] [28]

Materials Tested (Major Contituents)[c]	Type	Hardness (R_C)	Normalized Alloy Content[d]	Microstructural Condition
Cobalt Base Superalloys prepared by powder metallurgical techniques:				
#6 (Co, 29Cr, 2Ni, 5W, 1.5Fe)	Low carbide volume fraction, 33.8% M_7C_3.	45.0	1.0	Low solid solution strengthener content.
#6HC (Co, 29Cr, 2Ni, 5W, 1.5Fe)	High carbide volume fraction, 39.5% M_7C_3.	49.0	1.0	Low solid solution strengthener content.
#19 (Co, 30Cr, 1.4Ni, 10W, 1.9Fe)	High carbide volume fraction, 37.4% M_7C_3.	51.0	1.7	Moderate solid solution strengthener content.
#98M2 (Co, 30.5Cr, 4Ni, 17W, 3Fe)	High carbide volume fraction, 43.6% M_7C_3, 13.0% M_6C.	63.0	3.5	High solid solution strengthener content.
#3 (Co, 31Cr, 2Ni, 12W, 2Fe)	Very high carbide volume fraction, 46.3% M_7C_3, 8.9% M_6C.	57.0	2.0	High solid solution strengthener content.
#Star J (Co, 31.5Cr, 1Ni, 17W)	Very high carbide volume fraction, 41.0% M_7C_3, 8.9% M_6C.	59.0	2.6	Very high solid solution strengthener content.

Parameter Effects	Conclusions
Effect of increased carbide volume fraction.	Improves abrasive wear resistance in low-stress wear (RWAT)[a] against hard abrasives. Of limited value against softer abrasives in low-stress wear or in gouging conditions (GAWT)[a].
Effect of increased matrix strength.	Improves abrasive wear resistance in low-stress wear against hard abrasives. Of limited value against softer abrasives in low-stress wear or in gouging conditions.
Effect of microstructure.	Abrasion behavior is a strong function of specific abrasive conditions. No broad generalities in predicting wear resistance are warranted.
Effect of macrohardness.	Increased macrohardness gives improved wear resistance in low-stress applications against very hard abrasives. Macrohardness is an unsatisfactory gauge of wear resistance in low-stress applications against softer abrasives. Macrohardness is an unsatisfactory gauge of wear resistance in gouging applications.
Relation of inverse-hardness rule to abrasive wear.	The rule must be modified to take into account the rake angles of abrading particles, the size and hardness of multiphase particles, and the matrix-particle interactions.
Effect of closely spaced large carbides during wear.	Protect maxtrix against wear under low-stress abrasion conditions. Wear of the carbide particles governs the over-all wear rate.
Effect of small second-phase particles during wear.	May be dislodged from matrix and result in increased weight losses and enhanced abrasion environment.
Effect of load-time history.	The same abrasive employed under low-stress conditions and under gouging conditions acts quite differently in the two applications, even under similar normal loads.
Effect of one of the most commonly accepted low-stress abrasion tests.	Causes abrasive degradation which usually decreases the effectiveness of the abrasive.
Contributing factors of hardness and angularity of the abrasive.	Important in low-stress abrasion against materials with large carbides. Angularity is more important than hardness in low-stress abrasion against alloys with small carbides.

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[a] Wear resistance as measured by a low-stress wear technique (Rubber Wheel Abrasive Test) in which abrasive (SiO_2 or Al_2O_3) is gravity fed between a rotating rubber wheel and the test specimen and, by a gouging wear test (Gouging Abrasive Wheel Test) in which a grinding wheel is rotated against the specimen under pressure.

[b] Prepared at the Stellite Division, Cabot Corp.

[c] Approximate compositions only.

[d] A measure of matrix strength; the sum of the weight percentages of Ni, V, and W in the alloys, normalized against alloy #6.

QUALITATIVE EVALUATION OF THE EFFECTS OF MICROSTRUCTURAL CHARACTERISTICS ON THE WEAR RESISTANCE[a] OF WHITE CAST IRONS[b] [28]

Materials Tested	Heat Treatment	Microstructural Condition
White Irons: 15Cr-3Mo (ASTM532-Type II)	Austenitized at 1800 °F (980 °C) 1 hour, furnace cooled and stress relieved at 400 °F (205 °C) 2 hours.	Cr_7C_3 Carbides in tempered martensite. (overtempered martensite)
27Cr-2.5C (ASTM532-Type III)	Austenitized at 1850 °F (1010 °C) 2 hours, air cooled and stress relieved at 450 °F (230 °C) 1 hour.	Cr_7C_3 Carbides in tempered martensite. (Lightly tempered martensite)
Pearlitic White Iron (2.7C)	As-cast in sand.	Fe_3C Carbides in pearlitic matrix. High carbide volume fraction.
Pearlitic White Iron (3.5C)	As-cast in sand.	Fe_3C Carbides in pearlitic matrix. Low Carbide volume fraction.

Parameter Effects	Conclusions
Effect of Carbide volume fractions, carbide shape, and matrix strength.	Wear resistance is dependent on these parameters. A satisfactory balance of these parameters in alloying must be obtained to achieve an improvement in wear resistance.
Effect of macrohardness and matrix microhardness on wear resistance.	Generally, increased macrohardness and matrix microhardness improve RWAT[a] and GAWT[a] wear resistance.
Effect of carbide microhardness on wear resistance.	Generally, increased carbide microhardness does not improve RWAT and GAWT wear resistance. More emphasis should be placed on alloying and processing to optimize matrix properties.

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Materials Tested	Heat Treatment	Microstructural Condition
Ni-Hard 4 Irons (ASTM532-Type I)		High-Cr carbides in Austenite decomposition product ($\alpha + Fe_3C$) containing
	1380 °F (750 °C) for 8 hr, cooled to -320 °F (-195 °C), 410 °F (210 °C) for 1 hr.	5% Retained Austenite
	1020 °F (550 °C) for 4 hr, 840 °F (450 °C) for 16 hr, cooled to -320 °F (-195 °C), 410 °F (210 °C) for 4 hr.	20% Retained Austenite
	1380 °F (750 °C) for 8 hr, 1020 °F (550 °C) for 4 hr, 840 °F (450 °C) for 16 hr.	40% Retained Austenite
	450 °F (230 °C) for 4 hr.	85% Retained Austenite

- -

(Table Continued)

QUALITATIVE EVALUATION OF THE EFFECTS OF MICROSTRUCTURAL CHARACTERISTICS ON THE WEAR RESISTANCE[a] OF WHITE CAST IRONS[b] [28] (continued)

Parameter Effects	Conclusions
Effect of microstructural state on low stress wear behavior.	RWAT tests were strongly dependent on microstructural state.
Effects of microstructural state on gouging wear behavior.	GAWT tests were strongly dependent on microstructural state. The percentage of retained austenite may increase or decrease abrasion resistance depending on the relative amount and the specific wear process involved.
Valve of macro or micro-hardness as a gauge of wear resistance.	Not satisfactory. Not as good a gauge as compressive shear or ultimate strength.
Valve of hardness and tensile property correlations to wear.	Correlate as well to wear as do fatigue or fracture-mechanics parameters.
Effect of a very hard abrasive (Al_2O_3) on low stress wear (RWAT).	Matrix and Carbide undergo uniform attrition by a micro-machining action.
Effect of a very hard abrasive (Al_2O_3) on gouging wear (GAWT).	Matrix and carbide undergo uniform attrition by a micro-machining action.
Effect of an intermediate hard abrasive (SiO_2) on low stress wear (RWAT).	Matrix abraded preferentially by micro-machining then carbides which stand out in relief are chipped away at their exposed leading edges and are to a lesser extent lost by fracture and spalling. The resistance of the carbides to the softer SiO_2 abrasive appears to be mainly responsible for the 5 to 1 improvement in wear resistance over the Al_2O_3 abrasive.

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[a] Wear resistance as measured by a low-stress wear technique (Rubber Wheel Abrasive Test) in which abrasive (SiO_2 or Al_2O_3) is gravity fed between a rotating rubber wheel and the test specimen and, by a gouging wear test (Gouging Abrasive Wheel Test) in which a grinding wheel is rotated against the specimen under pressure.

[b] Cast irons produced at the Climax Molybdenum Research Laboratories.

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANT[12]

	Steam-oxygen gasifier fluidized bed (HYGAS); H_2O, CO_2, CO, H_2, H_2S, ash, char						Low-temperature first-stage reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char					
	1339°F, 980 psig, 1718 hr			1340°F, 925 psig, 1329 hr			1013°F, 921 psig, 1355 hr			977°F, 980 psig, 1554 hr		
		Total Sound Metal Loss[a]			Total Sound Metal Loss[a]			Total Sound Metal Loss[a]			Total Sound Metal Loss[a]	
Alloy/ Composition[c]	Depth of Penetration mils	in/yr	mm/yr	Depth of Penetration mils	in/yr	mm/yr	Depth of Penetration mils	in/yr	mm/yr	Depth of Penetration mils	in/yr	mm/yr
430 SS Fe-17Cr	3.4	.018	0.47				0.3	0.003	0.08			
304 SS 70Fe-9Ni-19Cr	0.7	.005	0.12				0.9	0.007	0.18			
321 SS Fe-10Ni-18Cr	1.2	.007	0.18				1.8	0.013	0.33			
316 SS 65Fe-14Ni-17Cr	3.5	.019	0.49				0.9	0.007	0.18			
309 SS 61Fe-15Ni-23Cr	0.4	.003	0.08	0.7	0.006	0.15	0.7	0.006	0.15	0.2	0.002	0.06
Armco 21-6-9 63Fe-9Ni-21Cr-8Mn	0.9	.006	0.14				1.8	0.013	0.33			
Armco 22-13-5 Fe-14Ni-21Cr-5Mn	0.2	.002	0.05				0.3	0.003	0.08			
Incoloy 800 47Fe-31Ni-21Cr	0.6	.004	0.10	0.8	0.007	0.17	0.6	0.005	0.13	0.2	0.002	0.06
Incoloy 800 (Al)				5.1	0.035	0.89				1.1	0.007	0.18
Incoloy 825 28Fe-42Ni-22Cr	1.0	.006	0.16									
RA 333 16Fe-45Ni-26Cr-3Co-4Mo-3W	0.6	.004	0.10	0.7	0.006	0.15						
Alloy X 20Fe-45Ni-22Cr-9Mo	0.6	.004	0.10									
Inconel 601 16Fe-60Ni-23Cr	2.2	.012	0.31				--	>8.4[d]		0.3	0.003	0.07
Inconel 600 7Fe-77Ni-16Cr		>.640	>16.2[d]				2.7	0.68	1.72			
IN-793 43Fe-32Ni-21Cr				2.3	0.016	0.42				0.3	0.003	0.08
446 SS 75Fe-24Cr				0.5	0.009	0.22				0.3	0.003	0.07
310 SS 52Fe-20Ni-25Cr				0.5	0.005	0.12	0.2	0.002	0.06			
310 SS (Al)[f]				2.4	0.031	0.79	1.0	0.007	0.17			
Inconel 671 48Ni-50Cr				0.4	0.007	0.17				0.2	0.002	0.06
Welded-U-Bends												
304 SS				No stress-corrosion cracks								
309 SS				No stress-corrosion cracks								
Incoloy 800				No stress-corrosion cracks								
Incoloy 825				No stress-corrosion cracks								
Inconel 600				Both specimens disappeared								

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANT[12] (continued)

	High-temperature second-stage reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char						Gasifier off-gas (BI-GAS); H_2O, CO_2, CO, H_2, N_2, CH_4, H_2S (ash and char entrained)		
	1306°F, 980 psig, 1554 hr			1271°F, 923 psig, 1355 hr			1700°F, 750 psig, 406 hr		
	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr
ncoloy 800	0.2	0.002	0.06	0.8	0.006	0.16	0.9	.074	1.88
ncoloy 800 (Al)[f]	2.7	0.016	0.40	5.2	0.036	0.90	3.0	.238	6.04
10 SS	0.2	0.002	0.06	0.4	0.004	0.10	0.4	.014	0.34
10 SS (Al)[f]	2.5	0.015	0.38	3.4	0.034	0.87	4.2	.211	5.36
09 SS	0.2	0.002	0.06	0.5	0.005	0.11	0.5	.061	1.55
46 SS	0.3	0.003	0.08	0.3	0.003	0.08	0.2	.009	0.22
nconel 601	0.2	0.002	0.06	1.7	0.012	0.31			
N-793	0.2	0.002	0.06	0.4	0.004	0.10	5.0	.213	5.40
nconel 671	0.1	0.002	0.05	0.5	0.005	0.13	0.2	.061	1.55
14 SS 52Fe-20Ni-24Cr							0.8	.027	0.70
A 330 Fe-36Ni-19Cr							2.2	.062	1.58
A 333							0.8	.022	0.55
rmco 22-13-5							0.8	.028	0.72

	Hydrogasifier upper reactor (HYGAS) off-gas (Slurry dryer); H_2O, CO, H_2, CH_4, CO_2, toluene, coal fines						Coal pretreater off-gas (HYGAS): neutral gas, H_2O, O_2, CH_4, N_2, coal fines and tar, some SO_2					
	591°F, 949 psig, 2909 hr			580°F, 985 psi, 1150 hr			797°F, 2.4 psig, 1719 hr			730°F, 2.7 psig, 1790 hr		
	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr
arbon Steel (A515)	0	0.011	0.28	--	0.0007		-- -- 2.0	0.008 0.002 (0.0143)[e]		4.5	0.024	0.61
arbon Steel (Al)[f]	11.5	0.035	0.89	--[g]	--[g]		--	0.0001		5.9	0.032	0.81
onel 400 64Ni-33Cu-2Fe	0	0.266	6.75	--[g]	0.0949 (0.1246)[e]							
04 SS	1.7	0.006	0.15	1.6	--[g]		0.2	0.0001		0.2	0.002	0.05
16 SS	1.5	0.009	0.22	--[g]	--[g]		--	0.0001		0.2	0.002	0.05
10 SS	4.0	0.013	0.32	1.0	--[g]		0.3	0.0007		3.6	0.022	0.56
30 SS	0.6	0.002	0.06	2.2 1.0	--[g]							
nconel 600	0.4	0.164	4.17	--[g]	0.0325 (0.0425)[e]							
ncoloy 800	0.4	0.002	0.05	--[g]	0.0002							
itanium	0.3	0.002	0.04	--[g]	--[g]							
elded-U-Bends												
04 SS	No stress-corrosion cracks			No stress-corrosion cracks			No visible cracks			No stress-corrosion cracks		
ncoloy 800	No stress-corrosion cracks			No stress-corrosion cracks								
16 SS							No visible cracks			No stress-corrosion cracks		

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANT[12] (continued)

	Gasifier fluidized bed (SYNTHANE): Reducing gas, H_2O, CO_2, CO, H_2, H_2S, coal fines, ash, char						Gasifier off-gas (SYNTHANE); reducing gas, H_2O, CO_2, CO, H_2, H_2S, small amount ash and char					
	1440°F, 600 psi, 181 hr			1434°F, 600 psi, 781.8 hr			1290°F, 600 psi, 181 hr			1284°F, 600 psi, 781.8 hr		
	Depth of Penetration	Total Sound Metal Loss		Depth of Penetration	Total Sound Metal Loss		Depth of Penetration	Total Sound Metal Loss		Depth of Penetration	Total Sound Metal Loss	
	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr
304 SS	1.7	0.105	2.67	0.2	0.005	0.13	2.7	0.140	3.56	0.8	0.011	0.29
309 SS	0.9	0.075	1.91	0.2	0.004	0.11	1.4	0.096	2.44	0.6	0.009	0.23
Incoloy 800	5.6	0.310	7.87	0.2	0.004	0.11	1.4	0.096	2.44	0.5	0.007	0.19
Incoloy 825	0.3	0.025	0.64	0.2	0.004	0.11	0.9	0.053	1.35	0.2	0.004	0.11
Alloy X	0.3	0.045	1.14	0.3	0.005	0.13	1.3	0.073	1.85	0.3	0.006	0.14
RA 333	0.5	0.034	0.85	0.2	0.004	0.10	1.0	0.058	1.47	0.6	0.002	0.04
316 SS	2.0	0.110	2.79	2.0	0.025	0.63	4.8	0.256	6.50	1.5	0.020	0.50
321 SS	3.4	0.215	5.46	1.3	0.017	0.43	2.0	0.121	3.07	1.3	0.018	0.46
Armco 21-6-9	3.3	0.185	4.70	0.5	0.007	0.19	4.5	0.247	6.27	0.4	0.007	0.17
Armco 22-13-5	1.4	0.100	2.54	0.3	0.006	0.14	3.5	0.179	4.55	0.4	0.007	0.17
430 SS	0.2	0.025	0.64	0.7	0.010	0.24	1.4	0.101	2.56	0.4	0.006	0.16
Inconel 600	0.6	2.505	63.63	34.4	0.878	22.30	1.9	1.350	34.29	15.1	0.582	14.77
Inconel 601	2.0	0.110	2.79	1.4	0.018	0.46	0.3	0.111	2.82	0.5	0.011	0.27

	Gasifier off-gas (CONOCO CO_2 Acceptor); 48H_2, 23H_2O, 12CH_4, 8.5CO, 6CO_2, 2.5N_2								
	1400-1450°F, 150 psi, 1000 hr			1400-1600°F, 150 psi, 2390 hr			1400-1600°F, 150 psi, 1455 hr		
	Depth of Penetration	Total Sound Metal Loss		Depth of Penetration	Total Sound Metal Loss		Depth of Penetration	Total Sound Metal Loss	
	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr
Incoloy 800	1.28	0.013	0.33	3.7	0.014	0.36	0.2	0.003	0.06
Incoloy 800 (Al)[f]	0	0.046	1.17	2.9	0.031	0.79	1.8	0.032	0.80
Incoloy 800 (Cr)[f]	0.59	0.011	0.27	2.4	0.010	0.24	0.7	0.007	0.17
310 SS	1.97	0.019	0.48	0.4	0.002	0.06	0.4	0.004	0.09
310 SS (Al)[f]	5.41	0.054	1.38	7.1	0.030	0.75	7.1	0.050	1.26
310 SS (Cr)[f]	0.39	0.005	0.13	1.7	0.007	0.19	0.2	0.003	0.07
309 SS	2.46	0.024	0.60	6.1[h]	0.023	0.59	0.4	0.003	0.09
304 SS	3.05	0.029	0.73	3.8[h]	0.019	0.49	0.6	0.005	0.12
IN-793	0.98	0.011	0.27	4.0	0.016	0.41	1.5	0.010	0.26
Inconel 671	0	0.003	0.08	0.2	0.002	0.05	0	0.002	0.06
Armco 22-13-5	4.43	0.042	1.06	6.9	0.026	0.67	0.6	0.005	0.12
Armco 21-6-9	3.05	0.029	0.73	6.4	0.034	0.86	3.0	0.019	0.48
Alloy X	0.98	0.011	0.29	1.91	0.008	0.20	1.1	0.008	0.20
Incoloy 825	0.39	0.005	0.13	6.2[h]	0.030	0.76	0.3	0.003	0.08

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANT[12] (continued)

Dolomite Regenerator off-gas (CONOCO CO_2 Acceptor); 3 CO, 27 CO_2, 70 N_2, trace H_2S

	1850°F, 150 psi, 1000 hr			1850°F, 150 psi, 1600 hr			1800-1900°F, 150 psi, 740 hr		
	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr	Depth of Penetration mils	Total Metal in/yr	Sound Loss mm/yr
Incoloy 800	4.13 15.26	0.041 0.173	1.05 4.41	Completely corroded					
Incoloy 800 (Al)[f]	4.72	0.052	1.32	12.97	0.079	2.01	18.3	0.252	6.40
Incoloy 800 (Cr)[f]	12.01	0.194	4.92	Completely corroded					
310 SS	5.02	0.051	1.29	17.09	0.412	10.46	8.3	0.916[i]	23.27[i]
310 SS (Al)[f]	4.92	0.051	1.31	11.77	0.080	2.03	14.4	0.215	5.46
310 SS (Cr)[f]	4.92 2.17	0.053 0.022	1.34 0.57	Essentially completely corroded Essentially completely corroded					
309 SS	6.40	0.088	2.24	Essentially completely corroded			8.9	0.406[i]	10.31[i]
304 SS	9.84 16.73	0.137 0.516	3.47 13.11	Completely corroded					
446 SS	1.97	0.024	0.62				2.9	0.354[i]	8.99[i]
IN-793	12.80	0.119	3.02	28.09	0.317	8.05	30.1	0.848	21.54
Inconel 671	0.00 5.91	1.095 0.923	27.80 23.45	Essentially completely corroded				>1.5[j]	>38.10[j]
Armco 21-6-9	6.50	0.062	1.58	24.33	0.199	5.05	5.8	0.688[i]	17.48[i]
Armco 22-13-5	5.61	0.068	1.74	Essentially completely corroded			5.2	0.899[i]	22.83[i]
Alloy X	10.33	0.351	8.91	Essentially completely corroded					
Incoloy 825	25.14	0.603	15.33	Completely corroded					
314 SS							7.4	0.404	10.26
150 Co-18Fe-28Cr							35.1	0.569	14.45
Crutemp 25 47Fe-25Ni-25Cr							9.0	0.496[i]	12.60[i]
HC-250 68Fe-28Cr-3C							5.3	0.118	4.78
HL-40 47Fe-19Ni-31Cr							15.4	0.211	5.36
HK-40 Fe-20Ni-28Cr							21.6	0.310	7.87
RA 330							14.3	1.040[i]	26.42[i]
RA 333							26.7	0.919	23.34
Haynes 188 Co-23-Ni-22Cr								>1.5[j]	>38.10[j]

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[a] Both gravimetric and metallographic analyses were used to determine the extent of corrosion. Most values are the average of two specimens, in a few cases values for both specimens are given. Rates are based on a total of scaling loss and penetration for the operation time extrapolated linearly to obtain a yearly rate. Shutdown and standby times were not included.

[b] Data for exposures in a total of ten locations for four pilot plants are included. The conditions are such that all constituents are gas phase except for dispersed solids. Average temperatures, pressures, and the type of environment are given as well as the exposure times which are for full operating conditions; standby periods were omitted.

[c] Approximate values only for major constituents; composition given for alloy the first time it appears in the table. Specimens were flat coupons for BI-GAS, 1/4 x 1 1/8 in square; for HYGAS and SYNTHANE, 1/4 x 1 1/8 x 2 1/8 in. Some welded U-specimens were included and are so designated.

[d] Samples were essentially completely corroded.

[e] Both gravimetric and metallographic values given, metallographic values in parentheses.

[f] (Al) = aluminized, (Cr) = chromized.

[g] Metal loss was negligible.

[h] Localized corroded areas.

[i] Second specimens essentially completely corroded.

[j] Both specimens completely corroded.

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12]

	Coal Pretreater Water Quench (HYGAS): H_2O, O_2, CO, CH_4, N_2							
	∿70 °F, atm pressure, 1575(2845) hr[d]				158 °F, 1.0 psig, 1719(3228) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational[a]	Total[a]	Max	Avg	Operational[a]	Total[a]	Max	Avg
Carbon Steel (A515)	7.8(26.7)[e]	4.3(14.8)[e]	---	---	54.1(93.3)[e] 51.8	28.8(49.6)[e] 27.6	(8.8)[e]	
Cast Iron	4.4	2.5	3.3	2.3	34.9(93.8) 33.2	18.6(49.9) 17.7	(17.6)	
Ni-Resist Fe-20Ni-3Cr-3Si	3.3	1.8	3.4	2.6	22.4(39.8) 21.5	11.9(21.1) 11.4	(3.9)	
Ni-Resist (Cu) Fe-18Ni-4Cr-3Si-7Cu	2.8	1.5	1.1	0.9	20.6(84.7) 20.5	11.0(45.0) 10.9	(15.0)	
Si-Iron Fe-15Si	0.6	0.3	8.7	6.3	14.5(82.6) 13.2	7.7(43.9) 7.0	(18.1)	
304 SS 70Fe-9Ni-19Cr	0.2	<0.1	2.4	1.5	--[f] --[f]	--[f] --[f]	13.1 15.6	9.3 7.9
18-18-2 Fe-18Ni-18Cr-2Si	0.3	0.2	2.4	1.2	0.2 0.3	0.1 0.1	9.7 13.6	5.5 6.7
Al Bronze Cu-10Al-3Fe-2Ni	1.7	0.9	3.0	1.5	8.0(19.9) 7.3	4.3(10.6) 3.9	(2.8)	
Titanium 50A	0.1	<0.1	0.1	---	0.1 0.1	-- --	-- --	-- --
Welded U-Bends								
Carbon Steel	No stress corrosion crack				No Visible Cracks			
329 SS Fe-4Ni-27Cr	No Stress Corrosion Cracks							
304 SS	No Stress Corrosion Cracks				No Visible Cracks			
18-18-2	No Stress Corrosion Cracks				No Visible Cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] continued

Product Gas Prequench tower (HYGAS): process condensate, H_2O, char fines, ash

	171 °F, 950 psig, 2909(10,429) hr[d]				205 °F, 990 psi, 1150(2010) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational[a]	Total[a]	Max	Avg	Operational[a]	Total[a]	Max	Avg
Carbon Steel (A515)	19.9(57.8)[e]	5.5(16.1)[e]	4.9	3.4	8.8(20.0)[e] 9.0	3.1(7.3)[e] 3.3	-- --	-- --
Cast Iron	13.5(37.3)	3.8(10.4)	2.0	1.6	6.0(20.7) 6.0	2.2(7.6) 2.2	5.4 6.5	4.1 3.6
Ni-Resist Fe-20Ni-3Cr-3Si	22.0(30.1)	6.1(8.4)	3.6	2.6	7.0(15.2) 6.6	2.6(5.5) 2.4	-- --	-- --
Ni-Resist (Cu) Fe-18Ni-4Cr-3Si-7Cu	21.7(39.7)	6.0(11.1)	3.4	2.4	6.9(14.5) 6.8	2.5(5.3) 2.5	-- --	-- --
304 SS 70Fe-9Ni-19Cr	<0.1	--	1.2	0.8	0.07 0.07	0.02 0.02	Not Measureable	
18-18-2 Fe-18Ni-18Cr-2Si	0.1	--	1.8	1.4	0.07 0.07	0.02 0.02	10.8 9.1	8.3 7.7
Al Bronze Cu-10Al-3Fe-2Ni	3.9(12.3)	1.1(3.4)	7.1	5.0	3.12(7.2) 3.3	1.1(2.6) 1.2	-- --	-- --
Titanium 50A	<0.1	--	--	--	--[f] --[f]	--[f] --[f]	-- --	-- --
410 SS Fe-12Cr	9.3(49.9)	2.6(13.9)	14.3	9.7	0.8 0.9	0.3 0.3	13.2 12.9	8.9 10.4
329 SS Fe-4Ni-27Cr					--[f] --[f]	--[f] --[f]	-- --	-- --
Welded U-Bends								
329 SS	No Stress Corrosion Cracks				No Visible Stress Corrosion Cracks			
304 SS	No Stress Corrosion Cracks				No Visible Stress Corrosion Cracks			
18-18-2	No Stress Corrosion Cracks				No Visible Stress Corrosion Cracks			

Feed slurry mix vessel (HYGAS): treated coal fines plus toluene

	180 °F, 1 atm, 288(2118) hr[d]		85 °F, 3 psi, 1150(2046) hr[d]	
	Corrosion Rate mils/year		Corrosion Rate mils/year	
Alloy/ Composition[c]	Operational	Total	Operational	Total
Carbon Steel	17.9 16.7	2.44 2.27	3.28 4.27	1.84 2.40
410 SS	0.18 0.30	0.02 0.04[g]	0.04 0.015	0.02 0.01
304 SS	0.06 0.03	0.01 0.004	0.022 0.015	0.01 0.01

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

	Coal pretreater quench tower off-gas (HYGAS): neutral gas, H_2O, O_2, CO, CH_4, N_2							
	140 °F, 0.4 psig, 1719(3228) hr[d]				174 °F, atm pressure, 1790(3296) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	36.4(46.4)	19.1(24.7)	---	---	43.0(68.4)	23.4(37.2)	---	---
	37.4	19.9	---	---				
410 SS	1.3	0.7	---	---	1.0	0.5	10.4	5.8
	1.2	0.7	---	---				
304 SS	0.1	0.1	---	---	<0.1	<0.1	3.3	1.6
	0.1	0.1	---	---				
316 SS 65Fe-14Ni-17Cr	---	---	---	---	<0.1	<0.1	1.2	0.9
	0.1	---	---	---				
U-Bends								
Carbon Steel	No visible cracks							
304 SS welded	No visible cracks				No stress corrosion cracks			
316 SS welded	No visible cracks				No stress corrosion cracks			

	Quench Separator Tower (HYGAS): process condensate, H_2O, char fines, ash							
	Oil Phase				Gas Phase			
	140 °F, 990 psi, 1150 hr operation 120 °F, 650 psi, 2010 hr standby				95 °F, 949 psig, 2909(10,429) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	30.0(46.5)	10.9(16.9)	---	---	145.3(131.7)	40.5(36.7)	5.6	4.3
	16.1(39.6)	5.8(14.4)	---	---				
410 SS	1.7	0.6	7.5	5.3	41.8(82.7)	11.7(23.1)	9.1	7.4
	4.4	1.6	9.4	7.8				
430 SS Fe-17Cr	0.7	0.2	10.6	7.4	4.8(22.6)	1.3(6.3)	11.8	6.5
	0.8	0.2	14.3	9.0				
304 SS	0.02	0.01	2.9	---	<0.1	---	10.3	5.8
	0.02	0.01	0.8	---				
U-Bends								
Carbon Steel	No Visible Stress Corrosion Cracks							
304 SS Welded	No Visible Stress Corrosion Cracks				No Visible Stress Corrosion Cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

Quench Tower Off-Gas (HYGAS): product gas

Alloy/ Composition[c]	97 °F, 909 psig, 1247(3356)hr[d]				108 °F, 900-1100 psi, 1596(6018)hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	77.2(131.9)	28.7(49.0)	8.6	4.6	(155) (171)	(41.2) (45.3)		
410 SS	5.6	2.1	9.6	7.6	1.43 1.04	0.52 0.38	5.9 8.2	12.9 18.5
304 SS	<0.1	<0.1	0.9	0.9	0.02 0.02	0.01 0.01	--- ---	--- ---
U-Bends								
Carbon Steel	No Stress Corrosion Cracks, Badly Corroded				No Stress Corrosion Cracks			
304 SS Welded					No Stress Corrosion Cracks			

Char/slurry mix tank (HYGAS): char, ash, water

Alloy/ Composition[c]	95 °F, 890 psi, 1350 hr (operation) 880 °F, 730 psi, 1760 hr (standby)				135 °F, 907 psig, 2909(8041) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	19.1(43.5) 6.7(13.5)	8.3(18.9) 2.9(5.9)	--- ---	--- ---	101.4(149.5)	36.7(54.1)	8.4	5.9
410 SS	1.6 0.2	0.7 0.07	11.4 3.6	8.8 ---	10.5(53.5)	3.8(19.4)	15.8	11.8
304 SS	0.02 0.07	0.01 0.03	--- ---	--- ---	<0.1	---	0.7	0.2

Gasifier Slag Quench (BI-GAS)

Alloy/ Composition[c]	vapor phase: sat'd H_2O 470 °F, 750 psig, 1043(10,225) hr[d]				liquid phase: char, ash, H_2O 70 °F, 750 psig, 1043(10,224) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	20.1(62.1)	2.05(6.3)	---	---	79.7(120.8)	8.1(12.3)	---	---
304 SS	<1	<1	5.5	---	<1	<1	---	---
2 1/4Cr-1Mo Fe-2.25Cr-1Mo	22.7(79.8)	2.31(8.1)	---	---	56.2(71.3)	5.7(7.3)	---	---
316 SS	<1	<1	---	---				
405 SS Fe-13Cr	<1	<1	4.4	2.6	<1	<1	---	---
329 SS	<1	<1	---	---	<1	<1	---	---
26-1 Fe-26Cr-1Mo	<1	<1	---	---	<1	<1	0.8	0.4
Welded U-Bonds								
304 SS	No Stress Corrosion Cracks				No Stress Corrosion Cracks			
329 SS	No Stress Corrosion Cracks				No Stress Corrosion Cracks			
26-1	No Stress Corrosion Cracks				No Stress Corrosion Cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PIOT PLANTS[12] (continued)

	Gas Washer (BI-GAS) liquid phase: H_2O, CO_2, CO, H_2, N_2, CH_4, H_2S, ash and char entrained				Vent Gas Washer (BI-GAS), liquid phase: char, ash, condensate			
	450 °F, 720 psig, 1043(10,224) hr[d]				225 °F, $\sim$5 psig, 803(8016)hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	18.5(114.9)	1.9(11.7)	---	---	43.6(94.8)	4.4(9.5)	---	---
304 SS	<1	<1	---	---	<1	<1	---	---
316 SS	<1	<1	---	---				
405 SS	2.5	<1	---	---	<1	<1	9.2	4.4
Monel 400 64Ni-33Cu-2Fe	15.9(18.9)	1.6(1.9)	---	---				
Incoloy 825	<1	<1	---	---				
Welded U-Bends								
Carbon Steel					No Stress Corrosion Cracks			
304 SS	No Stress Corrosion Cracks							
316 SS	No Stress Corrosion Cracks				No Stress Corrosion Cracks			
405 SS	No Stress Corrosion Cracks				No Stress Corrosion Cracks			

	Recycle gas washer (BI-GAS), liquid phase: coal fines and water				Cyclone Overflow Tank (BI-GAS) liquid phase: coal fines and water			
	130 °F, 760 psig, 778(8016)hr[d]				65-75 °F, atm pressure, 778(8016)hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	25.9(205.8)	2.5(20.0)	---	---	54.0(181.3)	5.2(17.6)	---	---
304 SS	<1	<1	---	---	<1	---	2.2	1.0
316 SS	<1	<1	1.4	1.3	<1	---	---	---
Monel 400 64Ni-33Cu-2Fe	16.9(25.9)	1.6(2.5)	---	---	3.3	<1	---	---
2 1/4 Cr-1Mo	40.5(67.4)	3.9(6.5)	---	---				
20Cb-3 Fe-33Ni-19Cr	<1	<1	---	---	<1	---	---	---
Welded U-Bends								
304 SS	No Stress Corrosion Cracks				No Stress Corrosion Cracks			
316 SS	No Stress Corrosion Cracks				No Stress Corrosion Cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

	Scrubber surge tank (SYNTHANE), venturi side, vapor phase: reducing gas, H_2O, CO_2, CO, H_2, H_2S, ash and char, mist from condensate							
	385 °F, 600 psig, 592(2046) hr[d]				445 °F, 600 psi, 618(3687) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	58.2(124.3)	16.8(36.0)			56.7(143.1)	9.5(24.0)	---	---
	54.0(136.1)	15.6(39.4)			55.3	9.3	---	---
Carbon Steel (Al)[h]	5.6(69.5)	1.6(20.2)			11.8(18.4)	2.0(3.1)	---	---
	6.1	1.8			12.0	2.0	---	---
410 SS	4.1	1.2	3.2	1.5	8.5(35.4)	1.4(6.0)	2.8	2.1
	4.1	1.2	6.9	6.1	22.7	3.8	6.9	3.7
430 SS	1.5	0.4	3.8	1.4	3.4	0.6	4.4	2.4
	1.5	0.4	2.3	0.9	4.3	0.7	3.0	1.2
304 SS	0.07	0.02	---	---	0.4	0.1	5.3	1.9
	0.07	0.02	---	---	0.3	0.1	1.5	1.1
316 SS	0.06	0.02	0.6	---	0.6	0.1	0.6	0.4
	0.06	0.02	0.7	0.5	0.3	0.1	0.9	0.6
Incoloy 800 47Fe-31Ni-21Cr	0.07	0.02	1.2	0.4	0.3	0.1	0.5	0.3
	0.07	0.02	---	---	0.9	0.1	0.7	0.5
Inconel 600 7Fe-77Ni-16Cr	0.9	0.3	4.8	1.3	0.9	0.1	0.7	0.6
	0.7	0.2	5.2	1.6	1.0	0.2	0.8	0.5
Monel 400	189.1(310.7)	54.7(88.9)	---	---	66.6(90.7)	11.2(15.2)	---	---
	222.6(293.0)	64.4(84.8)	---	---	60.9	10.2	---	---
Titanium 50A	0.10	0.03	---	---	0.6	0.1	1.0	0.7
	0.30	0.09	---	---	0.3	0.1	0.8	0.5
Welded U-Bends								
304 SS	No visible cracks				No visible cracks			
Incoloy 800	No visible cracks				No visible cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

	Scrubber surge tank (SYNTHANE) liquid phase: H_2O, condensate, ash, char, tar (traces)			
	385 °F, 600 psig, 592(2046) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg
Carbon Steel	55.3(182.0)	16.0(52.7)		
	51.6(229.4)	14.9(66.4)		
Carbon Steel (Al)[h]	5.8(79.9)	1.7(23.1)		
	4.9	1.4		
410 SS	4.4	1.3	7.9	2.6
	5.5	1.6	4.7	2.1
430 SS	2.8	0.8	---	---
	2.8	0.8	---	---
304 SS	0.09	0.03	---	---
	0.09	0.03	1.5	---
316 SS	0.15	0.04	1.2	---
	0.30	0.09	0.9	---
Incoloy 800 47Fe-31Ni-21Cr	0.13	0.04	0.6	---
	0.06	0.02	0.2	---
Inconel 600 7Fe-77Ni-16Cr	1.5	0.4	---	---
	1.3	0.4	7.0	2.4
Monel 400	56.8(119.9)	16.4(34.7)	---	---
	51.1(131.7)	14.8(38.1)	---	---
Titanium 50A	0.30	0.09	---	---
	0.30	0.09	---	---
Welded U-Bends				
304 SS	No visible cracks			
Incoloy 800	No visible cracks			

	Decanter (SYNTHANE) splash zone, liquids: H_2O, condensates, ash, char, tar (traces)							
	220 °F, <5 psig, 592(2046) hr[d]				190 °F, 5 psi, 618(3687) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	40.0(112.5)	11.6(32.5)	---	---	29.8(62.4)	5.0(10.5)	---	---
	47.4(161.3)	13.7(46.7)	---	---	28.3	4.8	---	---
410 SS	2.5	0.7	12.1	5.4	1.4	0.3	3.0	1.7
	0.7	0.2	4.9	1.8	1.4	0.3	2.6	1.4
430 SS	0.14	0.04	---	---	0.9	0.1	8.1	3.1
	0.14	0.04	---	---	0.9	0.1	13.4	4.9
304 SS	---[f]	---[f]	---	---	0.3	0.1	1.9	1.2
	---[f]	---[f]	---	---	0.3	0.1	2.0	1.1
Welded U-Bends								
Carbon Steel	No visible stress corrosion cracks				No visible cracks			
304 SS	No visible stress corrosion cracks				No visible cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

Decanter (SYNTHANE) solid-liquid zone: H_2O, condensate, ash, char, tar, solids

	190 °F, 5 psi, 618(3687) hr[d]				220 °F, <5 psig, 592(2046) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	21.3(52.4)	3.6(8.8)	---	---	28.1(78.4)	8.1(31.3)		
	17.0	2.9	---	---	29.6(69.6)	8.6(20.1)		
410 SS	0.9	0.1	1.7	1.0	0.9	0.3	12.8	3.3
	0.7	0.1	2.6	1.5	0.9	0.3	9.2	2.3
430 SS	0.4	0.1	4.4	2.4	0.6	0.2	4.6	2.5
	0.6	0.1	3.0	1.2	0.4	0.1	4.2	2.9
304 SS	0.1	0.1	5.3	1.9	---[f]	---[f]	---	---
	0.1	0.1	1.5	1.1	---[f]	---[f]	---	---
Welded U-Bends								
Carbon Steel	No visible cracks				No visible stress corrosion cracks			
304 SS	No visible cracks				No visible stress corrosion cracks			

Gasifier char cooler (SYNTHANE), vapor phase: saturated H_2O, char

	800 °F, 600 psi, 417(3421) hr[d]				600-900 °F, 600 psig, 592(2046) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition[c]	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	(73.5)	(9.0)	---	---	(145.0)	(45.0)	---	---
					(113.9)	(33.0)		
410 SS	10.5(56.7)	1.3(6.9)	5.8	2.8	4.9	1.4	14.8	8.8
	10.5	1.3	3.2	2.1	2.1	0.6	12.0	6.4
304 SS	2.4	0.3	1.6	1.2	0.2	---	7.7	3.6
	2.3	0.4	2.4	1.5	0.3	0.1	6.6	3.5
Welded U-Bends								
Carbon Steel	No visible cracks				No visible stress corrosion cracks			
304 SS	No visible cracks				No visible stress corrosion cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

	Gasifier Quench Tower (CONOCO, CO_2 Acceptor)				Regenerator Quench Tower (CONOCO, CO_2 Acceptor)			
	120 °F, 145 psig, 1215(3959) hr[d]				135 °F, 135 psig, 2990(4101) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	51.8(101.7)	15.9(31.2)	---	---	26.6(40.7)	11.2(17.2)	---	---
	50.7(101.7)	15.6(31.2)	---	---	26.7	11.2	---	---
410 SS	8.4(54.8)	2.6(16.8)	---	---				
	8.6(59.1)	2.6(18.1)	---	---				
304 SS	0.07	0.02	---	---	0.03	0.01	---	0.2
	0.07	0.02	---	---	0.08	0.03	---	---
316 SS	0.03	0.009	---	---	0.03	0.01	---	---
	0.03	0.009	---	---	0.06	0.02	---	---
Incoloy 825	0.01	0.004	---	---	0.01	---	0.68	0.42
	0.04	0.01	---	---	0.04	0.02	0.76	0.44
20Cb-3	0.04	0.01	---	---	0.07	0.03	---	---
	0.07	0.02	1.1	---	0.11	0.05	---	---
22-13-5 Fe-14Ni-21Cr	0.07	0.02	1.0	---	0.05	0.02	---	---
	0.4	0.1	5.9	3.9	0.04	0.02	---	---
Titanium 50A	0.14	0.04	---	---	0.04	0.02	---	---
	0.07	0.02	1.6	0.9	0.05	0.02	---	---
Cast Iron					14.6(27.2)	6.2(11.5)	---	---
					14.0	5.9	---	---
Ni-Resist (Cu)					14.1(12.3)	5.9(5.2)	---	---
					10.6	4.5	---	---
Ni-Resist					13.8(26.7)	5.8(11.2)	---	---
					13.1	5.5	---	---
18-18-2					0.1	0.4	---	---
					0.1	0.1	---	---
Al Bronze					7.3(12.6)	3.1(5.3)	---	---
					7.1	3.0	---	---
Welded U-Bends								
304 SS					No visible stress corrosion cracks			
Carbon Steel					No visible stress corrosion cracks			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12] (continued)

	Regenerator Quench Tower (CONOCO, CO_2 Acceptor)							
	130 °F, 130 psig, 1710(6479) hr[d]				130 °F, 135 psig, 2161(3911) hr[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy/ Composition	Operational	Total	Max	Avg	Operational	Total	Max	Avg
Carbon Steel	46.1(80.4)	12.2(21.2)	---	---	50.4(55.1)	27.9(30.5)	6.5	1.8
	42.2(62.5)	11.2(16.5)	---	---	48.4(65.7)	26.7(36.3)	2.2	1.5
304 SS	0.10	0.03	---	---	0.0	0.0	---	---
	0.10	0.03	---	---	0.0	0.0	---	---
316 SS	0.15	0.04	---	---	0.0	0.0	---	---
	0.15	0.04	---	---	0.0	0.0	---	---
Incoloy 825	0.10	0.03	---	---	0.0	0.0	---	---
	0.10	0.03	---	---	0.0	0.0	---	---
20Cb-3	0.10	0.03	1.8	1.2	0.0	0.0	---	---
	0.10	0.03	---	---	0.0	0.0	---	---
22-13-5 Fe-14Ni-21Cr	0.05	0.01	---	---	0.0	0.0	---	---
	0.05	0.01	0.7	---	0.0	0.0	---	---
Titanium 50A	0.26	0.07	---	---	0.1	0.0	---	---
	0.15	0.04	---	---	0.1	0.0	---	---
Cast Iron	48.8(107.6)	12.9(28.4)	---	---	53.3(69.3)	29.4(38.3)	---	---
	48.1(117.8)	12.7(31.1)	---	---	53.2	29.4	---	---
Ni-Resist (Cu)	59.8(86.1)	15.8(22.7)	---	---	32.1(60.0)	17.8(33.1)	2.4	1.7
	59.2(68.7)	15.6(18.1)	---	---	30.9	17.1	2.7	1.4
Ni-Resist	40.2(41.5)	10.6(11.0)	---	---	31.3(39.3)	17.3(21.7)	---	---
	44.2(56.9)	11.7(15.0)	---	---	31.0	17.1	---	---
18-18-2	0.15	0.04	---	---	0.1	0.0	---	---
	0.20	0.05	---	---	0.1	0.0	---	---
Al Bronze	16.9(60.5)	4.5(16.0)	---	---	17.3(23.2)	9.6(12.8)	---	---
	16.9(47.1)	4.5(12.4)	---	---	19.2	10.6	---	---
Welded U-Bends								
304 SS	No visible cracks				No stress corrosion cracking			
Carbon Steel	No visible cracks				No stress corrosion cracking (for plain unwelded coupon)			

---

[a] Both gravimetric and metallographic analyses were used to determine the extent of corrosion. In some cases both gravimetrically determined values for each of the duplicate specimens are given, in other cases an average appears. For specimens with larger corrosion rates the metallographically determined values are also given in parentheses. Rates are based on a total of scaling loss and penetration and are extrapolated linearly to obtain an annual rate based on both operational exposure time and time of full exposure which includes standby time.

[b] Data for a total of 17 locations for four pilot plants are included. Conditions are such that an aqueous or other liquid phase exists. Average temperatures, pressures, and the type of environment are given with exposure times for full operation as well as total exposure time which is the sum of operation plus standby time.

[c] Approximate values only for major constituents; compositions are not given every time an alloy appears in the table. Specimens were flat coupons for BI-GAS, 1/4 x 1 1/8 in square; for HYGAS and SYNTHANE 1/4 x 1 1/8 x 2 1/8 in. Some welded U-specimens were included and are so designated.

[d] First time given is the time of full operational conditions, the second time in parentheses is the total time the specimens were exposed in the system and includes the standby times.

[e] Values in parentheses are metallographically determined, the rest of the values are gravimetrically determined.

[f] Metal loss was negligible.

[g] Some pitting along one edge.

[h] Aluminized carbon steel.

CORROSION OF UNWELDED AND WELDED SPECIMENS[a] OF SELECTED ALLOYS IN A SIMULATED CORROSIVE GAS ENVIRONMENT[b] [31]

Alloy[a]	Scale	Internal Oxidation	Total Affected Depth[c]	Comments
	(μm)	(μm)	(μm)	
310HP[d] + 2Ti	12	26	38	Adherent oxide
310HP + 2Ti; welded	16	36	52	Adherent oxide
310HP + 3Ti	12	22	34	Adherent oxide
310HP + 3Ti; welded	14	22	36	Adherent oxide
Ni-30Cr[e] + 3Al	3	-	3	Spall-prone oxide
Ni-30Cr + 3Al; welded[f]	6	-	6	Spall-prone oxide
Ni-30Cr + 4Al; welded	4	-	4	Spall-prone oxide
Ni-30Cr + 4Ti	18	48	66	Adherent oxide
Ni-30Cr + 4Ti; welded	20	52	72	Adherent oxide

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[a] Unwelded specimens, wrought stock. Experimental alloys prepared by additions to the indicated base alloy. Welded specimens, wrought stock. Specimens produced by gas tungsten arc welding a bead along a plate of the stock. Specimens machined from the plate included fusion zone, heat affected zone and parent metal; 1/8 in thick specimens. Full and half full thickness penetration welds.

[b] Exposure: 1000 °C and 1 atm in gas composition 30 (vol %) H_2O, $1H_2S$, $30H_2$, Bal Ar for 100 hr.

[c] Total affected depth of attack equals sum of depths of scale layers, internal oxidation (or sulfidation) and intergranular corrosion.

[d] 310HP composition: 25.3 Cr, 19.9 Ni, 0.23 Ti, Bal Fe (HP signifies special high purity alloy).

[e] Ni-30Cr binary composition: 29.8 Cr, 0.16 Ti, Bal Ni.

[f] Some weld surface cracking observed.

SHORT-TERM CORROSION TESTS[a] OF ALLOYS[b] IN LOW BTU GAS ENVIRONMENTS[c][31]

Alloy[b]	Time[a]	Scaling[d]		Sub-scale Corrosion[d]	
	hr	Thickness (µm)	Type[e]	Depth (µm)	Type[e]
H_2O = 15 vol %[c]					
310 SS (Fe-18Ni-25Cr-Mn-Si)	48	6	spO,nS	25	iS,gbS
	48	(2 samples, both destroyed)			
233MS[f] (Fe-24Ni-22Cr-3Ti-Mn-Si)	48	8	adO	25	gbO
				+5	iS
	124	18	adO	40	gbO
				+20	iS
Fe-25Cr-20Ni-2Ti	48	8	adO	15	gbO
	124	14	adO	20	gbO
Fe-25Cr-20Ni-3Ti	76	14	adO	30	gbO,iS
Ni-30Cr-4Ti	76	20	adO	40	gbO
Ni-30Cr-4Ti/HP[g]	124	28	adO	50	gbO
Inconel 671 (51Ni-48Cr)	76	14	spO,nS	40	iS
H_2O = 10 vol %[c]					
310 SS (Fe-18Ni-25Cr-Mn-Si)	48	(2 samples, both destroyed)			
233MS[f] (Fe-24Ni-22Cr-3Ti-Mn-Si)	48	10	adO	10	gbO
				+20	iS
	48	8	adO	15	gbO
				+15	iS
Ni-30Cr	48	sample destroyed			
Ni-30Cr-4Ti/HP[g]	48	14	adO	25	gbO
Nimonic 81 (M313) (64Ni-30Cr-2Ti-Al)	48	8	adO	25	gbO
				+15	iS
Inconel 671 (51Ni-48Cr)	48	12-24	adO,nS	30	iS
	48	sample destroyed			
Inconel 690 (60Ni-30Cr-10Fe)	48	sample destroyed			

(table continued)

SHORT-TERM CORROSION TESTS[a] OF ALLOYS[b] IN LOW BTU GAS ENVIRONMENTS[c][31]

(continued)

Alloy[b]	Time[a] hr	Scaling[d] Thickness (μm)	Scaling[d] Type[e]	Sub-scale Corrosion[d] Depth (μm)	Sub-scale Corrosion[d] Type[e]
- - - H_2O = 6 vol %[c] - - -					
446SS (Fe-24Cr-Mn-Si)	48	sample destroyed			
310 SS (Fe-18Ni-25Cr-Mn-Si)	48	sample destroyed			
310 SS + 3Ti	48	12	adO	10 +20	gbO iS
Fe-25Cr-20Ni-3Ti	48	10	adO	20 +10	gbO iS
	48	sample destroyed			
Ni-30Cr[h]	48	sample destroyed			
Ni-30Cr-4Ti/HP[g]	48	12	adO	25	gbO
Pyromet 31 (55Ni-23Cr-14Fe-3Ti-2Al)	48	8	adO	50	iS,gbS, gbO
Inconel 671 (51Ni-48Cr)	48	8-20	adO,nS	50	iS
Incoloy 800 (32Ni-21Cr-46Fe-Mn)	48	sample destroyed			
Incoloy 801 (32Ni-21Cr-45Fe-Ti)	48	sample destroyed			

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[a] Initial exposure for 48 hr; some specimens put through a second cycle for 72 hr. Data for single specimens except where noted otherwise. Test temperature 1800 °F, pressure 1 atm.

[b] Sample of as-received wrought alloys. Test coupons machined to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) then ground to uniform finish with 120 grit SiC paper. Varieties of commercial alloys prepared by additions to the base alloy.

[c] Feed gas composition (vol %): 25 CO, 6 CH_4, 4 H_2, 15 H_2O, 1 H_2S, balance N_2. Large chemical shifts occurred. Water volume fractions varied.

[d] Extent, morphology, and qualitative chemical analysis of corrosion products determined by optical microscopy and dispersive x-ray analysis. Oxide products inferred by absence of sulfur.

[e] Corrosion indicators: S = sulfide, O = oxide, i = internal, gb = grain boundary, ad = adherent layer, sp = spalling layer, n = nodular.

[f] Variation of 310 SS.

[g] A high purity version with no Fe, Co, Mn, or Mo.

[h] Composition: 29.8 (wt %) Cr, 0.16 Ti, balance Ni, C <0.001.

SHORT TERM HIGH-PRESSURE CORROSION TESTS OF ALLOYS[a] EXPOSED TO SIMULATED COAL GASIFICATION ATMOSPHERE[b][31]

	Test 1: 1710 °F, 540 psi, 84 hr[b]		Test 2: 1780 °F, 490 psi, 96 hr[b]	
Alloy/Composition[a]	Weight Change mg/cm^2	Observed Corrosion	Weight Change mg/cm^2	Observed Corrosion
304 SS	-96.0	Slagging	-141.0	Severe slagging
Fe-9.6Ni-18.4Cr-1.3Mn-0.4Si	-24.8	Slagging		
316 SS	- 4.6	Sulfidation		
Fe-12.6Ni-17.5Cr-2.1Mo-1.6Mn-0.4Si-0.3Co				
309 SS	-12.3	Sulfidation	1.3	Spalling scale
Fe-1.35Ni-21.8Cr-1.9Mn-0.7Si				
446 SS	2.1	Spalling oxide	1.1	Spalling scale
Fe-24.1Cr-0.5Mn-0.5Si				
310 SS	1.4	Adherent oxide	0.8	Spalling scale
Fe-18.3Ni-24.6Cr-1.0Mn-0.9Si	1.0	Spalling scale	1.0	Spalling scale
310 HP[c]			0.9	Adherent scale
			0.9	Adherent scale
310 SS + 3Ti	2.1	Adherent scale	1.7	Local spalling
Fe-19.8Ni-24.2Cr-3.1Ti-1.5Mn-0.55Si-0.08C				
310 HP + 2Ti[c]	1.2	Adherent scale		
310 HP + 3Ti[c]	1.4	Adherent scale	1.0	Adherent scale
233 MS[d]	16.7	Slag from adjacent 304 SS collected here	1.8	Adherent scale
Fe-23.6Ni-22.0Cr-3.3Ti-1.52Mn-0.52Si-0.072C				
243 MS[d]			1.1	Adherent scale
Fe-22.8Ni-21.9Cr-3.5Ti-1.62Mn-0.55Si-0.080C				
Avesta 253 MA	1.3	Spalling	1.0	Sulfidation; mossy growth
66.2Fe-11.Ni-21.Cr-<.3Mn-1.7Si				
Fe-18Cr-5Al-1Mo-Hf	1.1	Adherent scale		
	0.6	Adherent scale		
Fe-18Cr-3Si-1Mo[e]	2.7	Spalling; nodule formation		
Incoloy 800	2.5	Slag at one edge	1.4	Nodule at hole
46Fe-32.5Ni-21.Cr-0.4Ti-0.4Al-0.8Mn-0.5Si			1.4	Adherent scale
Inconel 601	1.2	Sulfidation at hole only	2.8	Nodulation along edge
14.1Fe-60.5Ni-23.Cr-1.4Al-0.5Mn-0.2Si	-6.3	Sulfidation	2.8	Nodulation at edge
Ni-30Cr			5.5	Spalling scale; nodule at hole
			n.a.	Slagging
Ni-30Cr-4Ti	4.0	Adherent scale	2.9	Adherent scale
Ni-2.0Fe-28.4Cr-4.0Ti-0.43Mn-1.41Co-0.3Mo				
Ni-30Cr-4Ti/HP[f]	3.7	Adherent scale	3.8	Adherent scale; nodule at crevice
Ni-30Cr-4 Al	2.6	Adherent scale; nodules at one edge	1.6	Adherent scale
Ni-0.86Fe-30.1Cr-3.9Al-0.55Mn-2.05Co-0.46Mo				
Ni-30Cr-4Al/HP[f]	3.1	Some slag collection from adjacent IN 601	1.4	Adherent scale
Ni-30Cr-6Mo			n.a.	Sulfidation
Ni-30Cr-2Mn			n.a.	Sulfidation
Inconel 671	1.9	Sulfidation at corner	1.2	Adherent scale
51.4Ni-0.3Fe-48Cr-0.3Ti				
Inconel 690	1.5	Slag pick-up from adjacent 316 SS	1.2	Adherent scale
60Ni-9.5Fe-30Cr				
Incoloy 825	5.8	Slag pick-up from adjacent 316 SS		
42.Ni-30.Fe-21.5Cr-0.9Ti-3.0Mo-2.2Co				
Pyromet 31	3.5	Slag pick-up from adjacent 304 SS	0.9	Adherent scale
55.1Ni-14.5Fe-23.Cr-2.6Ti-1.7Al-2.Mo-1.1Nb				
M313	12.8	Slag pick-up from adjacent 304 SS		
63.8Ni-<1.Fe-30.Cr-1.8Ti-0.9Al				
IN X-750			2.3	Nodulation
73.Ni-7.0Fe-15.5Cr-2.5Ti-0.7Al				

(Table Continued)

SHORT TERM HIGH-PRESSURE CORROSION TESTS OF ALLOYS[a] EXPOSED TO SIMULATED COAL GASIFICATION ATMOSPHERE[b][31]
(continued)

	Test 3: 1770 °F, 500 psi, 96 hr				
	Weight Change	Scaling[g]		Sub-scale Corrosion[g]	
Alloy/Composition[a]	mg/cm^2	Thickness (μm)	Type[h]	Depth (μm)	Type[h]
304 SS Fe-9.6Ni-18.4Cr-1.3Mn-0.4Si	-141.0	n.a.	SLq	>100	gbS
309 SS Fe-1.35Ni-21.8Cr-1.9Mn-0.7Si	1.3	4	spO	22	iS
446 SS Fe-24.1Cr-0.5Mn-0.5Si	1.1	6	spO	--	--
310 SS[i] Fe-18.3Ni-24.6Cr-1.0Mn-0.9Si	0.9	4	spO	10	gbS
310 SS + 3Ti Fe-19.8Ni-24.2Cr-3.1Ti-1.5Mn-0.55Si-0.08C	1.7	7	adO	10	gbO
233 MS[d,i] Fe-23.6Ni-22.0Cr-3.3Ti-1.52Mn-0.52Si-0.072C	1.5	6	adO	6	gbO
Avesta 253 MA 66.2Fe-11.Ni-21.Cr-<.3Mn-1.7Si	1.0	20	nS/adO	50	iS
Fe-25Cr-20Ni[i]	0.9	4	adO	--	--
Fe-25Cr-20Ni-3Ti	1.0	4	adO	6	gbO
Incoloy 800[i] 46Fe-32.5Ni-21.Cr-0.4Ti-0.4Al-0.8Mn-0.5Si	1.4	5	adO	10	gbS
Inconel 601[i] 14.1Fe-60.5Ni-23.Cr-1.4Al-0.5Mn-0.2Si	2.8	4	nS/gbO	20	gbO
Ni-30Cr[i,j]	5.5	2	spO	--	--
Ni-30Cr-4Ti Ni-2.0Fe-28.4Cr-4.0Ti-0.43Mn-1.41Co-0.3Mo	2.9	12	adO	16	gbO
Ni-30Cr-4Ti/HP[f]	3.8	7	adO	10	gbO
Ni-30Cr-4Al Ni-0.86Fe-30.1Cr-3.9Al-0.55Mn-2.05Co-0.46Mo	1.6	3	adO	22	gbO
Ni-30Cr-4Al/HP[f]	1.4	3	spO	20	gbO
Inconel 671 51.4Ni-0.3Fe-48Cr-0.3Ti	1.2	6	adO	10	iO
Inconel 690 60Ni-9.5Fe-30Cr	1.2	4	adO	12	gbO
Pyromet 31 55.1Ni-14.5Fe-23.Cr-2.6Ti-1.7Al-2.Mo-1.1Nb	0.9	5	adO	32	gbO

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[a] Coupons machined to 1/2 in. x 3/4 in. x 1/8 in. (12.7 mm x 19.1 mm x 3.2 mm) from stock prepared by vacuum melting and rolling to 1/8 in. plate. Experimental 310 SS alloys prepared by melting commercial stock and Ti with enough Cr to maintain original Cr content. Ni-30 Cr alloys prepared from Nickel 200, Cr, and the modifying elements. Data for single coupons except where indicated otherwise.

[b] Gas analyses (vol %): Test 1, 19.1 CO, 11.4 CO_2, 10.2 CH_4, 18.6 H_2, 40.2 H_2O, 0.6 H_2S, P_{O_2} 1.1 x 10^{-15} atm, P_{S_2} 0.95 x 10^{-6} atm; test 2, 19.7 CO, 10.3 CO_2, 10.4 CH_4, 18.9 H_2, 40.0 H_2O, 0.7 H_2S, P_{O_2} 7.4 x 10^{-16} atm, P_{S_2} 1.0 x 10^{-6} atm; test 3, 20 CO, 10 CO_2, 10 CH_4, 19 H_2, 40 H_2O, 1 H_2S.

[c] 310 HP is a special high purity version of 310 SS containing no Mn or Si.

[d] Modified versions of 310 SS.

[e] Lockheed Palo Alto Research Laboratory alloy.

[f] HP signifies a high purity version containing no Mn, Fe, Co, or Mo.

[g] Extent, morphology, and qualitative chemical analysis of corrosion products determined by optical microscopy and dispersive x-ray analysis. Oxide products inferred by absence of sulfur.

[h] Corrosion indicators: S = sulfide, O = oxide, i = internal, gb = grain boundary, ad = adherent layer, sp = spalling layer, n = nodular, Lq = liquid.

[i] Results are average of data for two coupons.

[j] One coupon completely sulfidized.

CORROSION OF ALLOYS IN A SIMULATED HIGH-BTU ENVIRONMENT[a][31]

Alloy[b]	Scaling[c]		Sub-scale Corrosion[c]	
	Thickness (μm)	Type[d]	Depth (μm)	Type[d]
310 SS	3	nS/spO	30	gbS,iS
Fe-25Cr-20Ni	6	adO	15	iS
310SS+3Ti	12	adO	20	gbO
Fe-25Cr-20Ni-3Ti	10	adO	20	gbO
Fe-25Cr-20Ni-2Ti	10	adO	20	gbO
233[e] (Fe-22Cr-23Ni-3Ti)	10	adO	20	gbO
233MS[e] (Fe-22Cr-23Ni-3Ti and Mn, Si)	8	adO	10	gbO
233M[e] (Fe-22Cr-23Ni-3Ti and Mn)	8	adO	25	gbO
233S[e] (Fe-22Cr-23Ni-3Ti and Si)	8	adO	20	gbO
309SS	5	adO	35	iS,gbS
253MA		nS[f]		
Incoloy 800	8	nS/adO	60	iS,gbS
Incoloy 801[g]	10	adO	40	gbO
Incoloy 825	8	adO	10	iO
Incoloy 814E	4	spO	--	--
Ni-30Cr[h]	6 15	spO O,S	15 50	iS iS
Ni-30Cr-4Ti	14	adO	25	gbO
Ni-30Cr-4Ti/HP[i]	16	adO	30	gbO
Ni-30Cr-4Al	4	spO	--	--
Inconel 690	>1000	S		
Inconel 671	10	adO	10	iO
Inconel 601	7	adO	35	gbS
Inconel 617	5 7	adO adO	12 20	iS iS
Nimonic 81 (M313)	8	adO	30	gbO
Pyromet 31	8	adO	30	gbO

---

[a] Gas composition (vol %): 18 CO, 12 CO_2, 24 H_2, 5.0 CH_4, 40 H_2O, 1.0 H_2S, P_{O_2} 1.9 x 10^{-15} atm, P_{S_2} 3.7 x 10^{-6} atm. Temperature 1255K (1800 °F), pressure 1 atm, test duration 100h.

[b] Single samples of as-received wrought alloys. Test coupons machined to 1/2 in. x 3/4 in. x 1/8 in. (12.7 mm x 19.1 mm x 3.2 mm) then ground to uniform finish with 120 grit SiC paper. Varieties of commercial alloys prepared from stock by melting with indicated elements.

[c] Extent, morphology, and qualitative chemical analysis of corrosion products determined by optical microscopy and dispersive x-ray analysis. Oxide products inferred by absence of sulfur.

[d] Corrosion indications: S = sulfide, O = oxide, i = internal, gb = grain boundary, ad = adherent layer, sp = spalling layer, n = nodular.

[e] Variations of 310SS.

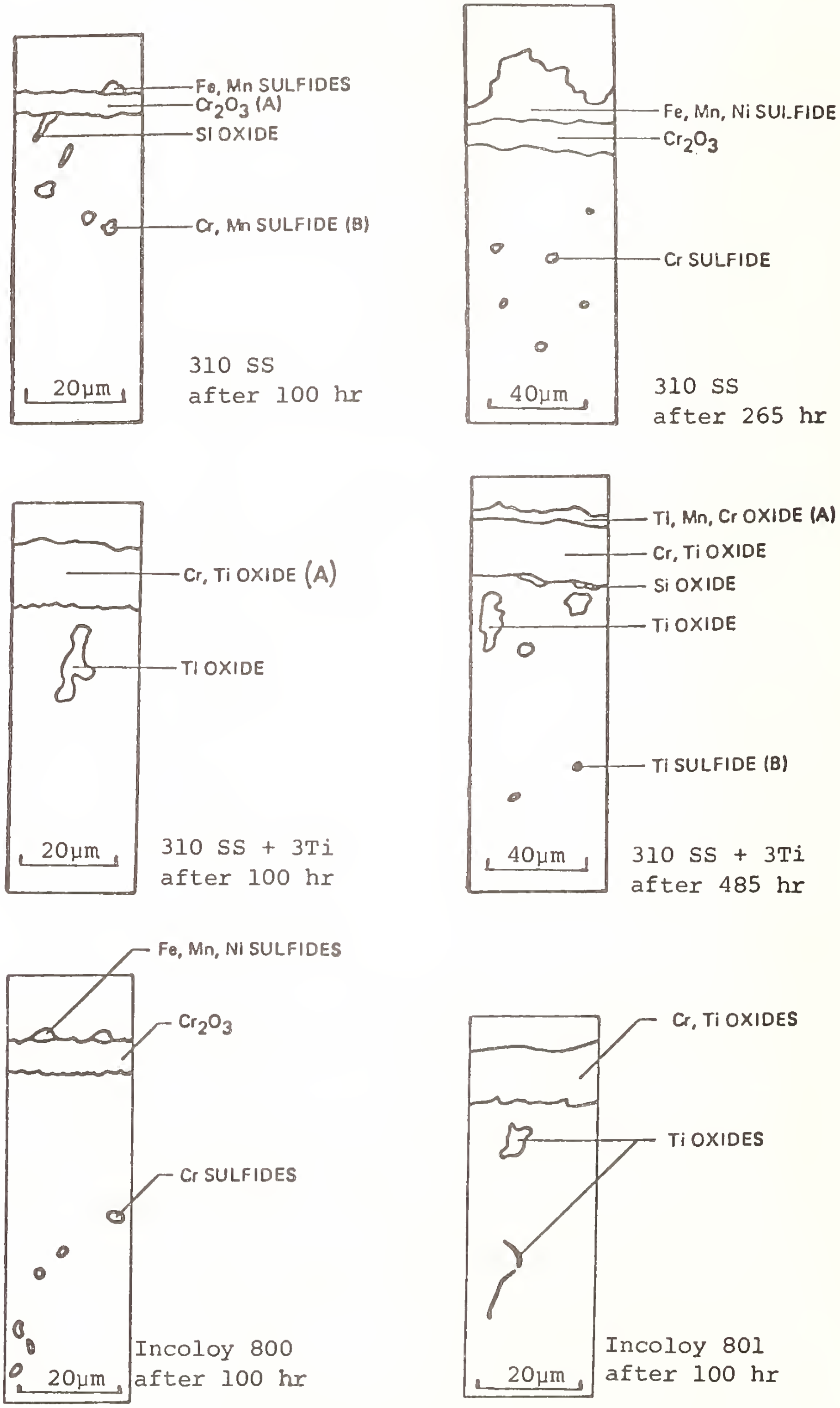
[f] Severe nodular sulfidation occurred.

[g] Results given are for a 124h test.

[h] Frequent sulfidation also observed; nonuniform corrosion.

[i] High purity version with no Fe, Co, Mn, or Mo.

CORROSION PRODUCTS[a] FORMED IN ALLOYS[b] EXPOSED TO A HIGH-BTU COAL GASIFICATION ATMOSPHERE[c][31]



310 SS after 100 hr

310 SS after 265 hr

310 SS + 3Ti after 100 hr

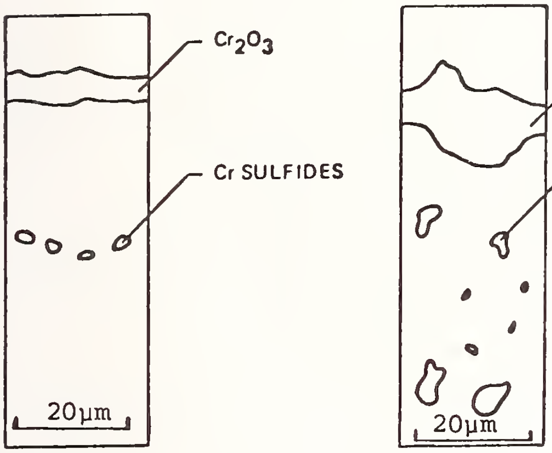
310 SS + 3Ti after 485 hr

Incoloy 800 after 100 hr

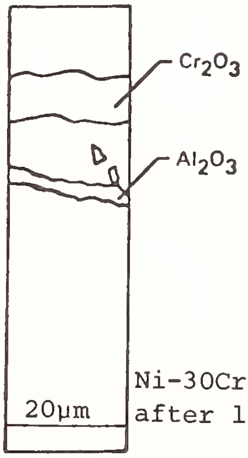
Incoloy 801 after 100 hr

(Data Continued)

CORROSION PRODUCTS[a] FORMED IN ALLOYS[b] EXPOSED TO A HIGH-BTU COAL GASIFICATION ATMOSPHERE[c][31], Continued



Ni-30Cr[d] after 100 hr



Ni-30Cr-4Al after 100 hr

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[a] After exposure specimens were prepared by common metallographic techniques. Extent, morphology, and qualitative chemical analysis of corrosion products were determined by optical microscopy and dispersive x-ray analysis.

[b] 310 SS (Fe-24.6Cr-18.3Ni-1.8Mn-0.9Si), 310 SS + 3Ti (Fe-24.2Cr-19.8Ni-3.1Ti-1.5Mn-0.6Si), Incoloy 800 (32.5Ni-46Fe-21Cr-0.4Ti-0.4Al-0.8Mn-0.5Si), Incoloy 801 (32Ni-44.5Fe-20.5Cr-1.1Ti-0.8Mn-0.5Si), Ni-30Cr (70Ni-29.8Cr-0.16Ti), Ni-30Cr-4Al (64Ni-2.0Fe-28.4Cr-4.0Ti-0.4Mn). Modified 310 alloy prepared by vacuum melting and casting. The 7.5cm billet was hot rolled at 1423 K to 3 mm plate and solution annealed at 1366 K for 2 hr. Approximately 5-10% ferrite present. Other alloys as received wrought material. Coupons machined to size, ground to uniform finish with 120 grit SiC paper, and cleaned ultrasonically with trichlorethylene followed by acetone.

[c] Feed gas composition (vol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1.0 H_2S, 40 H_2O. Test conditions: 1255 K (1800 °F), 1 atm; 100 hr excepted where noted. Tests for more than 100 hr involved thermal cycling. Calculated equilibrium partial pressures: O_2 1.9×10^{-15} atm, S_2 3.7×10^{-6} atm.

[d] Corrosion of this alloy was non-uniform, having regions of coherent oxide layers above internal Cr-sulfides (upper figure) and regions of disrupted oxide growth and somewhat more internal sulfidation (lower figure).

RESULTS OF CYCLIC EXPOSURE[a] ON THE CORROSION OF SELECTED ALLOYS IN A CORROSIVE GAS ATMOSPHERE[b][31]

	Weight Gain, mg/cm^2			
Alloy[c]	Cycle 1[a] 98 hr 98 hr total	Cycle 2[a] 98 hr 196 hr total	Cycle 3[a] 70 hr 266 hr total	Comments
310 SS[d]	Liquid NiS	Liquid NiS	Liquid NiS	
310 + 2Ti	1.25 1.18	1.52 0.16	1.21 Liquid NiS	Scale spalled. Protective oxide oxide layer failed.
310 HP + 3Ti[e]	2.04 2.32	2.43 --	3.20 --	Minor spallation.
Ni-30Cr-4Ti	2.48	3.21	3.52	Very adherent scale.
Ni-30Cr-3Al	0.05	2.30	3.46	Initial corrosion small in Al-containing Ni-30Cr alloys. Extended exposure results in formation of a mixed Al_2O_3-Cr_2O_3 surface layer. Local spalling of this layer occurred after extended exposure.
Ni-30Cr-4Al	0.18 0.18	2.23 2.27	0.95 0.50	
Ni-30Cr-9Mo	1.00	-0.54	-3.95	Weight loss occurred on extended exposure.
Inconel 671 (50Ni-50Cr)	1.96	2.45	2.88	Weight gain not attenuated with time of exposure.
INCO 814E (Ni-30Cr-0.5Ti-(3.4)Al-17Fe)	0.23	0.55	Liquid NiS	Little corrosion until after 196 hours. Liquid NiS sulfidation resulted from extended exposure.
M313 (Nimonic 81) (Ni-30Cr-2Ti-1Al)	2.11	2.55	2.70	Very adherent scale.
Pyromet 31 (Ni-23Cr-2.6Ti-1.7Al-14.5Fe-2Mo-1.1Nb)	3.13	3.80	3.89	Adherent scale.

---

[a] Testing consisted of subjecting samples to ∿100 hr cycles at temperature (1800 °F) in the corrosive gas and about 2-3 hrs for cool down to ambient temperature. Specimens weighed and examined after each cycle.

[b] Gas Composition (vol %): 35.0 H_2O, 0.9 H_2S, 1.59 H_2, 48.2 Ar; temperature 1800 °F (1255 °K).

[c] Coupons machined from wrought stock (hot rolled to 1/8 in thick) to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm). Experimental alloys prepared by additions to the indicated base alloy.

[d] Specimen replaced at the end of each interval.

[e] Second specimen inserted after 196 hours; exposed 70 hours. (HP signifies special high purity alloy, no Mn or Si).

EFFECT OF CUMULATIVE EXPOSURE TIME[a] ON THE CORROSION OF ALLOYS[b] IN A HIGH BTU COAL GASIFICATION ENVIRONMENT[c][31]

Alloy[b] (Composition)	Time[a] (hr)	Scaling[d]		Sub-scale Corrosion[d]	
		Thickness (μm)	Type[e]	Depth (μm)	Type[e]
310 Series					
310 SS (Fe-18Ni-25Cr-Mn-Si)	48	3	-	5	n.a.[g]
	100	5	spO	20	iS,gbS
	265	10-25	nS/spO	50	iS,gbS
310 SS + 3Ti	48	6	adO	10	gbO
	100	12	adO	15	gbO
	200	14	adO	20-30	gbO
	240	16	adO	20-30	gbO,iS
	300	16	adO	30-40	gbO,iS
Fe-25Cr-20Ni-3Ti	48	8	adO	15	gbO
	100	10	adO	15	gbO
	358	18	adO	50-60	gbO
Fe-25Cr-20Ni-2Ti	100	8	adO	20	gbO
	240	16	adO	30-40	gbO
233MS[f] (Fe-24Ni-22Cr-3Ti-Mn-Si)	100	10	adO	16	gbO
	200	14	adO	25	gbO
233[f] (Fe-22Cr-23Ni-3Ti)	100	10	adO	20	gbO
	240	18	adO	40	gbO
Ni-Base Alloys					
Inconel 671 (51Ni-48Cr)	100	10	adO	10	iO
	358	22	adO	25	iO
Inconel 601 (60Ni-23Cr-14Fe-Al)	48	4	adO	25	n.a.[g]
	100	7	adO	30-40	igS
	200	10	adO	50-70	igS
Pyromet 31 (55Ni-23Cr-14Fe-3Ti-2Al)	100	8	adO	30	gbO
	358	22	adO	80-100	gbO
Incoloy 800 (32Ni-21Cr-46Fe-Mn)	48	4	adO	20	n.a.[g]
	100	6	adO	60	iS
Incoloy 801 (32Ni-21Cr-45Fe-Ti)	124	10	adO	30-40	gbO
	300	16	adO	50-60	gbO,iS
	684[h]	24	adO	60-80	gbO

(Table Continued)

EFFECT OF CUMULATIVE EXPOSURE TIME[a] ON THE CORROSION OF ALLOYS[b] IN A HIGH BTU COAL GASIFICATION ENVIRONMENT[c][31]

(continued)

Ni-30Cr-4Ti	100	12	adO	25	gbO
	240	15	adO	45	gbO
	358	24	adO	60-70	gbO
	684[h]	36	adO	70-80	gbO
Nimonic 81 (M313) (64Ni-30Cr-2Ti-Al)	100	8	adO	30	gbO
	358	18	adO	70-80	gbO
	684[h]	24	adO	50-70	gbO

---

[a] Alloys exposed at 1800 °F (982 °C) and 1 atm using thermal cycling conditions. Cycles ordinarily lasted about 100 hr before cooling to ambient temperature in the furnace under argon. Cumulative times which are not multiples of 100 hr are due to premature termination of runs caused by equipment malfunction.

[b] Samples of as-received wrought alloys. Test coupons machined to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) then ground to uniform finish with 120 grit SiC paper. Varieties of commercial alloys prepared by additions to the indicated base alloy.

[c] Gas composition (vol %): 18 CO, 12 CO_2, 5 CH_4, 24 H_2, 1 H_2S, 40 H_2O; P_{O_2} 1.9×10^{-15} atm, P_{S_2} 3.7×10^{-6} atm.

[d] Extent, morphology, and qualitative chemical analysis of corrosion products determined by optical microscopy and dispersive x-ray analysis. Oxide products inferred by absence of sulfur.

[e] Corrosion indicators: S = sulfide, O = oxide, i = internal, gb = grain boundary, ad = adherent layer, sp = spalling layer, n = nodular.

[f] Variations of 310 SS.

[g] Not available.

[h] Results from tests at 300 psi.

CORROSION OF SELECTED ALLOYS[a] EXPOSED TO A CORROSIVE GAS ATMOSPHERE[b] [31]

Alloy[a]	Scale (μm)	Internal Oxidation (μm)	Intergranular Corrosion (μm)	Total Affected Depth[c] (μm)	Comments
310SS[d]	28	64	--	92	Internal sulfidation
	280	--	530	810	Sulfide liquation
	--	--	605	605	Sulfide liquation
310HP[d]	--	--	>1500	>1500	Sulfide liquation
	240	--	410	650	Sulfide penetration
310HP + 2 Ti[e]	50	--	280	330	Sulfide penetration
	24	38	--	62	Adherent oxide
	12	26	--	38	Adherent oxide
310HP + 3 Ti	16	22	--	38	Adherent oxide
	12	22	--	34	Adherent oxide
310HP + 3 Al	5	--	--	5	Spalling oxide
	5	--	--	5	Spalling oxide
310HP + 6 Mo	12	--	--	12	Spalling oxide beneath sulfide layer
Ni-30Cr[f]	6	30	--	36	Spalling oxide
	20	66	--	86	Spalling oxide
Ni-30Cr + 3 Al	5	--	--	5	Spall-prone oxide
	4	--	--	4	Spall-prone oxide
Ni-30Cr + 4 Al	5	--	--[g]	5	Spall-prone oxide
	6	--	--	6	Spall-prone oxide
Ni-30Cr + 4 Ti	24	54	--	78	Adherent oxide
	24	42	--	66	Adherent oxide
	18	48	--	66	Adherent oxide
Ni-30Cr + 6 Ti	24	38	--	62	Adherent oxide
Ni-30Cr + 9 Mo	12	54	--	66	Spalling oxide and internal sulfidation

---

[a] Wrought stock, hot rolled to 1/8 in sheet. Experimental alloys prepared by additions to the indicated base alloy. Coupons machined to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm).

[b] Gas composition: 30(vol %) H_2O, 1 H_2S, 30 H_2, Bal Ar; $P_{S_2} = 3 \times 10^{-6}$ atm, $P_{O_2} = 3 \times 10^{-15}$ atm. Conditions: 1000 °C and 1 atm total pressure, 100 hr exposure.

[c] Total affected depth is expressed as the sum of depths of formation of scale layers, internal oxidation (or sulfidation) and intergranular corrosion.

[d] 310SS Composition: 25Cr, 21Ni, 2Mn, 1.5Si, Bal Fe. 310HP Composition: 25.3Cr, 19.9Ni, 0.23Ti, Bal Fe (HP signifies special high purity alloy). Carbon <0.03 in 310 Stainless series.

[e] Titanium additions modify Cr_2O_3 scale and reduce the outward migration of Ni and/or Fe which form external sulfides and the inward migration of sulfur which can produce sulfidation at grain boundaries and internal sulfides.

[f] Ni-30Cr binary system composition: 29.8Cr, 0.16Ti, Bal Ni; Carbon <0.001 in Ni-30Cr series.

[g] Very scattered intergranular corrosion occured to a depth of about 70μ. The intergranular corrosion consisted of a penetration along single grain boundaries at widely dispersed points.

EFFECT OF SEVERAL GAS ENVIRONMENTS[a]
ON CORROSION OF SELECTED ALLOYS[b] [31]

Gas Composition (Vol. %)	Sulfidizing → ← Oxidizing				
H_2O	23.0	17.0	12.0	14.0	8.0
H_2S	1.2	1.2	1.2	1.6	1.7
H_2	49.0	51.0	54.0	54.0	58.0
Ar	Balance	Balance	Balance	Balance	Balance
P_{S_2} (10^{-6} atm)	3.4	3.2	2.8	4.8	4.9
P_{O_2} (10^{-6} atm)	7.8	3.5	1.7	2.3	0.66
Alloy[b]	**Weight Gain (mg/cm^2)**				
310 SS[c,d]	1.0	0.9	>50[e]	----	97.0[e]
310-5Al	1.5	0.7	0.6	1.0	0.1
310-5Al-5Mo	----	0.9	0.6	0.7	0.5
310-10Mo	----	1.0	----	2.4	----
310-5Mn	----	202.0[e,f]	----	----	----
IN 671[g]	1.6	1.3	1.1	1.0	5.9
Ni-20Cr-5Al[h]	1.8	0.6	0.1	----	43.3
Alloy[b]	**Total Affected Depth of Attack (μ)**				
310 SS	14	24	110	----	395
310-5Al	30	16	24	22	24
310-5Al-5Mo	----	16	20	14	14
310-10Mo	----	20	----	32	----
310-5Mn	----	570	----	----	----
IN 671	32	30	30	28	116[i]
Ni-20Cr-5Al	24	34	10	----	305

---

[a] Gas exposure: 24 hrs at 1000 °C and 1 atm.

[b] Material: Commercial alloys tested as well as experimental compositions based on 310 SS with elements added as indicated; 25 lb cast ingots homogenized in argon for 24 hrs at 2000 °F; 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) coupons machined from ingot material.

[c] As received composition (wgt %): .026C, 25.3Cr, 19.9Ni, .23Ti, Balance Fe.

[d] Extensive grain boundary penetration by S is evident.

[e] Liquid product formed.

[f] Mn additions promote corrosion of 310 SS in these test conditions.

[g] As received composition (wgt %): 52.17Ni, 47.12Cr, 0.20Ti, 0.19Si, 0.14Fe, 0.06C.

[h] As received composition (wgt %): 99.56Ni, 0.26Mn, 0.09C.

[i] The highest P_{S_2} resulted in grain boundary penetration by sulfur to a depth of about 200μ whereas a protective oxide layer only a tenth as thick forms in the other gas compositions.

OXIDATION OF EXPERIMENTAL AND COMMERCIAL ALLOYS[a] EXPOSED IN CYCLIC TESTS[b][31]

	Weight Change, mg/cm^2									
Alloy[a]/Composition	100 hr	200 hr	300 hr	400 hr	500 hr	600 hr	700 hr	800 hr	900 hr	1000 hr
310 SS	1.4	1.9	2.1	2.5	2.7	3.0[g]	3.1[g]	3.0[g]	3.1[g]	2.9[g]
(Fe-18Ni-25Cr-Mn-Si)	1.5	1.7	2.1	2.5	2.8					
310 HP[c]	0.5	0.6	0.5	late start						
(Fe-18Ni-25Cr)	0.5	0.6	0.5	late start						
304 SS	-22.3	-43.8	-58.8	-84.3	stopped					
(Fe-10Ni-18Cr-Mn-Si)	-20.6	-44.1	-65.5	-83.1	stopped					
309 SS	1.4	1.6	1.6	1.9	2.1					
(Fe-14Ni-22Cr-2Mn-Si)	1.6	1.5	1.7	2.0	2.1					
Fe-25Cr-20Ni	0.5[g]	0.6[g]	0.6[g]	0.6[g]	0.7[g]	0.7[g]	0.7[g]	0.5[g]	0.4[g]	0.5[g]
310 SS + 3Ti	1.0	1.6	1.5	1.0	0.2	-0.7[g]	-2.6[g]	-5.5[g]	-10.4[g]	-15.6[g]
(Fe-20Ni-24Cr-3Ti-Mn-Si-C)[d]	2.4	2.2	2.0	1.4	0.7					
310 HP + 3Ti[c]	1.3	1.6	1.7	1.8	2.0					
	0.9	1.2	1.4	n.a.	1.6					
Fe-25Cr-20Ni-3Ti	1.3[g]	1.4[g]	1.5[g]	1.8[g]	1.8[g]	1.4[g]	1.5[g]	1.6[g]	1.6[g]	1.4[g]
Fe-25Cr-20Ni-2Ti	1.7[g]	2.0[g]	2.2[g]	2.2[g]	2.0[g]	1.9[g]	1.9[g]	2.0[g]	1.9[g]	1.8[g]
233 MS[e]	2.6	2.7	1.9	late start						
(Fe-24Ni-22Cr-3Ti-Mn-Si-C)[d]	2.6	2.9	1.5	late start						
	2.3[g,h]	2.2[g,h]	2.3[g,h]	1.0[g]	-1.0[g]	-2.9[g]	-5.1[g]	-6.5[g]	-8.5[g]	-11.9[g]
243 MS[e]	2.0	1.4	1.0	late start						
(Fe-23Ni-22Cr-3Ti-Mn-Si-C)[d]	2.2	2.5	2.0	late start						
Incoloy 800	1.1	1.3	1.2	1.0	0.7					
(46Fe-33Ni-21Cr)	1.6	1.1	1.3	0.7	-0.6					
Incoloy 801	1.4	1.8	1.3	-1.2	-8.2					
(45Fe-32Ni-21Cr-Ti)	1.2	1.6	1.5	1.9	1.1					
Ni-30Cr	0.2	0.1	-1.0	-1.3	-1.8	-2.0[g]	-3.0[g]	-3.9[g]	-4.4[g]	-5.1[g]
	0.8	0.1	-0.4	-0.8	-1.2					
Ni-30Cr-4Ti	3.4[g]	4.0[g]	2.8[g]	-0.3[g]	-2.6[g]	-2.4[g]	-3.5[g]	-4.8[g]	-5.6[g]	-6.2[g]
Ni-30Cr-4Ti/HP[f]	0.1	0.6	1.0	1.4	1.7	3.3[g]	3.5[g]	3.6[g]	3.6[g]	3.4[g]
	2.3	2.9	3.3	n.a.	3.6					
Ni-30Cr-3Al/HP[f]	0.6	1.2	1.4	1.6	1.5					
	0.6	1.3	1.4	1.6	1.7					
Ni-30Cr-4Al/HP[f]	0.5	1.1	1.3	1.6	1.8					
	1.1	1.7	2.1	n.a.	2.6					
Incoloy 814E	0.1	0.4	0.3	0.4	0.3					
(48Ni-17Fe-30Cr-3.5Al)	0.2	0.2	0.1	0.2	0.2					
Inconel 671	0.8	0.7	0.5	0.5	0.5	0.6[g]	0.5[g]	0.4[g]	0.4[g]	0.4[g]
(51Ni-48Cr)	0.6	0.6	0.6	0.6	0.7					
Nimonic 81 (M313)	1.6	2.0	1.8	1.0	0.3	-0.1[g]	-0.5[g]	-0.8[g]	-1.0[g]	-1.3[g]
(64Ni-30Cr-2Ti)	1.8	1.9	2.0	1.5	1.1					
Pyromet 31	2.0	0.4	0.1	-0.4	-1.2					
(55Ni-15Fe-23Cr-3Ti-2Al-2Mo)	1.9	0.0	-0.1	-0.8	-1.6					
Inconel 690	0.6	0.7	0.7	0.8	0.9	0.9[g]	0.9[g]	0.8[g]	1.0[g]	1.0[g]
(60Ni-10Fe-30Cr)	0.8	0.9	0.9	0.9	1.0					
Inconel 601	1.2	1.5	1.7	1.9	2.0					
(60Ni-14Fe-23Cr)	1.4	1.3	1.7	1.9	2.0					

---

[a] Commercial alloys tested as well as experimental compositions. Coupons 1/2 in. x 3/4 in. x 1/8 in. (12.7 mm x 19.1 mm x 3.2 mm) were machined, then ground on 120 grit SiC paper, edges and corners rounded. Composition given is approximate only.

[b] Test temperature 1800 °F. Two samples of each alloy exposed in enclosed muffle type furnace into which clean dry air was circulated at about 100 sccm. Specimens cooled to ambient temperature between 100 hr cycles. Specimens heated and cooled within the furnace and weighed following each cycle after removal of loose scale. Weight change defined as the difference in weight after a given cycle (time in hours) relative to initial weight per unit area of the test coupon and, accordingly, is cumulative. No provision made for spall collection during the cycle. Negative values for the weight change indicate spalling loss of scale.

[c] High purity version containing no Mn or Si.

[d] Carbon content <0.1 wt %.

[e] Versions of 310 SS.

[f] High purity modified version of Ni-30Cr containing no Fe, Mn, Co, or Mo.

[g] Average of values for 2 specimens.

[h] [These average values obtained from a different table than that containing values for each coupon sample. In the case of all other alloys, the values in both tables agreed.]

RESULTS OF OXIDATION[a] IN A SULFUR-FREE GASIFICATION ATMOSPHERE AND SUBSEQUENT LIMITED H_2S EXPOSURE[a] OF SEVERAL ALLOYS[b][31]

Alloy[c]	Scale Thickness (μm)	Internal Oxidation (μm)	Total (μm)	Scale Adherence
310 SS	3	5	8	Good
310 SS + Ti	6	11	17	Good
310 HP + 3Ti[c]	8	15	23	Good
Ni-30 Cr	5	30	35	Spalls
IN X-750	6	18	24	Good
Incoloy 800	5	30	35	Good
Inconel 601	4	27	31	Good

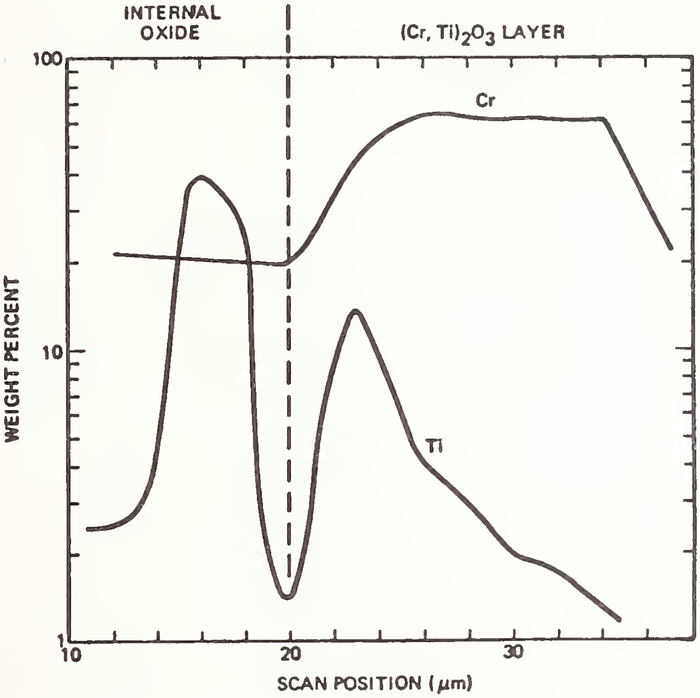
---

[a] Coupons subjected to oxidation in the following gas mixture (vol %): 32 H_2O, 20 CO, 14 CO_2, 5.5 CH_4, 28.5 H_2, for 48 hours at 1800 °F and atmospheric pressure. The furnace was then swept with argon and H_2S was introduced for 0.5 hr.

[b] Coupons 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) machined from wrought stock. Experimental alloys prepared by melting 310 SS commercial stock with Ti and enough Cr to maintain the Cr content of the original steel.

[c] 310 HP is a high purity version of 310 SS containing no Mn or Si.

ANALYSIS[a] OF OXIDATION PRODUCTS IN 310 SS + 3Ti[b] EXPOSED IN A HIGH-BTU COAL GASIFICATION ATMOSPHERE[c][31]



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[a] Electron microprobe analysis.

[b] Alloy composition (wt %): 24.2 Cr, 19.8 Ni, 3.1 Ti, 1.5 Mn, 0.6 Si, 0.080 C, balance Fe. Prepared by vacuum melting and casting. The billet was subsequently hot rolled at 1423 K to 3 mm plate and solution annealed at 1366 K for 2 hours. It contained 5-10% ferrite.

[c] Exposure conditions: 1255 K (1800 °F), 1 atm, 485 hours. Feed gas composition (vol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1 H_2S, 40 H_2O. Calculated equilibrium partial pressures, O_2 1.9×10^{-6} atm, S_2 3.7×10^{-15} atm.

Observations: No internal sulfides of Ti detected in specimens examined after 200 hours exposure. Duplex scale formed is apparently a solid solution oxide. Chromium is major metallic element with Ti constituting about 10% of the metal portion. A Ti gradient is present through the oxide layer, decreasing from about 20% at the oxide-metal interface to a few percent at the outer surface.

OXIDATION OF SEVERAL ALLOYS[a] IN A TEST ATMOSPHERE WITH A LOW P_{O_2} [b][31]

Alloy[a]	Scale Thickness (μm)	Internal Oxidation (μm)	Total (μm)	Scale Adherence[d]
310 SS	6	5	11	Good
310 + 2Ti	12	20	32	Good
310 HP + 2Ti[c]	15	30	45	Good
Ni-30 Cr	20	--	20	Spalls
Inconel 601	8	25	33	Good
Inconel 671	12	25	37	Good
Inconel 690	10	15	25	Spalls
Pyromet 31	16	25	41	Good

---

[a] Coupons were from wrought stock hot rolled 1/8 in thick machined to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm). Experimental alloys were prepared by melting commercial 310 SS stock with Ti and enough Cr to maintain the original Cr content.

[b] Test conditions: gas composition (vol %) 16 H_2O, 43 H_2, 41 Ar, no H_2S, $P_{O_2} = 2.4 \times 10^{-16}$ atm; 1800 °F (1255 K), atmospheric pressure, 100 hr duration.

[c] 310 HP is high purity version of 310 SS containing no Mn or Si.

[d] All alloys formed a protective layer of Cr_2O_3; some Ti, Al, or Mn may be incorporated into the predominant oxide.

CORROSION TESTS OF SELECTED INDUSTRIAL ALLOYS[a] IN A CORROSIVE GAS ATMOSPHERE[b] [31]

Alloy[a]	Scale (μm)	Internal Oxidation (μm)	Intergranular Corrosion (μm)	Total Affected Depth[c] (μm)	Comments
IN 671 (Ni-48Cr-0.3Ti)	18	40	-	58	Spalling oxide. Some internal sulfidation.
INCO 814E[d] (Ni-30Cr-17Fe-4Al-0.5Ti-0.5Si)	5	-	-	5	Oxidation only, Al_2O_3-based layer; small (<10μ) sulfide-containing nodules formed on surface.
	3	-	-	3	
Nimonic 81 (M313) (Ni-30Cr-1.8Ti-0.9Al)	20	46	-	66	Adherent oxide; resisted sulfidation; internal aluminum oxides observed.
	16	12	-	58	Adherent oxide.
IN 690 (Ni-30Cr-10Fe)	-	-	>1500	>1500	Sulfide penetration and liquation[e].

---

[a] Wrought stock, hot rolled to 1/8 in thick sheet. Compositions in wt %. Machined coupons 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm).

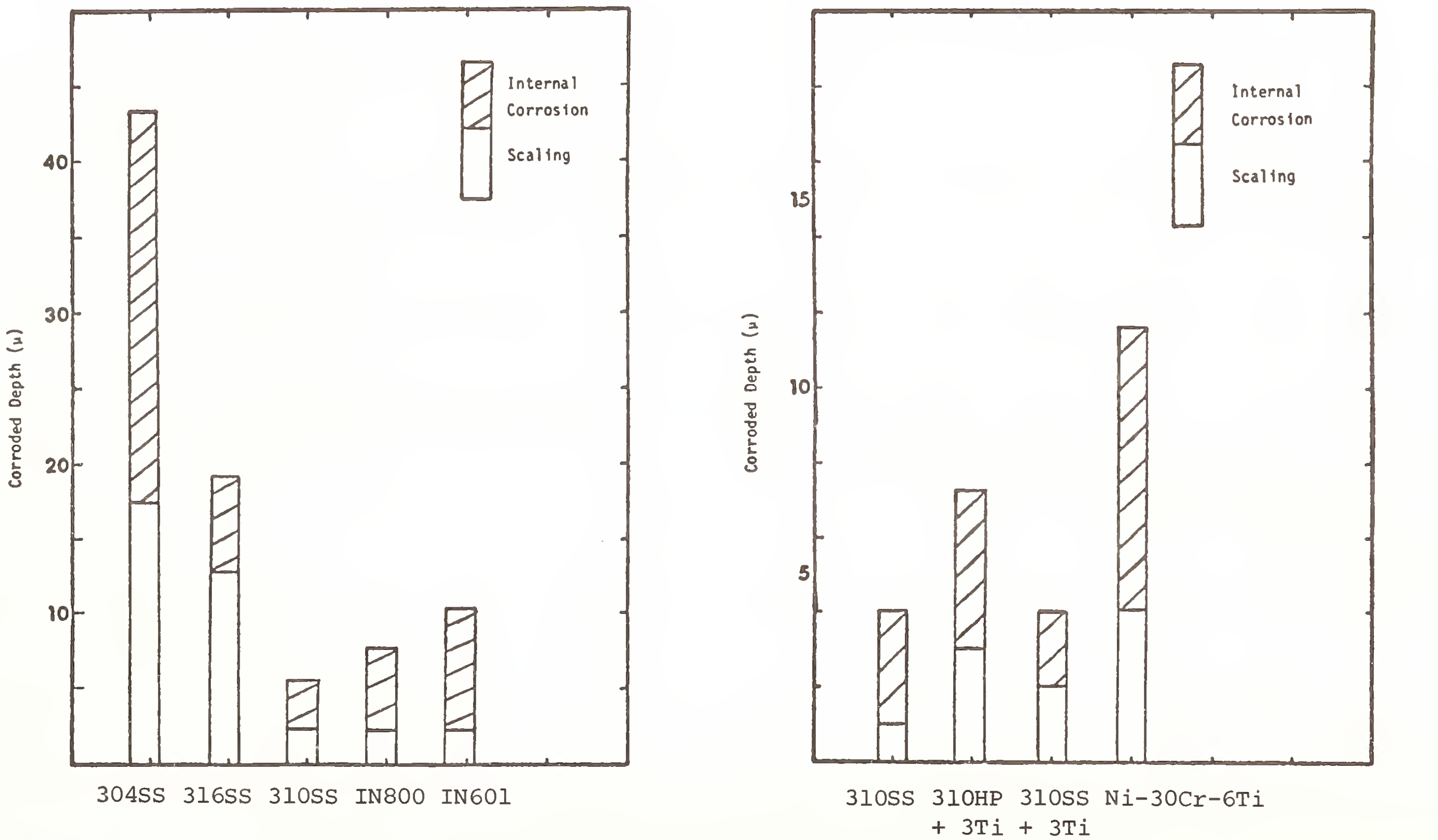
[b] 1000 °C at 1 atm total pressure in a gas consisting of 30 (vol %) H_2O, 1 H_2S, 30 H_2, bal Ar, 100 hr exposure.

[c] Total affected depth of attack equals sum of depth of scale layers, internal oxidation (or sulfidation) and intergranular corrosion.

[d] Not commercially available.

[e] Completely destroyed by sulfidation.

CORROSION OF COMMERCIAL[a] AND EXPERIMENTAL[b] ALLOYS IN A SIMULATED COAL GASIFICATION ATMOSPHERE[c] [31]



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[a] Commercial alloys: 304 SS, 316 SS, 310 SS, Incoloy 800, Inconel 601.

[b] Experimental alloys prepared, in the case of 310 SS, by melting the commercial stock and adding the addition element plus enough Cr to maintain the Cr content of the original. The Ni-30Cr-6Ti prepared from Nickel 200, Cr, and Ti. HP signifies special high purity alloy containing no Mn or Si.

[c] Test conditions: 1500 °F, 1000 psi, 100 hr duration, atmosphere (vol %) 18.2 CO, 19.6 CO_2, 7.4 CH_4, 53.6 H_2, 1.0-2.2 H_2S, P_{O_2} 3.5 x 10^{-18} atm, P_{S_2} 1.8-8.7 x 10^{-7} atm. Analysis of gas by mass spectroscopy.

EFFECT OF EXPOSURE TIME ON CORROSION OF SEVERAL ALLOYS IN A CORROSIVE GAS ENVIRONMENT[a] [31]

Gas Composition (Vol %)	24 hr	100 hr
H_2O	12.0	13.0
H_2S	1.2	1.1
H_2	54.0	52.0
Ar	Balance	Balance
P_{S_2} (10^{-6} atm)	2.8	2.1
P_{O_2} (10^{-6} atm)	1.7	2.3

Alloy[b]	Weight Gain (mg/cm^2)	Total Affected Depth (μ)	Weight Gain (mg/cm^2)	Total Affected Depth (μ)
310 SS[c]	50	110	117.0	560
310 + 5Al	0.6	24	0.1	20
310 + 5Al + 5Mo	0.6	20	0.8	34
310 + 10Mo	---	26	0.2	60
IN 671[d]	1.1	30	2.2	64
Ni-20Cr-5Al	0.1	10	61.0	460

---

[a] Conditions: 1000 °C and 1 atm.

[b] Commercial alloys tested as well as experimental compositions based on 310 SS with elements added as indicated. Ingots homogenized in argon for 24 hrs at 2000 °F. 1/2 in x 3/4 in x 3/8 in (12.7mm x 19.1mm x 3.2mm) coupons machined from ingot material.

[c] Commercial cast stock: .026 (wgt %) C, 25.3 Cr, 19.9 Ni, .23 Ti, Bal Fe.

[d] As received composition (wgt %): 52.17 Ni, 47.12 Cr, 0.20 Ti, 0.19 Si, 0.14 Fe, 0.06C.

CORROSION OF ALLOYS[a] EXPOSED TO A CORROSIVE GAS ATMOSPHERE[b] AT ATMOSPHERIC PRESSURE[31]

Alloy[a]/Composition	Weight Change (mg/cm^2)	Corrosion Product
310 SS	0.9	Scattered spalling
Fe-18.3Ni-24.6Cr-1.0Mn-0.9Si	0.9	Scattered spalling
233 MS[c]	2.9	Adherent oxide
Fe-23.6Ni-22.0Cr-3.3Ti-1.52Mn-0.52Si		
243 MS[c]	1.6	Adherent oxide
Fe-22.8Ni-21.9Cr-3.5Ti-1.62Mn-0.55Si		
233 M[c]	2.6	Adherent oxide;
Fe-22.7Ni-22.4Cr-3.2Ti-1.53Mn		Nodule on edge
233 S[c]	1.8	Adherent oxide
Fe-23.7Ni-22.1Cr-3.3Ti-0.51Si		
233[c]	2.9	Adherent oxide
Fe-22.9Ni-21.9Cr-3.2Ti		
310 + 3Ti	1.6	Adherent oxide
Fe-19.8Ni-24.2Cr-3.1Ti-1.5Mn-0.55Si	2.0	Adherent oxide
Incoloy 800	Totally corroded	
46Fe-32.5Ni-21.Cr-0.4Ti-0.4Al-0.8Mn-0.5Si		
Incoloy 801	1.4	Adherent oxide
44.5Fe-32.Ni-20.5Cr-1.1Ti-0.8Mn-0.5Si		
Ni-30Cr-4Ti	-6.3	Complete spalling
Ni-2.0Fe-28.4Cr-4.0Ti-0.43Mn-1.41Co	-2.9	of oxide
Ni-30Cr-4Ti/HP[d]	-7.2	Complete spalling
Ni-29.1Cr-4.5Ti		of oxide
Pyromet 31	-3.7	Complete spalling
14.5Fe-55.1Ni-23.Cr-2.6Ti-1.7Al-2.Mo-1.1Nb		of oxide

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[a] Coupons machined to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) from stock prepared by vacuum melting and rolling to 1/8 in plate. A heat of commercial purity 310 SS + 3 wt % Ti was produced as a wrought material.

[b] Gas composition (vol %): 30.0 H_2O, 1.0 H_2S, 30.0 H_2, 39.0 Ar. Conditions: 1800 °F, 1 atm pressure, 100 hours duration.

[c] Modified versions of 310 SS. Carbon level in the alloys is approximately 0.08.

[d] High purity modification containing no Fe, Co, Mn, and Mo.

HIGH PRESSURE CORROSION TESTS[a] OF SELECTED ALLOYS[b] IN A SIMULATED COAL GASIFICATION ATMOSPHERE[31]

Alloy[b]	Average Temperature °F	Weight Change (mg/cm^2)	Corrosion Products[c]
310 SS	1500	0.4	Adherent scale. Cr_2O_3 layer with Mn present.
310 SS + 2Ti		0.4	Adherent oxide. Protective surface layer of Cr and Ti oxides. Internal oxidation of Ti.
310 HP + 3Ti[d]		0.7	Adherent oxide.
Ni-30Cr-3Al		0.8	Adherent oxide. Protective surface layer.
Ni-30Cr-4Al		0.4	Adherent oxide.
Fe-16Cr-5Al-2Mo-1Hf[e]		0.3	Adherent oxide. Protective surface layer.
Ni-30Cr-3Al	1610	0.7	Adherent oxide.
Ni-30Cr-4Ti		1.2	Adherent oxide. Protective surface layer.
Fe-16Cr-4.5Al-0.5Y[f]		0.2	Adherent oxide. Protective surface layer.
Pyromet 31		1.2	Adherent oxide.
Inconel 671		0.5	Spalling oxide.
IN 814E		0.6	Spalling oxide. Localized corrosion.
310 SS	1650	0.5	Adherent scale. Voids along grain boundaries. Cr depletion.
310HP + 3Ti[d]		1.7	Adherent oxide.
Ni-30Cr-4Al		0.9	Spalling oxide.
Fe-17Cr-3Si-2Mo[e]		10.3	Nodular growths. Sulfidation.
Pyromet 31		2.5	Adherent oxide. Protective surface layers.
Inconel 671		0.8	Spalling oxide.
310SS + 2Ti	1680	0.8	Adherent oxide. Protective layer of Cr and Ti oxides. Internal oxidation of Ti.
Ni-30Cr		-13.8	Sulfidation at hole.
Ni-30Cr-3Al		1.2	Spalling oxide.
Ni-30Cr-4Ti		2.0	Adherent oxide.
Fe-18Cr-5Al-2Mo-1Hf[e]		0.3	Adherent oxide. Protective surface layer.
IN 814E		0.3	Oxide with local blistering.

(continued on next page)

HIGH PRESSURE CORROSION TESTS[a] OF SELECTED ALLOYS[b] IN A IN A SIMULATED COAL GASIFICATION ATMOSPHERE[31]

(continued)

Alloy[b]	Average Temperature °F	Weight Change (mg/cm^2)	Corrosion Products[c]
310 SS	1700	0.4	Adherent oxide.
310SS + 2Ti		1.3	Adherent oxide. Protective surface layer of Cr and Ti oxides. Internal oxidation of Ti.
310HP + 3Ti[d]		1.0	Adherent oxide.
Ni-30Cr-4Al		0.5	Spalling oxide.
Ni-30Cr-9Mo		0.1	Spalling oxide.
Nimonic 81		1.5	Adherent oxide. Protective surface layer.

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[a] Test Conditions: exposure time 208 hrs; pressure 510 ±40 psi; temperatures as indicated, temperature variation due to position in test chamber; Gas composition, Volume percent

Component	Dry Desired	Dry Actual	Wet Estimated
CO_2	20.0	18.1	9.8
CO	30.0	14.5	7.8
H_2	40.0	54.4	29.4
CH_4	8.3	7.4	4.0
H_2S	1.7	5.4	2.9
H_2O	-	-	46.0

Deviation of actual from desired composition was due to various operating problems. Supply of corrosive gas to specimens was limited to circulation by thermal convection because of failure of test vessel ceramic internals.

[b] Machined coupons 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) tested. Experimental alloys prepared from indicated base alloy by addition of stated elements.

[c] Total corrosion (scale thickness plus penetration depth) less than 20 μm in most cases.

[d] 310 HP is high purity version of 310 SS with no Mn or Si.

[e] Lockheed Palo Alto Research Laboratory material.

[f] Allegheny - Ludlum material.

EFFECT OF ALLOYING ADDITIONS TO TYPE 310SS[a] ON CORROSION BEHAVIOR IN A CORROSIVE GAS ENVIRONMENT[b][31]

Alloy[a]	Weight Gain (mg/cm^2)	Scale Thickness (μm)	Internal Corrosion[c] (μm)	Depletion[d] (μm)	Penetration[e] (μm)	Total Corrosion[f] (μm)	Scale Adherence
310SS	61.7	liquid	--	--	500	500	--
310 + 1 Al	41.2	liquid	--	--	500	500	--
310 + 2 Al	36.1	liquid	--	--	500	500	--
310 + 3 Al	1.4 1.4 1.1	5	16.0	12.0	1	33.0	fair
310 + 2 Ti	0.6 1.1	5	1	32.0	1	37.0	good
310 + 3 Ti	1.7 7.8[g]	5	14	16.0	1	35.0	good
310 + 1.5 Mo	6.7 39.6[h]	40.0	30.0	n.o.[i]	1	70.0	fair
310 + 3 Mo	26.3 52.0	10.0	30.0	n.o.	1	40.0	fair
310 + 6 Mo	24.3 23.1	10.0	30.0	n.o.	1	40.0	fair

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[a] Commercial cast stock: 20.4Ni, 24.75Cr, 1.84Mn, 0.70Si, 0.25Cu, 0.24Mg, 0.072C, Bal Fe. Experimental alloys prepared by melting commercial stock and adding modifying element plus enough chromium to maintain the Cr-content of the original material. Cast ingots homogenized by soaking in Argon at 1100 °C for 24 hrs and air cooling. 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) coupons were machined from the central section of the ingots.

[b] Conditions: 10 (vol %) H_2O, $15H_2S$, 52 H_2, Bal Ar at 1000 °C and 1 atm, 24 hr exposure.

[c] Depth of internally oxidized or sulfidized regions.

[d] Depth of underlying zones depleted of second phases, determined by visual variations between the sub-scale layer of the alloy and the unaffected interior regions.

[e] Penetration along grain boundaries only observed in association with severe sulfidation.

[f] Total corrosion is expressed as sum of scaling, internal corrosion, and depletion.

[g] Corrosion localized in a crevice.

[h] Addition of Mo to 310SS gives rise to a duplex scale under which internal sulfidation occurs and was found to be non-uniform in contrast to Al- and Ti-modified 310SS.

[i] Not observable by technique used.

EFFECT OF ALLOYING ADDITIONS TO IN 671 BASE ALLOY[a] ON CORROSION BEHAVIOR IN A CORROSIVE GAS ATMOSPHERE[b] [31]

Alloy[a]	Weight Gain (mg/cm^2)	Scale Thickness (μm)	Internal Corrosion[c] (μm)	Depletion[d] (μm)	Penetration[e] (μm)	Total Corrosion[f] (μm)	Scale Adherence
IN671	1.5 1.5	8	30	N.O.[g]	<1	38	Fair
IN671+2Ti	2.1 1.4	8	<1	20	<1	28	Good
IN671+2Al	5.9	10	50	N.O	<1	60	Fair
IN671+2Mo	4.6	10	30	N.O.	<1	40	Fair

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[a] Commercial cast stock: Ni-50Cr. Experimental alloys prepared by melting commercial stock and adding the modifying element. Cast ingots were homogenized by soaking in argon at 1100 °C for 24 hrs and air cooling. 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) coupons were machined from the central section of the ingots.

[b] Condition: 10 (vol/%) H_2O, 1.5H_2S, 52H_2, Balance Ar at 1000 °C and 1 atm.

[c] Depth of internally oxidized and sulfidized regions.

[d] Depth of underlying zones depleted of second phases, determined by visual variations between the sub-scale layer of the alloy and unaffected interior regions.

[e] Penetration along grain boundaries only observed in association with severe sulfidation.

[f] Total corrosion is expressed as sum of scaling, internal corrosion, and depletion.

[g] Not observable by techniques used.

EFFECT OF ALLOYING ADDITIONS TO IN 690 BASE ALLOY[a] ON CORROSION BEHAVIOR IN A CORROSIVE GAS ATMOSPHERE[b] [31]

Alloy[a]	Weight Gain (mg/cm^2)	Scale Thickness (μm)	Internal Corrosion[c] (μm)	Depletion[d] (μm)	Penetration[e] (μm)	Total Corrosion[f] (μm)	Scale Adherence
IN 690	209.0	liq.	--	--	--	>1mm	--
In 690 + 3Al	0.7 0.9	2	none	n.o.[g]	<1	2	fair
IN 690 + 4Al	0.6 4.6	2	none	n.o.	<1	2	fair
IN 690 + 4Ti	2.0	10	24	10	<1	44	good
IN 690 + 6Ti	2.8	8	24	10	<1	42	good
IN 690 + 6Mo	230.0[h] 147.0	6	20	n.o.	<1	26	fair
IN 690 + 9Mo	182.0[h] 112.0	6	20	n.o.	<1	26	fair

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[a] Commercial cast stock, IN 690 (Ni-30Cr-10Fe). Experimental alloys prepared from mixtures of Nickel 200, Cr, and the modifying element. Cast ingots homogenized by soaking in argon at 1100 °C for 24 hours and air cooling. 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm) coupons were machined from the central section of the ingot.

[b] Conditions: 10(wt %) H_2O, 1.5 H_2S, 52 H_2, Bal Ar at 1000 °C and 1 atm.

[c] Depth of internally oxidized or sulfidized regions.

[d] Depth of underlying zones depleted of second phases, determined by visual variations between the sub-scale layer of the alloy and the unaffected interior regions.

[e] Penetration along grain boundaries only observed in association with severe sulfidation.

[f] Total corrosion is expressed as sum of scaling, internal corrosion, and depletion.

[g] Not observable by technique used.

[h] Non-uniform corrosion. Properties of regions with continuous scale given. Liquid products also formed.

EFFECT OF Mn AND Si ON CORROSION OF 310SS AND Ni-30 Cr ALLOYS[a] IN CORROSIVE GAS ENVIRONMENTS[b][31]

Environment
← Oxidizing
Sulfidizing →

Alloy[a]	$27H_2O$-$1.0H_2S$		$18H_2O$-$1.0\ H_2S$		$15H_2O$-$1.4H_2S$	
	Total Affected Depth[c] (μm)	Corrosion Product	Total Affected Depth[c] (μm)	Corrosion Product	Total Affected Depth[c] (μm)	Corrosion Product
310SS[d]	12	Oxide layer Intergranular sulfides	58	Sulfide/oxide layer Intergranular sulfides	56	Sulfide/oxide layer Intergranular sulfides
310 + 2Mn	42	Sulfide/oxide layer Internal sulfide	44	Sulfide/oxide layer Internal sulfide	72	Sulfide/oxide layer Internal sulfide
310HP[d]	16	Oxide layer Internal sulfide	630	Liquation by sulfides	--	--
310HP + 2Mn	36	Oxide layer Internal sulfide	24	Oxide layer Internal sulfide	420	Liquation by sulfides
Ni-30Cr[e]	10	Oxide layer	58	Oxide layer Internal sulfide	38	Oxide layer Internal sulfide
Ni-30Cr + 2Mn	430	Sulfide layer Intergranular sulfides	490	Sulfide layer Intergranular sulfides	1220	Liquation by sulfides

---

[a] Wrought stock, hot rolled to 1/8 in thick. Experimental alloys prepared by additions to the indicated base alloy. Coupons machined to 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm).

[b] Exposure: 24 hours at 1000 °C, 1 atm pressure.

[c] Total affected depth of attack is the sum of the depths of scale layers, internal oxidation (or sulfidation) and intergranular corrosion.

[d] 310SS composition: 24 (wt %) Cr, 21 Ni, 2 Mn, 1.5 Si, Bal Fe. 310HP composition: 25.3 (wt %) Cr, 19.9 Ni, 0.23 Ti, Bal Fe (HP signifies special high purity alloy). Carbon <0.03 in 310 stainless series.

[e] Ni-30Cr composition: 29.8 (wt %) Cr, 0.16 Ti, Bal. Ni, Carbon <0.001 in Ni-30Cr series.

EFFECT OF PRESENCE OF Mn AND Si ON CORROSION OF 310SS ALLOYS[a] WITH ADDITIONS OF Ti, Al, AND Mo IN A CORROSIVE GAS ENVIRONMENT[b] [31]

Alloy[a]	Total Affected Depth[c] (μm)	Scale Adherence	Occurrence of Sulfidation
310SS[d]	48	Good	External layer, Internal precipitates
310 + 3Ti	12	Good	None
310HP[d] + 3TI	22	Good	None
310 + 3Al	3	Spalls	Internal precipitates
310HP + 3Al	4	Weak	None
310 + 6Mo	14	Good	External layer, Internal precipitates
310HP + 6Mo	8	Weak	None

---

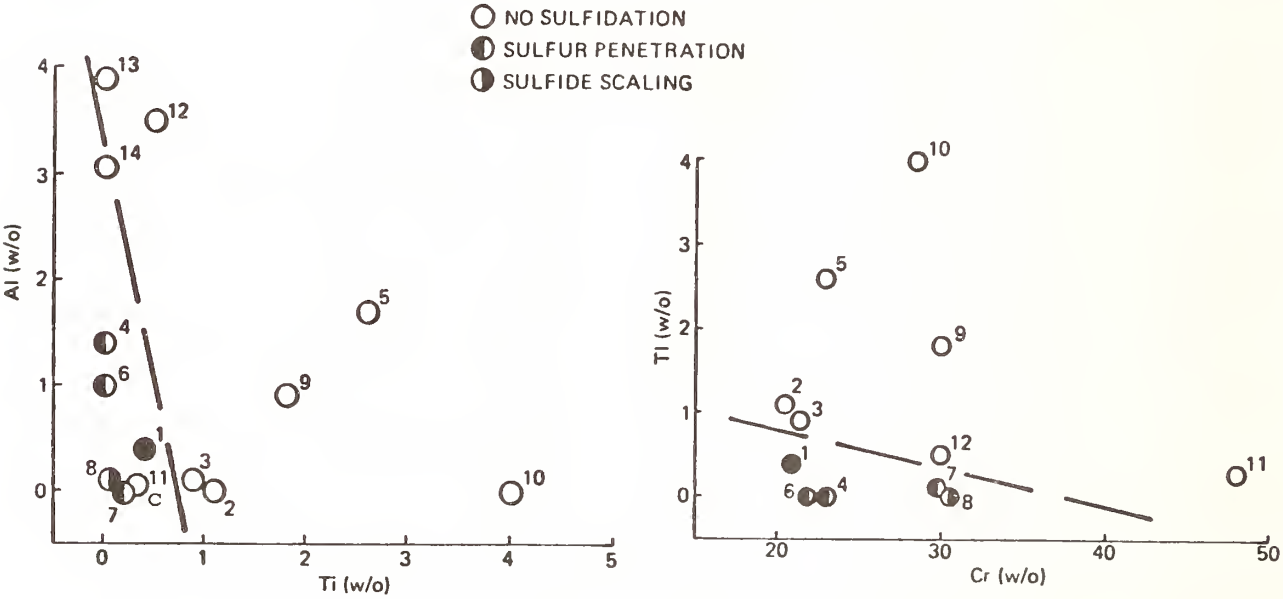
[a] Wrought stock, hot rolled to 1/8 in sheet. Experimental alloys prepared by additions to the indicated base alloy. Machined coupons 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x 3.2 mm).

[b] Gas composition: 20 (vol%) H_2O, 1.4 H_2S, 51 H_2, Bal Ar. Conditions: 24 hrs at 1000 °C, 1 atm pressure.

[c] Total affected depth is the sum of depths of scale layers, internal oxidation (or sulfidation) and intergranular corrosion.

[d] 310SS composition: 25(wt %) Cr, 21 Ni, 2 Mn, 1.5 Si, Bal Fe. 310HP composition: 25.3(wt %)Cr, 19.9 Ni, 0.23 Ti, Bal Fe (Note no Mn or Si present; HP signifies special high purity alloy). Carbon <0.03 in 310 stainless series.

EFFECT OF Al-Ti and Ti-Cr CONCENTRATIONS ON SULFIDATION OF ALLOYS[a] BY A HIGH-BTU COAL GASIFICATION ATMOSPHERE[b] [31]



Legend: 1 = Incoloy 800 (32.5Ni-46Fe-21Cr-0.4Ti-0.4Al-0.8Mn-0.5Si)
2 = Incoloy 801 (32Ni-44.5Fe-20.5Cr-1.1Ti-0.8Mn-0.5Si)
3 = Incoloy 825 (42Ni-30Fe-21.5Cr-1.0Ti-0.1Al-0.5Mn-0.2Si-3.0Mo-2.2Cu)
4 = Inconel 601 (60.5Ni-14.1Fe-23Cr-1.4Al-0.5Mn-0.2Si)
5 = Pyromet 31 (55.1Ni-14.5Fe-23Cr-2.6Ti-1.7Al-0.5Mn-0.2Si-1.1Nb-2.0Mo)
6 = Inconel 617 (54Ni-22Cr-1.0Al-9.0Mo-12.5Co)
7 = Ni-30Cr (70Ni-29.8Cr-0.16Ti)
8 = Inconel 690 (60Ni-9.5Fe-30Cr-<.5Mn)
9 = Nimonic 81 (63.8Ni-<1.0Fe-30Cr-1.8Ti-0.9Al-<.5Mn-<.5Si-<2.0Co)
10 = Ni-30Cr-4Ti (64Ni-2.0Fe-28.4Cr-4.0Ti-0.4Mn)
11 = Inconel 671 (51.4Ni-0.3Fe-48Cr-0.3Ti)[c]
12 = IN814E (48.5Ni-17Fe-30Cr-0.5Ti-3.5Al-0.5Si)
13 = Ni-30Cr-4Al (64Ni-30.1Cr-3.9Al)
14 = Ni-30Cr-3Al (64Ni-30.1Cr-3.0Al)

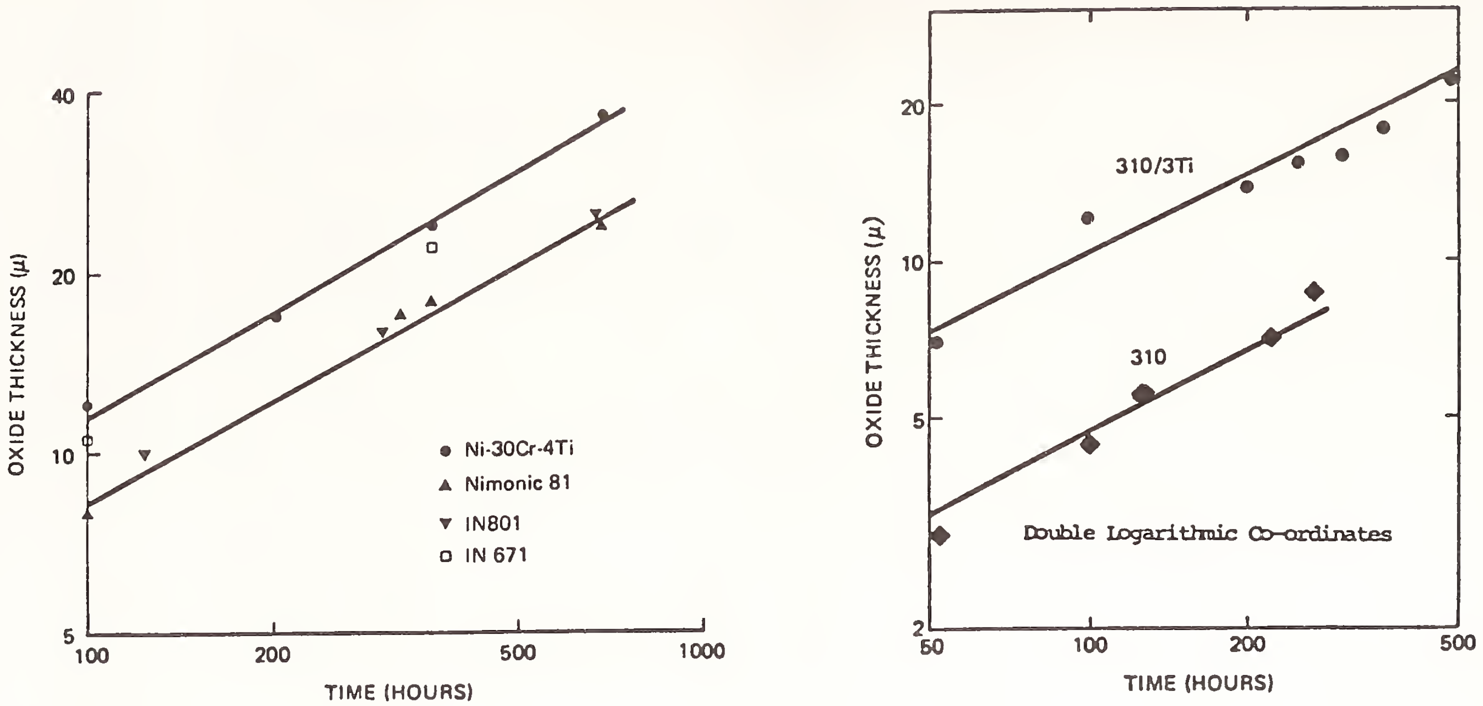
---

[a] As received wrought alloys machined to test coupon size, 1/2 in x 3/4 in x 1/8 in (12.7 mm x 19.1 mm x3.2 mm); ground to uniform finish with 120 grit SiC paper; cleaned ultrasonically with trichlorethylene followed by acetone.

[b] Feed gas composition (vol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1.0 H_2S, 40 H_2O. Test conditions: 1255 K (1800 °F), 1 atm, 100 hr. Calculated equilibrium partial pressures: O_2 1.9×10^{-15} atm, S_2 3.7×10^{-6} atm.

[c] 48 wt % Cr in IN671 was sufficient to insure sulfidation resistance without the presence of Al and with only 0.3 wt% Ti.

EFFECT OF Ti ADDITIONS ON THE OXIDATION KINETICS[a] OF CHROMIUM OXIDE-FORMING ALLOYS[b] IN A HIGH-BTU COAL GASIFICATION ATMOSPHERE[c] [31]



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[a] Coupons exposed at 1255 K (1800 °F) at 1 atm. Exposed coupons prepared by common metallographic techniques. Extent, morphology, and qualitative chemical analysis of corrosion products determined by optical microscopy and dispersive x-ray analysis or electron microprobe analysis. The rate laws are parabolic.

[b] Ti-enriched alloys tested: Ni-30Cr-4Ti (64Ni-2Fe-28Cr-4Ti), Nimonic 81 (64Ni-30Cr-2Ti-1Al, also Fe,Mn,Si,Co), Incoloy 801 (32Ni-45Fe-21Cr-1Ti, also Mn,Si), 310 SS + 3Ti (Fe-25Cr-18Ni-3Ti-Mn-Si). Inconel 671 (51Ni-48Cr) and 310 SS test values included for comparison. Coupons machined from as-received wrought alloys; ground to uniform finish with 120 grit SiC paper; cleaned ultrasonically with trichlorethylene followed by acetone.

[c] Feed gas composition (vol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1.0 H_2S, 40 H_2O; calculated partial pressures for equilibrium conditions, O_2 1.9 x 10^{-15} atm, S_2 3.7 x 10^{-6} atm.

EFFECT OF CHAR[a] PARTICLE SIZE ON CORROSION WEIGHT GAINS[b] OF SOME ALLOYS[c] IN CONTACT WITH THE CHAR[36]

Alloy	Time (hrs)	Char Quantity, gms	Char[a] Size	Weight Gain, mg/cm^2
Hastelloy X	96	3	Coarse	0.58
	96	3	Fine	4.05, 6.11, 9.09
	12	10	Coarse	12.0, 23.2, 11.8
	12	10	Fine	32.4, 37.0
Inconel 671	96	3	Coarse	-1.56
	96	3	Fine	6.78, 21.9
	12	10	Coarse	8.54
	12	10	Fine	61.3
Incoloy 800	96	3	Coarse	3.24
	96	3	Fine	4.95, 14.9
310 Stainless	96	3	Coarse	1.92, 1.75
	96	3	Fine	22.0

---

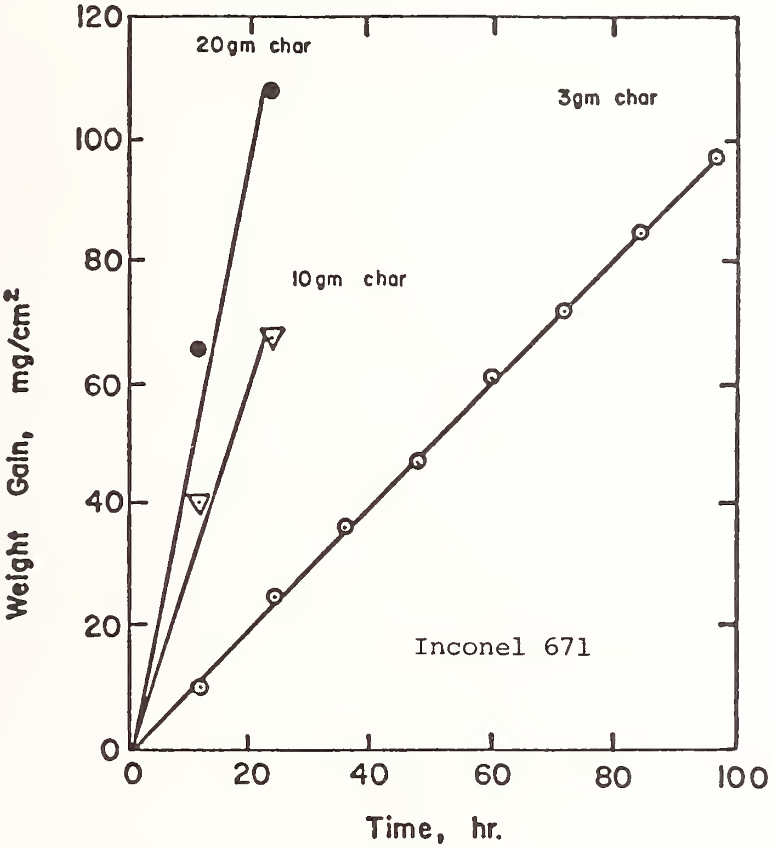
[a] Char used was FMC, High-Volatile B Bituminous, W. Kentucky Colonial mine; contains about 2.7 wt % sulfur. Char was sieved: coarse corresponds to -32 + 42 mesh, fine corresponds to -170 mesh. Analysis of sieved char as follows:

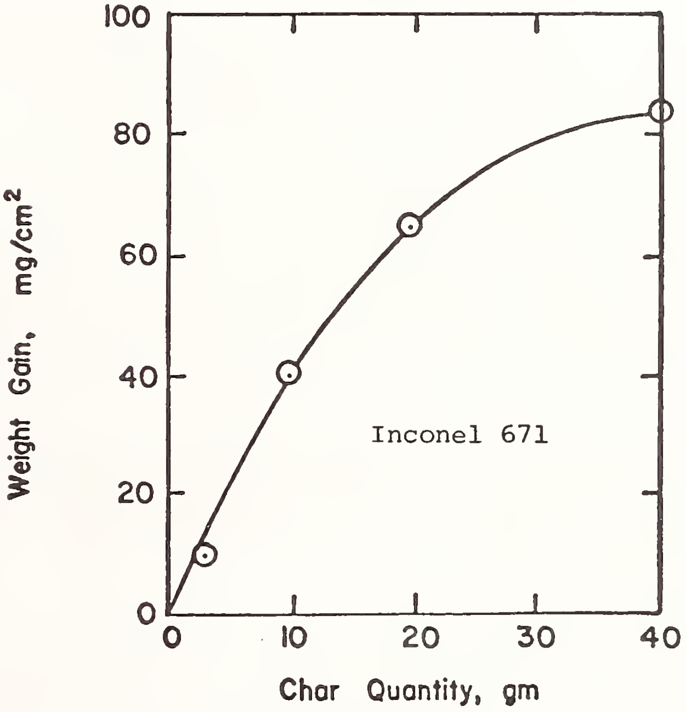
Mesh	Wt % of Total	% S	% Ash
+ 24	16.3	2.02, 2.26	10.9
- 24 + 32	4.3	2.03	13.4
- 32 + 42	6.7	2.00, 2.18	11.7, 14.6
- 42 + 60	11.9	1.96	11.7
- 60 + 80	11.2	2.50	14.2
- 80 + 115	10.8	2.86	12.6
- 115 + 170	10.2	2.87	11.3
- 170	28.6	2.98, 2.94	11.4, 11.2

[b] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; test temperature was 1800 °F. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale. It was also found that coarse char was more readily embedded in the scale than was fine.

[c] Alloys were obtained in sheets: 310 SS, Hastelloy X, Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

DEPENDENCE ON THE QUANTITY OF CHAR[a] OF THE CORROSION[b] OF ALLOYS[c] IN CONTACT WITH CHAR[36]





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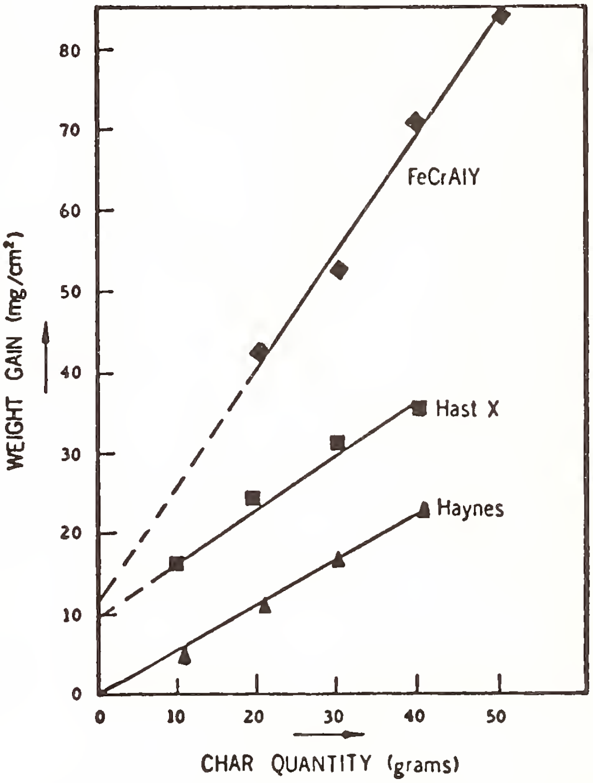
(Data Continued)

DEPENDENCE ON THE QUANTITY OF CHAR[a] OF THE CORROSION[b] OF ALLOYS[c] IN CONTACT WITH CHAR[36], Continued



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[a] Char used was -32+42 mesh FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine; contains about 2.7 wt % sulfur.

[b] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; exposure time was 12 hours, test temperature was 1800 °F; char quantity was varied. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale.

[c] Alloys used were Inconel 671, GE1541 (Fe-15Cr-4Al-1Y), Hastelloy X, and Haynes 188. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

EFFECT OF CHAR REPLENISHMENT ON THE REACTION PRODUCTS[a] FORMED WHEN ALLOYS[b] ARE SUBJECTED TO CORROSION BY CONTACT WITH CHAR[c] [36]

Alloy	No Char Replenishment[c] (96 hrs continuous run)	With Char Replenishment[c] (8-12 hour intervals)
310 Stainless	$NiFe_2O_4$, Cr_2O_3, Cr_7S_8(?)	Cr_3S_4, $FeCr_2S_4$
Hastelloy X	Cr_2O_3, $NiFe_2O_4$	Cr_3S_4
Inconel 671	Cr_2O_3, Cr_3S_4	Cr_3S_4
Incoloy 800	Cr_2O_3, $NiFe_2O_4$	Cr_3S_4, $FeCr_2S_4$
Haynes 188	Cr_2O_3, $NiFe_2O_4$(?), Cr_5S_6(?)	Cr_3S_4

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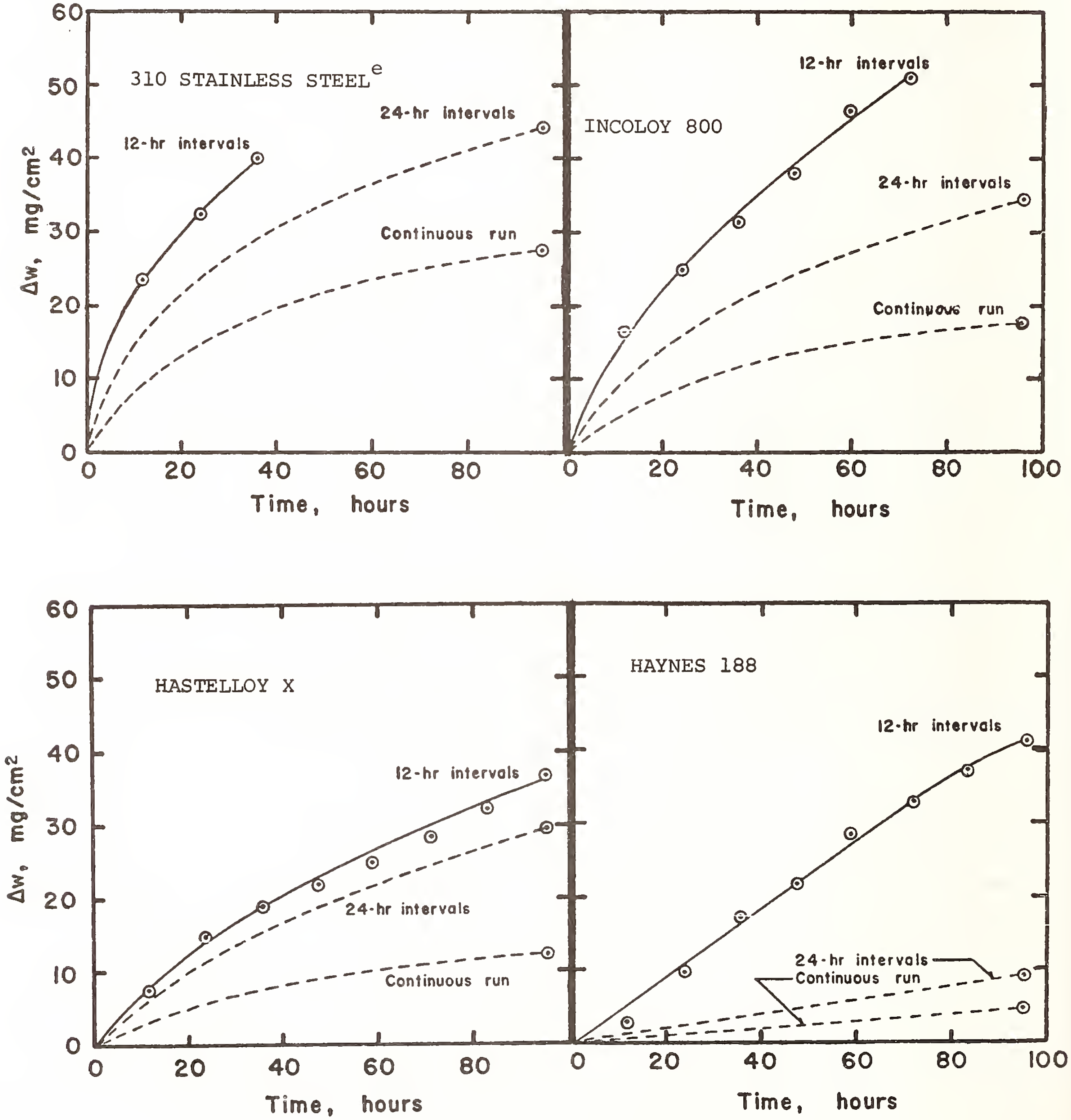
[a] X-ray diffraction analyses performed on the sample surface and probably represent only the external scale due to non-penetration of the beam beneath the scale. The phases are listed in order of their abundance.

[b] Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, and Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/10 silicon carbide paper; samples were washed in acetone and dried.

[c] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; 3 g char per sample was used; in one test the same charge of char was used and the test ran continuously for 96 hr, in the other test the 3 g of char was replenished every 8-12 hours. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale. Coal char used was -32+42 mesh FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine, containing about 2.7 wt% sulfur.

CORROSION KINETICS[a] OF ALLOYS[b] IN CONTACT WITH COAL CHAR[c]-- EFFECT OF CHAR REPLENISHMENT[d][36]



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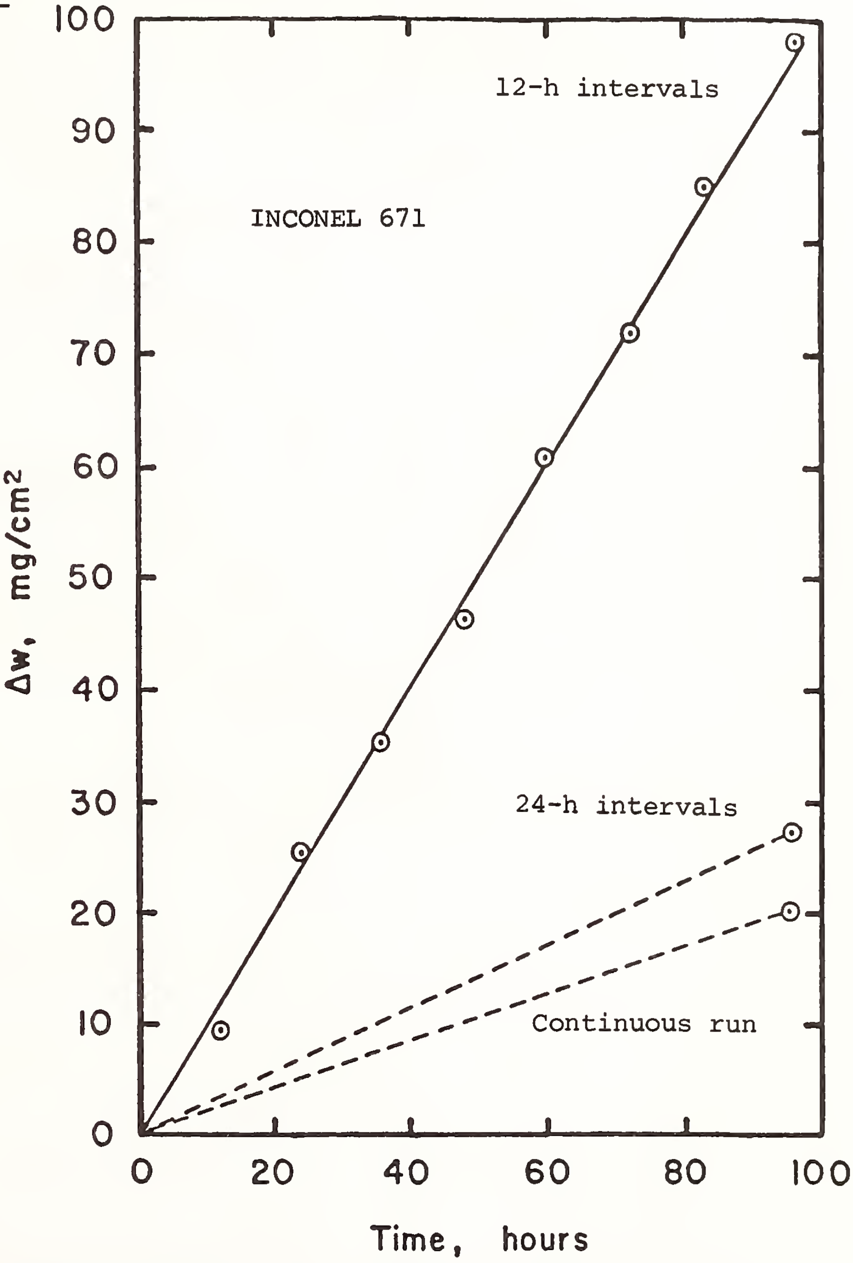
CORROSION KINETICS[a] OF ALLOYS[b] IN CONTACT WITH COAL CHAR[c]-- EFFECT OF CHAR REPLENISHMENT[d][36], Continued



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[a] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; test temperature was 1800 °F; 3 g char per sample was used. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight gain is plotted above versus exposure time. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from corrosion scale.

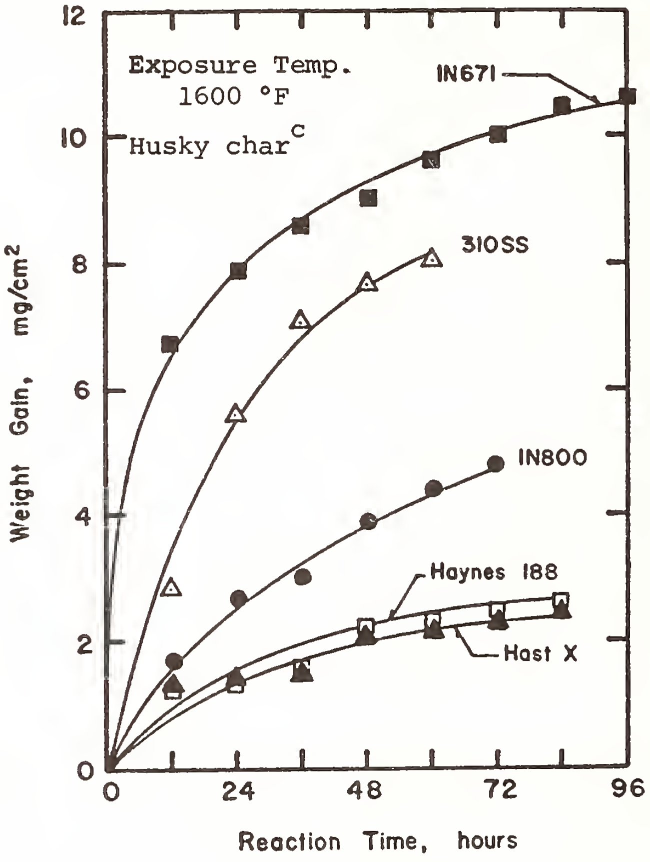
[b] Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, and Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

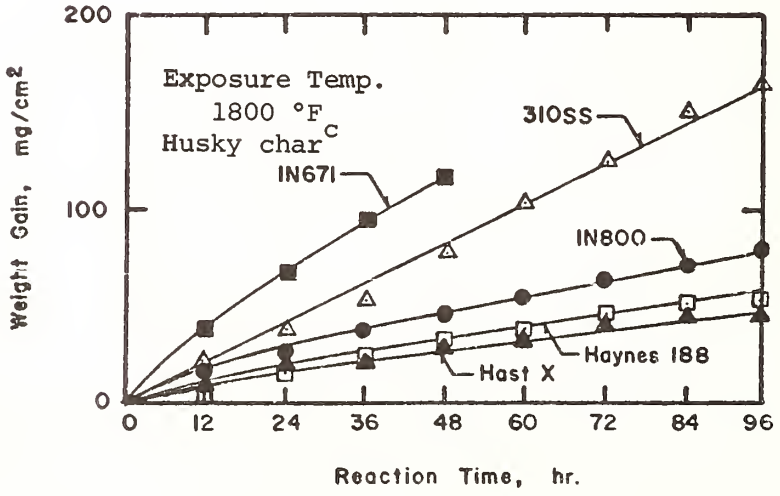
[c] Coal char used was -32+42 mesh FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine; contains about 2.7 wt % sulfur.

[d] One set of tests were run using 3 g char per sample continuously for 96 h; a second set also ran for 96 h but the 3 g char per sample was replenished every 24 h; a third set was run with char replenishment every 12 hr over the 96 h test period. Corrosion attack was generally sulfidation; sulfur in char was depleted during the long continuous runs without replenishment and some oxidation then occurred.

[e] 310 SS spalled excessively after 36 h with 12 h replenishment and was not tested further.

CORROSION KINETICS[a] OF SOME ALLOYS[b] IN LOW- AND HIGH-SULFUR CHARS[c] AT TWO TEMPERATURES[36]





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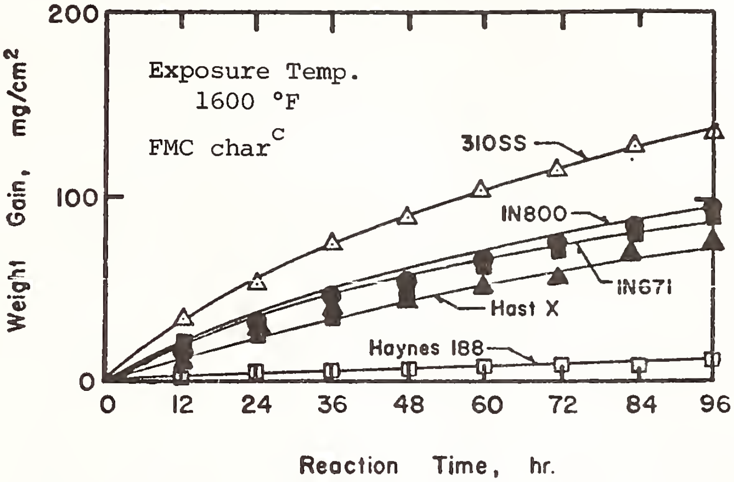
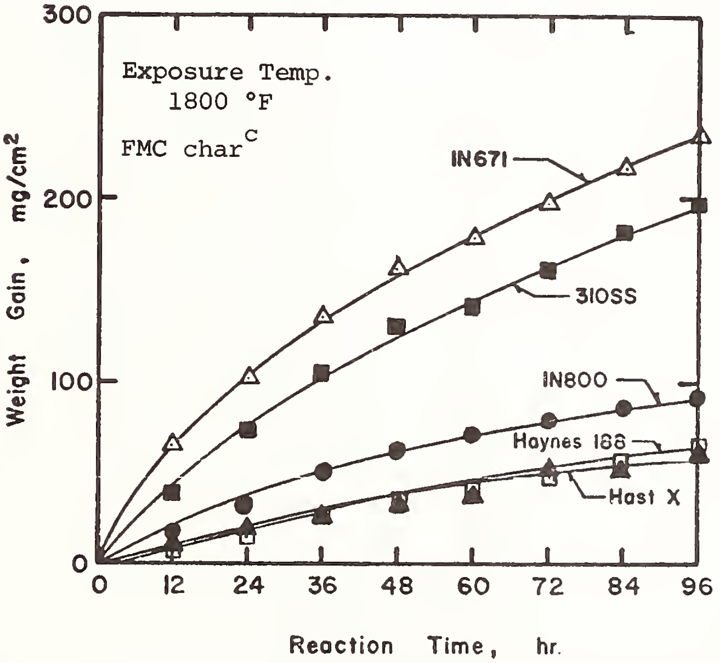
CORROSION KINETICS[a] OF SOME ALLOYS[b] IN LOW- AND HIGH-SULFUR CHARS[c] AT TWO TEMPERATURES[36], Continued





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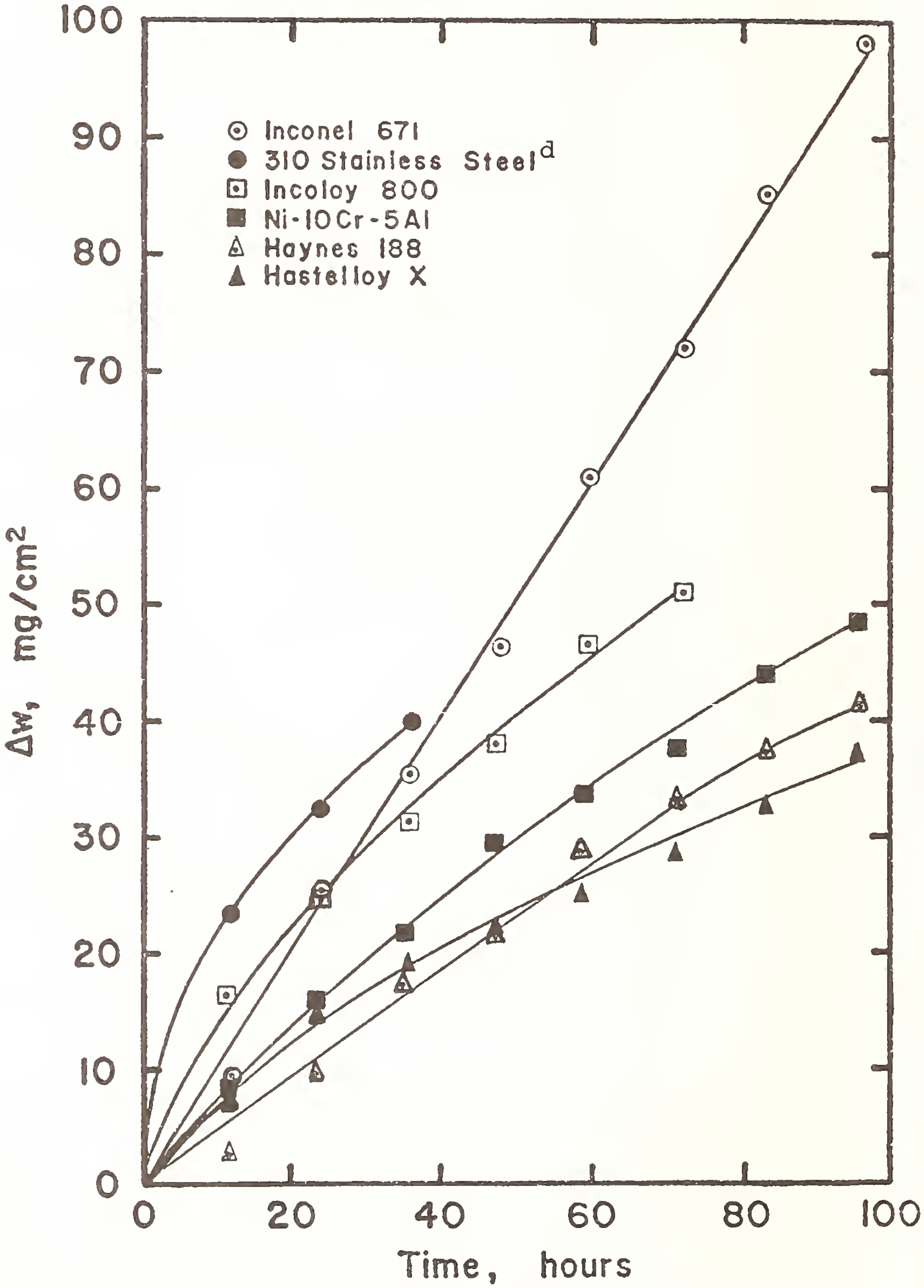
[a] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; 10 g char per sample was used; the char was replenished every 12 hours. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale.

[b] Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, and Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

[c] Coal chars used were Husky, N. Dakota lignite, containing about 0.9 wt % sulfur and FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine, containing about 2.7 wt % sulfur; chars -32+42 mesh.

COMPARATIVE CORROSION KINETICS[a] OF CHROMIA-FORMER ALLOYS[b] IN CONTACT WITH COAL CHAR[c] [36]



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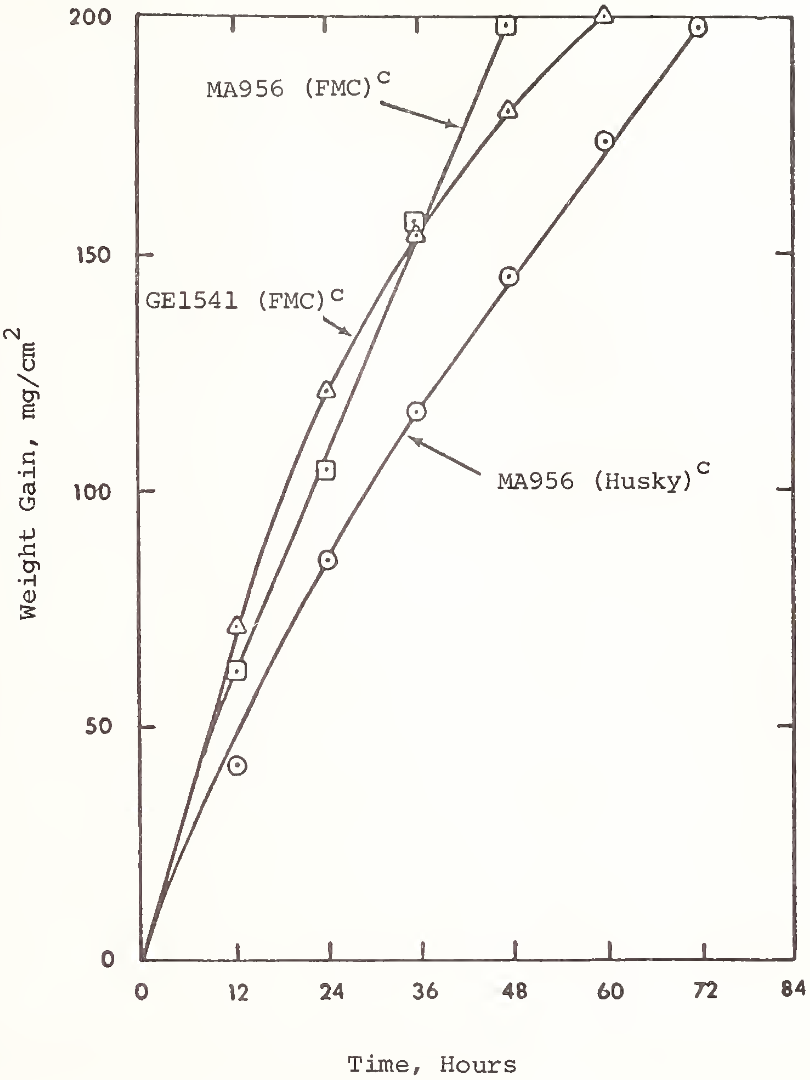
[a] Specimens were imbedded in char in ceramic or graphite boats in tube furnaces with an atmosphere of slowly flowing argon; test temperature was 1800 °F; 3 g char per sample was used; the char was replenished every 12 h. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight gain is plotted versus exposure time. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from corrosion scale.

[b] Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, and Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

[c] Coal char used was -32+42 mesh FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine; contains about 2.7 wt % sulfur.

[d] 310 SS spalled excessively after 36 h with 12 h replenishment and was not tested further.

CORROSION KINETICS[a] OF FeCrAlY ALLOYS[b] IN CONTACT WITH COAL CHAR[c][36]



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[a] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; test temperature was 1800 °F; 40 g char per sample was used; the char was replenished every 12 hours. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from corrosion scale.

[b] Alloys are Incoloy MA956 (20Cr-4.5Al-0.5Ti-0.5Y_2O_3-balance Fe) and GE1541 (14.4Cr-3.8Al-1.0Y-balance Fe). Samples 10 x 20 mm were sheared from sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

[c] Chars used were Husky, N.Dakota lignite, containing about 0.9 wt% sulfur and FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine, containing about 2.7 wt% sulfur; chars -32+42 mesh.

COMPARISON OF WEIGHT GAINS,[a] INTERNAL PENETRATION,[b] AND TOTAL METAL DEGRADATION[c] AS MEASURES OF THE CORROSION OF ALLOYS[d] IN CONTACT WITH COAL CHAR[e][36]

Alloy	Test Conditions at 1800 °F Time, hr[f]	Mesh Size	g char/sample	Weight gain[a] mg/cm^2	Internal Penetration[f] mils	Metal Degradation[c] mils
310 SS	54.5	-170	3	13.8	6.1	10.3
	96	-170	3	22.0	9.6	9.8
	4x24	unsieved	3	44.1	12.5	13.9
	2x12	unsieved	10	101.0	15.8	16.3
Hastelloy X	54.5	-170	3	7.1	4.3	4.8
	96	-170	3	9.1	5.6	4.0
	96	unsieved	3	11.6	4.0	7.6
	4x24	unsieved	3	29.4	6.8	8.1
	8x12	unsieved	3	36.7	15.7	17.1
	12	unsieved	10	15.5	5.9	24.5
	2x12	unsieved	10	33.0	11.8	19.1
Inconel 671	54.5	-170	3	15.2	10.3	14.6
	96	-170	3	21.9	7.9	19.0
	96	unsieved	3	20.1	4.2	10.2
	4x24	unsieved	3	27.5	15.2	31.5
	8x12	unsieved	3	98.7	21.1	22.7
	1x12	unsieved	10	44.2	7.9	14.0
	2x12	unsieved	10	110.0	15.2	12.7
				67.1	13.6	30.4
	1x12	unsieved	20	70.2	6.9	9.7
	2x12	unsieved	20	105.9	21.6	29.7
	1x12	unsieved	40	88.7	17.7	29.6
				84.6	14.4	28.3
	1x24	unsieved	20	90.0	20.4	39.5
Incoloy 800	54.5	-170	3	11.9	6.6	9.7
	96	-170	3	14.9	9.0	10.8
	96	unsieved	3	17.7	16.0	26.8
	4x24	unsieved	3	34.4	12.2	12.3
	2x12	unsieved	10	39.2	18.3	14.8
Haynes 188	54.5	-170	3	3.1	0.8	2.7
	96	-170	3	4.1	2.3	10.1
	96	unsieved	3	4.3	4.0	5.6
	4x24	unsieved	3	9.7	3.6	25.1
	8x12	unsieved	3	41.0	7.9	25.0
	12	unsieved	10	19.2	5.9	29.0
GE1541	12	unsieved	10	45.8	7.9	27.0

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[a] Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from corrosion scale.

[b] Measured metallographically.

[c] (Original thickness - distance between internal "fronts")÷2.

[d] Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, and Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

[e] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; coal char used was FMC, high-Volatile B Bituminous, W. Kentucky Colonial Mine; contains about 2.7 wt % sulfur.

[f] When time given is a single number the run was continuous with but a single charge of char. Other tests were conducted by replenishing the charge of char periodically, and the time is designated by two numbers, the number of times the char was changed and the time interval. For instance, 4x24 means the char was changed 4 times every 24 hours so that the total exposure was 96 hours.

CORROSION REACTION PRODUCTS OF SOME ALLOYS EXPOSED TO SULFUR ATMOSPHERE FROM DIRECT CONTACT WITH COAL CHAR[36]

Test Procedure: Alloy specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon. Tests were run with varying weights of char per sample. Some tests were run continuously for 96 hours with the same charge of char. In other runs the charge of char was replenished every 12 or 24 hours. Tests were conducted at 1600° and 1800 °F. A low-sulfur (∼0.9 wt% S) char, Husky, N. Dakota lignite, and a high-sulfur (∼2.7 wt% S) char, FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine were used. For some tests alloys were pre-oxidized either in air or in argon saturated with water vapor; oxidation temperatures ranged from 1800° to 2300 °F; time and temperature of oxidation were varied to produce a variety of oxide thicknesses.

Alloys Tested: 310 SS, Hastelloy X, Haynes 188, Incoloy 800 and Incoloy 800 coated with 63% Al-33%Cr-4%Hf, Inconel 671, GE1541 (14.4Cr-3.8Al-1.0Y-balance Fe), Incoloy MA956 (20Cr-4.5Al-0.5Ti-0.5Y_2O_3-balance Fe). Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, and Incoloy 800 were 0.125 in thick; Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces (except coated IN 800) were abraded through 4/0 silicon paper; samples were washed in acetone and dried. Two binary alloys were also tested, Fe-24Cr and Fe-13Al. The binary alloys were arc melted in a gettered argon atmosphere to form buttons approximately 100 g in weight. Buttons were remelted several times to insure homogeneity, then sliced with a spark cutter to slabs approximately 25 x 10 x 1 mm. Slabs were then prepared for testing similar to the commercial alloys.

General Results: Corrosion reaction was generally sulfidation until the sulfur was so depleted that the oxygen fugacity rose sufficiently to permit oxidation. Alloys exposed in continuous runs with no char replenishment formed some oxides. No carburization occurred in spite of high carbon activity. The higher the S content of the char, the greater the amount of char, and the higher the temperature, the greater the degree of corrosion. Generally, thick external sulfide scales formed with internal sulfides in the substrate both within grains and as intergranular particles and/or networks. Thickness of the scale and internal sulfidation zone increased with increasing frequency of char replenishment. Differences were noted in testing alloys one at a time and several together. If rather non-resistant alloys were present, they served to remove sulfur by rapid reaction and a more corrosion-resistant alloy appeared to have good corrosion resistance. The more corrosion-resistant alloy will have a better corrosion performance when tested with other alloys than when tested alone. In tests with pre-oxidized samples, results were virtually the same for these alloys which are chromia-formers as results for unoxidized samples. Alumina-formers initially showed a marked reduction in corrosion after pre-oxidation. Alumina films formed which protected the alloys at first but mechanical failure occurred, films broke down, and sulfidation took place. Oxide films do not protect edges and corners.

Specific Results

310 SS: The microstructure of scales formed in FMC char at 1600 °F and 1800 °F and in Husky char at 1800 °F consisted of massive external scales and extensive internal sulfidation. External scales and internal products were mainly Cr_3S_4 with minor amounts of $FeCr_2S_4$. In FMC char at 1800 °F random internal sulfides formed, but at 1600 °F and in Husky char at 1800 °F discrete bands of internal sulfides formed. Pre-oxidation formed film of NiO and Cr_2O_3 which offered no effective protection, the same corrosion features being observed on unoxidized samples.

Hastelloy X: Results as for 310 SS with the additional formation of NiS or metallic Ni in the scales. This alloy had a much thicker external scale in FMC at 1600 °F than in FMC at 1800 °F. Little internal sulfidation occurred at the lower temperature. External scales appeared to be mixtures of Fe and Cr sulfides with residual Mn. Some NiS in smaller amounts than other sulfides. Al, Ti and Si were present as oxides beneath the sulfide layer and also present as internal oxides. Pre-oxidation formed film of mixed spinels which offered no effective protection, the same corrosion features being observed on unoxidized samples. The alloy was also tested in an atmosphere of H_2-10% H_2S (no char) with markedly different scales formed. A thin outer layer formed with a matrix of mixed sulfide. An inner zone existed, about ten times thicker than the outer, with a matrix of the alloy almost completely Cr-depleted. Chromium sulfide containing some Fe constituted more than half the volume.

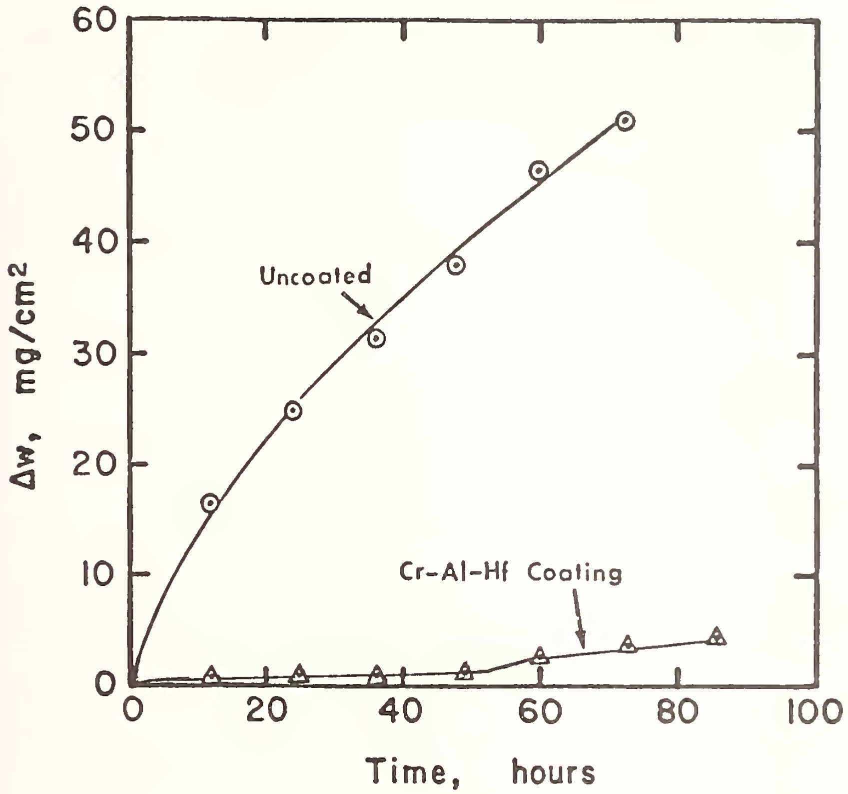
(Data Continued)

CORROSION REACTION PRODUCTS OF SOME ALLOYS EXPOSED TO SULFUR ATMOSPHERE FROM DIRECT CONTACT WITH COAL CHAR[36], continued

Specific Results, continued

Haynes 188:	Results as for 310 SS except that no $FeCr_2S_4$ was formed and NiS or metallic Ni was found in the scales. Pre-oxidation offered no effective protection, the same corrosion features being observed on unoxidized samples.
Incoloy 800:	Results as for 310 SS except that this alloy always formed a grain boundary network of internal sulfides which was "continuous" with the external sulfide scale. The network seemed to anchor the scale mechanically and minimized subsequent parting of the scale from the substrate. External scales appeared to be mixtures of Fe and Cr sulfides with residual Mn. Some NiS present in smaller amounts than other sulfides. Al, Ti and Si present as oxides beneath the sulfide layer and also present as internal oxides. In 96 hour tests with no char replenishment the matrix contained a semi-continuous intergranular network of a Cr-rich phase. Al and Ti formed very fine precipitates within grains. The intergranular phases in the internal reaction zone were Al and Ti oxides; sulfides formed inside the grains and were either Cr or Mn sulfides. No carbides were detected. Sulfur-rich regions were associated only with Cr-rich regions, and oxygen-rich regions were associated only with Ti and Al. The Cr-rich grain boundary phase in unreacted alloy is a thick block structure whereas the grain boundary phase in the reaction zone was much thinner and more elongated. Pre-oxidation formed film of mixed spinels which offered no effective protection, the same corrosion features being observed on unoxidized samples.
Incoloy 800 Coated:	An external scale of Cr_3S_4 formed with an internal zone of Al_2S_3 in a matrix of $CrAl_2S_4$. One of two samples spalled after 72 hours reaction.
Inconel 671:	Results as for 310 SS but with no formation of $FeCr_2S_4$ and with formation of NiS and metallic Ni. Random internal sulfides formed in FMC at 1800 °F and discrete bands of internal sulfides in FMC at 1600 °F and in Husky at 1800 °F. Pre-oxidation formed film of Cr_2O_3 which offered no effective protection, the same corrosion features being observed on unoxidized samples. The alloy was also tested in an atmosphere of H_2-10% H_2S (no char) with markedly different scales formed. A thick external scale, duplex in nature, formed. The thin outer portion had an NiS matrix with Cr_3S_4 dendrites, the dendrites having some Ni in solution. A very thin rim of NiS was at the outermost extremity of the layer containing the dendrites. The inner, compact layer was Cr_3S_4 with very fine stringers perpendicular to the layer. Stringers contained Ni, Cr, and S, probably as $NiCr_2S_4$. There was also a thin zone of internal sulfidation which also appeared to be the spinel sulfide.
GE1541:	Samples were pre-oxidized forming protective alumina films. Initial performance in char tests good but films broke down permitting subsequent extensive sulfidation. Nodules of iron and chromium sulfides formed where oxide film broke. No aluminum sulfide formed.
Incoloy MA956:	Results of char testing pre-oxidized samples similar to GE1541. Outer scale had a lamellar structure of alternate plates of chromium sulfide and a chromium-iron sulfide; structure has the appearance of a eutectic. External scale formed only on the exterior of the alumina film and formed whether or not obvious defects in the oxide film were observed. Extensive internal sulfidation occurred. Pre-oxidized samples were tested in a sulfur vapor atmosphere, 0.1 atm S at 1000 °C. Localized breakdown of oxide films occurred leading to extensive development of sulfide nodules on the surface of the film, primarily at edges and where sharp angles existed.
Fe-24Cr:	Pre-oxidized samples which formed a chromia film were also tested in sulfur vapor atmosphere. Nodules formed on the total surface of the oxide film independent of edges and corners. Nodules were a mixture of iron sulfide and chromium-iron sulfide.
FE-13Al:	Pre-oxidized samples were tested in sulfur vapor atmosphere. Localized breakdown of the alumina films occurred leading to extensive sulfide nodule formation on the exterior of the film. Aluminum sulfide formed readily, even on pre-oxidized samples, and was unstable and disintegrated in the moisture in the air.

EFFECT OF COATING[a] ON THE CORROSION[b] OF INCOLOY 800 IN CHAR[c] [36]



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[a] Coating consisted of 63% Al-33% Cr-4% Hf. One of two samples exhibited spalling after 72 hours reaction.

[b] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; test temperature was 1800°F; 3 g char per sample was used and the char was replenished every 12 hours. Weight gain is plotted above versus exposure time. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale.

[c] Coal char used was -32+42 FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine; contains about 2.7 wt % sulfur.

EFFECT OF PRE-OXIDATION[a] ON THE CORROSION[b] OF SOME ALLOYS[c] IN CONTACT WITH CHAR[d][36]

Alloy	Preoxidation[a] time/hr	Preoxidation Weight gain mg/cm^2	Char Corrosion[b] Weight gain mg/cm^2
310 SS	none	--	72.9
	12	0.24	--
	24	0.30	68.9
	36	0.46	91.1
Inconel 671	none	--	103.7
	12	0.05	102.9
	24	0.22	95.9
	36	0.77	90.6
Incoloy 800	none	--	36.8
	12	0.10	--
	24	0.73	30.1
	36	0.92	42.4
Hastelloy X	none	--	19.3
	12	0.42	30.7
	24	0.42	20.0
	36	0.09	44.1
Haynes 188	none	--	14.7
	12	0.45	21.7
	24	0.45	19.5
	36	?	23.7
GE1541 (FeCrAlY)	0	--	139.4
	12	0.30	38.3
	24	0.30	31.2
	36	0.25	0.9
	48	0.45	0.29

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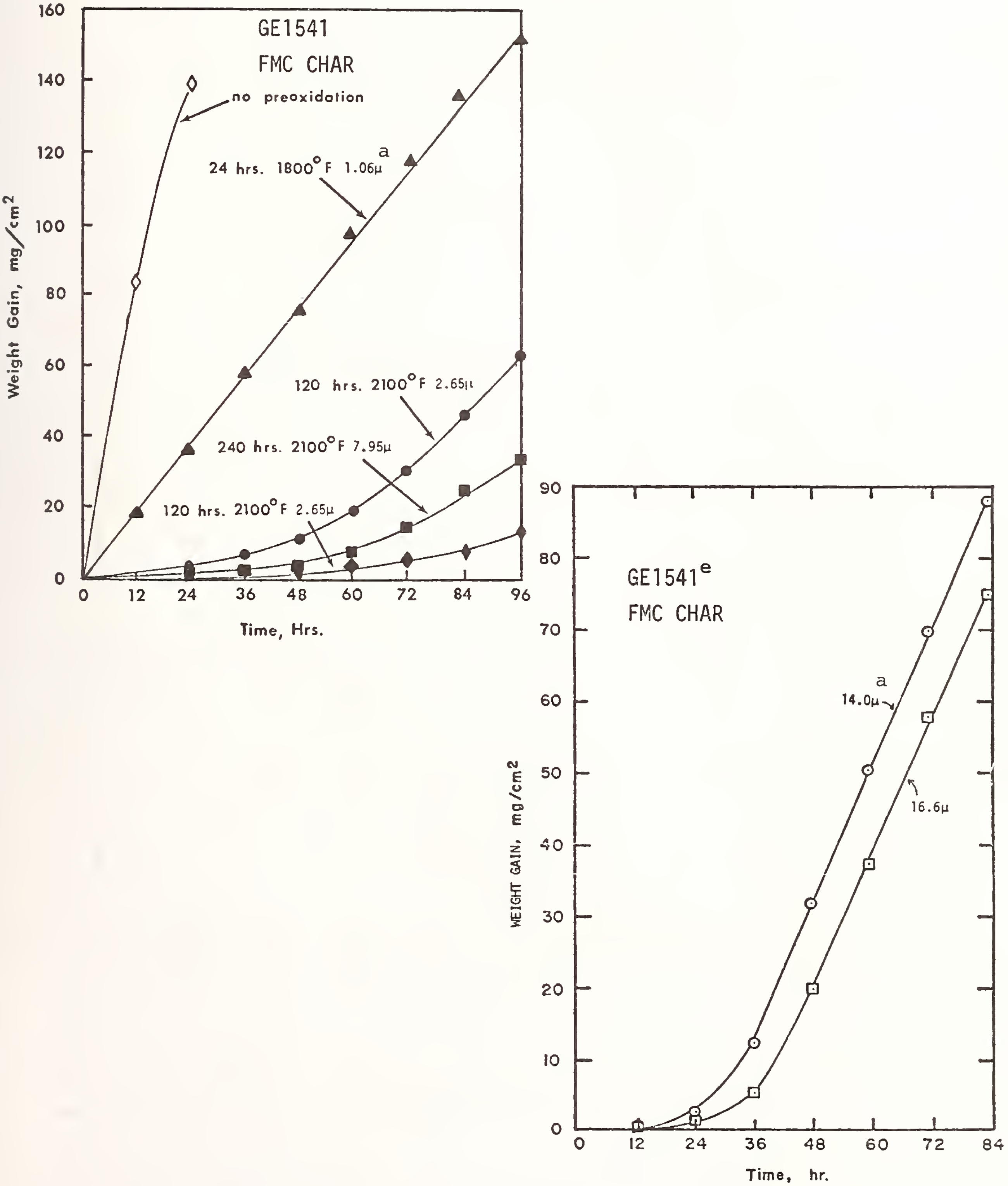
[a] Alloys were pre-oxidized at 1800 °F in argon saturated with water at ambient temperatures.

[b] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; 10 g char per sample was used; test ran for two twelve hour periods. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale.

[c] Alloys were obtained in sheets: 310 SS, Hastelloy X, Haynes 188, Incoloy 800 were 0.125 in thick, Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

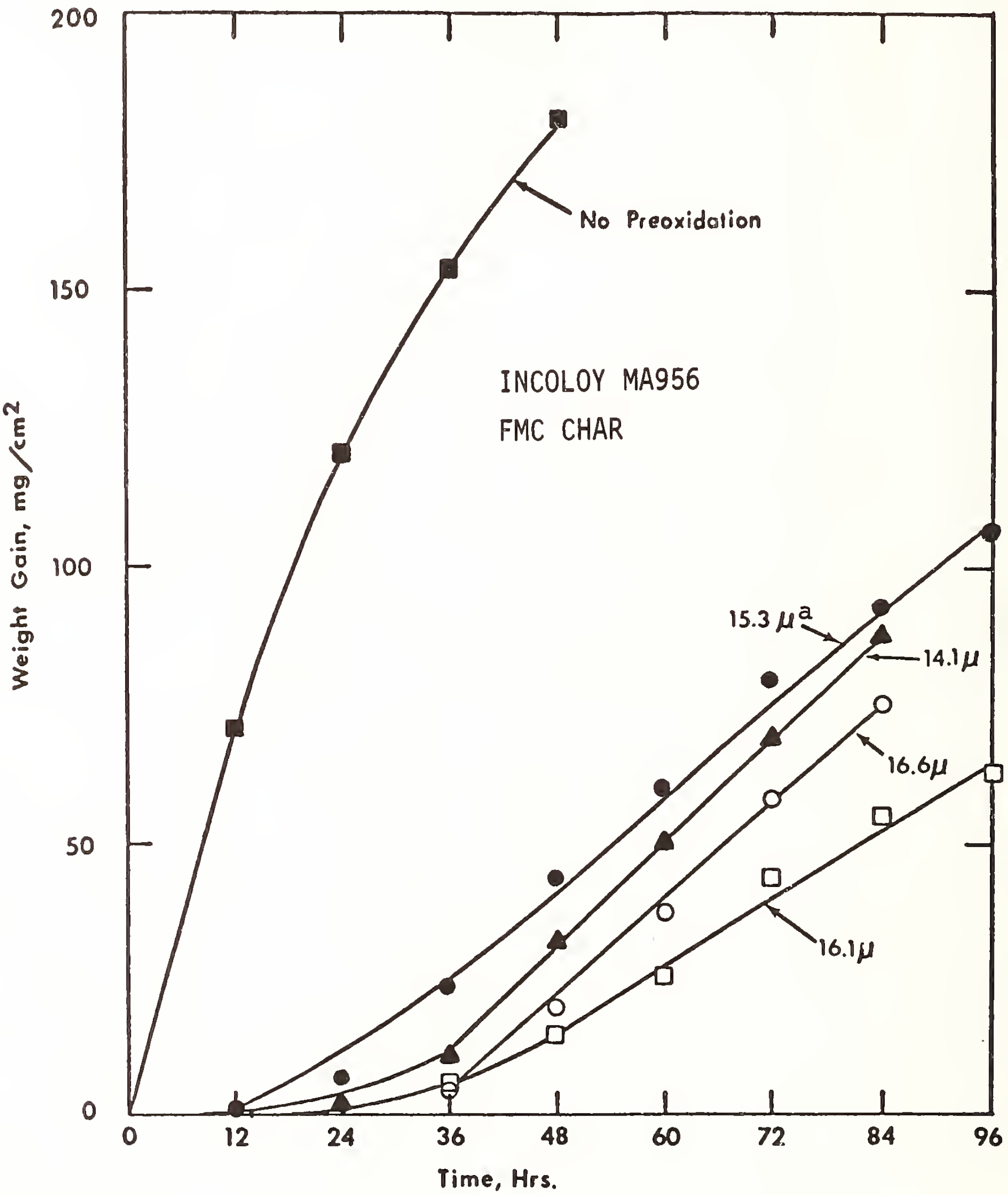
[d] Char used was -32+42 mesh FMC, High-Volatile B Bituminous, W. Kentucky Colonial Mine, containing about 2.7 wt % sulfur.

EFFECT OF PRE-OXIDATION[a] ON THE CORROSION KINETICS[b] OF ALUMINA-FORMER ALLOYS[c] IN CONTACT WITH COAL CHAR[d][36]



(Data Continued)

EFFECT OF PRE-OXIDATION[a] ON THE CORROSION KINETICS[b] OF ALUMINA-FORMER ALLOYS[c] IN CONTACT WITH COAL CHAR[d][36], Continued



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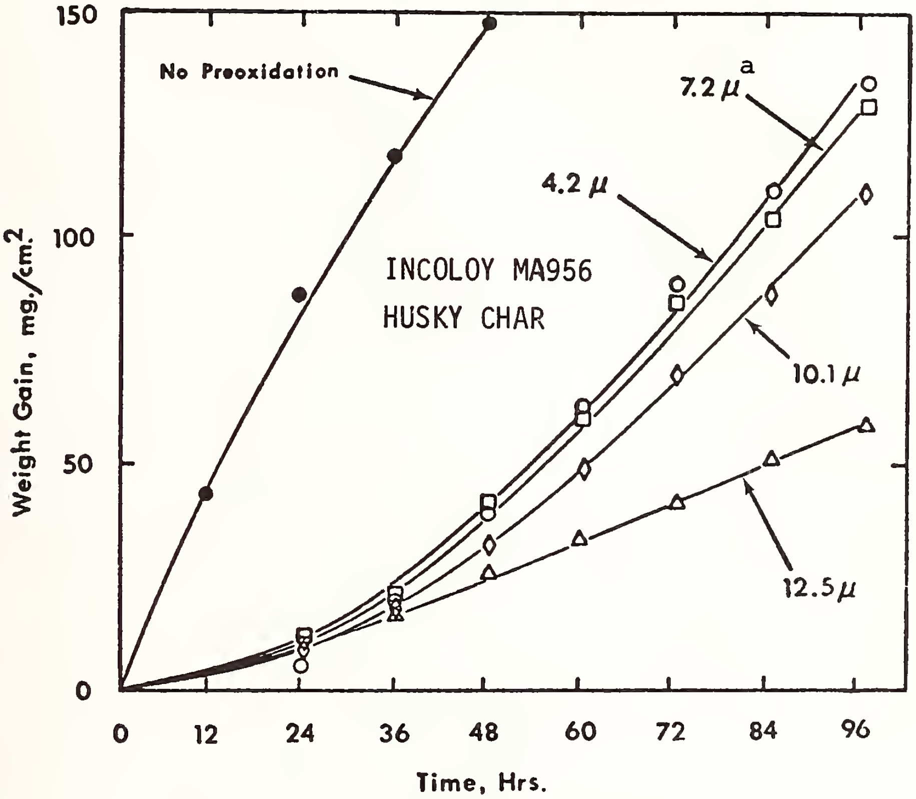
EFFECT OF PRE-OXIDATION[a] ON THE CORROSION KINETICS[b] OF ALUMINA-FORMER ALLOYS[c] IN CONTACT WITH COAL CHAR[d][36], Continued



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[a] Preoxidation took place either in air or in argon saturated with water vapor. Temperatures ranged from 1800°F to 2300°F. Oxidation time and temperature were varied to produce a variety of oxide thicknesses.

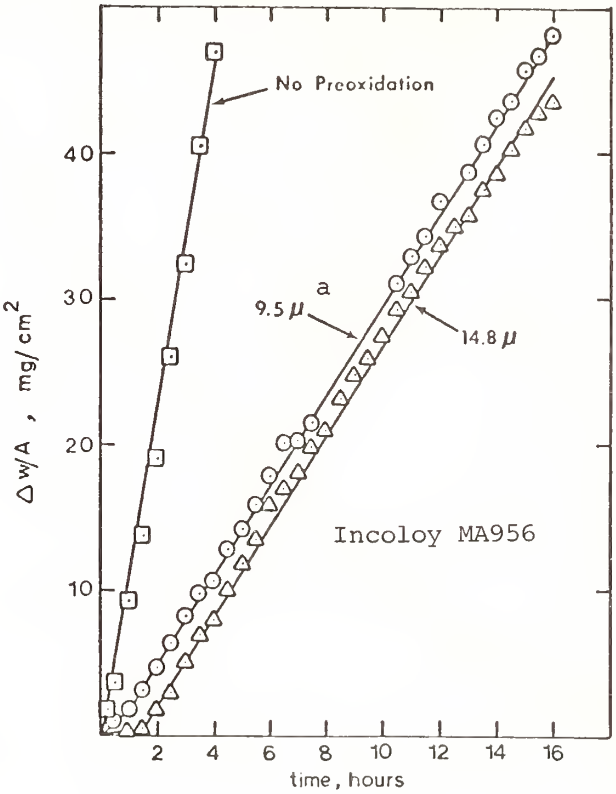
[b] Specimens were imbedded in char in ceramic or graphite boats in horizontal tube furnaces with an atmosphere of slowly flowing argon; 10 g char per samples was used; the char was replenished every 12 hours. Alloy samples were weighed before exposure; after exposure samples were brushed lightly to remove loosely adherent char and reweighed. Weight measurements give overly pessimistic corrosion rates because not all char particles adhering to the surface could be removed from the corrosion scale. Exposure temperature was 1800°F.

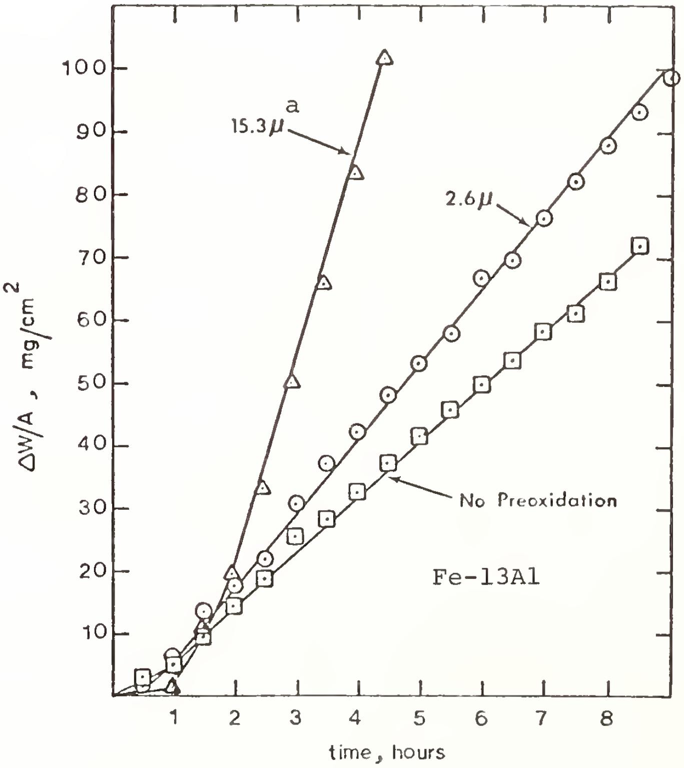
[c] Alloys tested were GE1541 (14.4Cr-3.8Al-1.0Y-balance Fe) and Incoloy MA956 (20Cr-4.5Al-0.5Ti-0.5Y_2O_3-balance Fe). Samples 10 x 20 mm were sheared from sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

[d] Coal chars used were -32+42 mesh, FMC High-Volatile B Bituminous, W. Kentucky Colonial Mine, containing about 2.7 wt % sulfur and Husky, N. Dakota lignite, containing about 0.9 wt % sulfur.

[e] Two samples were subjected to the same preoxidation treatment, 240 hours at 2300°F. Different films formed on the two samples.

EFFECT OF PRE-OXIDATION[a] ON THE CORROSION KINETICS[b] OF ALLOYS[c] IN SULFUR VAPOR[36]





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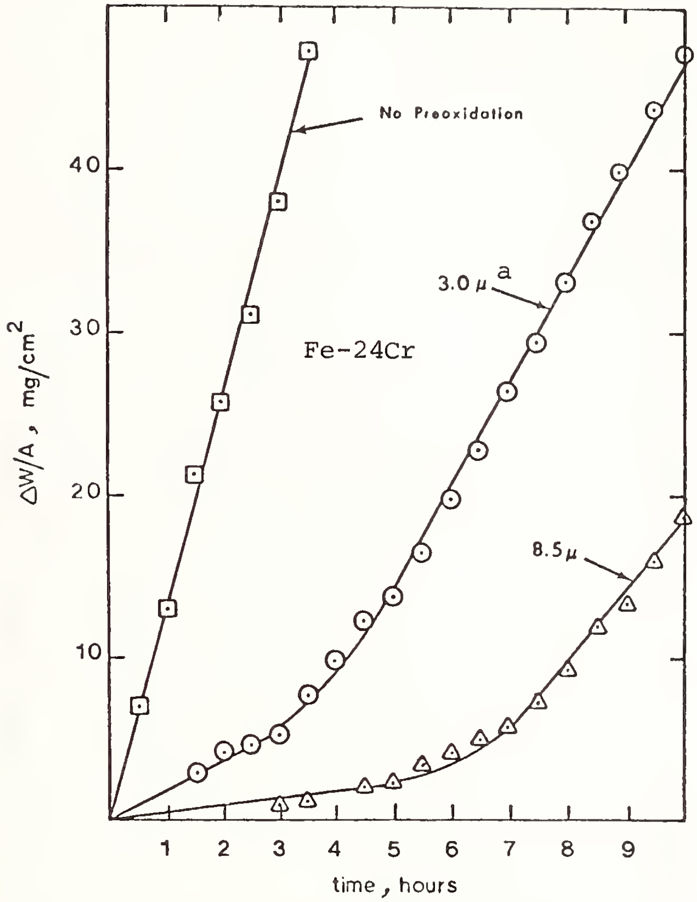
EFFECT OF PRE-OXIDATION[a] ON THE CORROSION KINETICS[b] OF ALLOYS[c] IN SULFUR VAPOR[36], Continued



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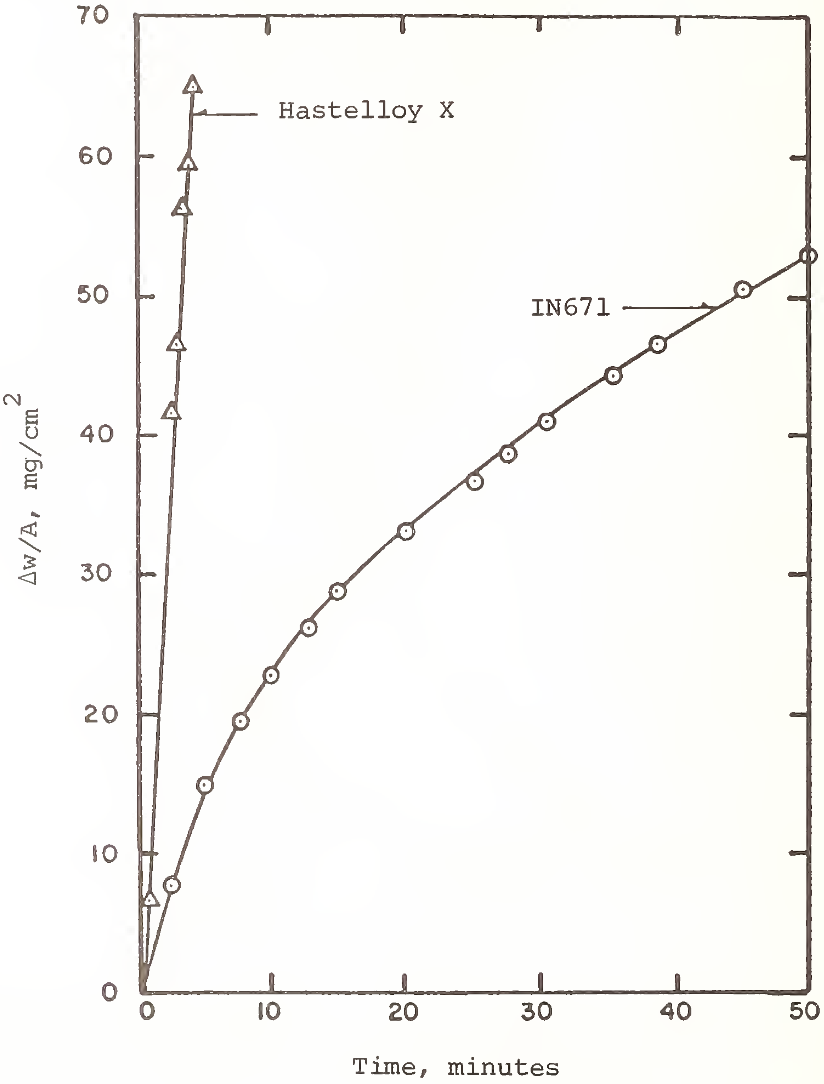
[a] Pre-oxidation took place either in air or in argon saturated with water vapor. Temperatures ranged from 1800°F to 2300°F. Oxidation time and temperature were varied to produce a variety of oxide thicknesses, designated in microns on the graphs.

[b] Specimens were subjected to corrosion by sulfur vapor in the same vessel in which they were pre-oxidized to avoid cooling and the accompanying thermal stresses which might cause the protective layers to spall. Sulfur vapor tests were conducted at 1000°C and 0.1 atm sulfur. Alloy samples were weighed before and after exposure. Weight gain per unit area is plotted against reaction time.

[c] Alloys tested were Incoloy MA956 (21Cr-4.5Al-0.5Ti-0.5Y_2O_3-balance Fe) and two binary alloys, Fe-24Cr and Fe-13Al. The binary alloys were arc melted in a gettered argon atmosphere to form buttons approximately 100 g weight. Buttons were remelted several times to insure homogeneity then sliced with a spark cutter to slabs approximately 25 x 10 x 1 mm. All surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

CORROSION KINETICS[a] OF TWO ALLOYS[b] IN H_2-H_2S[c][36]



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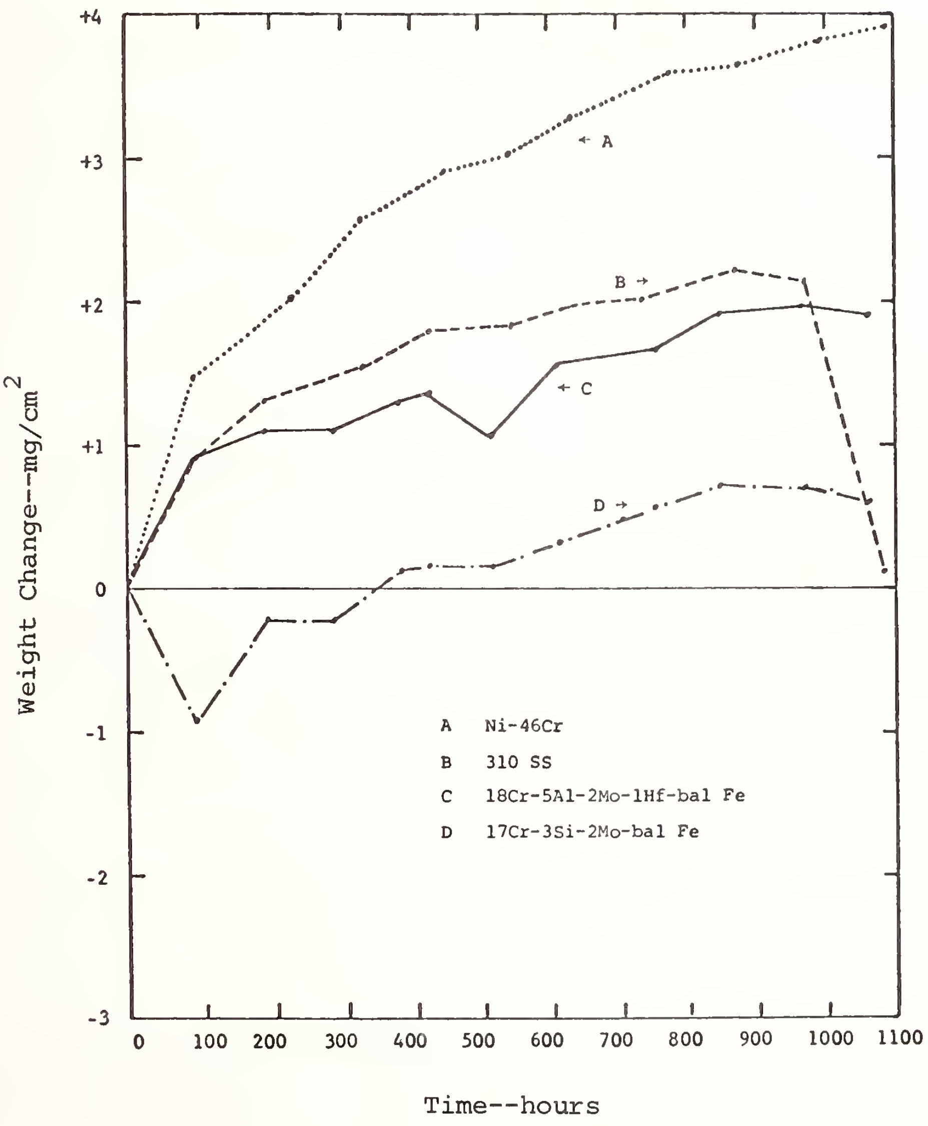
[a] Alloys were exposed at 1740 °F (950 °C). Weight gain per unit area is plotted above versus exposure time.

[b] Alloys were obtained in sheets: Hastelloy X 0.125 in thick, Inconel 671 0.25 in thick. Samples 10 x 20 mm were sheared from the sheets, sharp edges slightly rounded to reduce effect on scale spallation; all surfaces were abraded through 4/0 silicon carbide paper; samples were washed in acetone and dried.

[c] Atmosphere was H_2-10% H_2S (tests run at McMaster University, Hamilton, Ontario, Canada). Conditions of test provided a sulfur partial pressure nearly identical to that existing in corrosion tests using FMC char, see other corrosion kinetics pages with the same reference as this one.

CORROSION RESISTANCE OF COMMERCIAL AND EXPERIMENTAL[a] ALLOYS UNDER CYCLIC[b] EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[c] [34]



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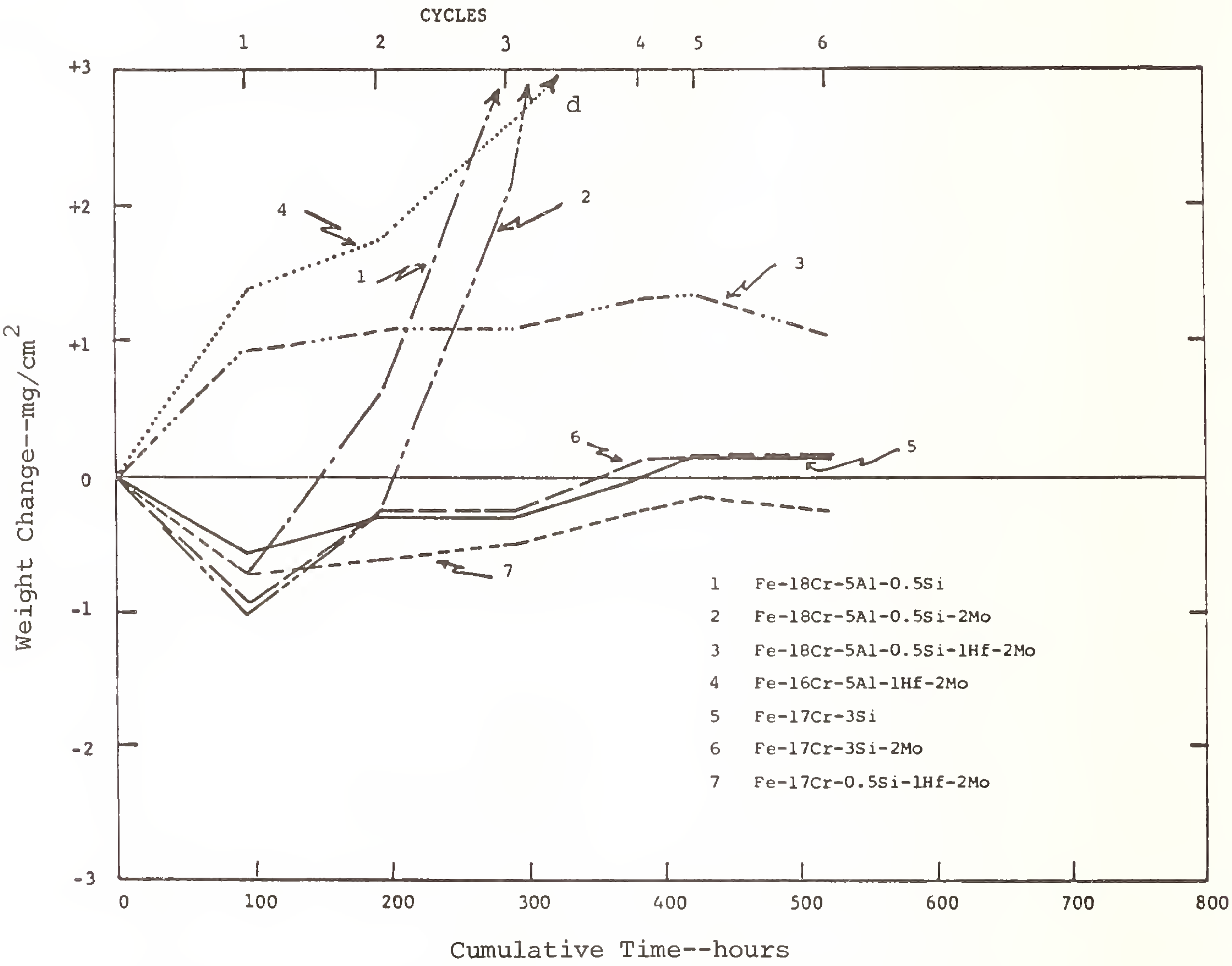
[a] Alloys vacuum induction melted. Ingots homogenized, forged, and rolled to plate.

[b] Nominal 100 hr cycles to 1255 K (1800°F), cool to ambient temperature in <1 min.

[c] Input gas composition: 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O; pressure 1 atm.

[d] Downturn of curve indicates potential break away from protective behavior.

CORROSION OF ALLOYS[a] SUBJECTED TO CYCLIC EXPOSURE[b] IN A COAL GASIFICATION ENVIRONMENT[c] [34]



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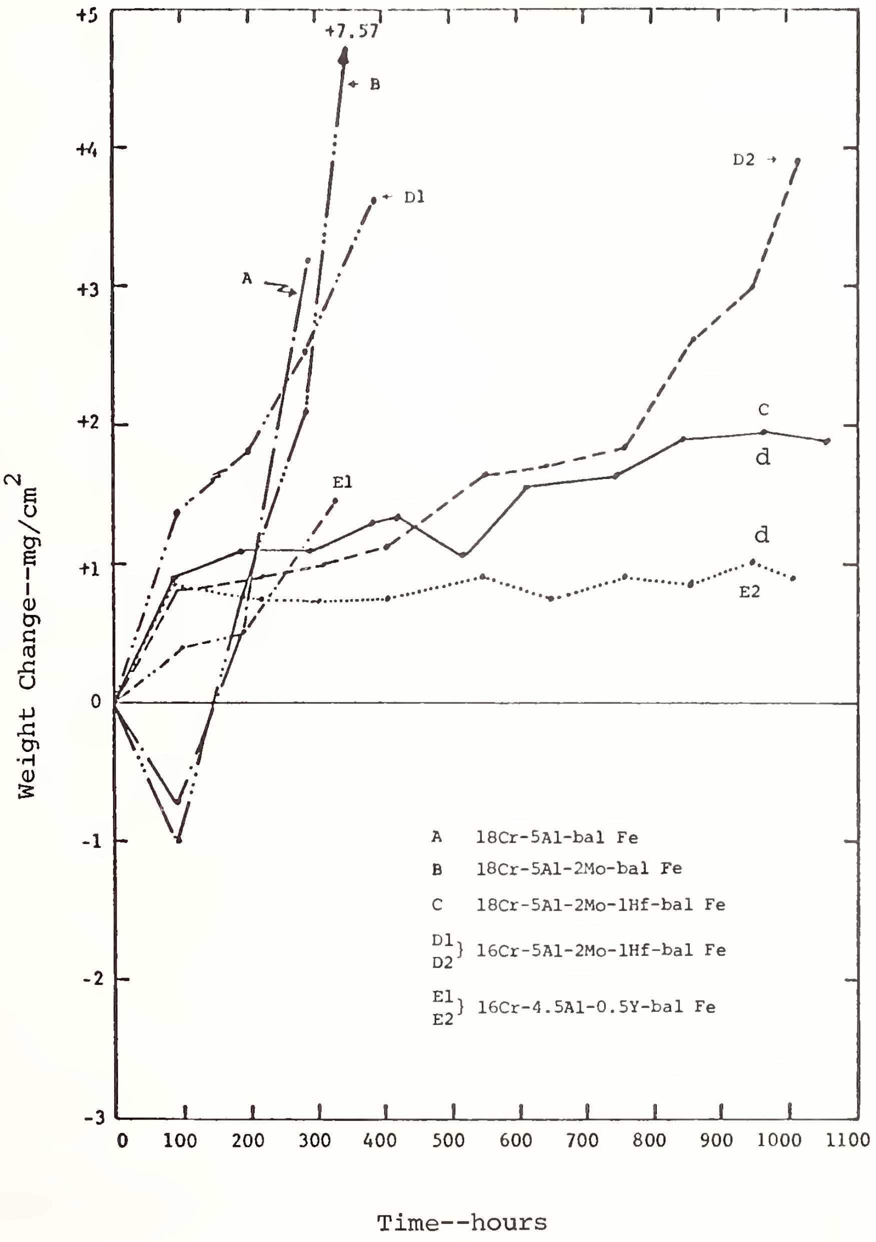
[a] Alloys prepared by nonconsumable electrode arc melting (120 gm ingot). Button ingots were turned and remelted 3 times (mix, homogenize) and drop cast. Cylindrical ingots heated 1 hr at 2000 °F (canned in stainless steel) and extruded to flat sheet bars (0.29 in x 1 in x 6 in, 4:1 reduction) at a ram speed of 12-IPM using copper sheath for die lubrication. Local defects were ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F (10% reduction per pass), 1/2 of sheet further rolled (1600 °F) to 0.070 in thickness. Surface conditioned by grit blasting.

[b] Samples exposed at 1800 °F and 1 atm for times indicated.

[c] Nominal gas composition (mol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O.

[d] Samples 1, 2, and 4 developed many sulfide failure spots during the second and third cycles. Weight gains began to increase rapidly and after 4 cycles the samples were attacked so severely they were removed from testing.

CORROSION RESISTANCE OF FeCrAl EXPERIMENTAL ALLOYS[a] UNDER CYCLIC[b] EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[c] [34]



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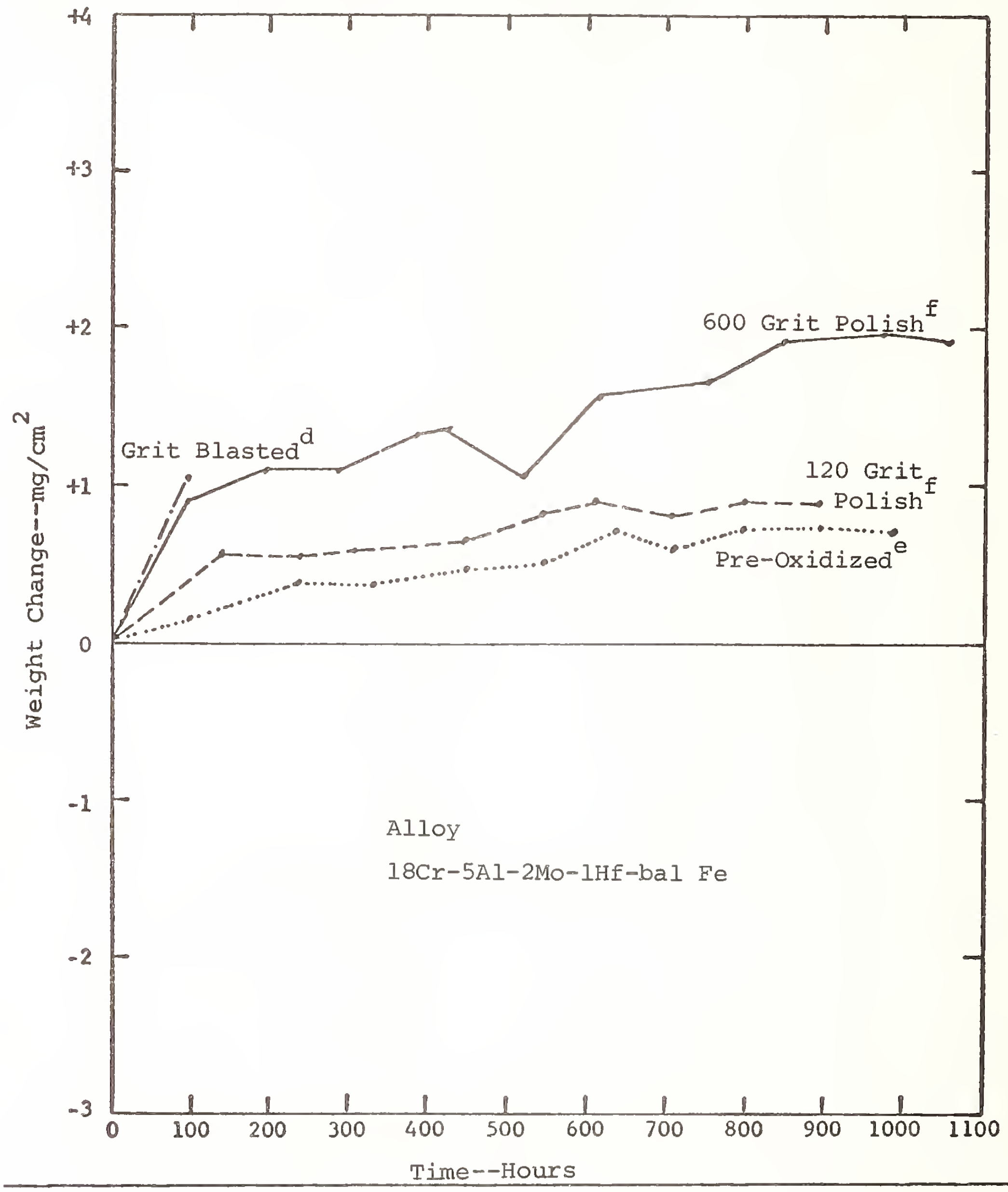
[a] Alloys vacuum induction melted. Ingots homogenized, forged, and rolled to plate.

[b] Nominal 100 hr cycles to 1255 K (1800°F), cool to ambient temperature in <1 min.

[c] Input gas composition: 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O; pressure 1 atm.

[d] Downturn of curve indicates potential break away from protective behavior.

EFFECT OF SURFACE CONDITION ON CORROSION BEHAVIOR OF FeCrAl EXPERIMENTAL ALLOY[a] UNDER CYCLIC[b] EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[c] [34]



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[a] Alloys were vacuum induction melted, homogenized, forged, and rolled to plate.

[b] Nominal 100 hr cycles to 1255 K (1800°F), cooled to room temperature in <1 min.

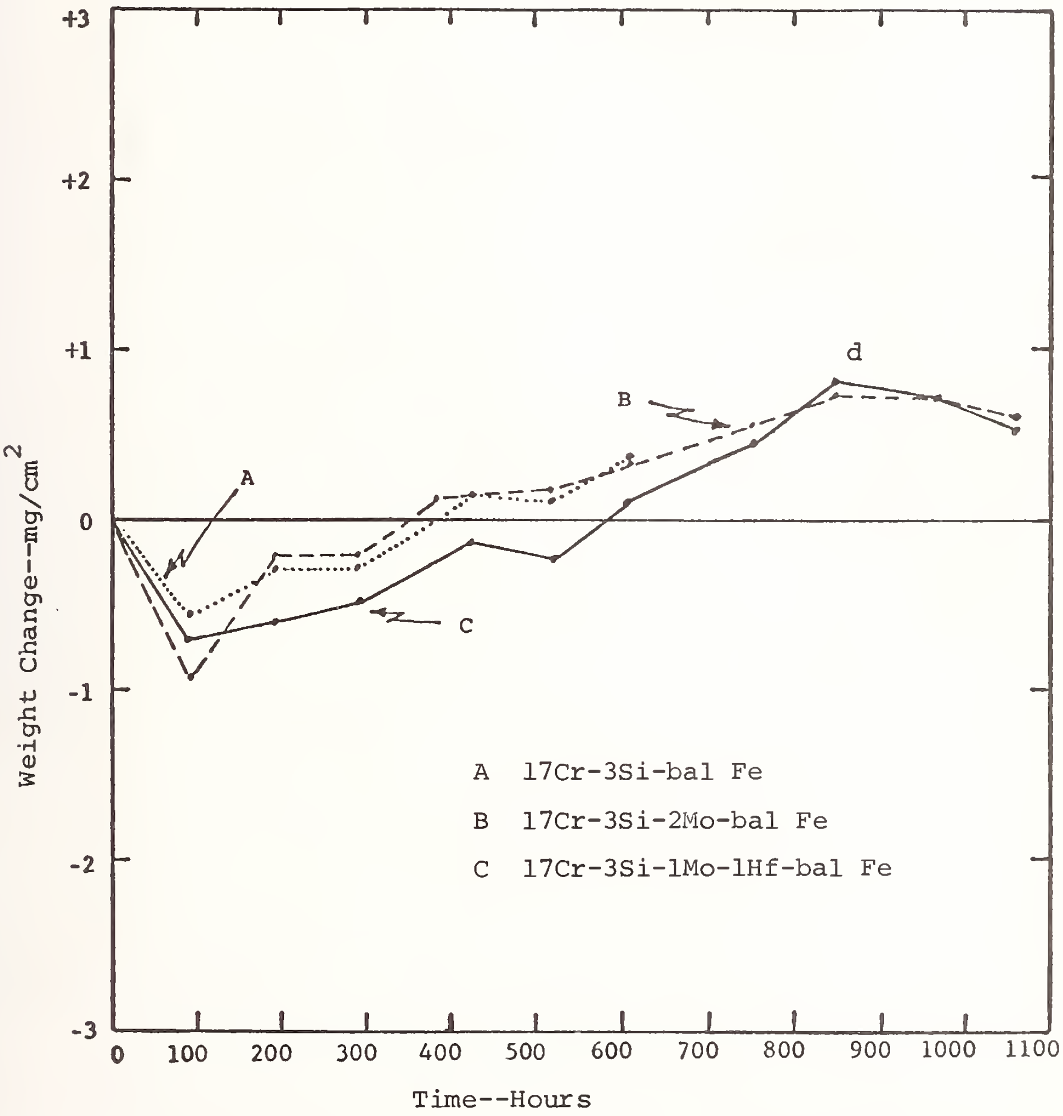
[c] Input gas composition: 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O; pressure 1 atm.

[d] Mill scale removed.

[e] Surface polished through 120 grit to remove affected material; oxidized 2 hr at 1800°F in air.

[f] Affected material removed.

CORROSION RESISTANCE OF FeCrSi EXPERIMENTAL ALLOYS[a] UNDER CYCLIC[b] EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[c] [34]



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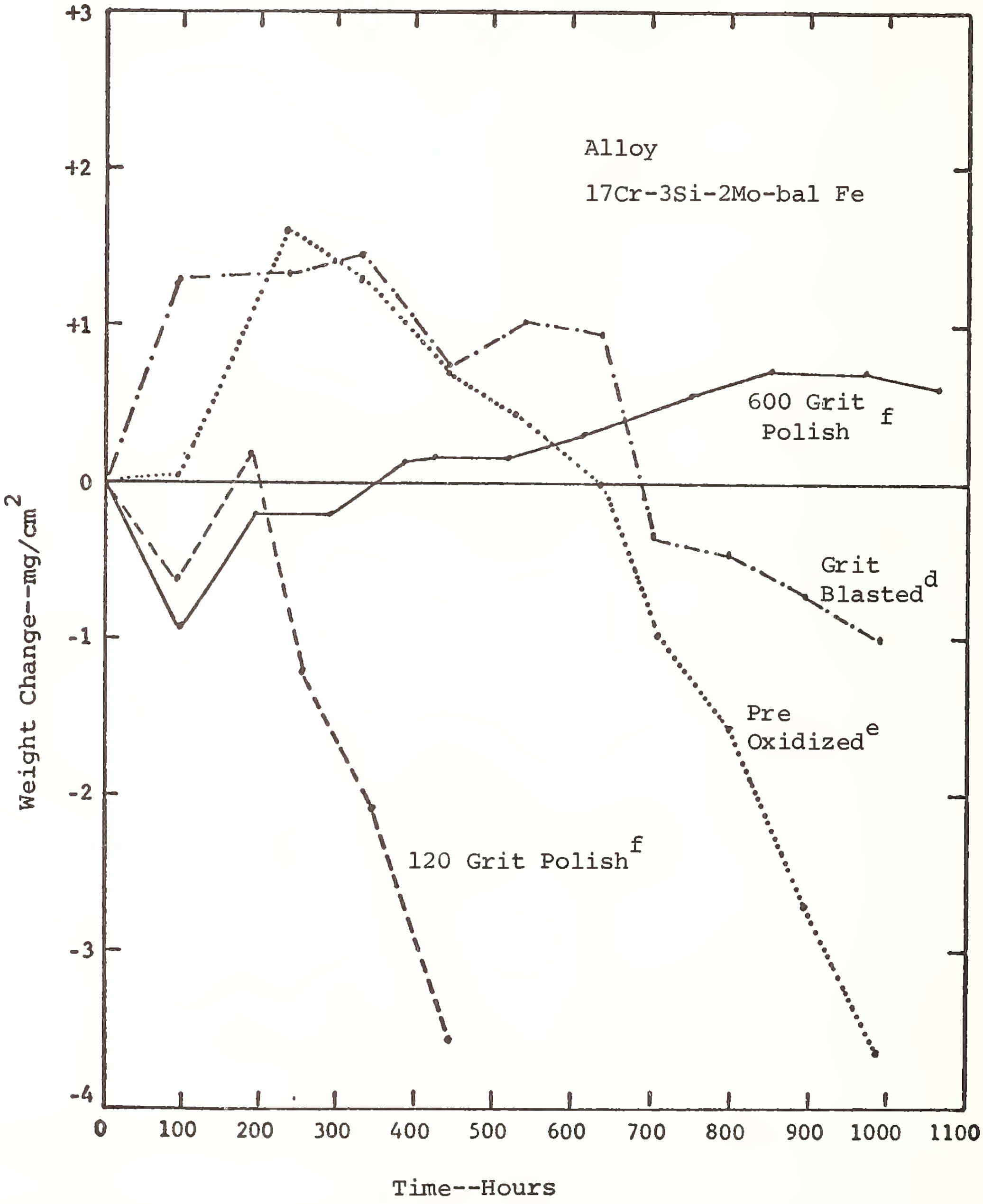
[a] Alloys prepared by vacuum induction melting. Ingots were homogenized, forged, and rolled to plate.

[b] Nominal 100 hr cycles to 1255 K (1800°F), cool to ambient temperature in <1 min.

[c] Input gas composition: 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O; pressure 1 atm.

[d] Downturn of curve indicates potential break away from protective behavior.

EFFECT OF SURFACE CONDITION ON CORROSION BEHAVIOR OF FeCrSi EXPERIMENTAL ALLOYS[a] UNDER CYCLIC[b] EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[c] [34]



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[a] Alloys were vacuum induction melted, homogenized, forged, and rolled to plate.

[b] Nominal 100 hr cycles to 1255 K (1800°F), cooled to room temperature in <1 min.

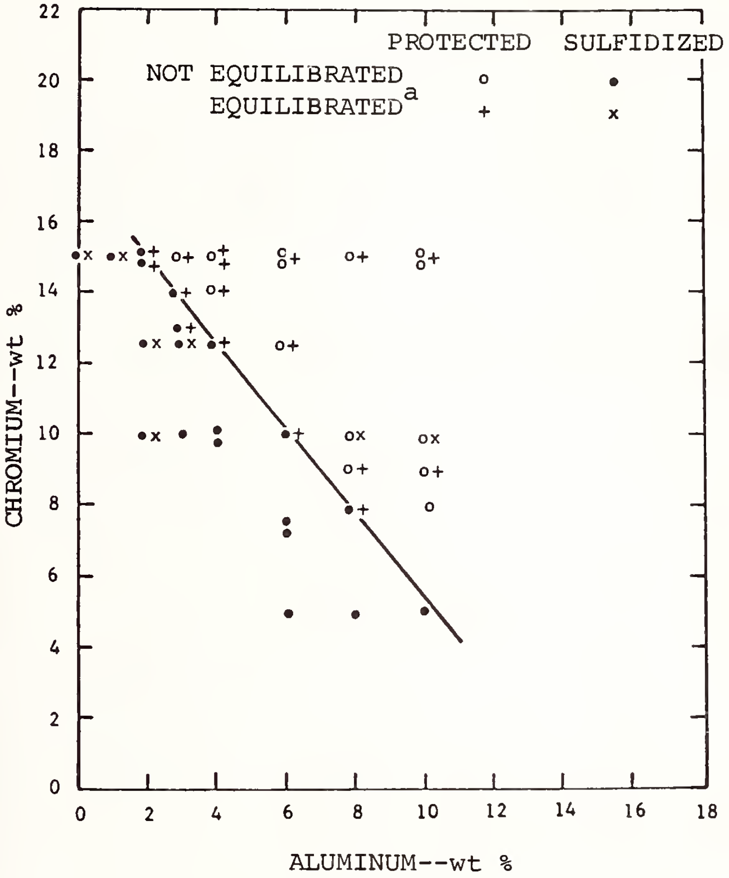
[c] Input gas composition: 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O; pressure 1 atm.

[d] Mill scale removed.

[e] Surface polished through 120 grit to remove affected material; oxidized 2 hr at 1800°F in air.

[f] Affected material removed.

EFFECT OF Cr AND Al CONTENT ON SULFIDATION RESISTANCE[a] OF Fe-Cr-Al ALLOYS[b] IN COAL GASIFICATION ATMOSPHERE[c][34]



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[a] Tests for sulfidation resistance in coal gasification atmosphere conducted at atmospheric pressure at 1800 °F for times varying from 24 to 96 hr. Gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec (unequilibrated condition). For equilibrium condition, gas percolated through a heated bed of fine/coarse alumina bubble grains fitted in the furnace tube to withing 1-inch of the lowest sample on the specimen rack.

[b] Alloys prepared by nonconsumable electrode arc melting (120 gm ingot). Button ingots were turned and remelted 3 times (mix, homogenize) and drop cast. Cylindrical ingots heated 1 hr at 2000 °F (canned in stainless steel) and extruded to flat sheet bars (0.29 in x 1 in x 6 in, 4:1 reduction) at a ram speed of 12-IPM using copper sheath for die lubrication. Local defects were ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F (10% reduction per pass), 1/2 of sheet further rolled (1600 °F) to 0.070 in thickness. Surface conditioned by grit blasting.

[c] Nominal gas composition (mol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O. Equilibrated gas also contains minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, CS.

[34]

SULFIDATION RESISTANCE OF EXPERIMENTAL Fe -Cr-Si/Al ALLOYS[a] EXPOSED TO A SYNTHETIC COAL GASIFICATION ATMOSPHERE

Alloy[a]	Steady State Test[b]			Cyclic Test[c]		
	Weight Gain mg/cm^2	Scale[d] Mil	Penetration Mil	Weight Gain mg/cm^2	Scale Mil	Penetration Mil
17Cr-3Si-bal Fe	-1.60	SO		--	--	--
17Cr-3Si-1Mo-1Hf-bal Fe	-2.49	SO,0.1-1.0		+0.52	SO,0.2-1.0	none
17Cr-3Si-2Mo-bal Fe	+161.6	SS		+0.60	SO,0.2-0.5	none
16Cr-4.5Al-0.5Y-bal Fe[e]	+1.25	AO		--	--	--
16Cr-4.5Al-0.5Y-bal Fe[e]	+1.06	AO,0.20	1.50	+0.90	AO,0.20	1.20
16Cr-5Al-2Mo-1Hf-bal Fe	+1.36	AO,0.10	0.40	+3.38	AO	--
18Cr-5Al-2Mo-1Hf-bal Fe	--	--	--	+1.89	AO,0.2	0.80
310 SS[f] Baseline alloy	+2.22	AO,0.3	1.50	+0.12	SO,0.3,IS	1.50
Ni-46Cr Baseline alloy	+3.40	AO,1.0	2.50	+3.88	AO,1.0,IO, IS, Cr depletion	2.50

[a] Alloys prepared by vacuum induction melting; ingots were homogenized, forged, and rolled to plate.

[b] Input gas composition (mol %): $24H_2$, 18CO, $12CO_2$, $5CH_4$, $1NH_3$, $0.5H_2S$, $39.5H_2O$; 1000 hr exposure at 1800 °F and 1 atm.

[c] Input gas composition (mol %): $24H_2$, 18CO, $12CO_2$, $5CH_4$, $1NH_3$, $1H_2S$, $39H_2O$; 1010-1084 hr cyclic exposure at 1800 °F and 1 atm; nominal 100 hr cycles, cool to ambient temperature in less than one minute, total of 10 cycles.

[d] SO - spalled oxide, SS - sulfide slag, AO - adherent oxide, IS - internal sulfidation, IO - internal oxidation.

[e] Allegheny - Ludlum alloy.

[f] Commercial 310 SS.

EFFECT OF SURFACE FINISH ON SULFIDATION RESISTANCE OF Fe-Cr-Al-Si EXPERIMENTAL ALLOYS[a] IN A SYNTHETIC COAL GASIFICATION ATMOSPHERE[b] [34]

Alloy[a]	Weight Gain - mg/cm^2 As Rolled[c]	 Grit Blasted[d]	 80 Grit Polish[e]	 120 Grit Polish[e]
16Cr-4Al-0.5Si-bal Fe	+1.75,SO[f]	+7.84,AO[f]	+0.18,SO[f]	+0.25,SO[f]
16Cr-6Al-0.5Si-bal Fe	+3.93,SO	+3.70,AO	+0.16,SO	-0.03,SO
18Cr-4Al-0.5Si-bal Fe	+1.56,SO	+10.81,AO	+0.21,SO	+0.009,SO
18Cr-6Al-0.5Si-bal Fe	+1.10,SO	+3.26,AO	+0.08,SO	+0.11,SO

---

[a] Alloys were vacuum induction melted. Ingots homogenized, forged, and rolled to plate. Composition in weight percent.

[b] Nominal gas composition: $24H_2$, $39H_2O$, 18CO, $12CO_2$, $5CH_4$, $1H_2S$, $1NH_3$; coupons exposed at 1600 °F, 1 atm, for 96 hr.

[c] Mill scale intact.

[d] Mill scale removed.

[e] Mill scale and underlying metal removed.

[f] AO - adherent oxide, SO - spalled oxide.

CORROSION OF Fe-Al-Cr-Mn ALLOYS[a] TESTED IN SEVERAL GASEOUS ENVIRONMENTS[34]

Conditions (except where specified): alloy surfaces polished[b], 1255 K (1800 °F), unequilibrated[c], atm. pressure

Alloy[a]	Air atmosphere 100 hr (120 cycles)[d] Weight Change mg/cm^2		Gas No. 1[e] 24 hr	Gas No. 2[f] 24 hr	Gas No. 2 60 hr	Gas No. 2, 24 hr equilibrated[f,g]	Gas No. 2, 24 hr 1172 K (1800 °F) equilibrated[f,g]	Gas No. 2, alloy surfa oxidized[d] equilibrate
310 SS base alloy			AO/SS[h]	AO,IS[h,i]		AO,IS[h]		SO,IS
Fe-8Al-10Cr	+1.25	AO		SO		D[i]		
Fe-8Al-2.5Mn-5Cr	+0.25	AO		SO	D		SS,IS	D
Fe-8Al-2.5Mn-10Cr	+0.36	AO		SO[i],SO	SO	D[i]	SS,IS	D
Fe-8Al-20Mn-10Cr	-0.20	AO	SO	SO		SS,IS		
Fe-8Al-20Mn-10Cr-3Mo	-1.30	SO				SS,IS		
Fe-8Al-20Mn-10Cr-6Mo	-6.05	SO				SS,IS		
Fe-8Al-20Mn-10Cr-9Mo	-4.83	SO				SS,IS		
Fe-8Al-20Mn-10Cr-2Ta	-6.98	SO				SS,IS		
Fe-8Al-20Mn-10Cr-0.5Y	+0.15	AO				SS,IS		
Fe-10Al-10Cr				SO		D[i]		
Fe-10Al-2.5Mn-5Cr	+0.23	AO		D			SS,IS	D
Fe-10Al-2.5Mn-10Cr	+0.16	AO		SO[i],SO	SO	D[i]	SS,IS	D
Fe-10Al-5Mn-5Cr	+0.10	AO		SO	SO		SS,IS	D
Fe-10Al-5Mn-10Cr	+0.16	AO		SO[i],SO	SO	D[i]	SS,IS	D
Fe-10Al-5Mn-15Cr	+0.29	AO		SO[i],SO	SO	D[i]	SS,IS	D
Fe-10Al-30Mn-5Cr	-0.59	AO		SS,IS				
Fe-10Al-30Mn-10Cr	-15.1	AO		SS,IS				
Fe-10Al-30Mn-15Cr	-14.2	AO		SS,IS				
Fe-12Al-2.5Mn-5Cr	+0.18	AO		D			SS,IS	D
Fe-12Al-2.5Mn-10Cr	+0.31	AO		SO,SS	SO,SS		SS,IS	D

---

[a] Alloys were arc melted and drop cast by the nonconsumable electrode process under argon at 1.5 atm. The cast structure was broken up by extrusion from 2000 °F and hot rolling from furnace temperature of 1600 °F (reduced 10% in thickness per pass and reheated between passes) to 0.1 in thick. Coupons were machined to 0.75 in x 0.25 in and rolled surfaces were ground flat and parallel (5 mils from each side).

[b] Local defects ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F with 10% reduction in thickness per pass. Half of sheet was further rolled (1600 °F) to 0.070 in thickness. Surfaces conditioned by grit blasting. Surfaces were ground flat and parallel, 0.005 in removed from each side to eliminate rolling defects and oxidized material. Surfaces and edges polished through 600 grit papers.

[c] Gas flowed upward in test chamber past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec.

[d] Cyclic exposure to air; samples heated for total 100 hr in slowly moving air; they were withdrawn from furnace every 50 min and cooled to ambient temperature; every 25 cycles, samples were weighed.

[e] Nominal reactive gas composition (mol %), not equilibrated: 50 H_2, 15 H_2O, 20 CO, 6 CO_2, 7 CH_4, 1.5 H_2S, 1 NH_3.

[f] Nominal gas composition (mol %), not equilibrated: 24 H_2, 39 H_2O, 18 CO, 12 CO_2, 5 CH_4, 1 H_2S, 1 NH_3. Equilibrated gas also contains minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, CS.

[g] To obtain equilibrated conditions, the inlet gas percolates through a heated bed of fine/coarse Al_2O_3 bubble grains fitted in the furnace tube to within 1-inch of the lowest sample on the specimen rack.

[h] AO - Adherent Oxide, SO - Spalled Oxide, SC - Sulfide Case, IS - Internal Sulfidation, SS - Sulfide Slag, D - Destroyed.

[i] Equilibrium vs. non-equilibrium comparative test run.

[Note: Temperature 1800 °F in seventh column heading above should read 1650 °F.]

CORROSION RESISTANCE OF Fe-Cr-Al-Mo-Hf EXPERIMENTAL ALLOYS TO COAL GASIFICATION ATMOSPHERE[a] [34]

Alloy[b]	Surface Preparation	Weight Change-mg/cm^2	Surface Condition[e]
Fe-19Cr-6Al-2Mo-1Hf	Burnished[c]	+0.90	AO
		+3.02	AO+AS
	120g Polish[d]	+1.25	AO
		+3.18	AO+AS
Fe-18Cr-5Al-1Mo-1Hf	Burnished	+0.87	AO
		+0.72	AO
	120g Polish	+1.54	AO+AS
		+1.06	AO+AS

---

[a] Coal gasification atmosphere (vol %): H_2 23.8-24.2, CO 17.9-18.1, CO_2 11.8-12.1, CH_4 4.9-5.0, NH_3 1.0, H_2S 1.0, H_2O 38.6-39.8, temperature 1800 °F, 1 atm, 494 hr exposure.

[b] Both heats prepared by Armco Steel Co. Research Laboratory. 5016 ingots cast in refractory brick molds to maintain slow rate of cooling. Heats then processed at Lockheed Palo Alto Research Laboratory.

[c] Mechanical polishing through 120 grit on SiC paper followed by acid pickling to clean the surface.

[d] Mechanical polishing through 120 grit on SiC paper followed by burnishing in an aluminum oxide media.

[e] AO - Adherent oxide, AS - Adherent sulfide

EFFECT OF PRE-OXIDATION AND Hf CONTENT ON CORROSION BEHAVIOR OF EXPERIMENTAL FeCrAlMoHf ALLOYS EXPOSED TO A SYNTHETIC COAL GASIFICATION ENVIRONMENT[a] [34]

Alloy	Pre-Oxidation Treatment	Wt % Hf	Weight Change-mg/cm^2	Surface[b]
Fe-19.1Cr-6.6Al-2.5Hf-1Mo	1 hour in Air at 1255 K (1800 °F) plus water quench	2.50	-0.95	AO,SO
	1 hour in H_2-H_2O at 1255K(1800 °F) with no cool		+1.46	AO, fine SO
	1 hour in H_2-H_2O at 811-922 K (1000-1200 °F) with no cool		+0.51	AO, fine SO
Fe-17.4Cr-6.3Al-1.05Hf-1Mo	1 hour in Air at 1255 K (1800 °F) plus water quench	1.05	+0.35	AO,SO edges
	1 hour in H_2-H_2O at 1255K(1800 °F) with no cool		+0.50	AO,SO
	1 hour in H_2-H_2O at 811-922 K (1000-1200 °F) with no cool		+0.11	AO,SO
Fe-18.6Cr-6.6Al-0.75Hf-1Mo	1 hour in Air at 1255 K (1800 °F) plus water quench	0.75	+0.82	AO
	1 hour in H_2-H_2O at 1255K(1800 °F) with no cool		+0.68	AO
	1 hour in H_2-H_2O at 811-922 K (1000-1200 °F) with no cool		-0.38	AO
Fe-18.3Cr-6.3Al-0.51Hf-1Mo	1 hour in Air at 1255 K (1800 °F) plus water quench	0.51	+5.47	AO,SO
	1 hour in H_2-H_2O at 1255K(1800 °F) with no cool		+1.01	AO
	1 hour in H_2-H_2O at 811-922 K (1000-1200 °F) with no cool		+0.88	AO
Fe-17.9Cr-5.3Al-0.37Hf-1Mo	1 hour in Air at 1255 K (1800 °F) plus water quench	0.37	+0.83	AO,SO
	1 hour in H_2-H_2O at 1255K(1800 °F) with no cool		none	AO
	1 hour in H_2-H_2O at 811-922 K (1000-1200 °F) with no cool		+1.83	AO
Fe-19.8Cr-5.3Al-0.11Hf-1Mo	1 hour in Air at 1255 K (1800 °F) plus water quench	0.11	-0.34	SO,AO
	1 hour in H_2-H_2O at 1255 K(1800 °F) with no cool		+0.19	SO,AO
	1 hour in H_2-H_2O at 811-922 K (1000-1200 °F) with no cool		+0.50	SO,AO

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[a] Input gas composition (vol %): $24H_2$, 18CO, $12CO_2$, $5CH_4$, $1NH_3$, $1H_2S$, $39H_2O$; exposed for 123 hr at 1255 K (1800 °F) and 1 atm.

[b] AO: Adherent oxide, SO: Spalling oxide

SULFIDATION AND AIR OXIDATION[a] RESISTANCE OF Fe-Al-Mn ALLOYS[b][34]

Conditions (except where specified): alloy surfaces polished,[c] 1255 K (1800 °F), unequilibrated,[d] 1 atm pressure

Alloy[b]	Air atmosphere 100 hr (120 cycles)[a] Weight Change mg/cm^2		Gas No. 1[e] 100 hr	Gas No. 1, 24 hr alloy surfaces oxidized[a]	Gas No. 2[f] 24 hr
310 SS base alloy	+1.25	AO[g]	AO,IS[g]		AO,IS[g]
Fe-3Al-2Mn	-376	SO			D
Fe-5Al	-5.38	SO	D		D
Fe-5Al-10Mn	-147	SO			D
Fe-5Al-20Mn	-237	SO (25 Cycles)	D		D
Fe-5Al-30Mn	-293	SO (25 Cycles)	SS,IS		D
Fe-6Al-30Mn	-207	SO (25 Cycles)	D		D
Fe-6Al-35Mn	-336	SO (25 Cycles)			D
Fe-7Al-30Mn	-293	SO (76 Cycles)	SS,IS		D
Fe-7Al-35Mn	-257	SO (25 Cycles)	SS,IS		D
Fe-7Al-40Mn	-285	SO (25 Cycles)	SS,IS		D
Fe-8Al	+2.51	SO	D		D
Fe-8Al-10Mn	+0.14	AO	D		D
Fe-8Al-20Mn	-1.50	AO	SS,IS	SC,IS	D
Fe-8Al-30Mn	-6.25	SO	SS,IS		D
Fe-8Al-35Mn	-128	SO (25 Cycles)	SS,IS		D
Fe-9Al-30Mn	+0.44	AO	SS,IS	SS,IS	D
Fe-10Al	+0.72	SO	D		D
Fe-10Al-5Mn	+0.10	AO	D	SS,IS	D
Fe-10Al-10Mn	-1.47	AO	D	SS,IS	D
Fe-10Al-20Mn	-1.15	AO	D	SC,IS	D
Fe-10Al-30Mn	-0.81	AO		SC,IS	D
Fe-12Al	-0.12	SO	D	SS,IS	D
Fe-12Al-2.5Mn	-0.07	AO	D	SS,IS	D
Fe-12Al-5Mn	-0.07	AO	D	SS,IS	D
Fe-15Al	NIL	AO			D
Fe-15Al-5Mn	+0.03	AO	SS,IS		D
Fe-15Al-10Mn	-0.41	SO	D		D

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[a] Cyclic exposure to air; samples heated for total 100 hr in slowly moving air; they were withdrawn from furnace every 50 min and cooled to ambient temperature; every 25 cycles, samples were weighed.

[b] Alloys were arc melted and drop cast by the nonconsumable electrode process under argon at 1.5 atm. The cast structure was broken up by extrusion from 2000 °F and hot rolling from furnace temperature of 1600 °F (reduced 10% in thickness per pass and reheated between passes) to 0.1 in thick. Coupons were machined to 0.75 in x 0.25 in and rolled surfaces were ground flat and parallel (5 mils from each side).

[c] Local defects ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F with 10% reduction in thickness per pass. Half of sheet was further rolled (1600 °F) to 0.070 in thickness. Surfaces conditioned by grit blasting. Surfaces were ground flat and parallel, 0.005 in removed from each side to eliminate rolling defects and oxidized material. Surfaces and edges polished through 600 grit papers.

[d] Gas flowed upward in test chamber past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec.

[e] Nominal reactive gas composition (mol %), not equilibrated: 50 H_2, 15 H_2O, 20 CO, 6 CO_2, 7 CH_4, 1.5 H_2S, 1 NH_3.

[f] Nominal gas composition (mol %), not equilibrated: 24 H_2, 39 H_2O, 18 CO, 12 CO_2, 5 CH_4, 1 H_2S, 1 NH_3.

[g] AO - Adherent Oxide, SO - Spalled Oxide, IS - Internal Sulfidation, SC - Sulfide Case, SS - Sulfide Slag, D - Destroyed.

RESULTS OF SCREENING FOR SULFIDATION[a] AND AIR OXIDATION RESISTANCE[a] OF EXPERIMENTAL Fe-Al-Mn-C(N) ALLOYS[b][34]

Alloy[b]	Test Conditions[a]: Air Atmosphere, 100 hr (120 cycles): Weight Change mg/cm²	Test Conditions[a]: Air Atmosphere, 100 hr (120 cycles): Corrosion Products[e]	Test Conditions[a]: Coal Gasification[c] Atmosphere, 24 hr: Corrosion Products[e]
310 SS Baseline Alloy[d]	+1.25	AO	AO, IS
5Al-20Mn-0.2N-bal Fe	-297	SO (50 Cycles)	D
5Al-20Mn-0.4N-bal Fe	-279	SO (50 Cycles)	D
5Al-20Mn-1.0C-bal Fe	-234	SO (50 Cycles)	D
7Al-20Mn-0.75C-bal Fe	-142	SO	D
7Al-20Mn-1.0C-bal Fe	-83.1	SO	D
7Al-30Mn-0.75C-bal Fe	-280	SO (50 Cycles)	D
7Al-30Mn-1.0C-bal Fe	-244	SO (50 Cycles)	D
8Al-10Mn-0.75C-bal Fe	-17.8	SO	D
8Al-20Mn-0.75C-bal Fe	-36.6	SO	D
8Al-20Mn-1.0C-bal Fe	-171	SO	D
8Al-20Mn-1.2C-bal Fe	-73.8	SO	D
8Al-25Mn-1.2C-bal Fe	-76.3	SO	D
8Al-30Mn-0.5C-bal Fe	-119	SO (75 Cycles)	D
8Al-30Mn-0.75C-bal Fe	-116	SO (50 Cycles)	D
8Al-30Mn-1.0C-bal Fe	-169	SO (75 Cycles)	D
8Al-35Mn-0.75C-bal Fe	-167	SO (50 Cycles)	D
8Al-35Mn-1.0C-bal Fe	-198	SO (50 Cycles)	D
8Al-40Mn-0.75C-bal Fe	-265	SO (25 Cycles)	SS, IS

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[a] Tests for sulfidation resistance in coal gasification atmospheres conducted at atmospheric pressure and 1255 K (1800 °F); gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec. Tests for resistance to oxidation at 1255 K (1800 °F) on cyclic exposure to air; samples heated for total of 100 hr in slowly moving air; they were withdrawn from furnace every 50 min and cooled to ambient temperature; every 25 cycles, samples were weighed; samples removed from test when excessive oxidation attack observed.

[b] Alloys prepared by nonconsumable electrode arc melting (120 g ingots) under argon at 1.5 atm. Button ingots were turned and remelted 3 times (mixed and homogenized) and drop cast to cylindrical ingots (1 in x 1.5 in high). Ingots heated 1 hr at 2000 °F (canned in stainless steel) and extruded to flat sheet bars (0.29 in x 1 in x 6 in, 4:1 reduction) at ram speed of 12-IPM using copper sheath for die lubrication. Local defects ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F with 10% reduction in thickness per pass. Half of sheet was further rolled (1600 °F) to 0.070 in thickness. Surfaces conditioned by grit blasting. Surfaces were ground flat and parallel, 0.005 in removed from each side to eliminate rolling defects and oxidized material. Surfaces and edges polished through 600 grit papers.

[c] Nominal coal gasification composition (mol %): 24 H_2, 39 H_2O, 18 CO, 12 CO_2, 5CH_4, 1 H_2S, 1 NH_3.

[d] Commercial alloy.

[e] AO-adherent oxide, SO-spalled oxide, SS-sulfide slag, IS-internal sulfidation, D-destroyed.

EFFECT OF MINOR ALLOYING VARIATIONS AND PRE-OXIDATION TREATMENTS ON OXIDE ADHERENCE OF EXPERIMENTAL IRON ALLOYS IN A SYNTHETIC COAL GASIFICATION ENVIRONMENT[a] [34]

	Composition[b]							
	Cr		Al		Hf		Mo	
Heat No.	Added	Measured[c]	Added	Measured[c]	Added	Measured[c]	Added	Surface[d]
1	18.0	18.6	5.0	5.3	0.5	0.09	-	Heavy Spall
2	18.0	17.4	5.0	5.4	1.0	0.40	-	Mild Edge Spall
3	20.0	19.6	6.0	6.3	0.5	0.40	-	Mild Edge Spall
4	18.0	18.8	6.0	5.7	0.5	0.42	-	Heavy Spall
5	18.0	18.4	6.0	6.0	1.0	0.76	-	Fine Spall
6	18.0	19.0	5.0	4.9	1.0	0.96	-	Adherent
7	20.0	21.6	6.0	6.1	1.0	1.13	-	Heavy Spall
8	20.0	19.8	5.0	5.3	0.5	0.11	1.0	Heavy Spall
8[e]	20.0	19.8	5.0	5.3	0.5	0.11	1.0	Heavy Spall
8[f]	20.0	19.8	5.0	5.3	0.5	0.11	1.0	Heavy Spall
9	20.0	19.0	6.0	6.3	0.5	0.33	1.0	Mild Edge Spall
10	18.0	17.9	5.0	5.3	0.5	0.37	1.0	Mild Spall
10[e]	18.0	17.9	5.0	5.3	0.5	0.37	1.0	Adherent
10[f]	18.0	17.9	5.0	5.3	0.5	0.37	1.0	Adherent
11	20.0	18.6	5.0	5.0	1.0	0.38	1.0	Edge Spall
12	18.0	17.8	5.0	5.1	1.0	0.40	1.0	Adherent
13	18.0	18.3	6.0	6.3	0.5	0.51	1.0	Fine Spall
13[e]	18.0	18.3	6.0	6.3	0.5	0.51	1.0	Adherent
13[f]	18.0	18.3	6.0	6.3	0.5	0.51	1.0	Adherent
14	19.0	18.6	6.0	6.6	1.0	0.75	1.0	Adherent
15	18.0	17.4	6.0	6.3	1.0	1.05	1.0	Heavy Spall
15[e]	18.0	17.4	6.0	6.3	1.0	1.05	1.0	Heavy Spall
15[f]	18.0	17.4	6.0	6.3	1.0	1.05	1.0	Heavy Spall
16	18.0	17.5	5.0	5.2	1.0	1.17	1.0	Heavy Spall
17	20.0	19.1	6.0	6.6	1.0	2.50	1.0	Heavy Spall
17[e]	20.0	19.1	6.0	6.6	1.0	2.50	1.0	Fine Spall
17[f]	20.0	19.1	6.0	6.6	1.0	2.50	1.0	Fine Spall

[a] Samples were exposed for 100 hr, at 1255 K (1800 °F), input gas composition (vol %): $39H_2O$, $24H_2$, 18CO, $12CO_2$, $5CH_4$, $1NH_3$, $1H_2S$.

[b] Base element of the alloy is iron with the amounts of the other elements given in weight percent.

[c] Measured values are from microprobe analyses (200 μm beam) of 10 points in the sample.

[d] Comments refer only to oxide behavior; no difference in sulfidation behavior was noted for these tests.

[e] Pre-oxidized 1 hr in H_2-H_2O ($\log P_{O_2} = -15.0$) at 811-922 K (1000-1400 °F).

[f] Pre-oxidized 1 hr in H_2-H_2O ($\log P_{O_2} = -15.0$) at 1255 K (1800 °F).

TRANSITION FROM NON-PROTECTIVE TO PROTECTIVE SCALE FORMATION ON ALLOYS IN SIMULATED COAL GASIFICATION ENVIRONMENT[a] WITH VARYING H_2O-H_2S CONTENT[34]

Environmental Reactants[a]				310 SS[b]			Incoloy 800[b]	
H_2O %	H_2S %	Log P_{H_2O}/P_{H_2}	Log P_{H_2S}/P_{H_2}	Weight Change PPM	Degree of Sulfidation	Reaction Products, mils	Weight Change PPM	Degree of Sulfidation
15.2	1.39	-.341	-1.38	+26866	Surface Slag	Liquid sulfide, spalled on cooling; others not determined.	-54761	Surface Slag
16.7	1.68	-.383	↕	+29282	Surface Slag	Liquid sulfide, spalled on cooling; solid sulfide subscale, 4; solid oxide subscale, 1; internal sulfidation, 13; internal carburization, 15.	+52391	Surface Slag
18.5	1.34	-.239		+5194	Surface Slag	Liquid sulfide surface; others not determined.	+2183	Surface Slag
21.2	1.29	-.165		+2189	Internal	Not determined.	+7735	Surface Slag
22.7	1.56	-.218		+108	Internal	Solid oxide surface, 0.5; internal oxidation, 0.2; internal sulfidation, 1-4; internal carburization, 3-5.	+45698	Surface Slag
25.8	1.47	-.136		+1132	Internal	Solid oxide surface, 0.2; internal sulfidation, 0.6.	+1065	Internal
26.6	1.48	-.126		+2087	Internal	Solid oxide surface, 0.3; internal oxidation, 0.2; internal sulifdation, 1.	+2792	Internal
37.6	1.02	+.184		+1077[c]	None	Not determined.	+2358[c]	Not Determined
45.8	1.07	+.249	-1.38	+1219[c]	None	Solid oxide surface, 0.2; internal oxidation, 0.6.	+1783[c]	None

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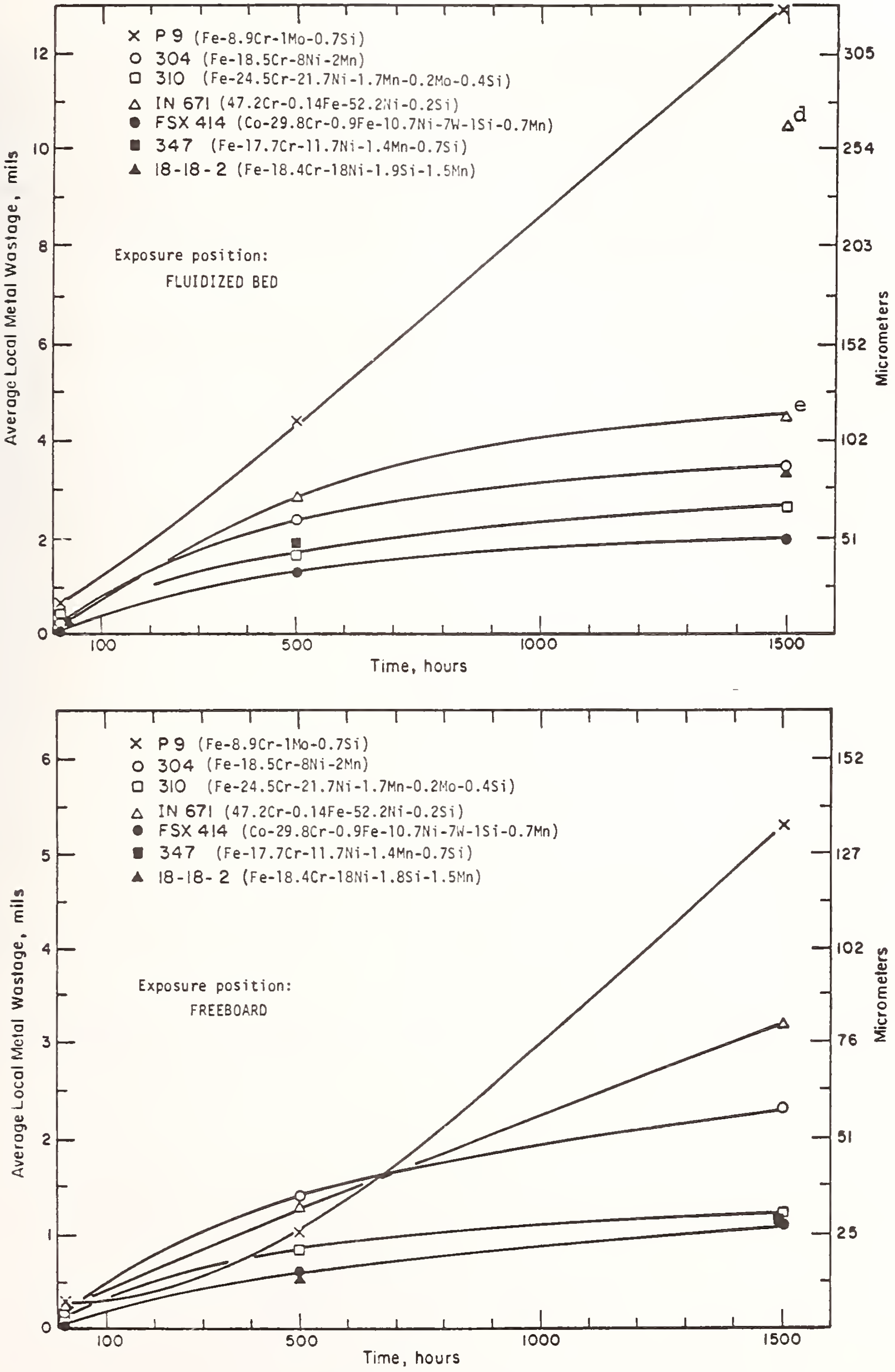
[a] Composition of the atmosphere varied, assorted mixtures of H_2, CO, CO_2, CH_4, H_2S, NH_3 and H_2O were used; the P_{H_2S}/P_{H_2} ratio was constant and the P_{H_2O}/P_{H_2} was varied. Experiments were run at atmospheric pressure and 1800 °F for 19-24 hours except as noted otherwise.

[b] Composition (wt %): Incoloy 800, 44.66Fe, 21.48Cr, 31.23Ni, 0.26Al, 0.41Ti, 0.56Cu, 0.88Mn, 0.44Si, 0.08C; 310 SS, 52.59Fe, 24.76Cr, 19.05Ni, 0.21Cu, 1.70Mn, 0.72Si, 0.05C, 0.49Mo, and 0.38Co. The alloys were arc melted and drop cast by the non-consumable electrode process under argon at 1.5 atm. The cast structure was broken up by extrusion from a temp. of 2000 °F and hot rolling from a furnace temp. of 1600 °F (reduced 10% in thickness per pass and reheated between passes) to 0.1 in thickness. Coupons were machined to 0.75 in x 0.25 in and rolled surfaces were ground flat and parallel (5 mils from each side).

[c] 100 hr exposures.

LOCAL METAL WASTAGE[a] AS A FUNCTION OF TIME FOR ALLOYS[b] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[c][37]



(Data Continued)

LOCAL METAL WASTAGE[a] AS A FUNCTION OF TIME FOR ALLOYS[b] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[c] [37], continued

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[a] Determined by microscopic examination. Points for each alloy obtained by averaging the data for the two or three specimens on each probe run.

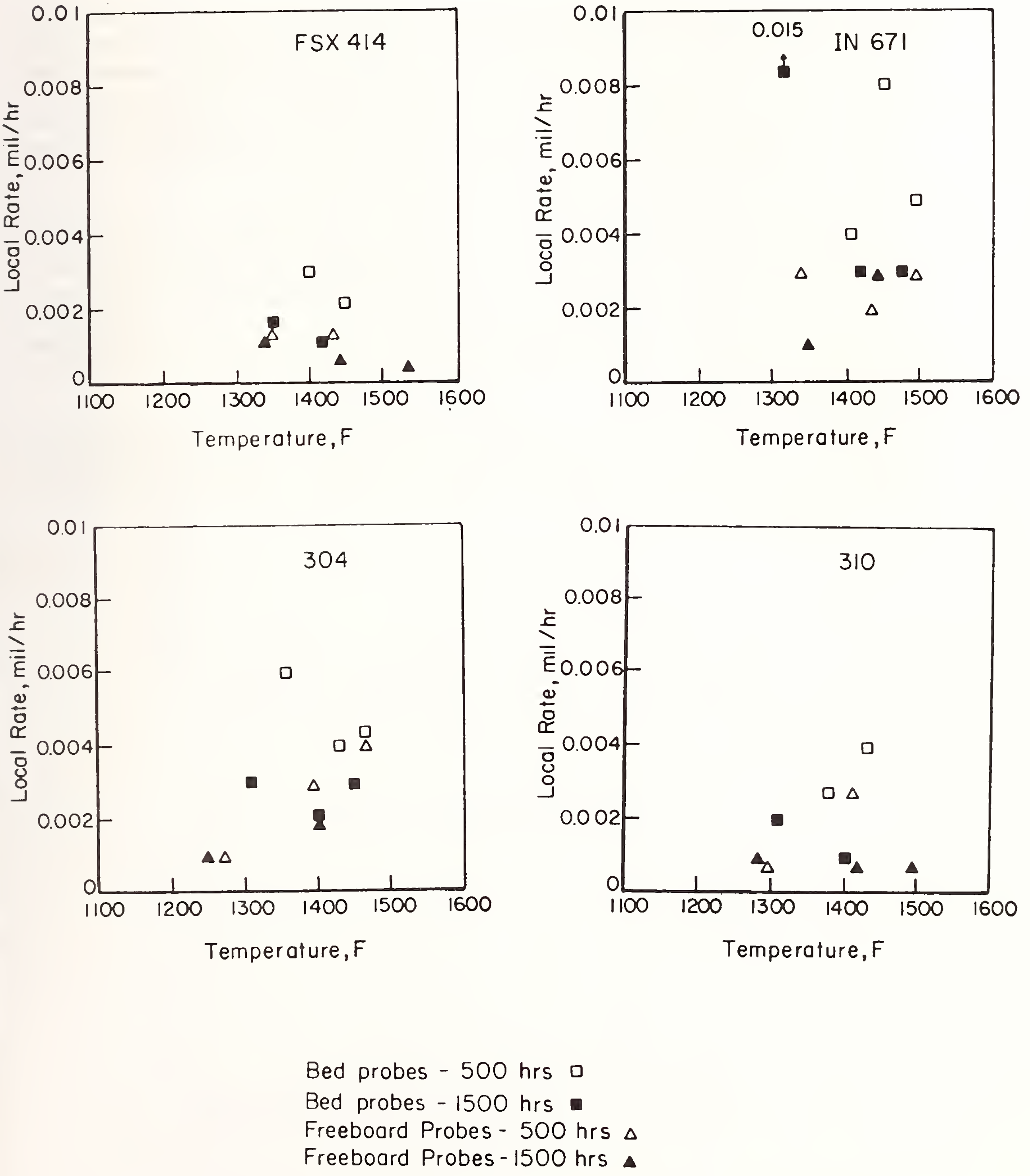
[b] Test specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 1.00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 obtained as cast rod from which specimens were machined. As machined specimens were solvent rinsed before exposure. Twenty-one specimens were used to make up 18-in air-cooled tube probes.

[c] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

[d] Average of values for three specimens; data for one specimen differed from the other two by a factor of 5.

[e] Average of values for two specimens which agreed reasonably closely.

LOCAL METAL WASTAGE[a] AS A FUNCTION OF TEMPERATURE FOR ALLOYS[b] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[c][37]



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(Data Continued)

LOCAL METAL WASTAGE[a] AS A FUNCTION OF TEMPERATURE FOR ALLOYS[b] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[c] [37], continued

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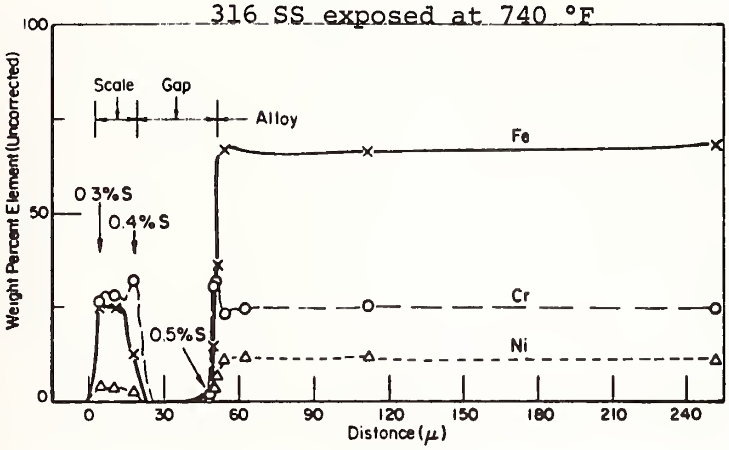
[a] Local rate of metal loss calculated based upon microscopic examination of specimen with a correction for the area of the specimen showing visible evidence of attack. This calculation provides a local rate of attack for the specific area, i.e. total weight loss divided by the area of local attack which is more representative of the rate which may determine the life of heat exchanger tube materials.

[b] Alloys tested: FSX414 (Co-29.8Cr-0.9Fe-10.7Ni-7W-1Si-0.7Mn), Inconel 671 (47.2Cr-0.14Fe-52.2Ni-0.2Si), 304 SS (Fe-18.5Cr-8Ni-2Mn), 310 SS (Fe-24.5Cr-21.7Ni-1.7Mn-0.2Mo-0.4Si). Test specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 1.00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 obtained as cast rod from which specimens were machined. As machined specimens were solvent rinsed before exposure. Twenty-one specimens were used to make up 18-in air-cooled tube probes.

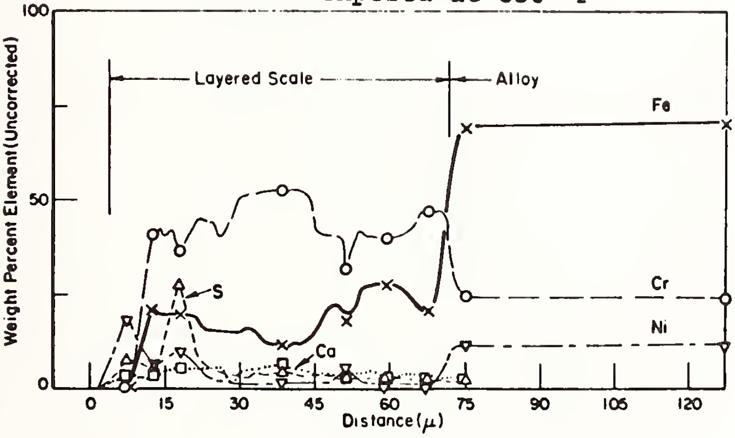
[c] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

ANALYSIS[a] OF SCALE/METAL INTERFACE OF ALLOYS[b] EXPOSED[c] AT LOW TEMPERATURES IN A FLUIDIZED BED COAL COMBUSTOR[d][37]

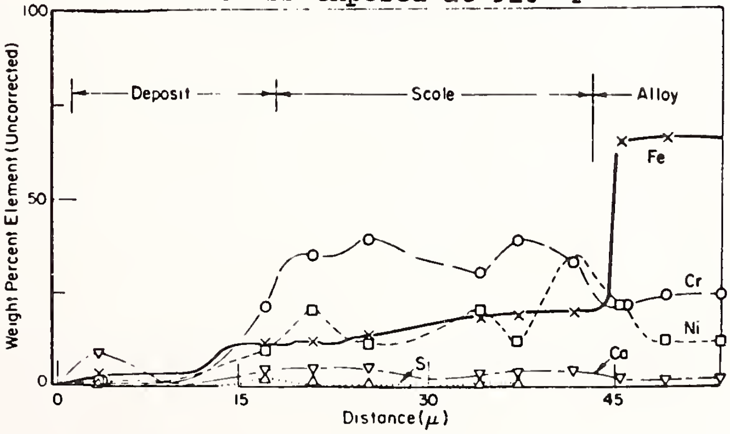
316 SS exposed at 740 °F



316 SS exposed at 850 °F



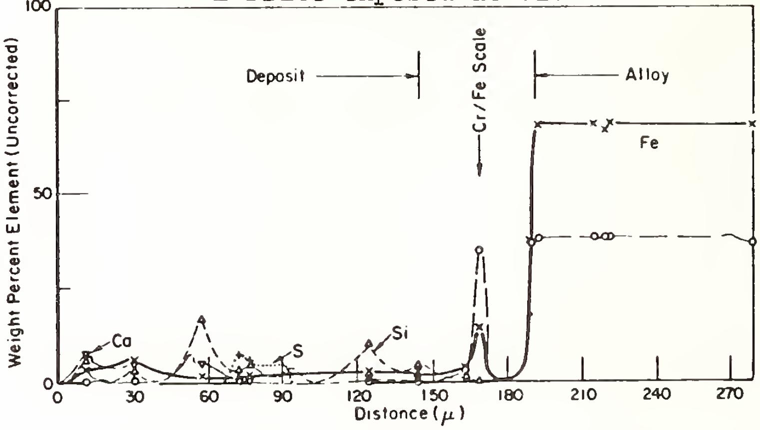
316 SS exposed at 910 °F



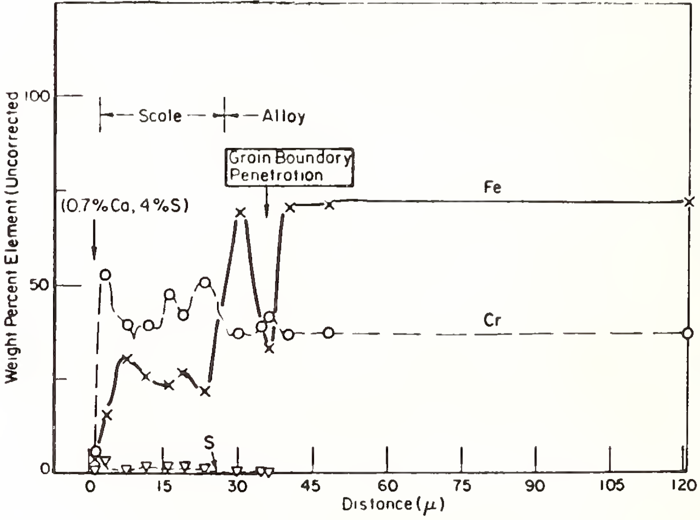
(Data Continued)

ANALYSIS[a] OF SCALE/METAL INTERFACE OF ALLOYS[b] EXPOSED[c] AT LOW TEMPERATURES IN A FLUIDIZED BED COAL COMBUSTOR[d][37], continued

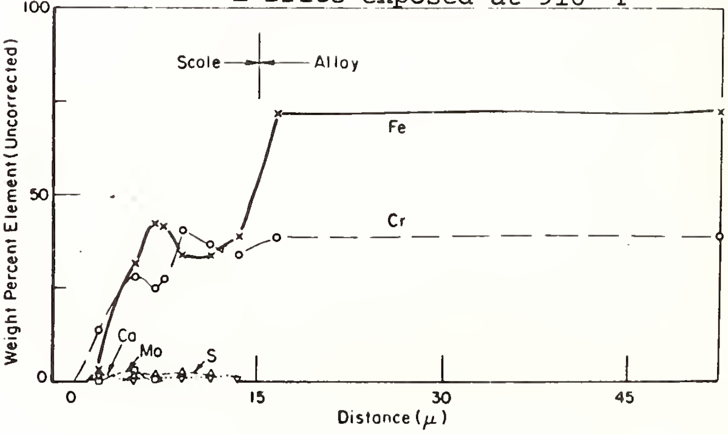
E-Brite exposed at 715 °F



E-Brite exposed at 840 °F



E-Brite exposed at 910 °F



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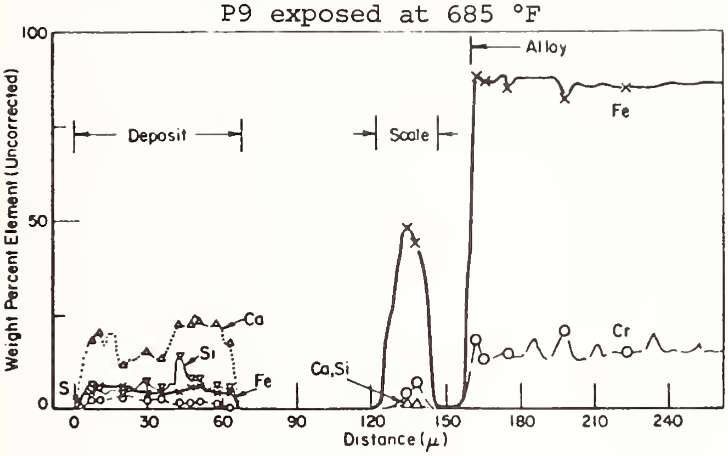
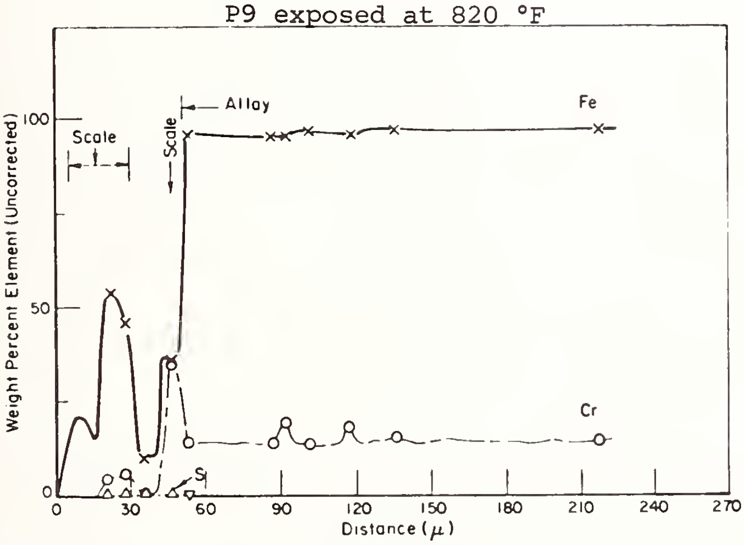
(Data Continued)

ANALYSIS[a] OF SCALE/METAL INTERFACE OF ALLOYS[b] EXPOSED[c] AT LOW TEMPERATURES IN A FLUIDIZED BED COAL COMBUSTOR[d] [37], continued

P9 exposed at 685 °F



P9 exposed at 820 °F



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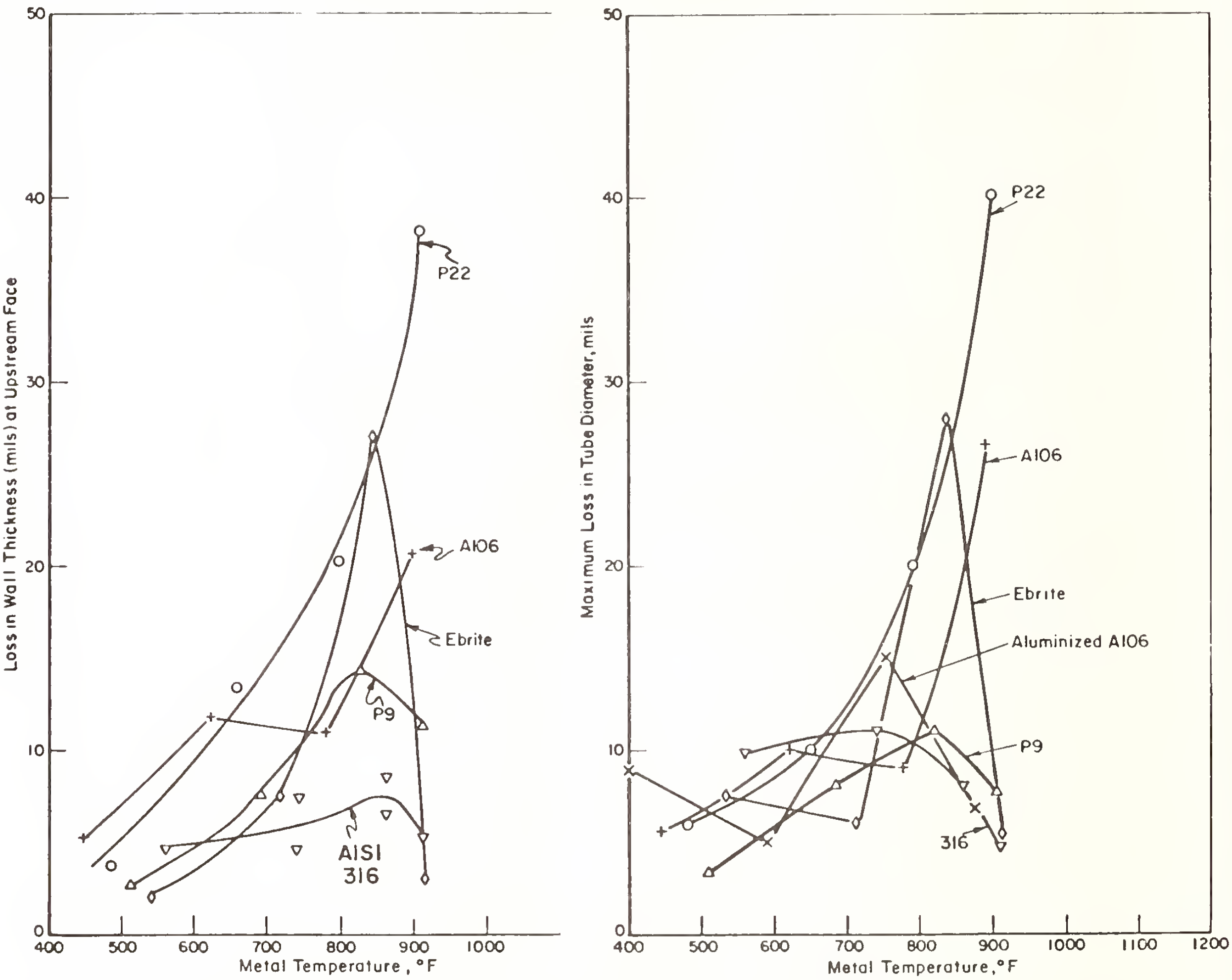
[a] After exposure, specimens were mounted in epoxy to preserve scale and deposits, and sectioned across a diameter. Photomicrographs were taken of scale cross-sections and corresponding electron-probe microanalyzer line scans of the upstream faces of specimens.

[b] Alloys tested: AISI 316 SS (17Cr-10Ni-2Mo), E-Brite (26Cr-1Mo), P9 (9Cr-1Mo). Cylindrical test specimens were machined from tube stock to 1.25 in OD, 1.01 in ID, and 0.97 in long. Twenty-four specimens formed a tube probe.

[c] Exposure at temperatures ranging from 400°F to ∿900°F for 144 hr.

[d] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

METAL LOSS[a] VERSUS TEMPERATURE OF ALLOYS[b] EXPOSED[c] AT LOW TEMPERATURES IN A FLUIDIZED BED COAL COMBUSTOR[d][37]



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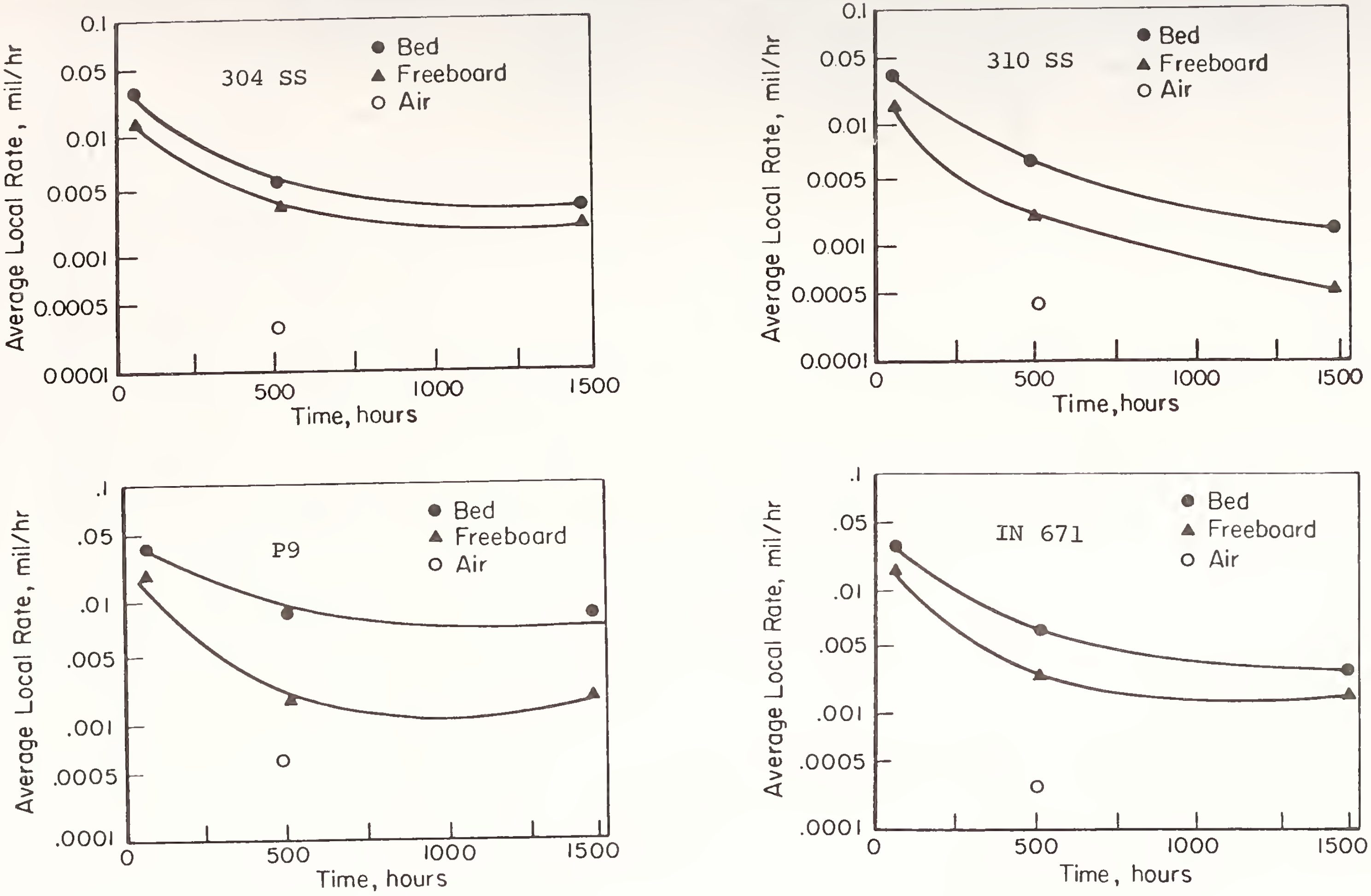
[a] After exposure, specimens were mounted in epoxy to preserve scale and deposits, sectioned across a diameter. One cut face was metallographically polished and measurements were made with a digital travelling microscope. Metal losses plotted are maximum changes in tube diameter and wall thickness at the upstream face. Estimated mean errors are + 1.0 and -1.3 mils for the diameters and +0.5 and -1.2 for thickness measurements.

[b] Alloys tested: A106 carbon steel, A106 carbon steel aluminized (diffused Al cast; pack aluminized 5 hr at 1700 °F in 15% Al-12Si + 2.5% NH_4CL + 82.5% Al_2O_3, Battelle), P22 (2 1/4 Cr-1 Mo), P9 (9Cr-1Mo), E-Brite (26Cr-1Mo), AISI 316 SS (17Cr-10Ni-2Mo). Cylindrical test specimens were machined from tube stock to 1.25 in OD, 1.01 in ID, and 0.97 in long. Twenty-four specimens (four sets of each alloy) formed a tube probe.

[c] Exposure at temperatures ranging from 400°F to ∿900°F for 144 hr.

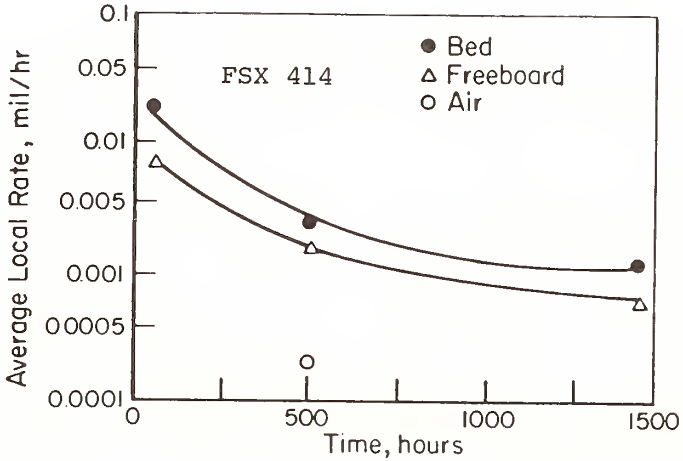
[d] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmosperic pressure.

CORROSION RATE DATA[a] FOR ALLOYS[b] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[c][37]



(Data Continued)

CORROSION RATE DATA[a] FOR ALLOYS[b] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[c] [37], continued



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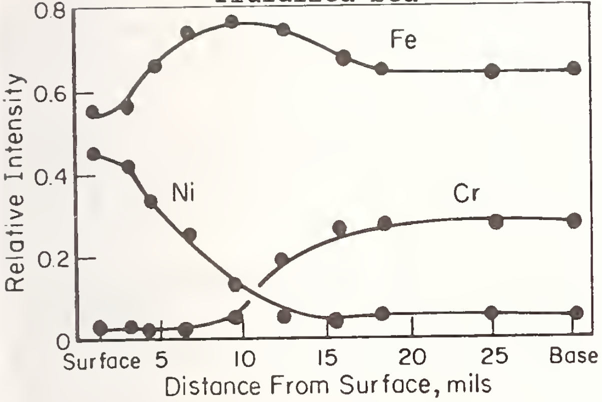
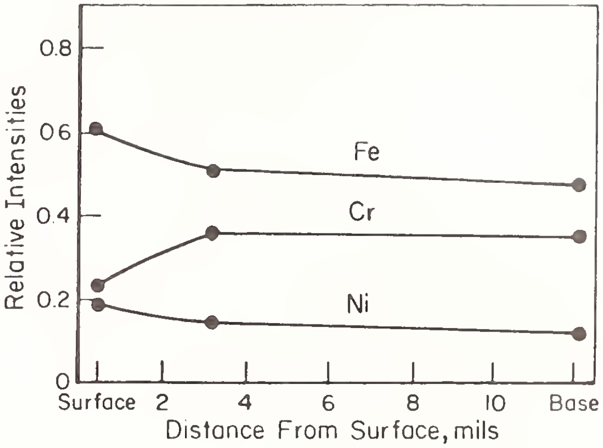
[a] Local rate of metal loss calculated based upon microscopic examination of specimens with a correction for the area of the specimen showing visible evidence of attack. This calculation provides a local rate of attack for the specific area, i.e. total weight loss divided by the area of local attack which is more representative of the rate which may determine the life of heat exchanger materials than a rate based on the total area of the specimen. Weight loss determined after descaling of specimens by mechanical removal of loose deposit, then soaking in 11% NaOH + 5% $KMnO_4$ solution at 200 °F, and then a cathodic treatment in 10% H_2SO_4 containing 1-ethyl-quinolinium iodide inhibitor.

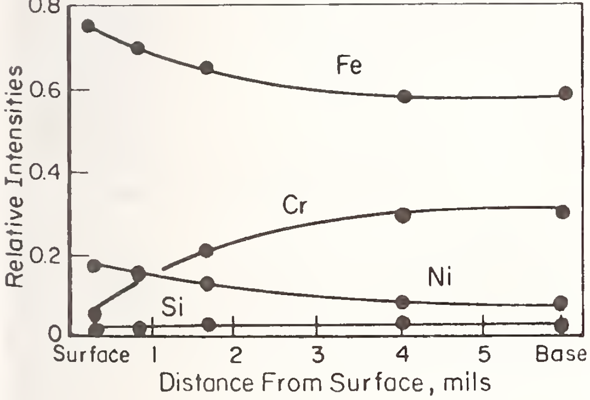
[b] Alloys tested: 304 SS (Fe-18.5Cr-8Ni-2Mn), 310 SS (Fe-24.5Cr-21.7Ni-1.7Mn-0.2Mo-0.4Si), P9 (Fe-8.9Cr-1Mo-0.7Si), Inconel 671 (47.2Cr-0.14Fe-52.2Ni-0.2Si), FSX414 (Co-29.8Cr-0.9Fe-10.7Ni-7W-1Si-0.7Mn). Cylindrical test specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 1.00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 obtained as cast rods from which specimens were machined. As-machined specimens were solvent rinsed before exposure. Twenty-one specimens were used to make up 18-in air-cooled tube probes.

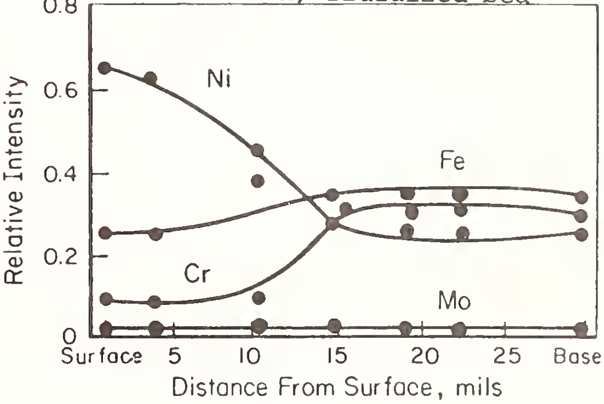
[c] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure. Values labeled "air" in graphs obtained by inserting probe in an electrical resistance furnace operated at 1650 °F (899 °C). Specimen temperatures were held at 1200 to 1580 °F by blowing air through probe.

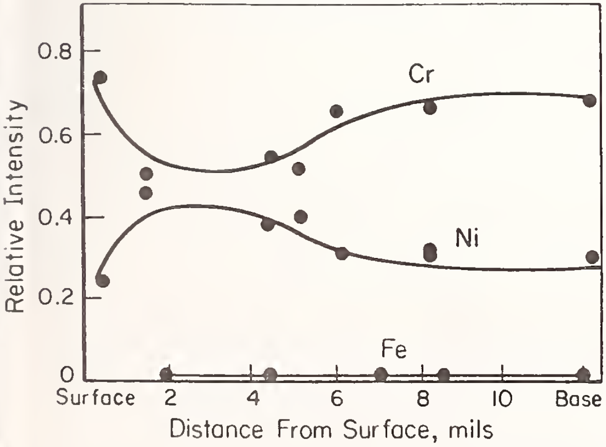
CHEMICAL ASSAY[a] OF ALLOYS[b] AFTER EXPOSURE IN A FLUIDIZED BED COAL COMBUSTOR[c][37]

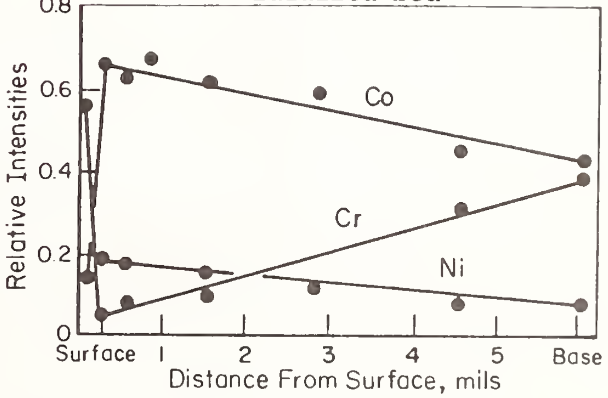

304 SS, 1620 °F, 1080 h, fluidized bed


310 SS, 1465 °F, 500 h, fluidized bed


18-18-2, 1440 °F, 500 h, freeboard


Incoloy 825, 1620 °F, 1080 h, fluidized bed


IN 671, 1482 °F, 1500 h, fluidized bed

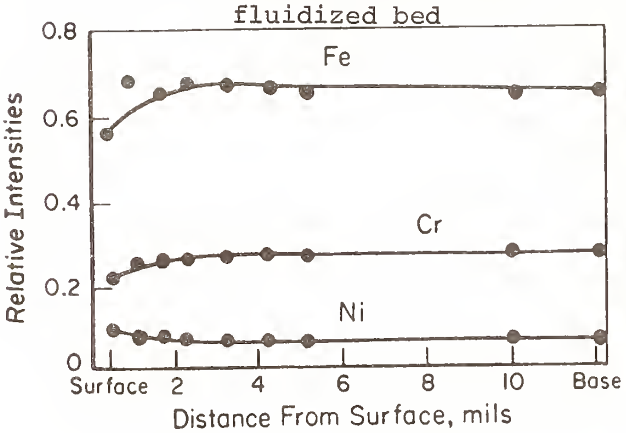

FSX 414, 1475 °F, 1500 h, fluidized bed

- -

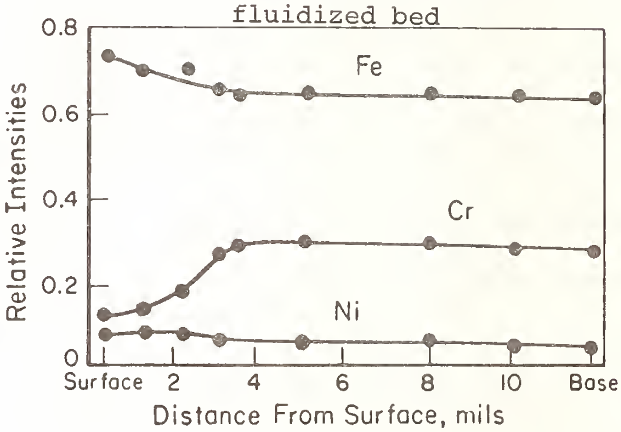
(Data Continued)

CHEMICAL ASSAY[a] OF ALLOYS[b] AFTER EXPOSURE IN A FLUIDIZED BED COAL COMBUSTOR[c][37], continued

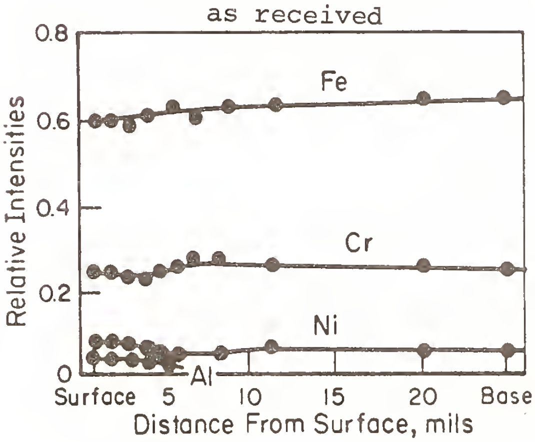
347 SS, 1455 °F, 500 h, fluidized bed



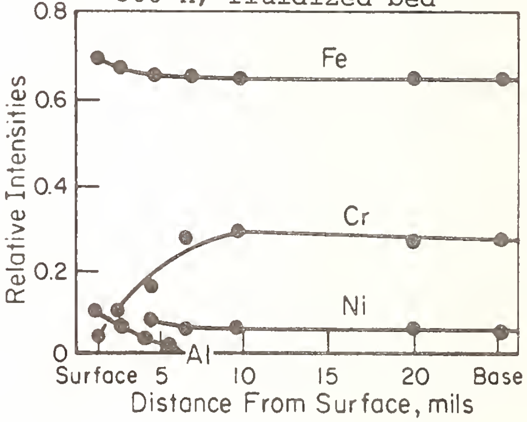
347 SS, 1620 °F, 1080 h, fluidized bed



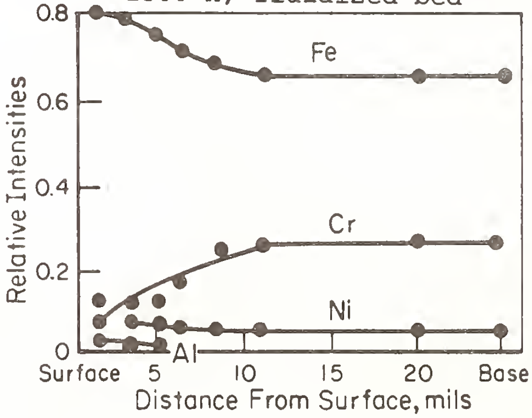
FeCrAl coat on 304 SS as received



FeCrAl coat on 304 SS, 1480 °F, 500 h, fluidized bed



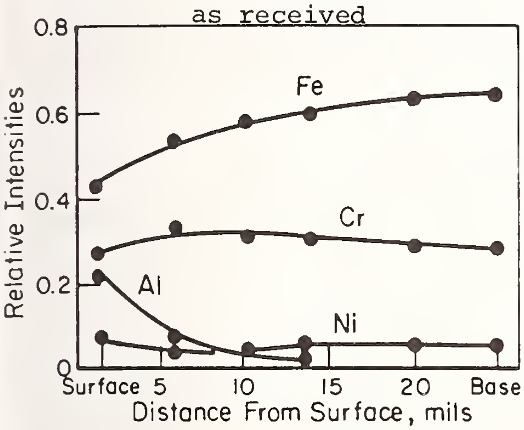
FeCrAl coat on 304 SS, 1465 °F, 1500 h, fluidized bed



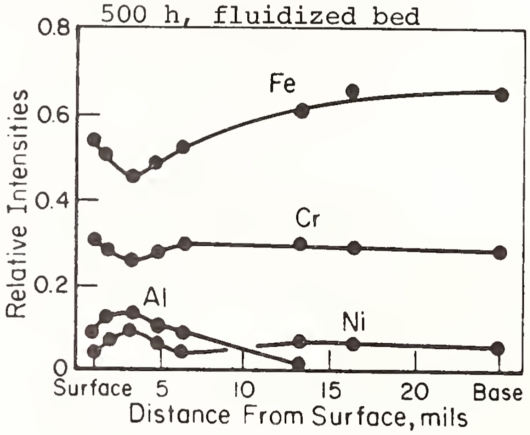
(Data Continued)

CHEMICAL ASSAY[a] OF ALLOYS[b] AFTER EXPOSURE IN A FLUIDIZED BED COAL COMBUSTOR[c] [37] continued

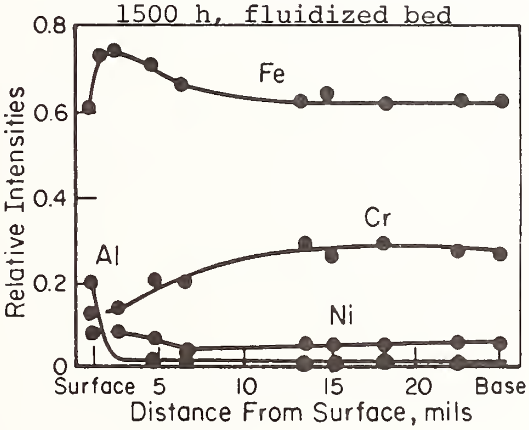
HI-35 coat on 304 SS, as received



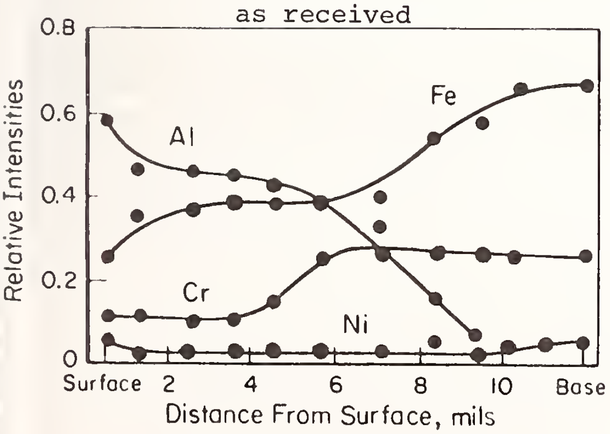
HI-35 coat on 304 SS, 1460 °F, 500 h, fluidized bed



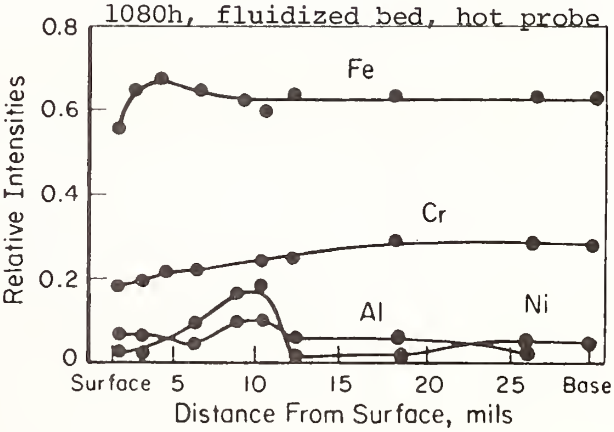
HI-35 coat on 304 SS, 1442 °F, 1500 h, fluidized bed



Pack Al coat on 304 SS, as received



Pack Al coat on 304 SS, 1620 °F, 1080h, fluidized bed, hot probe



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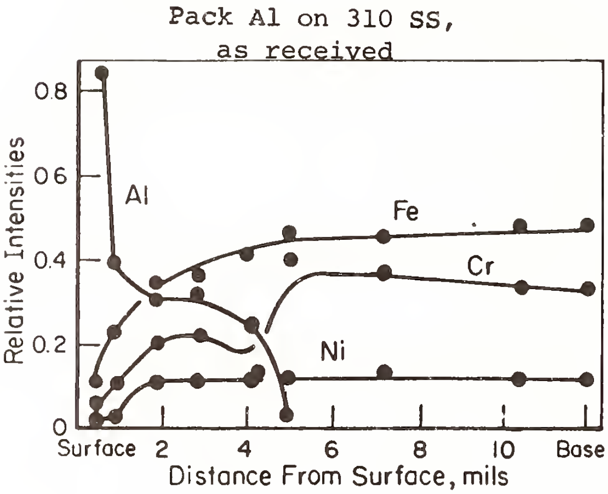
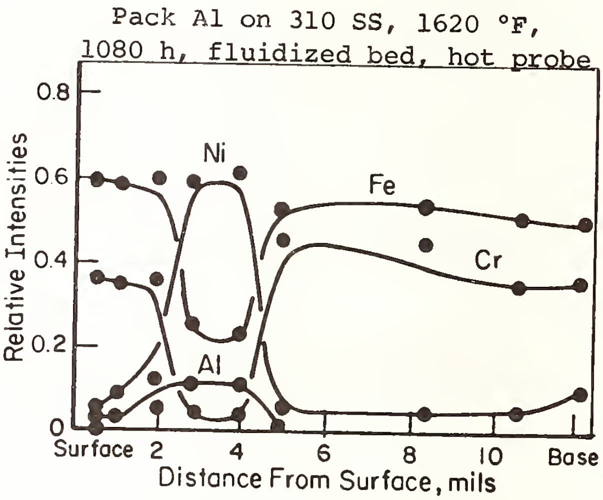
(Data Continued)

CHEMICAL ASSAY[a] OF ALLOYS[b] AFTER EXPOSURE IN A FLUIDIZED BED COAL COMBUSTOR[c][37], continued



Pack Al on 310 SS, as received



Pack Al on 310 SS, 1620 °F, 1080 h, fluidized bed, hot probe

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[a] X-ray emission analysis of metallographic sections of exposed specimens.

[b] Alloys tested: 304 SS (Fe-18.5Cr-8Ni-2Mn), 310 SS (Fe-24.5Cr-21.7Ni-1.7Mn-0.2Mo-0.4Si), 18-18-2 (Fe-18.4Cr-18Ni-1.9Si-1.5Mn), Incoloy 825 (30Fe-21.5Cr-42Ni-3Mo-2.25Cu-0.25Si-0.5Mn), IN 671 (47.2Cr-0.14Fe-52.2Ni-0.2Si), FSX414 (Co-29.8Cr-0.9Fe-10.7Ni-7W-1Si-0.7Mn), 347 SS (Fe-17.7Cr-11.7Ni-0.7Si-1.4Mn), FeCrAl coating (Fe-15Cr-10Al-8Ni-1Mo-1Si; coating consists of two 3.5 mil plasma sprayed layers, the first of which was anneal bonded (Union Carbide)), HI 35 (AlCr coating; duplex coating of Al over a chromized 304SS with a case depth of 10 mil (Alloy Surfaces)), Pack Al coating (diffused Al case; five hours 700°F in 15% Al-12Si + 2.5% NH_4Cl + 82.5% Al_2O_3(Battelle)). Cylindrical test specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 1.99 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 obtained as cast rods from which specimens were machined. As machined specimens were solvent rinsed before exposure. Twenty-one specimens were used to make up 18-in air-cooled tube probes.

[c] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

EFFECT OF EXPOSURE[a] IN A FLUIDIZED BED COAL COMBUSTOR[b] ON THE MICROSTRUCTURE[c] OF ALLOYS[d][37]

Alloy	Test Conditions	Microstructure
304 SS (Fe-18.5Cr-8Ni-2Mn)	1200 to 1500 °F for 10, 500, and 1500 hr in the freeboard and the fluidized bed	Freeboard exposure--carbide precipitation occurred at grain boundaries. No intergranular attack detected. Cr depletion found only to ∿0.5 mil (12.6 μm) into the substrate metal. Fluidized bed exposure--intergranular precipitates formed to depth of 10 mils (254 μm).
	1620 °F for 1080 hr in the lower fluidized bed	Specimen showed carbon content of 0.5%, picked up from environment. Three types of reaction zones found. Zone one--heavy attack causing a sugaring effect on the outer grains (whole grains lost); Cr depletion; Cr oxides and Ni sulfide formed. Zone two--dense reaction product within grains and in grain boundaries extending about 6 mils (152 μm) into substrate metal; Cr sulfides formed. Zone three--lesser amount of reaction product in remaining substrate; less S found than in other zones but high in carbon.
310 SS (Fe-24.5Cr-21.7Ni-0.2Mo-0.4Si-1.7Mn)	Untested--as received	Large grains containing many small spherical Cr-rich inclusions; inclusions probably σ-phase.
	∿1500 °F for 10, 500, and 1500 hr in the fluidized bed	Progressive growth of σ-phase occurred with time. Large increase in the depth of affected base metal occurs with time increase from 10 to 500 hr but next 1000 hr has little effect. Major change is Cr depletion of alloy. Cr-rich oxide forms at metal/scale interface. Apparently dynamic equilibrium for alloy depletion is established in ∿30 hr which is probably the time required to form a continuous Cr-rich oxide layer of sufficient thickness at the metal/scale interface to lower the O_2 partial pressure to the value (10^{-9} atm) below which Cr does not oxidize.
	1620 °F for 1080 hr in the lower fluidized bed	Progressive growth of the σ-phase is greatly accelerated at this higher temperature.
18-18-2 (Fe-18.4Cr-18Ni-1.9Si-1.5Mn)	1440 °F for 500 hr in the freeboard and 1500 hr in the fluidized bed	Most of the change was intergranular and intragranular precipitation occurring in 500 hr or less. Precipitates are Cr-rich sites for which the Si and Ni concentrations are higher than in the matrix by factors of 7 and 2. Precipitate is a Cr-Ni sulfide. The number of the precipitates is reduces near the exposed surface. Cr and Si are depleted from matrix. Cr depletion occurred to depth of ∿4mils (100 μm). Cr and Si depletion results in increase of Fe and Ni concentrations near surface. Cr and Si oxides formed on surface and little or no internal oxidation occurred. Cr sulfide forms as a few intragranular particles near the surface.
347 SS (Fe-17.7Cr-11.7Ni-0.7Si-1.4Mn)	1460 °F for 1500 hr in the freeboard and 500 hr in the fluidized bed.	Little or no change in the internal microstructure for any exposure. Freeboard--grain boundaries at the surface have disappeared. A few sulfide particles observed near the surface. Fluidized bed--grain boundaries provided paths for heavy surface attack. Large amounts of S found in the interior of grains near the surface. Cr and Fe reduction near the surface in part a result of S pickup which has penetrated to depth of 1.5 mils (36 μm) and in part due to preferential oxidation of Cr. In-bed specimens suffered more internal oxidation and more extensive sulfidation due to the erosive removal of a protective oxide layer.
	1620 °F for 1080 hr in the lower fluidized bed	Deeper oxidation attack than at lower temperatures. The oxidation caused marked Cr depletion of grains in the attacked layer.
Incoloy 825 (21.5Cr-30Fe-42Ni-3Mo-0.25Si-0.5Mn-2.25Cu)	1620 °F for 1080 hr in the fluidized bed	Deep intergranular oxide penetration observed plus two precipitate phases (short needles and rounded particles) which formed to depth of 15 mils (370 μm). Major reduction in Cr and significant reduction in Fe found in the reacted layer and a major increase in the Ni concentration. Short needled precipitate developed to depth of 25 mils (640 μm). Rounded grains contain S. Both precipitates have higher Cr concentration than the matrix. Upstream side of the specimen showed deeper penetration than the other sides due to removal of protective oxide by erosion.

(Data Continued)

EFFECT OF EXPOSURE[a] IN A FLUIDIZED BED COAL COMBUSTOR[b] ON THE MICROSTRUCTURE[c] OF ALLOYS[d] [37], Continued

Alloy	Test Conditions	Microstructure
IN 671 (47.2Cr-0.14Fe-52.2Ni-0.2Si)	range of temperatures for 500 and 1500 hr in both freeboard and fluidized bed	Freeboard and fluidized bed exposures--gross pitting on the downstream side of the specimens, adjacent areas unattacked. Precipitation of Cr-rich solid solution out of Ni-rich matrix occurred. Cr depletion to a depth of ∿6-8 mils (152-203 μm) below an oxide layer. Detailed examination of large pit showed Cr depletion from substrate for depth of 2 mils from the reacting interface. Above the interface unreacted Ni and Cr oxide were found. Little or no S was detected.
P9 (Fe-8.9Cr-1Mo-0.7Si)	1100°F to 1400°F for 500 and 1500 hr in the freeboard and fluidized bed	Very little or not change in microstructure or alloy depletion observed.
FSX 414 (Co-29.8Cr-0.9Fe-10.7Ni-7W-1Si-0.7Mn)	Untested--as received	Cr-rich phase forms interconnected islands in a Co-rich matrix. Ni in the alloy occurs with the Co and the W segregates to the Cr-rich phase. A few equiaxed particles of CrS are present in islands.
	1350-1550 °F for 500 and 1500 hr in the fluidized bed	Island structures are only slightly modified. Surface reaction is initiated in 10 hr and continues to grow with time--a result of Cr depletion and formation of Cr-rich oxide at the metal/scale interface. Metal side of interface is enriched in Co and Ni with particles of CrS. Dense Cr-rich needles form in Co-rich matrix as result of Cr-depletion in the matrix at the depleted zone to the base metal interface. No internal sulfidization detected in or beyond the interface reaction zone.
FeCrAl Coating on 304 SS (Fe-15Cr-10Al-8Ni-1Mo-1Si coat consists of two 3.5 mil plasma sprayed layers, the first of which was anneal bonded)	Untested--as received	Inner layer has a thin Al_2O_3 layer formed on surface during thermal bonding. Outer layer contains higher Al concentration with Al_2O_3 concentration sites.
	1400-1500 °F for 500 and 1500 hr in the freeboard and the fluidized bed	Both layers were retained for up to 500 hr in the bed and 1500 hr in the freeboard. After 1500 hr in the bed the outer layer was lost on the upstream side. There was a loss of Cr from the outer layer after 500 hr in the bed and from both layers after 1500 hr in bed and freeboard. Major change is loss of Cr to form Cr_2O_3 scale. Cr loss from matrix of inner layer is through formation of a Cr-rich precipitate at the substrate/coating interface and the inner layer. Al in the outer layer concentrates in a laminar oxide phase probably surrounding individual plasma-sprayed particles. Major attack besides erosion is by internal oxidation. No S attack was detected.
HI 35 Coating on 304 SS (AlCr duplex coating of Al over a Chromized 304 SS with a case depth of 10 mils)	Untested--as received	Coating is actually diffusion alloyed barrier layers--Cr deposition and diffusion to give a 10 mil (254 μm) case depth. Over this Cr-enriched case Al was deposited and diffused 3 mils (76.2 μm) into the chromized layer. Duplex coating thus has Al-rich layer of chromized metal and the remaining case with a lower level of Al. Cr layer contains 2 phases, a ferritic matrix enriched with Cr and a Ni-Al-rich precipitate (probably Ni_3Al). NiAl-rich phase decreases with increasing distance from Al-rich interface.
	1400-1500 °F for 10, 500, and 1500 hr in the fluidized bed	Average thickness of Al-rich outer layer decreased ∿0.5 mil (12.7 μm) in 1500 hr, and outer layer became progressively more internally oxidized with time. Concentration gradient of Ni_3Al phase reduced after 10 hr. Depth of chromized case not must increased after 10 hr but was increased after 500 and 1500 hr exposures. Straight line of demarcation between chromized layer and substrate indicates intragranular diffusion. Al distribution altered appreciably by exposure. After 500 hr Al is depleted to depth 2 mils (50.8 μm) from outer layer and in 1500 hr Al depletion extends through the outer layer. Internal oxidation has occurred and aluminides have formed. In the remaining chromized layer the Al concentration of the matrix has diffused deeper into substrate, otherwise has not altered. Ni content changes in the layers are the same as for Al, but concentration changes for Cr and Fe differ. Chromizing produced decreasing Cr concentration gradient through the case, and in the outer layer where Al diffused into the chromized layer the relative amount of Cr decreased. After exposure, part of the Al diffused out of the outer layer and/or reacted to form internal Al_2O_3 during 500 hr. Reaction restored Cr concentration to level of as-chromized condition. After 1500 hr matrix Cr and Al concentration dropped markedly below the original duplex coat due to internal oxidation. Duplex coating susceptible to internal oxidation. No S found after 500 hr exposure. Few very small particles containing S found in matrix of coating after 1500 hr.

(Data Continued)

EFFECT OF EXPOSURE[a] IN A FLUIDIZED BED COAL COMBUSTOR[b] ON THE MICROSTRUCTURE[c] OF ALLOYS[d][37], Continued

Alloy	Test Conditions	Microstructure
Pack Al Coating on 304 SS and 310 SS (Diffused Al case--five hr at 1700 °F in 15% Al-12Si + 2.5% NH_4Cl + 82.5% Al_2O_3)	Untested--as received	Aluminizing of 304 SS produces a case thickness nearly 2-1/2 times that on 310 SS. Al concentrations are about the same for both but the gradient at the case/substrate interface differs--for 310 SS the gradient is very steep but for 304 SS the gradient extends over 2-3 mils (50-75 μm).
	1620 °F for 1080 hr in the fluidized bed	No change in coating thickness produced by exposure. Significant increase in number of oxide particles at or near exposed surface. Al diffuses out of the case to form Al_2O_3 on the surface. For 304 SS the Al depletion extends to 6 mils (150 μm) deep as compared to Al depletion depth of $\sim$2 mils (50 μm) for 310 SS. Larger number of Al_2O_3 particles found in aluminized layer of 304 SS than of 310 SS. Ni_3Al layer formed at the original aluminized case/substrate interface by Ni diffusing out of the substrate for about 20 mils for 304 SS and only about 8 mils for 310 SS. Diffusion results in transformation of austenite to ferrite. Ni-depleted zone also shows σ-phase but only a very small amount in 304 SS.
316 SS[e] (Fe-17Cr-9.8Ni-2.5Mo-0.75Si)	Expected temperature <250 °F for 1100 hr in the fluidized bed (metal temperatures were found to have varied significantly from one test position to another)	A number of the tubes failed in the 1100 hr period. Tubes in the upper part of bed were eroded over entire length to depth of as much as 100 mils (2540 μm) on the upstream side. Tubes at lower levels of bed had much less metal wastage and an oxide film. Little or no substrate reaction was detected in tubes which were subjected to intermediate temperatures as compared with extensive reaction in tubes at high temperatures. Attack is type characteristic of sulfidation-oxidation reaction. Erosion was major problem for tubes at low temperatures and corrosion the major problem for high temperatures.

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[a] Test alloys and coatings were exposed for varying periods of time at temperatures controlled by air (or water) cooling of specimens and measured by thermocouples in the vessel and on the specimens.

[b] Facility consists of a 24-in diameter refractory-lined fluidized bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

[c] By photomicrography and x-ray emission analysis.

[d] Cylindrical specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 1.00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 obtained as cast rod from which specimens were machined. As machined specimens were solvent rinsed before exposure. Coated specimens were wire brushed and/or hand abraded with emery cloth and solvent rinsed before exposure. Twenty-one specimens were used to make up 18-in air-cooled tube probes.

[e] Water-cooled bayonet-type tubes were tested.

ANALYSIS OF OXIDE SCALES FORMED ON ALLOYS[a] EXPOSED TO AIR OXIDATION[b] [37]

Alloy[a]	Temperature °F	X-Ray Diffraction Analysis of Scale				
		$FeCr_2O_4$	Cr_2O_3	$(CrFe)_2O_3$	Fe_2O_3	NiO
P9 (9Cr-1Mo)	378	--	--	--	Strong	--
	610	--	--	--	Strong	--
	740	--	Weak	Strong	Medium	--
	1020	--	Weak	Strong	Strong	--
E-Brite	420	Unidentified				
(26Cr-1Mo)	630	--	Weak	Strong	Weak	--
	790	--	Strong	Weak	Medium	--
	1068	--	Strong	Weak	Weak-Medium	--
AISI 316 SS	470	--	Medium	Strong	Weak	--
(17Cr-10Ni-2Mo)	650	--	Medium	Weak	Strong	--
	830	--	Strong	Medium	Medium	--
	1068	Medium	Strong	Strong	Weak	--

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[a] Cylindrical test specimens were machined from tube stock to 1.25 in OD, 1.01 in ID, and 0.97 in long. Twenty-four specimens formed a tube probe.

[b] Tube probes were inserted in an electrical resistance furnace maintained at 1600 °F for 144 hours. Specimens were cooled so as to provide the lower temperatures stated.

CORROSION RESISTANCE OF Fe-Cr-Al ALLOYS[a] TO VARIOUS REACTIVE GAS MIXTURES[b] [34]

	Weight Change (mg/cm^2) -- Corrosion Products[c]									
ALLOY[a]	GAS A 1800 °F 24 HR		GAS B 1800 °F 24 HR		GAS C 1800 °F 24 HR		GAS D 1800 °F 24 HR		GAS E 1550 °F 50 HR	
310 SS Base Alloy			-4.82	SS	+46.7	SS	+65.4	SS	+205.5	SS
IN671 (50Cr-50Ni)					+0.82	SO			+3.86	AO[d]
Fe-16Cr-4.5Al	-0.47	SO	+0.29	SO	+0.08	SO	+0.47	SO	+1.73	AO
Fe-16Cr-4.5Al-0.5Si	-0.48	SO	+0.55	SO	+0.21	SO	-0.02	SO	--	
Fe-16Cr-4.5Al-0.5Si-0.75Mn	-1.02	SO	-0.48	SO	-1.34	SO	+0.12	SO	+1.44	AO
Fe-16Cr-4.5Al-1.0Si	-0.33	SO	-0.08	SO	-0.23	SO	+0.08	SO	+3.06	AO
Fe-18Cr-6Al	-0.28	SO	+0.19	SO	-0.23	SO	+0.11	SO	+2.44	AO
Fe-18Cr-6Al-0.5Si	-0.42	SO	-0.10	SO	+0.26	SO	+0.24	SO	+2.38	AO
Fe-18Cr-6Al-1.0Si	-0.39	SO	-0.10	SO	-0.54	SO	nil	SO	+1.82	AO
Fe-16Cr-4.5Al-0.5Y[e]					+0.22	AO			+0.2	AO[d]
Fe-16Cr-4.5Al-0.5Y					+0.74	SO			+1.61	AO[d]
Fe-18Cr-4.0Al					+0.26	SO			+1.05	AO[d]
Fe-16Cr-4.5Al-0.5Hf					+0.31	AO			+0.69	AO[d]
Fe-17Cr-3.0Al					-0.06	SO			+30.1	SS[d]
Fe-18Cr-2.0Al					+0.40	AO			+79.3	SS[d]
Fe-17Cr-3.0Si					-0.17	SO			+0.20	AO[d]

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[a] Alloys prepared by nonconsumable electrode arc melting (120 gm ingots). Button ingots were turned and remelted 3 times (mix, homogenize) and drop cast. Cylindrical ingots were heated 1 hr at 2000 °F (canned in stainless steel) and extruded at a ram speed of 12-IPM using copper sheath for die lubrication to flat sheet bars (0.29 in x 1 in x 6 in/4:1 reduction). Local defects were ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F (10% reduction/pass), 1/2 of sheet further rolled (1600 °F) to 0.070 in thickness. Surface conditioned by grit blasting.

[b] Tests for sulfidation resistance in coal gasification atmospheres conducted at atmospheric pressure; gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec.

	Composition - Vol %				
	GAS-A	GAS-B	GAS-C	GAS-D	GAS-E
H_2	39.3	39.2	34.0	34.6	34.8
CO	12.3	12.2	25.5	26.0	26.1
CO_2	19.7	19.6	17.0	17.3	17.4
CH_4	8.2	8.2	7.1	7.2	7.3
NH_3	-	1.7	1.5	1.4	1.5
H_2O	18.9	17.1	13.5	11.3	10.7
H_2S	1.60	2.04	1.42	2.16	2.18

[c] SO - Spalled Oxide, AO - Adherent Oxide, SS - Sulfide Slag.

[d] 1500 °F, 48Hr, 2.09H_2S-14.2H_2O

[e] Alleghany-Ludlum "Y".

EFFECT OF Si ADDITIONS ON SULFIDATION RESISTANCE[a] OF Fe-Cr-Al ALLOYS[b][34]

	Weight Change (mg/cm^2) - Corrosion Product[c]					
Alloy[b]	Test 1[d] 96 HR		Test 2[e] 96 HR		Test 3[f] 25 HR	
Fe-16Cr-4.5Al	+0.6	SO	-0.59	SO		
Fe-16Cr-4.5Al-0.25Si	+0.14	SO	-0.67	SO		
Fe-16Cr-4.5Al-0.5Si	+0.36	SO	-0.76	SO		
Fe-16Cr-4.5Al-1.0Si	+0.07	SO	-1.89	SO		
Fe-16Cr-4.5Al-0.75Mn	+1.68	SO	+18.03	AO		
Fe-16Cr-4.5Al-0.5Si-0.75Mn	+1.85	SO	+19.54	AO		
Fe-16Cr-4.5Al-1.0Si-1.5Mn	+5.71	SO	+16.70	AO		
Fe-17Cr-3Al					-0.53	SO
Fe-17Cr-3Si					-0.06	SO
Fe-18Cr-2Al					+0.17	SO
Fe-18Cr-2Si					-0.57	SO
Fe-18Cr-1Al-1Si					-0.91	AO
Fe-18Cr-4Al	+0.64	SO	-9.95	SO		
Fe-18Cr-6Al					-0.91	SO
Fe-18Cr-6Al-0.5Si					-0.63	SO
Fe-18Cr-6Al-1Si					-0.45	SO
Fe-18Cr-6Al-2Si					-0.57	SO
Fe-19Cr-1Al					+0.97	AO
Fe-19Cr-1Si					-0.08	SO
Fe-20Cr					+106.0	SS

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[a] Tests for sulfidation resistance in coal gasification atmospheres conducted at atmospheric pressure and 1800 °F; gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec. Nominal gas composition (vol %): 18 CO, 12 CO , 24 H_2, 5 CH_4, 1 H_2S, 1 NH_3, 39 H_2O.

[b] Alloys prepared by nonconsumable electrode arc melting (120 gm ingots). Botton ingots were turned and remelted 3 times (mix, homogenize) and drop cast. Cylindrical ingots heated 1 hr at 2000 °F (canned in stainless steel) and extruded at ram speed of 12-IPM using copper sheath for die lubrication to flat sheet base (0.29 in x 1 in x 6 in/4:1 reduction). Local defects ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in thick sheet from 1600 °F (10% reduction/pass); 1/2 of sheet further rolled (1600 °F) to 0.070 in thickness. Surfaces conditioned by grit blasting.

[c] AO - Adherent Oxide (Cr_2O_3),

SO - Spalled Oxide (Al_2O_3),

SS - Sulfide slag.

[d] Temperature Overshoot to 2150 °F for < 16 hr.

[e] Low Water-High H_2S Input for 10-15 hr. at end of run, 20% H_2O and 1.5% H_2S estimated.

[f] Nominal gas composition as given in footnote a.

CORROSION OF Fe-Cr-Al ALLOYS[a] IN EXTENDED LIFE TEST[b] [34]

Alloy[a]	Weight Change mg/cm^2	Corrosion Product[c]
Fe-16Cr-4.5Al	-0.57	SO
Fe-16Cr-4.5Al-0.5Si	-0.43	SO
Fe-18Cr-6Al	-0.49	SO
Fe-18Cr-6Al-0.5Si	-0.08	SO

---

[a] Alloys prepared by nonconsumable electrode arc melting (120 gm ingots). Button ingots were turned and remelted three times (mix, homogenize) and drop cast. Cylindrical ingots heated 1 hr at 2000 °F (canned in stainless steel) and extruded at a ram speed of 12-IPM using copper sheath for die lubrication to flat sheet bars (0.29 in. x 1 in. x 6 in./4:1 reduction). Local defects were ground off, surfaces polished through 120 grit. Conditioned bars rolled to 0.1 in. thick sheet from 1600 °F (10 percent reduction/pass); 1/2 of sheet further rolled (1600 °F) to 0.070 in. thickness. Surfaces conditioned by grit blasting.

[b] Nominal gas composition (mol %): 18 CO, 12 CO_2, 24 H_2, 5 CH_4, 1 H_2S, 39 H_2O. Test conducted at 1255 K (1800 °F) and 1 atm for 500 hr.

[c] SO = spalled oxide; no delectable penetration by sulfur; developed random spots of sulfidation, particularly at edges and holes.

SULFIDATION RESISTANCE OF Cr AND Mo-BASE ALLOYS IN A SYNTHETIC COAL GASIFICATION ENVIRONMENT[a] [34]

	Weight Change (mg/cm^2)--Corrosion Products[b]		
	Not Equilibrated		Equilibrated[c]
Alloy	24 Hr	60 Hr	96 Hr
Cr		+3.29 AO	
Cr-0.5Y	+0.02 AO	+1.61 AO	
Cr-0.5La	+0.29 AO		
Cr-2Fe		+3.07 AO	
Cr-2Mn		+2.11 AO	
Mo-0.5Ti-0.1Zr (TZM-Mo)			+0.03 AS

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[a] Sulfidation resistance tested at 1255 K (1800 °F) and 1 atm. Nominal gas composition (mol %): $24H_2$, $39H_2O$, 18CO, $12CO_2$, $5CH_4$, $1H_2S$, $1NH_3$. Gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec.

[b] AO--Adherent Oxide, AS--Adherent Sulfide. Cr-base alloys form stable Cr_2O_3, Mo-base forms stable MoS_2.

[c] Inlet gas percolated through a heated bed of fine/coarse Al_2O_3 bubble grains fitted in furnace tube to within 1 inch of the lowest sample on the specimen rack. Equilibrated gas also contains minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, CS.

SULFIDATION[a] OF Fe-Cr-Al-Mn ALLOYS[b] AS AFFECTED BY GAS FLOW RATE AND EQUILIBRATION[c] [34]

24 HR-1255 K (1800 °F)--Coal Gasification Atmosphere[a]

Alloy[b]	Non-equilibrated Gas				Equilibrated Gas
	1000 cc/min[d]		2000 cc/min[e]		1000 cc/min
	Weight Change (mg/cm^2)		Weight Change (mg/cm^2)		
Fe-10Cr-8Al-2.5Mn	-2.44	SO[f]	-2.95	SO	Destroyed[g]
Fe-10Cr-8Al	-0.10	SO	-1.13	SO	Destroyed
Fe-10Cr-10Al-2.5Mn	-2.07	SO	-7.03	SO	Destroyed
Fe-10Cr-10Al	-0.47	SO	-3.37	SO	Destroyed
Fe-10Cr-10Al-5Mn	-3.35	SO	-4.32	SO	Destroyed
Fe-15Cr-10Al-5Mn	-4.83	SO	-8.37	SO	Destroyed

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[a] Tests for sulfidation resistance in coal gasification atmospheres conducted at atmospheric pressure and 1255 K (1800 °F); nominal coal gasification composition (mol %): 24 H_2, 39 H_2O, 18 CO, 12 CO_2, 5 CH_4, 1 H_2S, 1 NH_3. Gas flowed upward past samples at indicated flow rates.

[b] Alloys were arc melted and drop cast by the non-consumable electrode process under argon at 1.5 atm. Cast structure was broken up by extrusion from 2000 °F (canned in stainless steel) and hot rolling from 1600 °F (reduced 10 percent in thickness per pass and reheated between passes) to 0.1 in thick. Coupons machined to 0.75 in. x 0.25 in. and rolled surfaces were ground flat and parallel (5 mil from each side).

[c] Inlet gas percolated through a heated bed of fine/coarse Al_2O_3 bubble grains fitted in the furnace tube to within 1 in. of the lowest sample on the specimen rack. Also contains minor reactants: HS; COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, and CS.

[d] Linear flow rate 0.56 cm/s.

[e] Linear flow rate 1.12 cm/s.

[f] SO--Spalled Oxide.

[g] Fully converted to sulfides and oxides, no metal remaining.

APPEARANCE OF ALLOY SPECIMEN[a] SURFACES AFTER OXIDATION IN AIR[b][37]

Alloy[a]	Temperature °F	Appearance of Oxide Scale[c] 6	12	9	3
48 HOUR EXPOSURE					
A106, Carbon steel Aluminized[d]	215	Grey	Grey	Gold	Gold
	530	Patchy Network of Gold-Colored Oxide			
	710	Patchy Network of Gold-Colored Oxide			
	810	Patchy Network of Gold-Colored Oxide			
A106, Carbon steel	270	Dark Blue	Gold	Gold	Gold
	570	Patchy Network of Gold-Colored Oxide			
	730	Black Scale			
	830	Thin, Black Scale	Heavy Black Scale		
P22 (2 1/4Cr-1Mo)	330	Purple	Blue	Dark Blue	Purple
	615	Dark Blue	Grey	Light Blue	Light Gold
	740	Blue/Grey	Black	Blue/Grey	Black
	849	Black Scale			
P9(9Cr-1Mo)	380	Light Gold	Dark Gold	Light Gold	
	635	Purple			Light Gold
	760	Light Blue			
	870	Silver	Silver	Light Blue	
E-Brite (26Cr-1Mo)	440	Silver	Light Blue	Silver	
	665	Light Gold	Dark Gold		
	780	Dark Gold	Light Blue	Dark Blue	
	890	Gold	Yellow/Green		
AISI 316SS (17Cr-10Ni-2Mo)	490	Light Gold	Dark Gold	Light Gold	Dark Gold
	690	Light Gold	Dark Gold		
	795	Dark Gold	Light Blue	Dark Blue	
	900	Gold	Purple	Light Gold	
144 HOUR EXPOSURE					
A106, Carbon steel Aluminized	238	Yellow	Yellow	Silver	Silver
	515	Yellow/Powdery		Purple/Gold	
	670	Gold/Blue	Gold/Grey		
	880	Blue/Grey	Silver/Grey		
A106, Carbon steel	280	Gold/Grey	Blue/Black	Gold/Grey	
	555	Grey	Black Scale	Yellow/Powdery	Black Scale
	680	Silver/Blue	Rusty Scale	Black Scale	Silver Scale
	925	Rusty Scale	Black	Rusty Scale	Black

(Table Continued)

APPEARANCE OF ALLOY SPECIMEN[a] SURFACES AFTER OXIDATION IN AIR[b][37]

-Continued-

Alloy[a]	Temperature °F	Appearance of Oxide Scale[c] 6	12	9	3
* * * 144 HOUR EXPOSURE, continued * * *					
P22 (2 1/4Cr-1Mo)	330	Rusty	Gold/Blue	Gold	
	587	Grey	Blue/Black Rusty Scale		
	680	Rust-Red Scale			
	970	Rusty	Blue/Black Scale	Rusty/Black	
P9 (9Cr-1Mo)	378	Rusty	Yellow/Powdery	Light Gold	
	610	Grey	Black/Rusty Scale	Silver/Blue	
	740	Rusty	Black/Rusty Scale	Blue/Black	
	1020	Blue/Black		Rusty/Black	
E-Brite (26Cr-1Mo)	420	Yellow Powdery on Silver			
	630	Yellow/ Powdery	Black	Gold/Blue	
	790	Gold	Gold/Blue/Black		
	1068	Black	Grey/Green		
316SS (17Cr-10Ni-2Mo)	470	Yellow Powder on Silver			
	650	Gold & Yellow Powder	Black	Gold & Yellow Powder	Black
	830	Blue/Black			
	1068	Grey/Black			

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[a] Cylindrical test specimens were machined from tube stock to 1.25 in OD, 1.01 in ID, and 0.97 in long. Twenty-four specimens (four sets of each alloy) formed a tube probe.

[b] Tube probes were inserted in an electrical resistance furnace maintained at 1600 °F for the stated test periods. Specimens were cooled to provide the lower temperatures stated.

[c] The locations refer to clock positions around the diameter of the probe when installed in the furnace.

[d] Diffused Al case - pack aluminized 5 hr at 1700 °F in 15% Al-12Si + 2.5% NH_4Cl + 82.5% Al_2O_3.

EFFECT OF Mn ADDITIONS ON CORROSION BEHAVIOR OF Fe-Cr-Al ALLOYS[a][34]

Alloy[b]	Air Oxidation, 120 hr[b]		Coal Gasification Atmosphere, 24 hr[c]	
	Weight Change mg/cm^2	Corrosion Products[d]	Weight Change mg/cm^2	Corrosion Products[d]
Fe-8Al-5Cr-Mn	+3.24	SO	D	
Fe-8Al-5Cr-1.5Mn			D[e]	
Fe-8Al-5Cr-2.5Mn	+0.25	AO	D	
			-5.51	SO
Fe-8Al-10Cr-Mn	+2.61	SO/EF	-0.10	SO
Fe-8Al-10Cr-1.5Mn			-10.10	SO
Fe-8Al-10Cr-2.5Mn	+0.36	AO	-2.44	SO
			-2.00	SO
Fe-8Al-10Cr-5.0Mn			+1.58	(SO)[e]
Fe-8Al-15Cr-Mn			-0.05	SO
Fe-10Al-2.5Cr-5.0Mn			D[e]	
Fe-10Al-5Cr-Mn	+1.33	SO	D	
Fe-10Al-5Cr-2.5Mn	+0.23	AO	D	
Fe-10Al-5Cr-5.0Mn	+0.10	AO	-2.13	SO
Fe-10Al-10Cr-Mn	+1.08	SO	-0.47	SO
Fe-10Al-10Cr-1.5Mn			+51.3	SO[f]
			+0.93	SO[e]
Fe-10Al-10Cr-2.5Mn	+0.16	AO	-2.09	SO
			-1.44	SO
Fe-10Al-10Cr-5.0Mn	+0.16	AO	-3.35	SO
			-3.19	SO
Fe-10Al-15Cr-Mn	+1.46	SO	-0.69	
			-0.55	
			-0.45	SO
Fe-10Al-15Cr-1.5Mn			-0.70	SO[f]
			+7.9	SO[e]
Fe-10Al-15Cr-2.5Mn			+5.51	SO
Fe-10Al-15Cr-5.0Mn	+0.29	AO	-4.8	SO
			-9.22	SO
Fe-12Al-5Cr-2.5Mn	+0.18	AO	D	
Fe-12Al-10Cr-2.5Mn	+0.31	AO	-4.34	SO/SS

(Table Continued)

EFFECT OF Mn ADDITIONS ON CORROSION BEHAVIOR OF Fe-Cr-Al ALLOYS[a] [34]

(continued)

[a] Alloys were arc melted and drop cast by the nonconsumable electrode process under argon at 1.5 atm. Cast structures were broken up by extrusion from 2000 °F (canned in stainless steel) and hot rolling from 1600 °F (10% reduction in thickness per pass and reheated between passes) to 0.1-in thickness. Rolled surfaces were ground flat and parallel (5 mils from each side).

[b] 100 cycles. Tests for resistance to oxidation at 1255 K (1800 °F) on cyclic exposure to air; samples heated for total of 100 hr in slowly moving air; they were withdrawn from furnace every 50 min and cooled to ambient temperature; every 25 cycles, samples were weighed; samples removed from test when excessive oxidation attack observed.

[c] Nominal coal gasification composition (mol %): 24 H_2, 39 H_2O, 18 CO, 12 CO_2, 5 CH_4, 1 H_2S, 1 NH_3, unequilibrated. Tests conducted at atmospheric pressure and 1255 K (1800 °F); gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec.

[d] EF-edge failure; AO-adherent oxide; D-destroyed; SS-sulfide slag; SO-spalled oxide.

[e] 47 hr test.

[f] Equilibrated gas. Inlet gas percolated through a heated bed of fine/coarse Al_2O_3 bubble grains fitted in the furnace tube to within 1 inch of the lowest sample on the specimen rack. Also contains minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, CS.

CORROSION OF SELECTED ALLOYS[a] IN EQUILIBRATED AND NON-EQUILIBRATED SYNTHETIC COAL GASIFICATION ENVIRONMENTS[b][34]

Alloy[a]	Composition	Weight Change (mg/cm^2)--Corrosion Products[c] 24 hr-Not Equilibrated[b]		24 hr Equilibrated[b]		96 hr Equilibrated[b]	
1	Fe-10Cr-2Al	Destroyed		Destroyed			
2	Fe-10Cr-4Al	Destroyed		--			
3	Fe-10Cr-6Al	+6.57	AO,SS	--			
4	Fe-10Cr-8Al	-0.10	SO	Destroyed			
5	Fe-10Cr-10Al	-0.47	SO	Destroyed			
6	Fe-15Cr-3Al	+0.24	AO	Destroyed			
7	Fe-15Cr-4Al	+0.27	SO	+0.49	SO	+0.42	SO
8	Fe-15Cr-6Al	nil	SO	--		+0.39	SO
A/L-Y[e]	Fe-16Cr-4.5Al-0.56Y	+0.69	AO	+0.39	AO	+0.49	AO
ARMCO-18SR	Fe-18Cr-2Al-1Si	+0.32	AO	+0.45	AO	+0.69	AO
446 SS	Fe-24Cr	+3.41	AO	+1.33	AO	+5.86	AO
304 SS	Fe-9.10Ni-18.76Cr	+149.4	SS	+167.2	SS	--	
Incoloy 800	Fe-30.84Ni-20.60Cr	+0.83	AO	+0.61	SO	+2.09	SO
309 SS	Fe-14.70Ni-22.97Cr	+0.72	AO	+0.42	AO	+1.42	AO
314 SS	Fe-20.0Ni-24.0Cr	-2.25	SO	-0.69	SO		
310 SS	Fe-20.2Ni-25.0Cr	+2.18	SO	+0.60	SO	+1.80	AO
Inconel 600	6.99Fe-Bal Ni-15.82Cr	+0.51	AO,SS	+0.79	AO,SS	+1.68	AO
RA 333	15.50Fe-Bal Ni-26.20Cr-3.8Mo-2.7W	+17.0	SS	+25.4	SS		
Inconel 671	Bal Ni-50.0Cr-0.35Ti	+4.58	AO,SS	-0.09	AO,SS		
Inconel 657	Bal Ni-50.0Cr-1.5Cb	+1.26	AO,SS	+1.12	AO,SS	+2.54	AO
Haynes 188	23.3Ni-Bal Co-23.4Cr-14.6W-0.06Mo	-0.24	SO	+0.42	SO	+2.41	AO,SS
A/L-RV 18[e]	31.5Ni-Bal Co-35.0Cr	+112.9	SS	+156.6	SS		
A/L-RV 19[e]	18.55Fe-Bal Ni-25.8Co-25.58Cr	+3.24	AO,SS	+0.36	AO,SS		

(Table Continued)

CORROSION OF SELECTED ALLOYS[a] IN EQUILIBRATED AND NON-EQUILIBRATED SYNTHETIC COAL GASIFICATION ENVIRONMENTS[b][34]

(continued)

[a] Alloys numbered 1 through 8 are experimental compositions prepared by arc melting and drop casting by the nonconsumable electrode process under argon at 1.5 atm. Cast structure was broken up by extrusion from 2000 °F (canned in stainless steel) and hot rolling from 1600 °F (reduced 10% per pass and reheated between passes) to 0.1 in thick. Coupons machined to 0.75 in x 0.25 in. Rolled surfaces were ground flat and parallel (5 mil removed from each side).

[b] Nominal gas composition (mol %): 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 1 H_2S, 39 H_2O. Gas flowed upward past samples at 1000 cc/min, linear flow rate was 0.56 cm/sec. For equilibration the inlet gas percolates through a heated bed of fine/coarse Al_2O_3 bubble grains fitted in the furnace tube to within one inch of the lowest sample on the specimen rack. Equilibrated gas also contains minor reactants: HS, COS, S_2, S, O_2, O, SO, SO_2, N_2, H, OH, CS_2, CS.

[c] AO-adherent oxide, SO-spalled oxide, SS-sulfide slag.

[d] In 24 hr test, 1.1% H_2S, 32.9% H_2O; in 96 hr test, 1.0 % H_2S, 39.3% H_2O.

[e] Alleghany-Ludlum alloys, RV18 and RV19 are experimental.

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]

Components[b]	Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr Aqueous	Corrosion Rate,[f] mils/yr Gaseous	Pit Depth,[g] mils Aqueous max	Pit Depth,[g] mils Aqueous ave	Pit Depth,[g] mils Gaseous max	Pit Depth,[g] mils Gaseous ave
H_2S 0.2 mol% CO_2 15 mol% NH_3 0.3 mol% H_2 17 mol% CO 10 mol% CH_4 7 mol% H_2O 27 vol% Toluene 23 vol% HCN 500 ppm phenol 1000 ppm chloride 3000 ppm	Liquid temperature 200 °F Gas pressure 1000 psig Gas temperature 600 °F Liquid pressure 1000 psig lb quench/lb gas 3.5	7.6	304 SS/70Fe-9Ni-19Cr	0	0				
			316 SS/65Fe-14Ni-17Cr	0	0			2.6	1.6
			329 SS/Fe-4Ni-27Cr	0	0				
			18-18-2/Fe-18Ni-18Cr-2Si	0.4	0				
			Armco 22-13-5/Fe-14Ni-21Cr-5Mn	0.4	0				
			20Cb-3/Fe-33Ni 19Cr	0	0				
			26-1/Fe-26Cr-1Mo	0.5	0				
			Incoloy 800/47Fe-31Ni-21Cr	3.3	2.0				
			Incoloy 825/30Fe-22Cr-42Ni-3Mo	0	-0.4				
			Hastelloy C/Ni-16Cr-6Fe-15Mo	-0.4	0				
			Hastelloy G/Ni-22Cr-20Fe-7Mo	0	-0.4				
			Titanium	-0.7	0			1.5	1.1
		9.7	304 SS	0.4	0				
			410 SS/Fe-12Cr	2.3	0.9	2.2	1.5		
			430SS/Fe-17Cr	0.9	0.9	1.3	1.1	1.5	1.2
			Carbon steel (A515)	11.9	4.5				
			Cast iron	10.4	1.5				
			Ni-resist/Fe-20Ni-3Cr-3Si	3.8	1.0	1.2	0.8	1.1	0.8
			Ni-resist(Cu)/Fe-18Ni-4Cr-3Si-7Cu			0.8	0.7	0.6	0.4
			18-2/Fe-18Cr-2Mo	0.5	0	2.6	1.1	0.8	0.5
		9.3	Aluminum 1100	8.3	1.4	3.0	2.0		
			Aluminum 6061	9.6	1.4	3.5	2.4		
		9.5	Monel 400/64Ni-33Cu-2Fe	24.8	6.6				
			Al bronze/Cu-10Al-3Fe-2Ni	14.7	2.8				
		9.2	18-2	0.5	0				
			Ni-resist	23.5	5.2				
			Ni-resist(Cu)	15.2	4.3				

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]
-Continued-

Components[b]		Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr Aqueous	Corrosion Rate,[f] mils/yr Gaseous	Pit Depth,[g] mils Aqueous max	Pit Depth,[g] mils Aqueous ave	Pit Depth,[g] mils Gaseous max	Pit Depth,[g] mils Gaseous ave
compositions and conditions the same as the preceding test except HCN 100 ppm phenol nil			9.2	304 SS	0.4	0				
				316 SS	0.4	0				
				329 SS	0	0				
				18-18-2	0.5	0				
				Armco 22-13-5	0	0				
				20Cb-3	-0.4	0				
				26-1	0.5	0				
				Incoloy 800	0.4	1.7				
				Incoloy 825	0	0				
				Hastelloy C	0	0				
				Hastelloy G	0	0				
				Titanium	0	0				
			9.5	304 SS	0	0				
				410 SS	0.9	0	1.2	0.8		
				430 SS	0.4	0.4				
				Carbon steel	73.3	3.5				
				Cast iron	111	2.5				
				Ni-resist	68.4	1.9				
				Ni-resist(Cu)			0.6	0.4	0.7	0.4
				18-2	0	-0.5	1.9	0.6	2.5	1.0
			9.5	Aluminum 1100	13.8	1.4	3.0	2.3		
				Aluminum 6061	15.4	1.4	3.3	2.7		
			10.6	Monel 400	3.8	4.8				
				Al-bronze	55	3.3				
			9.4	18-2	0.5	0.5				
				Ni-resist	29.5	4.3				
				Ni-resist(Cu)	16.9	4.5				
H_2S	0.8 mol%	Liquid temperature 400 °F	8.5	304 SS	1.3	1.7	1.3	0.9	3.9	2.3
CO_2	18 mol%	Gas pressure 1210 psig		316 SS	0.5	0.4				
NH_3	0.45mol%	Gas temp. 400 °F		329 SS	0	0				
H_2	22 mol%	Liquid pressure 1210 psig		18-18-2	0.5	2.7	2.6	1.4	3.0	2.5
CO	19 mol%	lb quench/lb gas --		Armco 22-13-5	0	0.4				
CH_4	15 mol%			20Cb-3	-0.4	-0.4				
				26-1	0	0				
H_2O	20 vol%			Incoloy 800	0.8	0.4	2.8	1.3	2.2	1.9
Toluene	3 vol%			Incoloy 800	0	0			2.2	1.6
HCN 200 ppm				Hastelloy C	0	0				
phenol 700 ppm				Hastelloy G	0	0			1.9	1.0
chloride 3000 ppm				Titanium	-1.4	-1.4			1.2	0.8
			7.2	304 SS	2.1	1.7				
				410 SS	125.6	33.6				
				430 SS	55.5	31.4				
				Carbon steel	58	23				
				Cast iron	69.5	32				
				Ni-resist	46.7	32.5	1.1	0.8	0.5	0.4
				Ni-resist(Cu)						
				18-2			1.3	1.0	1.8	0.8
			7.6	Aluminum 1100	95.6	-8.42	13.7	9.7		
				Aluminum 6061	70.9	-7.0	8.5	6.7		
			9.4	Monel 400	170	71.6				
				Al bronze	245	93.6				

(Tabled Continued)

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]
-Continued-

Components[b]	Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr		Pit Depth,[g] mils			
				Aqueous	Gaseous	Aqueous		Gaseous	
						max	ave	max	ave
		3.9	18-2	1.5	0.5				
			Ni-resist	39.7	18.5				
			Ni-resist(Cu)	51.9	28.6				
compositions and conditions the same as the preceding test except		8.5	304 SS	7.2	1.3	2.6	2.2		
			316 SS	2.4	1.3	2.5	1.6		
			329 SS	0.6	0.5				
toluene nil			18-18-2	6.3	3.2	2.1	1.5	1.4	0.8
chloride 100 ppm			Armco 22-13-5	0.8	0.4				
			20Cb-3	0.4	0.4				
			26-1	0.4	0.9				
			Incoloy 800	1.7	2.1	3.4	1.8		
			Incoloy 825	0.4	1.2				
			Hastelloy C	-0.4	0				
			Hastelloy G	0	0.4				
			Titanium	-0.7	-0.7	1.6	1.0		
		8.2	304 SS	1.3	0.9				
			410 SS	16.1	15.3	2.2	1.9		
			430 SS	5.0	3.9	1.7	1.3		
			Carbon steel	43.9	49.7				
			Cast iron	41.7	53.4				
			Ni-resist	26.2	31.8	0.4	0.3		
			Ni-resist(Cu)			0.6	0.4		
			18-2	1.0	1.0	1.5	1.0	0.7	0.4
		6.4	Aluminum 1100	-1.4	-6.81	2.0	1.2		
			Aluminum 6061	0	-6.90	1.7	1.1		
		8.3	Monel 400	133.8	104				
			Al bronze	289	173				
		7.5	18-2	1.0	0.5				
			Ni-resist	25.8	22.7				
			Ni-resist(Cu)	30.2	29.0				
H_2S 0.02 mol%	Liquid temp. 120 °F	7.5	304 SS	0	0.5	1.1	0.9		
CO_2 3.2 mol%	Gas pressure 131 psig		316 SS	0	0				
NH_3 0.52 mol%	Gas temp. 200 °F		329 SS	0.5	0				
H_2 56 mol%	Liquid pressure 126 psig		18-18-2	2.5	2	0.8	0.6		
CO 15 mol%	lb quench/lb gas 1		Armco 22-13-5	0	0				
CH_4 10 mol%			20Cb-3	0	0				
N_2 0.18 mol%			26-1	0	0				
			Incoloy 800	0	0				
H_2O 15 vol%			Incoloy 825	0	0				
toluene nil			Hastelloy C	0	0				
HCN 100 ppm			Hastelloy G	0.4	0				
phenol 100 ppm			Titanium	0	0	1.3	1.0		
chloride 3000 ppm									
		7.9	304 SS	0	1.3				
			410 SS	16	20	1.1	0.8		
			430 SS	-4.8	1.9				
			Carbon steel	34.4	2.3				
			Cast iron	4.2	1.3	2.0	1.4		
			Ni-resist	2.5	0.9				
			Ni-resist(Cu)						
			18-2	--	--				
		6.5	Aluminum 1100	1.4	0			1.0	0.7
			Aluminum 6061	0	0				
		7.8	Monel 400	1.5	3.5				
			Al bronze	4.5	0				

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]
-Continued-

Components[b]	Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr		Pit Depth,[g] mils			
						Aqueous		Gaseous	
				Aqueous	Gaseous	max	ave	max	ave
	↓	9.2	18-2	1.0	0.5				
			Ni-resist	10.1	6.7				
			Ni-resist(Cu)	12.5	6.5				
compositions and conditions the same as the preceding test except HCN nil phenol nil chloride 100 ppm		8.4	304 SS	0.4	0	1.2	0.9		
			316 SS	0.5	0.5				
			329 SS	0	0				
			18-18-2	0.5	0.5				
			Armco 22-13-5	0.5	0				
			20Cb-3	0.5	0				
			26-1	0	0				
			Incoloy 800	0	0.4				
			Incoloy 825	0	0				
			Hastelloy C	0	0				
			Hastelloy G	0	0				
			Titanium	0.7	0.7				
	↕	8.7	304 SS	0.5	0				
			410 SS	3.2	2.8				
			430 SS	0.5	0.9				
			Carbon steel	12.6	11.7				
			Cast iron	18.8	13				
			Ni-resist	3.1	7.5				
			Ni-resist(Cu)						
			18-2	--	--				
		8.1	Aluminum 1100	0	0	1.1	0.9		
			Aluminum 6061	0	0	1.3	0.8	5.6	1.7
		8.0	Monel 400	2.8	3.5				
			Al bronze	1.7	2.2				
		8.5	18-2	1.0	1.0				
			Ni-resist	10	1.9				
			Ni-resist(Cu)	6.2	2.4				
H_2S 0.34 mol%	Liquid temperature 462 °F	3.9	304 SS	7.2	2.2	1.5	1.1		
CO_2 7 mol%	Gas pressure 1215 psig		316 SS	4.2	4.2				
NH_3 nil	Gas temp. 597 °F		329 SS	0.5	2.6				
H_2 15 mol%	Liquid pressure 1200 psig		18-18-2	7.1	6.6	1.5	1.2	1.3	0.9
CO 26 mol%	lb quench/lb gas 0.23		Armco 22-13-5	0.4	0.8			1.5	0.8
CH_4 10 mol%			20Cb-3	0.8	2.5				
N_2 0.5 mol%			26-1	0.9	1.9				
			Incoloy 800	0.8	2.9			2.4	1.4
H_2O 42 vol%			Incoloy 825	0.8	2.7				
Toluene nil			Hastelloy C	0.4	0.4				
HCN 200 ppm			Hastelloy G	0	0.4				
phenol nil			Titanium	0	2.8	1.6	0.8	1.4	0.8
chloride 3000 ppm									
	↑	3.9	304 SS	2.9	1.7				
			410 SS	74.7	-0.4	1.9	1.5		
			430 SS	13.7	8.6			1.6	1.5
			Carbon steel	112.7	32.2			2.4	1.4
			Cast iron	61.4	30.1				
			Ni-resist	19	30.6			0.5	0.4
			Ni-resist(Cu)						
			18-2	1.4	1.9	3.0	2.3		
		3.9	Aluminum 1100	7.1	-11.4	10	7.2		
			Aluminum 6061	-4.3	-7.1	3	1.9		
		3.8	Monel 400	160	114				
			Al bronze	89.3	194				

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]
-Continued-

Components[b]	Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr Aqueous	Corrosion Rate,[f] mils/yr Gaseous	Pit Depth,[g] mils Aqueous max	Pit Depth,[g] mils Aqueous ave	Pit Depth,[g] mils Gaseous max	Pit Depth,[g] mils Gaseous ave
↓	↓	3.9	18-2	5.4	0				
			Ni-resist	59.5	23.4				
			Ni-resist(Cu)	75.5	65.1				
compositions and conditions the same as the preceding test except		3.5	304 SS	4.3	3.5	1.3	1.0		
			316 SS	4.2	3.8			1.7	1.4
			329 SS	0.5	0.5				
HCN nil			18-18-2	3.7	4.1	2.0	1.4	1.3	1.2
chloride 100 ppm			Armco 22-13-5	0.5	0.5				
↕			20Cb-3	0.9	0.9	1.4	1.1		
			26-1	0.4	0.8				
			Incoloy 800	1.0	0.5	2.1	1.4		
			Incoloy 825	0.5	1.0				
			Hastelloy C	0	0.8				
			Hastelloy G	0.8	0.4				
			Titanium	0	0	1.7	1.3		
		3.1	304 SS	2.2	1.3				
			410 SS	56	5.4				
			430 SS	12.8	3.6				
			Carbon steel	165.0	48.0			0.8	0.6
			Cast iron	153.2	45.4				
			Ni-resist	37.3	28.6				
			Ni-resist(Cu)						
			18-2	--	--	2.0	1.1		
		3.5	Aluminum 1100	-13.6	-8.4				
			Aluminum 6061	-6.9	-4.1				
		2.9	Monel 400	165	100				
			Al bronze	138	48.2				
		4.2	18-2	2.9	1.5				
			Ni-resist	66.3	38.6				
			Ni-resist(Cu)	84.0	32.9				
H_2S 1.1 mol%	Liquid temp. 462 °F	8.5	304 SS	2.5	0.9	1.6	1.3		
CO_2 21 mol%	Gas pressure 1210 psig		316 SS	1.7	2.2			1.6	1.4
NH_3 0.6 mol%	Gas temp. 950 °F		329 SS	0	0.5				
H_2 19 mol%	Liquid pressure 1200 psig		18-18-2	4	0.9	2.4	1.9	1.4	1.0
CO 9 mol%	lb quench/lb gas 0.57		Armco 22-13-5	0	0.9				
CH_4 13 mol%			20Cb-3	0	0.8				
N_2 0.1 mol%			26-1	0.5	1.8				
			Incoloy 800	0	1.7	1.3	1.1		
H_2O 36 vol%			Incoloy 825	0	4.1				
Toluene 0.04 vol%			Hastelloy C	0	0				
HCN 10 ppm			Hastelloy G	0	0				
phenol 6000 ppm			Titanium	-0.7	-0.7	1.3	0.8		
chloride 3000 ppm									
↕		9.0	304 SS	4.3	4.7				
			410 SS	150	76.4				
			430 SS	61.4	58				
			Carbon steel	72.9	89.2				
			Cast iron	91.6	86.8				
			Ni-resist	89.1	173.6				
			Ni-resist(Cu)						
			18-2	--	--	1.0	0.8	1.7	0.9
		8.6	Aluminum 1100	-5.3	-52.8	1.0	0.7	1.2	0.8
			Aluminum 6061	-3.7	-17.2	0.6	0.4	1.4	1.1
		9.0	Monel 400	142.0	140.5				
			Al bronze	227	326.2				
		7.2	18-2	3.5	6.1				
			Ni-resist	50.5	34				
			Ni-resist(Cu)	55.9	40.7				

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]
-Continued-

Components[b]	Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr Aqueous	Corrosion Rate,[f] mils/yr Gaseous	Pit Depth,[g] mils Aqueous max	Pit Depth,[g] mils Aqueous ave	Pit Depth,[g] mils Gaseous max	Pit Depth,[g] mils Gaseous ave
compositions and conditions the same as the preceding test except HCN nil phenol 1000 ppm chloride 100 ppm		7.9	304 SS	4.7	6.3	1.0	0.8		
			316 SS	2.7	3.4				
			329 SS	0.5	1.1				
			18-18-2	4.1	25.5	1.0	0.9	0.8	0.6
			Armco 22-13-5	0.4	1.3				
			20Cb-3	0	1.6				
			26-1	0.5	2.8				
			Incoloy 800	0.8	1.6			1.4	0.9
			Incoloy 825	0.4	2.4				
			Hastelloy C	0	0.8				
			Hastelloy G	0.4	0.4				
			Titanium	0	-0.7				
		9.3	304 SS	2.7	3.4				
			410 SS	94.9	61.1				
			430 SS	138.2	100				
			Carbon steel	56.5	77.5				
			Cast iron	66	97.5				
			Ni-resist	58.4	63.5				
			Ni-resist(Cu)			0.8	0.6		
			18-2	--	--	1.0	0.7		
		9.0	Aluminum 1100	71.6	-20.4	15.4	13.1		
			Aluminum 6061	48.5	-10.9	10.6	9.0		
		9.0	Monel 400	209	4.3				
			Al bronze	460.1	264.2				
		7.5	18-2	3.9	3.9				
			Ni-resist	51.1	40.2				
			Ni-resist(Cu)	65.7	49.0				
H_2S 0.35 mol%	Liquid temp. 230 °F	4.7	304 SS	0	0				
CO_2 5 mol%	Gas pressure 100 psig		316 SS	0	0				
NH_3 0.002 mol%	Gas temp. 500 °F		329 SS	0	0				
H_2 48 mol%	Liquid pressure 95 psig		18-18-2	0	0	3.2	1.8		
CO 27 mol%	lb quench/lb gas 0.91		Armco 22-13-5	0	0	0.6	0.5		
CH_4 5 mol%			20Cb-3	0	0				
N_2 0.5 mol%			26-1	0	0				
			Incoloy 800	0.5	0				
H_2O 14 vol%			Incoloy 825	0	0				
toluene nil			Hastelloy C	0	0				
HCN 100 ppm			Hastelloy G	0	0				
phenol 100 ppm			Titanium	-2.0	0				
chloride 3000 ppm									
		5.7	304 SS	0.5	0.5				
			410 SS	3	3				
			430 SS	2.3	1.5				
			Carbon steel	18.5	12.3				
			Cast iron	28	20				
			Ni-resist	8	7.5				
			Ni-resist(Cu)						
			18-2			0.7	0.6		
		5.4	Aluminum 1100	136	0	22.6	14.4		
			Aluminum 6061	72.6	-1.3	8.0	6.3		
		5.1	Monel 400	6.3	16.5				
			Al bronze	5.5	2.3				
		7.0	18-2	0	0				
			Ni-resist	10.6	5.3				
			Ni-resist(Cu)	16	5				

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS EXPOSED TO VARIOUS ENVIRONMENTS FOR 50 HOURS[38]
-Continued-

Components[b]	Test Conditions	pH[c]	Alloy[d]/ Composition[e]	Corrosion Rate,[f] mils/yr Aqueous	Corrosion Rate,[f] mils/yr Gaseous	Pit Depth,[g] mils Aqueous max	Pit Depth,[g] mils Aqueous ave	Pit Depth,[g] mils Gaseous max	Pit Depth,[g] mils Gaseous ave
compositions and conditions the same as preceding test except		4.3	304 SS	0	0.5				
			316 SS	0	-0.5				
			329 SS	0	0				
HCN nil			18-18-2	0	0.5				
phenol nil			Armco 22-13-5	0	0				
chloride 100 ppm			20Cb-3	0	0.5				
			26-1	0	0				
			Incoloy 800	-0.5	0.5				
			Incoloy 825	-0.5	0.5				
			Hastelloy C	0	0				
			Hastelloy G	0	0				
			Titanium	0	-0.7				
		4.6	304 SS	0.4	0				
			410 SS	4.8	10.8				
			430 SS	2.7	1.3				
			Carbon steel	136	21.7				
			Cast iron	45.9	15.9				
			Ni-resist	13.9	10.2				
			Ni-resist(Cu)						
			18-2	--	--	0.6	0.5		
		6.2	Aluminum 1100	-2.8	-4.2				
			Aluminum 6061	-2.6	-5.4				
		6.2	Monel 400	1.2	3.6				
			Al bronze	6.6	7.0				
		7.0	18-2	0	0				
			Ni-resist	6.7	4.3				
			Ni-resist(Cu)	4.8	3.1				

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[a] Tests conducted in autoclaves; liquid added (water or water-toluene) to a volume approximately one half of autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place, autoclave purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated. A constant flow of 5 scfh (0.14 m^3/hr) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave. Environments designed to simulate quench steps of a variety of coal gasification pilot plants.

[b] Input concentrations of components. Gaseous components specified in mol %; liquids in volume % or parts per million by weight of liquid.

[c] Measured pH of liquid at end of test.

[d] Specimens were machined to 1 in square by 1/8 to 3/8 in. thick, polished (240 grit), cleaned ultrasonically and weighed. After exposure specimens were cleaned according to NACE standard TM-01-69 with modified cleaning time of 20 min. and reweighed.

[e] Approximate composition given for each alloy the first time it appears in the table and is not repeated.

[f] Corrosion rate was calculated from the weight loss by the following equation

$$\text{mils/yr} = \frac{\text{weight loss (mg)} \times \text{constant}}{\text{area (in}^2\text{)} \times \text{time (hr)} \times \text{alloy density (g/cc)}}$$

. Specimens were exposed both in liquid in the autoclave and above the liquid. Data are for one specimen in each phase. A negative corrosion rate means a gain in weight; zero rate corresponds to a measured weight difference of less than 1 mg.

[g] Pitting was evaluated by an in-focus/out-of-focus microscope technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil.

AQUEOUS CORROSION RATE RANGES OF ALLOYS IN A VARIETY OF ENVIRONMENTS[a] [38]

Alloy	Composition[b]	Corrosion Rate,[c] mils/yr Aqueous min	Aqueous max	Gaseous min	Gaseous max
304 SS	70Fe-9Ni-19Cr	0	7	0	6
316 SS	65Fe-14Ni-17Cr	0	4	0	4
329 SS	Fe-4Ni-27Cr	0	<1	0	3
18-18-2	Fe-18Ni-18Cr-2Si	0	7	0	26
Armco 22-13-5	Fe-14Ni-21Cr-5Mn	0	<1	0	1
20Cb-3	Fe-33Ni-19Cr	0	<1	0	3
26-1	Fe-26Cr-1Mo	0	<1	0	3
Incoloy 800	47Fe-31Ni-21Cr	0	3	0	3
Incoloy 825	30Fe-22Cr-42Ni-3Mo	0	<1	0	4
Hastelloy C	Ni-16Cr-6Fe-15Mo	0	<1	0	<1
Hastelloy G	Ni-22Cr-20Fe-7Mo	0	<1	0	<1
Titanium		0	<1	0	3
410 SS	Fe-12Cr	<1	150	0	76
430 SS	Fe-17Cr	<1	138	<1	100
Carbon steel	(A515)	12	165	2	89
Cast iron		4	153	1	98
Ni-resist	Fe-20Ni-3Cr-3Si	5	84	3	65
Ni-resist (Cu)	Fe-18Ni-4Cr-3Si-7Cu	3	89	<1	174
18-2	Fe-18Cr-2Mo	0	5	0	61
Aluminum 1100		1	136	0	1
Aluminum 6061		10	73	0	1
Monel 400	64Ni-33Cu-2Fe	1	209	4	141
Al-bronze	Cu-10Al-3Fe-2Ni	2	460	0	326

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[a] Tests conducted in autoclaves in a variety of environments; see preceding table for detailed data, the various components and test conditions, and the test methods.

[b] Approximate composition only.

[c] Corrosion rates from preceding table. The minimum and maximum rates found for all environments are given here.

EFFECT OF AMMONIA AND WATER CONTENT AT SEVERAL TEMPERATURES AND PRESSURES ON THE AQUEOUS CORROSION[a] OF FOUR ALLOYS[38]

Alloy[b]	Corrosion Rate,[c] mils/yr		Pit Depth,[d] mils				Test Variables[a]				
	Aqueous	Gaseous	Aqueous		Gaseous		Temperature °F	Pressure psia	NH_3 %	H_2O %	pH
			max	ave	max	ave					
Carbon Steel	20.8	9.6	0.5	0.4	0.5	0.4	250	150	0.1	20	8.3
410 SS	13.0	3.6[e]	1.2[e]	0.7	1.0	0.6					
304 SS	0.1	<0.1	0.3	0.2	1.0[f]	0.4					
316 SS	<0.1	<0.1	0.3	0.2	0.4	0.3					
Carbon Steel	7.4	8.8	0.3	0.2	0.4	0.2	250	150	0.6	20	8.4
410 SS	10.2	9.7[g]	0.7	0.5	0.6	0.4					
304 SS	0.1	<0.1	2.9[h]	1.2[h]	1.0[h]	0.5					
316 SS	0.1	<0.1	0.6	0.4	0.7	0.5					
Carbon Steel	29.6	12.1	0.7	0.6	1.0	0.6	250	600	0.1	5	7.8
410 SS	3.9	4.2	0.6	0.5	0.7	0.5					
304 SS	0.5	0.2	3.8	2.5	0.2	0.2					
316 SS	0.3	0.1	0.4	0.3	0.4	0.3					
Carbon Steel	16.6	9.4	0.8	0.4	0.4	0.3	250	600	0.6	5	8.2
410 SS	3.2	5.1	0.6	0.4	0.6	0.5					
304 SS	0.1	0.1	0.3	0.2	0.4	0.3					
316 SS	0.1	0.1	0.3	0.2	0.4	0.2					
Carbon Steel	8.4	4.4	2.0	1.6	0.7	0.6	250	600	0.6	5	8.6
410 SS	1.4	0.5	0.4	0.2	0.6	0.2					
304 SS	<0.1	<0.1	0.2	0.2	0.2	0.1					
316 SS	<0.1	<0.1	0.2	0.1	0.2	0.1					
Carbon Steel	14.5	13.7	0.5	0.4	0.6	0.5	350	600	0.1	23	7.7
410 SS	15.6	4.5	0.8	0.7	0.7	0.4					
304 SS	0.5	0.1	1.7[i]	0.2	0.3	0.2					
316 SS	0.3	0.1	0.3	0.2	0.3	0.2					
Carbon Steel	19.3	6.1	0.5	0.4	0.6	0.4	350	600	0.6	22.5	4.9
410 SS	14.1	4.8	0.7	0.5	0.5	0.4					
304 SS	0.2	<0.1	0.3	0.2	0.3	0.1					
316 SS	0.2	<0.1	0.3	0.2	0.3	0.2					
Carbon Steel	14.6	10.9	0.8	0.7	0.7	0.5	350	600	0.6	23	7.7
410 SS	7.2	2.1	0.5	0.4	0.7	0.6					
304 SS	0.3	0.1	0.4	0.3	0.5	0.4					
316 SS	0.2	-0.1	0.4	0.3	0.5	0.3					
Carbon Steel	13.2	11.2	0.4	0.3	1.0	0.7	350	1210	0.1	11	5.1
410 SS	10.1	3.4	0.5	0.4	0.7	0.4					
304 SS	0.3	0.1	0.3	0.2	0.3	0.2					
316 SS	0.2	0.1	0.4	0.2	0.3	0.2					
Carbon Steel	14.7	11.5	1.1	0.6	0.7	0.5	350	1210	0.6	11	4.5
410 SS	12.7	4.4	1.0	0.8	0.6	0.4					
304 SS	0.8	0.1	0.8	0.4	0.4	0.3					
315 SS	0.4	0.1	0.4	0.3	0.3	0.2					
Carbon Steel	2.2[j]	10.9	0.6	0.4	0.6	0.4	462	600	0.1	79	8.2
410 SS	11.8	4.8	0.6	0.5	0.4	0.3					
304 SS	1.3	0.8	0.3	0.1	0.2	0.1					
316 SS	1.3	0.8	0.5	0.3	0.3	0.2					
Carbon Steel	6.3	14.7	0.5	0.4	0.5	0.4	462	600	0.6	79	8.4
410 SS	10.0	5.0	0.5	0.4	0.6	0.5					
304 SS	2.0	1.1	0.4	0.3	0.3	0.2					
316 SS	2.2	1.1	0.4	0.3	0.4	0.3					
Carbon Steel	18.6	8.4	0.6	0.4	0.6	0.5	462	600	0.6	79.3	4.7
410 SS	24.8	3.5	0.7	0.5	0.5	0.4					
304 SS	1.0	0.8	0.5	0.4	0.5	0.3					
316 SS	1.4	1.1	0.4	0.3	0.4	0.3					
Carbon Steel	9.1	3.7	0.5	0.4	0.5	0.4	462	1210	0.1	39	7.7
410 SS	29.0	13.2	0.8	0.6	0.5	0.4					
304 SS	2.3	1.4	0.2	0.1	0.4	0.2					
316 SS	1.8	1.6	0.4	0.3	0.3	0.2					
Carbon Steel	5.9	3.2	0.5	0.3	0.8	0.4	462	1210	0.6	39	7.8
410 SS	15.5	11.4[k]	0.3	0.2	0.3	0.2					
304 SS	2.1	1.5	0.5	0.2	0.3	0.2					
316 SS	2.2	1.2	0.6	0.3	0.3	0.2					

(Table Continued)

EFFECT OF AMMONIA AND WATER CONTENT AT SEVERAL TEMPERATURES AND PRESSURES ON THE AQUEOUS CORROSION[a] OF FOUR ALLOYS[38]

-Continued-

[a] Tests conducted in autoclaves to simulate quench steps of coal gasification processes. Liquid was added to a volume approximately one half of the autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place, autoclave purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated, a constant flow of 5 scfh (0.14 m^3/hr) of new gas was maintained and a condenser and pump automatically fed condensate back to the autoclave. Fixed conditions for these tests were: CO_2 0%, CO 27%, H_2S 1.1%, HCN nil, phenol nil, chloride 3000 ppm, time 150 hr. pH value is that measured at end of test.

[b] Machined specimens were polished (240 grit), cleaned ultrasonically and weighed. After exposure specimens were cleaned according to NACE standard TM-01-69 with modified cleaning time of 20 min and reweighed.

[c] Corrosion rate was calculated from the weight loss by the following equation,

$$\text{mils/yr} = \frac{\text{weight loss (mg) x constant}}{\text{area (in}^2\text{) x time (hr) x alloy density (g/cc)}}$$

Triplicate specimens were exposed. Values in table are the averages of the corrosion rates for three specimens. Where the spread between minimum and maximum is large, the value is footnoted. A negative corrosion rate means a gain in weight.

[d] Pitting was evaluated by an in-focus/out-of-focus microscope technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measureable pit depth was 0.1 mil. The values are the averages of the data for the triplicate specimens, where the spread between minimum and maximum is large, the value is footnoted.

[e] Gaseous corrosion rates were 3.6, 0.5, 6.8. Aqueous max pit depths were 2.0, 0.9, 0.8.

[f] Pit depths were 0.3, 2.2, 0.4.

[g] Corrosion rates were 4.9, 12.8, 11.5.

[h] Aqueous max pit depths were 5.5, 0.8, 2.4. Aqueous ave depths were 2.0, 0.3, 1.4. Gaseous max depths were 0.5, 2.1, 0.3.

[i] Aqueous max pit depths were 0.4, 0.3, 4.4.

[j] Aqueous corrosion rates were 0.8, 1.8, 4.0.

[k] Gaseous corrosion rates were 10.8, 15.2, 8.1.

AQUEOUS CORROSION DATA FOR FOUR ALLOYS IN THE PRESENCE OF INHIBITORS[a] [38]

Test Conditions[b]					Corrosion Rate,[c] mils/yr		Pit Depth,[d] mils			
Time hr	Temperature °F	Pressure psi	pH	Alloy	Aqueous	Gaseous	Aqueous max	Aqueous ave	Gaseous max	Gaseous ave
OS-22 INHIBITOR,[a] 10 ppm										
400	250	600	3.8	carbon steel	10.3[e]	7.7	0.5	0.3	0.4	0.2
				304 SS	0.5	0.1	0.3	0.2	0.3	0.2
				316 SS	< 0.1	0.1	0.3	0.2	0.3	0.1
				410 SS	4.8	0.8	1.0	0.6	0.4	0.3
OS-22 INHIBITOR, 100 ppm										
400	250	600	7.9	carbon steel	3.5	4.6	0.5	0.3	0.9	0.7
				304 SS	0.1	0.1	0.2	0.2	0.3	0.1
				316 SS	0.3	0.1	0.3	0.1	0.2	0.3
				410 SS	4.9	6.5	0.4	0.3	1.0	0.6
OS-22 INHIBITOR, 1000 ppm										
150	250	600	8.4	carbon steel	1.0	0.8	0.3	0.2	0.4	0.2
				304 SS	< 0.1	0.1	0.1	0.1	---	---
				316 SS	< 0.1	0.1	0.2	0.2	0.2	0.2
				410 SS	0.4	0.3	0.3	0.2	0.3	0.2
50	350	1210	5.1	carbon steel	58	12	0.6[f]	0.4[f]	0.4[g]	0.2[g]
				304 SS	2.4	0.5	0.2[g]	0.2[g]	0.1[f]	0.1[f]
				316 SS	0.9	0.3	0.1	0.1	0.1[f]	0.1[f]
				410 SS	24	15	0.1	0.1	0.4[g]	0.3[g]
150	350	1210	4.4	carbon steel	14	2.7	0.5	0.4	0.4	0.2
				304 SS	0.8	0.1	0.4	0.2	0.2	0.1
				316 SS	0.9	0.1	0.1	0.1	0.2[g]	0.1[g]
				410 SS	11	0.3	0.8	0.7	0.3	0.2
WS-62 INHIBITOR,[a] 1000 ppm										
150	250	600	8.5	carbon steel	2.5	1.5	0.5	0.3	0.4	0.2
				304 SS	0.1	0.1	0.2	0.1	0.2[g]	0.1[g]
				316 SS	0.1	0.1	0.2	0.1	0.2	0.1
				410 SS	2.2	1.3	0.5	0.4	0.4	0.3
50	350	1210	4.5	carbon steel	38	18	0.4	0.3	0.1	0.1
				304 SS	0.48	0.1	0.1	0.1	0.3	0.1
				316 SS	0.45	0.1	0.3	0.2	0.3[g]	0.2
				410 SS	21	13	0.3	0.2	0.2[f]	0.2[f]
150	350	1210	5.2	carbon steel	21	13	0.5	0.4	0.5	0.4
				304 SS	2.4	0.1	0.6	0.6	0.3	0.2
				316 SS	1.4	0.1	0.6	0.5	0.3[f]	0.1[f]
				410 SS	35	12	0.8	0.6	0.7	0.5

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[a] Betz Petromeen OS-22, oil-soluble, recommended for low pH (2 to 7) systems; and Betz Petromeen WS-62, water-soluble, for systems where pH is 9 to 10 and H_2S, NH_3, and HCN are present.

[b] Tests conducted in autoclaves, liquid added (water or water-toluene) to a volume approximately one half of autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place and autoclave purged with N_2 and brought to desired temperature and pressure; at equilibrium gases were introduced, and circulated; a constant flow-through of 5 scfh (0.14 m^3/hr) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave. Conditions maintained constant for these tests were CO_2 nil, HCN and phenol nil, CO 27%, H_2S 1.1%, chloride 3000 ppm, NH_3 0.6%, and the balance N_2.

[c] Specimens were machined to 1-in square by 1/8 to 3/8 in thick with a 5/16-in diameter hole near one edge, polished (240 grit), cleaned ultrasonically and weighed. After exposure, specimens were cleaned according to NACE Standard TM-01-69 with modified cleaning time of 20 min and reweighed. Corrosion rate in mils/year was calculated from the weight loss by the following equation

$$\text{mils/year} = \frac{\text{weight loss (mg)} \times \text{constant}}{\text{area (sq. in)} \times \text{time (hr)} \times \text{alloy density (gm/cc)}}$$

Except where noted otherwise, values in table are the average of data for three samples.

[d] Pitting was evaluated by an in-focus/out-of-focus microscopic technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil.

[e] [The three values given in the report are 3.4, 23.7, and 3.7 without any notation to explain the discrepant values.]

[f] Value for one sample only; other two samples showed no pitting.

[g] Average for two samples; third sample showed no pitting.

EFFECT OF VARIOUS CONSTITUENTS[a] ON THE AQUEOUS CORROSION OF FOUR ALLOYS[b] EXPOSED IN A STATIC SYSTEM[c][38]

	Corrosion Rate,[d] mils/yr				Pit Depth,[e] mils				Test Variables[a]							
	Aqueous		Gaseous		Aqueous		Gaseous									
Alloy[c]	min	max	min	max	max	ave	max	ave	Time hr	pH	CO_2 %	CO %	H_2S %	HCN ppm	phenol ppm	chloride ppm
Carbon steel	29.1	31.1	20.6	28.0					50	9.3	0	0	0.1	0	100	0
410 SS	1.59	2.04	-2.52	-2.93												
304 SS	0.35	0.77	-0.17	-0.22												
316 SS	0.12	0.60	-0.04[f]	0.38												
Carbon steel	77.1	92.7	29.5	32.0					50	8.4	0	0	1.1	500	6000	0
410 SS	7.02	15.3	13.8	15.1												
304 SS	2.11	3.51	1.54	2.97												
316 SS	2.76	2.94	1.16	2.22												
Carbon Steel	10.8[f]	27.6	7.54	11.6					150	9.4	0	0	0.1	500	6000	3000
410 SS	1.19	3.37	1.53	2.20			0.6	0.4								
304 SS	0.72	0.79	0.43	0.81												
316 SS	0.46	0.81	0.68	0.83	0.4	0.2										
Carbon Steel	29.7	32.7	17.7	36.1[g]	0.5	0.4	1.5	0.9	150	9.0	0	0	1.1	10	0	3000
410 SS	3.33	4.08	4.08	6.11	1.1	0.8	1.6	0.6								
304 SS	0.48	1.03	0.83	2.24												
316 SS	0.97	2.29	1.23	2.50			0.6	0.6								
Carbon Steel	49.1	63.1	44.5	57.7	0.6	0.4	0.6	0.4	50	8.7	0	9	0.1	500	100	3000
410 SS	12.7[f]	20.0	7.34	9.86	1.2	0.7	0.8	0.5								
304 SS	1.30	1.65	0.74	1.22												
316 SS	1.42	1.80	0.95	1.44	0.3	0.2										
Carbon Steel	59.9	60.7	48.5	54.7					50	7	0	9	1.1	10	6000	0
410 SS	23.0	25.8	10.6	13.1	1.6	0.7	0.5	0.4								
304 SS	4.43	4.97	-0.17	2.42												
316 SS	3.82	4.67	2.07	3.62												
Carbon Steel	72.7	106	13.9	18.6					150	4.0	0	9	0.1	0	0	3000
410 SS	94.2	100	14.5[f]	40.5			2.0	1.6								
304 SS	3.60	4.22	2.57	4.57	2.0	1.2	2.2	1.7								
316 SS	2.55	2.94	2.30	4.92	1.8	1.4	1.6	1.2								
Carbon Steel	39.2	42.0	16.1	21.1			0.6	0.4	150	7.9	0	9	1.1	10	0	0
410 SS	11.7	17.7	41.6	69.0	2.9	1.2	1.8	1.6								
304 SS	1.95	2.06	1.87	2.10			1.3	0.6								
316 SS	2.10	2.24	1.71	2.04	0.4	0.3	0.7	0.5								
Carbon Steel	60.5	83.0	27.2	41.1	0.6	0.5	0.6	0.4	50	7.9	0	27	0.1	10	100	3000
410 SS	41.9	47.8	2.93	4.13	0.8	0.4										
304 SS	1.01	1.13	0.26	0.56												
316 SS	0.82	1.07	0.04[f]	0.24												
Carbon Steel	94.2[f]	152.9	55.6[f]	74.8			0.8	0.4	50	3.5	0	27	1.1	0	6000	3000
410 SS	86.5	104	59.3	61.1												
304 SS	5.14	5.29	2.75	3.08	0.8	0.5										
316 SS	3.18	5.15[g]	3.01[f]	5.54												
Carbon Steel	30.7	42.1	12.0	28.9	0.8	0.6	0.9	0.6	150	8.3	0	27	0.1	500	0	0
410 SS	21.9	54.3	2.28	2.90	1.6	1.0	1.0	0.6								
304 SS	1.33	1.45	0.32	0.47	0.2	0.2	0.4	0.3								
316 SS	0.89	1.22	0.38	0.63	0.5	0.4	0.5	0.5								
Carbon Steel	8.65	13.8	9.41	15.7	1.9	1.6	1.6	1.2	150	8.5	0	27	1.1	0	100	0
410 SS	32.4	34.5	24.4	30.4	0.6	0.4	1.2	1.1								
304 SS	5.38	8.48	2.91[f]	7.34	1.0	0.6	0.9	0.7								
316 SS	4.47	5.83	2.51	2.82			0.4	0.4								
Carbon Steel	9.68	13.0	12.2	13.7					50	9.5	3.2	0	0.1	0	0	0
410 SS	2.96	3.19	2.96[f]	8.16												
304 SS	1.30	1.40	0.82	1.04												
316 SS	0.55	1.47	0.83	0.91												
Carbon Steel	51.2	58.4	46.1	52.8					50	9.1	3.2	0	0.1	10	100	0
410 SS	4.80	7.48	5.83	8.27	1.2	0.8	0.8	0.6								
304 SS	1.90	2.26	1.10	1.68												
316 SS	2.13	2.98	0.81	1.51												
Carbon Steel	15.9	21.7	11.9	15.8					50	8.1	3.2	0	1.1	500	0	3000
410 SS	24.8	73.5	43.9	50.9												
304 SS	1.34	1.87	2.32	3.16	1.0	0.7										
316 SS	0.90	0.97	0.56[f]	1.32												
Carbon Steel	4.91	5.49	7.13	8.55	2.2	1.6	1.0	0.9	150	10.1	3.2	0	0.1	0	6000	3000
410 SS	3.02	3.37	-0.19	-0.42	2.7	2.1										
304 SS	0.40	0.41	0.06	0.15	0.6	0.4										
316 SS	0.15	0.20	0.04[f]	0.20	1.4	0.9	1.0	0.7								
Carbon Steel	90.2	113	46.3[f]	75.8					50	7.9	3.2	9	1.1	500	6000	3000
410 SS	93.1	172	132	219[g]												
304 SS	3.53	3.66	2.40	4.10												
316 SS	2.99	3.21	2.07	3.51												

(Table Continued)

EFFECT OF VARIOUS CONSTITUENTS[a] ON THE AQUEOUS CORROSION OF FOUR ALLOYS[b] EXPOSED IN A STATIC SYSTEM[c][38] cor

	Corrosion Rate,[d] mils/yr				Pit Depth,[e] mils				Test Variables[a]							
	Aqueous		Gaseous		Aqueous		Gaseous		Time		CO_2	CO	H_2S	HCN	phenol	chlo
Alloy[c]	min	max	min	max	max	ave	max	ave	hr	pH	%	%	%	ppm	ppm	ppm
Carbon Steel	20.9	31.7	9.19	15.2					150	8.1	3.2	9	0.1	0	100	3000
410 SS	6.31	6.41	2.59	4.32	1.2	1.0	1.1	0.9								
304 SS	0.56	0.76	0.29	0.35												
316 SS	0.24	0.45[g]	0.18	0.25												
Carbon Steel	42.0	46.4	26.2	42.2					150	7.7	3.2	9	0.1	10	0	0
410 SS	4.22	13.0	11.9	22.6[g]	0.6	0.4	1.6	1.0								
304 SS	0.38	0.83	1.11	1.25	0.6	0.4	0.7	0.6								
316 SS	0.46	0.77	1.12	1.45												
Carbon Steel	19.8	23.4	11.9	25.2					150	8.3	3.2	9	0.1	10	100	100
410 SS	11.8	15.4	1.90[f]	22.4	1.2	1.0	0.8	0.6								
304 SS	0.79	1.05	0.26	0.74	0.5	0.3	1.9	1.5								
316 SS	0.84	0.94	0.38	0.56												
Carbon Steel	37.6	40.1	26.2	33.2					150	9.0	3.2	9	0.33	10	100	0
410 SS	14.8	15.3	9.09	10.0	2.2	1.3	1.0	0.8								
304 SS	1.56	1.91	1.65	1.76												
316 SS	1.74	1.75	1.60	1.74												
Carbon Steel	31.1	38.2	33.7	38.9					150	8.0	3.2	9	0.33	10	100	100
410 SS	12.6[f]	38.6	10.5	12.8	1.4	1.2	1.8	1.4								
304 SS	2.15	2.45	1.14	1.43												
316 SS	2.21	2.39	0.87	1.21												
Carbon Steel	38.7	47.1	23.9	29.0	0.7	0.6	0.7	0.6	150	8.7	3.2	9	0.33	10	100	3000
410	13.1	16.0	6.15[f]	12.4	1.1	0.8	1.4	1.0								
304 SS	1.49	1.78	0.55	0.97			1.2	0.7								
316 SS	1.66	1.82	0.73	1.00	1.6	0.7										
Carbon Steel	39.6	41.9	43.6	46.4					150	8.6	3.2	9	1.1	10	100	100
410 SS	13.3	14.2	10.2	11.4	1.9	0.7	2.2	2.0								
304 SS	2.28	2.35	1.86	2.24												
316 SS	2.45	2.68	1.82	2.42												
Carbon Steel	34.1	38.7	19.7	32.0			1.4	1.2	150	7.9	3.2	9	1.1	500	100	0
410 SS	12.4	13.4	12.3	13.5	0.8	0.4	1.8	1.1								
304 SS	1.33	1.48	1.09	1.46			0.2	0.2								
316 SS	1.61	1.86	1.27	1.57			0.4	0.3								
Carbon Steel	75.1	80.0	42.4	63.4					50	8.4	3.2	27	1.1	0	0	3000
410 SS	25.0	28.5	11.4[f]	25.1	0.8	0.7	1.4	0.8								
304 SS	2.97	3.15	0.26	1.06												
316 SS	4.03	4.45	1.91	2.20												
Carbon Steel	89.3	116[g]	53.0[f]	72.9					150	8.0	3.2	27	0.1	10	6000	3000
410 SS	45.0	59.0	9.88[f]	24.2	1.0	0.6	0.7	0.6								
304 SS	2.91	3.52	1.08	1.75												
316 SS	2.71	3.08	1.17	1.98												
Carbon Steel	43.7	49.8	20.4[f]	37.6			1.0	0.8	150	7.4	3.2	27	0.1	500	100	0
410 SS	54.3	60.8	27.9[f]	54.0												
304 SS	1.88	1.99	1.26	1.97	1.5	1.1	1.2	0.9								
316 SS	1.63	1.81	1.22	1.44	0.9	0.5	0.4	0.4								
Carbon Steel	27.7	30.2	9.76	14.5					150	7.4	3.2	27	1.1	10	500	0
410 SS	4.68	9.13	4.68	6.78	0.6	0.4										
304 SS	1.71	1.80	1.11	1.63												
316 SS	1.52	1.65	0.94	1.03												
Carbon Steel	46.5	50.5	27.8	41.1					50	8.8	21	0	0.1	0	0	0
410 SS	11.2	11.6	4.88	7.29												
304 SS	1.93	2.12	1.08	1.30												
316 SS	0.62	1.12	1.09	1.16												
Carbon Steel	53.2	58.0	27.3	34.4					50	8.2	21	0	1.1	0	100	3000
410 SS	3.85	4.41	8.86	11.3	1.0	0.7										
304 SS	1.60	2.29	1.08	1.61												
316 SS	1.14	1.72	1.38	1.66												
Carbon Steel	22.7	27.3	18.2	21.0					150	9.1	21	0	0.1	10	6000	0
410 SS	10.4	15.9	4.80	6.79	0.7	0.5	1.5	0.9								
304 SS	0.57	0.72	0.49	0.70												
316 SS	0.96	1.12	0.62	0.65												
Carbon Steel	30.7	40.8	14.4	24.0	0.3	0.2	1.6	1.1	150	8.5	21	0	1.1	10	100	3000
410 SS	3.13	4.90	4.08	4.62	0.4	0.3	0.6	0.3								
304 SS	0.93	1.05	1.06	1.46												
316 SS	1.73	1.83	1.19	1.46												
Carbon Steel	72.1	74.9	42.9	50.4	1.0	0.7	1.1	0.8	50	7.0	21	9	0.1	500	0	0
410 SS	63.7	115	63.9	136	0.6	0.4	0.9	0.6								
304 SS	1.67	2.21	3.36	3.95	0.6	0.4	0.2	0.2								
316 SS	1.05	1.37	0.58	1.06			0.4	0.3								

(Table Continued)

EFFECT OF VARIOUS CONSTITUENTS[a] ON THE AQUEOUS CORROSION OF FOUR ALLOYS[b] EXPOSED IN A STATIC SYSTEM[c][38] continued

	Corrosion Rate,[d] mils/yr				Pit Depth,[e] mils				Test Variables[a]							
	Aqueous		Gaseous		Aqueous		Gaseous		Time		CO_2	CO	H_2S	HCN	phenol	chloride
Alloy[c]	min	max	min	max	max	ave	max	ave	hr	pH	%	%	%	ppm	ppm	ppm
Carbon Steel	40.9	47.7	19.7	24.5			0.5	0.4	50	9.8	21	9	1.1	0	6000	0
410 SS	53.7	72.2	42.1	89.5	0.4	0.3	0.6	0.5								
304 SS	3.29	3.64	2.63	2.83	0.8	0.6	0.4	0.3								
316 SS	2.94	3.76	2.01	2.98	0.8	0.3	0.2	0.1								
Carbon Steel	40.4	50.5	7.17[f]	18.5	1.4	0.9	1.0	0.8	150	8.8	21	9	0.1	10	6000	3000
410 SS	27.9	28.7	3.25	6.56	1.8	1.6	0.6	0.5								
304 SS	1.09	1.51	0.70	1.30	0.5	0.4										
316 SS	1.10	1.15	0.77	1.07	0.5	0.3	0.8	0.3								
Carbon Steel	31.3	33.0	14.6	18.3	0.3	0.2			150	8.5	21	9	1.1	10	100	3000
410 SS	13.5	22.4	22.4	35.1	0.7	0.5	0.9	0.5								
304 SS	1.53	1.69	1.27	1.80	1.4	1.0	1.4	1.3								
316 SS	1.69	1.83	1.35	1.55	1.1	0.5	0.5	0.4								
Carbon Steel	89.7	96.9	18.4	28.8			0.5	0.4	50	8.5	21	27	0.1	10	0	3000
410 SS	16.4	18.6	3.00	5.10	0.8	0.4	1.6	0.5								
304 SS	1.00	1.09	0.68	0.80			1.0	0.6								
316 SS	0.93	1.00	0.96	1.23												
Carbon Steel	41.0	64.1	45.7	50.9	1.8	1.3	1.0	0.7	50	5.1	21	27	1.1	0	100	0
410 SS	13.2	20.4	7.02	13.4	0.7	0.4	0.6	0.3								
304 SS	2.75	3.01	0.63	2.29	1.0	0.5										
316 SS	3.26	3.72	2.35	2.52			0.6	0.4								
Carbon Steel	35.9	37.2	22.1	28.2	0.7	0.5	0.3	0.3	150	7.9	21	27	0.1	500	6000	0
410 SS	36.6	55.2	4.16	7.23	1.3	1.0	1.0	0.7								
304 SS	1.53	1.62	0.57	0.79												
316 SS	0.90	1.60	0.79	1.13												
Carbon Steel	11.7	52.8	28.8	35.4	0.8	0.7	0.8	0.6	150	7.9	21	27	1.1	500	0	3000
410 SS	17.5	18.8	10.9	12.7	0.6	0.4	1.3	1.1								
304 SS	2.21	2.41	0.93	2.26												
316 SS	1.61	2.30	1.16	1.58												

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[a] Test variables as indicated; constant factors, H_2O 40%, NH_3 0.6%, balance N_2. Pressure 1210 psig (8.34 MPa), temperature 462 °F (512 K). pH value is that measured at end of test.

[b] Specimens were machined to 1 in square by 1/8 to 3/8 in thick, polished (240 grit), cleaned ultrasonically and weighed. After exposure specimens were cleaned according to NACE Standard TM-01-69 with modified cleaning time of 20 min and reweighed.

[c] Tests conducted in autoclaves to simulate the quench step of coal gasification processes; liquid added to a volume approximately one-half of autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place, autoclave purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated. A constant flow of 5 scfh (0.14 m^3/h) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave.

[d] Corrosion rate was calculated from the weight loss by the following equation:

$$\text{mils/yr} = \frac{\text{weight loss (mg)} \times \text{constant}}{\text{area (in}^2\text{)} \times \text{time (hr)} \times \text{alloy density (g/cc)}}.$$

Triplicate specimens were exposed both in liquid in the autoclave and above the liquid. The data are the minimum and maximum values of the three corrosion rates reported. Where the spread between minimum and maximum values is large and the intermediate value is very close to one of the extremes the data are footnoted. A negative corrosion rate means a gain in weight.

[e] Pitting was evaluated by an in-focus/out-of-focus microscope technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil. The triplicate specimens of each alloy were examined for pitting. The data reported in this table are the maximum values of those reported for a given alloy in a given test. Where no values are reported the pitting was not measurable.

[f] The third corrosion rate is very close to the minimum value.

[g] The third corrosion rate is very close to the maximum value.

EFFECT OF VARIOUS CONSTITUENTS[a] ON THE AQUEOUS CORROSION OF FOUR ALLOYS[b] EXPOSED IN A DYNAMIC SYSTEM[c] [38]

	Corrosion Rate[d], Mils/Yr		Pit Depth[e], Mils				Test Variables[a]						
			Aqueous		Gaseous								
Alloy[b]	Aqueous	Gaseous	max	ave	max	ave	pH	CO_2 %	CO %	H_2S %	HCN ppm	Phenol ppm	Chlori ppm
Carbon steel	18.3	13.8	0.2	0.1	0.2	0.1	9.3	0	0	0.1	500	0	0
304 SS	0.6	0.5	0.1	0.1	0.1	0.1							
316 SS	0.3	0.3	0.2	0.1	0.1	0.1							
329 SS	0.2	0.2	0.1	0.1	0.1	0.1							
Carbon steel	32.8	49.7[f]	0.2	0.2	<0.1	<0.1	9.6	0	9	1.1	10	0	0
304 SS	2.4	2.0	0.2	0.1	0.1	<0.1							
316 SS	3.8	2.1	0.1	0.1	0.2	0.1							
329 SS	1.4	0.25	<0.1	<0.1	<0.1	<0.1							
Carbon steel	33.3	8.2	<0.1	<0.1	0.2	0.1	7.9	3.2	9	0.33	10	100	0
304 SS	1.3	0.29[g]	0.2	0.1	0.2	0.1							
316 SS	1.9	0.6	0.1	0.1	0.1	<0.1							
329 SS	0.4	0.1	<0.1	<0.1	<0.1	<0.1							
Carbon steel	53.6	13.1	0.4	0.3	0.2	0.1	5.1	3.2	9	0.33	10	100	3000
304 SS	1.79	0.85	1.8	0.6	0.2	0.2							
316 SS	1.80	0.60	0.6	0.2	0.4	0.3							
329 SS	0.14	0.1	0.2	0.2	0.2	0.2							
Carbon steel	52	41.0	0.4	0.2	0.5	0.4	4.1	3.2	9	1.1	10	100	100
304 SS	1.6	1.2	0.3	0.1	0.2	0.1							
316 SS	1.3	1.0	0.3	0.2	0.2	0.1							
329 SS	0.1	0.1	<0.1	<0.1	<0.1	<0.1							
Carbon steel	23.9	22.4	0.2	0.2	0.1	0.1	4.4	3.2	9	1.1	500	100	0
304 SS	0.9	0.7	0.1	0.1	0.1	0.1							
316 SS	1.0	1.0	0.1	0.1	0.1	<0.1							
329 SS	0.38	0.24	0.2	0.1	0.1	<0.1							
Carbon steel	33.1	11.5	0.3	0.3	0.5	0.2	7.3	3.2	9	0.33	10	100	100
304 SS	1.65	0.85	0.2	<0.1	0.2	0.2							
316 SS	2.9	1.10	0.1	<0.1	<0.1	<0.1							
329 SS	0.2	<0.1	0.1	<0.1	<0.1	<0.1							
Carbon steel	35.0	16.7	0.7	0.4	0.4	0.2	7.9	3.2	27	0.1	500	100	0
304 SS	1.2	0.9	0.3	0.2	0.4	0.2							
316 SS	1.7	1.7	0.3	0.2	0.3	0.1							
329 SS	0.6	0.3	0.3	0.2	0.1	0.1							
Carbon steel	42.3	36.4	0.3	0.2	0.2	0.2	8.8	21	0	1.1	10	100	3000
304 SS	0.5	0.48	0.2	0.1	0.2	<0.1							
316 SS	0.45	0.35	0.1	<0.1	0.3	0.1							
329 SS	0.20	0.15	0.1	<0.1	<0.1	<0.1							
Carbon steel	21.5	12.7	0.6	0.4	0.4	0.2	6.9	21	9	0.1	0	6 000	3000
304 SS	0.6	0.5	0.1	0.1	<0.1	<0.1							
316 SS	1.2	0.9	0.3	0.2	0.2	0.1							
329 SS	0.1	0.1	<0.1	<0.1	<0.1	<0.1							
Carbon steel	42.1	35.6	0.7	0.4	0.5	0.4	5.8	21	9	1.1	10	100	3000
304 SS	1.5	1.3	0.2	0.1	1.0	0.3							
316 SS	1.4	1.2	0.2	0.2	0.2	0.2							
329 SS	0.3	0.3	0.2	0.1	0.2	<0.1							
Carbon steel	32.3	8.2	0.6	0.4	0.4	0.2	7.8	21	27	0.1	500	6000	0
304 SS	1.8	0.4	<0.1	<0.1	<0.1	<0.1							
316 SS	3.1	1.2	<0.1	<0.1	<0.1	<0.1							
329 SS	0.3	<0.1	<0.1	<0.1	<0.1	<0.1							
Carbon steel	28.2	13.9	0.7	0.4	0.5	0.4	4.3	21	27	1.1	500	0	3000
304 SS	1.2	1.0	0.3	0.2	0.2	0.1							
316 SS	1.8	1.7	0.3	0.2	0.2	0.1							
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1							
Carbon steel	29.6	20.0	0.2	0.2	0.2	0.1	3.8	21	27	1.1	500	6000	0
304 SS	1.8	1.0	0.2	0.1	0.1	0.1							
316 SS	1.3	0.9	0.1	0.1	0.1	0.1							
329 SS	0.1	0.1	<0.1	<0.1	<0.1	<0.1							

(Table Continued)

EFFECT OF VARIOUS CONSTITUENTS[a] ON THE AQUEOUS CORROSION OF FOUR ALLOYS[b]

EXPOSED IN A DYNAMIC SYSTEM[c][38]

-Continued-

[a] Test variables as indicated; constant factors, H_2O 40%, NH_3 0.6%, balance N_2. Pressure 1210 psig (8.34 MPa), temperature 462 °F (512 K), time of test 150 hrs. pH value is that measured at end of test.

[b] Specimens were machined to 1 in. square by 1/4 in. thick (329 SS was 1/8 in. thick), ground to 240 grit finish, cleaned by scrubbing in alconox and hot water, hot water rinsed, cleaned ultrasonically in alcohol 5 min, dried in cold air, stored in desiccator until used. Before exposure coupons were weighed to 4 mg and measured to 0.001 in. After exposure specimens were cleaned according to NACE Standard TM-01-69 with modified cleaning time of 20 min. and reweighed.

[c] Tests were conducted in autoclaves to simulate the quench step of coal gasification processes; liquid was added to a volume approximately one-half of autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place, autoclave purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated. A constant flow of 5 scfh (0.14 m^3/hr) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave. This series of tests differs from those outlined in the immediately preceding tables on aqueous corrosion in that the system was altered to provide a dynamic environment in which there was a continuous liquid input and periodic discharge to obtain a flow through the system.

[d] Corrosion rate was calculated from the weight loss by the following equation

$$\text{mils/yr} = \frac{\text{weight loss (mg)} \times \text{constant}}{\text{area(in}^2) \times \text{time (hr)} \times \text{alloy density (g/cc)}}$$

. Duplicate specimens were exposed both in liquid in the autoclave and above the liquid. The data given are the average of the values for duplicate specimens. For averages where the spread between the two values is unduly large the data are footnoted.

[e] Pitting was evaluated by an in-focus/out-of-focus microscope technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil. The duplicate specimens of each alloy were examined for pitting. The data in the table are the averages of the two values for each alloy.

[f] The values for the two specimens are 18.6 and 80.7 [is 18.6 a misprint for 81.6?].

[g] The values for the two specimens are 0.09 and 0.48.

COMPARISON OF THE EFFECT OF STATIC AND DYNAMIC CONDITIONS[a] ON THE AQUEOUS CORROSION OF THREE ALLOYS[b][38]

Test[e]	Type[a]	Corrosion Rate[c], mils/yr						Pit Depth[d], mils											
		Carbon steel		304 SS		316 SS		Carbon steel				304 SS				316 SS			
		Aqueous	Gaseous	Aqueous	Gaseous	Aqueous	Gaseous	Aqueous		Gaseous		Aqueous		Gaseous		Aqueous		Gaseous	
								max	ave	max	ave	max	ave	max	ave	max	ave	max	ave
1	Static	40.5	18.9	2.0	2.0	2.2	1.9			0.5	0.4			0.7	0.6	0.4	0.3	0.6	0.5
	Dynamic	32.8	49.6	2.3	2.0	3.8	2.0	0.2	0.1	<0.1	<0.1	0.1	0.1	0.2	<0.1	0.2	0.1	0.3	0.2
2	Static	38.6	28.6	1.7	1.7	1.8	1.7												
	Dynamic	33.5	8.2	1.3	0.8	1.9	0.6	<0.1	<0.1	0.3	0.1	0.2	0.1	0.3	0.2	0.2	0.1	0.1	<0.1
3	Static	41.6	26.7	1.6	0.7	1.7	0.8	0.7	0.6	0.7	0.6			0.9	0.5	1.6	0.7		
	Dynamic	53.6	13.0	1.8	0.8	1.8	0.6	0.4	0.3	0.2	0.1	1.2	0.1	0.2	0.1	0.5	0.2	0.4	0.3
4	Static	40.6	45.1	2.3	2.1	2.6	2.0												
	Dynamic	51.5	41.0	1.6	1.2	1.3	1.0	0.3	0.2	0.4	0.3	0.2	0.1	0.2	0.1	0.6	0.4	0.4	0.1
5	Static	37.0	25.2	1.4	1.2	1.7	1.4			1.3	1.1			0.2	0.2			0.4	0.3
	Dynamic	23.8	22.4	0.9	0.7	1.0	1.0	0.2	0.1	0.2	0.1	0.1	0.1	0.1	<0.1	0.1	0.1	0.2	<0.1
6	Static	34.0	36.3	2.3	1.3	2.3	1.0												
	Dynamic	33.0	11.5	1.7	0.8	2.8	1.0	0.6	0.6	0.5	0.2	0.1	<0.1	0.2	0.1	0.2	<0.1	<0.1	<0.1
7	Static	47.3	26.0	1.9	1.7	1.6	1.4			1.0	0.8	1.3	0.9	1.0	0.7	0.7	0.4	0.3	0.3
	Dynamic	35.0	16.7	1.2	1.7	0.9	1.6	0.7	0.3	0.4	0.2	0.3	0.1	0.3	0.1	0.3	0.2	0.2	0.1
8	Static	36.3	18.7	1.0	1.2	1.8	1.3	0.3	0.2	1.6	1.2								
	Dynamic	42.3	36.4	0.5	0.5	0.5	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.2	<0.1	0.2	<0.1	0.2	0.1
9	Static	46.5	13.3	1.2	1.0	1.1	0.9	1.4	0.9	0.9	0.7	0.5	0.4			0.2	0.2	0.8	0.3
	Dynamic	21.4	12.7	0.6	0.5	1.2	0.9	0.5	0.4	0.3	0.2	0.1	0.6	<0.1	<0.1	0.2	0.2	0.2	0.1
10	Static	31.9	16.6	1.6	1.5	1.7	1.5	0.3	0.2			0.9	0.6	1.0	0.7	1.1	0.5	0.5	0.4
	Dynamic	42.1	35.5	1.4	1.3	1.4	1.2	0.6	0.3	0.4	0.3	0.4	0.2	0.9	0.3	0.2	0.2	0.2	0.1
11	Static	36.5	25.3	1.6	0.7	1.4	1.1	0.7	0.5	0.3	0.3								
	Dynamic	32.3	8.1	1.8	0.4	3.0	1.2	0.5	0.4	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
12	Static	29.8	31.4	2.3	1.5	2.0	1.4	0.8	0.6							0.3	0.2		
	Dynamic	28.2	13.9	1.2	1.0	1.8	1.7	0.7	0.4	0.5	0.3	0.3	0.2	0.2	0.1	0.2	0.1	0.2	0.1

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[a] Tests were conducted in autoclaves to simulate the quench step of coal gasification processes; liquid was added to a volume approximately one-half of the autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place, autoclave purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated. A constant flow of 5 scfh (0.14 m^3/h) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave. Tests performed in this fashion are designated static tests. The tests designated dynamic were conducted with a continuous liquid input and periodic discharge to obtain a flow through the system. Test conditions are given under footnote e.

[b] See footnotes of the two tables immediately preceding this one for information on specimen handling.

[c] See footnotes of the two tables immediately preceding for calculation of corrosion rates; values here are averages of duplicate specimens exposed both in liquid and above liquid in the autoclave.

[d] See footnotes of the two tables immediately preceding for measurement of pit depths. Where no values appear the pitting was not measurable.

[e] All tests are for 150 hours. Constant factors for the pairs of tests are: H_2O 40%, NH_3 0.6%, balance N_2; pressure 1210 psig (8.34 MPa), temperature 462 °F (512 K). pH value is that measured at end of test. Variable quantities which are the same for pairs of the tests follow:

Test	CO_2, %	CO, %	H_2S, %	HCN, ppm	phenol, ppm	chloride, ppm	pH (static)	(dynamic)
1	0	9	1.1	10	0	0	7.9	9.6
2	3.2	9	0.33	10	100	0	9.0	7.9
3	3.2	9	0.33	10	100	3000	8.7	5.1
4	3.2	9	1.1	10	100	100	8.6	4.1
5	3.2	9	1.1	500	100	0	7.9	4.4
6	3.2	9	0.33	10	100	100	8.0	7.3
7	3.2	27	0.1	500	100	0	7.4	7.9
8	21	0	1.1	10	100	3000	8.5	8.8
9	21	9	0.1	0	6000	3000	8.8	6.9
10	21	9	1.1	10	100	3000	[illegible]	[illegible]

AQUEOUS CORROSION DYNAMIC TESTING[a] OF ALLOYS[b] IN SIMULATED PILOT PLANT QUENCH ENVIRONMENTS[38]

Alloy[b]	Corrosion Rate[c], Mils/Yr		Pit Depth[d], Mils				Time,hr	pH[e]	Environment
			Aqueous		Gaseous				
	Aqueous	Gaseous	max	ave	max	ave			
Carbon steel[f]	6.3	3.7	0.2	0.2	0.2	0.1	150	9.4	CO_2 6.3%, CO 14.2%, H_2S 0.04%, NH_3 0.5%, H_2O 22.1%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm, temperature 240 °F, pressure 132 psig (Conoco Lignite plant, CO_2 Acceptor process).
304 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
316 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Carbon steel	23.9	22.8	0.4	0.2	0.4	0.3	150	8.9	CO_2 6.3%, CO 14.2%, H_2S 0.04%, NH_3 0.5%, CH_4 10.1%, H_2 46.5%, H_2O 22.1%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm, temperature 240 °F, pressure 132 psig (Conoco Lignite Plant, CO_2 Acceptor Process) Duplicate specimens used. At time intervals given, one of pair was removed, replaced with an unexposed coupon, and test restarted. During replacement, coupons were exposed to air and subjected to cyclic heating and cooling. The 2000 hour coupon was subjected to 3 such air exposures and thermal cycles. Specimens exposed for 150 and 400 h were subjected to H_2 flow control problem.
304 SS	<0.1	<0.1	0.3	0.2	0.2	0.2			
316 SS	<0.1	<0.1	0.2	0.1	0.2	0.1			
329 SS	<0.1	<0.1	0.2	0.1	0.2	0.1			
Carbon steel	11.1	14.2	0.5	0.4	0.6	0.4	400	9.0	
304 SS	<0.1	<0.1	0.3	0.2	0.4	0.2			
316 SS	0.2	<0.1	0.5	0.2	0.2	0.2			
329 SS	<0.1	<0.1	0.4	0.1	0.2	0.1			
Carbon steel	2.3	2.5	0.6	0.5	0.6	0.4	1000	9.2	
304 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
316 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Carbon steel	10.7	10.4	0.6	0.3	0.5	0.3	450	9.4	
304 SS	<0.1	<0.1	0.2	0.2	0.2	0.1			
316 SS	<0.1	<0.1	0.2	0.1	0.2	<0.1			
329 SS	<0.1	<0.1	0.2	0.1	0.1	<0.1			
Carbon steel	11.4	19.2	1.1	0.8	0.8	0.6	2000	9.4	
304 SS	<0.1	<0.1	0.3	0.2	0.2	0.1			
316 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
329 SS	<0.1	<0.1	0.3	0.2	0.2	0.1			
Carbon steel[f]	8.3	10.7	0.6	0.5	0.7	0.4	150	7.4	CO_2 16.3%, CO 14.4%, H_2S 0.86%, NH_3 0.38%, H_2O 20.8%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm, temperature 380 °F, pressure 1200 psig (HYGAS plant).
304 SS	0.5	0.2	0.2	0.1	0.1	0.1			
316 SS	0.4	0.4	0.1	0.1	0.2	0.1			
329 SS	0.2	<0.1	0.1	0.1	0.1	0.1			
Carbon steel	18.5	8.4	0.2	0.1	0.2	0.1	150	5.8	CO_2 16.3%, CO 14.4%, H_2S 0.86%, NH_3 0.38%, CH_4 13.1%, C_2H_6 0.43%, C_6H_6 0.14%, toluene 16.4%, H_2 17.1%, H_2O 20.8%, NCN 100 ppm, phenol 500 ppm, chloride 3000 ppm, temperature 380 °F, pressure 1200 psig (HYGAS Plant). Duplicate specimens used. At time intervals given, one of pair was removed, replaced with an unexposed coupon, and test restarted. During replacement, coupons were exposed to air and subjected to cyclic heating and cooling. The 2000 hour coupon was subjected to 3 such air exposures and thermal cycles.
304 SS	0.5	0.2	0.6	0.2	<0.1	<0.1			
316 SS	0.4	0.1	<0.1	<0.1	<0.1	<0.1			
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Carbon steel	34.5	11.5	0.3	0.1	0.2	0.1	400	8.3	
304 SS	0.1	<0.1	0.2	0.1	0.2	<0.1			
316 SS	0.2	<0.1	0.1	<0.1	<0.1	<0.1			
329 SS	0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Carbon steel	6.6	3.5	1.6	0.7	0.9	0.6	1000	9.5	
304 SS	4.6	2.0	1.0	0.7	<0.1	<0.1			
316 SS	2.6	2.5	0.3	0.2	<0.1	<0.1			
329 SS	3.6	7.2	0.9	0.2	0.5	0.3			
Carbon steel	6.8	7.0	0.4	0.2	0.3	0.2	450	8.6	
304 SS	0.4	0.2	<0.1	<0.1	<0.1	<0.1			
316 SS	0.4	0.3	<0.1	<0.1	<0.1	<0.1			
329 SS	0.2	<0.1	<0.1	<0.1	<0.1	<0.1			
Carbon steel	4.5	2.4	1.2	0.8	0.7	0.4	2000	8.6	
304 SS	2.1	1.6	1.6	1.1	1.4	1.2			
316 SS	1.6	1.2	1.2	0.8	0.6	0.5			
329 SS	2.5	1.4	1.0	0.8	0.8	0.6			
Carbon steel[f]	34.3[g]	13.1	0.7	0.5	0.4	0.3	150	8.2	CO_2 13.5%, CO 10.5%, H_2S 1%, NH_3 0.52%, H_2O 49.5%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm, temperature 495 °F, pressure 1100 psig (BI-GAS/Synthane Plants).
304 SS	4.0	2.5	0.6	0.3	0.4	0.2			
316 SS	8.6	4.0	0.5	0.3	0.3	0.2			
329 SS	0.4	0.2	0.5	0.2	0.2	0.1			
Carbon steel[f]	37.2	23.5	0.5	0.3	0.7	0.3	150	7.5	CO_2 13.5%, CO 10.5%, H_2S 1%, NH_3 0.52%, CH_4 9.0%, C_2H_6 0.66%, toluene 0.09%, H_2 14.5%, H_2O 49.5%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm, temperature 495 °F, pressure 1100 psig (BI-GAS/Synthane Plants). Duplicate specimens were used. Tests were terminated at the given intervals, both coupons removed, new duplicates put in place, and the tests restarted.
304 SS	3.4	3.0	0.2	0.2	0.1	0.1			
316 SS	5.7	4.8	0.3	0.2	0.3	0.1			
329 SS	0.3	0.2	<0.1	<0.1	<0.1	<0.1			
Carbon steel[f]	7.7	8.9	0.6	0.3	0.5	0.2	400	8.7	
304 SS	2.0	1.8	0.3	0.2	0.3	0.2			
316 SS	3.7	3.2	0.2	0.1	0.1	<0.1			
329 SS	0.2	0.2	0.2	0.1	0.1	<0.1			
Carbon steel[f]	10.6	12.2	0.7	0.4	0.6	0.4	1000[h]	5.8	
304 SS	1.3	1.0	0.4	0.2	0.3	0.2			
316 SS	2.3	2.0	0.4	0.2	0.3	0.2			
329 SS	<0.1	<0.1	0.3	0.2	0.3	0.2			

(Table Continued)

AQUEOUS CORROSION DYNAMIC TESTING[a] OF ALLOYS[b] IN SIMULATED PILOT PLANT QUENCH ENVIRONMENTS[38]

-Continued-

[a] Tests conducted in autoclaves to simulate the quench step of coal gasification processes; liquid added to a volume approximately on of autoclave capacity; specific impurities added based on total weight of liquid in autoclave; test specimens put in place, autocla purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated. A constant flow 5 scfh (0.14 m^3/h) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave. Provision was for a dynamic environment in which there was a continuous liquid input and periodic discharge to obtain a flow through the system.

[b] Specimens were machined to 1 in. square by 1/4 in. thick (329 SS was 1/8 in. thick), ground to 240 grit finish, cleaned by scrubbin alconox and hot water, rinsed, cleaned ultrasonically in alcohol 5 min., dried in cold air and stored in desiccator until used. Bef exposure coupons were weighed to 4 mg and measured to 0.001 in. After exposure specimens were cleaned according to NACE Standard TM-01-69 with modified cleaning time of 20 min and reweighed.

[c] Corrosion rate was calculated from the weight loss by the following equation:

$$\text{mils/yr} = \frac{\text{Weight loss (mg)} \times \text{constant}}{\text{area (in}^2\text{)} \times \text{time (hr)} \times \text{alloy density (g/cc)}}$$

. Specimens were exposed both in liquid in the autoclave and ab the liquid. The data are for single specimens except where noted otherwise.

[d] Pitting was evaluated by an in-focus/out-of-focus microscope technique on the top edge and the bottom of the pits. Some 15 to 20 pi depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the ave of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil.

[e] pH value is for solution at end of test.

[f] Data in this group of four alloys are for duplicate specimens.

[g] Values for these two specimens are 26.2 and 42.3, a much wider spread than rest of data.

[h] Test terminated at 964 h due to equipment failure.

AQUEOUS CORROSION[a] OF ALLOYS SUBJECTED TO FOUR SIMULATED PILOT PLANT QUENCH ENVIRONMENTS FOR 400 HOURS[38]

Alloy[b]	Corrosion,[c] mils/yr		Pit Depth,[d] mils			
	Aqueous	Gaseous	Aqueous		Gaseous	
			max	ave	max	ave
Environment 1:	22.1 (mole %) H_2O, 46.5 H_2, 14.2 CO, 6.3 CO_2, 10.1 CH_4, 0.5 NH_3, 0.04 H_2S; quench bottom temperature 240 °F, pressure 132 psig, based on lignite coal feed (Conoco coal - CO_2 acceptor).					
304 SS[e]	<0.1	<0.1	0.7	0.5	1.0	0.8
(70Fe-9Ni-19Cr)	0.1	<0.1	0.9	0.7	1.0	0.6
	<0.1	<0.1	0.6	0.4	0.6	0.5
	0.4	<0.1	0.5	0.3	<0.1	<0.1
316 SS	0.9	0.2	0.9	0.6	0.8	0.6
(65Fe-14Ni-17Cr)	0.3	<0.1	0.9	0.5	0.8	0.5
329 SS	-<0.1	-<0.1	0.6	0.4	0.8	0.5
(Fe-4Ni-27Cr)	-<0.1	-<0.1	0.7	0.4	0.7	0.5
18-18-2	0.3	0.1	1.0	0.7	0.6	0.5
(Fe-18Ni-18Cr-2Si)	0.4	-0.5	1.0	0.6	0.7	0.5
20Cb-3	0.2	<0.1	0.8	0.5	0.7	0.5
(Fe-33Ni-19Cr)	0.2	<0.1	0.8	0.7	0.9	0.6
26-1	<0.1	<0.1	0.8	0.5	0.7	0.5
(Fe-26Cr-1Mo)	<0.1	0.2	0.8	0.6	0.8	0.5
Incoloy 800	0.4	0.2	0.7	0.6	<0.1	<0.1
(47Fe-31Ni-21Cr)						
Incoloy 825	-<0.1	-<0.1	1.0	0.5	0.6	0.5
(30Fe-22Cr-42Ni-3Mo)	-<0.1	-<0.1	0.8	0.5	1.0	0.6
Hastelloy C	-<0.1	-<0.1	<0.1	<0.1	<0.1	<0.1
(Ni-16Cr-6Fe-15Mo)	-<0.1	-<0.1	<0.1	<0.1	<0.1	<0.1
Hastelloy G	-<0.1	-<0.1	0.7	0.5	0.7	0.5
(Ni-22Cr-20Fe-7Mo)	-<0.1	-<0.1	0.7	0.5	0.7	0.5
Titanium	-<0.1	-<0.1	0.9	0.5	0.9	0.5
	-<0.1	-<0.1	0.6	0.4	0.8	0.4
410 SS	0.3	0.3	1.9	1.5	2.3	1.2
(Fe-12Cr)	0.6	0.3	1.9	1.5	1.8	1.2
430 SS	0.4	0.1	1.5	1.3	<0.1	<0.1
(Fe-17Cr)	1.0	0.2	1.6	1.3	1.6	0.6
Carbon steel	5.8	2.8	1.6	1.0	0.8	0.7
(A515)	11	4.2	2.0	1.6	1.1	0.8
Cast iron	7.9	4.5	1.0	0.8	<0.1	<0.1
	10	5.3	1.1	0.9	<0.1	<0.1
Ni-resist	2.8	2.5	0.6	0.5	0.6	0.5
(Fe-20Ni-3Cr-3Si)	5.4	2.2	0.9	0.7	0.6	0.4
Ni-resist (Cu)	1.8	1.1	1.2	0.9	0.8	0.6
(Fe-18Ni-4Cr-3Si-7Cu)	2.4	1.3	2.7	1.8	1.4	1.0
18-2	0.2	<0.1	0.5	0.3	0.3	0.2
(Fe-18Cr-2Mo)	0.2	<0.1	0.5	0.3	0.4	0.2
Aluminum 1100	1.0	-0.8	1.8	2.6	0.7	0.6
	0.9	-0.7	1.3	1.8	0.9	0.8
Aluminum 6061	1.3	-0.3	1.3	1.9	0.6	0.8
	1.4	-0.3	1.3	2.0	0.7	1.0
Monel 400	5.7	3.0	0.7	0.9	0.6	0.8
(64Ni-33Cu-2Fe)	6.0	3.3	0.5	0.7	0.7	0.9
Al-bronze	7.0	7.6	0.8	1.2	0.9	1.2
(Cu-10Al-3Fe-2Ni)	8.0	7.1	0.9	1.1	0.9	1.1

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS SUBJECTED TO FOUR SIMULATED PILOT PLANT QUENCH ENVIRONMENTS FOR 400 HOURS[38] (cont.)

Alloy[b]	Corrosion,[c] mils/yr		Pit Depth,[d] mils			
	Aqueous	Gaseous	Aqueous		Gaseous	
			max	ave	max	ave
Environment 2: 50.0 (mole %) H_2O, 15.1 H_2, 14.8 CO, 10.8 CO_2, 8.0 CH_4, 0.32 NH_3, 0.75 H_2S; quench bottom temperature 494 °F, pressure 1204 psig, Eastern coal feed (BI-GAS).						
304 SS[e]	2.5	1.8	0.6	0.9	0.6	0.7
	2.6	1.9	0.5	0.8	0.5	0.7
	8.6	3.9	1.0	0.8	1.7	1.3
	7.9	4.2	1.8	1.4	1.7	1.0
316 SS	2.6	2.1	0.6	0.7	0.6	1.0
	2.2	3.2	0.5	0.8	0.7	0.9
329 SS	0.1	0.1	0.8	1.1	0.7	1.0
	<0.1	0.1	0.7	1.0	0.6	0.7
18-18-2	1.9	1.9	0.7	0.8	0.7	1.2
	2.0	2.0	0.7	0.8	0.8	1.0
Armco 22-13-5 (Fe-14Ni-21Cr-5Mn)	0.4	0.3	0.6	0.9	0.7	0.8
	0.4	0.3	0.6	0.8	0.6	1.1
20Cb-3	0.4	0.4	0.6	1.0	0.6	0.8
	0.5	0.4	0.5	0.8	0.6	0.7
26-1	<0.1	<0.1	0.7	1.0	0.6	0.8
	<0.1	<0.1	0.6	0.8	0.6	0.7
Incoloy 800	0.7	0.6	0.7	0.8	0.6	0.9
	0.8	0.7	0.5	0.7	0.6	0.8
Incoloy 825	0.2	0.2	0.5	0.7	0.7	1.0
	0.1	0.2	0.7	0.8	0.7	1.1
Hastelloy C	<0.1	<0.1	0.9	1.5	0.7	0.8
	<0.1	<0.1	0.7	0.8	0.7	1.0
Hastelloy G	<0.1	<0.1	0.7	1.0	0.7	0.8
	<0.1	<0.1	0.7	1.0	0.5	0.6
Titanium	-0.2	0.1	0.5	0.7	0.7	0.8
	-0.2	0.1	0.5	0.7	0.6	0.7
410 SS	13	5.8	2.1	1.9	1.9	1.5
	14	6.5	1.7	1.3	2.0	1.6
430 SS	9.3	3.2	1.8	1.6	1.5	1.1
	24	3.9	3.0	2.4	1.4	1.1
Carbon steel	11	9.9	1.0	0.7	0.8	0.7
	11	6.3	3.5	1.8	1.0	0.7
Cast iron	32	24	1.5	1.2	1.3	1.0
	6.2	19	0.9	0.7	1.2	0.9
Ni-resist	23	33	1.9	1.2	1.8	1.5
	39	26	1.8	1.3	1.6	1.2
Ni-resist (Cu)	21	24	0.8	0.6	0.9	0.7
	29	11	1.0	0.8	1.0	0.9
18-2	11	3.8	2.0	1.4	1.0	1.0
	10	3.0	2.2	1.8	1.3	0.9
Aluminum 1100	-14	-41	1.5	2.5	1.3	2.0
	-9.4	-51	2.4	3.2	1.1	1.7
Aluminum 6061	-35	-5.0	1.5	2.3	1.6	2.4
	-4.8	-4.1	1.4	2.4	2.0	2.4
Monel 400	59	25	0.7	1.0	0.8	1.0
	16	13	1.0	1.4	0.8	1.0
Al-bronze	227	272	1.2	1.7	0.7	1.0
	217	159	1.2	1.6	0.8	1.5

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS SUBJECTED TO FOUR SIMULATED
PILOT PLANT QUENCH ENVIRONMENTS FOR 400 HOURS[38] (cont.)

Alloy[b]	Corrosion,[c] mils/yr		Pit Depth,[d] mils			
	Aqueous	Gaseous	Aqueous		Gaseous	
			max	ave	max	ave
Environment 3:	49.2 (mole %) H_2O, 14.0 H_2, 10.2 CO, 13.7 CO_2, 10.4 CH_4, 0.66 C_2H_6, 0.52 NH_3, 1.08 H_2S, 0.090 toluene; quench bottom temperature 496 °F, pressure 981 psig, Eastern coal feed (Synthane).					
304 SS[e]	1.7	2.3	0.7	0.5	0.6	0.5
	1.7	2.4	0.7	0.5	0.8	0.6
	2.5	1.5	<0.1	<0.1	1.2	0.8
	2.5	1.4	0.9	0.9	<0.1	<0.1
316 SS	1.7	2.3	1.3	1.0	1.0	0.8
	2.2	2.4	1.0	0.6	1.0	0.8
329 SS	0.3	0.3	0.7	0.4	0.7	0.5
	0.3	0.3	0.8	0.5	1.0	0.6
18-18-2	1.8	1.9	1.5	1.0	0.7	0.6
	1.9	1.8	1.0	0.9	1.0	0.8
Armco 22-13-5	0.5	0.4	0.9	0.5	0.7	0.4
	0.6	0.5	0.9	0.6	0.6	0.4
20 Cb-3	0.5	0.7	0.9	0.6	0.9	0.6
	0.5	0.7	0.7	0.6	1.1	0.6
26-1	0.2	0.2	0.8	0.6	0.8	0.6
	0.2	0.2	0.8	0.6	0.8	0.6
Incoloy 800	0.9	1.0	0.7	0.3	1.2	0.8
	1.4	1.2	1.1	0.7	1.2	0.8
Incoloy 825	0.3	0.4	0.7	0.5	0.9	0.6
	0.2	0.3	0.6	0.5	0.8	0.5
Hastelloy C	0.1	0.1	0.7	0.6	0.8	0.5
	<0.1	0.3	0.7	0.6	0.7	0.6
Hastelloy G	0.1	<0.1	0.9	0.6	0.8	0.5
	0.2	0.1	0.7	0.6	0.8	0.6
Titanium	<0.1	<0.1	0.8	0.6	0.8	0.6
	<0.1	-0.5	0.8	0.5	0.9	0.6
410 SS	3.8	2.7	1.4	1.0	1.0	0.8
	4.4	2.9	1.7	1.4	1.1	0.9
430 SS	3.4	1.6	0.5	0.5	1.2	0.7
	3.2	1.4	1.2	0.8	0.6	0.5
Carbon steel	6.8	7.7	1.0	0.8	1.2	0.9
	7.2	7.8	2.0	1.6	1.9	1.6
Cast iron	2.6	4.9	<0.1	<0.1	0.6	0.6
	0.3	2.9	<0.1	<0.1	<0.1	<0.1
Ni-resist	14	12	<0.1	<0.1	<0.1	<0.1
	8.8	12	<0.1	<0.1	<0.1	<0.1
Ni-resist (Cu)	13	9.3	<0.1	<0.1	1.0	0.7
	10	7.4	<0.1	<0.1	<0.1	<0.1
18-2	2.7	4.0	<0.1	<0.1	<0.1	<0.1
	3.3	4.0	<0.1	<0.1	<0.1	<0.1
Environment 4:	20.8 (mole %) H_2O, 17.1 H_2, 14.4 CO, 16.3 CO_2, 13.1 CH_4, 0.43 C_2H_6, 0.38 NH_3, 0.86 H_2S, 0.14 C_6H_6, 16.4 toluene; quench bottom temperature 380 °F, pressure 1200 psig, Eastern coal feed (HYGAS).					
304 SS[e]	0.4	0.4	0.1	0.1	<0.1	<0.1
	0.5	0.4	2.7	2.1	1.0	0.6
	0.9	0.4	4.0	2.7	2.0	1.2
	0.8	0.4	2.3	1.5	0.9	0.8
316 SS	0.3	0.5	<0.1	<0.1	<0.1	<0.1
	0.4	0.6	<0.1	<0.1	1.4	1.2

(Table Continued)

AQUEOUS CORROSION[a] OF ALLOYS SUBJECTED TO FOUR SIMULATED PILOT PLANT QUENCH ENVIRONMENTS FOR 400 HOURS[38] (cont.)

Alloy[b]	Corrosion,[c] mils/yr Aqueous	Corrosion,[c] mils/yr Gaseous	Pit Depth,[d] mils Aqueous max	Pit Depth,[d] mils Aqueous ave	Pit Depth,[d] mils Gaseous max	Pit Depth,[d] mils Gaseous ave
Environment 4: (continued)	20.8 (mole %) H_2O, 17.1 H_2, 14.4 CO, 16.3 CO_2, 13.1 CH_4, 0.43 C_2H_6, 0.38 NH_3, 0.86 H_2S, 0.14 C_6H_6, 16.4 toluene; quench bottom temperature 380 °F, pressure 1200 psig, Eastern coal feed (HYGAS).					
329 SS	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
	0.2	0.2	<0.1	<0.1	<0.1	<0.1
18-18-2	0.5	0.5	1.3	1.0	<0.1	<0.1
	0.5	0.4	<0.1	<0.1	1.3	0.9
Armco 22-13-5	-0.1	0.2	0.1	0.1	<0.1	<0.1
	<0.1	0.1	0.1	0.1	0.8	0.6
20 Cb-3	<0.1	0.3	<0.1	<0.1	<0.1	<0.1
	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
26-1	0.2	0.1	<0.1	<0.1	<0.1	<0.1
	0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Incoloy 800	0.2	0.3	<0.1	<0.1	0.8	0.7
	0.3	0.3	<0.1	<0.1	1.2	0.9
Incoloy 825	-<0.1	0.1	<0.1	<0.1	<0.1	<0.1
	0.1	0.1	<0.1	<0.1	<0.1	<0.1
Hastelloy C	-<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	-<0.1	-<0.1	<0.1	<0.1	<0.1	<0.1
Hastelloy G	-<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Titanium	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
410 SS	14	55	1.6	1.2	1.6	0.9
	14.6	83	1.5	0.7	1.0	0.7
430 SS	4.4	2.6	0.9	0.4	1.8	1.0
	3.3	2.3	0.8	0.4	1.9	0.8
Carbon steel	-1.2	4.8	1.3	1.0	<0.1	<0.1
	1.8	3.7	1.0	0.8	<0.1	<0.1
Cast iron	0.6	6.5	3.6	2.9	<0.1	<0.1
	0.8	5.4	3.8	2.8	<0.1	<0.1
Ni-resist	18	9.4	<0.1	<0.1	<0.1	<0.1
	21	8.0	<0.1	<0.1	<0.1	<0.1
Ni-resist (Cu)	14	8.6	<0.1	<0.1	<0.1	<0.1
	12	9.6	<0.1	<0.1	<0.1	<0.1
18-2	2.5	1.1	<0.1	<0.1	<0.1	<0.1
	2.4	1.5	<0.1	<0.1	<0.1	<0.1

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[a] Tests conducted in autoclaves to simulate quench steps of four coal gasification processes. Initial pH values varied 6.0-7.4, at 200 hr 6.6-9.7, after test 7.7-9.7.

[b] Approximate compositions given for alloys the first time the alloy appears in the table and not repeated. Specimens were machined to 1 in. square by 1/8 to 3/8 in. thick, polished (240 grit), cleaned ultrasonically and weighed. After exposure, specimens were cleaned according to NACE Standard TM-01-69 with modified cleaning time of 20 min. and reweighed.

[c] Corrosion rate calculated from the weight loss by the following equation:

$$\text{mils/yr} = \frac{\text{weight loss (mg)} \times \text{constant}}{\text{area (in}^2\text{)} \times \text{time (hr)} \times \text{alloy density (g/cc)}}.$$

Duplicate specimens were exposed both in liquid and above liquid in the autoclave. Data for each specimen are given. A negative corrosion rate means a gain in weight; a rate of 0.1 corresponds to the minimum measurable weight difference.

[d] Pitting was evaluated by an in-focus/out-of-focus microscopic technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil.

[e] 304 SS was exposed with two separate groups of the alloys, providing four sets of data.

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF ONE SIMULATED PILOT PLANT QUENCH ENVIRONMENT[b][38]

	Corrosion Rate[c], Mils/Yr		Pit Depth[d], Mils					
			Aqueous		Gaseous			
Alloy[a]	Aqueous	Gaseous	max	ave	max	ave	Time,hr	Environment[b]
Carbon steel	20.8^e	8.0^e	0.4^e	0.3^e	0.3^e	0.2^e	150	Standard: CO$_2$ 16.3%, CO 14.4%, (CO/CO$_2$ = 0.9), H$_2$S 0.86%, NH$_3$ 0.38%, CH$_4$ 13.1%, C$_2$H$_6$ 0.43%, C$_6$H$_6$ 0.14%, toluene 16.4%, H$_2$ 17.1%, H$_2$O 20.8% N$_2$ 0%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm. Standard temperature 380 °F, standard pressure 1200 psig.
304 SS	0.3	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	10.3	5.7	1.0	0.6	0.5	0.2	500	Standard
304 SS	0.4	0.3	<0.1	<0.1	<0.1	<0.1		
Carbon steel	4.0	3.9	0.3	0.2	0.2	0.2	2000	Standard
304 SS	0.2	0.1	0.2	0.1	0.2	0.1		
316 SS	0.2	0.2	0.2	0.2	0.2	<0.1		
329 SS	0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	12.0^e	5.8^e	0.4^e	0.3^e	0.2^e	0.1^e	150	Standard with temperature 300 °F (H$_2$O 5.5%, N$_2$ 15.3%)
304 SS	0.1	0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	6.0	5.0	0.3	0.1	0.2	0.1	150	Standard with temperature 250 °F (H$_2$O 2.5%, N$_2$ 18.3%)
304 SS	<0.1	<0.1	0.2	0.1	<0.1	<0.1		
316 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	0.2	0.1	0.2	0.1		
Carbon steel	7.5	6.7	0.2	0.1	0.2	0.1	150	Standard with temperature 150 °F (H$_2$O 0.3%, N$_2$ 20.5%)
304 SS	<0.1	<0.1	<0.1	<0.1	0.2	0.1		
316 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	<0.1	<0.1	0.2	0.1		
Carbon steel	13.1^f	8.2^f	0.2^f	0.1^f	0.3^f	0.2^f	150	Standard with pressure 900 psig (H$_2$O 21.4%)
304 SS	0.4	0.2	<0.1	<0.1	<0.1	<0.1		
Carbon steel	20.9	14.4	<0.1	<0.1	<0.1	<0.1	150	Standard with H$_2$ 0%, N$_2$ 17.1%
304 SS	0.7	<0.1	<0.1	<0.1	<0.1	<0.1		
316 SS	0.7	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	20.9	7.7	0.2	0.1	0.2	0.1	150	Standard with CH$_4$ 0%, C$_2$H$_6$ 0%, N$_2$ 13.5%
304 SS	0.8	0.6	0.2	0.1	0.2	0.1		
316 SS	0.4	0.3	<0.1	<0.1	<0.1	<0.1		
329 SS	0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	10.7	5.3	0.3	0.2	0.3	0.2	150	Standard with C$_6$H$_6$ 0%, toluene 0%, N$_2$ 16.5%
304 SS	0.2	<0.1	<0.1	<0.1	<0.1	<0.1		
316 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	22.0	17.0	0.4	0.3	0.3	0.2	150	Standard with CO$_2$ 20.5%, CO 10.2%, (CO/CO$_2$ = 0.5)
304 SS	0.5	0.2	0.2	0.1	0.2	0.1		
316 SS	0.3	0.1	0.2	0.1	0.1	<0.1		
329 SS	0.1	0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	6.5	4.9	0.3	0.2	0.5	0.3	1000	Standard with CO$_2$ 20.5%, CO 10.2%, (CO/CO$_2$ = 0.5)
304 SS	0.2	0.1	0.3	0.2	0.1	<0.1		
Carbon steel	16.5	11.9	0.4	0.2	0.2	0.2	150	Standard with CO$_2$ 10.2%, CO 20.5%, (CO/CO$_2$ = 2.0)
304 SS	0.3	0.1	0.2	0.2	0.2	0.2		
316 SS	0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	15.2	9.8	0.3	0.1	0.2	0.2	150	Standard with NH$_3$ 0.8%
304 SS	0.5	0.2	0.2	0.1	0.2	0.1		
316 SS	0.5	0.2	<0.1	<0.1	<0.1	<0.1		
329 SS	0.2	0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	12.7^e	9.2^e	0.3^e	0.2^e	0.3^e	0.2^e	150	Standard with NH$_3$ 0.8%
304 SS	0.6	0.2	<0.1	<0.1	<0.1	<0.1		
Carbon steel	18.0	11.1	0.4	0.2	0.2	0.1	150	Standard with NH$_3$ 0.1%
304 SS	0.4	0.1	<0.1	<0.1	<0.1	<0.1		
316 SS	0.3	0.2	<0.1	<0.1	<0.1	<0.1		
329 SS	0.1	0.2	<0.1	<0.1	<0.1	<0.1		
Carbon steel	7.6^f	7.9^f	1.2^f	0.4^f	1.4^f	0.9^f	150	Standard with NH$_3$ 0.1%, temperature 150 °F (H$_2$O 0.3%, N$_2$ 20.5%)
304 SS	0.3	0.3	<0.1	<0.1	<0.1	<0.1		
Carbon steel	18.2^f	9.8^f	0.7^f	0.4^f	0.8^f	0.5^f	150	Standard with CO$_2$ 20.5%, CO 10.2%, (CO/CO$_2$ = 0.5), NH$_3$ 0.8%
304 SS	0.8	0.4	<0.1	<0.1	<0.1	<0.1		
Carbon steel	16.2^f	13.5^f	1.1^f	0.5^f	0.9^f	0.3^f	150	Standard with CO$_2$ 10.2%, CO 20.5%, (CO/CO$_2$ = 2.0), NH$_3$ 0.8%
304 SS	0.9	0.5	<0.1	<0.1	<0.1	<0.1		
Carbon steel	10.0	5.2	0.7	0.4	1.0	0.8	1000	Standard with CO$_2$ 10.2%, CO 20.5%, (CO/CO$_2$ = 2.0), NH$_3$ 0.8%
304 SS	0.2	0.1	<0.1	<0.1	<0.1	<0.1		

(Table Continued)

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF ONE SIMULATED PILOT PLANT QUENCH ENVIRONMENT[b][38]
-Continued-

Alloy[a]	Corrosion Rate[c], Mils/Yr		Pit Depth[d], Mils				Time,hr	Environment[b]
			Aqueous		Gaseous			
	Aqueous	Gaseous	max	ave	max	ave		
Carbon steel	18.6	20.5	0.3	0.2	0.2	0.1	150	Standard with H_2S 0.5%
304 SS	0.4	0.2	<0.1	<0.1	<0.1	<0.1		
316 SS	0.2	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	7.9[e]	5.3[e]	1.3[e]	0.9[e]	0.6[e]	0.4[e]	1000	Standard with H_2S 0.5%
304 SS	0.3	0.1	0.3	0.2	0.2	0.1		
Carbon steel	27.8	22.7	0.4	0.2	0.2	0.1	150	Standard with H_2S 1.5%
304 SS	0.4	<0.1	<0.1	<0.1	<0.1	<0.1		
316 SS	0.4	<0.1	<0.1	<0.1	<0.1	<0.1		
329 SS	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	7.6[f]	5.6[f]	1.9[f]	1.3[f]	1.4[f]	0.7[f]	1000	Standard with H_2S 1.5%
304 SS	0.2	0.2	0.4	0.2	0.3	0.2		
Carbon steel	12.8[f]	13.1[f]	0.4[f]	0.2[f]	0.3[f]	0.1[f]	150	Standard with H_2S 1.5%, pressure 900 psig (H_2O 2
304 SS	0.4	0.3	0.3	0.2	<0.1	<0.1		
Carbon steel	32.5[f]	11.4[f]	0.7[f]	0.3[f]	0.8[f]	0.2[f]	150	Standard with H_2S 0.1%, pressure 300 psig (H_2O 6
304 SS	0.4	0.2	<0.1	<0.1	<0.1	<0.1		
Carbon steel	10.3	4.6	2.0	1.2	1.5	0.9	1000	Standard with H_2S 0.1%, pressure 300 psig (H_2O 6
304 SS	0.3	0.1	0.3	0.2	0.2	0.1		
Carbon steel	5.6[e]	4.0[e]	0.6[e]	0.3[e]	0.5[e]	0.3[e]	500	Standard with H_2S 1.5%, NH_3 0.8%, temperature 35
304 SS	<0.1	0.1	<0.1	<0.1	<0.1	<0.1		

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[a] Specimens were machined to 1 in square by 1/4 in thick (329 SS was 1/8 in thick), ground to 240 grit finish, cleaned by scrubbing in alconox and hot water, rinsed, cleaned ultrasonically in alcohol 5 min, dried in cold air and stored in desiccator until used. Before exposure coupons were weighed to 4 mg and measured to 0.001 in. After exposure specimens were cleaned according to NACE Standard TM-01- with modified cleaning time of 20 min and reweighed.

[b] Tests conducted in autoclaves to simulate the quench step of a coal gasification process (HYGAS); liquid added to a volume approximately one-half of autoclave capacity; specified impurities added based on total weight of liquid in autoclave; test specimens put in place, autoclave purged with N_2 and brought to test temperature and pressure. At equilibrium gases were introduced and circulated. A constant flow of 5 scfh (0.14 m^3/h) of new gas was maintained and a condenser and pump automatically fed condensate back to autoclave. Provision was made for a dynamic environment in which there was a continuous liquid input and periodic discharge to obtain a flow through the system. The standard environment given is based on demonstration plant concepts (HYGAS process).

[c] Corrosion rate was calculated from the weight loss by the following equation:

$$\text{mils/yr} = \frac{\text{Weight loss (mg) x constant}}{\text{area (in}^2\text{) x time (hr) x alloy density (g/cc)}}$$

Specimens were exposed both in liquid in the autoclave and above the liquid. values are averages for duplicate specimens except where noted.

[d] Pitting was evaluated by an in-focus/out-of-focus microscopic technique on the top edge and the bottom of the pits. Some 15 to 20 pit depth readings were taken per specimen and the results given in terms of max (the maximum pit depth measured, mils) and ave (the average of the 10 largest pit depths measured, mils). Minimum measurable pit depth was 0.1 mil. Values are averages for duplicate specimens except where noted.

[e] Data are the average for 5 specimens.

[f] Data are the average for 6 specimens.

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EFFECT OF EXPOSURE TO A MIXED GAS ENVIRONMENT[a] ON THE MINERALOGY[b] OF SiC AND SIALON REFRACTORIES [9]

Material	As-Received	After Exposure[a]	Comments
SiC (oxy-nitride bond)	SiC (P), Si_2ON_2 (M)	Cristobalite (P), SiC (M), Quartz (T)	Completely disintegrated
SiC (silicate bond)	SiC (P), α-Si_3N_4 (M), Si_2ON_2 (M), β-Si_3N_4 (T)	Cristobalite (P), SiC (M), Quartz (T)	Samples intact but with large increase in volume; disintegrated easily in handling
SiC (direct bond)	SiC (P), Cristobalite (M)	Cristobalite (P), SiC (M), Quartz (T)	Completely disintegrated
Sialon	β'-Si_3N_4 solid solution (P), $2Si_3N_4.3Al_2O_3$ (Average Compressive Strength 32,000 psi)	β'-Si_3N_4 solid solid solution (P), $2Si_3N_4.3Al_2O_3$ (M), α-Al_2O_3 (T) (Average Compressive Strength 25,000 psi)	Samples intact but outer 0.3 mm changed color from dark gray to white--outer layer consisted of Mullite (P) and Cristobalite (M)

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[a] Environment: mixed gas composition (feed gas) = 24% H_2, 18% CO, 12% CO_2, 5% CH_4, 2% NH_3, 1% H_2S, 38% H_2O; temperature = 980° C; pressure = 1000 psi; time = 1000 hr.

[b] Constituents determined by x-ray diffraction; letters in parentheses after the constituents indicate relative quantity, P = principal constituent, M = minor constituent, T = trace.

EFFECT OF FLOWING HIGH-BTU GAS[a] ON THE SILICA CONTENT[b] OF AN ALUMINA-SILICA REFRACTORY[c] [9]

Exposure Time hr	Silica content, weight percent[b]				
	In Reaction Vessel[e]		Crushed Material[g] In Standpipe[f]		
	Bar Samples[g]	Powder Samples[g]	Inlet	Middle	Exit
0[d]	36.3	36.3	36.3	36.3	36.3
50	36.6	37.9			
100	36.6	37.1	34.0	35.3	34.9
150	35.9	37.1			
200	36.3	37.2			
250	36.5	36.8			

[a] Steam-gas mixture composition: 45% H_2O, 55% high-Btu gas composed of 39.5% H_2, 30.9% CO, 21.0% CO_2, 8.6% CH_4. Temperature 980° C, pressure 1000

[b] Silica content in weight percent, ±0.4 wt% based on five replicates at 50 hours exposure (99% confidence level).

[c] Refractory is a dense 55% Al_2O_3-fireclay calcine aggregate (A. P. Green's Lo-Abrade) with intermediate-purity calcium aluminate cement (Universal Atlas Cement's Refcon).

[d] All samples were prefired in air at 980° C for 24 hr, then exposed.

[e] An average of 6scf/h of the steam/gas mixture passed through the standpipe into the reaction vessel; superficial velocity was calculated to be 0.04 ft/min in vessel.

[f] Samples were exposed in the 1-in standpipe so that they could be exposed to higher gas velocities than in the reaction vessel. Superficial velocit was calculated to be 1.4 ft/min.

[g] Bar samples were 1 in x 1 in x 2 in; powder samples were minus 20-mesh material contained in alumina crucibles; crushed material was 1/2 by 1/4-in.

EFFECT OF EXPOSURE[a] TO A VARIETY OF ENVIRONMENTS ON THE P_2O_5 CONTENT OF A PHOSPHATE-BONDED REFRACTORY[b] [9]

Chemical Environment	Temperature	Pressure	Time	Wt % P_2O_5[c]
Cured[d] only				2.97
Air-Fired	1100° C		24 hr	3.91
Air-Fired	1100° C		250 hr	3.58
Pure steam	1100° C	1000 psi	250 hr	3.41
Pure H_2	1100° C	1000 psi	250 hr	0.03[e]
Pure CO	1100° C	1000 psi	125 hr	3.70
Pure CO_2	1100° C	800 psi	250 hr	3.52
Mixed Gas[f]	1000° C	1000 psi	160 hr	2.97

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[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths of time.

[b] A 90% Al_2O_3 ramming mix, phosphate bonded; General Refractories' Brikram 90R.

[c] By wet chemical analysis.

[d] Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250 °F 28 h, heated at 50 °F/h to 500 °F, held 24 h, heated at 50 °F/h to 1000 °F, held 24 h, cooled slowly back to ambient temperature, and the resulting sample sawed to size.

[e] No significant reduction in strength was found in spite of loss of P_2O_5; the amount of cristobalite present was reduced by hydrogen exposure, the only mineralogical change to occur in the series of exposures.

[f] Mixed gas composition (feed gas): 24% H_2, 18% CO, 12% CO_2, 5% CH_4, 2% NH_3, 1% H_2S, 38% H_2O.

EFFECT OF VARIOUS ALKALI-GAS EXPOSURES[a] ON THE ALKALI CONTENT[b] OF SOME REFRACTORIES[9]

Refractory Cement	Manufacturer Brand Name Manufacturer	Alkali Content[b] of Specimens after Treatment[a]														
		A Prefired		B alkali-gas		C solution, air fired		D solution, alkali-gas		E 50% soln, air fired		F 50% soln, mixed gas		G 25% soln, air fired		25% mix
		K_2O	Na_2O	K_2O	Na_2O	K_2O	Na_2O	K_2O	Na_2O	K_2O	Na_2O	K_2O	Na_2O	K_2O	Na_2O	K_2O
Dense 95% tabular Al_2O_3 castable high-purity calcium aluminate	Castolast G Harbison-Walker CA-25 Alcoa	0.008	0.18	0.24	0.33	1.3	1.3	1.3	1.4	2.40	1.30	2.10	1.40	1.10	0.78	0.84
Dense 90% tabular Al_2O_3 castable high-purity calcium aluminate	DOE 90 Generic Preparation CA-25, Alcoa	0.01	0.20	0.24	0.22	1.3	1.5	1.5	1.5							
Dense 55% Al_2O_3 fire clay calcine castable high-purity calcium aluminate	Lo-Abrade A. P. Green CA-25 Alcoa	0.54	0.28	1.4	0.51	2.9	1.9	3.5	2.0	3.90	1.80	5.00	2.00	2.70	1.40	2.90
Dense 45% Al_2O_3 fire clay calcine castable medium-purity calcium aluminate	H.S. Brikcast BF General Refractories Refcon Universal Atlas Cement	0.12	0.06	0.82	0.30	2.4	1.5	3.3	2.0	--	--	--	--	--	--	--
Dense 45% Al_2O_3 fire clay calcine castable low-purity calcium aluminate	B&W Kaocrete D Babcock & Wilcox Secar 50 Lone Star Lafarge	0.26	0.04	1.8	0.52	2.9	1.8	3.5	2.0							
Dense 90% tabular Al_2O_3 castable phosphate	Resco Cast AA-22 Resco Products	0.008	0.07	0.70	0.33	1.5	1.1	2.4	1.1							
Lightweight 50% Al_2O_3 insulating castable, pyrophyllite aggregate high-purity calcium aluminate	Litecast 75-28 General Refractories CA-25 Alcoa	--	--							5.70	2.70	6.00	2.60	3.00	1.20	3.50
90% tabular Al_2O_3 ramming mix phosphate	Brikram 90R General Refractories	0.02	0.15	1.3	0.53	1.1	0.82	1.4	0.76	2.20	1.10	1.90	0.93	1.40	0.80	1.50
45% Al_2O_3 fired super duty brick, clay aggregate	KX-99 A. P. Green	--	--							2.10	0.65	2.10	0.62	1.30	0.29	1.60

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[a] All samples were given treatment A, followed by one of the other exposures listed:

A--Samples were fired in air at 980° C for 24 hr.

B--A 2:1 mixture by weight of KOH/NaOH was placed in a Pt crucible and surrounded by test specimens in the reaction vessel. Feed gas comp was 26% H_2, 21% CO, 14% CO_2, 5% CH_4, 34% H_2O. The specimens were subjected to the resulting atmosphere for 200 hr at 980° C, 1000 psi. the end of the test the alkali had been reduced about 50% and the KOH/NaOH ratio was 1.58 in the crucible.

C--Samples were soaked for 24 hr in a solution of 500g KOH and 250g NaOH in 600 ml water, oven dried at 125° C for 24 hr, and then air fir 980° C for 200 hr.

D--Samples were soaked and dried as in C, and then subjected to the same alkali-gas atmosphere described in B.

E--Samples were soaked for 24 hr in a 50% by weight solution of KOH-NaOH, then air fired at 980° C for 250 hr.

F--Samples were soaked for 24 hr in a 50% by weight solution of KOH-NaOH, then exposed to a steam-containing high-Btu atmosphere at 980° C 250 hr at 1000 psi. [Feed gas presumed to be 25% H_2, 21% CO, 13% CO_2, 5% CH_4, 36% H_2O.]

G--Samples were soaked for 24 hr in a 25% by weight solution of KOH-NaOH, then air fired at 980° C for 250 hr.

H--Samples were soaked for 24 hr in a 25% by weight solution of KOH-NaOH, then exposed to a steam-containing high-Btu gas as in F.

[b] Alkali content is in weight percent.

EFFECT OF VARIOUS ENVIRONMENTS ON THE MINERALOGICAL PHASES OF VARIOUS REFRACTORIES [9]

fractory	Brand Name Manufacturer	Phases Present[a] After		Phases changes[a] Occuring in Fired Samples After Exposure To			
		Curing and Drying[b]	Firing to 1100° C	Steam[c]	Hydrogen[d]	Carbon Monoxide[e]	Mixed Gases[f]
nse 95% Al_2O_3 stable, Cal- um Aluminate nd	Castolast G Harbison-Walker	α-Al_2O_3, CA, β-$NaAl_{11}O_{17}$, C_3AH_6, gibbsite, mullite	α-Al_2O_3, CA_2, β-$NaAl_{11}O_{17}$, CA	CA disapoeared $CaAl_2Si_2O_8$ formed	none	CA disappeared	CA_2 decreased
nse 55% Al_2O_3 stable, Cal- um Aluminate nd	Lo-Abrade A. P. Green	mullite, α-Al_2O_3, CA, cristobalite	mullite, α-cristobalite, α-Al_2O_3, CA_2, CA_6, $CaAl_2Si_2O_8$, C_2AS, rutile	mullite and $CaAl_2Si_2O_8$ increased, α-cristobalite decreased, CA_2, CA_6, and C_2AS disaooeared	$CaAl_2Si_2O_8$ formed	CA_2 decreases, CA_6 and C_2AS disappeared	CA_2 disappeared
ghtweight 50% $_2O_3$ Insulating stable, Calcium uminate Bond	Litecast 75-28 General Refractories	kyanite, quartz, α-Al_2O_3	kyanite, α-Al_2O_3, mullite, quartz, α-cristobalite, rutile, C_2AS, CA_2	kyanite, quartz, C_2AS, CA_2, α-cristobalite, and rutile disappeared, mullite increased, $CaAl_2Si_2O_8$ formed in large amounts		C_2AS disappeared	quartz decreased
nse 45% Al_2O_3 stable, Cal- um Aluminate nd	H.S. Brikcast BF General Refractories						CA_2 and C_2AS disappeared, $CaAl_2Si_2O_8$ increased
% Al_2O_3 ram- ng mix, Phos- ate Bond	Brikram 90R General Refractories	α-Al_2O_3, quartz, β-$NaAl_{11}O_{17}$, cristobalite	α-Al_2O_3, α-cristobalite, quartz	α-cristobalite & quartz disappeared, tridymite formed	none		α-Al_2O_3 decreased
nse 90% Al_2O_3 stable, Phos- ate Bond	Resco Cast AA-22 Resco Products						none
lcium Alumin- e Neat Cement 8% Al_2O_3)	CA-25 Alcoa	α-Al_2O_3, CA, C_3AH_6, gibbsite, possibly gypsum	α-Al_2O_3, CA_2, β-$NaAl_{11}O_{17}$	β-$NaAl_{11}O_{17}$ increased slightly	none		none
% Al_2O_3 brick	99AD A. P. Green	α-Al_2O_3, β-$NaAl_{11}O_{17}$	α-Al_2O_3, β-$NaAl_{11}O_{17}$	β-$NaAl_{11}O_{17}$ disappeared	β-$NaAl_{11}O_{17}$ disappeared	none	β-$NaAl_{11}O_{17}$ disappeared
% Al_2O_3 brick	Arco-90 General Refractories	α-Al_2O_3, mullite, cristobalite	α-Al_2O_3, mullite, α-cristobalite, β-$NaAl_{11}O_{17}$	β-$NaAl_{11}O_{17}$ disappeared	β-$NaAl_{11}O_{17}$ disappeared	none	none
% Al_2O_3 tar- pregnated ick	Ufala Tl Harbison-Walker	mullite, cristobalite, α-Al_2O_3	mullite, α-cristobalite, α-Al_2O_3, rutile	tridymite formed, α-cristobalite decreased, αAl_2O_3 and mullite increased	none	none	none
% Al_2O_3 fired per duty brick	KX-99 A. P. Green	mullite, cristobalite	mullite, α-cristobalite, tridymite, rutile, α-Al_2O_3	α-cristobalite & α-Al_2O_3 disappeared, tridymite appeared	none	none	tridymite appeared

hases identified by x-ray diffraction. Cement notation used to identify some phases: A = Al_2O_3, C = CaO, H = H_2O.

amples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

xposure to 100% steam was at 1100° C for 250 hr at 1000 psi.

xposure to 100% hydrogen was at 1100° C for 250 hr at 1000 psi.

xposure to 100% carbon monoxide was at 1100° C for 125 hr at 1000 psi.

xposure was at 1000° C for 160 hr at 1000 psi to an atmosphere provided by feed gas of 24% hydrogen, 18% carbon monoxide, 12% carbon dioxide, 5% ethane, 1% hydrogen sulfide, 38% steam.

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE MINERAL PHASES[b] PRESENT IN MEDIUM-ALUMINA CASTABLE REFRACTORIES[23]

Test Temperature[e] °C	Phases Present[b]			
	A56[c]		A50[d]	
	Untreated[e]	Treated[e]	Untreated[e]	Treated[e]
ambient	A_3S_2, S(c), CAS_2(T), CA, C_2AH_8, α-A	A_3S_2, S(c), CAS_2(H), α-A, tCAS_2(T)	A_3S_2, S(c), C_2AS, CA, CA_2, C_2AH_8, tCAS_2(T)	A_3S_2, S(c CAS_2(T), CAS_2(H)
610	A_3S_2, S(c), CA_2, α-A, tCAS_2(T)	A_3S_2, S(c), CAS_2(H), α-A, tCAS_2(T)	A_3S_2, S(c), C_2AS, CA, CA_2, tCAS_2(T)	A_3S_2, S(c CAS_2(T), CAS_2(H)
1010	A_3S_2, S(c), CAS_2(T), CA, α-A, tC_2AS, tCA_2	A_3S_2, S(c), CAS_2(H), α-A, tCAS_2(T)	A_3S_2, S(c), C_2AS, CA, CA_2, tCAS_2(T)	A_3S_2, S(c CAS_2(T), CAS_2(H)
1210	A_3S_2, S(c), CAS_2(T), CA_2, α-A, tC_2AS	A_3S_2, S(c), CAS_2(T), α-A	A_3S_2, S(c), C_2AS, CAS_2(T), CA_2, CA_6	A_3S_2, S(c CAS_2(T)
1310	A_3S_2, S(c), CAS_2(T), α-A	A_3S_2, S(c), CAS_2(T), α-A	A_3S_2, S(c), C_2AS, CAS_2(T), CA_6	A_3S_2, S(c CAS_2(T)

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[a] Treatment consisted of placing specimens in a pressure vessel, heating to 310° C in a H_2O-saturated environment, holding for 65 hours, then raising the temperature to 610° C (when saturation temperature of 342° C was reached steam was vented to maintain vapor pressure at 15.0 MPa (2180 psi)), maintaining exposure conditions for 16 hours, cooling to 500° C and venting steam to ambient pressure, and finally allowin specimens to cool to ambient temperature.

[b] Phases determined by x-ray diffraction at ambient temperature; cement notation used A = Al_2O_3, C = CaO, H = H_2O, S = SiO_2, S(c) = cristobalite, (T) = triclinic form, (H) = hexagonal form, t = trace.

[c] A56 is an NBS-prepared medium-alumina castable refractory bonded with high-purity calcium aluminate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3 0.2 wt% Na_2O, 1.9 wt% others and loss on ignition. Concrete batches of 2000 g were dry-mixed to homogeneity; water added slowly to "ball-in-hand" consistency (11.0 %) bars 75 x 15 x 7.5 mm were cast in gang molds with combination of vibration and tam-ing; after casting placed in 95+ % relative humidity at 22°-25° C for 24 hours; bar removed from molds and dried at 110° C for 48 hours.

[d] A50 is an NBS-prepared medium-alumina castable refractory bonded with medium-purity calcium aluminate cement: 50.4 wt% Al_2O_3, 8.4 wt% CaO, 38.4 wt% SiO_2, 1.1 wt% Fe_2O_3 0.1 wt% Na_2O, 1.6 wt% others and loss on ignition. Specimens prepared as were thos of A56 except that casting water was 12.5 %.

[e] Untreated specimens were heated to the test temperature at ∿5° C/min and held at temperature for 15 hours. Treated specimens were subjected to the hydrothermal treatment described in a and then heated to the test temperature at ∿5° C/min and held at temperature for 15 hours.

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE MINERAL PHASES[b] PRESENT IN CASTABLE REFRACTORIES[23]

Treatment Temperature	Phases Present[b] in Apparent Order of Abundance High-Alumina Castable[c]	Phases Present[b] in Apparent Order of Abundance Medium-Alumina Castable[d]
Ambient Temperature--as prepared	α-Alumina (α-A), CA, CA_2	Mullite (A_3S_2), Cristobalite, α-Alumina (α-A), CA_2, Anorthite (CAS_2), CA, Amorphous Phase
110° C (230° F)	α-A, C_3AH_6, Gibbsite (AH_3)	Cristobalite, A_3S_2, α-A, Gibbsite (AH_3), C_3AH_6, CAS_2
210° C (410° F)	α-A, Boehmite (AH), C_3AH_6, $C_4A_3H_3$ (trace)	Cristobalite, A_3S_2, Boehmite (AH), α-A, C_3AH_6, CAS_2, $C_4A_3H_3$
310° C (590° F)		A_3S_2, Cristobalite, α-A, AH, $C_4A_3H_3$, CAS_2, C_3AH_6
350° C (662° F) 375° C (707° F)	α-A, $C_4A_3H_3$	
410° C (770° F) 510° C (950° F)	α-A, $C_4A_3H_3$	A_3S_2, Cristobalite, CAS_2, α-A, Tridymite

[a] Treatment consisted of sealing specimens in a pressure chamber with water and raising the temperature to produce high-pressure steam, holding the temperature for 20 hours, allowing the vessel to cool to ambient temperature, and air-drying the specimens for 24 hours.

[b] Mineral phases determined at ambient temperature by x-ray diffraction; cement notation used in table: A = Al_2O_3, C = CaO, H = H_2O, S = SiO_2.

[c] Refractory is a high-purity (95%) tabular alumina bonded with calcium aluminate cement (Castolast G).

[d] Refractory is a medium-purity (55%) alumina, calcined flint clay, mullite bonded with calcium aluminate cement (Lo-Abrade).

EFFECT OF STEAM-CARBON DIOXIDE ATMOSPHERE[a] ON THE MINERAL PHASES[b] OF HIGH-ALUMINA CASTABLE REFRACTORY[c] [23]

Test Temperature °C	Test Pressure MPa	Test Time Hours	Mineral Phases Present[b]
Ambient	Ambient	0 (control)	α-Alumina (α-A), CA_2, CA
110	0.1	90	α-Alumina (α-A), Gibbsite (AH_3), C_3AH_6, CA_2, CA, β-Alumina (β-A)
210	0.8	90	α-Alumina (α-A), Boehmite (AH), CA_2, $CaCO_3$, β-Alumina (β-A), CA
310	2.4	90	α-Alumina (α-A), Boehmite (AH), $CaCO_3$, CA_2, CA
410	4.0	90	α-Alumina (α-A), $CaCO_3$, Boehmite (AH), CA, β-Alumina (β-A), CA_2
510	3.9	90	α-Alumina (α-A), $CaCO_3$, Boehmite (AH), β-Alumina (β-A), Gibbsite (AH_3), CA_2
610	6.9	42	α-Alumina (α-A), Boehmite (AH), $CaCO_3$, Gibbsite (AH_3), CA_2, β-Alumina (β-A)
710	2.4	90	α-Alumina (α-A), CA_2, $CaCO_3$, Boehmite (AH), β-Alumina (β-A)
910	4.5	90	α-Alumina (α-A), CA_2, Boehmite (AH), $CaCO_3$, β-Alumina (β-A)

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[a] Refractory was exposed to 70% H_2O-30% CO_2 atmosphere in a pressure vessel which was charged with the gases so that the calculated amounts of H_2O and CO_2 at ambient temperature would provide a pressure of 7 MPa (∿1000 psi) at the test temperature; the actual monitored pressure proved to be substantially less than 7 MPa most of the time.

[b] Mineral phases determined by x-ray diffraction; cement notation used: A = Al_2O_3, C = CaO, H = H_2O.

[c] Refractory is an NBS-prepared high-alumina castable bonded with calcium aluminate cement: 94.4 wt% Al_2O_3, 4.5 wt% CaO, 0.1 wt% SiO_2, 0.1 wt% Fe_2O_3, 0.2 wt% Na_2O.

EFFECT OF EXPOSURE TO VARIOUS GASES AND CONDITIONS ON THE MINERAL PHASES PRESENT IN A MEDIUM-ALUMINA REFRACTORY[a] [23]

Gas Environment	Temperature °C	Pressure MPa (psi)	Time h	Mineral Phases Present[b]
Control, fired for 5 hr at 1000°C				S_c, A_3S_2, α-A, CA_2, CA, CAS_2(T)
Carbon dioxide	610	(1000)	65	S_c, A_3S_2, α-A, CA_2, CA, CAS_2(T)
50% CO_2 and 50% H_2O	610	(1000)	20	S_c, A_3S_2, α-A, CAS_2(T), $C\bar{C}$(tr), S_t(tr)
50% CO_2 and 50% H_2O	610	(1000)	165	S_c, A_3S_2, α-A, CAS_2(T), $C\bar{C}$(tr), S_t(tr)
Control				A_3S_2, S_c, CA, α-A, CAS_2(T,tr), CA_2(tr)
Steam[c]	400 620	2.07 4.14	17 100	A_3S_2, S_c, CAS_2(T)[d], α-A, CA(tr)
Control				A_3S_2, S_c, α-A, CA_2, CAS_2
70% H_2O and 30% CO_2[e]	510	7.5	90	A_3S_2, S_c, α-A, CAS_2, CA_2
	510	15.0	90	A_3S_2, S_c, CAS_2, α-A, CA_2
	710	7.5	90	A_3S_2, S_c, CAS_2, α-A, CA_2(tr), S_t(tr)
	710	15.0	90	A_3S_2, S_c, CAS_2, α-A, CA_2(tr), S_t(tr)
	910	7.5	90	A_3S_2, S_c, CAS_2, CA_2(tr), S_t(tr)
	910	15.0	90	A_3S_2, S_c, CAS_2, α-A, CA_2(tr), S_t(tr)

---

[a] An NBS-prepared medium-alumina castable refractory bonded with high-purity calcium aluminate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3, 0.2 wt% Na_2O, 1.9 wt% others and loss on ignition.

[b] Phases identified by x-ray diffraction; cement notation used, A = Al_2O_3, C = CaO, $\bar{C}$ = CO_2, S = SiO_2, S_c = cristobalite, S_t = tridymite, T = triclinic, tr = trace.

[c] The pressure chamber was initially evacuated and 150 ml water was metered into the chamber; the chamber was then heated and held at the temperatures and pressures for the times given which are bracketed together; phases determined after the total 117 hour exposure.

[d] This compound only moderately crystallized.

[e] Specimens were first heated in argon at ambient pressure; when temperature equilibrium reached water and carbon dioxide were metered into the chamber; after 90 hour exposure the specimens were cooled to 500°C and the gases slowly vented.

EFFECT OF HEAT TREATMENT ON THE MINERAL PHASES
OF SEVERAL ALUMINA REFRACTORIES[a] [16]

MATERIAL	Phases Present[b]													
Firing Temperature	A_3S_2	α-A	S	CA	CA_2	CA_6	C_2AS	CAH_{10}	C_3AH_6	AH_3	CAS_2	γ-Fe_2O_3	$CaFe_2O_4$	$3CaO.Al_2O_3$·$CaCO_3.11H_2O$
Calcined kaolin/calcium aluminate cement[c]														
25°C	S		S	M	W		M	T						
100	S		S	T	T		M		W	W				
200	S		S	T	T		M		W	W				
400	S		S	T	T		M							
600	S		S	W	T		M							
800	S		S	W	T		M				T			
1000	S		S	T	W		M				T			
1200	M		S		W	W	S				S			
1350	M		S			W					S			
Calcined kaolin/calcium aluminate cement[d]														
25°C	S	S	S	T				T	T	T				
100	S	S	S	T			T		T	T				
200	S	S	S	W	T				T	T				
400	S	S	S	T	T									
600	S	S	S	T	T									
800	S	S	S	T	T		W							
1000	S	S	S	T	T		T				W			
1200	S	S	S		M	T					S			
1350	S	S	S			T					S			
Tabular Al_2O_3/calcium aluminate cement[e]														
25°C		S		W				W	T	W				
100		S		W					W	W				
200		S		W					W	W				
400		S		W										
600		S		W										
800		S		W										
1000		S		T	M	W								
1200		S		M		W								
1350		S			W	M								
50% Al_2O_3 insulating castable[f]														
25°C	S	M	M	W	T			T	T			W	T	T
100	S	M	M	W	T			T	T	T		W	T	T
200	S	M	M	T	T					T		T	T	
400	S	M	M	T	T							T	T	
600	S	M	M	T	T							W	T	
800	S	S	M	T	T							W	T	
1000	S	M	M	T	W							T	W	
1200	S	S	S		T	T					T	M	T	

---

[a] Samples were cast, vibrated one minute, cured sealed in plastic 24 hr at ambient temperature, cured in air 24 hr at 100°C, fired at 60°C/hr to 200°, 400°, 600°, 800°, 1000°, 1200°, and 1350°, and soaked at temperature 5 hr, furnace cooled to ambient temperature.

[b] Identity and relative quantity of compounds present determined by x-ray diffraction analysis; cement notation used-- A = Al_2O_3, C = CaO, H = H_2O, S = SiO_2; relative quantity indicated by S = strong, M = medium, W = weak, T = trace.

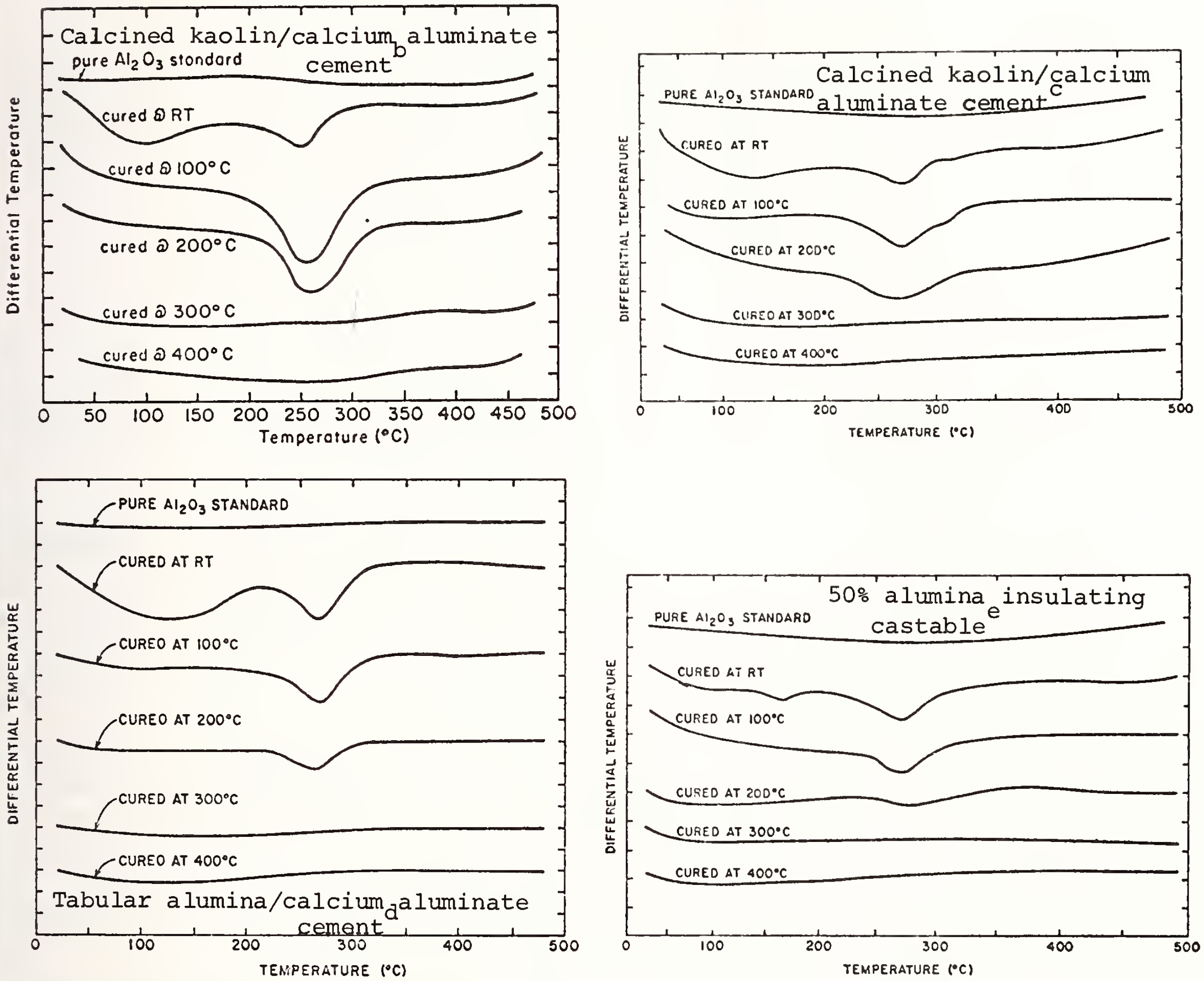
[c] 75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement), water added to ball-in-hand consistency, 13.5% of aggregate and cement.

[d] 75% Mulcoa M-47 aggregate, 25% CA-25 (Alcoa), water to ball-in-hand consistency, 11.3% of aggregate and cement.

[e] 75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-hand consistency, 10.4% of aggregate and cement.

[f] Litecast 75-28 (General Refractories), a lightweight insulating castable, calcium aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF HEAT TREATMENT ON THE STABILITY[a] OF CHEMICAL PHASES PRESENT IN SEVERAL ALUMINA REFRACTORIES[16]



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[a] Determined by differential thermal analysis, samples heated at 5 °C/minute.

[b] 75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement), water added to ball-in-hand consistency, 13.5% of aggregate and cement.

[c] 75% Mulcoa M-47 aggregate, 25% Calcium Aluminate Cement CA-25 (Alcoa), water to ball-in-hand consistency, 11.3% of aggregate and cement.

[d] 75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-hand consistency, 10.4% of aggregate and cement.

[e] Litecast 75-28 (General Refractories), a lightweight insulating castable, calcium aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF STEAM ON THE MINERAL PHASES[a] OF A CALCIUM ALUMINATE CEMENT[b][24]

Temperature °C	Pressure psig	Time hr	Mineral Phases Present[a]
25	ambient	0	CA_2, small amounts of α-A, CA
93	10	20	CA_2 (intensities greatly reduced), C_3AH_6 and AH_3 present as minor phases
110	15	46	C_3AH_6, AH_3, AH, α-A, CA_2(tr)
210	200	4	C_3AH_6, AH, α-A (tr)
210	150	3	C_3AH_6, AH (crystallinity of AH improved)
210	150	15	C_3AH_6, AH (AH well crystallized)
210	150	7	C_3AH_6, AH (both major phases), α-A (minor phase)
100	15	3	no change
365	1100	15	$C_4A_3H_3$, AH (both major phases), α-A (minor phase)
310	970	6	no change
410	1130	2	no change
410	1120	14	$C_4A_3H_2$, α-A, AH (all major phases; AH dissociating)
410	1120	8	$C_4A_3H_3$, α-A, AH (all major phases; AH dissociating, α-A increasing)
450	1130	1	no change
450	1130	1	no change
450	1130	1	no change
475	1130	1	CA_2, CA, $C_4A_3H_3$, α-A (all major phases), AH(tr)
475	1130	15	CA_2, CA, $C_4A_3H_3$, α-A (all major phases), CA_2 increasing
500	1075	3	no change
550	1100	4	CA_2, CA, a-A (all major phases), CA_2 increasing
575	1100	22	CA_2, CA, α-A
600	1030	1	CA_2, CA, α-A (CA_2 increasing at the expense of α-A, and CA)
600	1030	3	no change
600	1050	15	CA_2 (major phase), α-A (minor phase)
700	1000	3	no change
800	1000	16	CA_2, α-A(tr)
900	1060	1	no change
1000	1000	1	no change

---

[a] Specimen was subjected to steam in a pressure vessel constructed so as to permit *in situ* examination of specimens and identification of compounds by energy dispersive x-ray diffraction; EDXD patterns were taken at the various pressures and temperatures without removing the specimen from the environment.

[b] Neat high-purity calcium aluminate cement (CA-25, Alcoa) dried at 110°C and fired at 1010°C for 5 hours.

DISINTEGRATION OF SOME FE-DOPED REFRACTORIES DUE TO EXPOSURE TO CARBON MONOXIDE-CONTAINING ATMOSPHERES UNDER VARYING PRESSURES AT 500°C[27]

Exposure Conditions	DOE 90 generic castable[a]	DOE 50% Al_2O_3 castable[b]	DOE 90% Al_2O_3 ramming mix[c]
Pressure: 600 psi Atmosphere: carbon monoxide Time: 100 hr	Undoped samples turned gray from uniform carbon deposition, such deposition not seen at atmospheric pressure. At a doping level of 0.5 wt% Fe total disintegration occurred.	Carbon deposition in the undoped samples was not uniform and serious degradation was observed. Carbon tends to form balls increasing local strains and bringing on spalling damage. Small amounts of Fe dopant causes complete destruction.	Undoped samples showed no significant degration of strength and no apparent accelerated carbon deposition. Samples doped with 0.5 wt% Fe suffered complete disintegration whereas samples doped with 1.0 wt% Fe suffered a small amount of spalling and no measurable strength degradation.
Pressure: 200 psi Atmosphere: carbon monoxide Time: 100 hr	Carbon deposition on the undoped samples was not as great as at 600 psi. All Fe-doped samples completely disintegrated.	Carbon deposition on the undoped samples was not as great as at 600 psi. All Fe-doped samples completely disintegrated.	Undoped samples showed no carbon deposition. All Fe-doped samples completely disintegrated.
Pressure: 200 psi Atmosphere: 80% carbon monoxide-20% water Time: 100 hr	All samples were doped with 0.5 wt% Fe, and all completely disintegrated.	All samples were doped with 0.5 wt% Fe, and all completely disintegrated.	All samples were doped with 0.5 wt% Fe. Samples survived exposure with a small loss of strength.
Pressure: 500 psi Atmosphere: 80% carbon monoxide-20% water Time: 100 hr	All samples completely disintegrated when doped at the 0.5 wt% Fe level.	All samples completely disintegrated when doped at the 0.5 wt% Fe level.	All samples completed disintegrated when doped at the 0.5 wt% Fe level.
Pressure: atmospheric Atmosphere: mixed gas[d] Time: 1000 hr	Undoped as well as samples doped with 0.5, 1.0, and 2.0 wt% Fe showed no signs of disintegration.	Undoped as well as samples doped with 0.5, 1.0, and 2.0 wt% Fe showed no signs of disintegration.	Undoped as well as samples doped with 0.5 and 1.0 wt% Fe and with 1.0 wt% Fe_2O_3 showed no signs of disintegration.

[a] DOE 90 generic castable: 65 wt% tabular alumina (25 wt% 6 to 10 mesh, 20 wt% 10 to 20 mesh, 20 wt% less than 20 mesh), 10 wt% calcined alumina (less than 325 mesh), 25 wt% calcium aluminate cement (Casting Grade CA-25 cement), all Alcoa materials. Materials were dry mixed for 2 min, then water added with continued mixing to ball-in-hand consistency (∿605 ml); refractory then poured into 2 in x 2 in x 2 in aluminum molds, vibrated for 5 min, sealed in plastic for 24 hr, then fired for 5 hr in air at 1100°C.

[b] DOE generic castable: 75 wt% calcined kaolin (25 wt% 6 to 10 mesh, 20 wt% 10 to 20 mesh, 15 wt% less than 20 mesh, 20 wt% less than 200 mesh), 25 wt% calcium aluminate cement (Casting Grade CA-25, Alcoa). Samples were prepared as described in footnote a except that the water used was ∿700 ml.

[c] DOE generic ramming mix: 82 wt% tabular alumina (30 wt% 6 to 10 mesh, 20 wt% 10 to 20 mesh, 15 wt% less than 20 mesh, 17 wt% less than 48 mesh), 15 wt% calcined alumina (less than 325 mesh), 3 wt% bentonite; to this was added 1 wt% hydrated alumina, 6 wt% phosphoric acid (85%), and 0.25 wt% water. Dry materials were mixed and then hand mixed in plastic bags with the liquids; mixture was aged for 18 hr; samples formed by die pressing at 500 psi, curing at 250 °C in air for 12 hr, then firing at 1100 °C for 5 hr.

[d] Simulated coal gasification atmosphere: 14% CO, 5% CO_2, 45% H_2, 17% H_2O, 17% CH_4, 0.1% H_2S.

[Note: Top line of next to last paragraph in last column of table should read "All samples completely".]

RELATIVE CORROSION RESISTANCE OF REFRACTORIES EXPOSED[a] TO SLAG ATTACK[32]

Average Slag Composition During Test -- wt % Exposure Time 200 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O/K_2O	TiO_2	SO_3	P_2O_5	V_2O_5
47.8	22.4	12.8	9.6	4.5	3.2	0.8	0.01	0.09	0.04

Refractory Material	Brand Name Manufacturer	Maximum Depth[b] of Removal, mm
Al_2O_3(99), brick	99 AD A. P. Green	16
Al_2O_3(99), fused cast brick	Monofrax A2 Carborundum	3
Al_2O_3(95)-CaO(5), castable	B&W Kao-Tab CS Babcock & Wilcox	27
Al_2O_3(94)-CaO(5), castable	Purotab Kaiser Refractories	24
Al_2O_3(93)-P_2O_5(6), castable	B&W Kao Phos 30 Babcock & Wilcox	20
Al_2O_3(90)-SiO_2(9), brick	Greenal-90 A. P. Green	10
Al_2O_3(91)-SiO_2(8), brick	Kricor Kaiser Refractories	12
Al_2O_3(91)-SiO_2(8), brick	Korundal XD Harbison-Walker	7
Al_2O_3(89)-Cr_2O_3(10), brick	CS 612 Kaiser Refractories	5
Al_2O_3(84)-SiO_2(9)-P_2O_5(4), brick	Chemal 85 B C. E. Refractories	7
Cr_2O_3(40)-Fe_2O_3(23)-Al_2O_3(21)-MgO(10), ramming mix	Kemram C. E. Refractories	21
MgO(53)-Cr_2O_3(20)-Al_2O_3(17)-Fe_2O_3(8), brick	Dibond 50 General Refractories	8
MgO(59)-Cr_2O_3(19)-Al_2O_3(13)-Fe_2O_3(7), brick	GR-200 General Refractories	7
MgO(64)-Cr_2O_3(15)-Al_2O_3(13)-Fe_2O_3(6), brick	Nucon 60 Harbison-Walker	7
Cr_2O_3(80)-MgO(8)-Fe_2O_3(6), fused cast brick	Monofrax E Carborundum	$\sim$0

(Table Continued)

RELATIVE CORROSION RESISTANCE OF REFRACTORIES EXPOSED[a] TO SLAG ATTACK[32]

(Table Continued)

Average Slag Composition During Test -- wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O/K_2O	TiO_2	SO_3	V_2O_5
27.0	15.5	37.3	9.0	7.7	0.5-1.5	0.34	0.04	0.03

Refractory Material	Brand Name Manufacturer	Maximum Depth[b] of Removal, mm
$Al_2O_3(99)$, brick	99 AD A. P. Green	57
$Al_2O_3(99.5)$, brick	Alundum Norton	∿25
$Al_2O_3(90)-Cr_2O_3(10$, brick	CS 612 Kaiser	∿10
$MgO(53)-Cr_2O_3(20)-Al_2O_3(17)-Fe_2O_3(8)$, brick	Dibond 50 General Refractories	∿5
$MgO(59)-Cr_2O_3(19)-Al_2O_3(13)-Fe_2O_3(7)$, brick	GR-200 General Refractories	∿5
$SiC(79)-Si_3N_4(18.5)$, brick	Refrax 20 Carborundum	64
$SiC(73)-Al_2O_3(14)-SiO_2(11)$, brick	Harbide Harbison-Walker	64
$Al_2O_3(85)-SiO_2(9)-P_2O_5(4)$, brick	Chemal 85 B C. E. Refractories	64
$Al_2O_3(93)-P_2O_5(1)$, castable	-- Pryor-Giggey	33
$Al_2O_3(81)-Cr_2O_3(10)-P_2O_5(7)$, ramming mix	I-75 Harbison-Walker	18
Al_2O_3(Winnofos Bond), brick	ICI-B Imperial Chemical	56
$Al_2O_3(99)-Na_2O(0.5)$, brick	Monofrax A1 Carborundum	19
$Al_2O_3(99)-B_2O_3(0.5)$, brick	Monofrax A2 Carborundum	22
$Cr_2O_3(80)-MgO(8)-Fe_2O_3(6)$, fused cast brick	Monofrax E Carborundum	∿0
$Al_2O_3(80)$, brick	SR 504C Corhart Refractories	17

(Table Continued)

RELATIVE CORROSION RESISTANCE OF REFRACTORIES EXPOSED[a] TO SLAG ATTACK[32]

(Table Continued)

Average Slag Composition During Test -- wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	Cr_2O_3	MgO	Na_2O	K_2O	TiO_2	SO_3	V_2O_5
25.9	27.0	30.7	8.7	0.4	3.0	1.0	1.0	0.4	0.03	<0.01

Refractory Material	Brand Name Manufacturer	Maximum Depth[b] of Removal, mm
$MgO(53)-Cr_2O_3(20)-Al_2O_3(17)-Fe_2O_3(8)$, brick	Dibond 50 General Refractories	11.4
$MgO(59)-Cr_2O_3(19)-Al_2O_3(13)-Fe_2O_3(7)$, brick	GR-200 General Refractories	8.1
$MgO(64)-Cr_2O_3(15)-Al_2O_3(13)-Fe_2O_3(6)$, brick	Nucon 60 Harbison-Walker	11.4
$MgO(63)-Cr_2O_3(18)-Al_2O_3(5)-Fe_2O_3(12)$, brick	Guidon Harbison-Walker	5.8
$MgO(63)-Cr_2O_3(17)-Al_2O_3(10)-Fe_2O_3(9)$, brick	Krilex 621 Kaiser Refractories	8.9
$Al_2O_3(90)-Cr_2O_3(10)$, brick	Ruby Harbison-Walker	10.7
$Al_2O_3(81)-Cr_2O_3(17)$, brick	852Z (Serv-M) Taylor Refractories	14.5
$Al_2O_3(68)-Cr_2O_3(32)$, brick	TS 1290 Union Carbide	16.0
$Si_2ON_2(70)-Si_3N_4(20)-SiC(10)$, brick	Sioxyn Norton	62.7
$Al_2O_3(92)-SiO_2(8)$, brick	Kricor Kaiser Refractories	35.6
$Al_2O_3(56)-SiO_2(27)-ZrO_2(16)$, brick	ZRX Taylor	73.7
MgO, Al_2O_3, brick	Experimental Spinel Taylor	22.9
$Al_2O_3(21)-Cr_2O_3(40)-Fe_2O_3(23)$, ramming mix	Kemram C. E. Refractories	11.4
$Al_2O_3(98)$, brick	SR 504C Corhart Refractories	19.6
$Cr_2O_3(80)-MgO(8)-Fe_2O_3(6)$, fused cast brick	Monofrax E Carborundum	1.9
$Al_2O_3(50)-ZrO_2(34)-SiO_2(14)$, fusion cast brick	Monofrax R Carborundum	73.7

(Table Continued)

RELATIVE CORROSION RESISTANCE OF REFRACTORIES EXPOSED[a] TO SLAG ATTACK[32]

(Table Continued)

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[a] Exposure to slag attack took place in a 24-in diameter, 13-in high furnace. Test specimens were 9-in x 4.5-in x 3.2-in brick wedges mounted around the circumference of the vessel with the small end of the brick exposed to the slag. Most specimens were manufacturer-supplied bricks. Some ramming mixes and castables were tested; these were formed in a mold, dried, and prefixed in situ to 1500 °C prior to adding the slag. The furnace was fired with natural gas, air, and oxygen to a temperature ∿1500 °C. Oxygen partial pressure was maintained at 10^{-2} to 10^{-3} Pa by adjusting the ratio of the three component gases. The furnace cavity was changed with up to 75 kg of synthetic slag. Some rotary motion of the slag was achieved by the tangential impingement of the flames from three burners on the surface of the melt. Wet chemical analyses were performed on samples of slag drawn at intervals of 100 hr or less during the course of the tests. The slag compositions given in the table are the average values.

[b] Depth is measured from the original hot face.

RELATIVE CORROSION RESISTANCE OF WATER-COOLED REFRACTORIES EXPOSED[a] TO SLAG ATTACK[32]

Refractory Material	Brand Name Manufacturer	Maximum Depth[b] of Removal, mm

Average Slag Composition During Test -- Wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	FeO	MgO	Na_2O	K_2O	TiO_2
38.9	19.4	21.7	2.9	8.8	5.5	1.1	1.0	1.0

SiC(90)-Si_2ON_2(9), brick	Crystolon 63 Norton	3-4
SiC(73)-Al_2O_3(14)-SiO_2(11), brick	Harbide Harbison-Walker	4-7
SiC(75)-Si_3N_4(23), brick	Refrax 20 Carborundum	4-5
Si_2ON_2(70)-Si_3N_4(20)-SiC(10), brick	Sioxyn Norton	47-52

Average Slag Composition During Test -- Wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	FeO	MgO	Na_2O	K_2O	TiO_2	Cr_2O_3
39.5	16.3	24.0	0.4	6.6	6.4	1.4	0.8	1.0	0.1

MgO(53)-Cr_2O_3(20)-Al_2O_3(17)-Fe_2O_3(8)-SiO_2(2)-CaO(1), brick	Dibond 50 General Refractories	8
MgO(59)-Cr_2O_3(19)-Al_2O_3(13)-Fe_2O_3(7)-SiO_2(1.5)-CaO (0.5), brick	GR-200 General Refractories	8
MgO(63)-Cr_2O_3(18)-Al_2O_3(5)-Fe_2O_3(12)-SiO_2(1)-CaO(1), brick	Guidon Harbison-Walker	8
MgO(60)-Cr_2O_3(15.5)-Al_2O_3(15)-Fe_2O_3(7)-SiO_2(1.5)-CaO (1), brick	Krilex 911 Kaiser Refractories	17

Average Slag Composition During Test -- Wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	FeO	MgO	Na_2O	K_2O	TiO_2
39.4	17.1	25.8	2.8	4.9	6.4	1.3	1.0	1.1

Al_2O_3(91.6)-SiO_2(8.0)-Fe_2O_3(0.15)-Alkali(0.15), brick	Kricor Kaiser Refractories	10
Al_2O_3(83.9)-SiO_2(9.0)-Fe_2O_3(1.0)-TiO_2(2.3)-P_2O_5(3.6), brick	Chemal 85 B C. E. Refractories	17
Al_2O_3(89.7)-Cr_2O_3(10.0)-SiO_2(0.1)-Fe_2O_3(0.1)-Alkali (0.1), brick	Ruby Harbison-Walker	7
Al_2O_3(81.1)-Cr_2O_3(16.6)-P_2O_5(0.8)-SiO_2(0.5)-Fe_2O_3(0.5) -Na_2O (0.5), brick	852Z (Serv-M) Taylor Refractories	9

(Table Continued)

RELATIVE CORROSION RESISTANCE OF WATER-COOLED REFRACTORIES EXPOSED[a] TO SLAG ATTACK[32] (Table Continued)

Average Slag Composition During Test -- Wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	FeO	Fe	MgO	Na_2O	K_2O	TiO_2
38.4	20.4	28.8	1.3	4.9	1.0	2.8	0.6	0.4	1.0

Refractory Material	Brand Name Manufacturer	Maximum Depth[b] of Removal, mm
Cr_2O_3(39.6)-Al_2O_3(21.4)-Fe_2O_3(22.6)-MgO(9.6)-SiO_2(2.5)-TiO_2(0.6)-P_2O_5(3.7), Ramming Mix	Kemram C. E. Refractories	2
Al_2O_3(85.2)-Cr_2O_3(9.7)-SiO_2(1.9)-Fe_2O_3(0.5)-Na_2O(0.4)-P_2O_5(2.3), Ramming Mix	Shamrock 888 Taylor Refractories	3
Al_2O_3(89.5)-SiO_2(6.0)-Alkali(0.2)-P_2O_5(3.7)-Other(0.6), Ramming Mix	Brikram 90R General Refractories	8
Al_2O_3(89.6)-MgO(3.4)-SiO_2(0.7)-P_2O_5(6.2)-Alkali(0.1), Ramming Mix	Resco Cast AA-22 Resco	8
Al_2O_3(95)-SiO_2(0.2)-Na_2O(0.2)-Fe_2O_3(0.05)-P_2O_5(4.55), Ramming Mix	Lavalox X-95 Lava Crucible	10
Al_2O_3(67)-Cr_2O_3(32), brick	LT5 Union Carbide	2

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Average Slag Composition During Test -- Wt % Exposure Time 1000 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	FeO	Fe	MgO	Na_2O	K_2O	TiO_2
36.9	17.4	29.2	2.8	3.2	0.4	7.3	1.4	0.8	0.6

Al_2O_3(60)-Cr_2O_3(27)-MgO(6)-Fe_2O_3(4)-SiO_2(2), fused cast brick	Monofrax K-3 Carborundum	4
Cr_2O_3(80)-MgO(8)-Fe_2O_3(6)-Al_2O_3(5)-SiO_2(1), fused cast brick	Monofrax E Carborundum	2
SiC(75)-Si_3N_4(23), brick	Refrax 20 Carborundum	38
SiC(73)-Al_2O_3(14)-SiO_2(11), brick	Harbide Harbison-Walker	36
SiC(90)-Si_2ON_2(9), brick	Crystolon 63 Norton	32
Al_2O_3(91.6)-SiO_2(8.0)-Fe_2O_3(0.15)-Alkali(0.15), brick	Kricor Kaiser Refractories	46

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(Table Continued)

RELATIVE CORROSION RESISTANCE OF WATER-COOLED REFRACTORIES EXPOSED[a] TO SLAG ATTACK [32] (Table Continued)

Average Slag Composition During Test -- Wt % Exposure Time 500 hr

SiO_2	Al_2O_3	CaO	Fe_2O_3	FeO	Fe	MgO	Na_2O	K_2O	TiO_2
24.4	15.5	39.0	4.2	9.0	1.0	5.7	<0.1	<0.1	1.0

Refractory Material	Brand Name Manufacturer	Maximum Depth[b] of Removal, mm
Al_2O_3(89.7)-Cr_2O_3(10), brick	CS 612 Kaiser Refractories	10
Al_2O_3(81.1)-Cr_2O_3(16.6)-P_2O_5(0.8)-SiO_2(0.5)-Fe_2O_3(0.5)-Na_2O (0.5), brick	852Z (Serv-M) Taylor Refractories	3
Al_2O_3(92)-Cr_2O_3(7.5)-SiO_2(0.5), brick	AR90 Findlay	21
Al_2O_3(84.5)-Cr_2O_3(10.5)-SiO_2(0.2), brick	86B Lava Crucible	10
MgO(63)-Cr_2O_3(18)-Fe_2O_3(12)-Al_2O_3(5)-SiO_2(1)-CaO(1), brick	Guidon Harbison-Walker	4
MgO(60)-Cr_2O_3(15.5)-Al_2O_3(15)-Fe_2O_3(7)-SiO_2(1.5)-CaO(1), brick	Krilex 911 Kaiser Refractories	4
MgO(55)-Cr_2O_3(20)-Al_2O_3(8)-FeO(11)-SiO_2(2.5)-CaO(0.5)-TiO_2(1.5), brick	Corhart RFG Corhart Refractories	5

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[a] Exposure to slag attack took place in a 24-in diameter, 13-in high furnace. The basic brick test specimens were 9-in x 4.5-in x 3.2-in brick wedges mounted around the circumference of the vessel with the small end of the brick exposed to the slag. Most specimens were manufacturer-supplied brick. Some ramming mixes and castables were tested; these were formed in a mold, dried, and prefired in situ to 1500 °C prior to adding the slag. In performing these tests in which the bricks were water-cooled, the bricks were cut so as to provide three different lengths so that there were different thermal gradients operating. The furnace was fired with natural gas, air, and oxygen to a temperature $\sim$1500°C. Oxygen partial pressure was maintained at 10^{-2} to 10^{-3} Pa by adjusting the ratio of the three component gases. The furnace cavity was charged with up to 75 kg of synthetic slag. Some rotary motion of the slag was achieved by the tangential impingement of the flames from three burners on the surface of the melt. Wet chemical analyses were performed on samples of slag drawn at intervals of 100 hr or less during the course of the tests. The slag compositions given in the table are the average values.

[b] Depth is measured from the original hot face; the values given are for the maximum value found for one of the three bricks of different length for each material, usually for the longest brick.

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c][12]

		Ambient Temp.		1400 °F		Ambient Temp.		1400 °F	
Material (Brand Name)	Exposure[d]	Volume Loss[e]	% Change	Volume Loss[e]	% Change	Rod Penetration[f]	% Change	Rod Penetration[f]	% Change
Two exposures in gasifier off-gas (SYNTHANE); reducing gas, H_2O, CO_2, CO, H_2, H_2S, ash and char (small amounts); ∿1290 °F, 1000 psi, exposure time not given.									
90% Alumina Dense Castable, CA Bond[g] (Castolast G)	U	0.50		0.20		2.0			
	E1	0.85	+70	0.33	+65				
	E2	0.79	+58			1.7	-15		
60% Alumina Dense Castable, CA Bond (Mizzou Castable)	U	1.54		0.63		2.9			
	E1	0.68	-56	0.45	-29				
	E2	0.80	-48			1.02	-65		
90+% Alumina Light Castable, CA Bond (Purolite 30)	U	17.9		24.7					
	E1	disintegrated, could not be tested							
90+% Alumina Light Castable, CA Bond (Greencast-97L)	U	6.48		4.18					
	E1	7.04	+ 8.6	5.01	-20				
60% Alumina Dense Castable, CA Bond (Super Brikcast A)	U	2.67				4.6			
	E2	0.58	-78			1.14	-75		
55% Alumina Lightweight Insulating Castable, CA Bond (Litecast 75-28)	U	4.11		4.42		7.9			
	E1	7.13	+73	7.07	-60				
	E2	12.44	+203			19.9	+152		
70% Alumina (Mullite), Vitreous Bond, Fired Brick (Mul-8)	U	0.70		0.56		1.5			
	E1	0.68	- 2.9	0.61	+ 8.9				
	E2	0.59	-15			0.69	-54		
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U	0.28		0.14		0.9			
	E1	0.33	+18	0.24	+71				
	E2	0.37	+32			0.71	-21		
90+% Alumina, Self Bonded Dense Fired Brick (Kricor)	U	0.61		0.38		1.5			
	E1	0.79	+30	0.56	+47				
	E2	0.80	+31			1.44	- 4.0		
99+% Alumina, Self Bonded, Dense Fired Brick (H-W Corundum)	U	0.94		0.45		2.4			
	E1	0.78	-17	0.65	+44				
	E2	1.13	+20			1.54	-36		
77% Alumina Vitreous Bond Light Insulating Fired Brick (B&W Insalcor)	U	4.83		4.03					
	E1	14.2	+194	10.4	+158				
98+% Alumina, Self Bonded Light Insulating Fired Brick (Alfrax B 101)	U	4.37		3.12					
	E1	9.09	+108	5.12	+64				
99+% Alumina, Self Bonded Fused-Cast Dense Brick (Monofrax A)	U	0.36		0.17		2.4			
	E1	0.33	- 8.3	0.10	-41				
	E2	0.22	-39			0.77	-68		
Silicon Carbide Silicon Nitride Bonded, Dense Fired Brick (Refrax 20)	U	0.13		0.14					
	E1	8.98	+6808	[h]					
	E2	2.86	+2200			4.3	+378		
Alumina-Zirconia-Silica Fused-Cast Brick	U	0.04				0.7			
	E2	0.50	+1150			0.89	+27		
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U	0.48				2.1			
	E2	0.66	+38			0.71	-66		
Refired Ufala TI[i]	E2	0.57	+19			1.22	-42		
45-50% Alumina, Vitreous Bond, High Fired Super-duty Brick (KX-99)	U	0.70				1.9			
	E2	0.79	+13			0.97	-49		
Refired KX-99[i]	E2	0.67	- 4.3			2.0	+ 5.3		
60% Alumina Phosphate Bonded Ramming Mix (Wasp #60)	U	2.69		1.01					
	E1	2.00	-26	1.76	+68				
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	1.19		0.34		2.6			
	E1	1.05	-12	0.35	+ 2.9				
	E2	0.79	-34			1.9	-27		

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c] [12]

(Table Continued)

Material (Brand Name)	Exposure[d]	Ambient Temp.		1400 °F		Ambient Temp.		1400 °F	
		Volume Loss[e]	% Change	Volume Loss[e]	% Change	Rod Penetration[f]	% Change	Rod Penetration[f]	% Change
Two exposures in gasifier off-gas (SYNTHANE); reducing gas, H_2O, CO_2, CO, H_2, H_2S, ash and char (small amounts; ~1290 °F, 1000 psi, exposure time not given. (exposure data continued)									
52% Alumina Light Castable, CA Bond (Litecast 80)	U	7.38		4.18					
	E1	14.6	+98	13.9	+233				
70% Alumina, Vitreous Bond Fired Brick (Hi Lumite 70 D)	U	1.98		1.07					
	E1	h		h					
85% Alumina Phosphate Bonded Fired Brick (Altex 85-B)	U	0.22		--		1.1			
	E1	0.45	+105	0.31					
	E2	0.42	+91			2.1	+91		
80+% Alumina Phosphate Bonded Fired Brick (Alumex P-8)	U	0.33		--		1.1			
	E1	0.66	+100	0.41					
	E2	0.51	+55			1.2	+ 9.1		
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00		0.35		2.2			
	E1	0.94	-6.0	0.45	+29				
	E2	1.32	+32			2.2	0		
Silicon Carbide Silicon Oxynitride Bond Brick (Crystolon 63)	U	0.31				1.2			
	E2	3.78	+1119			1.80	+50		
73% Alumina Phosphate Bonded Dense Ramming Mix (Blu Ram)	U	1.32				2.06			
	E2	0.79	-53			1.25	-39		
73% Alumina Phosphate Bonded Dense Ramming Mix (Blu Ram H.S.)	U	1.34				1.74			
	E2	1.68	+25			2.44	+40		
One exposure in the fluidized bed of the gasifier (SYNTHANE); reducing gas as in above, plus coal fines, ash and char; 1800 °F, 1000 psi, exposure time not given									
90% Alumina Dense Castable CA Bond (Castolast G)	U	0.50				2.0			
	E	0.53	+ 6.0			1.0	-50		
60% Alumina Dense Castable, CA Bond (Mizzou Castable)	U	1.54				2.9			
	E	0.33	-79			0.9	-69		
90+% Alumina Light Castable, CA Bond (Greencast-97L)	U	6.48				11.2			
	E	3.31	-49			9.2	-18		
60% Alumina Dense Castable, CA Bond (Super Brikcast A)	U	2.67				4.6			
	E	0.49	-82			0.7	-85		
55% Alumina Lightweight Insulating Castable, (Litecast 75-28)	U	4.11				7.9			
	E	3.36	-18			21.6	+173		
70% Alumina (Mullite), Vitreous Bond, Fired Brick (Mul-8)	U	0.70				1.5			
	E	0.47	-33			0.7	-53		
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U	0.28				0.9			
	E	0.32	+14			0.6	-33		
90+% Alumina Self Bonded Dense Fired Brick (Kricor)	U	0.61				1.5			
	E	0.57	- 6.7			0.9	-40		
99+% Alumina, Self Bonded Dense Fired Brick (H-W Corundum)	U	0.94				2.4			
	E	1.04	+11			1.1	-54		
77% Alumina Vitreous Bond Light Insulating Fired Brick (B&W Insalcor)	U	4.83				8.8			
	E	7.36	+52			11.8	+34		

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c] [12]

(Table continued)

		Ambient Temp.		1400 °F		Ambient Temp.		1400 °F	
Material (Brand Name)	Exposure[d]	Volume Loss[e]	% Change	Volume Loss[e]	% Change	Rod Penetration[f]	% Change	Rod Penetration[f]	% Change
One exposure in the fluidized bed of the gasifier (SYNTHANE); reducing gas in above, plus coal fines, ash and char; 1800 °F, 1000 psi, exposure time not given. (exposure data continued)									
98+% Alumina, Self Bonded Light Insulating Fired Brick (Alfrax B 101)	U	4.37				7.2			
	E	4.67	+ 6.9			7.4	+ 2.8		
99+% Alumina, Self Bonded Fused-Cast Dense Brick (Monofrax A)	U	0.36				1.3			
	E	0.26	-28			0.4	-69		
Silicon Carbide Silicon Nitride Bonded Dense Fired Brick (Refrax 20)	U	0.13				0.9			
	E	crumbled				poor specimen			
Zirconium Silicate Brick, Vitreous Bond	U	1.24				2.6			
	E	1.79	+44			2.7	+ 3.8		
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U	0.48				2.1			
	E	0.63	+31			0.7	-67		
45-50% Alumina, Vitreous Bond, High Fired Super-duty Brick (KX-99)	U	0.70				1.9			
	E	0.66	- 5.7			0.9	-53		
60% Alumina Phosphate Bonded Ramming Mix (Wasp #60)	U	2.69				4.1			
	E	2.24	-17			2.4	-41		
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	1.19				2.6			
	E	3.03	+155			0.7	-73		
70% Alumina, Vitreous Bond Fired Brick (Hi Lumite 70 D)	U	1.98				5.0			
	E	3.11	+57			4.0	-20		
85% Alumina Phosphate Bonded Fired Brick (Altex 85-B)	U	0.22				1.1			
	E	0.44	+100			0.4	-64		
80+% Alumina Phosphate Bonded Fired Brick (Alumex P-8)	U	0.33				1.1			
	E	0.53	+61			0.5	-55		
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00				2.2			
	E	1.25	+25			1.4	-36		
Silicon Carbide Silicon Oxynitride Bond Brick (Crystolon 63)	U	0.31				1.2			
	E	poor specimen				poor specimen			
Three exposures in gasifier off-gas (CONOCO, CO_2 Acceptor); 48 H_2, 23 H_2O, 12 CH_4, 8.5 CO, 6 CO_2, 2.5 N_2 (Vol %); 1500 °F, 150 psig, ∿800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3).									
90% Alumina Dense Castable CA Bond (Castolast G)	U	0.50		0.20		0.20		0.17	
	E1	0.56	+12	0.24	+20	0.12	-40	0.07	-59
	E2	0.68	+36	0.47	+135				
	E3	0.89	+78	0.37	+85				
60% Alumina Dense Castable CA Bond (Mizzou Castable)	U	1.54		0.63		0.29		0.13	
	E2	0.76	-51	0.45	-29				
	U	1.54		0.29[j]					
	E3	1.21	-22	0.40	+38				
90+% Alumina Light Castable, CA Bond (Purolite 30)	U	17.9		24.7		1.87		3.48	
	E1	15.9	-11	47.1	+91	2.36	+26	6.67	+92
	E2	31.2	+74	26.9	- 8.9				
90+% Alumina Light Castable, CA Bond (Greencast-97L)	U	6.48		4.18		1.12		0.88	
	E1	3.69	-43	2.20	-47	0.76	-32	0.45	-49
	E2	3.93	-39	3.18	-24				
	E3	6.72	- 3.8	6.83	+63				
60% Alumina Dense Castable, CA Bond (Super Brikcast A)	U	2.67		1.00		0.46		0.39	
	E3	1.01	-58	0.38	-62				

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c] [12]

(Table continued)

		Ambient Temp.		1400 °F		Ambient Temp.		1400 °F	
Material (Brand Name)	Exposure[d]	Volume Loss[e]	% Change	Volume Loss[e]	% Change	Rod Penetration[f]	% Change	Rod Penetration[f]	% Change
Three exposures in gasifier off-gas (CONOCO, CO_2 Acceptor); 48 H_2, 23 H_2O, 12 CH_4, 8.5 CO, 6 CO_2, 2.5 N_2 (Vol %); 1500 °F, 150 psig, ~800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3). (data continued)									
55% Alumina Lightweight Insulating Castable CA Bond (Litecast 75-28)	U	4.11		4.42		0.79		1.00	
	E2	7.29	+77	6.39	+45				
	E3	19.3	+370	15.0	+240				
70% Alumina (Mullite), Vitreous Bond, Fired Brick (Mul-8)	U	0.70		0.56		0.15		0.10	
	E1	0.97	+39	0.52	- 7.1	0.24	+60	0.13	+30
	E2	0.65	- 7.1	0.30	-46				
	E3	0.80	+14	0.55	- 1.8				
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U	0.28		0.14		0.09		0.05	
	E1	0.32	+14	0.17	+21	0.09	0	0.06	+20
	E2	0.57	+104	0.39	+180				
	E3	0.31	+11	0.20	+43				
90+% Alumina, Self Bonded Dense Fired Brick (Kricor)	U	0.61		0.38		0.15		0.14	
	E1	0.76	+24	0.36	- 5.3	0.19	+27	0.09	-36
	E2	0.59	- 3.3	0.33	-15				
99+% Alumina, Self Bonded Dense Fired Brick (H-W Corundum)	U	0.94		0.45		0.24		0.10	
	E1	1.14	+21	0.63	+40	0.27	+13	0.13	+30
	E2	1.09	+16	0.70	+56				
	E3	1.69	+80	0.84	+87				
77% Alumina Vitreous Bond Light Insulating Fired Brick (B&W Insalcor)	U	4.83		4.03		0.88		0.64	
	E1					1.05	+19	1.30	+103
	E2	4.80 (6.15)[k]	- 0.6 (-27)[k]	9.19 (7.86)[k]	+128 +95				
	U	4.83		0.88[j]					
	E3	8.13	+68	6.76	+670				
98+% Alumina, Self Bonded Light Insulating Fired Brick (Alfrax B 101)	U	4.37		3.12		0.72		0.54	
	E1	4.75	+ 8.7	3.71	+19	0.80	+11	1.03	+91
	E2	5.86	+57	6.22	+99				
	E3	4.49	+ 2.7	2.42	-22				
99% Alumina, Self Bonded Fused-Cast Dense Brick (Monofrax A)	U	0.36		0.17		0.13		0.11	
	E1	0.18	-50	0.19	+12	0.10	-23	0.04	-64
	E2	0.33	- 8.3	0.13	-24				
	E3	0.22	-39	0.16	- 0.6				
Silicon Carbide Silicon Nitride Bonded Dense Fired Brick (Refrax 20)	U	0.13		0.14		0.09		0.16	
	E1	0.28	+115	0.14	0	0.13	+44	0.08	-50
	E2	1.89	+1350	1.62	+1150				
	E3	1.03	+760	-					
70% Alumina (Mullite), Vitreous Bond Dense Fired Brick (Alumex 70-HD)	U	1.02		0.48		0.20		0.10	
	E3	1.53	+50	0.55	+16				
Zirconium Silicate Brick, Vitreous Bond	U	1.24		0.70		0.26		0.15	
	E3	2.21	+79	1.52	+120				
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U	0.48		-		0.21		-	
	E3	0.65	+35	0.47	-				
45-50% Alumina, Vitreous Bond, High Fired Superduty Brick (KX-99)	U	0.70		0.35		0.19		0.10	
	E3	0.69	- 1.4	0.43	+23				
60% Alumina Phosphate Bonded Ramming Mix (Wasp #60)	U	2.69		1.01		0.41		0.16	
	E1	specimens cracked							
	E2	1.78	-34	1.47	+75				
	E3	2.38	-12	1.75	+73				
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	1.19		0.34		0.26		0.10	
	E1	specimen cracked							
	E2	0.66	-45	0.51	+50				
	E3	0.84	-29	0.52	+53				
52% Alumina Light Castable, CA Bond (Litecast 80)	U	7.38		4.18		1.19		0.61	
	E1	specimen cracked							
	E2	16.1	+118	36.1	+164				

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c] [12]

(Table continued)

		Ambient Temp.		1400 °F		Ambient Temp.		1400 °F	
Material (Brand Name)	Exposure[d]	Volume Loss[e]	% Change	Volume Loss[e]	% Change	Rod Penetration[f]	% Change	Rod Penetration[f]	% Change
Three exposures in gasifier off-gas (CONOCO, CO_2 Acceptor); 48 H_2, 23 H_2O, 12 CH_4, 8.5 CO, 6 CO_2, 2.5 N_2 (Vol %); 1500 °F, 150 psig, ~800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3). (data continued)									
90+% Alumina Dense Castable, CA Bond (Greencast-97)	U	0.60		0.60		0.24		0.06	
	E1	1.98	+230	1.07	+78	0.31	+29	0.15	+150
70% Alumina, Vitreous Bond Fired Brick (Hi Lumite 70 D)	U	1.98		1.07		0.50		0.16	
	E1	3.43	+173	3.41	+220	0.57	+14	0.43	+169
	E2	1.85	- 6.6	0.76	-29				
85% Alumina Phosphate Bonded Fired Brick (Altex 85-B)	U	0.22		0.26		0.11		0.06	
	E1	0.33	+50	0.23	-12	0.11	0	0.09	+50
80+% Alumina Phosphate Bonded Fired Brick (Alumex P-8)	U	0.33		0.29		0.11		0.08	
	E1	0.38	+15	0.21	-28	0.11	0	-	
	U	0.33		0.30					
	E2	0.55	+67	0.29	- 3.3				
90% Al_2O_3-10% Cr_2O_3 Solid Solution Fired Brick (CS 612)	U	0.49		0.37		0.13		-	
	E1	0.71	+45	0.44	+18	0.14	+ 7.7		
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00		0.35		0.22		0.11	
	E3	2.55	+155	1.81	+420				
Silicon Carbide Silicon Oxynitride Bond Brick (Crystolon 63)	U	0.31		0.21		0.12		0.09	
	E3	1.42	+360	-					
Three exposures in dolomite regenerator (CONOCO CO_2 Acceptor); 70 N_2, 27CO_2, 3CO, H_2S trace (Vol %); 1850 °F, 150 psi, ~800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3)									
90% Alumina Dense Castable CA Bcnd (Castolast G)	U	0.50		0.20		0.20		0.17	
	E1	0.43	-14	0.40	+100	0.16	-20	0.09	-47
	E2	0.56	+12	0.35	+75	0.15	-25	0.08	-53
	E3	0.66	+32	0.24	+20				
60% Alumina Dense Castable CA Bond (Mizzou Castable)	U	1.54		0.63		0.29		0.13	
	E2	4.52	+193	2.52	+300	0.62	+114	0.37	+185
	U	1.54		0.29[j]					
	E3	1.63	+ 5.8	0.76	+160				
90+% Alumina Light Castable, CA Bond (Purolite 30)	U	17.9		24.7		1.87		3.48	
	E1	95.7	+430	fractured		10.7	+472	broke up	
90+% Alumina Light Castable, CA Bond (Greencast-97L)	U	6.48		4.18		1.12		0.88	
	E1	4.11	-37	3.09	-26	0.73	-35	0.52	-41
	E2	6.05	- 6.6	4.19	+ 0.2	0.95	-15	0.73	-17
	E3	13.0	+101	14.4	+240				
60% Alumina Dense Castable, CA Bond (Super Brikcast A)	U	2.67		1.00		0.46		0.39	
	E3	1.34	-50	0.87	-13				
55% Alumina Lightweight Insulating Castable, CA Bond (Litecast 75-28)	U	4.11		4.42		0.79		1.00	
	E2	15.6	+280	13.1	+196	3.25	+311	2.71	+171
	E3	16.3	+300	19.8	+350				
70% Alumina (Mullite), Vitreous Bond, Fired Brick (Mul-8)	U	0.70		0.56		0.15		0.10	
	E1	0.61	-13	0.24	-57	0.18	+20	0.07	-30
	E2	0.49	-30	0.32	-43	0.11	-27	0.07	-30
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U	0.28		0.14		0.09		0.05	
	E1	0.33	+18	0.12	-14	0.08	-11	0.02	-60
	E2	1.08[l]	+290	0.42[l]	+200	0.17[l]	+89	0.09[l]	+80
	E3	0.48	+71	0.47	+240				
90+% Alumina, Self Bonded Dense Fired Brick (Kricor)	U	0.61		0.38		0.15		0.14	
	E1	0.64	+ 5.0	0.28	-26	0.15	0	0.08	-43
	E3	0.47	-23	0.19	+50				
99+% Alumina, Self Bonded Dense Fired Brick (H-W Corundum)	U	0.94		0.45		0.24		0.10	
	E1	1.43	+52	0.77	+71	0.28	+17	0.18	+80
	E2	1.02	+ 8.5	0.27	-40	0.24	0	0.08	-20
	E3	1.24	+32	0.56	+24				

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c] [12]

(Table continued)

Material (Brand Name)	Exposure[d]	Ambient Temp. Volume Loss[e]	Ambient Temp. % Change	1400 °F Volume Loss[e]	1400 °F % Change	Ambient Temp. Rod Penetration[f]	Ambient Temp. % Change	1400 °F Rod Penetration[f]	1400 °F % Change
Three exposures in dolomite regenerator (CONOCO CO_2 Acceptor); 70 N_2, 27 CO_2, 3 CO, H_2S Trace (Vol %); 1850 °F, 150 psi, ∿800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3). (data continued)									
77% Alumina Vitreous Bond Light Insulating Fired Brick (B&W Insalcor)	U	4.83		4.03		0.88		0.64	
	E1	4.80	- 0.62	9.19	+128	0.79	-10	0.68	+ 6.3
	E2	8.98	+86	4.00	- 0.7	1.48	+68	0.59	- 7.8
	U	4.83		0.88[j]					
	E3	4.04	-16	1.77	+360[m]				
98+% Alumina, Self Bonded Light Insulating Fired Brick (Alfrax B 101)	U	4.37		3.12		0.72		0.54	
	E1	3.85	-12	3.58	+15	0.72	0	0.66	+22
	E2	6.42	+47	5.09	+63	1.13	+57	1.07	+98
	E3	4.37	0	4.65	+49				
99+% Alumina, Self Bonded Fused-Cast Dense Brick (Monofrax A)	U	0.36		0.17		0.13		0.11	
	E1	0.22	-39	0.14	-18	0.13	0	0.06	-45
	E2	0.14	-61	0.13	-24	0.07	-46	0.04	-64
	E3	0.19	-47	0.08	-53				
Silicon Carbide Silicon Nitride Bonded Dense Fired Brick (Refrax 20)	U	0.13		0.14		0.09		0.16	
	E1	0.12	- 7.7	0.09	-36	0.09	0	0.05	-69
	E2	0.15	+15	0.08	-43	0.05	-44	0.06	-63
	E3	0.15	+15	Crumbled					
70% Alumina (Mullite), Vitreous Bond Dense Fired Brick (Alumex 70-HD)	U	1.02		0.48		0.20		0.10	
	E3	1.09	+ 6.9	0.24	-50				
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U	0.48		-		0.21		-	
	E3	0.38	-21	0.16					
45-50% Alumina, Vitreous Bond High Fired Superduty Brick (KX-99)	U	0.70		0.35		0.19		0.10	
	E3	0.54	-23	0.26	-26				
60% Alumina Phosphate Bonded Ramming Mix (Wasp #60)	U	2.69		1.01		0.41		0.16	
	E1	specimen cracked							
	E2	0.77	-71	0.88	-13	0.15	-63	0.14	-13
	E3	0.89	-67	0.47	-54				
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	1.19		0.34		0.26		0.10	
	E1	0.59	-50	0.28	-18	0.17	-35	0.07	-30
	E2	0.64	-46	0.55	+62	0.09	-65	0.08	-20
		(0.34)[k]	(-71)[k]	(0.19)[k]	(-44)[k]				
	E3	0.25	-79	0.19	-44				
52% Alumina Light Castable, CA Bond (Litecast 80)	U	7.38		4.18		1.19		0.61	
	E1	fractured							
	E2	24.0	+225	45.3	+984	2.0	+68	5.92	+870
90+% Alumina Dense Castable, CA Bond (Greencast-97)	U	0.60		0.60		0.24		0.06	
	E1	2.15	+260	1.42	+137	0.40	+67	0.26	+333
70% Alumina, Vitreous Bond Fired Brick (Hi Lumite 70 D)	U	1.98		1.07		0.50		0.16	
	E1	1.89	- 4.5	0.59	-45	0.29	-42	0.08	-50
	E2	2.20	+11	0.78	-27	0.37	-26	0.15	- 6.3
85% Alumina Phosphate Bonded Fired Brick (Altex 85-B)	U	0.22		0.26		0.11		0.06	
	E1	0.28	+27	0.12	-54	0.10	- 9	0.05	-17
80+% Alumina Phosphate Bonded Fired Brick (Alumex P-8)	U	0.33		0.29		0.11		0.08	
	E1	0.25	-25	0.17	-41	0.10	- 9		
	U	0.33		0.30[j]					
	E2	0.53	+60	0.30	0	0.12		0.09	
90% Al_2O_3-10% Cr_2O_3 Solid Solution Fired Brick (CS 612)	U	0.49		0.37		0.13		-	
	E1	0.55	+12	0.32	-14	0.14	+ 7.7		
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00		0.35		0.22		0.11	
	E3	2.02	+102	1.99	+470				

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c] [12]

(Table continued)

Material (Brand Name)	Exposure[d]	Ambient Temp. Volume Loss[e]	Ambient Temp. % Change	1400 °F Volume Loss[e]	1400 °F % Change	Ambient Temp. Rod Penetration[f]	Ambient Temp. % Change	1400 °F Rod Penetration[f]	1400 °F % Change
Three exposures in dolomite regenerator (CONOCO, CO_2 Acceptor); 70 N_2, 27 CO_2, 3 CO, H_2S trace (Vol %); 1850 °F, 150 psi, ~800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3). (data continued)									
Silicon Carbide Silicon Oxynitride Bond Brick (Crystolon 63)	U	0.31		0.21		0.12		0.09	
	E3	0.30	- 3.2	0.02	-90				
One exposure in gasifier off-gas (BI-GAS); H_2O, CO_2, CO, H_2, N_2, CH_4, H_2S, ash and char (entrained); 1800 °F, 750 psi, exposure time not given									
60% Alumina Dense Castable, CA Bond (Super Brikcast A)	U	2.67		-		4.6		-	
	E	0.90	-66	0.30		1.9	-59	0.7	
55% Alumina Lightweight Insulating Castable, CA Bond (Litecast 75-28)	U	4.11		-		7.9		-	
	E	22.1	+438	9.0		23.2	+194	9.2	
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U	0.28		-		0.9		-	
	E	0.39	+39	0.21		0.7	-22	0.25	
70% Alumina (Mullite), Vitreous Bond Dense Fired Brick (Alumex 70-HD)	U	1.06		-		2.1		-	
	E	1.43	+35	0.66		2.2	+ 4.8	1.5	
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U	-		-		-		-	
	E	0.81		0.58		3.1		0.9	
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	-		-		-		-	
	E	1.01		0.40		1.8		0.5	
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00		-		7.2		-	
	E	2.84	+184	1.67		3.4	-53	2.5	
One exposure in gasifier off-gas (BATTELLE); 1800 °F, 100 psi, ~50 hr exposure									
60% Alumina Dense Castable, CA Bond (Mizzou Castable)	U	0.50[n]				0.20[n]			
	E	-				-			
70% Alumina (Mullite), Vitreous Bond, Fired Brick (Mul-8)	U	0.70[n]				0.15			
	E	0.79	+13			0.15	0		
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U	0.28[n]				0.09[n]			
	E	0.24	-14			0.07	-22		
Silicon Carbide, Clay Bonded	U	-				-			
	E	0.43				0.01			
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	1.19[n]				0.26[n]			
	E	0.55	-54			0.10	-62		
80+% Alumina Phosphate Bonded Fired Brick (Alumex P-8)	U	0.33[n]				0.11[n]			
	E	0.42	+27			0.08	-27		
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00[n]				0.22[n]			
	E	5.44	+444			0.85	+286		
One exposure in combustor off-gas (BATTELLE); 2000 °F, >100 psi, ~50 hr exposure.									
60% Alumina Dense Castable, CA Bond (Mizzou Castable)	U	-				-			
	E	0.50[n]				0.20[n]			
Silicon Carbide, Clay-Bonded	U	-				-			
	E	0.43				0.06			
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U	0.43[n]				0.17[n]			
	E	0.50	+16			-			
45-50% Alumina, Vitreous Bond High Fired Superduty Brick (KX-99)	U	0.62[n]				0.16[n]			
	E	0.54	-13			0.14	-13		
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U	1.19[n]				0.26			
	E	0.45	-62			0.14	-46		
90% Alumina Phosphate Bonded Dense Castable (Resco Cast AA-22)	U	1.00[n]				0.72[n]			
	E	4.02	+302			0.63	-13		

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c][12]
(Table continued)

Material (Brand Name)	Exposure[d]	Site[c]	Ambient Temp. Volume Loss[e]	Ambient Temp. % Change	1400 °F Volume Loss[e]	1400 °F % Change	Ambient Temp. Rod Penetration[f]	Ambient Temp. % Change	1400 °F Rod Penetration[f]	1400 °F % Change
Three exposures in gasifier off-gas of high temperature reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char; ~1250 °F, 900-1100 psi, exposure times for 1 and 2 not given, exposure 3 >1355 hr.										
90 % Alumina Dense Castable, CA Bond (Castolast G)	U		0.50		0.20		0.20		0.17	
	E1	0	1.83	+266	1.38	+590	0.29	+45	0.19	+12
		9	1.24	+148	0.82	+310	0.23	+15	0.09	-47
	E3	0	0.91	+ 82			0.19	- 5.0		
		1	0.68	+ 36			0.16	-20		
		8	0.81	+ 62			0.18	-10		
		9	1.02	+104			0.16	-20		
60% Alumina Dense Castable, CA Bond (Mizzou Castable)	U		1.54		0.63		0.29		0.13	
	E2	0	0.71	- 54	0.36	- 43	0.21	-28	0.13	0
		9	1.00	- 35	0.71	+ 13	0.24	-17	0.17	+31
		0	0.80	- 48	0.29	- 54	0.18	-38	0.10	-23
(2 specimens in exposure 2)		9	0.70	- 55	0.18	- 71	0.16	-45	0.09	-31
	E3	0	0.73	- 53			0.18	-38		
		1	0.50	- 68			0.15	-48		
		8	0.68	- 56			0.19	-34		
		9	0.70	- 55			0.22	-24		
60% Alumina Dense Castable, CA Bond (Super Brikcast A)	U		2.67		1.00		0.46		0.39	
	E3	0	0.62	- 77			0.15	-69		
		1	0.41	- 85			0.14	-70		
		8	0.53	- 80			0.15	-69		
(2 specimens in exposure 3)		9	0.53	- 80			0.14	-70		
		0	0.64	- 76			0.18	-61		
		1	0.69	- 74			0.17	-63		
		8	0.57	- 79			0.14	-70		
		9	0.66	- 75			0.15	-69		
55% Alumina Lightweight Insulating Castable, CA Bond (Litecast 75-28)	U		4.11		4.42		0.79		1.00	
	E3	0	17.2	+318			2.37	+200		
		1	11.1	+170			1.75	+122		
		8	14.3	+248			2.24	+184		
		9	10.8	+163			1.74	+120		
70% Alumina (Mullite), Vitreous Bond, Fired Brick (Mul-8)	U		0.70		0.56		0.15		0.10	
	E1	0	0.66	- 5.7	1.05	+ 88	0.18	+ 20	0.22	+120
		9	0.82	+ 17	0.70	+ 25	0.16	+ 6.7	0.16	+ 60
	E2	0	0.87	+ 24	0.67	+ 20	0.24	+ 60	0.16	+ 60
		9	0.77	+ 10	0.58	+ 3.6	0.19	+ 27	0.13	+ 30
	E3	0	1.04	+ 49			0.21	+ 40		
		1	0.74	+ 5.7			0.18	+ 20		
		8	0.58	- 17			0.15	0		
		9	0.59	- 16			0.14	- 6.7		
85% Alumina Phosphate Bonded Dense Fired Brick (Chemal 85 B)	U		0.28		0.14		0.09		0.05	
	E1	0	0.42	+ 50	0.19	+ 36	0.12	+ 33	0.06	+ 20
		9	0.39	+ 39	0.22	+ 57	0.12	+ 33	0.06	+ 20
	E2	0	0.39	+ 39	0.22	+ 57	0.12	+ 33	0.04	- 20
		9	0.28	0	0.21	+ 50	0.11	+ 22	0.06	+ 20
	E3	0	0.37	+ 32			0.11	+ 22		
		1	0.35	+ 25			0.11	+ 22		
		8	0.31	+ 11			0.10	+ 11		
		9	0.36	+ 29			0.10	+ 11		
90+% Alumina, Self Bonded Dense Fired Brick (Kricor)	U		0.61		0.38		0.15		0.14	
	E1	0	0.69	+ 13	0.51	+ 34	0.17	+ 13	0.16	+ 14
		9	0.47	- 23	0.21	- 45	0.11	- 27	0.07	- 50
	E2	0	0.78	+ 28	0.38	0	0.17	+ 13	0.09	- 36
		9	0.77	+ 26	0.47	+ 24	0.18	+ 20	0.09	- 36
	E3	0	0.82	+ 34			0.19	+ 27		
		1	0.73	+ 20			0.17	+ 13		
		8	0.60	- 1.6			0.17	+ 13		
		9	0.61	0			0.14	- 6.7		

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c][12]

(Table continued)

			Ambient Temp.		1400 °F		Ambient Temp.		1400 °F	
Material (Brand Name)	Exposure[d]	Site[o]	Volume Loss[e]	% Change	Volume Loss[e]	% Change	Rod Penetration[f]	% Change	Rod Penetration[f]	% Change
Three exposures in gasifier off-gas of high temperature reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char; ~1250 °F, 900-1100 psi, exposure times for 1 and 2 not given, exposure 3 >1355 hr.										
99+% Alumina, Self Bonded Dense Fired Brick (H-W Corundum)	U		0.94		0.45		0.24		0.10	
	E1	0	0.93	- 1.1	0.77	+ 71	0.18	- 25	0.12	+ 20
		9	0.87	- 7.4	0.43	- 4.4	0.20	- 17	0.13	+ 30
	E2	0	0.82	- 13	0.25	- 44	0.17	- 29	0.08	- 20
		9	1.20	+ 28	0.75	+ 67	0.21	- 13	0.13	+ 30
	E3	0	1.22	+ 30			0.24	0		
		1	1.08	+ 15			0.22	- 8.3		
		8	1.09	+ 16			0.22	- 8.3		
		9	0.95	+ 1.1			0.20	- 17		
77% Alumina Vitreous Bond Light Insulating Fired Brick (B&W Insalcor)	U		4.83		4.03		0.88		0.64	
	E1	0	7.63	+ 58	6.23	+ 55	1.26	+ 43	0.91	+ 42
		9	6.75	+ 40	8.18	+103	1.16	+ 32	1.29	+102
98+% Alumina, Self Bonded Light Insulating Fired Brick (Alfrax B 101)	U		4.37		3.12		0.72		0.54	
	E1	0	4.50	+ 3.0	3.68	+ 18	0.77	+ 6.9	0.66	+ 22
		9	4.44	+ 1.6	3.89	+ 25	0.82	+ 14	0.66	+ 22
70% Alumina (Mullite), Vitreous Bond Dense Fired Brick (Alumex 70-HD)	U		1.02		0.48		0.20		0.10	
	E3	0	0.93	- 8.8			0.19	- 5.0		
		1	0.72	- 29			0.16	- 20		
		8	0.93	- 8.8			0.19	- 5.0		
		9	0.99	- 2.9			0.21	+ 5.0		
60% Alumina, Tar Impregnated Fired Brick (Ufala TI)	U		0.48				0.21			
	E3	0	0.43	- 10			0.12	- 43		
		1	0.49	+ 2.1			0.14	- 33		
		8	0.39	- 19			0.12	- 43		
		9	0.47	- 2.1			0.13	- 38		
45-50% Alumina, Vitreous Bond, High Fired Superduty Brick (KX-99)	U		0.70		0.35		0.19		0.10	
	E3	0	0.82	+ 17			0.18	- 5.3		
		1	0.71	+ 1.4			0.16	- 16		
		8	0.71	+ 1.4			0.17	- 11		
		9	0.76	+ 8.6			0.19	0		
90% Alumina Phosphate Bonded Ramming Mix (Brikram 90)	U		1.19		0.34		0.26		0.10	
	E2	0	0.91	- 24	0.49	+ 44	0.20	- 23	0.12	+ 20
		9	0.67	- 44	0.39	+ 15	0.16	- 38	0.11	+ 10
(2 specimens in exposure 2)		0	1.10	- 7.6	0.62	+ 82	0.25	- 3.8	0.10	0
		9	0.64	- 46	0.55	+ 62	0.15	- 42	0.09	- 10
90+% Alumina Dense Castable, CA Bond (Greencast-97)	U		0.60		0.60		0.24		0.06	
	E2	0	3.83	+538	broke up		0.50	+108	broke up	
		9	5.48	+ 8.13	4.40	+633	0.79	+229	0.69	+1050
70+% Alumina, Vitreous Bond Fired Brick (Hi Lumite 70 D)	U		1.98		1.07		0.50		0.16	
	E1	0	2.77	+ 40	1.76	+ 64	0.47	- 6.0	0.24	+ 50
		9	1.51	- 24	0.84	- 21	0.29	- 42	0.17	+ 6.3
	E2	0	0.87	- 56	0.67	- 37	0.24	- 52	0.16	0
		9	0.77	- 61	0.58	- 46	0.19	- 62	0.13	- 19
85% Alumina Phosphate Bonded Fired Brick (Altex 85-B)	U		0.22		0.26		0.11		0.06	
	E1	0	0.42	+ 91	0.37	+ 42	0.11	0	0.09	+ 50
		9	0.21	- 4.5	0.27	+ 3.8	0.08	- 27	0.08	+ 33
	E2	0	0.28	+ 27	0.20	- 23	0.10	- 9.1	0.05	- 17
		9	0.41	+ 86	0.28	+ 7.7	0.11	0	0.07	+ 17
80+% Alumina Phosphate Bonded Fired Brick (Alumex P-8)	U		0.33		0.30		0.11		0.08	
	E1	0	0.49	+ 48			0.12	+ 9.1		
		9	0.39	+ 18			0.14	+ 27		
	E2	0	0.42	+ 27	0.32	+ 6.7	0.14	+ 27	0.19	+138
		9	0.58	+ 76	0.36	+ 20	0.13	+ 18	0.14	+ 75

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[a] Specimens were exposed in pilot plants in gaseous phase atmospheres; full conditions to which the refractories were subjected are not specified; time periods, when given, are only approximate.

- -

(Table Continued)

EFFECT OF EXPOSURE TO COAL GASIFICATION PILOT PLANT CONDITIONS[a] ON THE BONDING OF REFRACTORIES[b] AS MEASURED BY ABRASION TESTING[c][12]

(Table Continued)

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[b] Brick specimens were prepared by diamond saw sectioning of commercial refractories supplied by manufacturers. Castables were mixed with amount of distilled water recommended by manufacturers, poured into 9-in straights in wooden molds, cured in 100% humidity for 48 hr, then saw cut, fired to 1500 °F and cooled. All refractories were fired to 1500 °F for 4 hr in air before all testing both before and after exposure. Sample sizes varied for different pilot plants: Synthane and Conoco 4 x 2 x 1 in; Hygas, 9 x 2-1/2 x 4-1/2 in brick; Bigas, 5 x 2 x 1 in; Battelle 1.6 x 1.6 x 1 in.

[c] Rotating Rod Abrasion Tests were performed to measure any changes in the bond of the refractories due to exposure; test results do not represent abrasion or erosion resistance of refractories under gasification conditions. Procedure consists of rotating the end of a weighted (20 lb) rod (1 in diameter, 10 in long KT-SiC) on the face of a specimen at a determined rpm (36 rpm) for a determined time; abrasive grain (250 grams of SiC, -20 + 35 mesh ASTM) is applied between rod and specimen to intensify the abrasive effect; high temperature tests are performed by heating the specimen to the test temperature, attaining equilibrium in ∿one hour and then rotating the rod.

[d] U = unexposed, E1 = first exposure, E2 = second exposure, etc.

[e] Volume loss calculated from weight loss; expressed as cc per 1000 revolutions of the rod.

[f] Rod penetration is measured by a dial gauge resting on the rod and weight assembly; expressed as dial movement in mm per 1000 revolutions.

[g] CA bond = calcium aluminate bond.

[h] Fractured during testing.

[i] Specimens were refired to 2640 °F for 4 hr before exposure.

[j] Although the same values are given in the tables for most unexposed samples, these values differed.

[k] Values in parentheses are conflicting values for same data reported in different tables of the set of reports.

[l] A "skin" had formed on the refractory; the values given in the table are for tests with the "skin" still on. After removing the skin, abrasion tests were repeated - volume loss, room temperature 0.64, at 1400 °F, 0.20; rod penetration, room temperature 0.14, at 1400 °F, 0.07.

[m] Value reported is not consistent with the unexposed and exposed values but it is not possible to determine which of the three values is correct.

[n] Average properties of all unexposed specimens evaluated in this exposure.

[o] Hygas samples, 9 x 2-1/2 x 4-1/2 in bricks, were placed so that the 2-1/2 x 4-1/2 in face was exposed to the gasifier conditions. Slices, one inch thick, were cut from each end and both sides of each slice were tested after exposure three. Test site is the distance in inches from the hot face of the brick.

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE PHASES PRESENT IN VARIOUS HIGH-ALUMINA DENSE CASTABLE REFRACTORIES[b][39]

Treatment Conditions[a]				XRD Analysis Results[d]								DTA-TGA Analyses			
Atmosphere	Temperature °F	Pressure psi	Time[c]	Alumina	Boehmite	Calcite	Gibbsite	CA	CA_2	C_3AH_6	Aragonite	% Weight Loss	% Boehmite	% Calcite	% CaO, Dry Basis
94% ALUMINA[e]															
Air (dried)	230	ambient	24 h	M			tr	tr		tr					
CGA exposure	500	500	10 d	M	M	M					tr	16.0	16.3	8.1	4.8
	500	500	20 d									4.1	7.8	6.7	3.9
	500	500	30 d	M	m	M						5.1	13.3	7.1	4.2
CGA exposure	1000	1000	10 d	M		M					tr				
	1000	1000	30 d	M		M					tr	3.4	0	6.8	3.9
CGA, H_2O saturated	447	1000	30 d	M	M	M						6.6	22.3	5.5	3.3
93% ALUMINA[f]															
Air (dried)	230	ambient	24 h	M					m						
CGA exposure	500	500	10 d	M	M	M					m				
	500	500	30 d	M	m	M					m				
CGA exposure	1000	1000	10 d	M		M			tr						
	1000	1000	30 d	M		M									
CGA, H_2O saturated	447	1000	30 d	M	M	M									
90-95% ALUMINA[g]															
Air (dried)	230	ambient	24 h	M				m							
CGA exposure	500	500	10 d	M	M	M					tr	5.0	13.5	6.7	3.9
	500	500	20 d									3.8	9.2	5.5	3.2
	500	500	30 d	M	M	M					tr	4.7	11.4	6.7	3.9
CGA exposure	1000	1000	10 d	M		M									
	1000	1000	30 d									3.1	0	6.4	3.7
90-95% ALUMINA[h]															
Air (dried)	230	ambient	24 h	M					m						
CGA exposure	500	500	10 d	M	M	M						5.7	16.0	7.4	4.3
	500	500	20 d									4.1	9.8	6.0	3.4
	500	500	30 d	M	M	M						5.0	13.2	6.9	4.1
CGA exposure	1000	1000	10 d	M		M									
	1000	1000	30 d									3.7	0	7.6	4.5
CGA, H_2O saturated	447	1000	30 d	M	M	M						6.4	23.9	3.5	2.1
93% ALUMINA[i]															
Air (dried)	230	ambient	24 h	M				m							
CGA exposure	500	500	10 d	M	M	M						5.5	16.5	9.1	5.4
	500	500	20 d	M	m	M						4.4	7.9	7.2	4.2
	500	500	30 d	M	M	M					tr	5.7	13.3	8.3	4.9
CGA exposure	1000	1000	10 d	M		M						3.9	0	9.0	5.3
	1000	1000	30 d									3.9	0	8.0	4.5
CGA, H_2O saturated	447	1000	30 d	M	M	M						7.5	29.1	5.2	2.9
H_2O/CO, H_2O satd.	390	465	10 d	M	M	m						6.4	19.1	3.5	2.1
H_2O/CO	500	465	10 d	M	M	M						6.2	14.4	8.7	5.2
	1000	465	10 d	M		M						3.6	0	7.1	4.1
CGA with H_2S	1000	1000	10 d	M		M						3.7	0	7.5	4.3
	1000	1000	20 d	M		M						4.1	0	9.4	5.5
	1000	1000	30 d	M		M						3.7	0	7.8	4.5
CGA with H_2S, H_2O saturated	447	1000	30 d	M	M	M						6.6	29.1	5.1	3.1
91% ALUMINA[j]															
Air (dried)	230	ambient	24 h	M			tr	m		tr					
CGA exposure	500	500	10 d	M	M	M					m	8.4	24.5	10.8	6.7
	500	500	20 d									6.5	15.9	9.3	5.5
	500	500	30 d	M	M	M					tr	8.3	24.1	10.5	6.3
CGA exposure	1000	1000	10 d	M		M					tr	4.6	0	10.3	6.1
	1000	1000	30 d									4.9	0	10.1	6.0
H_2O/CO, H_2O satd.	390	465	10 d	M	M	m						7.8	20.0	3.8	2.3
H_2O/CO	500	465	10 d	M	M	M						8.9	24.7	11.7	7.2
	1000	465	10d	M		M						4.2	0	7.3	4.3
CGA with H_2S	1000	1000	10 d	M		M						2.6	0	4.3	2.5
	1000	1000	20 d	M		M						5.5	0	10.8	6.4
	1000	1000	30 d	M		M						5.4	0	10.94	6.5
CGA with H_2S, H_2O saturated	447	1000	30 d	M	M	M						8.3	37.3	5.2	3.2

(Table Continued)

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE PHASES PRESENT IN VARIOUS HIGH-ALUMINA DENSE CASTABLE REFRACTORIES[b][39]

(Table Continued)

Treatment Conditions[a]				XRD Analysis Results[d]								DTA-TGA Analyses			
Atmosphere	Temperature °F	Pressure psi	Time[c]	Alumina	Boehmite	Calcite	Gibbsite	CA	CA2	C_3AH_6	Aragonite	% Weight Loss	% Boehmite	% Calcite	% Ca
91% ALUMINA[k]															
Air (dried)	230	ambient	24 h	M					M						
CGA exposure	500	500	10 d	M	M	M					m	7.5	24.9	8.5	5
	500	500	20 d									5.1	13.7	6.9	4
	500	500	30 d	M	M	M					tr	6.9	22.3	8.0	4
CGA exposure	1000	1000	10 d	M		M				m		3.8	0	8.5	5
	1000	1000	30 d									4.0	0	7.7	4
CGA, H_2O saturated	447	1000	30 d	M	M	M									

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[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18 CO, 12 CO_2, 24 H_2, 41 H_2O and 5 CH_4, another CGA with 40% H_2O and 1% H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (in vol %). Samples w exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vess After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the co centrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel hea to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for bot vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] All cement bonded castables were cast in molds either 12 x 3 x 1/2 in or 3 x 3/4 x 3/4 in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. All specimens were stored at 230 °F until tested.

[c] Time units are given, either h for hours or d for days.

[d] Phases identified by x-ray diffraction analysis; M = major phase, m = minor phase, tr = trace. Cement notation used (C = CaO, A = Al H = H_2O) to specify some compounds. No data are given for the phases present after firing in air.

[e] 94% Alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Greencast-94, A.P. Green; CA-25 Calcium Aluminate Cem Alcoa).

[f] 93% Alumina dense castable, calcium aluminate (72% alumina, 25% calcia) bonded (B&W Kao-Tab 93, Babcock & Wilcox; C-3 cement, Babcock Wilcox).

[g] 90-95% Alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Castolast G, Harbison-Walker; CA-25 Calcium Alumin Cement, Alcoa).

[h] 90-95% Alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Purotab, Kaiser Refractories; CA-25 Calcium Alumin Cement, Alcoa).

[i] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alc CA-25 Calcium Aluminate Cement, Alcoa).

[j] 91% Alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alc Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[k] 91% Alumina dense castable, UMR-3 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alc C-3, a 72% alumina-25% calcia cement, Lone Star Lafarge).

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE PHASES PRESENT IN VARIOUS INTERMEDIATE-ALUMINA REFRACTORIES[b] [39]

Treatment Conditions[a]				XRD Analysis Results[d]									DTA-TGA Analyses			
Atmosphere	Temperature °F	Pressure psi	Time[c]	Kyanite	Mullite	α-Quartz	β-Cristobalite	Alumina	Boehmite	Calcite	$CaAl_2O_4$	Bayerite	% Weight Loss	% Boehmite	% Calcite	% CaO, Dry Basis
54-57% ALUMINA DENSE CASTABLE[e]																
Air (dried)	230	ambient	24 h		M		M	m			m					
CGA exposure	500	500	10 d		M		M	M	m	m			4.2	16.0	4.2	2.4
	500	500	20 d		M		M	m		m			3.1	7.9	3.7	2.2
	500	500	30 d		M		M	m	tr	m			4.5	13.4	5.5	3.2
CGA exposure	1000	1000	10 d		M		M	m		m						
	1000	1000	30 d										1.6	0	3.1	1.8
CGA, H_2O saturated	447	1000	30 d		M		M	m	tr	m		tr	4.2	8.2	2.7	1.6
-57% ALUMINA DENSE CASTABLE[f]																
Air (dried)	230	ambient	24 h		M		M	m			m					
CGA exposure	500	500	10 d		M		M	m	m	m			5.7	17.2	7.0	4.1
	500	500	20 d										3.6	7.5	5.7	3.3
	500	500	30 d		M		M	m	m	m			5.3	14.1	7.2	4.2
CGA exposure	1000	1000	10 d		M		M	m		m						
	1000	1000	30 d										2.3	0	4.4	2.6
CGA, H_2O saturated	447	1000	30 d		M		M	m	m	m		m	5.3	13.5	4.1	2.4
H_2O/CO, H_2O satd.	390	465	10 d		M		M	m	m	tr			5.0	27.2	2.0	1.2
H_2O/CO	500	465	10 d		M		M	m	m	m			6.3	11.7	7.4	4.4
	1000	465	10 d		M		M	m		m			2.0	0	3.43	2.0
CGA with H_2S	1000	1000	10 d		M		M	m		m			2.0	0	3.9	2.3
	1000	1000	20 d		M		M	m		m			2.6	0	5.0	2.8
CGA with H_2S, H_2O saturated	447	1000	30 d		M		M	m	m	m						
59% ALUMINA INSULATING CASTABLE[g]																
Air (dried)	230	ambient	24 h	M	M	m	m	m			m					
CGA exposure	500	500	10 d	M	M		m	m	tr	m			4.9	12.1	6.2	3.7
	500	500	20 d										4.2	9.8	6.1	6.7
	500	500	30 d	M	M		m	m	m	m			5.2	15.0	6.7	3.9
CGA exposure	1000	1000	10 d	M	M		m	m		m						
	1000	1000	30 d	M	M	m	m	m		m			1.9	0	3.4	1.9
CGA, H_2O saturated	447	1000	30 d	M	m	m		m			m	m	5.3	11.5	1.5	0.9
54% ALUMINA INSULATING CASTABLE[h]																
Air (dried)	230	ambient	24 h	M		M		m			m					
CGA exposure	500	500	10 d	M		M		M	tr	M			3.9	13.0	4.3	2.5
	500	500	30 d	M		M		M	tr	m			3.2	10.4	3.8	2.2
CGA exposure	1000	1000	10 d	M		M		M		m			4.1	13.3	4.4	2.6
	1000	1000	20 d	M		M		M								
	1000	1000	30 d	M		M		M		m			1.4	0	2.2	1.3
CGA, H_2O saturated	447	1000	30 d	M		M		M			m	m	5.3	9.1	2.8	1.7
H_2O/CO, H_2O satd.	390	465	10 d	m		M		m	tr				4.2	14.1	1.0	0.6
H_2O/CO	500	465	10 d	m		M		m	tr	tr			3.5	12.2	3.8	2.2
	1000	465	10 d										1.4	0	2.3	1.3
CGA with H_2S	1000	1000	10 d	M		M		M		m	m		1.0	0	1.7	1.0
	1000	1000	20 d	M		M		M		m	m		1.3	0	2.2	1.3
	1000	1000	30 d	M		M		M		m	m		1.3	0	1.9	1.1
CGA with H_2S, H_2O saturated	447	1000	30 d	M		M		M	tr	tr	m		7.3	6.4	3.3	2.0

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[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18 CO, 12 CO_2, 24 H_2, 41 H_2O, and 5 CH_4, another CGA with 40% H_2O and 1% H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (in vol %). Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] All cement bonded castables were cast in molds either 12 x 3 x 1/2 in or 3 x 3/4 x 3/4 in, cured 24 hr in air at 100% numidity at ambient temperature, and dried at 230 °F for 24 hr. All specimens were stored at 230 °F until tested.

[c] Time units are given, either h for hours, or d for days.

[d] Phases identified by x-ray diffraction analysis; M = major phase, m = minor phase, tr = trace. No data are given for the phases present in the fired condition.

[e] 54-57% Alumina, 34-37% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (Lo-Abrade, A.P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[f] 57% Alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[g] 59% Alumina, 33% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Kast-O-Lite 30, A.P. Green; CA-25, Calcium Aluminate Cement, Alcoa).

[h] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75; C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE PHASES PRESENT IN VARIOUS PHOSPHATE-BONDED REFRACTORIES[b][39]

Treatment Conditions[a]				XRD Analysis Results[d]			
Environment	Temperature °F	Pressure psi	Time[c]	Alumina	$AlPO_4$ (Berlinite)	$AlPO_4$ (orthorhombic)	Unidentified
-96% ALUMINA RAMMING MIX[e]-							
Air (fired)	1000	ambient	18 h	M	tr	tr	
CGA exposure	500	500	10 d	M	m		
	500	500	20 d	M	m		
	500	500	30 d	M	m		
CGA exposure	1000	1000	10 d	M	M		
	1000	1000	20 d	M	m	tr	
	1000	1000	30 d	M	M		
CGA, H_2O saturated	447	1000	30 d	M	m		m
-96% ALUMINA RAMMING MIX[f]-							
Air (fired)	1000	ambient	18 h	M		tr	
CGA exposure	500	500	10 d	M	tr	tr	
CGA exposure	1000	1000	10 d	M	tr	m	
CGA, H_2O saturated	447	1000	30 d	M			m
-90% ALUMINA RAMMING MIX[g]-							
Air (fired)	1000	ambient	18 h	M	tr		
CGA exposure	500	500	10 d	M	m		
CGA exposure	1000	1000	10 d	M	M	tr	
CGA, H_2O saturated	447	1000	30 d	M	M		tr

[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18 CO, 12 CO_2, 24 H_2, 41 H_2O and 5 CH_4. Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] Ramming mix specimens were prepared by hand ramming in 3 x 3/4 x 3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[c] Time units are given, either h for hours or d for days.

[d] Phases identified by x-ray diffraction analysis; M = major phase, m = minor phase, tr = trace.

(Continued)

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE PHASES PRESENT IN VARIOUS PHOSPHATE-BONDED REFRACTORIES[b][39], Continued

5% Alumina dense phosphate-bonded ramming mix (Greenpak-90P, A.P. Green).

5% Alumina dense phosphate-bonded ramming mix (90 Ram H.S., C-E Refractories).

0% Alumina dense phosphate-bonded ramming mix (Brikram 90R, General Refractories).

B.1 Corrosion Effects, Chemical Reactions, and Phase Changes

B.1.2 Refractories

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE PHASES PRESENT IN CALCIUM ALUMINATE CEMENTS[b][39]

Treatment Conditions[a]				XRD Analysis Results[d], Initially Dry[b]/Hydrated[b]									DTA-TGA Analyses Initially Dry Cement			
Atmosphere	Temperature °F	Pressure psi	Time[c]	Alumina	Boehmite	Calcite	Aragonite	CA	CA_2	C_2AS	$C_{12}A_7$	$Ca_4Al_6O_{12}SO_4$	% Weight Loss	% Boehmite	% Calcite	% Ca
79% ALUMINA, 18% CALCIA CEMENT[e]																
Air-dried	230	ambient	24 h	M/				M/			m					
CGA exposure	500	500	10 d	M/	M/	M/	m/						17.6	46.5	24.3	16.
	500	500	20 d	M/M	M/m	M/M							8.9	23.3	12.2	7.
	500	500	30 d	M/	M/	M/	m/									
CGA exposure	1000	1000	10 d	M/		M/										
	1000	1000	20 d	M/M		M/M							11.7	0	24.5	15.
	1000	1000	30 d	M/M		M/M							11.8	0	25.0	15.
CGA, H_2O saturated	447	1000	30 d		M/M	m/tr										
72% ALUMINA, 26% CALCIA CEMENT[f]																
Air-dried	230	ambient	24 h	m/				M/	m/							
CGA exposure	500	500	10 d	tr/	M/	m/	M/									
	500	500	20 d	m/m	M/M	M/M	m/	m/m	m/m				24.5	64.7	32.8	24.
	500	500	30 d	tr/	M/	m/	m/						13.5	19.0	12.2	7.
CGA exposure	1000	1000	20 d	/M		/M		/m	/M				14.7	0	31.3	20.
CGA, H_2O saturated	447	1000	30 d		/M	/m										
72% ALUMINA, 25% CALCIA CEMENT[g]																
Air-dried	230	ambient	24 h	m/				m/	M/			m/				
CGA exposure	500	500	10 d	tr/	M/	m/	m/						21.4	67.0	24.9	17.
	500	500	20 d	/m	M/M	M/m	tr/m		M/				9.9	28.9	12.1	7.
	500	500	30 d	tr/	M	m/	m/									
CGA exposure	1000	1000	10 d	m/M		M/M			M/M							
	1000	1000	20 d	M/M		M/M			M/M				11.2	0	21.0	13.
	1000	1000	30 d	M/		M/			m/				12.1	0	24.0	15.
CGA, H_2O saturated	447	1000	30 d		/M	/m										
58% ALUMINA + TITANIA, 33% CALCIA CEMENT[h]																
Air-dried	230	ambient	24 h	m/				M/	M/	M/						
CGA exposure	500	500	20 d		M/M	M/M			m/m	M/M						
CGA exposure	1000	1000	20 d			/M			m/m	M/M			11.7	0	22.8	14.
	1000	1000	30 d										13.8	0	28.6	18.
CGA, H_2O saturated	447	1000	30 d			/m				/m						
44% ALUMINA + TITANIA, 36% CALCIA CEMENT[i]																
Air-dried	230	ambient	24 h					M/	m/	M/						
CGA exposure	500	500	20 d		m/m	M/M			m/m	M/m						
CGA exposure	1000	1000	20 d			M/M			m/m	M/M			13.0	0	27.5	17.
	1000	1000	30 d										11.6	0	23.5	14.
CGA, H_2O saturated	447	1000	30 d		/M	/m				/m						

---

[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18 CO, 12 CO_2, 24 H_2, 41 H_2O, and 5 CH_4, another CGA with 40% H_2O and 1% H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (in vol %). Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtai the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vess heated to the test temperature the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate fo both vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] Cements were tested as initially dry powders and as neat cement specimens. Hydrated neat cement samples (water/cement ratio of ~0.3) w cast as 1/2-in cubes, cured in air at 100% humidity for 24 hr, and dried at 230 °F for 24 hr. Samples were stored at 230 °F until tes

[c] Time units are given, either h for hours or d for days.

[d] Phases identified by x-ray diffraction analysis; M = major phase, m = minor phase, tr = trace. Cement notation used (C = CaO, A = Al_2 H = H_2O, S = SiO_2) to specify some compounds. No data are given for the phases present after firing in air.

[e] 79% Alumina, 18% calcia cement (CA-25 Calcium Aluminate Cement, Alcoa).

[f] 72% Alumina, 26% calcia cement (Secar 71(250), Lone Star Lafarge).

[g] 71.5-72.5% Alumina, 24-25% calcia cement (C-3, Babcock & Wilcox).

[h] 58% Alumina + titania, 33% calcia cement (Refcon, Universal Atlas Cement).

[i] 44% Alumina + titania, 36% calcia cement(Lumnite, Universal Atlas Cement).

EFFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE PHASES PRESENT IN CASTABLE ALUMINA REFRACTORIES[c] [39]

-93% ALUMINA DENSE CASTABLE[f]-

Treatment Conditions[a]				XRD Analysis Results[e]					DTA-TGA Analyses			
Environment	Temperature °F	Pressure psi	Time[d]	α-Al_2O_3	Boehmite	Calcite	C_3AH_6	CA	% Weight Loss	% Boehmite	% Calcite	% CaO, Dry Basis
Air (dried)	230	ambient	24 h	M				m				
Saturated steam vapor	447	410	10 d	M	M	tr	m		6.5	20.2	5.4	
liquid	447	410	10 d	M	M	tr	m		6.7	22.0	7.9	
CGA with H_2S, saturated vapor	447	1000	44 d	M	M	m			8.1	24.9	7.8	4.8
liquid	447	1000	44 d	M	M	m	tr		8.0	25.5	5.1	3.1
CGA with H_2S, saturated[g]	465	1000	5 d	M	m	m			6.5	12.4	7.8	4.8
followed by firing in air[h]	1000	ambient	18 h	M		m			3.8	0	7.3	4.3
Cycling tests--repeat of preceding exposure followed by air firing												
1 cycle				M		m			4.0	0	8.3	4.9
2 cycles				M		m			4.2	0	8.7	5.1
3 cycles				M		m			4.1	0	8.5	5.0
4 cycles				M	tr	m			3.9	0	8.0	5.0
5 cycles				M		m	tr		4.5	0	9.5	5.6

-87% ALUMINA DENSE CASTABLE[i]-

Environment	Temperature °F	Pressure psi	Time[d]	α-Al_2O_3	Boehmite	C_3AH_6	CA_2	C_2AS	Calcite	% Weight Loss	% Boehmite	% Calcite	% CaO, Dry Basis
Air (dried)	230	ambient	24 h	M		m		m					
Saturated steam vapor	447	410	10 d	M	M	m	tr			6.4	15.1	10.5	
liquid	447	410	10 d	M	M	m	tr			6.5	14.9	12.6	
CGA with H_2S, saturated vapor	447	1000	44 d	M	M				m	8.1	18.9	6.2	3.8
liquid	447	1000	44 d	M	M					8.5	15.2	8.5	5.2
CGA with H_2S, saturated	465	1000	5 d	M					m				
followed by firing in air	1000	ambient	18 h	M					m				
Cycling tests--repeat of preceding exposure followed by air firing													
1 cycle				M					m	5.9	0	11.6	6.9
2 cycles				M					m	6.5	0	12.4	7.4
3 cycles				M					m	5.5	0	8.4	4.9
4 cycles				M					m	5.4	0	8.0	4.6
5 cycles				M					m	5.9	0	12.2	7.2

64% ALUMINA-28% SILICA DENSE CASTABLE[j]-

Environment	Temperature °F	Pressure psi	Time[d]	Mullite	α-Al_2O_3	Boehmite	β-Cristobalite	Calcite	% Weight Loss	% Boehmite	% Calcite	% CaO, Dry Basis
Air (dried)	230	ambient	24 h			m						
Air (fired)	500	ambient	18 h			m						
Air (fired)	1000	ambient	18 h			M						
Saturated steam vapor	447	410	10 d	M	m	m	tr		3.7	9.5		
liquid	447	410	10 d	M	m	m	tr		4.2	11.0		
CGA with H_2S, saturated vapor	447	1000	44 d	M	m	m	tr	m	5.0	10.1	3.9	2.3
liquid	447	1000	44 d	M	m	m	tr	m	5.8	14.0	5.7	3.4
CGA with H_2S, saturated	465	1000	5 d	M	m	m	tr	m	6.1	10.9	7.0	4.2
followed by firing in air	1000	ambient	18 h	M	m		m	m	4.6	0	7.9	4.6
Cycling tests--repeat of preceding exposure followed by air firing												
1 cycle				M	m		m	m	3.7	0	7.4	4.3
2 cycles				M	m		tr	m	3.9	0	8.1	4.7
3 cycles				M	m		tr	m	2.7	0	6.2	3.6
4 cycles				M	m		tr	m	2.8	0	5.7	3.3
5 cycles				M	m		tr	m	3.0	0	5.8	3.4

58% ALUMINA-30% SILICA DENSE CASTABLE[k]-

Environment	Temperature °F	Pressure psi	Time[d]	Mullite	α-Al_2O_3	Boehmite	C_3AH_6	C_2AH_{18}	Calcite	Cristobalite	C_2AS	% Weight Loss	% Boehmite	% Calcite	% CaO, Dry Basis
Air (dried)	230	ambient	24 h	M	tr		tr								
Saturated steam vapor	447	410	10 d	M		m	m	tr				4.4	8.7	7.3	
liquid	447	410	10 d	M		m						7.0	10.1		
CGA with H_2S, saturated vapor	447	1000	44 d	M	tr	m			tr	tr	tr	8.1	18.9	6.2	3.8
liquid	447	1000	44 d	not tested											
CGA with H_2S, saturated	465	1000	5 d	M	tr	m			tr	tr		6.7	13.2	6.6	4.0
followed by firing in air	1000	ambient	18 h	not tested											
Cycling tests--repeat of preceding exposure followed by air firing															
1 cycle				M	tr				m	tr		4.2	0	8.3	4.9
2 cycles				M	tr				m	tr		4.8	0	9.4	5.6
3 cycles				M	tr				m	tr		3.0	0	6.2	3.6
4 cycles				M	tr				m	tr	tr	3.1	0	6.5	3.8
5 cycles				M	tr				m	tr		4.1	0	8.8	5.1

(Table Continued

EFFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE PHASES PRESENT IN CASTABLE ALUMINA REFRACTORIES[c] [39], Continued

Treatment Conditions[a]					XRD Analysis Results[e]						DTA-TGA Analyses			
Environment		Temperature °F	Pressure psi	Time[d]							% Weight Loss	% Boehmite	% Calcite	% CaO· B
-54% ALUMINA-40% SILICA INSULATING CASTABLE[l]-														
					α-Quartz	Kyanite	α-Al_2O_3	Boehmite	CA	Calcite				
Air (dried)		230	ambient	24 h	M	m	m		m					
Saturated steam	vapor	447	410	10 d	M	m	m				4.1	4.0		
	liquid	447	410	10 d	M	m	tr	tr			3.7	4.0		
CGA with H_2S, saturated	vapor	447	1000	44 d	M	m	tr	tr		m				
	liquid	447	1000	44 d	M	m	m	tr		m				
CGA with H_2S, saturated		465	1000	5 d	M	m	m	tr		m				
followed by firing in air		1000	ambient	18 h	M	m	m			m				
Cycling tests--repeat of preceding exposure followed by air firing														
	1 cycle				M	m	m			m				
	2 cycles				M	m	m			m				
	3 cycles				M	m	m			m				
	4 cycles				M	m	m			m				
	5 cycles				M	m	m			m				
-47% ALUMINA-40% SILICA INSULATING CASTABLE[m]-														
					Mullite	α-Al_2O_3	β-Cristobalite	Boehmite						
Air (dried)		230	ambient	24 h		tr	tr	m						
Air (fired)		500	ambient	18 h		tr	tr	m						
Saturated steam	vapor	447	410	10 d	M						7.6	13.5		
	liquid	447	410	10 d	M						4.7	10.1		
-35% ALUMINA-53% SILICA INSULATING CASTABLE[n]-														
					α-Quartz	α-Al_2O_3	C_2AS	Bayerite						
Air (dried)					no data									
Saturated steam	vapor	447	410	10 d	M	m	m	tr			5.7	5.4		
	liquid	447	410	10 d	M	m	m	tr			5.8	5.5		

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[a] Samples were exposed in a steam generator, both in vapor and in the liquid in the bottom of the vessel. After placement of samples, the vessel was heated to the desired steam pressure and where tests included other gases, these were then added so as to obtain the desired overall concentrations. The overall composition of the coal gasification atmosphere (CGA) is (in vol %) 18 CO, 12 CO_2, 24 H_2, 40 H_2O, 5 CH_4, and 1 H_2S. A gaseous flow rate was maintained so as to provide one complete change in atmosphere every 24 hours. The vapor was 85% steam saturated in these tests.

[b] Other tests showed that boehmite formation occurred in steam-saturated atmospheres and resulted in very large increases in the flexural strength. The cycling tests were designed to investigate the effect of repetitive formation and decomposition of boehmite on the refractories.

[c] After casting, specimens were cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hours. Specimens were stored at 230 °F until tested.

[d] Time units are given, either h for hours, or d for days.

[e] Phases identified by x-ray diffraction analysis; M = major phase, m = minor phase, tr = trace. Cement notation used (C = CaO, A = Al_2O_3, H = H_2O, S = SiO_2) to specify some compounds. No data are given for most refractories for the phases present after firing in air.

[f] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

[g] 85% steam saturated; this exposure is the one forming the first step in the cycling tests, forming boehmite.

[h] The firing step, following the saturated CGA exposure completed one cycle, decomposing the boehmite.

[i] 87.4% Alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; Refcon, 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

[j] 63.8% Alumina, 28.3% silica castable, UMR-8 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement)(Mulcoa 60 and Mulgrain M47, C-E Minerals; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

[k] 58.6% Alumina, 29.6% silica castable, UMR-5 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement)(Mulcoa 60 and Mulgrain M47, C-E Minerals; Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

[l] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[m] 46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

[n] 34.5% Alumina, 52.5% silica insulating castable (WSL-50, A.P. Green).

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B.1.3 Coatings and Surface Treatments

RESULTS OF CORROSION TESTING[a] OF VARIOUS COATING-SUBSTRATE SYSTEMS[33]

Coating	Bond Coat	Substrate	Deposition Technique[b]	Exposure Time, hr	Performance
Al_2O_3	--	1020 cold-rolled steel	PS	100	Some retardation of corrosion; substrate formed some type of molten sulfide eutectic
Al_2O_3	NiCrAl[c]	304 SS	PS	100	Resisted corrosion; spalled during cooling
Al_2O_3	NiCrAl	310 SS	PS	100	Resisted corrosion; spalled during cooling
Al_2O_3	NiCrAl	316 SS	PS	100 500	Resisted corrosion Resisted corrosion; spalled during cooling
Al_2O_3	NiCrAl	Incoloy 800	PS	100	Resisted corrosion
Al_2O_3	Hf	304 SS	IP	100	Retarded corrosion
Al_2O_3	Triboloy 800	310 SS	IP	100	Resisted corrosion; spalled during cooling
ZrO_2(CaO stabilized)	--	1020 cold-rolled steel	PS	100	Substrate formed some type of molten sulfide eutectic
ZrO_2(CaO stabilized)	--	Incoloy 800	PS	500	Resisted corrosion
ZrO_2(CaO stabilized)	NiCr	304 SS	PS	100	Retarded corrosion
ZrO_2(CaO stabilized)	NiCr	310 SS	PS	100	Resisted corrosion
ZrO_2(CaO stabilized)	NiCr	316 SS	PS	500	Resisted corrosion
ZrO_2(CaO stabilized)	NiCrAl	304 SS	PS	100 500	Resisted corrosion Resisted corrosion
ZrO_2(CaO stabilized)	NiCrAl	310 SS	PS	100	Resisted corrosion
ZrO_2(CaO stabilized)	NiCrAl	316 SS	PS	100	Resisted corrosion
ZrO_2(CaO stabilized)	NiCrAl	Incoloy 800	PS	100	Resisted corrosion
$MgO.ZrO_2$	--	Incoloy 800	PS	500	Resisted corrosion
$MgO.ZrO_2$	NiCr	304 SS	PS	100 500	Resisted corrosion; spalled one side during cooling Resisted corrosion
$MgO.ZrO_2$	NiCr	310 SS	PS	100	Resisted corrosion; spalled on edges during cooling
$MgO.ZrO_2$	NiCrAl	304 SS	PS	100	Resisted corrosion
$MgO.ZrO_2$	NiCrAl	310 SS	PS	100	Resisted corrosion; spalled during cooling
Cr_3C_2(25%Ni-Cr)	--	304 SS	PS	100	Resisted corrosion; spalled during cooling
Cr_3C_2(25%Ni-Cr)	--	316 SS	PS	500	Corroded
Cr_3C_2(25%Ni-Cr)	--	Incoloy 800	PS	500	Retarded corrosion
Cr_3C_2(Ni-Al)	--	Incoloy 800	PS	500	Corroded
Cr_3C_2(Ni-Al)	NiCr	304 SS	PS	500	Retarded corrosion for up to 100 hr but corroded in 500 hr
Cr_3C_2(Ni-Al)	NiCr	316 SS	PS	500	Retarded corrosion for up to 100 hr but corroded in 500 hr
Cr_3C_2(Ni-Al)	NiCrAl	304 SS	PS	100	Resisted corrosion
Cr_3C_2(Ni-Al)	NiCrAl	Incoloy 800	PS	100	Resisted corrosion
Co-Cr-Al	NiCr	304 SS	PS	100 500	Retarded corrosion Corroded
Co-Cr-Al	NiCrAl	304 SS	PS	100	Resisted corrosion
Co-Cr-Ni	NiCrAl	310 SS	PS	100	Retarded corrosion
Triboloy 800	NiCr	304 SS	PS	100	Retarded corrosion
Triboloy 800	NiCr	310 SS	PS	100	Resisted corrosion
Triboloy 800	NiCrAl	304 SS	PS	100	Retarded corrosion
Triboloy 800	NiCrAl	310 SS	PS	100	Resisted corrosion
$MgO.Al_2O_3$	NiCrAl+(NiCrAl+50%$MgO.Al_2O_3$)	316 SS	PS	100	Resisted corrosion; spalled during cooling
$MgO.Al_2O_3$	NiCrAl+(NiCrAl+50%$MgO.Al_2O_3$)	Incoloy 800	PS	100	Resisted corrosion; spalled during cooling
Boride[d]	--	304 SS		100	Corroded
Cr	--	SA285	diffused	100	Corroded; specimen converted to molten sulfide eutectic
Cr + Al	--	SA285	diffused	100	Corroded; specimen converted to molten sulfide eutectic

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[a] Gaseous environment (vol %): 39 H_2O, 24 H_2, 12 CO_2, 18 CO, 5 CH_4, 1 NH_3, 1 H_2S. Tests run at 1800 °F (∿980 °C) and atmospheric pressure. Gas mixture flowed through the test vessel at a rate producing an exchange of one vessel volume every 10 minutes.

[b] PS = plasma sprayed (∿200-250 μm thick). IP = ion plated (∿30 μm thick) with metal intermediate 1 to 3 μm thick.

[d] Boron diffused coating ∿50 μm thick produced by gaseous diffusion accompanied by pack-cementation (Boroloy process, Lindberg).

[c] 74Ni-24Cr-1Al.

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B.2 Erosion, Erosion/Corrosion, and Abrasion Effects

B.2.1 Alloys

EROSION TEST[a] DATA FOR VARIOUS IRON-BASED ALLOYS[1]

terial	Composition	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
4 SS	17Cr-9Ni-2Mn-1Si-bal Fe, wrought			1.00	0.73
304 SS	Aluminized 304 SS	Alloy Surfaces	0.918	0.904	
6 SS	17Cr-12Ni-2.5Mo-2Mn-1Si-bal Fe, wrought		1.19	0.99	0.56
0 SS	0.12C-17Cr-1Mn-1Si-bal Fe, wrought			0.93	0.62
coloy 800	46Fe-21Cr-32.5Ni	Huntington Alloys	1.08	0.83	0.57
coloy 800H	46Fe-21Cr-32.5Ni-0.07C, wrought	Huntington Alloys	1.08	0.91	0.54
800	Aluminized Incoloy 800	Alloy Surfaces	0.758	0.891	
-40	Fe-26Cr-20Ni-0.4C, cast		1.04	0.93	0.78
330	0.05C-1.5Mn-1.3Si-19Cr-35Ni-bal Fe, wrought	Rolled Alloys Corp.	1.04	0.91	0.79
-250	high Cr iron		0.93	1.14	1.59
raph-Air tool steel	1.4C-1.9Mn-1.2Si-1.9Ni-1.5Mo-bal Fe, wrought	Timken Roller Bearing Co.	1.16	1.19	
-37	5Cr-1Ti-14W-8V-3.9C-13Mn-bal Fe, cast	Oregon Graduate Center		1.41	1.49
Cr iron	25Cr-2Ni-2Mn-0.5Si-3.5C-bal Fe, cast	Oregon Graduate Center		1.19	1.16
aynes 93	17Cr-16Mo-6.3Co-3C-bal Fe, cast	Stellite		1.25	1.00
ild steel	0.15C-bal Fe		1.19	0.76	

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rosion test conditions: 1/2-inch square specimens subjected to erosion by 7μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 tmosphere, 5 g/min abrasive flow.

elative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated rom weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

mp = angle of impingement.

EROSION TEST[a] DATA FOR VARIOUS METALS AND NON-STEEL ALLOYS[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b]		
			20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
W, wrought	GE tungsten		0.37	0.48	0.17
W with diffused B	Borofuse[d] W		0.02	0.32	0.46
Mo, wrought	Molybdenum		0.52	0.52	1.32
Mo with diffused B	Borofuse[d] PM Moly	CM-MDC[e]	0.09	0.25	0.28
Mo-0.5Ti-0.08Zr-0.03C with diffused B	Borofuse[d] MT 104	Syl-MDC[f]	0.03	0.30	0.19
Ta	Tantalum		0.568	0.416	
Ta_3N_5	Tantalum nitride	Albany	0.514	0.493	
31Cr-12.5W-2.4C-bal Co, cast	Stellite 3	Stellite		1.04	1.61
30Cr-4.5W-1.5Mo-1.7Cr-bal Co, wrought	Stellite 6K	Stellite		1.08	1.06
31Cr-12.5W-2.4C-bal Co with diffused B	Borofuse[d] Stellite 3	Stellite-MDC	0.37	0.92	0.83
25.5Cr-7.5W-0.5C-10.5 Ni-bal Co with diffused B	Borofuse[d] Stellite 31	Stellite-MDC	0.40	1.40	1.37
28Cr-4W-1.0C-bal Co with diffused B	Borofuse[d] Stellite 6	Stellite-MDC	0.45	1.29	1.40
22Cr-14.5W-22Ni-0.15C-bal Co, wrought	Haynes 188	Stellite		0.97	0.83
20Cr-15W-10Ni-1.5Mn-0.15C-bal Co, wrought	Haynes 25	Stellite		0.96	0.85
6Al-4V-bal Ti, wrought	Ti-6Al-4V		1.56	1.26	0.54
11.5Mo-6Zr-4.5Sn-bal Ti, wrought	Beta III Ti			0.90	0.57
25Cr-18Fe-3Co-3Mo-3W-1.5Mn-bal Ni,wrought	RA-333	Rolled Alloys, Corp.	1.04	0.80	0.80
76Ni-15.5Cr-8Fe, wrought	Inconel 600	Huntington Alloys		0.92	0.61
50Ni-48Cr-0.4Ti, wrought	Inconel 671	Huntington Alloys	1.06	0.77	0.62
1.86Be-0.47Cu-0.36Ti-bal Ni	00440	Kawecki Berylco.		1.001	
10(Ni,Cu,Fe)-90W, p&s[g]	W-10	Kennametal	0.48	0.70	0.44
1.9Be-0.24Co-bal Cu	00025	Kawecki Berylco.	1.44	1.12	
	SPA	Abex Inc.	1.11	1.08	0.97

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] Borofuse = a patented diffusion-bonded boriding surface treatment.

[e] CM-MDC = Climax Molybdenum Co. and Materials Development Corp.

[f] Syl-MDC = Sylvania Electric Products Inc. and Materials Development Corp.

[g] p&s = pressed and sintered.

EROSION TEST[a] DATA FOR VARIOUS WELD OVERLAYS[1]

Material	Nominal Composition	Source	Relative Erosion Factor[b] 20° C, 90° imp[c]
No. 1 Alloy, Arc[d]	30Cr-12W-2.5C-bal Co	Cabot	1.098
No. 1 Alloy, Tig[e]	30Cr-12W-2.5C-bal Co	Cabot	1.036
No. 21 Alloy, Tig	27Cr-5Mo-2.8Ni-0.25C-bal Co	Cabot	1.029
No. 90 Alloy, Arc	27Cr-2.75C-bal Fe	Cabot	1.377
No. 90 Alloy, Tig	27Cr-2.75C-bal Fe	Cabot	1.221
No. 94 Alloy, Arc	29Cr-3Co-3.3C-bal Fe	Cabot	1.332
No. 94 Alloy, Tig	29Cr-3Co-3.3C-bal Fe	Cabot	1.149
1016 Alloy, Arc	32Cr-17W-2.5C-bal Co	Cabot	1.103
1016 Alloy, Tig	32Cr-17W-2.5C-bal Co	Cabot	1.123
Comp. 2, Arc	60% WC- 40% Stellite 6	Cabot	1.205
Comp. 2, Tig	60% WC-40% Stellite 6	Cabot	1.287
Comp. 4E	40% Haynes 47-60% Stellite 954	Cabot	1.306
Comp. 40E	14Cr-4Si-4Fe-3.4B-0.75C-bal Ni	Cabot	1.464

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[a] Erosion test conditions: 1/2-inch square specimens are subjected to erosion by 27µ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C- bal Co.

[c] imp = angle of impingement.

[d] Arc = arc-weld application of overlay.

[e] Tig = tungsten-inert gas weld application of overlay.

EFFECT OF OXIDIZING[a] AND REDUCING[b] ATMOSPHERES ON THE EROSION[c] OF SOME ALLOYS[21]

Alloy Type	Major Alloying Constituents	Hardness HK$_{200}$[e]	Equivalent Weight Loss[d] Oxidizing[a] 90°	45°	Reducing[b] 90°	45°
446 SS	25 Cr, 1 Si, 1.5 Mn	214	0.41	0.35	0.73	1.1
304 SS[f]	19 Cr, 10 Ni	198	0.59	0.37	1.6	1.5
316 SS	17 Cr, 12 Ni	321	----	----	1.2	1.3
310 SS	25 Cr, 21 Ni	415	0.32	0.28	0.58	0.64
Incoloy 800	22 Cr, 30 Ni	382	0.42	0.32	0.56	0.64
Inconel 601	23 Cr, 60 Ni	440	0.29	0.24	0.23	0.49
Inconel 671	50 Cr, 50 Ni	427	0.26	0.28	0.15	0.25

[a] Gas composition: 13% O_2, 10% CO_2, 64% N_2, 13% H_2O.

[b] Gas composition: 8% H_2, 12% CO, 17% H_2O, 5% CO_2, 52% N_2, 6% other.

[c] Metal specimens typically 3 cm long, 1 cm wide and 0.5 mm thick were subjected to erosion in a high-temperature flame erosion apparatus; specimen design permitted surface exposure at 90° and 45° to the direction of the gas and erosive particle flow; scribe marks on the unexposed faces of each sample were used to determine the thickness of material lost from the exposed surfaces; tests were conducted at 1020° C; abrasive material 150 μm SiC particles; particle velocity 55 m/s as measured by rotating disk, time-of-flight method.

[d] Equivalent Weight Loss = weight loss of sample (mg) based on thickness of sample lost/weight of abrasive used (g).

[e] HK = Knoop Hardness.

[f] Loose oxide scale observed under oxidizing conditions; scale spalled on cooling to ambient temperature.

DEPENDENCE OF EROSION[a] OF SOME ALLOYS AND PLATE ON ABRASIVE PARTICLE VELOCITY[b][21]

Material	Particle Velocity (m/s)	Relative Weight Loss[c] 25° C	500° C	1000°C
Chromium plate on steel	11	0.07	0.06	0.62
	21	0.11	0.08	0.61
	31	0.15	0.11	0.46
	42	0.14	0.20	0.73
	52	0.16	0.18	----
310 SS	11	0.08	0.09	----
	21	0.15	0.20	----
	31	0.18	0.25	----
	42	0.21	0.33	----
	52	0.29	0.55	----
304 SS	11	0.10	0.10	----
	21	0.19	0.21	----
	31	0.24	0.30	----
	42	0.25	0.38	----
	52	0.33	0.29	----

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[a] Specimens were subjected to erosion in a gas-abrasive jet device; CO_2 propellant; abrasive 50 μm Al_2O_3; 2 min exposure; particle velocity measured by rotating disk, time-of-flight method; high temperature achieved by passing current through samples and heating the propellant gas-particle mixture.

[b] Angle of Impingement 90°.

[c] Relative Weight Loss = weight loss of samples (mg)/ weight of abrasive used (g).

DEPENDENCE OF EROSION[a] OF SOME ALLOYS AND PLATE ON IMPINGEMENT ANGLE[b][21]

Material	Impingement Angle (°)	Relative Weight Loss[c] 25°C	500°C
Chromium plate on steel	20	0.15	0.01
	30	0.13	0.02
	45	0.15	0.08
	70	0.14	----
	90	0.17	0.11
310 SS	20	----	0.47
	30	----	0.28
	45	----	0.30
	70	----	0.34
	90	----	0.14
304 SS	20	----	0.33
	30	----	0.35
	45	----	0.26
	70	----	0.23
	90	----	0.26

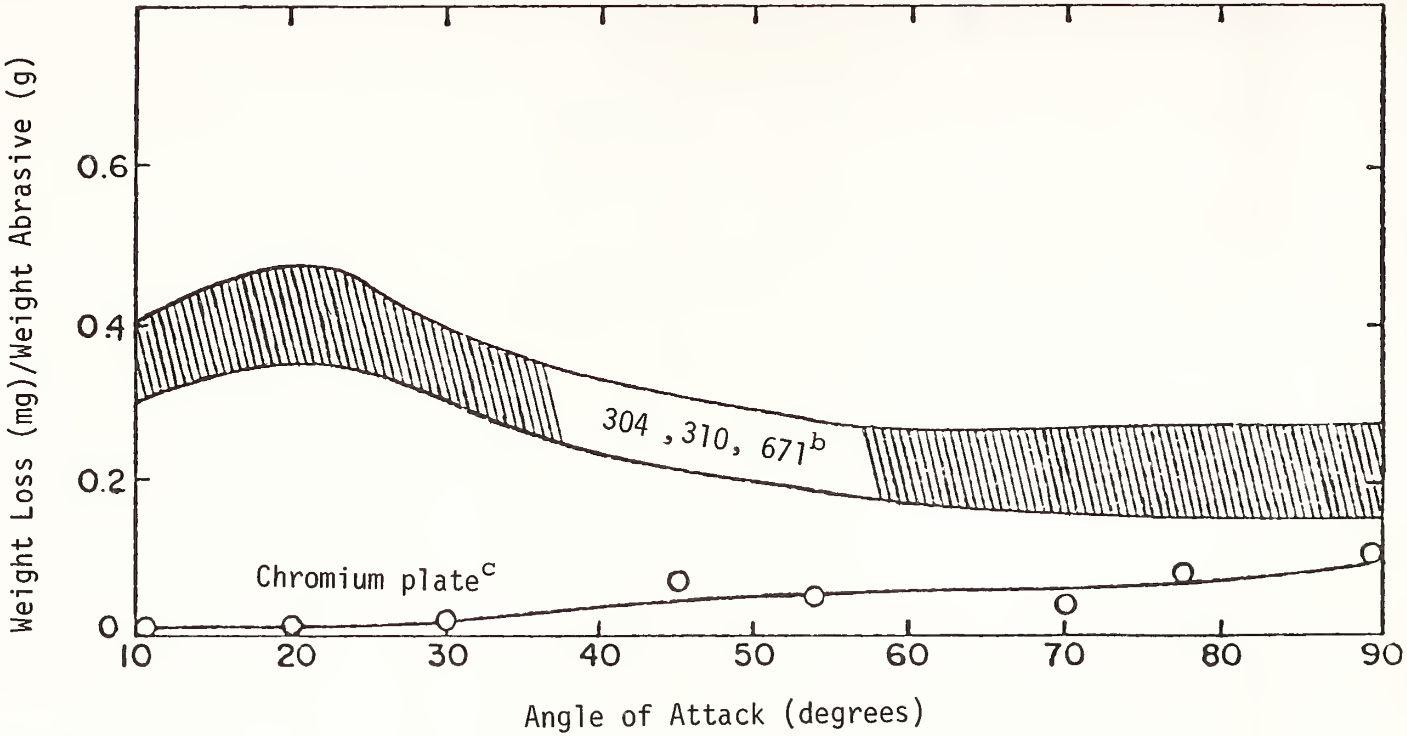
---

[a] Specimens were subjected to erosion in a gas-abrasive jet device; CO_2 propellant; abrasive 50 µm Al_2O_3; 2 min exposure; particle velocity measure by rotating disk, time-of-flight method; high temperature achieved by passing current through samples and heating the propellant gas-particle mixture

[b] Particle velocity 31 m/s.

[c] Relative Weight Loss = weight loss of sample (mg)/ weight of abrasive used (g).

EFFECT OF IMPINGEMENT ANGLE ON THE HIGH-TEMPERATURE EROSION[a] OF SOME ALLOYS[b] AND CHROMIUM PLATE[c] [21]



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[a] Specimens were subjected to erosion in an air-abrasive jet device; CO_2 propellant; particle velocity 31 m/s as measured by rotating disk, time-of-flight method; exposure time 2 min; abrasive 50 µm Al_2O_3; temperature 500 °C, achieved by passing current through the samples and by heating the propellant gas-particle mixture.

[b] Alloys are Type 304 SS, Type 310 SS, and Inconel 671.

[c] Plate is thick chromium plate on steel.

EFFECT OF IMPINGEMENT ANGLE ON THE HIGH-TEMPERATURE EROSION[a] OF SOME ALLOYS[21]

Alloy Type	Major Alloying Constituents	Vickers Hardness[b]	Thickness Change (μm/hr)			
			90°	45°	5°	-5°
446 SS	25 Cr, 1 Si, 1.5 Mn	186	-16	-1	+5	+4
304 SS	19 Cr, 10 Ni	161	-23	-11	+7	+4
310 SS	25 Cr, 21 Ni	154	-5	-3	+4	+4
Incoloy 800	22 Cr, 30 Ni	159	-12	-7.5	+2.5	+7
Inconel 601	23 Cr, 60 Ni	145	-12	-8	+4	+3
Inconel 671	50 Cr, 50 Ni	285	-12	-4	+3	+3
309 SS	23 Cr, 14 Ni	160	-15	-14	+4	+5

[a] Multi-specimen wafers about 1 mm thick with faces oriented at 90°, 45°, 5° and -5° to particle flow were subjected to erosion in a high-temperature flame erosion apparatus; temperature 990° C (achieved by passing current through samples and by heating the propellant gas-particle mixture); abrasive 240 mesh Al_2O_3; flow rate 3.8 g/min; average particle velocity 46 m/s (measured by rotating disk, time-of-flight method); air flow rate 180 ft^3/h, oxygen flow rate 4.0 ft^3/h, propane flow rate 40 ft^3/h (reducing conditions); test duration 50 minutes.

[b] Value for as-received alloy, ambient temperature.

Alloy Type	Major Alloying Constituents	Hardness HK_{200}[e]	Weight Loss[c]				Penetration[d]			
			25°C		500°C		25°C		500°C	
			5 µm	50 µm	5 µm	50 µm	5 µm	50 µm	5 µm	50 µm
250 MS	18 Ni, 9 Co, 5 Mo	386	0.08	0.12	0.04	0.95	10	9	0.5	16
446 SS	25 Cr, 1 Si, 1.5 Mn	214	0.05	0.05	0.01	0.20	10	6	0.6	11
304 SS	19 Cr, 10 Ni	198	0.05	0.47	0.02	0.26	7	26	0.2	12
316 SS	17 Cr, 12 Ni	321	0.04	0.10	0.01	0.21	7	9	0.8	13
310 SS	25 Cr, 21 Ni	415	0.03	0.09	0.02	0.20	5	9	0.8	13
Incoloy 800	22 Cr, 30 Ni	382	0.06	0.32	0.01	0.26	8	20	0.4	18
Inconel 601	23 Cr, 60 Ni	440	0.06	0.30	<0.01	0.19	8	20	0.4	14
Inconel 671	50 Cr, 50 Ni	427	0.02	0.11	0.01	0.15	4	9	0.4	13
Haynes 8C77	16 Cr, 4 Al + Ni + Y_2O_3			0.16		0.38		5		16
Chromium (rolled, ductile, ultra pure)		230		0.14		0.11		9		8
Chromium-low Fe alloy		587		0.26		0.21		7		6
Chromium plate on steel		985		0.13		0.05		4		5

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[a] Abrasive material is metallographic polishing grade Al_2O_3 with a narrow size distribution; two particle sizes were used, 5 µm and 50 µm; Al_2O_3 hardness HK_{200} 2100[e] at 25° C.

[b] Metal specimens typically 3 cm long, 1 cm wide and 0.5 mm thick were subjected to erosion in an air-abrasive jet device; Al_2O_3 abrasive propelled by CO_2; particle velocity 30 m/s as measured by rotating disk, time-of-flight method; angle of impingement 45°; exposure time 2 minutes; high temperature achieved by passing current through samples up to 200 amperes at 10 volts and by heating the propellant gas-particle mixture.

[c] Weight Loss = weight loss of sample (mg)/weight of abrasive used (g); weight loss was determined by direct weighing after exposure and cleaning; results are the average of tests on 5 specimens of each alloy.

[d] Penetration = penetration in sample (µm)/weight of abrasive used (g); penetration measured by microscopic or micrometer methods to ±1 to 10 µm depending on surface; results are the average of tests on 5 specimens of each alloy.

[e] HK = Knoop Hardness.

EFFECT OF DIFFERENT ABRASIVES ON THE EROSION[a] OF TYPE 304 SS[21]

Abrasive	Particle Size	Hardness HK,[d] 25°C	Weight Loss[b] 25°C	Weight Loss[b] 500°C	Penetration[c] 25°C	Penetration[c] 500°C
Al_2O_3	5 μm	2100	0.05	0.02	7	0.2
Al_2O_3	50 μm	2100	0.47	0.26	26	12
Pumice 4F	5-50 μm	560	0.21	0.04	29	2.7
Pumice F	5-100 μm	560	0.10	0.03	8	1.7
SiO_2	5-50 μm	820	0.50	0.21	45	12

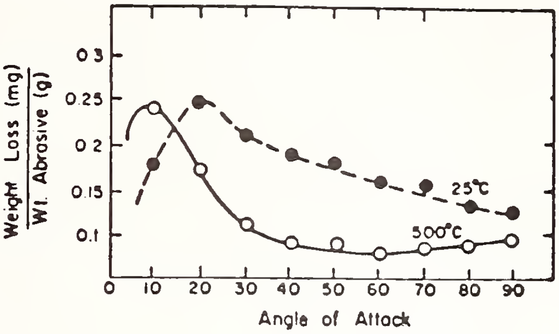
[a] Metal specimens typically 3 cm long, 1 cm wide and 0.5mm thick were subjected to erosion in an air-abrasive jet device; CO_2 propellant; particle velocity 30 m/s as measured by rotating disk, time-of-flight method; angle of impingement 45°; exposure time 2 minutes; high temperature achieved by passing current through samples up to 200 amperes at 10 volts and by heating the propellant gas-particle mixture.

[b] Weight Loss = weight loss of sample (mg)/weight of abrasive used (g); weight loss was determined by direct weighing after exposure and cleaning.

[c] Penetration = penetration in sample (μm)/weight of abrasive used (g); penetration measured by microscopic or micrometer methods to ±1 to 10 μm depending on surface.

[d] HK = Knoop Hardness.

EFFECT OF IMPINGEMENT ANGLE AND TEMPERATURE ON THE EROSION[a] OF 304 SS[21]



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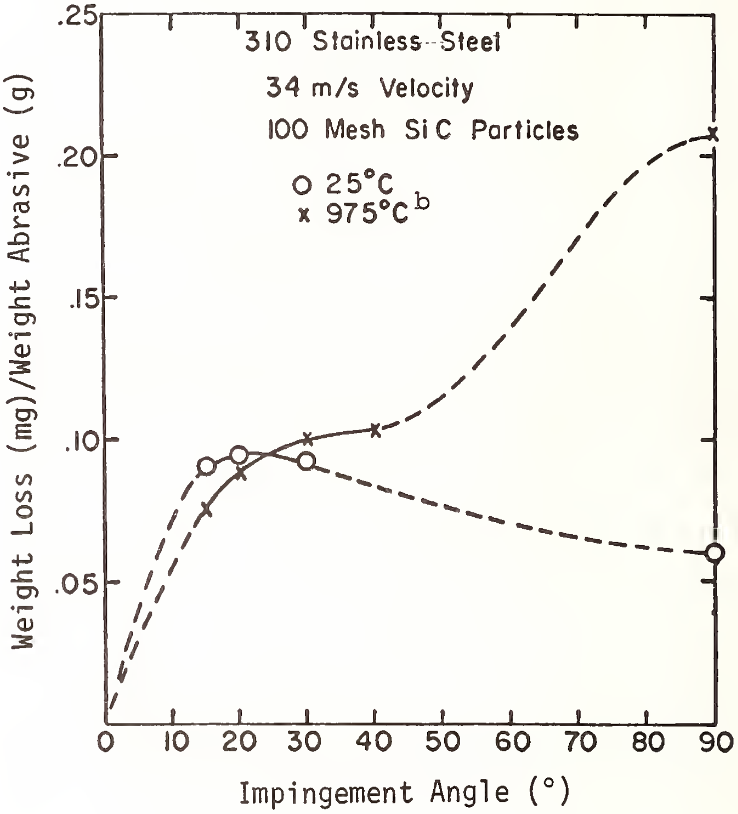
[a] Specimens were subjected to erosion in an air-abrasive jet device; CO_2 propellant; particle velocity 30 m/s as measured by rotating disk, time-of-flight method; abrasive Al_2O_3, particle size 50 μm; particle flow rate 5 g/min; 2 min test duration.

EFFECT OF IMPINGEMENT ANGLE AND TEMPERATURE ON THE EROSION[a] OF 310 SS[21]



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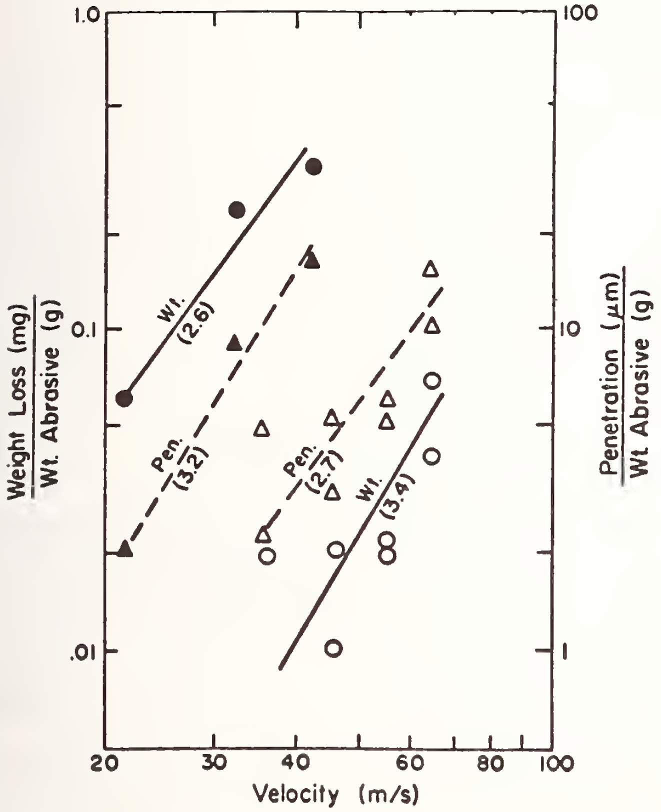
[a] Specimens were subjected to erosion in a flame-erosion apparatus; each point is the accumulated average of a number of tests of about one hour duration on a single sample.

[b] Tests at 25 °C were conducted in air; tests at 975 °C were in an air-oxygen-propane mixture, composition approximately 65% N_2, 10% O_2, 10% CO_2, and 15% H_2O (oxidizing atmosphere).

EFFECT OF EROSION PARTICLE[a] SIZE ON THE EROSION[b] OF TYPE 304 SS[21]



Particle Size

○ △ 5 μm Al_2O_3

● ▲ 50 μm Al_2O_3

Angle of Impingement
90°

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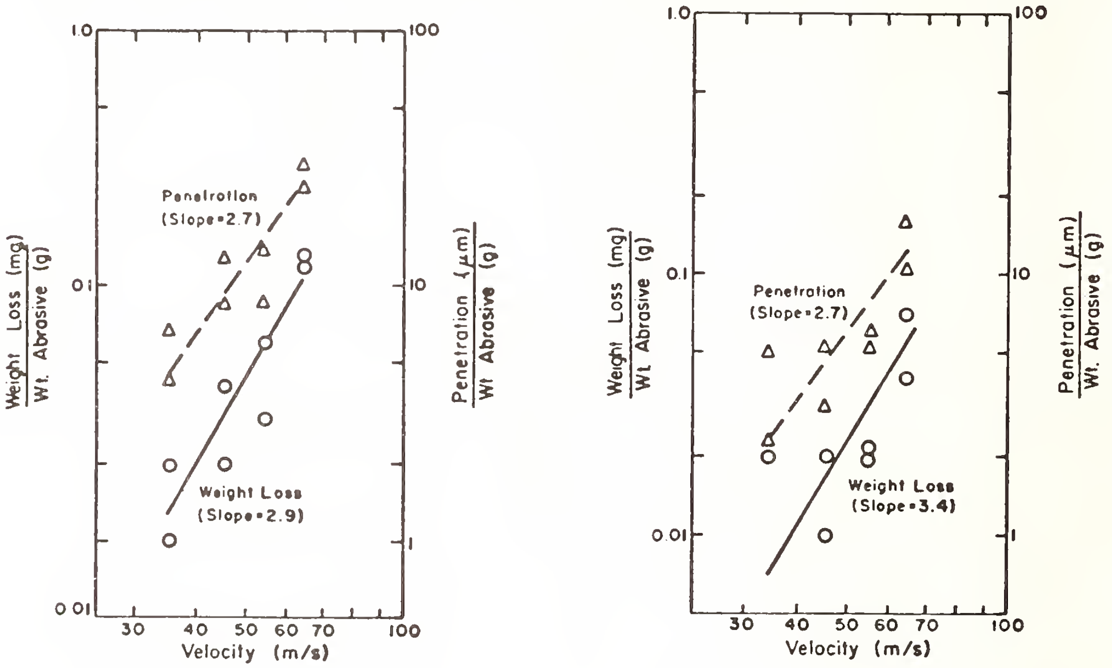
[a] Abrasive material is metallographic polishing grade Al_2O_3 with a narrow size distribution; Knoop hardness HK_{200} 2100 at 25 °C; particle size as indicated.

[b] Metal specimens typically 3 cm long, 1 cm wide and 0.5 mm thick were subjected to erosion in an air-abrasive jet device; CO_2 propellant; particle velocities measured by rotating disk, time-of-flight method; angle of impingement as indicated; temperature 25 °C; abrasive flow rate 5 g/min.

EFFECT OF ANGLE OF IMPINGEMENT ON THE EROSION[a] OF TYPE 304 SS[21]



Impingement Angle 45° Impingement Angle 90°

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[a] Metal specimens typically 3 cm long, 1 cm wide and 0.5 mm thick were subjected to erosion in an air-abrasive jet device; CO_2 propellant; particle velocities measured by rotating disk, time-of-flight method; angle of impingement as indicated; temperature 25 °C; abrasive flow rate 5 g/min. Abrasive material is metallographic polishing grade Al_2O_3 with a narrow size distribution; Knoop hardness HK_{200} 2100 at 25 °C; particle size 5 μm.

EROSION TEST[a] DATA FOR MARTENSITIC STEEL-BONDED CARBIDES[1]

Material[b]	Composition	Relative Erosion Factor[c] 20° C, 90° imp[d]	 350° C, 90° imp[d]	 550° C, 90° imp[d]
FeWC-33		0.73	0.86	1.01
AZ-31HF	TiC in H-13 die steel	1.14	1.16	1.24
AZ-30HS 42	TiC in M-42 steel	1.10	1.33	1.48
AZ-20-1	TiC-(Fe,Ni,Cr,Mo)C	1.11	1.23	1.23
FeTiC-23	TiC-(Fe,Ni,Cr,Mo)C	1.14	1.26	1.26
FeTiC-29HS 10	TiC in M-10 die steel	1.12	1.35	1.03
AZ-27Cr	TiC in D_2 die steel	1.14		

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[a] Erosion test conditions: 1/2-inch square specimens are subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Source of materials, Oregon Graduate Center; all materials pressed and sintered.

[c] Relative Erosion Factor = $\frac{\text{Volume Loss of Sample}}{\text{Volume Loss of Stellite 6B}}$; volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[d] imp = angle of impingement.

EROSION TEST[a] DATA FOR TUNGSTEN CARBIDES[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
WC, <1.5% Co binder	K-602	Kennametal	0.01	0.11	0.13
WC, 5.8% binder, p&s[d]	K68	Kennametal		0.43	0.50
WC, 6% Co binder, p&s[d,e]	Carboloy 883	Carboloy		0.38	1.53
WC, 6% Co binder, p&s[d,e]	Carboloy 895	Carboloy		0.19	1.32
WC, 6% Co binder, p&s[d,e]	CA 4	Carmet Co.		0.25	0.47
WC, 6% Co binder, p&s[d,e]	CA 306	Carmet Co.		0.23	0.36
WC, 6% Co binder, p&s[d,e]	2A5	Fansteel		0.33	0.48
WC, 6% Co-1% Cr binder, p&s[d]	K-714	Kennametal	0.01	0.26	0.25
WC, 6% Ni binder, p&s[d]	K-801	Kennametal		0.32	0.46
WC, 7% Co binder, p&s[d,e]	VR 54	Fansteel		0.32	0.50
WC, 8.8% Co binder, p&s[d]	K86	Kennametal		0.78	1.03
WC, 11.5% binder, p&s[d]	K94	Kennametal		0.57	0.84
WC, 10.2% Co-4% Cr binder, p&s[d]	K-701	Kennametal	0.02	0.25	0.47
WC-11.5TaC-8TiC-8.5Co	GE 370		0.07	0.56	
WC, 25% binder, p&s[d]	K90	Kennametal		1.01	1.21
WC-12TiC-10TaC-CbC-6.5Co, p&s[d,e]	VR 73	Fansteel		0.57	0.89
WC, unknown bond (TiC coating), p&s[d,e]	Carboloy 523	Carboloy		0.31	0.72
WC, dispersion strengthened	Ramet I		0.02	0.35	
Borofuse[f] WC		MDC[g]	0.01	0.02	0.72
90WC-5Co-5Ni, p&s[d]	5S-3	Oregon[h]		0.61	0.87
92(W,Cr)C-8Ni, p&s[d]	9S-3	Oregon[h]		0.46	0.86
90(W,Cr)C-10Ni, p&s[d]	10S-3	Oregon[h]		0.62	0.92
88(W,Cr)C-12Ni, p&s[d]	11S-3	Oregon[h]		0.82	0.99
WC, 12.2% binder, p&s[d]	3109	Kennametal		0.62	0.80
WC, 7.8% binder, p&s[d]	3406	Kennametal		0.42	0.49

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] p&s = pressed and sintered.

[e] These materials experienced slight oxidation at 700° C.

[f] Borofuse = a patented diffusion-bonded boriding surface treatment.

[g] MDC = Materials Development Corporation.

[h] Oregon = Oregon Graduate Center.

ABRASION TEST[a] DATA FOR VARIOUS MATERIALS[1]

Material	Test Condition[b]	Volume Loss[c] Upper Sample	Volume Loss[c] Lower Sample	Improvement over Mild Steel[d]
Mild Steel	abrasive	0.0535	0.0368	1[e]
	no abrasive	0.1833	0.1797	0.25
	abrasive, heat, steam	0.1375	0.1282	0.34
Borofuse[f] Mild Steel	no abrasive	0.0169	0.0214	2.4
WC coating[g] (0.003 in) on mild steel	abrasive			2.27
T-800 coating[g] (0.003 in) on mild steel	abrasive			3.57
Graph-Air tool steel	abrasive	0.0007	0.0029	25.1
	no abrasive			45.6
	-14 mesh coal			150.5
	-14 mesh ash			53.1
316 SS	abrasive	0.0277	0.0288	1.60
	abrasive, heat, steam	0.0523	0.0533	0.86
Borofuse 316 SS	no abrasive	0.0004	0.0005	103.8
24% Chromium White Iron	abrasive	0.0026	0.0024	18.1
	no abrasive	0.0004	0.0044	18.8
	-14 mesh coal			66.4
	-14 mesh ash			36.5
AISI 4140	abrasive	0.0145	0.0148	3.08
	no abrasive	0.0458	0.0308	1.18
Stellite 6	abrasive	0.0088	0.0132	4.10
	no abrasive	0.0054	0.0059	7.99
	abrasive, heat, steam	0.0131	0.0147	3.25
Borofuse[f] Stellite 6	no abrasive	0.0088	0.0088	5.2
Borofuse[f] 440C SS	no abrasive	0.0005	0.0007	71.5
LW-IN40[h]	no abrasive	0.0001	0.00004	917.9
LC-4[h]	no abrasive	0.0003	0.0004	146.5
HC-250	no abrasive	0.0011	0.0010	42.0
SPA[i]	no abrasive	0.0252	0.0214	1.9

[a] Abrasion resistance was measured by thrust washer wear testing: 1 1/4-inch outer diameter washers were manufactured from the materials; two washers were contacted under a load of 110 psi; the top sample rotated against the stationary lower sample at a rate of 100 cycles per minute; abrasive was entrapped between the two washers; test duration was 4000 cycles.

[b] Abrasive = 27μ Al_2O_3; heat = externally applied heat 250°C; steam = introduction of steam between the two washers.

[c] Volume loss, calculated from weight loss and density data, is given in cubic centimeters.

[d] $\text{Improvement over Mild Steel} = \frac{\text{Total Volume Loss of Mild Steel (tested with } Al_2O_3)}{\text{Total Volume Loss of Samples}}$, where Total Volume Loss equals the sume of the volume loss of both upper and lower washer samples.

[e] Mild steel tested with alumina abrasive only is the standard against which all others are compared.

[f] Borofuse = a patented diffusion-bonded boriding surface treatment.

[g] A modified plasma spray process developed by Specom, Inc.

[h] These coating materials also had outstanding abrasion resistance when tested against other materials.

[i] An Abex Inc. alloy.

ABRASION TEST[a] DATA FOR 316 SS PAIRED WITH VARIOUS ALLOYS[1]

Material	Test Condition[b]	Volume Loss[c] 316 SS (upper)	Volume Loss[c] Lower Sample	Improvement over Mild Steel[d]
PTFE (polytetrafluoroethylene)	abrasive	0.0016	0.0394	2.20
	abrasive, heat, steam	0.0004	0.0374	2.39
Graph-Air tool steel	abrasive			8.8
	no abrasive	0.0009	0.0027	24.41 21.5[e]
	abrasive, heat, steam	0.0029	0.0058	10.4
Stellite 6	no abrasive	0.0012	0.0103	
	abrasive, heat, steam	0.0029	0.0177	4.38
	fly ash[f]	0.0029	0.0063	
24% Chromium iron	abrasive			8.4
	no abrasive			5.6
	abrasive, heat, steam	0.0026	0.0114	6.45
LW-IN40	no abrasive	0.0019	0.0005	37.4
LC-4	no abrasive	0.0173	0.0433	1.5
No. 90 Alloy Tig[g]	no abrasive	0.0107	0.0003	8.25
No. 90 Alloy Arc[g]	no abrasive	0.0038	0.0074	8.07
No. 94 Alloy Tig[g]	no abrasive	0.0127	0.0002	6.98
No. 94 Alloy Arc[g]	no abrasive	0.0106	0.0006	8.08
Comp. 4E[g]	no abrasive	0.0056	0.0017	12.63
Comp. 2 Tig[g]	no abrasive	0.0175	0.0057	3.89
Comp. 2 Arc[g]	no abrasive	0.0195	0.0033	3.95
No. 21 Alloy Tig[g]	no abrasive	0.0122	0.0034	5.78
No. 1 Alloy Tig[g]	no abrasive	0.0165	0.0029	4.65
No. 1 Alloy Arc[g]	no abrasive	0.0209	0.0022	3.92
1016 Alloy Tig[g]	no abrasive	0.0172	0.0103	3.28
1016 Alloy Arc[g]	no abrasive	0.0151	0.0017	5.37
Comp. 40E[g]	no abrasive	0.0113	0.0009	7.37

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[a] Abrasion resistance was measured by thrust washer wear testing: 1 1/4-inch outer diameter washers were manufactured from the materials; two washers were contacted under a load of 110 psi; the top sample (all 316 SS in this series) rotated against the stationary lower sample at a rate of 100 cycles per minute; abrasive was entrapped between the two washers; test duration was 4000 cycles.

[b] Abrasive = 27μ Al_2O_3; heat = externally applied heat 250°C; steam = introduction of steam between the two washers.

[c] Volume loss, calculated from weight loss and density data, is given in cubic centimeters.

[d] Improvement over Mild Steel = $\frac{\text{Total Volume Loss of Mild Steel (tested with } Al_2O_3\text{)}}{\text{Total Volume Loss of Samples}}$, where Total Volume Loss equals the sum of the volume loss of both upper and lower washer samples.

[e] Value appearing in another of the series of reports.

[f] Fly ash = top ash produced in the Morgantown Energy Research Center Gas Producer.

[g] Tig = tungsten-inert gas overlay, Arc = arc-welded overlay. All alloys from Cabot Corp. Compositions given as:

No. 90 Alloy = 27Cr-2.75C-bal Fe
No. 94 Alloy = 29Cr-3Co-3.3C-bal Fe
Comp. 4E = 40% Haynes 47-60% Stellite 954
Comp. 2 = 60% WC-40% Stellite 6
No. 21 Alloy = 27Cr-5Mo-2.8Ni-0.25C-bal Co
No. 1 Alloy = 30Cr-12W-2.5C-bal Co
1016 Alloy = 32Cr-17W-2.5C-bal Co
Comp. 40E = 14Cr-4Si-4Fe-3.4B-0.75C-bal Ni

ABRASION TEST[a] DATA FOR 440C SS PAIRED WITH VARIOUS ALLOYS[1]

aterial	Test Condition	Volume Loss[b] 440C SS (upper)	Volume Loss[b] Lower Sample	Improvement over Mild Steel[c]
tellite 6	no abrasive	0.0001	0.0101	
	fly ash[d]	0.0003	0.0088	
	fly ash, steam,[e] external heating to 500°F	0.0020	0.0044	
o. 90 Alloy Tig[f]	no abrasive	0.0016	0.0027	20.89
o. 90 Alloy Arc[f]	no abrasive	0.0104	0.0017	7.44
o. 94 Alloy Tig[f]	no abrasive	0.0012	0.0019	28.71
o. 94 Alloy Arc[f]	no abrasive	0.0013	0.0023	25.42
omp. 4E[f]	no abrasive	0.0019	0.0010	31.69
omp. 2 Tig[f]	no abrasive	0.0027	0.0011	23.61
omp. 2 Arc[f]	no abrasive	0.0037	0.0011	18.80
No. 21 Alloy Tig[f]	no abrasive	0.0041	0.0083	7.24
No. 1 Alloy Tig[f]	no abrasive	0.0063	0.0060	7.36
No. 1 Alloy Arc[f]	no abrasive	0.0041	0.0027	13.40
1016 Alloy Tig[f]	no abrasive	0.0059	0.0062	7.44
1016 Alloy Arc[f]	no abrasive	0.0051	0.0025	11.93
Comp. 40E[f]	no abrasive	0.0001	0.0028	31.73

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[a] Abrasion resistance was measured by thrust washer wear testing: 1 1/4-inch outer diameter washers were manufactured from the materials; two washers were contacted under a load of 110 psi; the top sample (all 440C SS in this series) rotated against the stationary lower sample at a rate of 100 cycles per minute; abrasive was entrapped between the two washers; test duration was 4000 cycles.

[b] Volume loss, calculated from weight loss and density data, is given in cubic centimeters.

[c] $$\text{Improvement over Mild Steel} = \frac{\text{Total Volume Loss of Mild Steel (tested with } Al_2O_3)}{\text{Total Volume Loss of Samples}},$$
where Total Volume Loss equals the sum of the volume loss of both upper and lower washer samples.

[d] Fly ash = top ash produced in the Morgantown Energy Research Center Gas Producer.

[e] Steam = introduction of steam between the two washers.

[f] Tig = tungsten-inert gas overlay, Arc = arc-welded overlay. All alloys from Cabot Corp. Compositions given as:

No. 90 Alloy = 27Cr-2.75C-bal Fe
No. 94 Alloy = 29Cr-3Co-3.3C-bal Fe
Comp. 4E = 40% Haynes 47-60% Stellite 954
Comp. 2 = 60% WC-40% Stellite 6
No. 21 Alloy = 27Cr-5Mo-2.8Ni-0.25C-bal Co
No. 1 Alloy = 30Cr-12W-2.5C-bal Co
1016 Alloy = 32Cr-17W-2.5C-bal Co
Comp. 40E = 14Cr-4Si-4Fe-3.4B-0.75C-bal Ni

ABRASION TEST[a] DATA FOR MISCELLANEOUS PAIRS OF ALLOYS[1]

Materials[b]	Volume Loss[c] Upper Sample	Volume Loss[c] Lower Sample	Improvement ov Mild Steel[d]
Graph-Air tool steel LW-IN40	0.0005	0.0004	99.6
Graph-Air tool steel LC-4	0.0020	0.0009	30.9
LW-IN40 LC-4	0.0008	0.0001	105.0
Borofuse[e] 316 SS Stellite 6	0.0001	0.0065	13.8
Borofuse[e] 316 SS Borofuse Stellite 6	0.0002	0.0018	43.9
Borofuse[e] 440C SS Stellite 6	0.0006	0.0029	25.6
Borofuse[e] 440C SS Borofuse Stellite 6	0.0021	0.0086	8.5

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[a] Abrasion resistance was measured by thrust washer wear testing: 1 1/4-inch outer diameter washers were manufactured from the materials; two washers wer contacted under a load of 110 psi; the top sample rotated against the stationary lower sample at a rate of 100 cycles per minute; abrasive can be entrapped between the two washers but for the above samples, no abrasive was used; test duration was 4000 cycles.

[b] The first named of the pairs of materials is the upper sample, the second named is the lower sample.

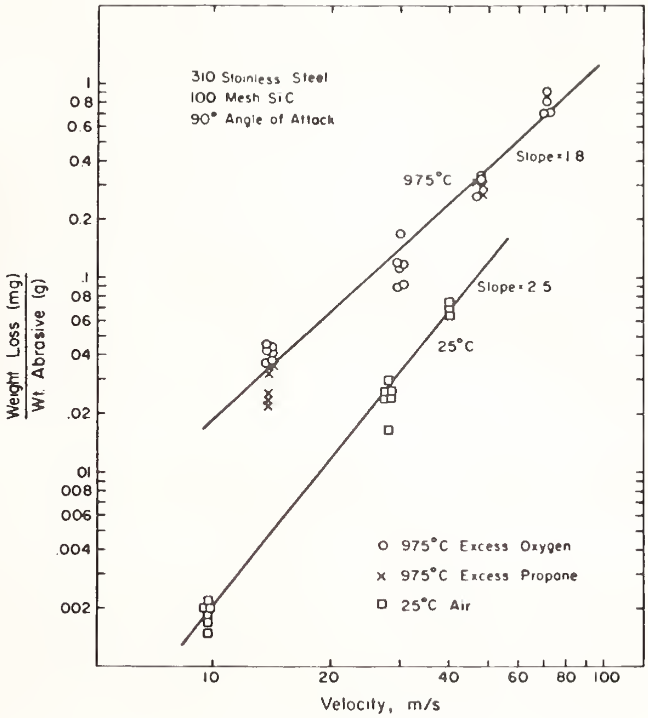
[c] Volume loss, calculated from weight loss and density data, is given in cubic centimeters.

[d] $$\text{Improvement over Mild Steel} = \frac{\text{Total Volume Loss of Mild Steel (tested with Al}}{\text{Total Volume Loss of Samples}}$$

where Total Volume Loss equals the sum of the Volume Loss of both upper and lower washer samples.

[e] Borofuse = a patented diffusion-bonded boriding surface treatment.

EFFECT OF PARTICLE VELOCITY ON EROSION[a] OF 310 SS[21]



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[a] Specimens were subjected to erosion by 100 mesh SiC; tests were for one hour except for 73 m/s at 975 °C and 40 m/s at 25 °C which lasted 1/2 hour; particle velocities measured by rotating disk, time-of-flight method; angle of impingement 90°; combustion gas atmospheres used at high temperature with the following compositions:

Excess Oxygen--

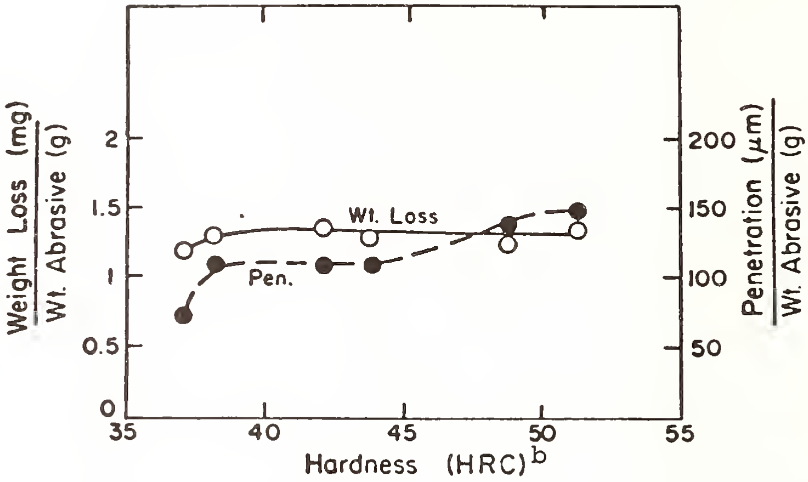
Velocity m/s	Composition, mole%			
	N_2	O_2	CO_2	H_2O
14	61	5	14	20
30	68	12	8	12
48	64	12	10	14
72	66	14	8	12

Excess Propane--

Velocity m/s	Composition, mole%						
	N_2	O_2	CO_2	CO	H_2	HC	H_2O
14	57	*	9	9	5	*	20
48	50	3	5	12	7	6	17

*Trace

EFFECT OF VARIATION OF HARDNESS ON THE EROSION[a] OF TYPE 250 MS[21]



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[a] Specimens were 18Ni-250 MS hardened to different levels and subjected to erosion by SiO_2 in an air-abrasive jet device; particle size 5-50 μm; particle velocity 17 m/s as measured by rotating disk, time-of-flight method; abrasive flow rate 5 g/min; temperature 25 °C; propellant CO_2.

[b] HRC = Rockwell C.

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11]

y/ position[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			1650			1650
Pressure, psi			atmospheric			1000
Velocity, ft/s			100			100
Time, hr			100			50
Volume % H_2S			1.0			1.0
oloy 800 e-31Ni-21Cr	0.2	130.1	Very heavy erosion, possible melting	0.2	10.8	Large E/C[g] areas, rest of sample covered with small pits
	0.2	118.2	Large deep erosion area on E/C[g] surface; general attack on back surface			
	0.2	1.0	Pitting and general attack on back surface			
	0.3	165.5	Severe attack with signs of melting			
oloy 800(Al)[h]	0.5	0.9	Pitting of coating in eroded areas	0.7	5.4	General specimen discoloration only
onel 601 e-60Ni-23Cr	0.1	1.0	Some edge attack on reverse side	0.7	53.3	Large E/C area damage and whole E/C surface very rough
	0.5	31.6	Intact scale E/C surface and general attack all surfaces			
SS Fe-20Ni-25Cr	0.4	1.7	Some edge attack on reverse side	0.3	2.0	Large E/C area damage, back of specimen pitted
	0.3	9.1	Pits all surfaces			
	0.2	14.5	Pits all surfaces; deep pits back side			
SS (Al)[h]	0.5	1.2	Few minor pits on both surfaces	0.2	0.7	General specimen discoloration only
333 Fe-45Ni-26Cr	-	0.5	No visible attack	2.8	11.0	All of E/C surface rough, back had some pits
1866 -18Cr-5Al	0.4	7.0	Many large pits on eroded surface	1.8	2.6	E/C surface covered with large very shallow pits
SS Fe-24Cr	0.3	5.6	No visible attack	0.6	1.9	Small E/C area with a compact scale still present after cleaning
	0.5	11.9	Pits all surfaces			
	0.8	1.2	Few pits E/C surface; few large shallow pits back surface			
onel 671 Ni-50Cr	0.5	0.9	No visible attack	0.7	3.8	Small E/C damage area
	0.4	0.9	Slight pitting back of specimen			
	0.3	0.9	Melt pits back surface			
	0.6	1.1	Melt pits back surface			
temp 25 Fe-25Ni-25Cr	0.4	0.6	Minor pitting at edge on reverse side	0.5	5.5	All sample pitted, most pits around E/C area
nes 188 o-23Ni-22Cr	0.2	0.5	Minor edge corrosion, reverse side	5.9	49.8	Badly corroded with melting
	0	0.7	Few pits all surfaces and general attack one corner back surface			
	0	0.2	Few pits and general attack in one corner of back surface			
-Cr-W No. 1 o-30Cr-12W				0.6	0.8	Sample discoloration under E/C impact area
ellite 6B 7Co-28Cr-3Ni	0.1	0.6	No signs of corrosion			
scalloy 30/50W e-49Ni-28Cr	1.0	3.0	Slight pitting on E/C surface; many large pits on back surface			
-40 SS e-20Ni-28Cr	0.2	6.2	Pitting attack on E/C surface			
loy X 0Fe-45Ni-22Cr-9Mo	3.7	22.6	Localized pitting on E/C surface; severe attack on back face			
nicro 32X e-32Ni-22Cr	0.3	113.8	Extensive localized E/C			
ltimet N155 9Fe-20Ni-21Cr-20Co	0.2	3.2	Pitting attack all surfaces			
ynes 150 o-18Fe-28Cr	0.2	0.7	No signs of corrosion			
pertherm T63WC e-36Ni-28Cr-15Co-5W	0.7	4.7	Extensive corrosion on back surface			
-40 SS 7Fe-19Ni-31Cr	0.1	4.0	Fine pitting attack under E/C stream; slight pits on back surface			
9 SS e-4Ni-27Cr	0.6	1.6	Slight pits on back surface			

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c][11]
(Table continued)

Alloy/ Composition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			100
Time, hr			100			100
Volume % H_2S			none, N_2 atmosphere			none, N_2 + 40% H_2O atmosphere
Incoloy 800	0.7	3.2	Some pitting evident	0.5	0.9	No visible erosion
Incoloy 800(Al)	0.2	2.1	Blackening and some roughening of coating	0.7	1.1	Some coating roughening at sides
Inconel 601	0.3	1.3	Pitting evident	0.4	6.9	Some pitting on top surface
310 SS	0.2	1.1	Small damaged area on top surface	-	0.3	No visible attack
310 SS(Al)	0.7	5.1	Blackening and some loss of coating	0.9	2.8	Some roughening of coating
RA-333	0.7	1.7	Visible attack on erosion surface	0.5	1.0	Some edge attack
LM-1866	1.5	3.5	Irregular attack on erosion surface	0.2	0.4	No visible attack
446 SS	1.5	3.0	Some pitting evident	3.7	4.3	Slight general attack visible on top surface
Inconel 671	0.6	1.6	Some pitting on erosion surface	0.7	1.2	No visible attack
Crutemp 25	0.1	1.1	No visible erosion	0.3	0.6	No visible attack
Haynes 188	0.4	1.8	Widespread top surface attack	-	0.5	Impact area visible after cleaning
Temperature, °F			1500			1800
Pressure, psi			1000			1000
Velocity, ft/s			100			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	26.9	39.7	Very heavy attack on both surfaces	23.0	50.9	Very badly attacked, both surfaces
	0.7	1.2	Slight edge attack back surface	0.3	201.3	Very deep E/C pit and slight attack on back surface
	0.5	0.7	Few pits on both surfaces			
Incoloy 800(Al)	2.0	4.5	Loss of coating from both surfaces	0.6	1.1	Coating pitted, but intact
	0.3	0.8	Dark intact scale all surfaces			
Inconel 601	23.2	33.9	Very heavy attack on both surfaces	11.3	36.2	Very badly attacked, possible melting
	0.6	4.1	Light general attack E/C surface; major general attack back surface			
310 SS	10.2	15.6	Heavy attack on both surfaces	2.8	25.3	Badly attacked, both surfaces
	0.4	0.6	No signs of attack			
310 SS(Al)	1.6	3.6	Some loss of coating from both surfaces	1.9	2.9	Coating roughened and pitted, but stil intact
	0.2	0.5	Intact dark scale over all E/C surface			
RA-333	13.9	22.9	Heavy attack on both surfaces	10.0	14.9	Possible melting on erosion surface, badly corroded
	0.2	1.2	Pitting attack all surfaces			
LM-1866	0.4	1.1	Pitting attack on both surfaces, erosion impact area visible	1.1	9.1	Visible attack on erosion surface
	0.3	0.8	Slight discoloration E/C surface			
446 SS	5.8	10.7	Eroded area visible, heavy attack on both surfaces	0.7	20.6	Pitting on erosion surface, heavy edg corrosion on reverse surface
	0.4	0.9	No signs of attack			
Inconel 671	0.7	0.9	Some edge corrosion, very little erosion	0.6	7.6	Bad edge corrosion, both surfaces
	0.6	0.8	No signs of attack	0.6	1.1	Few pits back surface
	0.2	0.8	No signs of attack			
Crutemp 25	5.8	9.7	Heavy attack on both surfaces	7.9	23.9	Heavily pitted on both surfaces
	0.3	0.8	Slight discoloration E/C surface			
Haynes 188	11.0	17.4	Heavy attack on both surfaces	17.2	75.7	Very deep erosion pit, possible meltin reverse side corrosion
	0.6	1.1	Very slight general attack E/C surface			
Co-Cr-W No. 1	0.2	0.7	Discoloration all surfaces			
	0.2	0.2	No signs of any attack; slight discoloration on back surface			
Stellite 6B	0.2	0.2	No signs of attack	0.1	1.1	No signs of attack
Wiscalloy 30/50W	0.1	0.1	Few pits on back surface	0.2	17.7	Small shallow E/C pit; back surface badly edge attacked
HK-40 SS	0.8	1.3	No signs of attack on E/C or back surface; 2 small pits on sides	0.2	1.8	Pits all surfaces
Alloy X	0.6	0.6	Many small pits on E/C side; larger pits on back	0.3	122.8	Major attack E/C surface and edge attack back surface
Sanicro 32X	0.1	0.4	Light general attack over all E/C surface	0.2	72.2	Large E/C attack and edge attack back surface
Multimet N155	0.4	0.7	Fine pits on erosion area	0.6	147.6	Major E/C pit
Haynes 150	0.2	0.2	No signs of attack	0.3	127.3	Major E/C pit
Supertherm T63WC	0.6	0.8	Few pits in E/C surface	1.3	52.3	Major general attack all surfaces
HL-40 SS				0.1	4.2	Slight E/C pits & edge attack back sur
329 SS				1.2	1.7	Slight intact scale back surface
Fe-36Cr-36Ni	0.3	0.3	No signs of attack			

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[e][11]
(Table continued)

lloy/ Composition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			1800			1800
Pressure, psi			1000			1000
Velocity, ft/s			100			50
Time, hr			50			50
Volume % H_2S			0.1			1.0
ncoloy 800	11.4	62.3	Very deep erosion pit, possible melting	0.4	33.6	Localized E/C area; some back surface corrosion
ncoloy 800(Al)	1.6	3.6	Some discoloration and roughening of coating	0.9	1.9	No visible E/C
nconel 601	0.4	169.5	Very deep erosion damage, minimal corrosion	5.1	135.1	Deep localized E/C; some back surface corrosion
10 SS	2.2	8.1	Small erosion pit	1.0	5.0	Limited shallow pitting
10 SS(Al)	2.1	3.6	Bottom surface, some corrosion on coating	0.3	1.3	No visible E/C
A-333	3.2	8.1	Erosion pit, reverse surface corrosion	0.9	90.4	Deep E/C and corrosion, both surfaces
M-1866	0.4	0.8	Some edge corrosion	14.9	16.9	Some general E/C
46 SS	0.7	9.1	Erosion damage and reverse surface corrosion	0.9	7.3	Localized E/C near edge; some back surface corrosion
Inconel 671	0.6	1.1	Some pitting and edge corrosion	1.0	2.5	Localized pitting
rutemp 25	0.4	64.4	Deep erosion damage, extensive corrosion	0.7	1.7	Localized pitting
Haynes 188	1.0	2.0	Some corrosion on reverse surface	0.5	106.0	Deep localized E/C; some back surface corrosion
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100	TEST WITH FINE FMC CHAR[c]		100
Time, hr			100			100
Volume % H_2S			1.0			1.0
Incoloy 800	0.6	27.4	Large area erosion-corrosion. Some back surface corrosion	0.6	25.6	Heavy erosion damage, possible melting
	0.2	68.8	Large erosion surface and gold colored intact scale on E/C surface; gold scale also on back surface			
	0.2	44.4	Large eroded surface with intact gold colored scale on E/C surface			
	0.4	4.4	Localized E/C, back surface corrosion			
Incoloy 800(Al)	0.9	3.6	Localized pitting, erosion surface	0.8	5.6	Loss of coating on erosion surface
Inconel 601	0.2	15.8	Two areas of erosion-corrosion. Localized back surface corrosion	0.2	5.7	Distinctive pitting on both surfaces
	2.7	26.3	General corrosion all surfaces			
310 SS	0.5	12.1	Areas of pitting, erosion surface	0.7	14.8	Heavy pitting/corrosion around impingement zone
	0.1	12.2	Pits all surfaces but less attack under erosion stream			
	0.4	13.0	Pits all surfaces but less attack under erosion stream			
310 SS(Al)	1.2	1.5	Few minor pits, erosion surface	1.9	4.6	Loss of coating around impingement zone and on reverse surface
RA-333	0.3	5.7	Area of pitting, erosion surface	1.0	13.3	Extensive pitting around impingement zone and on reverse surface
LM-1866	1.1	14.4	Several large pits on erosion surface	0.3	16.8	Extensive attack around impingement zone
446 SS	0.7	18.6	Area with numerous pits, erosion surface	5.6	15.5	Heavy pitting/corrosion on erosion surface
	0.7	10.4	Intact scale all surfaces, large E/C area			
	0.5	15.9	Intact scale all surfaces, large E/C area with large pits			
Inconel 671	0.1	3.9	Area of shallow pits, erosion surface	1.1	7.0	Pitting/corrosion on erosion surface
	0.5	0.8	Intact scale under E/C stream, and melt pit bottom surface			
	0.4	1.5	Intact scale under E/C stream			
	0.5	8.2	Limited E/C, little back surface corrosion			
Crutemp 25	0.7	10.9	Numerous small pits, erosion surface	3.7	11.9	Extensive attack on erosion surface
Haynes 188	0.2	2.5	Few small pits, erosion surface	0.7	5.3	Pitting extensive on erosion surface
	0.3	1.5	Fine pits all surfaces, major attack back surface			
	0.3	0.7	Fine pits all surfaces			

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11]
(table continued)

Alloy/ Composition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Co-Cr-W No. 1	0.3	1.3	Very limited E/C.			
Stellite 6B	0.4	0.9	Few small E/C pits			
Wiscalloy 30/50W	0.2	1.3	Localized E/C pits, back surface corrosion			
HK-40 SS	1.4	6.4	Area of E/C			
Alloy X	0.6	2.1	Localized small pits on erosion surface			
Sanicro 32X	0.7	15.7	Localized significant E/C			
Multimet N155	0.6	4.6	Some pitting of erosion surface			
Haynes 150	0.7	2.2	Few small pits on erosion surface			
Supertherm T63WC	0.8	2.8	Limited E/C, localized back surface corrosion			
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			50
Time, hr			100			100
Volume % H_2S			0.5			1.0
Incoloy 800	0.1	98.1	Heavy erosion, possible melting	0.4	2.3	Few erosion surface pits
Incoloy 800(Al)	0.8	1.5	Loss of coating around inpingement area	1.2	5.6	Few erosion surface pits
Inconel 601	0.1	1.8	Some reverse surface corrosion	0.3	12.1	Area of significant erosion. Significar back surface corrosion
310 SS	0.2	1.9	Pitting on erosion surface; reverse surface edge corrosion	0.4	6.8	One small erosion pit
310 SS(Al)	0.5	2.0	Pitting on erosion surface and reverse surface	1.3	2.6	Surface roughening erosion surface
RA-333	0.2	0.6	Pitting on erosion surface	0.2	19.4	Large area of erosion
LM-1866	0.3	5.6	Well defined circular erosion area	1.1	2.7	Few small erosion pits
446 SS	0.6	1.3		0.9	3.9	Two erosion pits
Inconel 671	0.3	0.7	No visible attack	0.6	0.5	Few minor pits, one eroded edge
Crutemp 25	0.5	0.9	Pitting on erosion surface	0.3	2.3	Few minor erosion pits
Haynes 188	0.2	1.2	Blistering and pitting on erosion surface	0.4	7.9	Small area of erosion

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[a] Alloy samples 1 x 1 x 1/4-in were subjected to erosion in coal gasification atmosphere (1 test was run in N_2 and 1 in $N_2 + H_2O$) under the indicated conditions, impingement angle 45°; values are for one specimen per test; some materials were included in more than one test.

[b] Coal gasification atmosphere input gas: 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, either 0.1, 0.5 or 1.0% H_2S and the balance H_2O.

[c] Char from Western Kentucky coal prepared by COED process, -20 + 40 mesh (840 to 420 μm) used in all tests but one. That test was run with fine FMC char, -100 +140 mesh (149 to 105 μm).

[d] Average corrosion of the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in uneroded area.

[e] Maximum effect on the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in eroded area and pits.

[f] Approximate values only for major constituents; compositions given for alloy the first time it appears in Table.

[g] E/C = erosion/corrosion.

[h] Aluminum coating applied to specimens by pack diffusion process by Alon Processing Inc. (Alonized).

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY DOLOMITE[b] AND ALUMINA[c] IN COAL GASIFICATION ATMOSPHERE[d] [11]

loy/ omposition[e]	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments
Erodent			Dolomite[c]			Dolomite[c]
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			100
Time, hr			50			50
Volume % H_2S			0.1			1.0
coloy 800 7Fe-31Ni-21Cr	0.4	0.8	No visible erosion	0.4	0.6	No visible attack
coloy 800(Al)[h]	0.7	0.8	Slight pitting	0.3	0.6	Minor tarnishing of erosion side
conel 601 6Fe-60Ni-23Cr	0.1	0.3	No visible erosion	0.4	0.5	No visible attack
0 SS 2Fe-20Ni-25Cr	0.2	0.3	No visible erosion	0.3	0.5	No visible attack
0 SS(Al)[h]	0.8	1.2	Slight pitting	0.6	1.0	Discoloration of aluminide coating
-333 6Fe-45Ni-26Cr	0.3	0.4	No visible erosion	0.4	0.5	No visible attack
-1866 e-18Cr-5Al	--	0.1	No visible erosion	0.2	0.7	Significant edge corrosion
46 SS 75Fe-24Cr	0.2	0.4	No visible erosion	0.3	0.6	No visible attack
nconel 671 48Ni-50Cr	0.6	0.8	No visible erosion	0.5	0.8	Slight pitting on erosion surface
rutemp 25 47FE-25Ni-25Cr	--	0.3	No visible erosion	0.4	0.6	Pitting on erosion surface
aynes 188 Co-23Ni-22Cr	0.3	0.4	No visible erosion	0.3	0.6	No visible attack
Erodent			**Alumina[d]**			**Alumina[d]**
Temperature, °F			**1800**			**1800**
Pressure, psi			**atmospheric**			**atmospheric**
Velocity, ft/s			**50**			**100**
Time, hr			**50**			**50**
Volume % H_2S			**1.0**			**0.5**
ncoloy 800	0.8	5.8	General overall corrosion and pits on E/C[i] surface	0.5	15.0	Large general attack E/C[i] surface
ncoloy 800(Al)	0.9	8.9	Localized E/C area stain and a few pits on E/C surface	0.2	0.8	Intact dark scale E/C surface
nconel 601	0.2	0.7	Back surface pitting attack	0.2	7.7	General attack E/C surface
10 SS	0.5	2.5	E/C surface many small pits	0.2	20.2	General attack E/C surface
10 SS(Al)	0.3	1.3	Slight discoloration only	0.5	1.5	Intact dark scale E/C and back surface
A-333	0.2	7.6	Pitting and general corrosion on E/C surface; general overall corrosion on back side edges	0.4	11.4	General attack on E/C and back surface
M-1866	0.3	1.3	Large shallow pits on E/C surface	0.2	1.8	Light general attack E/C surface
446 SS	0.5	1.5	Scale still attached to E/C surface and slight edge pitting attack on back surface	0.5	1.7	Scale still intact on E/C surface
Inconel 671	0.1	0.5	Very localized E/C area pit	0.5	3.0	Localized pitting on E/C surface
Crutemp 25	0.5	14.0	Large E/C area with some scale still attached	0.2	16.0	Pitting attack and general attack on E/C surface
Haynes 188	0.2	1.2	Slight pitting over all E/C surface	0.2	1.2	Very slight surface attack E/C surface
Co-Cr-W No. 1 Co-30Cr-12W	0.2	0.2	Surface discoloration	0.2	0.2	Intact scale on E/C surface

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY DOLOMITE[b] AND ALUMINA[c] IN COAL GASIFICATION ATMOSPHERE[d] [11]
(Table Continued)

Alloy/ Composition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Erodent			Alumina[d]			Alumina
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			160
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	0.2	1.7	Slight pitting back surface	13.8	46.8	Extensive E/C, significant corrosion
Incoloy 800(Al)	0.4	5.4	Localized E/C; incomplete scale removal	0.3	1.3	Very limited E/C, corrosion
Inconel 601	0.7	2.2	Slight amount of scale on E/C surface	7.6	33.6	Extensive E/C, limited corrosion
310 SS	0.3	0.8	No signs of corrosion	7.8	38.8	Extensive E/C, limited corrosion
310 SS(Al)	0.9	1.9	Incomplete scale removal	0.2	1.2	Very limited E/C, corrosion
RA-333	0.2	1.2	Slight E/C area damage	14.4	51.4	Extensive E/C, significant corrosion
LM-1866	0.9	2.9	Corrosion product still attached to sample	1.9	4.4	Limited E/C, corrosion
446 SS	0.7	2.2	Localized E/C area	1.7	5.2	Limited E/C, corrosion
Inconel 671	0.6	1.6	Some corrosion product still attached to sample	0.7	1.7	Very limited E/C, corrosion
Crutemp 25	0.4	1.9	Localized E/C area, back side pitting	9.3	43.3	Extensive E/C, limited corrosion
Haynes 188	0.5	1.0	No signs of corrosion	3.4	11.3	Significant E/C, limited corrosion
Co-Cr-W No. 1	0.1	1.6	No signs of corrosion			
Erodent			Alumina[d]			
Temperature, °F			1800			
Pressure, psi			atmospheric			
Velocity, ft/s			200			
Time, hr			50			
Volume % H_2S			1.0			
Incoloy 800	24.1	84.1	Very extensive E/C, some corrosion			
Incoloy 800(Al)	4.1	49.6	Extensive E/C, coating penetrated locally			
Inconel 601	12.2	77.2	Very extensive E/C, some corrosion			
310 SS	10.0	57.0	Extensive E/C, some corrosion			
310 SS(Al)	3.6	43.6	Extensive E/C, coating penetrated locally			
RA-333	16.7	60.2	Extensive E/C, some corrosion			
LM-1866	3.8	12.3	Significant E/C			
446 SS	7.4	33.4	Extensive E/C, some corrosion			
Inconel 671	3.0	24.0	Significant E/C			
Crutemp 25	21.4	141.4	Very extensive E/C, some corrosion			
Haynes 188	14.5	82.5	Very extensive E/C, some corrosion			

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[a] Alloy samples 1 x 1 x 1/4 in were subjected to erosion in coal gasification atmosphere under the indicated conditions, impingement angle 45°; values are for one specimen per test.

[b] From Conoco Coal, -20 + 40 mesh.

[c] Tabular alumina, -20 + 40 mesh (Grade T61, Alcoa).

[d] Coal gasification atmosphere input gas in volume percent: 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, either 0.1, 0.5, or 1.0% H_2S, and the balance H_2O.

[e] Approximate values only for major constituents; composition given for alloy the first time it appears in table.

[f] Average corrosion of the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in uneroded area.

[g] Maximum effect on the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in eroded area and pits.

[h] Aluminum coating applied to specimens by pack diffusion process by Alon Processing Inc. (Alonized).

[i] E/C = erosion/corrosion.

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION[b] IN COAL GASIFICATION ATMOSPHERE[c] [11]

loy/ omposition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			1650			1650
Pressure, psi			1000			1000
Velocity, ft/s			10			100
Time, hr			100			100
Volume, % H_2S			1.0			1.0
ncoloy 800 47Fe-31Ni-21Cr	0.3	1.3	No E/C[g], limited corrosion	0.4	28.4	Extensive E/C[g], localized back surface corrosion
ncoloy 800(Al)[h]	0.4	1.4	Localized E/C erosion surface	0.4	1.4	Very limited E/C, corrosion
nconel 601 16Fe-60Ni-23Cr	0.9	2.9	Little E/C, localized corrosion on back surface	0.4	8.4	General E/C, localized back surface corrosion
10 SS 52Fe-20Ni-25Cr	0.9	1.9	Little E/C, extensive edge corrosion	0.7	8.7	Localized E/C, back surface corrosion
10 SS(Al)[h]	0.2	0.7	No E/C, limited corrosion	0.6	1.6	Very limited E/C, corrosion
A-333 16Fe-45Ni-26Cr	3.1	29.1	Significant E/C, back surface edge corrosion	5.3	23.3	Uniform pitting E/C surface, back surface corrosion
M-1866 Fe-18Cr-5Al	0.5	1.0	No E/C, limited corrosion	0.2	0.6	Limited E/C, corrosion
446 SS 75Fe-24Cr	0.4	1.4	No E/C, limited corrosion	0.2	0.6	Very limited E/C, corrosion
Inconel 671 48Ni-50Cr	1.0	10.4	Localized E/C, limited corrosion	6.7	28.7	Extensive E/C, sone corrosion
Crutemp 25 47Fe-25Ni-25Cr	0.6	1.2	No E/C, localized corrosion back surface	0.5	19.5	Localized E/C, significant back surface corrosion
Haynes 188 Co-23Ni-22Cr	0.5	11.5	Shallow localized E/C, localized corrosion back surface	12.0	25.0	Extensive E/C, corrosion
Temperature, °F			1800			1800
Pressure, psi			1000			1000
Velocity, ft/s			10			100
Time, hr			100			100
Volume, % H_2S			1.0			1.0
Incoloy 800	0.9	16.9	Localized E/C at edges, erosion surface	17.6	45.6	Extensive general E/C
Incoloy 800(Al)	0.3	0.8	Little visible attack	0.3	1.3	No visible E/C
Inconel 601	0.2	13.1	General E/C; localized corrosion, back surface	8.7	27.6	Extensive E/C with melting, both surfaces
310 SS	0.4	1.9	Minor pitting, erosion surface	0.5	8.0	Localized shallow E/C pitting
310 SS(Al)	0.5	1.5	Little visible attack	0.9	2.8	Limited visible E/C
RA-333	3.4	12.9	General E/C, erosion surface; corrosion at edges, back surface	29.6	56.6	Extensive E/C, both surfaces
LM-1866	1.0	2.9	Little E/C, slight corrosion at supports on back surface	1.1	23.0	Large shallow area on erosion surface
446 SS	0.7	1.2	Little E/C, pitting corrosion on back surface	1.3	18.8	Numerous small pits, attack at one edge
Inconel 671	0.3	0.6	Little E/C, severely corroded area at back surface support	0.7	2.1	Very limited pitting, erosion surface
Crutemp 25	0.6	1.6	Localized shallow E/C	1.1	6.1	Numerous small pits, erosion surface
Haynes 188	0.4	6.9	Localized E/C pitting, little back surface corrosion	1.0	27.5	General shallow E/C; some reverse surface corrosion

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION[b] IN COAL GASIFICATION ATMOSPHERE[c] [11]
(Table Continued)

Alloy/ Composition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			1800			1800
Pressure, psi			atmospheric			1000
Velocity, ft/s			100		PREOXIDIZED[i]	100
Time, hr			100			100.
Volume, % H_2S			1.0			1.0
Incoloy 800	0.3	0.5	No visible attack	0.8	5.8	Intact scale under erosion stream and edge attack top of E/C surface
Incoloy 800(Al)	0.7	1.2	No evidence of loss of coating	0.5	1.5	No signs of attack
Inconel 601	0.2	0.7	No visible attack	1.7	24.7	General attack all surfaces
310 SS	0.3	0.6	No visible attack	0.7	1.7	Fine pitting E/C surface
310 SS(Al)	0.4	0.5	No loss of coating	0.9	2.9	Sample discoloration
RA-333	0.2	0.4	No visible attack	3.7	26.7	General attack overall E/C surface
LM-1866	--	0.5	No visible attack	0.4	1.4	Small amount of intact scale on E/C surface
446 SS	0.4	0.5	No visible attack	0.3	5.3	General attack overall E/C surface
Inconel 671	0.6	0.7	No visible attack	0.9	1.9	Intact scale E/C surface and edge attack top of back surface
Crutemp 25	0.2	0.7	No visible attack	0.7	3.7	Light general attack all surfaces
Haynes 188	0.5	0.7	No visible attack	2.7	9.7	General attack all surfaces
Co-Cr-W No.1 Co-30Cr-12W				0.3	1.3	Intact scale E/C surface; edge attack back surface

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[a] Alloy samples 1 x 1 x 1/4 in were subjected to erosion in coal gasification atmosphere under the indicated conditions, impingement angle 45°; values are for one specimen per test.

[b] No particulate erodent was used for these tests, gas velocities were as indicated.

[c] Coal gasification atmosphere input gas in volume percent: 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, either 0.1, 0.5, or 1.0% H_2S, and the balance H_2O.

[d] Average corrosion of the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in uneroded area.

[e] Maximum effect on the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after expsoure and cleaning; measurements after exposure made in eroded area and pits.

[f] Approximate values only for major constituents; composition given for alloy the first time it appears in table.

[g] E/C = erosion/corrosion.

[h] Aluminum coating applied to specimens by pack diffusion process by Alon Processing Inc. (Alonized).

[i] Before testing, samples were preoxidized for 24 hr in coal gasification atmosphere without H_2S present.

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COARSE HUSKY CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11]

loy/ omposition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			-1650-			-1650-
Pressure, psi			atmospheric			1000
Velocity, ft/s			100			100
Time, hr			100			50
Volume % H_2S			1.0-			1.0-
ncoloy 800 47Fe-31Ni-21Cr	0.1	74.1	Severe erosion area and pitting on E/C[g] surface	0.8	12.8	Overall pits both surfaces and an erosion area on E/C[g] surface
	0.2	31.2	Large erosion/corrosion area top right corner of E/C surface	0.5	1.5	Fine pitting on E/C surface and back of specimen
				0.6	7.6	Many small pits on E/C surface; many large pits on back surface
ncoloy 800(Al)[h]	0.2	0.5	Sample discoloration	0.1	3.1	General corrosion, scale broke off E/C surface in a few areas
nconel 601 16Fe-60Ni-23Cr	0:4	2.4	Few pits all surfaces	0.1	137.6	Large erosion pit
10 SS 52Fe-20Ni-25Cr	0.2	1.8	Slight E/C area and pits on back surface	0.9	2.4	Small erosion area
10 SS (Al)[h]	0.1	1.1	Sample discoloration	0.3	1.5	General corrosion over all surfaces
A-333 16Fe-45Ni-26Cr	0.2	0.8	Few pits all surfaces	0.5	63.5	Small deep erosion pit on E/C surface; a large deep pit on back surface
M-1866 Fe-18Cr-5Al	0.2	0.2	No signs of attack.	0.6	1.1	Compact scale formed on E/C surface except on erosion area
46 SS 75Fe-24Cr	0.3	1.3	Slight E/C area	1.0	2.0	General attack on impact area on E/C side
Inconel 671 48Ni-50Cr	0.4	0.9	Edge attack back surface	0.7	1.2	Pitting attack on E/C surface
	0.7	1.7	Intact dark scale E/C surface; three edges attacked bottom surface	0.6	1.1	Few pits on E/C surface
				0.7	1.2	Slight E/C area
Crutemp 25 47Fe-25Ni-25Cr	0.2	1.2	Very slight E/C area	0.5	3.8	General attack on impact area on E/C surface
Haynes 188 Co-23Ni-22Cr	0.4	0.9	Few pits on back surface	2.4	13.4	All surfaces attacked
Co-Cr-W No. 1 Co-30Cr-12W	0.2	0.2	Sample discoloration	0.1	0.6	Surface discoloration all sides
Stellite 6B 57Co-28Cr-3Ni	0.2	0.8	No sign of attack	0.4	0.9	No signs of E/C
				0.2	0.7	Four large shallow pits on back surface
Wiscalloy 30/50W Fe-49Ni-28Cr	0.2	0.7	Intact dark scale all surfaces	1.5	10.0	Many small pits on E/C surface; few small pits on back surface
				0.5	1.5	E/C surface fine pits except none under impact stream, large pits on back surface
HK-40 SS Fe-20Ni-28Cr	0.3	0.8	Few pits top edge E/C surface	0.4	0.9	Few pits on back surface
				0.8	2.3	Many small pits on E/C surface; general and pitting attack on back surface
Alloy X 20Fe-45Ni-22Cr-9Mo	0.8	5.8	Intact scale and pits all surfaces	0.9	73.9	Severe corrosion with melting present
				-	-	Specimen completely destroyed
Sanicro 32X Fe-32Ni-22Cr	0.5	4.0	Edge attack top of E/C surface	0.2	4.8	General pitting on all surfaces and on E/C area
				0.2	11.2	Many small pits and erosion area on E/C surface; many large shallow pits on back
Multimet N155 29Fe-20Ni-21Cr-20Co	0.3	21.3	Severe attack in two areas on E/C surface near edges	0.5	9.5	Few small pits and erosion areas on E/C surface; many small & large pits on back
				0.5	4.0	General fine pitting overall, large pit E/C surface
Haynes 150 Co-18Fe-28Cr	1.0	3.0	Light general attack E/C surface	0.3	1.3	Slight pitting on E/C surface
				0.3	4.8	General area of E/C; few pits on back surface
Supertherm T63WC Fe-36Ni-28Cr-15Co-5W	0.3	0.8	Apparent corrosion area deep edge E/C surface, localized small pits	1.9	16.9	Many pits on erosion area on E/C surface, back of sample badly pitted
				0.2	1.8	Fine pits, back surface
HL-40 SS 47Fe-19Ni-31Cr	0.2	2.5	No signs of attack	0.2	1.2	Few pits on E/C surface, pits and general corrosion on back surface
329 SS Fe-4Ni-27Cr	1.0	2.0	Very light general attack E/C surface	0.5	2.0	Few small pits on E/C surface; few large shallow pits on back surface
Fe-31Cr-28Ni				0.9	1.9	Slight pitting all surfaces
Fe-36Cr-36Ni				0.2	0.7	Few pits, back surface

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COARSE HUSKY CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c][11]

(Table Continued)

Alloy/ Composition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			50			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	0.2	0.3	Minor reverse side corrosion	0.2	0.6	Some edge corrosion on reverse surface
Incoloy 800(Al)	0.1	0.6	Some loss of coating on erosion side	0.6	3.5	Extensive loss of coating on erosion surface, pits on reverse surface
Inconel 601	0.5	0.7	Large pit on erosion side	0.4	0.6	Some reverse surface corrosion at edge
310 SS	0.3	0.7	Some pitting on erosion side	0.3	0.5	Faint outline visible of impingement a
310 SS (Al)	2.0	3.0	Extensive loss of coating on erosion side	0.3	0.9	Some roughening and loss of coating on erosion surface
RA-333	0.5	0.7	Some reverse side corrosion at edges	0.2	0.4	Some small pits, mainly on reverse sur
LM-1866	0.1	0.4	Some pitting and minor corrosion	0.3	1.7	Outline visible of impingement area
446 SS	0.7	0.9	Pitting on reverse side	0.5	0.8	No visible attack
Inconel 671	0.8	1.0	Pitting on erosion side, edge corrosion on reverse side	0.5	1.3	Pitting on both surfaces
Crutemp 25	0.3	0.5	Minor pitting on erosion side	0.7	1.2	Pitting on both surfaces
188	0.5	0.7	Edge corrosion on both sides	0.4	0.6	Corrosion visible on lower edge of sam
Temperature, °F			1800			1800
Pressure, psi			1000			1000
Velocity, ft/s			50			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	0.4	155.6	Very deep and wide erosion damage, possible melting	8.0	31.9	Deep wide eroded region, reverse surfa corrosion
Incoloy 800(Al)	0.7	1.6	Surface roughening on erosion surface	0.5	1.5	Some roughening of the coating
Inconel 601	0.3	0.7	No visible attack	1.0	37.9	Deep eroded region and edge corrosion
310 SS	1.1	10.5	Pitting around erosion area, reverse surface corrosion	3.7	10.7	Significant top & reverse side corrosi
310 SS (Al)	1.1	4.0	Extensive loss of coating on erosion side	2.1	3.1	Some blackening and roughening of coat
RA-333	0.6	5.1	Pitting on erosion surface, reverse surface corrosion	36.6	46.6	Extensive corrosion on both surfaces, possible melting
LM-1866	1.0	3.5	Shallow wide pitting on top surface	8.9	13.9	Significant erosion
446 SS	5.0	10.9	Extensive reverse surface corrosion	11.8	17.8	Badly corroded on both surfaces
Inconel 671	0.9	7.8	Four deep pits on erosion surface	15.5	72.4	Very badly attacked on both surfaces, possible melting
Crutemp 25	0.8	9.7	Pitting around erosion area, reverse surface corrosion	4.1	27.1	Significant damage on both surfaces
Haynes 188	0.6	1.0	Pitting around erosion area, pitting on reverse surface	1.9	9.8	Heavily pitted and edge corrosion
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			100
Time, hr			100			100
Volume % H_2S			0.1			1.0
Incoloy 800	-	0.4	Minor reverse side corrosion	0.2	0.8	Some erosion visible. Corrosion on reverse surface
				0.3	48.3	Deep E/C pit
Incoloy 800 (Al)	0.2	0.7	Extensive roughening on erosion side	0.2	3.5	Coating blackened on erosion surface Coating removed from impingement zone
Inconel 601	2.8	3.3	One pit on erosion surface	0.1	6.7	Deep pit on erosion surface; corrosior on reverse surface
310 SS	0.2	0.6	Some minor edge corrosion	0.6	0.7	Pitting on reverse surface
310 SS (Al)	0.7	2.0	Extensive pitting of coating on erosion side	1.0	2.4	Blackening & loss of coating, both su
RA-333	0.2	0.4	Pitting on erosion side	0.4	2.3	Edge corrosion on reverse surface
LM-1866	0.7	1.2	Some corrosion evident on all surfaces	0.3	3.3	Deep pit on erosion surface
446 SS	0.4	0.8	Extensive pitting attack on erosion side	0.5	1.1	Corrosion on reverse surface

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COARSE HUSKY CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11]

(Table Continued)

loy/ omposition[f]	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
nconel 671	0.5	1.0	Pitting attack on erosion side	0.6	1.2	Edge corrosion on reverse surface
				0.8	1.3	Intact scale back surface
Crutemp 25	-	0.6	Some pitting attack on erosion side & edge	0.3	0.7	Pitting on reverse surface
Haynes 188	0.3	0.5	Pitting on erosion side, minor reverse side corrosion	0.5	0.8	Blisters & corrosion on reverse surface
Co-Cr-W No. 1				1.6	2.6	Scale still intact at some points on all surfaces
Stellite 6B				0.3	1.3	No attack
Alloy X				0.2	0.2	No signs of attack
Sanicro 32X				0.2	0.7	No attack
Multimet N155				0.3	0.8	Slight attack top left corner of E/C surface
Haynes 150				0.3	1.3	Slight attack top edge on E/C surface
Supertherm T63WC				0.1	1.1	No attack
HL-40 SS				0.2	0.5	No signs of attack
329 SS				1.3	1.8	Intact scale E/C and back surface
Fe-31Cr-28Ni				0.7	4.7	No signs of attack

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[a] Alloy samples 1 x 1 x 1/4 in were subjected to erosion in coal gasification atmosphere under the indicated conditions, impingement angle 45°; values are for one specimen per test.

[b] Char from Western coal processed by the Husky Oil Company, -20 +40 mesh.

[c] Coal gasification atmosphere input gas in volume percent: 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, either 0.1, 0.5, or 1.0% H_2S, and the balance H_2O.

[d] Average corrosion of the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in uneroded area.

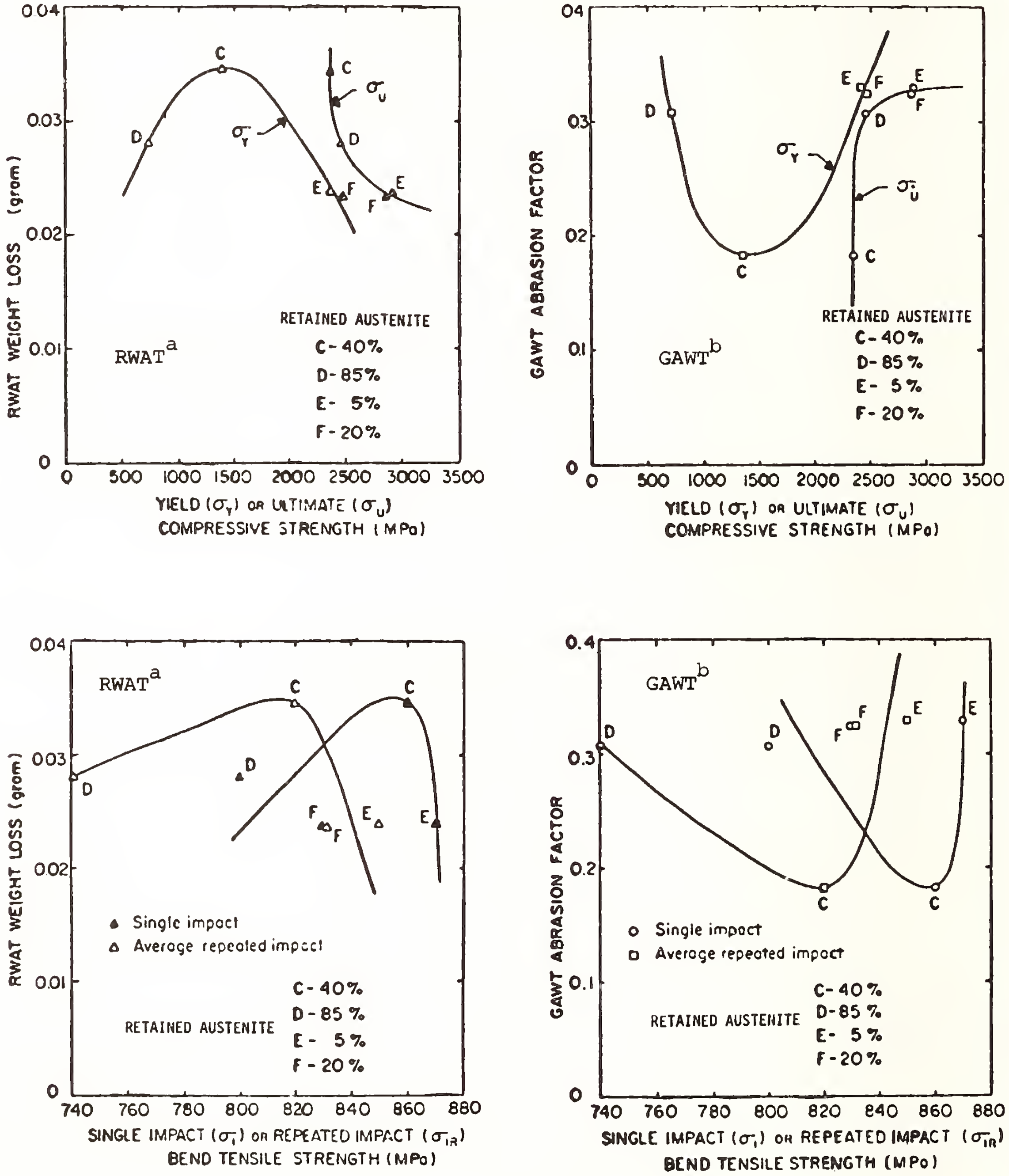
[e] Maximum effect on the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in eroded area and pits.

[f] Approximate values only for major constituents; composition given for alloy the first time it appears in the table.

[g] E/C = erosion/corrosion.

[h] Aluminum coating applied to specimens by pack diffusion process by Alon Processing Inc. (Alonized).

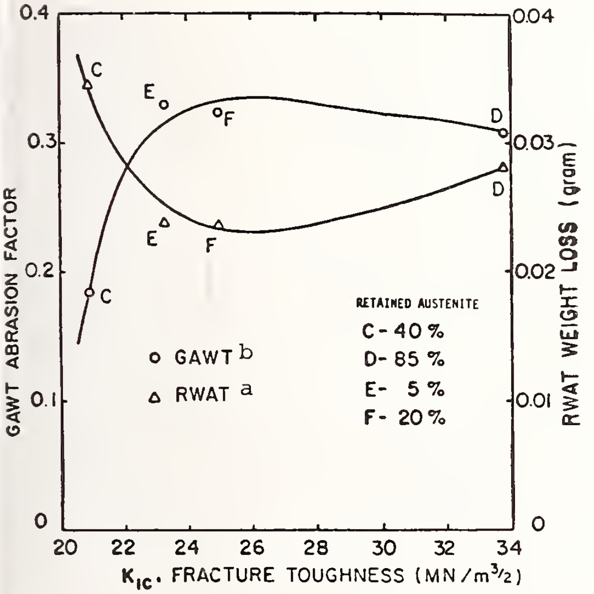
LOW-STRESS[a] AND GOUGING[b] WEAR OF Ni-HARD 4 IRONS AS A FUNCTION OF STRENGTH[28]

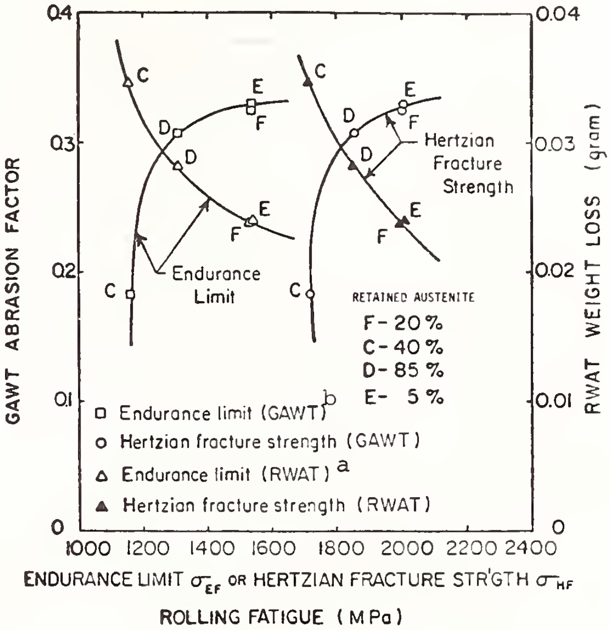


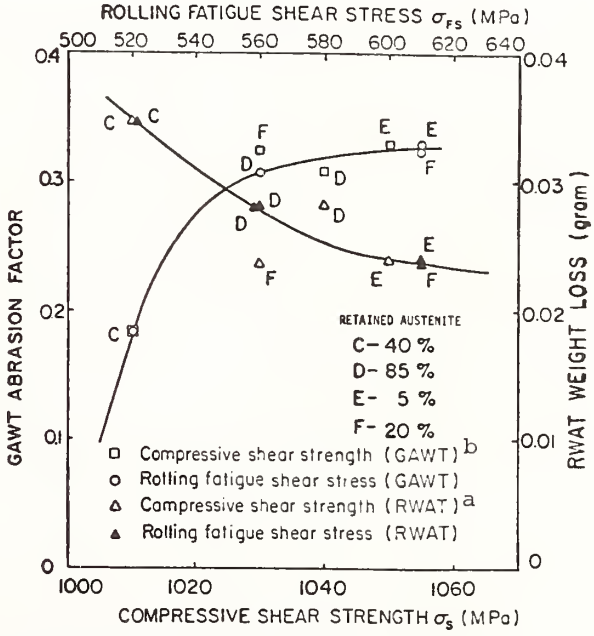
(Data Continued)

LOW-STRESS[a] AND GOUGING[b] WEAR OF Ni-HARD 4 IRONS AS A FUNCTION OF STRENGTH[28]

(Data Continued)







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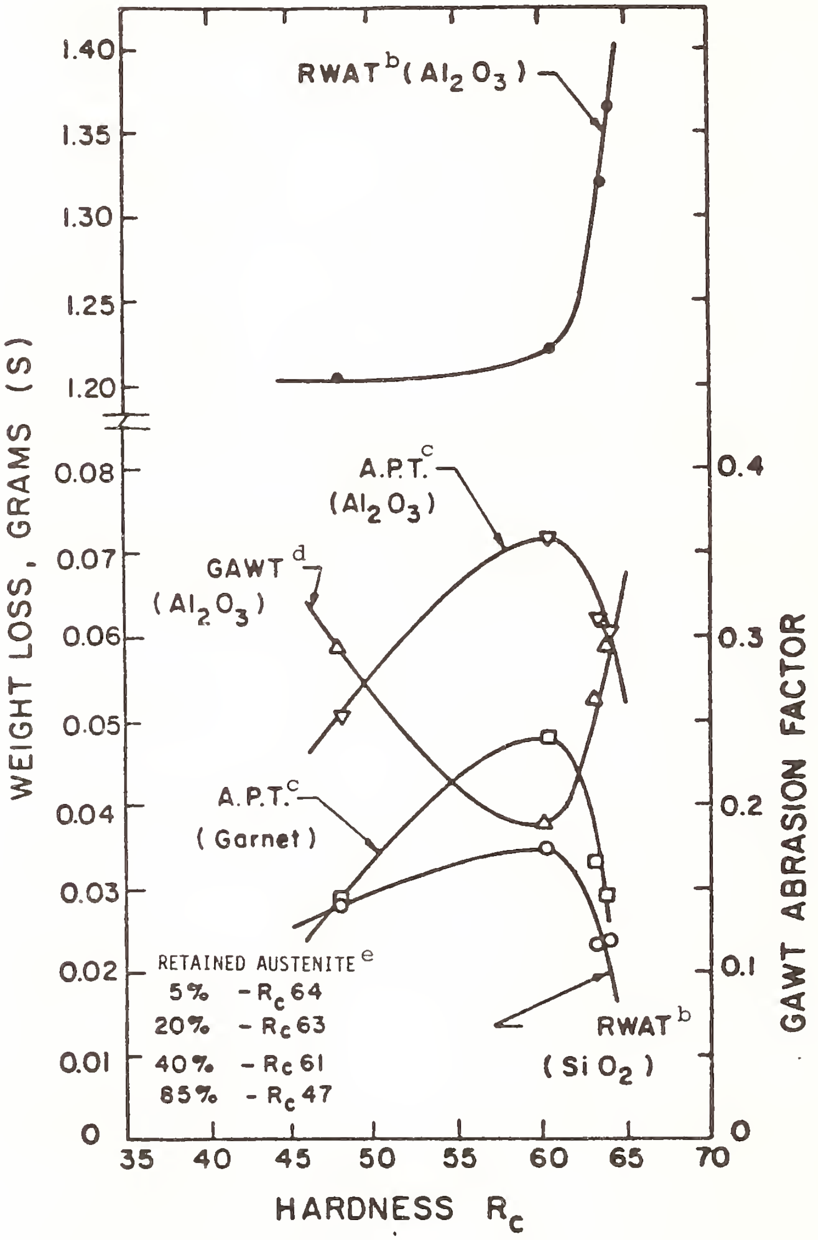
[a] Wear resistance measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive is gravity fed between a rotating rubber wheel and a test specimen (12.7 mm x 25.4 mm x 76.2 mm). Abrasive used is a silica sand, uniform in shape, screen size -50 +70 mesh, KHN 750. The wheel rotates at a constant speed of 200 rpm (surface rate 2.38 m/s), applied load is 30 lb corresponding to a stress of 60 psi. Results are reported as specimen weight per 713 m of abrasive travel. Each data point is the average of three tests.

[b] Wear resistance as measured by a Gouging Abrasive Wheel Test (GAWT); a 254 mm diameter, 70 mesh bonded alumina wheel (Type AR-51177) is rotated at 27 rpm against two samples which are diametrically opposed. Each sample is pressed against the wheel at a nominal stress of 18.4 psi. One block, 1020 hot-rolled steel is the reference material, the other is the test alloy. Test is run in two steps with samples interchanged at the midway point to cancel systematic errors. Results are reported as an Abrasion Factor, the ratio of weight loss of sample per 732 m travel to weight loss of 1020 standard per 732 m travel. Each data point is the average of three tests.

[c] Alloys are four Ni-Hard 4 irons, ASTM532-Type I; containing high-chromium carbides in austenite decomposition product with 5%, 20%, 40%, and 85% retained austenite (all Climax alloys).

WEIGHT LOSS OF Ni-HARD 4 IRONS[a] SUBJECTED TO WEAR TESTS AS A FUNCTION OF MACROHARDNESS(R_c) [28]



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[a] Alloys are four Ni-Hard 4 iro ASTM532-Type I; containing hi chromium carbides in austenit decomposition product with 5% 20%, 40%, and 85% retained austenite (all Climax alloys)

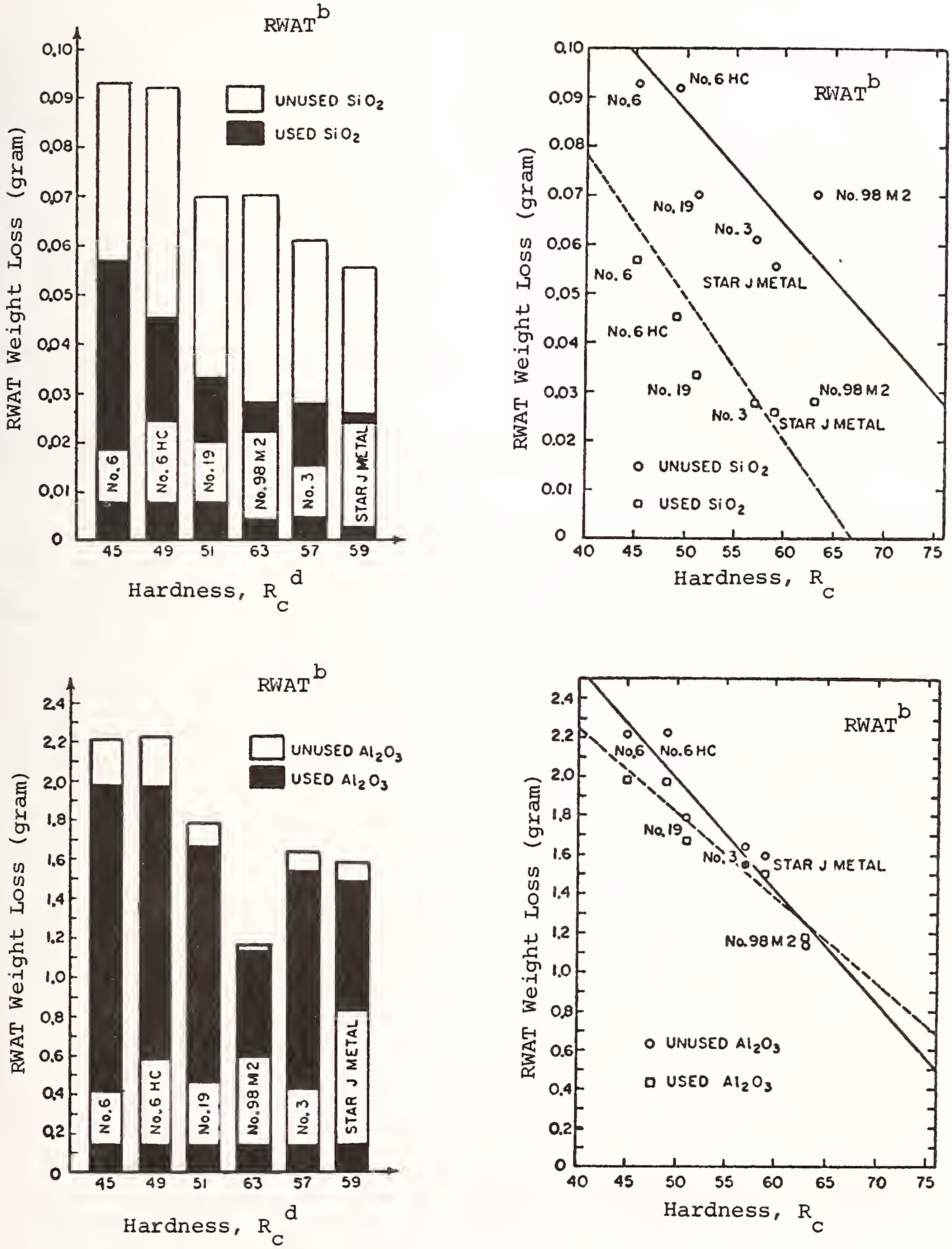
[b] Wear resistance measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive is gravity fed betwe a rotating rubber wheel and a test specimen (12.7 mm x 25.4 mm x 76.2 mm). Abrasives use are a silica sand, uniform in shape, screen size -50+70 mes KHN 750, and an angular alumi nominally 70 mesh, KHN 1700. The wheel rotates at a consta speed of 200 rpm (surface rat 2.38 m/s), applied load is 30 corresponding to a stress of psi. Results are reported as specimen weight loss per 713 of abrasive travel. Each dat point is the average of three tests.

[c] AMAX Pin Test involves abrasi particles trapped between the rigid wearing surface of the p like sample and the rigid plat on which an abrasive cloth (al mina or garnet papers) rests. Tests performed at Climax Labs

[d] Wear resistance as measured by a Gouging Abrasive Wheel Test (GAWT); a 254 mm diameter, 70 mesh bonded alumina wheel (Typ AR-51177) is rotated at 27 rpm against two samples which are diametrically opposed. Each sample is pressed against the wheel at a nominal stres of 18.4 psi. One block, 1020 hot-rolled steel, is the reference material, the othe is the test alloy. Test is run in two steps with samples interchanged at the midwa point to cancel systematic errors. Results are reported as an Abrasion Factor, the ratio of weight loss of sample per 732 m travel to weight loss of 1020 standard pe 732 m travel. Each data point is the average of three tests.

[e] Percent retained austenite decreases from left to right.

WEIGHT LOSS OF Co-BASE ALLOYS[a] SUBJECTED TO LOW-STRESS[b] AND GOUGING[c] WEAR AS A FUNCTION OF MACROHARDNESS (R_C) [28]



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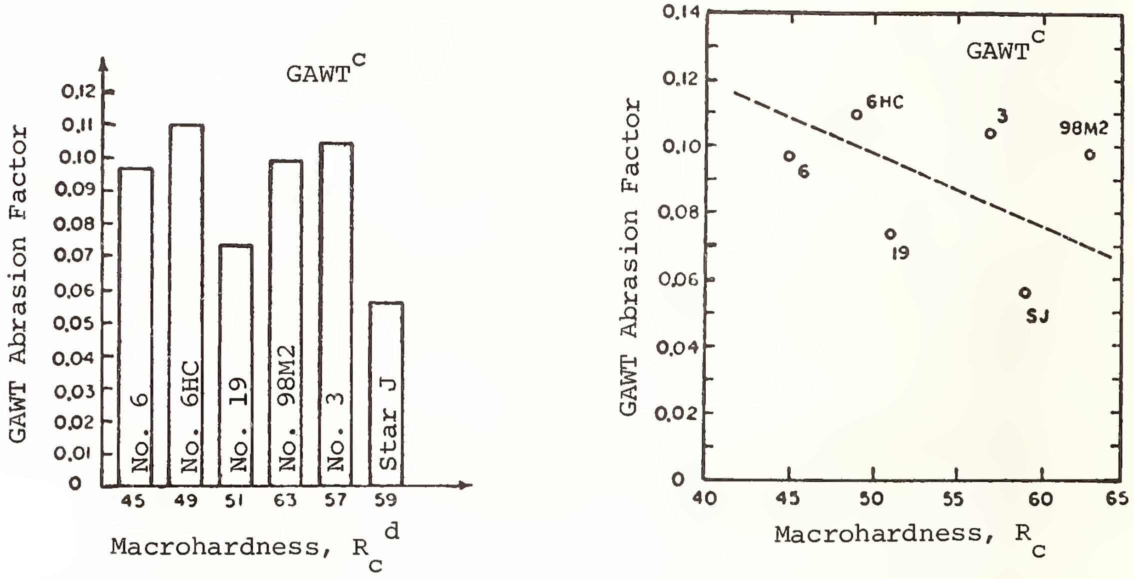
(Data Continued)

WEIGHT LOSS OF Co-BASE ALLOYS[a] SUBJECTED TO LOW-STRESS[b] AND GOUGING[c] WEAR AS A FUNCTION OF MACROHARDNESS(R_c)[28], Continued



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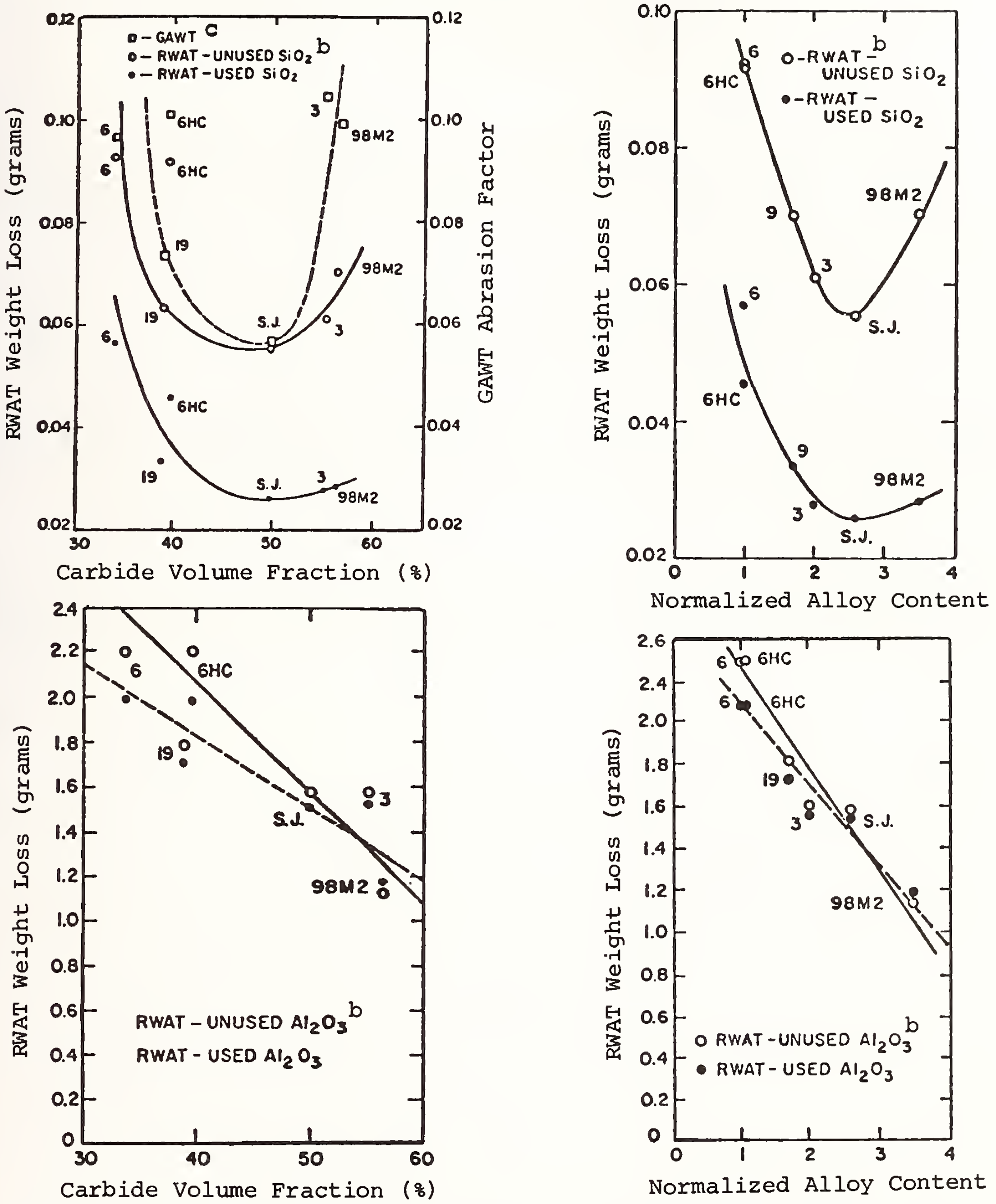
[a] Cobalt-base superalloys prepared by powder metallurgical techniques: #6, low carbide volume fraction; #6HC, high carbide; #19, high carbide; #98M2, high ca bide; #3, very high carbide; #Star J, very high carbide (all Stellite material

[b] Wear resistance measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive is gravity fed between a rotating rubber wheel and a test specimen (12.7 mm x 25.4 mm x 76.2 mm). Abrasives used are a silica sand, uniform in shape, screen size -50+70 mesh, KHN 750, and an angular alumina, nominally 70 mesh, KHN 1700. The designation "used" means that the abrasives were used for one previous test. The wheel rotates at a constant speed of 200 rpm (surface rate 2.38 m/s), applied load is 30 lb corresponding to a stress of 60 psi. Results are reported as specimen weight loss per 713 m of abrasive trave Each data point is the average of three tests.

[c] Wear resistance measured by a Gouging Abrasive Wheel Test (GAWT); a 254 mm dia eter, 70 mesh bonded alumina wheel (Type AR-51177) is rotated at 27 rpm agains two samples which are diametrically opposed. Each sample is pressed against t wheel at a nominal stress of 18.4 psi. One block, 1020 hot-rolled steel, is t reference material, the other is the test alloy. Test is run in two steps wit samples interchanged at the midway point to cancel systematic errors. Results are reported as an Abrasion Factor, the ratio of weight loss of sample per 732 travel to weight loss of 1020 standard per 732 m of travel. Each data point i the average of three tests.

[d] In the histograms, instead of being ordered on Rockwell C hardness, the alloys are ordered so that the carbide volume fraction and/or matrix solid-solution strengthener content increase from left to right.

WEIGHT LOSS OF Co-BASE ALLOYS[a] SUBJECTED TO LOW-STRESS[b] AND GOUGING[c] WEAR AS A FUNCTION OF ALLOY COMPOSITION[d][28]



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[a] Cobalt-base superalloys prepared by powder metallurgical techniques: #6, low carbide volume fraction; #6HC, high carbide; #19, high carbide; #98M2, high carbide; #3, very high carbide; #Star J, very high carbide (all Stellite materials).

[b] Wear resistance measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive is gravity fed between a rotating rubber wheel and a test specimen (12.7 mm x 25.4 mm x 76.2 mm). Abrasives used are a silica sand, uniform in shape, screen size -50+70 mesh, KHN 750, and an angular alumina, nominally 70 mesh, KHN

(Data Continued)

WEIGHT LOSS OF Co-BASE ALLOYS[a] SUBJECTED TO LOW-STRESS[b] AND GOUGING[c] WEAR AS A FUNCTION OF ALLOY COMPOSITION[d][28]

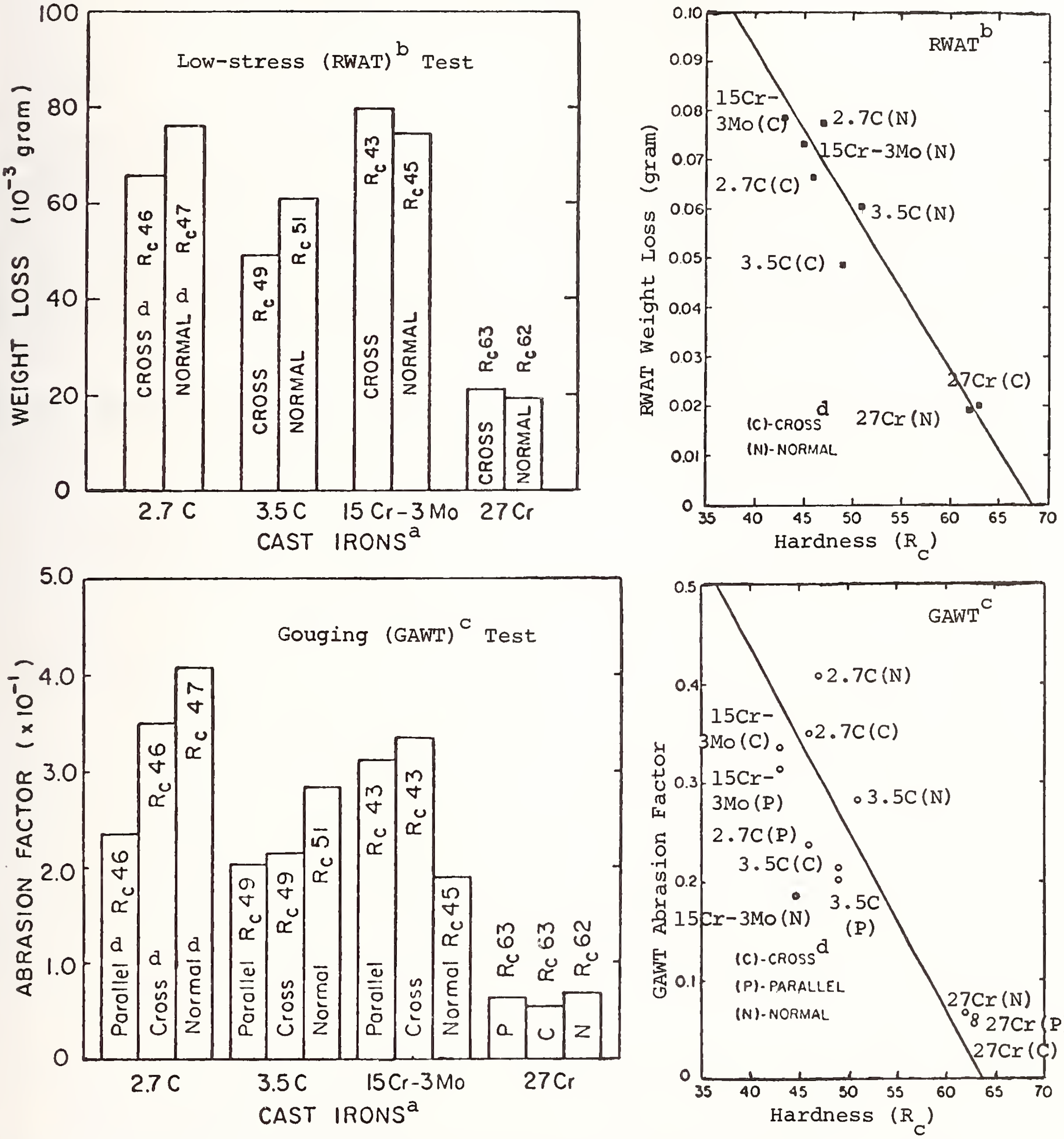
(Data Continued)

1700. The designation "used" means that the abrasives were used for one previous test. The wheel rotates at a constant speed of 200 rpm (surface rate 2.38 m/s), applied load is 30 lb corresponding to a stress of 60 psi. Results are reported as specimen weight loss per 713 m of abrasive travel. Each data point is the average of three tests.

[c] Wear resistance measured by a Gouging Abrasive Wheel Test (GAWT); a 254 mm diameter, 70 mesh bonded alumina wheel (Type AR-51177) is rotated at 27 rpm against two samples which are diametrically opposed. Each sample is pressed against the wheel at a nominal stress of 18.4 psi. One block, 1020 hot-rolled steel, is the reference material, the other is the test alloy. Test is run in two steps with samples interchanged at the midway point to cancel systematic errors. Results ar reported as an Abrasion Factor, the ratio of weight loss of sample per 732 m trav to weight loss of 1020 standard per 732 m of travel. Each data point is the average of three tests.

[d] Composition expressed as percent carbide volume fraction and as normalized alloy content. Normalized alloy content is a measure of matrix strength, the sum of the weight percentages of Ni, V, and W in the alloys, normalized against alloy #6

WEIGHT LOSS OF WHITE CAST IRONS[a] SUBJECTED TO LOW-STRESS[b] AND GOUGING[c] WEAR TESTS AS A FUNCTION OF MACROHARDNESS (R_c) [28]



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[a] Cast irons tested are two Pearlitic White Irons (2.7C and 3.5C) and ASTM532-Type II (15Cr-3Mo) and ASTM532-Type III (27Cr-2.5C) (all Climax alloys).

[b] Wear resistance measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive is gravity fed between a rotating rubber wheel and a test specimen (12.7 mm x 25.4 mm x 76.2 mm). Abrasive is a silica sand, uniform in shape, screen size -50 +70 mesh, KHN 750. The wheel rotates at a constant speed of 200 rpm (surface rate 2.38 m/s), applied load is 30 lb corresponding to a stress of 60 psi. Results are

(Data Continued)

WEIGHT LOSS OF WHITE CAST IRONS[a] SUBJECTED TO LOW-STRESS[b] AND GOUGING[c] WEAR TESTS AS A FUNCTION OF MACROHARDNESS(R_c)[28], Continued

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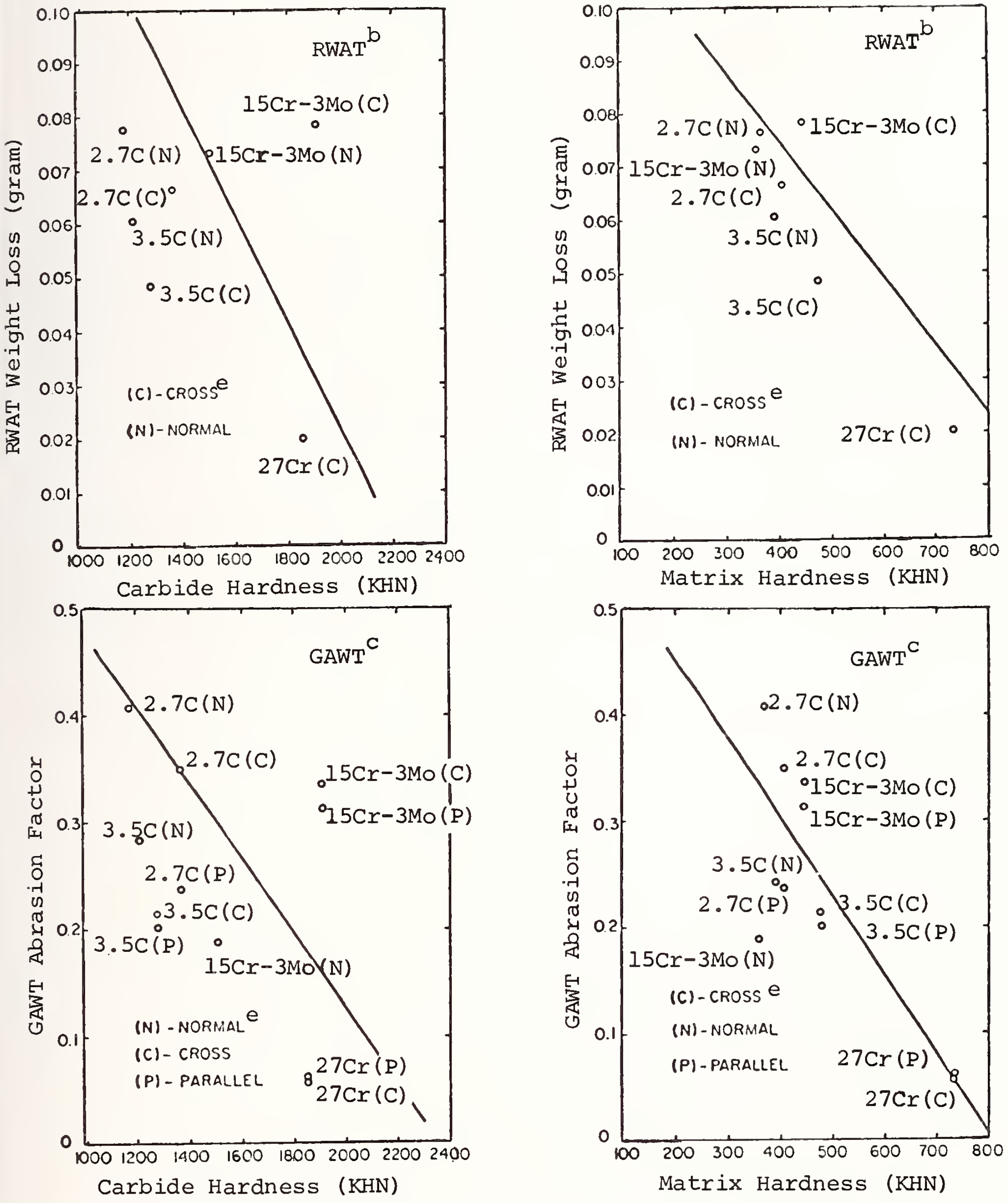
reported as specimen weight loss per 713 m of abrasive travel. Each data point i the average of three tests.

[c] Wear resistance as measured by a Gouging Abrasive Wheel Test (GAWT); a 254 mm dia eter, 70 mesh bonded alumina wheel (Type AR-51177) is rotated at 27 rpm against t samples which are diametrically opposed. Each sample is pressed against the whee at a nominal stress of 18.4 psi. One block, 1020 hot-rolled steel, is the refere material, the other is the test alloy. Test is run in two steps with samples int changed at the midway point to cancel systematic errors. Results are reported as an Abrasion Factor, the ratio of weight loss of sample per 732 m travel to weight loss of 1020 standard per 732 m of travel. Each data point is the average of thr tests.

[d] Results are for wear directions normal to, across, and parallel to the solidifica direction, the tests thereby allowing dendrite orientation to serve as a microstr tural variable.

EFFECT OF MICROHARDNESS[a] ON THE LOW-STRESS[b] AND GOUGING[c] WEAR RESISTANCE OF WHITE CAST IRONS[d][28]



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[a] Expressed as Knoop Hardness Number (KHN) for carbide hardness and matrix hardness.

[b] Wear resistance measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive is gravity fed between a rotating rubber wheel and a test specimen (12.7 mm x 25.4 mm x 76.2 mm). Abrasive used is a silica sand, uniform in shape, screen size -50+70 mesh, KHN 750. The wheel rotates at a constant speed of 200 rpm (surface rate 2.38 m/s), applied load is 30 lb corresponding to a stress of 60 psi. Results are reported as specimen weight loss per 713 m of abrasive travel. Each data

(Data Continued)

EFFECT OF MICROHARDNESS[a] ON THE LOW-STRESS[b] AND GOUGING[c] WEAR RESISTANCE OF WHITE CAST IRONS[d][28]

(Data Continued)

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point is the average of three tests.

[c] Wear resistance as measured by a Gouging Abrasive Wheel Test (GAWT); a 254 mm d eter, 70 mesh bonded alumina wheel (Type AR-51177) is rotated at 27 rpm against samples which are diametrically opposed. Each sample is pressed against the wh at a nominal stress of 18.4 psi. One block, 1020 hot-rolled steel is the refer material, the other is the test alloy. Test is run in two steps with samples i changed at the midway point to cancel systematic errors. Results are reported an Abrasion Factor, the ratio of weight loss of sample per 732 m travel to weig loss of 1020 standard per 732 m travel. Each data point is the average of thre tests.

[d] Cast irons tested are two Pearlitic White Irons (2.7C and 3.5C) and ASTM532-Typ (15Cr-Mo) and ASTM532-Type III (27Cr-2.5C) (all Climax alloys).

[e] Results are for wear directions normal to, across, and parallel to the solidific direction, the tests thereby allowing dendrite orientation to serve as a microst tural variable.

QUALITATIVE EVALUATION OF THE EFFECTS OF MICROSTRUCTURAL CHARACTERISTICS ON THE WEAR RESISTANCE[a] OF COBALT BASE SUPERALLOYS[b] [28]

Materials Tested (Major Contituents)[c]	Type	Hardness (R_C)	Normalized Alloy Content[d]	Microstructural Condition
Cobalt Base Superalloys prepared by powder metallurgical techniques:				
#6 (Co, 29Cr, 2Ni, 5W, 1.5Fe)	Low carbide volume fraction, 33.8% M_7C_3.	45.0	1.0	Low solid solution strengthener content.
#6HC (Co, 29Cr, 2Ni, 5W, 1.5Fe)	High carbide volume fraction, 39.5% M_7C_3.	49.0	1.0	Low solid solution strengthener content.
#19 (Co, 30Cr, 1.4Ni, 10W, 1.9Fe)	High carbide volume fraction, 37.4% M_7C_3.	51.0	1.7	Moderate solid solution strengthener content.
#98M2 (Co, 30.5Cr, 4Ni, 17W, 3Fe)	High carbide volume fraction, 43.6% M_7C_3, 13.0% M_6C.	63.0	3.5	High solid solution strengthener content.
#3 (Co, 31Cr, 2Ni, 12W, 2Fe)	Very high carbide volume fraction, 46.3% M_7C_3, 8.9% M_6C.	57.0	2.0	High solid solution strengthener content.
#Star J (Co, 31.5Cr, 1Ni, 17W)	Very high carbide volume fraction, 41.0% M_7C_3, 8.9% M_6C.	59.0	2.6	Very high solid solution strengthener content.

Parameter Effects	Conclusions
Effect of increased carbide volume fraction.	Improves abrasive wear resistance in low-stress wear (RWAT)[a] against hard abrasives. Of limited value against softer abrasives in low-stress wear or in gouging conditions (GAWT)[a].
Effect of increased matrix strength.	Improves abrasive wear resistance in low-stress wear against hard abrasives. Of limited value against softer abrasives in low-stress wear or in gouging conditions.
Effect of microstructure.	Abrasion behavior is a strong function of specific abrasive conditions. No broad generalities in predicting wear resistance are warranted.
Effect of macrohardness.	Increased macrohardness gives improved wear resistance in low-stress applications against very hard abrasives. Macrohardness is an unsatisfactory gauge of wear resistance in low-stress applications against softer abrasives. Macrohardness is an unsatisfactory gauge of wear resistance in gouging applications.
Relation of inverse-hardness rule to abrasive wear.	The rule must be modified to take into account the rake angles of abrading particles, the size and hardness of multiphase particles, and the matrix-particle interactions.
Effect of closely spaced large carbides during wear.	Protect maxtrix against wear under low-stress abrasion conditions. Wear of the carbide particles governs the over-all wear rate.
Effect of small second-phase particles during wear.	May be dislodged from matrix and result in increased weight losses and enhanced abrasion environment.
Effect of load-time history.	The same abrasive employed under low-stress conditions and under gouging conditions acts quite differently in the two applications, even under similar normal loads.
Effect of one of the most commonly accepted low-stress abrasion tests.	Causes abrasive degradation which usually decreases the effectiveness of the abrasive.
Contributing factors of hardness and angularity of the abrasive.	Important in low-stress abrasion against materials with large carbides. Angularity is more important than hardness in low-stress abrasion against alloys with small carbides.

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[a] Wear resistance as measured by a low-stress wear technique (Rubber Wheel Abrasive Test) in which abrasive (SiO_2 or Al_2O_3) is gravity fed between a rotating rubber wheel and the test specimen and, by a gouging wear test (Gouging Abrasive Wheel Test) in which a grinding wheel is rotated against the specimen under pressure.

[b] Prepared at the Stellite Division, Cabot Corp.

[c] Approximate compositions only.

[d] A measure of matrix strength; the sum of the weight percentages of Ni, V, and W in the alloys, normalized against alloy #6.

QUALITATIVE EVALUATION OF THE EFFECTS OF MICROSTRUCTURAL CHARACTERISTICS ON THE WEAR RESISTANCE[a] OF WHITE CAST IRONS[b] [28]

Materials Tested	Heat Treatment	Microstructural Condition
White Irons: 15Cr-3Mo (ASTM532-Type II)	Austenitized at 1800 °F (980 °C) 1 hour, furnace cooled and stress relieved at 400 °F (205 °C) 2 hours.	Cr_7C_3 Carbides in tempered martensite. (overtempered martensite)
27Cr-2.5C (ASTM532-Type III)	Austenitized at 1850 °F (1010 °C) 2 hours, air cooled and stress relieved at 450 °F (230 °C) 1 hour.	Cr_7C_3 Carbides in tempered martensite. (Lightly tempered martensite)
Pearlitic White Iron (2.7C)	As-cast in sand.	Fe_3C Carbides in pearlitic matrix. High carbide volume fraction.
Pearlitic White Iron (3.5C)	As-cast in sand.	Fe_3C Carbides in pearlitic matrix. Low Carbide volume fraction.

Parameter Effects	Conclusions
Effect of Carbide volume fractions, carbide shape, and matrix strength.	Wear resistance is dependent on these parameters. A satisfactory balance of these parameters in alloying must be obtained to achieve an improvement in wear resistance.
Effect of macrohardness and matrix microhardness on wear resistance.	Generally, increased macrohardness and matrix microhardness improve RWAT[a] and GAWT[a] wear resistance.
Effect of carbide microhardness on wear resistance.	Generally, increased carbide microhardness does not improve RWAT and GAWT wear resistance. More emphasis should be placed on alloying and processing to optimize matrix properties.

Materials Tested	Heat Treatment	Microstructural Condition
Ni-Hard 4 Irons (ASTM532-Type I)		High-Cr carbides in Austenite decomposition product ($\alpha+Fe_3C$) containing
	1380 °F (750 °C) for 8 hr, cooled to -320 °F (-195 °C), 410 °F (210 °C) for 1 hr.	5% Retained Austenite
	1020 °F (550 °C) for 4 hr, 840 °F (450 °C) for 16 hr, cooled to -320 °F (-195 °C), 410 °F (210 °C) for 4 hr.	20% Retained Austenite
	1380 °F (750 °C) for 8 hr, 1020 °F (550 °C) for 4 hr, 840 °F (450 °C) for 16 hr.	40% Retained Austenite
	450 °F (230 °C) for 4 hr.	85% Retained Austenite

(Table Continued)

QUALITATIVE EVALUATION OF THE EFFECTS OF MICROSTRUCTURAL CHARACTERISTICS ON THE WEAR RESISTANCE[a] OF WHITE CAST IRONS[b] [28] (continued)

Parameter Effects	Conclusions
Effect of microstructural state on low stress wear behavior.	RWAT tests were strongly dependent on microstructural state.
Effects of microstructural state on gouging wear behavior.	GAWT tests were strongly dependent on microstructural state. The percentage of retained austenite may increase or decrease abrasion resistance depending on the relative amount and the specific wear process involved.
Valve of macro or micro-hardness as a gauge of wear resistance.	Not satisfactory. Not as good a gauge as compressive shear or ultimate strength.
Valve of hardness and tensile property correlations to wear.	Correlate as well to wear as do fatigue or fracture-mechanics parameters.
Effect of a very hard abrasive (Al_2O_3) on low stress wear (RWAT).	Matrix and Carbide undergo uniform attrition by a micro-machining action.
Effect of a very hard abrasive (Al_2O_3) on gouging wear (GAWT).	Matrix and carbide undergo uniform attrition by a micro-machining action.
Effect of an intermediate hard abrasive (SiO_2) on low stress wear (RWAT).	Matrix abraded preferentially by micro-machining then carbides which stand out in relief are chipped away at their exposed leading edges and are to a lesser extent lost by fracture and spalling. The resistance of the carbides to the softer SiO_2 abrasive appears to be mainly responsible for the 5 to 1 improvement in wear resistance over the Al_2O_3 abrasive.

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[a] Wear resistance as measured by a low-stress wear technique (Rubber Wheel Abrasive Test) in which abrasive (SiO_2 or Al_2O_3) is gravity fed between a rotating rubber wheel and the test specimen and, by a gouging wear test (Gouging Abrasive Wheel Test) in which a grinding wheel is rotated against the specimen under pressure.

[b] Cast irons produced at the Climax Molybdenum Research Laboratories.

METAL WASTAGE DATA OF ALLOYS[a] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[b][37]

Exposure Time hr	Temperature °F	°C	Weight Loss[c] grams	Rate[d] mil/hour	Local Ra e mil/hou
			304 SS[f]		
			Freeboard		
10	1201	(650)	0.0177	0.0041	0.03
	1445	(785)	0.0390	0.0090	0.02
	1546	(841)	--	--	--
500	1275	(691)	0.1185	0.0006	0.01
	1395	(757)	0.1911	0.0009	0.03
	1465	(796)	0.3307	0.0015	0.04
1500	1255	(680)	0.3998	0.0006	0.01
	1400	(760)	0.4676	0.0007	0.02
	1485	(807)	--	--	--
			Fluidized Bed		
10	1367	(741)	0.0621	0.0143	0.09
	1424	(773)	0.0570	0.0132	0.03
	1480	(804)	0.0577	0.0133	0.03
500	1360	(738)	0.5399	0.0025	0.05
	1430	(777)	0.4525	0.0021	0.01
	1465	(796)	0.4789	0.0022	0.01
1500	1290	(699)	1.5239	0.0024	0.03
	1390	(754)	0.7239	0.0011	0.02
	1450	(788)	1.8303	0.0028	0.03
			In Air[g]		
500	1340	(727)	0.0309	0.0001	-
	1475	(802)	0.0586	0.0003	-
	1535	(835)	0.1135	0.0005	-
			310 SS[f]		
			Freeboard		
10	1245	(674)	0.0130	0.0030	0.00
	1456	(791)	0.0265	0.0060	0.02
	1554	(845)	0.0439	0.0090	0.02
500	1295	(702)	0.0661	0.0003	0.008
	1410	(766)	0.1749	0.0008	0.00
	1475	(802)	--	--	--
1500	1285	(696)	0.3451	0.0005	0.00
	1415	(769)	0.1786	0.0003	0.00
	1495	(813)	0.2738	0.0004	0.00

(Table Continued)

TAL WASTAGE DATA OF ALLOYS[a] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[b][37]
(continued)

sure Time	Temperature		Weight Loss[c]	Rate[d]	Local Rate[e]
r	°F	°C	grams	mil/hour	mil/hour
310 SS[f], continued					
Fluidized Bed					
	1375	(746)	0.0484	0.0110	0.028
	1432	(778)	0.1219	0.0281	0.042
	1487	(808)	--	--	--
	1375	(746)	0.2733	0.0012	0.003
	1435	(799)	0.3968	0.0018	0.004
	1470	(799)	--	--	--
	1305	(707)	1.0535	0.0016	0.002
	1400	(760)	0.6155	0.0009	0.001
	1460	(793)	--	--	--
In Air[g]					
	1365	(740)	0.0445	0.0002	--
	1490	(810)	0.0790	0.0004	--
	1545	(841)	0.1537	0.0007	--
347 SS[f]					
Fluidized Bed					
	1420	(771)	0.4558	0.0021	0.004
	1455	(791)	0.3483	0.0016	0.002
Freeboard					
	1365	(740)	0.4708	0.0007	0.001
	1465	(796)	0.3752	0.0006	0.001
18-18-2[f]					
Freeboard					
	1370	(743)	0.0907	0.0004	0.0008
	1440	(782)	0.1270	0.0006	0.0012
Fluidized Bed					
	1365	(740)	2.0418	0.0031	0.0031
	1435	(780)	0.9593	0.0015	0.0015
Inconel 671[f]					
Freeboard					
	1324	(718)	0.0229	0.0051	0.007
	1500	(816)	0.0375	0.0084	0.028
	--		--	--	--
	1335	(724)	0.2023	0.0009	0.003
	1430	(777)	0.1635	0.0007	0.002
	1495	(813)	0.1412	0.0006	0.003

(Table Continued)

METAL WASTAGE DATA OF ALLOYS[a] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[b][37]
(continued)

Exposure Time hr	Temperature °F	 °C	Weight Loss[c] grams	Rate[d] mil/hour	Local Rate[e] mil/hour
			Inconel 671[f], continued		
			Freeboard, continued		
1500	1325	(719)	0.6054	0.0009	0.001
	1440	(782)	1.3117	0.0020	0.003
	1530	(832)	--	--	--
			Fluidized Bed		
10	1390	(754)	0.0403	0.0090	0.022
	1447	(786)	0.0539	0.0120	0.040
	1501	(816)	0.0320	0.0071	0.018
500	1400	(760)	0.7168	0.0032	0.004
	1445	(785)	1.0200	0.0046	0.008
	1495	(813)	0.5922	0.0026	0.005
1500	1340	(727)	4.0611	0.0060	0.015
	1417	(769)	1.4114	0.0021	0.003
	1482	(805)	1.9107	0.0028	0.003
			In Air[g]		
500	1420	(771)	0.0400	0.0002	--
	1500	(816)	0.0715	0.0003	--
	1580	(860)	0.0961	0.0004	--
			FSX 414[f]		
			Freeboard		
10	1359	(737)	0.0124	0.0026	0.0066
	1514	(823)	0.0177	0.0038	0.0094
	1567	(852)	0.0125	0.0027	0.0066
500	1360	(738)	0.0566	0.0002	0.0012
	1435	(779)	0.0963	0.0004	0.0014
	1485	(807)	--	--	--
1500	1350	(732)	0.1943	0.0003	0.0009
	1455	(790)	0.1984	0.0003	0.0007
	1520	(827)	0.1719	0.0002	0.0005
			Fluidized Bed		
10	1398	(759)	0.0260	0.0055	0.0138
	1456	(800)	0.0393	0.0084	0.0279
	1498	(814)	--	--	--
500	1410	(766)	0.2973	0.0013	0.0030
	1450	(788)	0.3464	0.0015	0.0021
	1490	(810)	--	--	--
1500	1350	(732)	0.8513	0.0012	0.0015
	1425	(774)	0.8004	0.0011	0.0011
	1475	(801)	--	--	--

(Table Continued)

TAL WASTAGE DATA OF ALLOYS[a] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[b][37]
(continued)

sure Time r	Temperature °F	 °C	Weight Loss[c] grams	Rate[d] mil/hour	Local Rate[e] mil/hour
			FSX414[f], continued		
			In Air[g]		
)	1435	(779)	0.0419	0.0002	--
	1510	(821)	0.0782	0.0003	--
	1570	(854)	0.0547	0.0002	--
			P9[f]		
			Freeboard		
)	1110	(599)	0.0798	0.0184	0.018
	1391	(755)	0.1034	0.0239	0.080
	1526	(830)	0.1075	0.0248	0.062
)	1200	(649)	0.4543	0.0021	0.0021
)	1185	(640)	2.2851	0.0035	0.0035
			Fluidized Bed		
)	1350	(732)	0.1793	0.0414	0.059
	1405	(763)	0.1466	0.0338	0.068
	1464	(796)	0.1157	0.0267	0.045
)	1320	(716)	1.9181	0.0089	0.0089
)	1245	(674)	5.8909	0.0091	0.0091
			In Air[g]		
)	1240	(671)	0.0351	0.0001	--
	1455	(790)	0.1036	0.0003	--
	1525	(830)	7.2167	0.033	--

lindrical test specimens were machined from tube or bar stock to 1.25 in .17 cm) OD, 1.00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 tained as cast rod from which specimens were machined. As machined specimens re solvent rinsed before exposure. Twenty-one specimens were used to make 18-in air-cooled tube probes.

cility consists of a 24-in diameter refractory-lined fluidized-bed combustor arged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer arry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

ight loss determined after descaling of specimens by mechanical removal of ose deposit, then soaking in 11% NaOH + 5% $KMnO_4$ solution at 200 °F, and en a cathodic treatment in 10% H_2SO_4 containing 1-ethyl-quinolinium iodide hibitor.

te of metal loss calculated by assuming uniform attack around the specimen oviding an average rate of attack. 1 mil hr = 25.4 µm/hr.

(Table Continued)

METAL WASTAGE DATA OF ALLOYS[a] EXPOSED IN A FLUIDIZED BED COAL COMBUSTOR[b] [37] (continued)

[e] Local rate of metal loss calculated based upon microscopic examination of spec with a correction for the area of the specimen showing visible evidence of att This calculation provides a local rate of attack for the specific area, i.e., total weight loss divided by the area of local attack which is more representa of the rate which may determine the life of heat exchanger tube materials. 1 mil/hr = 25.4 μm hr.

[f] Alloy compositions:

304 SS	Fe-18.5Cr-8Ni-2Mn
310 SS	Fe-24.5Cr-21.7Ni-1.7Mn-0.2Mo-0.4Si
347 SS	Fe-17.7Cr-11.7Ni-0.7Si-1.4Mn
18-18-2	Fe-18.4Cr-18Ni-1.9Si-1.5Mn
Inconel 671	47.2Cr-0.14Fe-52.2Ni-0.2Si
FSX414	Co-29.8Cr-0.9Fe-10.7Ni-7W-1Si-0.7Mn
P9	Fe-8.9Cr-1Mo-0.7Si

[g] Probe was inserted in an electrical resistance furnace operating at 1650 °F (899 °C). Specimen temperatures were held at 1200 to 1580 °F by blowing air through probe.

EROSION-CORROSION METAL LOSS OF ALLOYS EXPOSED AT LOW TEMPERATURES IN A FLUIDIZED BED COAL COMBUSTOR[c][37]

Alloy[a]	Temperature °F	Change in Diameter[d] (mils)		Change in Wall Thickness[d] (mils)			
		Plane[e] 6-12	Plane[e] 3-9	6[e]	12[e]	9[e]	3[e]
A106 Carbon Steel, Aluminized[f]	400	- 9	+ 3.4				
	590	- 5	0				
	755	-15	-10				
	875	- 2.6	- 6.9				
A106 Carbon Steel	445	- 5.5	- 1.1	- 5.4	+ 0.5	- 0.5	- 1.3
	620	-10	0	-11.0	0	0	+ 1.2
	775	- 9[g]	- 4	-11.2	- 8.2	+ 0.4	- 1.4
	890	-26.5	-23.7	-20.7	- 2.8	-21.1	- 3.7
P22 (2-1/4Cr-1Mo)	480	- 6	- 2	- 3.7	- 4.8	- 2.2	- 2.1
	655	-10	+ 1	-13.41	- 0.54	- 1.09	- 1.14
	790	-20	-11	-20.3	- 7.6	-10.0	- 9.7
	900	-40.2	-32.3	-38.2	- 5.4	-27.7	- 6.4
P9(9Cr-1Mo)	510	- 3.4	- 3.3	- 2.7	- 0.1	- 3.5	- 0.5
	685	- 8	0	- 7.5	+ 0.8	+ 2.6	+ 1.1
	820	-11	- 7	-14.3	- 1.1	- 4.3	- 4.8
	905	- 7.7	- 6.4	-11.4	- 2.1	- 1.1	- 6.3
E-Brite (26Cr-1Mo)	535	- 7.5	- 3.2	- 1.9	- 5.7	- 3.0	- 1.6
	715	- 6[g]	- 5	- 7.5	+ 1.4	- 2.9	- 1.4
	840	-28.0[g]	- 6	- 27.2	- 7.5	- 9.0	- 3.5
	910	- 4.2	- 5.4	- 3.1	- 1.5	- 1.8	- 2.4
316 SS(17Cr-10Ni-2Mo)	560	- 9.8	- 4.0	- 4.7	- 3.4	- 2.6	- 1.4
	740	-11[g]	- 4	- 7.3	- 0.4	- 1.7	- 4.5
	860	- 8[g]	- 5	- 8.6	- 0.7	- 6.6	- 2.8
	910	- 4.8	- 3.1	- 5.3	- 0.8	- 0.9	- 1.2

(Table Continued)

EROSION-CORROSION METAL LOSS OF ALLOYS[a] EXPOSED[b] AT LOW TEMPERATURES IN A FLUIDIZED BED COAL COMBUSTOR[c] [37]

(continued)

[a] Cylindrical test specimens were machined from tube stock to 1.25 in OD, 1.01 in ID and 0.97 in long. Twenty-four specimens (four sets of each alloy) formed a tube probe.

[b] Exposure at indicated temperatures for 144 hours.

[c] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

[d] After exposure, specimens were mounted in epoxy to preserve scale and deposits, sectioned across a diameter. One cut face was metallographically polished and measurements were made with a digital travelling microscope in the planes corresponding to the 6 to 12 o'clock and 3 to 9 o'clock positions of the probe as installed. Estimated mean errors are +1.0 and -1.3 mils for the diameters and +0.5 and -1.2 for thickness measurements.

[e] Locations 3, 6, 9 and 12 refer to clock positions around diameter of probe.

[f] Diffused Al case-pack aluminized 5 hr at 1700 °F in 15% Al-12 Si + 2.5% NH_4Cl + 82.5% Al_2O_3 (Battelle).

[g] Orientations subjective, location markers not distinguishable.

EROSION-CORROSION TESTING OF ALLOYS[a] IN A FLUIDIZED BED COAL COMBUSTOR[b][37]

Analysis of Scale Layers[c] Adhering to Test Specimens on Probes[a]

oy[b]	Exposure Time, hr	Temperature °F	(°C)	Phases Identified[d] Fe_2O_3	Fe_3O_4	$CaSO_4$	$K_3Fe(SO_4)_3$	$CaFe_2Si_3O_{12}$
		Freeboard						
) SS (Fe-24.5Cr-21.7Ni- 1.7Mn-0.2Mo-0.4Si)	10	1456	(790)	S	VF	MF	VF	--
conel 671 (47.2Cr-0.14Fe- 52.2Ni-0.2Si)		1500	(816)	S	--	--	--	--
X414 (Co-29.8Cr-0.9Fe- 0.7Ni-7W-1Si-0.7Mn		1514	(824)	S	VF	M	--	--
(Fe-8.9Cr-1Mo-0.7Si)		1526	(830)	S	--	M	VF	--
4SS (Fe-18.5Cr-8Ni-2Mn)	500	1395	(757)	S	--	VF	M	--
0SS		1410	(766)	S	--	VF	MF	--
conel 671		1430	(777)	S	--	--	F	--
X414		1435	(780)	S	--	VF	F	--
7SS (Fe-17.7Cr-11.7Ni- .7Si-1.4Mn)	1500	1365	(740)	M	--	M	S	--
35[e]		1385	(752)	MF	--	M	S	--
4SS		1400	(760)	MF	--	M	S	--
0SS		1415	(769)	M	--	F	S	--
CrAlNi[e]		1425	(775)	M	--	VF	S	--
conel 671		1440	(782)	S				
X414		1455	(790)	S	M	MF	M	--
		Fluidized Bed						
0SS	10	1432	(778)	S	F			
conel 671		1447	(786)	S	F			
X414		1456	(791)	S	MF	VF		
		1464	(795)	M	MS	F		
4SS	500	1430	(777)	F	MS	VF	--	F
0SS		1435	(780)	F	M	VVF	--	MF
conel 671		1445	(785)	VF	--	VVF	VF	S
X414		1450	(788)	F	--	VVF	VF	S
-18-2 (Fe-18.4Cr-18Ni- 1.9Si-1.5Mn)	1500	1365	(740)	M	S	F	--	--
35[e]		1375	(746)	M	MS	F	--	--
4SS		1390	(754)	M	MS	F	--	--
0SS		1400	(760)	MS	MS	F	--	--
CrAlNi[e]		1410	(766)	MS	M	F	--	--
conel 671		1417	(770)	M	MS	F	--	--
X414		1425	(774)	MS	M	F	--	--

(Table Continued)

EROSION-CORROSION TESTING OF ALLOYS[a] IN A FLUIDIZED BED COAL COMBUSTOR[b][37]
continued

Analysis of Deposits[f] on Erosion Corrosion Specimens[a]

Location	Freeboard[g]		Fluidized Bed[h]	
Exposure Time	500 hr	1500 hr	500 hr	1500 hr
	Weight Percentages[i]			
Fe	4-6	4-12	5-10	8-12
Si	5-10	4-10	5-10	7-10
Ca	10-15	20-30	20-30	30-40
Al	3-5	1-3	4-6	1-4
K	10-20	5-15	5-10	1-5
Na	2-4	1-3	1-2	0.5-2
Cr	0.3	1-5	4-6	2-5
Ni	0.03	0.02-1	0.03	0.3-0.6
Mg	0.5	0.7	0.5	0.5-1
Mn	0.03	0.03-0.06	0.1	0.06-0.3
Ti	0.1	0.1	0.2	0.1
Co	0.03	0.01-0.03	0.03	0.06-0.5
Ba	0.03	0.02	0.01	0.02
B	0.01	0.02	0.01	0.02
W	--	<0.03	--	<0.03
Mo	--	<0.005	--	0.01-0.02
V	<0.01	<0.01	0.02	0.01-0.02
Cu	<0.01	0.005-0.01	0.01	0.01-0.03
Zn	--	<0.1	--	<0.1
Sr	0.01	0.01	0.01	0.01

---

[a] Test specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 1.00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. FSX414 obtained as cast rods from which specimens were machined. As machined specimens were solvent rinsed before exposure. Twenty-one specimens were used to make up 18-in air-cooled tube probes. Composition of an alloy is given only the first time it appears in the table.

[b] Facility consists of a 24-in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

[c] Scale is defined as that material formed by reaction with the base metal exposed to the combustor atmosphere and tightly adherent to it.

[d] X-ray diffraction relative intensities for the phases are indicated by S-strong, M-medium, F-faint, and V-very.

[e] These are coatings. HI35 is a duplex coating of Al over a chromized 304 SS with a case depth of 10 mil (Alloy Surfaces). FeCrAlNi (Fe-15Cr-10Al-8Ni-1Mo-1Si) coating consists of two 3.5 mil plasma sprayed layers, first of which was anneal bonded, on a 304SS base (Union Carbide).

[f] The deposit is defined as the loosely adhering particles of flyash or bed material that can be removed from the test specimens with a stiff brush or light mechanical tapping.

[g] The major phases in the freeboard deposits were $CaSO_4$, $K_3Fe(SO_4)_3$, and SiO_2.

[h] The major phases in the bed deposits were $CaSO_4$, Fe_2O_3, $Ca_3Fe_2Si_3O_{12}$, and SiO_2.

[i] The range given covers that obtained by optical spectrographic analysis on three samples from each probe.

EROSION-CORROSION OF UNCOOLED ALLOY PROBES[a] EXPOSED[b] IN A FLUIDIZED BED COAL COMBUSTOR[c] [37]

	Lower Fluidized Bed[b]		Upper Fluidized Bed[b]	
oy	Weight Loss,[d] Grams	Average Wastage, mils	Weight Loss,[d] grams	Average Wastage, mils
SS e-18.5Cr-8Ni-2Mn)	21.3668	27.952	-	-
SS e-17.7Cr-11.7Ni-0.7Si-1.4Mn)	3.2060	4.138	1.6955	2.1883
SS e-24.5Cr-21.7Ni-1.7Mn-0.2Mo-0.4Si)	-	-	0.6882	0.8879
oloy 825 0Fe-21.5Cr-42Ni-3Mo-2.25Cu-0.25Si-0.5Mn)	1.9360	2.4625	0.7207	0.9167

---

st specimens were machined from tube or bar stock to 1.25 in (3.17 cm) OD, 00 in (2.54 cm) ID, and 0.97 in (2.46 cm) long. As machined specimens were lvent rinsed before exposure.

posure was for 1080 hr in the fluidized bed at 1620 °F (882 °C). Upper bed sition was 25 in from the lower bed position.

cility consists of a 24-in diameter refractory-lined fluidized-bed combustor arged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, st Virginia, <8 mesh. Combustor operated at atmospheric pressure.

ight loss determined after descaling of specimens by mechanical removal of loose posits then soaking in 11% NaOH +5% $KMnO_4$ solution at 200 °F, and then a cathodic eatment in 10% H_2SO_4 containing 1-ethyl-quinolinium iodide inhibitor.

COMPARISON OF SCALE THICKNESS[a] FORMED ON ALLOYS[b] IN AIR[c] AND IN A FLUIDIZED BED COAL COMBUSTOR[d] [37]

Alloy[b]	Air[c]		Fluidized Bed Combustor[d]	
	Temperature, °F	Thickness,[a] μm	Temperature, °F	Thicknes μm
P9(9Cr-1Mo)	610	1-2	685	2-20
	740	4-7	820	20-45
	1020		905	--
E-Brite	630		715	10
(26Cr-1Mo)	790	0.5-1	840	$\lesssim 25$
	1068	1-3	910	~ 10
AISI 316 SS	650	$\lesssim 1$	740	25
(17Cr-10Ni-2Mo)	830	$\lesssim 2.5$	860	55
	1068	1-2	910	~ 15

---

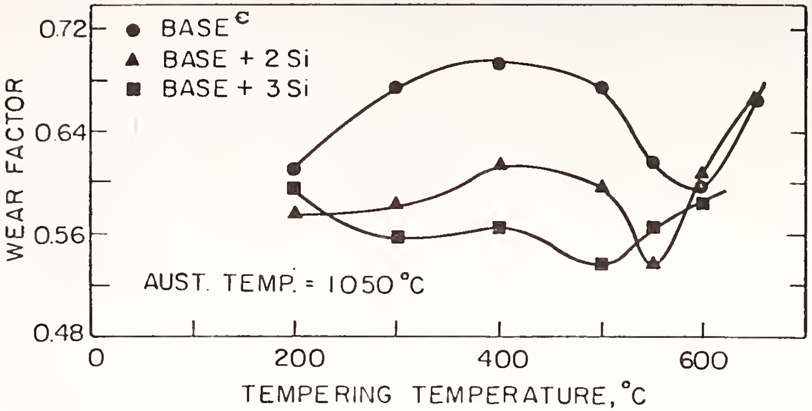
[a] After exposure, specimens were mounted in epoxy to preserve scale and deposi and sectioned across a diameter. One cut face was metallographically polish and measurements were made with a digital travelling microscope.

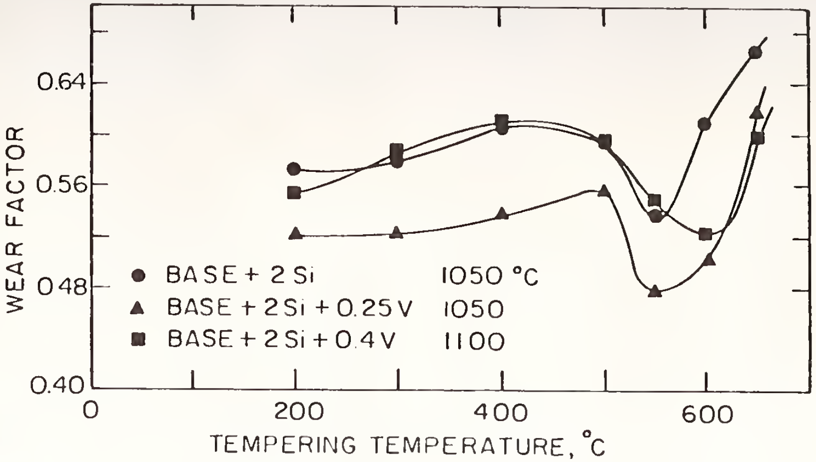
[b] Cylindrical test specimens were machined from tube stock to 1.25 OD, 1.01 ID and 0.97 in long. Twenty-four specimens formed an air-cooled tube probe. Exposure time 144 hours.

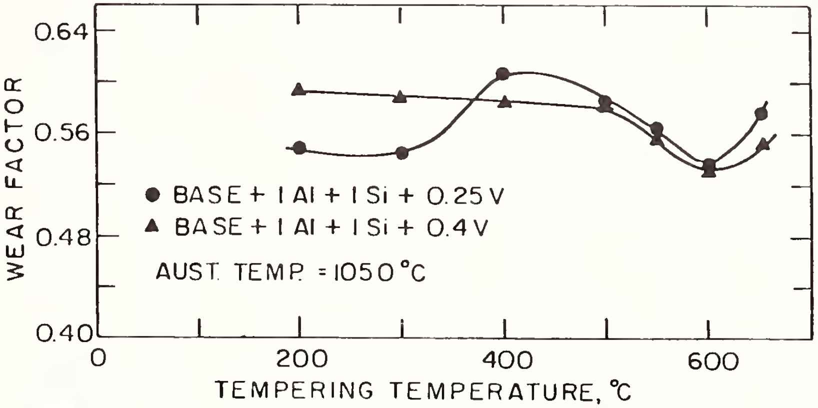
[c] Tube probes were inserted in an electrical resistance furnace maintained at 1600 °F for 144 hours. Specimens were cooled so as to provide the lower temperatures stated.

[d] Facility consists of a 24-in diameter refractory-lined fluidized-bed combust charged with Illinois No. 6 coal, +8 to -200 mesh, and limestone from Greer Quarry, West Virginia, <8 mesh. Combustor operated at atmospheric pressure.

ABRASION RESISTANCE[a] OF SOME EXPERIMENTAL SECONDARY HARDENING MARTENSITIC STEELS[b] [11]







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[a] Simulated high-stress two-body abrasion determined on a Pin-on-Disc tester (120 grit SiC paper, 2.2 m wear path, 1 kg load). Wear Factor = (wear rate of specimen)/(wear rate of standard), where the wear rate = volume loss/(distance x load), and the volume loss = weight loss/density. The standard is annealed AISI 1020.

[b] Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks, cut from the bars, were austenitized 1 hour at the temperatures indicated, oil quenched, and tempered 1 hour at the indicated temperatures.

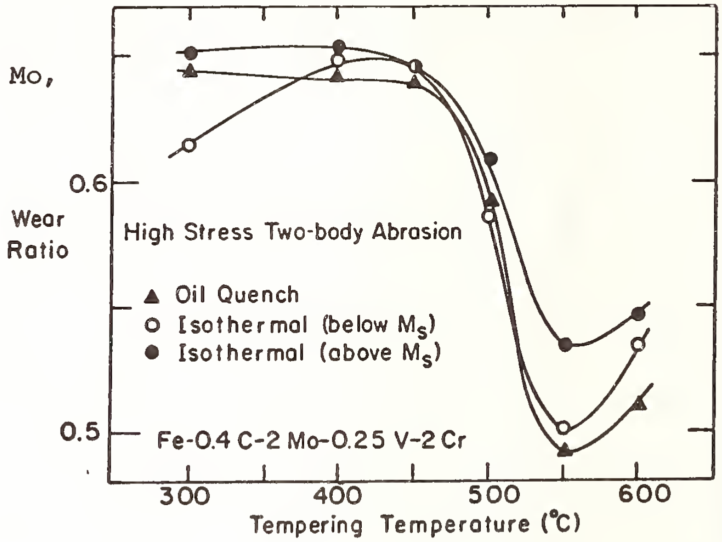
[c] Base alloy composition: 0.36 C, 0.5 Mn, 1.0 Cr, 3.0 Ni, 2.0 Mo, balance Fe.

ABRASION RESISTANCE[a] OF SOME EXPERIMENTAL SECONDARY HARDENING BAINITIC STEELS[b] FOR VARIOUS HEAT TREATMENTS[c][41]

Base alloy: 0.4 C, 2 Mo,
0.25 V

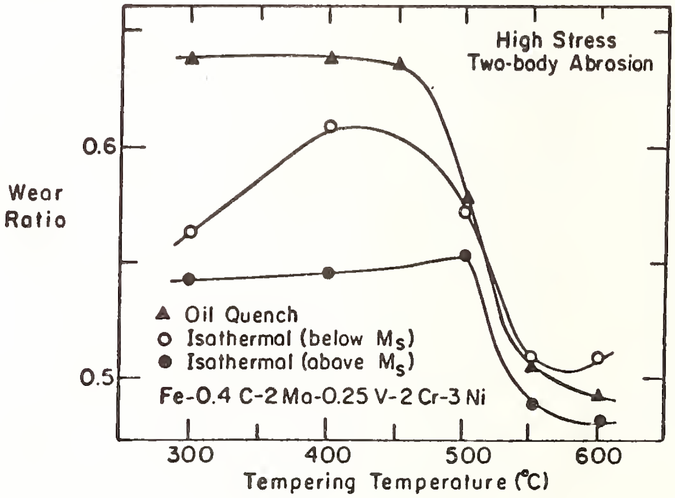
Base + 2 Cr
M_s = 270 °C

Effect of oil quench or isothermal transformation



Base + 2 Cr + 3 Ni
M_s = 240 °C

Effect of oil quench or isothermal transformation



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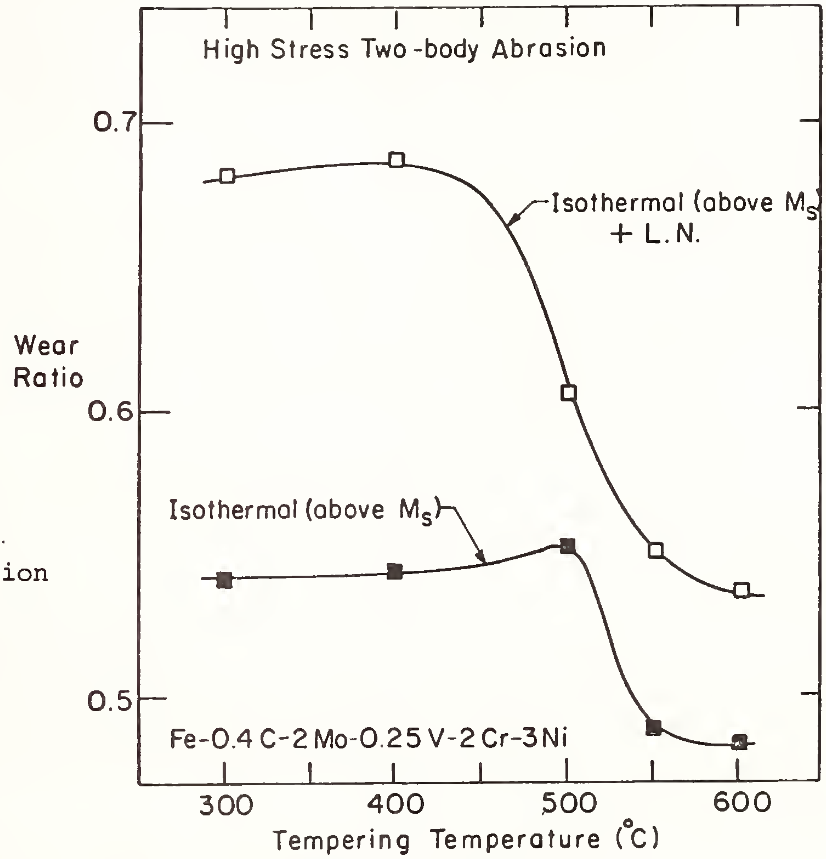
(Data Continued)

ABRASION RESISTANCE[a] OF SOME EXPERIMENTAL SECONDARY HARDENING BAINITIC STEELS[b] FOR VARIOUS HEAT TREATMENTS[c][41], Continued

Base + 2 Cr + 3 Ni
M_s = 240 °C

Effect of cryogenic quench after isothermal transformation



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[a] Simulated high-stress two-body abrasion determined on a pin-on-disc tester (120 grit SiC paper, 2.2 m wear path, 1 kg load). Wear ratio = (wear rate of specimen)/ (wear rate of standard), where wear rate = volume loss/ (distance x load), and the volume loss = weight loss/density. The standard is annealed AISI 1020.

[b] Prepared as 11.3 kg ingots in an induction furnace under an argon atmosphere from 99.9% pure materials. Ingots homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks, cut from the bars, were subjected to the indicated heat treatments. Sample pins (1/4 inch diameter) were machined from the specimen blanks.

[c] All specimens were austenitized at 1000 °C for 1 hour followed by one of the following treatments as indicated on the graphs:

1. oil quench
2. isothermal treatment for 1 hour above or below the indicated M_s
3. isothermal treatment for 1 hour followed by quenching in liquid nitrogen (L.N.)

After one of the above treatments the specimens were tempered at the indicated temperatures for 1 hour.

GOUGING ABRASION WEAR[a] OF EXPERIMENTAL AND COMMERCIAL STEELS[41]

Alloy	Heat Treatment	Tempering Temperature[b]	Gouging Wear Factor[c]
Secondary Hardening Martensitic Steel[d]			
0.38 C, 0.84 Mn, 1.05 Si, 1.11 Cr, 3.05 Ni, 1.94 Mo, 0.38 V, 1.0 Al, 0.030 S, 0.024 P, balance Fe	Austenitized at 900 °C for 1 hour[e], oil quenched	200 °C	0.224
		300	0.230
		500	0.232
		550	0.235
Modified Ultra-High Strength Steel			
AISI 4340 + 1.5 Al + 1.5 Si	(Wrought) Austenitized at 1000 °C for 1 hour, oil quenched	300	0.220
	(Cast) Austenitized at 1000 °C for 1 hour, oil quenched	300	0.227
Commercial Steels[f]			
AISI 4340			0.26
HiC/12S			0.24
12S			0.27

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[a] Determined on Jaw-Crusher apparatus described by Borik and Sponseller, J. Mater. 6 (3), 576 (1971), modified to have two sets of plates instead of the original one set. Tests were run at ESCO Corporation.

[b] Tempered for 1 hour.

[c] Wear factor = weight loss of sample/weight loss of standard. The standard used was a T1 steel of BHN 269.

[d] Cast as 50 lb. ingot by air induction melting. Ingots were forged at 2000 °F (1093 °C), normalized at 2150 °F (1177 °C), austenitized at 1652 °F (900 °C) for 1 hour and quenched to simulate oil quenching.

[e] Table reporting results quotes austenitizing temperature of 1652 °F (900 °C), but text says 1922 °F (1050 °C) was used.

[f] Data from ESCO Corporation.

SIMULATED HIGH-STRESS TWO-BODY ABRASION[a] OF EXPERIMENTAL[b] AND COMMERCIAL STEELS[41]

Alloy[b]	Heat Treatment	Tempering Temperature[c]	Wear Factor[d]
Experimental Matrix Steels			
0.46 C, 4.11 Cr, 2.8 Mo, 1.62 W, 1.38 V, balance Fe[e]	Austenitized at 1000 °C for 1 hour, oil quenched	as quenched	0.437
		200 °C	0.392
		300	0.460
		400	0.465
		450	0.442
		500	0.458
		550	0.404
		600	0.423
		650	0.469
0.47 C, 4.20 Cr, 2.2 Mo, 0.70 W, 1.43 V, balance Fe	Austenitized at 1000 °C for 1 hour, oil quenched	as quenched	0.494
		200	0.494
		300	0.564
		400	0.584
		450	0.520
		500	0.548
		550	0.514
		600	0.470
		650	0.549
0.52 C, 4.30 Cr, 2.2 Mo, 1.68 W, 0.67 V, balance Fe	Austenitized at 1000 °C for 1 hour, oil quenched	as quenched	0.458
		200	0.472
		300	0.523
		400	0.560
		450	0.528
		500	0.541
		550	0.449
		600	0.475
		650	0.588
0.38 C, 4.40 Cr, 2.0 Mo, 0.49 W, 0.43 V, balance Fe	Austenitized at 1100 °C for 1 hour, oil quenched	as quenched	-
		200	0.527
		300	0.570[f]
		400	0.570[f]
		450	-
		500	0.540[f]
		550	0.514
		600	0.453
		650	0.495[f]
Experimental Cr-Si-Mo Steels			
0.3 C, 2.0 Cr, 1.5 Si, 0.3 Mo, balance Fe[g]	Austenitized at 900 °C for 1 hour, oil quenched	as quenched	0.54
		100	0.57
		150	0.56
		200	0.58
		250	0.59
		300	0.61
		400	0.64
		500	0.68

(Table Continued

SIMULATED HIGH-STRESS TWO-BODY ABRASION[a] OF EXPERIMENTAL[b] AND COMMERCIAL STEELS[41]

continued

Alloy[b]	Heat Treatment	Tempering Temperature[c]	Wear Factor[d]
Experimental Cr-Si-Mo Steels			
0.3 C, 2.0 Cr, 1.5 Si, 0.3 Mo, balance Fe[g]	Austenitized at 900 °C for 1 hour, oil quenched, liquid N_2 refrigeration for 24 hours		0.57
0.4 C, 2.0 Cr, 1.5 Si, 0.3 Mo, balance Fe	Austenitized at 900 °C for 1 hour, oil quenched	as quenched	0.59
		100	0.57
		150	0.52
		200	0.57
		250	0.57
		300	0.57
		400	0.60
		500	0.63
0.4 C, 2.0 Cr, 1.5 Si, 0.3 Mo, balance Fe	Austenitized at 900 °C for 1 hour, oil quenched, liquid N_2 refrigeration for 24 hours		0.61
0.3 C, 3.0 Cr, 1.5 Si, 0.3 Mo, balance Fe	Austenitized at 900 °C for 1 hour, oil quenched	as quenched	0.54
		100	0.55
		150	0.54
		200	0.55
		250	0.60
		300	0.58
		400	0.61
		500	0.63
0.3 C, 3.0 Cr, 1.5 Si, 0.3 Mo, balance Fe	Austenitized at 900 °C for 1 hour, oil quenched , liquid N_2 refrigeration for 24 hours		0.58
Modified Ultra-High Strength Steel			
AISI 4340 + 1.5 Al + 1.5 Si[h]	Austenitized at 1000 °C for 1 hour, oil quenched	300	0.55
	Austenitized at 1000 °C for 1 hour, isothermal transformation at 350 °C for 1 hour, (above M_s temperature)	as quenched	0.52
		300	0.63[i]

(Table Continued)

SIMULATED HIGH-STRESS TWO-BODY ABRASION[a] OF EXPERIMENTAL[b] AND COMMERCIAL STEELS[41]

continued

oy[b]	Heat Treatment	Tempering Temperature[c]	Wear Factor[d]
	Modified Ultra-High Strength Steel		
	Austenitized at 1000 °C for 1 hour, isothermal transformation at 350 °C for 1 hour, (above M_s temperature), liquid N_2 refrigeration for 24 hours	300	0.70
	Austenitized at 1000 °C for 1 hour, isothermal transformation at 250 °C for 1 hour, (below M_s temperature)	as quenched	0.45
		300	0.52
	Commercial Steels[j]		
0			1.0[k]
			0.589
0			0.620
M			0.575

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etermined on a pin-on-disc apparatus (120 grit SiC abrasive, 2.2 m wear path, kg load).

repared as 11.3 kg ingots in an induction furnace under argon atmosphere from .9% pure raw materials. Ingots homogenized at 1200 °C for 24 hours and rged at 1200 °C to bars about 2.5 cm thick. Specimen blanks, cut from the rs, were subjected to the indicated heat treatment. Sample pins (1/4 inch ameter) were machined from the specimen blanks.

empered for 1 hour, unless otherwise indicated, followed by a water quench.

ear factor = (wear rate of specimen)/(wear rate of standard), where the wear ate = volume loss/(distance x load), and the volume loss = weight loss/density. e standard is annealed AISI 1020.

mposition corresponds to VASCO MA steel.

alue estimated from reported graphical results.

ated to correspond to a commercial ESCO steel which was not identified further.

repared by addition of Al and Si to remelted commercial, vacuum arc remelt, ircraft quality AISI 4340 in an induction furnace under argon.

alue conflicts with graphical results indicating a value ~0.53.

s received condition.

ll wear factors referred to 1020 steel standard.

BLE OF CONTENTS

EROSION TEST[a] DATA FOR ALUMINA REFRACTORIES[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
Al_2O_3, densified	Lucalox	Gen. Electric	0.03	0.40	0.57
Modified Al_2O_3	AlSi Mag 840	3-M Co.	0.86	2.94	very high
Al_2O_3, $\rho=3.65$	AV-30	McDaniel		1.15	
Al_2O_3, $\rho=3.7$	AP-35	McDaniel		0.89	
Al_2O_3, $\rho=3.85$	McD-998	McDaniel		0.78	
Al_2O_3, p&s[d]	Iso A-242	A.P. Green		1.07	0.73
99.7% Al_2O_3, p&s[d]	SC-99.7P	Krohn	0.39	1.63	1.49
99.5% Al_2O_3, p&s[d]	AL-995 S	Wesgo	0.22	1.08	0.59
99.5% Al_2O_3, p&s[d]	AD 995	Coors		2.25	
99.5% Al_2O_3, p&s[d]	Wearox	Wesgo	0.20	1.00	1.46
99.5% Al_2O_3, p&s[d]	AlSi Mag 838	3-M Co.	0.25	1.41	0.62
99+% Al_2O_3, p&s[d]	SC-99P	Krohn	16.42	12.49	very high
98% Al_2O_3	AD 98	Coors	0.18	0.88	0.81
98% Al_2O_3, p&s[d]	SC-98 D	Krohn	0.30	1.29	1.12
97.6% Al_2O_3, p&s[d]	AL-300 S	Wesgo	0.09	1.04	1.21
96% Al_2O_3, p&s[d]	AlSi Mag 614	3-M Co.	0.26		0.87
94% Al_2O_3, p&s[d]	AL-500 S	Wesgo	0.11	1.22	1.04
94% Al_2O_3, p&s[d]	SC-95 AM	Krohn	0.29	1.41	1.74
85% Al_2O_3	AlSi Mag 798	3-M Co.	0.64	2.00	1.15
85% Al_2O_3	Arlcite	Ferro Corp.	0.40	1.81	1.11

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] p&s = pressed and sintered.

EROSION TEST[a] DATA FOR MISCELLANEOUS ALUMINA-CONTAINING REFRACTORIES[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp
60% Al_2O_3-40% Si_3N_4	GE102 Sialon	Gen. Electric	0.66	2.03	2.05
50% Al_2O_3-50% Si_3N_4	GE128 Sialon	Gen. Electric	0.39	1.55	2.27
13% Al_2O_3-87% Si_3N_4	GE129 Sialon	Gen. Electric	8.24	4.61	2.20
Al_2O_3-Si_3N_4, 90% dense, 10% porosity	Sialon		1.00+	1.00+	1.00+
Mullite+glass, ρ=2.8 [$3Al_2O_3.2SiO_2$]	MV-30			2.56	
Al_2O_3-2MgO-25TiB_2-3.5WC, p&s[d]	BT-9	Oregon Graduate Center		0.37	0.36
Al_2O_3-2MgO-30TiB_2-3.5WC, p&s[d]	BT-10	Oregon Graduate Center		0.30	0.25
Al_2O_3-1.7MgO-38TiB_2-3.5WC, p&s[d]	BT-11	Oregon Graduate Center	0.05	0.33	0.26
Al_2O_3-1.5MgO-49TiB_2-3.5WC, p&s[d]	BT-12	Oregon Graduate Center		0.35	0.16
Al_2O_3-2MgO-30TiB_2-3.5WC, p&s[d]	BT-24	Oregon Graduate Center		0.32	0.20
Al_2O_3-TiC, p&s[d]		Babcock & Wilcox		0.19	0.30

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27µ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] p&s = pressed and sintered.

EROSION TEST[a] DATA FOR SILICON CARBIDE-CONTAINING REFRACTORIES[1].

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b]		
			20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
SiC, hot-pressed	N SiC	Norton	0.05	0.12	0.44
SiC, standard grade	KT SiC	Carborundum	0.03	0.24	0.68
SiC, fine grade (pressed & sintered)	KT SiC	Carborundum	0.13	0.96	1.07
SiC, recrystallized dense	NC 430	Norton		0.47	0.98
SiC, recrystallized	NC 435	Norton		1.80	1.48
SiC, recrystallized	HD 430	Norton		0.40	0.38
SiC, recrystallized	HD 435	Norton		0.80	0.32
SiC, 98% dense		Gen. Electric		0.05	0.02
SiC	SDIP-1-1	Carborundum	0.11	0.41	0.68
SiC	SDIP-1-2	Carborundum	0.15	0.45	0.52
SiC	SDIP-1-3	Carborundum	0.11	0.47	0.43
SiC	SDIP-1-4	Carborundum	0.12	0.44	0.43
SiC	SDIP-1-5	Carborundum	0.15	0.50	0.85
SiC	SDIP-1-6	Carborundum	0.14	0.43	0.66
SiC, sintered	Lot 1	Carborundum	0.045	0.391	
SiC, sintered, heat-treated	Lot 2	Carborundum	0.068	0.389	
SiC, sintered	Lot 3	Carborundum	0.072	0.474	
SiC, sintered, heat-treated	Lot 4	Carborundum	0.057	0.472	
90% SiC-10% SiO_2, pressed & sintered	Carbofrax D	Carborundum	0.05	0.49	1.38
SiC, SiO_2-bonded	Kellogg 4A	Ferro Corp.	0.43	0.88	0.43
Modified Kellogg 4A	Kellogg Fil	Ferro Corp.	0.35	0.37	4.74
Modified Kellogg 4A	Kellogg 4A-Mod	Ferro Corp.	0.35	0.37	4.74
SiC, SiO_2/Si_3N_4-bonded	Kellogg KN	Ferro Corp.	0.31	0.72	0.33
Modified Kellogg KN	Kellogg NA	Ferro Corp.	0.10	0.39	
80% SiC-19% Si_3N_4-1% SiO_2, pressed & sintered	Refrax 20C	Carborundum	0.27	0.91	1.15
SiC-Si_3N_4, hot-pressed	Noroc-33	Norton	0.05	0.20	0.42
CVD[d] SiC on HIP[e] SiC	Lummus 1-8	MTC and Ceradyne	0	0	
SiC-ZrB_2, hot-pressed	ZRBSC-D	Norton	0.14	0.32	0.69
SiC-ZrB_2-graphite, hot-pressed	ZRBSC-M	Norton		6.36	high

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] CVD = chemically vapor deposited.

[e] HIP = hot isostatic pressed.

EROSION TEST[a] DATA FOR VARIOUS CARBONITRIDES[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Facto	
			20° C, 90° imp[c]	700° C, 90° imp[c]
85.5(Ti,Cr)CN-14.5Ni, p&s[d]	SCr-1	Oregon[e]	1.67	1.89
85.8(Ti,Cr)CN-14.2Ni, p&s[d]	SCr-2	Oregon	1.58	1.71
86(Ti,Cr)CN-14Ni, p&s[d]	SCr-3	Oregon	1.52	1.75
84(Ti,Cr,Mo)CN-13Ni-3Mo, p&s[d]	SCr-9	Oregon	0.56	0.54
84(Ti,Mo)CN-13Ni-3Mo, p&s[d]	SN-4F	Oregon	0.85	0.80
85(Ti,Mo)CN-12Ni-3Mo, p&s[d]	SN-5F	Oregon	0.82	1.17
85(Ti,Mo)CN-12Ni-3Mo, p&s[d]	SN-6F	Oregon	0.85	0.91
94(Ti,Mo)CN-5Ni-1Mo, p&s[d]	SN-305-1	Oregon	0.80	0.73
89(Ti,Mo)CN-9Ni-2Mo, p&s[d]	SN-309-3	Oregon	0.80	0.69
84(Ti,Mo)CN-13Ni-3Mo, p&s[d]	SN-3F2	Oregon	0.74	0.74
97(Ti,Mo)CN-2Ni-0.5Mo, p&s[d]	C-2	Oregon	0.75	0.47
TiCN, p&s[d]		Teledyne Wah Chang		0.98
MoTiCN, p&s[d]		Teledyne Wah Chang	0.93	
MoTiCN, cast		Teledyne Wah Chang	0.80	

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] p&s = pressed and sintered.

[e] Oregon = Oregon Graduate Center.

EROSION TEST[a] DATA FOR SILICON NITRIDE REFRACTORIES[1]

erial	Brand Name or Other Designation	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
N_4, hot-pressed	Lot 1321	Ceradyne	0.03	0.18	0.57
N_4, reaction-bonded			6.17	5.50	6.51
N_4, hot-pressed		Norton	0.04	0.40	0.12
N_4-SiC, hot-pressed	Noroc-33	Norton	0.05	0.20	0.42
Si_3N_4-13% Al_2O_3	GE129 Sialon	Gen. Electric	8.24	4.61	2.20
Si_3N_4-50% Al_2O_3	GE128 Sialon	Gen. Electric	0.39	1.55	2.27
Si_3N_4-60% Al_2O_3	GE102 Sialon	Gen. Electric	0.66	2.03	2.05
N_4-Al_2O_3, 90% ense, 10% porosity	Sialon		1.00+	1.00+	1.00+
Si_3N_4-80%SiC-SiO_2	Refrax 20C	Carborundum	0.27	0.91	1.15

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rosion test conditions: 1/2-inch square specimens subjected to erosion by 7μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 tmosphere, 5 g/min abrasive flow.

elative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated rom weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

mp = angle of impingement.

EROSION TEST[a] DATA FOR MISCELLANEOUS REFRACTORIES[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b]		
			20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
B_4C, hot-pressed	Norbide	Norton	0.16	0.38	0.21
B_4C, hot-pressed	Lot 1076	Ceradyne	0	0	0.38
TiB_2, pressed & sintered	KB TiB_2		0.05	0.13	weight gain
TiB_2	Refractory boride		0.19	0.60	1.30
ZrB_2-SiC, hot-pressed	ZRBSC-D	Norton	0.14	0.32	0.69
ZrB_2-SiC-graphite,[d] hot-pressed	ZRBSC-M	Norton		6.36	
$MgAl_2O_4$, hot-pressed		Trans Tech		1.84	2.56
$45MgAl_2O_4$-55MgO, hot-pressed	5527	Trans Tech		3.39	2.84
$91MgAl_2O_4$-9MgO, hot-pressed	4879	Trans Tech		2.44	2.77
$97MgAl_2O_4$-3MgO, hot-pressed	4310	Trans Tech		2.56	2.76
TiC-Al_2O_3, pressed & sintered		Babcock & Wilcox		0.19	0.30
TiC, 25% Ni-6% Mo binder, pressed & sintered	K162B	Kennametal		1.35	1.67
TiC, 19% Ni binder, pressed & sintered	K151A	Kennametal		1.37	1.62
CbC, cast				3.56	
HfC, cast				3.49	
TaC, cast				2.48	
Chromite, pressed & sintered		Union Carbide		2.44	3.43
Cubic BN		Gen. Electric		0	0
C	diamond	Gen. Electric		0	0

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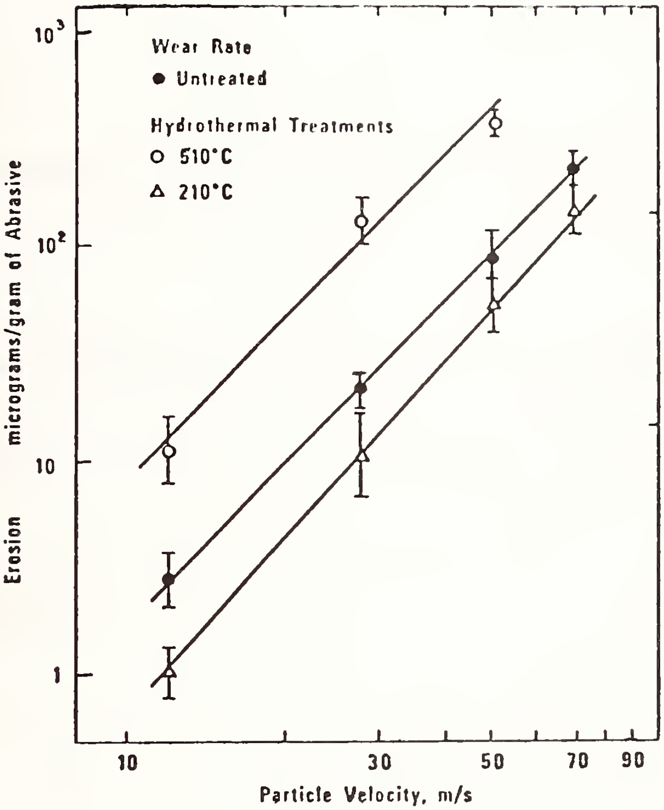
[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] $\text{Relative Erosion Factor} = \frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement.

[d] Oxidation was observed.

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE EROSION[b] OF A HIGH-ALUMINA CASTABLE REFRACTORY[c] [22]



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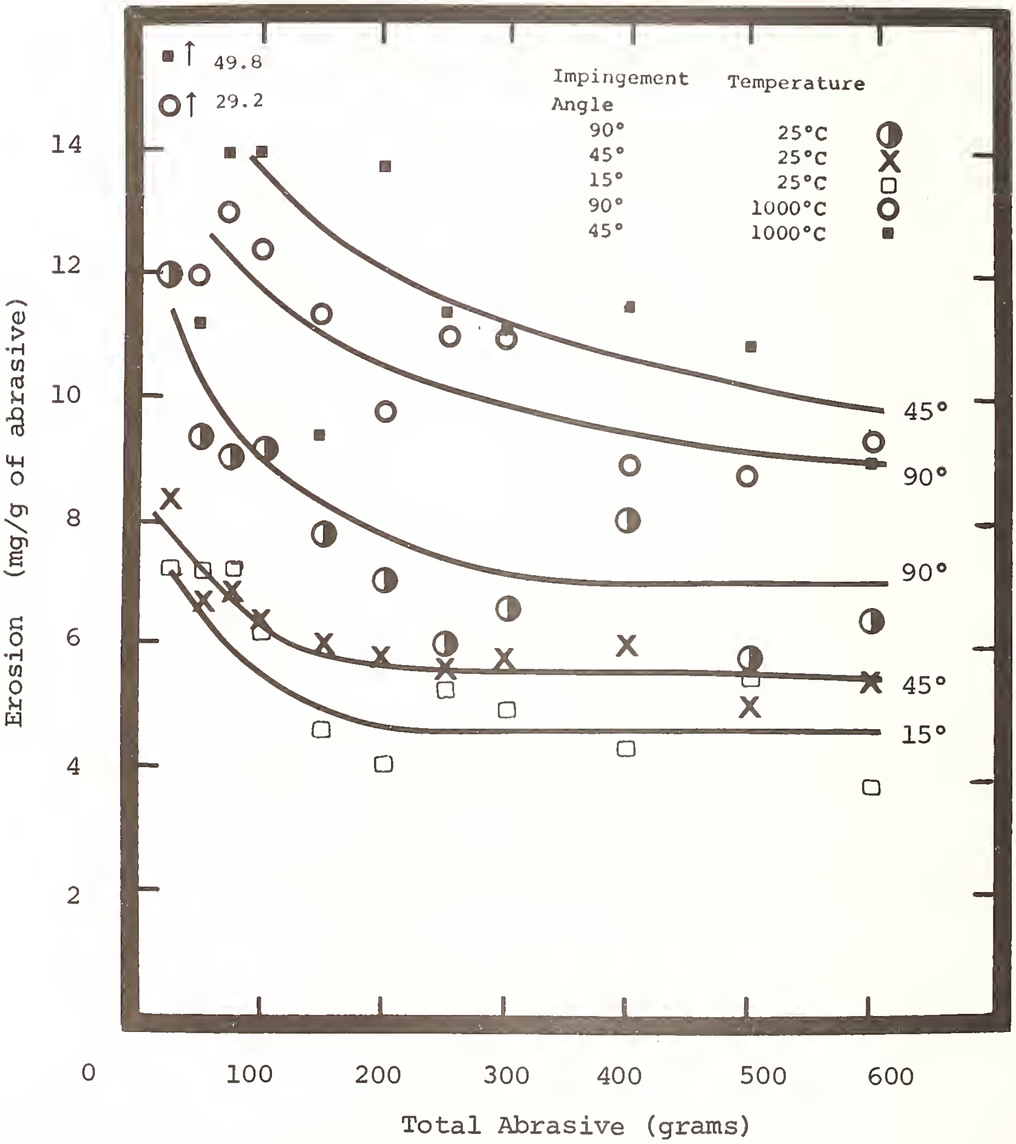
[a] Specimens were sealed in a pressure chamber with 3 ml of water and held for 4 hours at the indicated temperature.

[b] Specimens were subjected to erosion by 100 g of 150 μm SiC at 25 °C; impingement angle 90°; error bars represent one standard deviation from the mean.

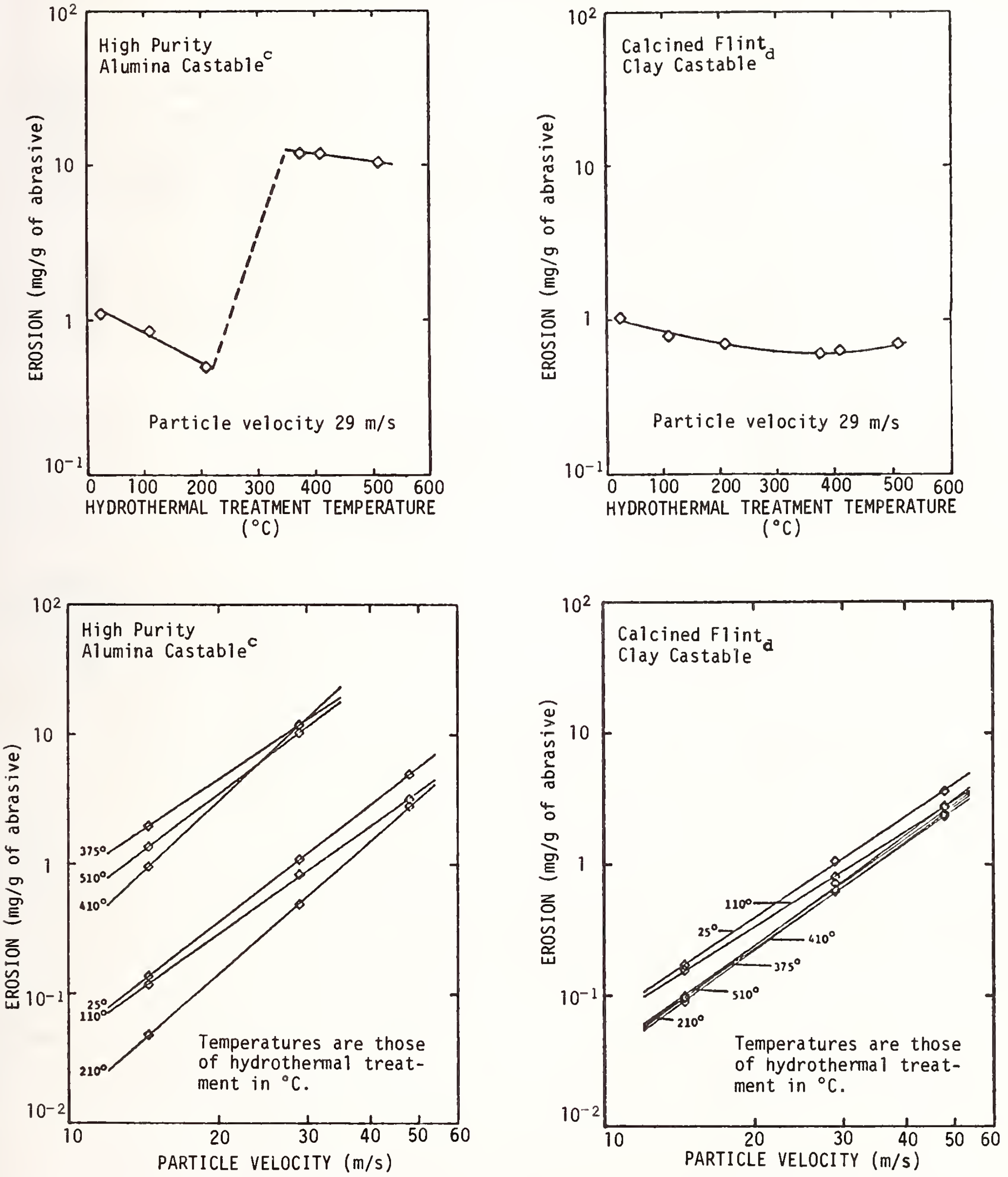
[c] The refractory is a high-purity (95%) tabular alumina bonded with calcium aluminate cement (Castolast G).

EFFECT OF QUANTITY OF ABRASIVE AND TEMPERATURE ON EROSION OF CASTABLE REFRACTORY[22]



Samples of a high-alumina calcium aluminate-bonded castable were subjected to erosion by 150 μm (100 mesh) SiC at velocities of 70-90 m/s. Each specimen was exposed to 600 g of abrasive, using increments of 25 g for the first 100 g exposure, 50 g increments for the next 200 g, then 100 g increments for the final 300 g.

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE EROSION[b] OF ALUMINA CASTABLE REFRACTORIES[c,d][22]



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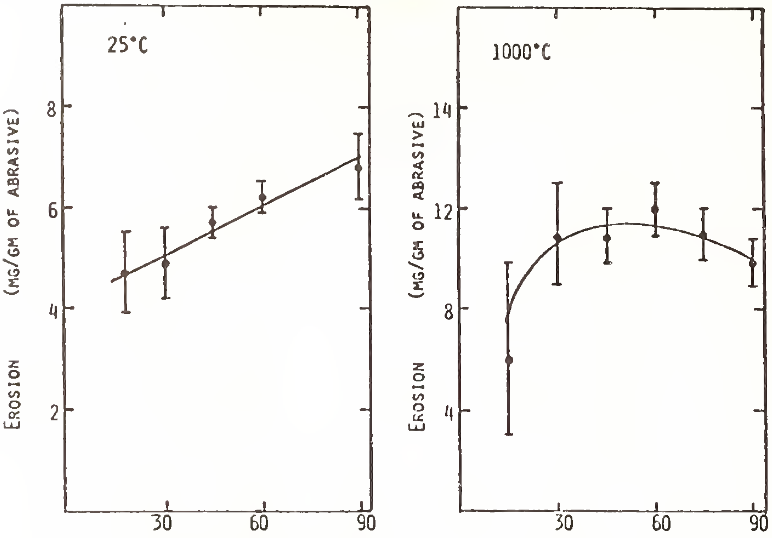
[a] Treatment consisted of sealing samples in a 21 ml pressure chamber with ∿3 ml water and raising the temperature to produce high-pressure steam; treatment time 20 hours; pressure vessel allowed to cool to ambient temperature; samples air-dried for 24 hours.

[b] Erosion tests at ambient temperatures subjected samples to 100 g of 100 mesh (150 μm) SiC, 90° impingement angle at indicated particle velocities; erosion is expressed as weight loss of sample divided by weight of abrasive used; drastic change in erosion values for high-purity refractory is attributed to the formation of a hydration phase between 200 and 300 °C.

[c] Analysis on dried basis (wt %): Al_2O_3 93.7, CaO 5.6, SiO_2 0.1, Fe_2O_3 0.3, others 0.3; a tabular alumina bonded with calcium aluminate cement (Castolast G).

[d] Analysis on dried basis (wt %): Al_2O_3 55, CaO 5, SiO_2 36, Fe_2O_3 1.3, others 2.7; a mullite bonded with calcium aluminate cement (Lo-Abrade).

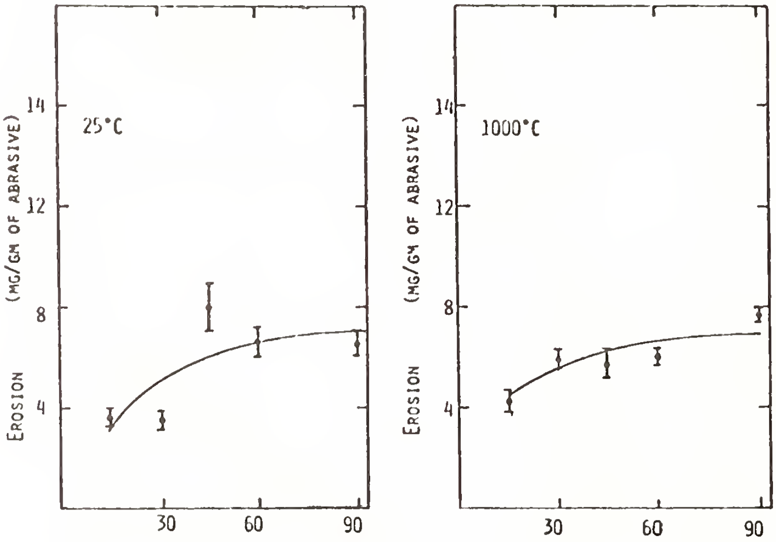
EFFECT OF IMPINGEMENT ANGLE ON EROSION OF SOME CASTABLE REFRACTORIES[22]



High-Purity Alumina Castable with Calcium Aluminate Cement:

Al_2O_3	94.4 wt%
CaO	4.5
SiO_2	0.1
Fe_2O_3	0.1
Na_2O	0.2

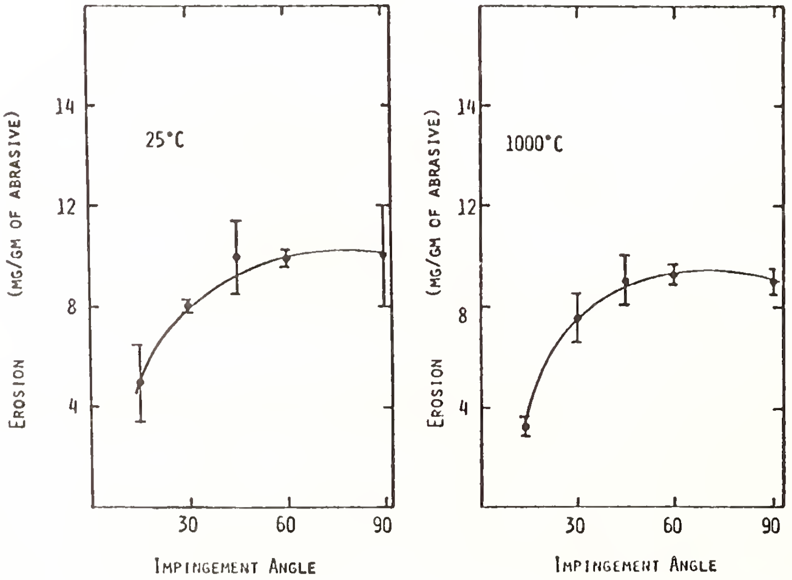
(NBS preparation)



Calcined Flint Clay Castable with Calcium Aluminate Cement:

Al_2O_3	55.6 wt%
CaO	4.5
SiO_2	37.0
Fe_2O_3	0.8
Na_2O	0.2

(NBS preparation)



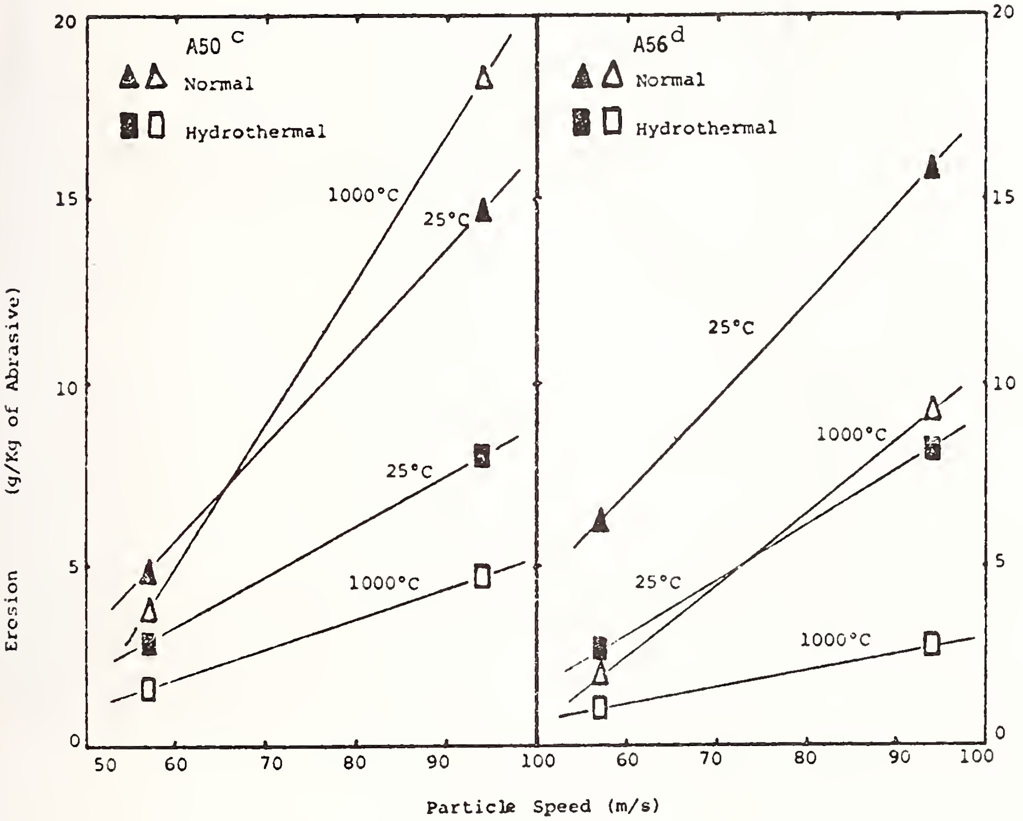
High-Alumina Castable Phosphate-Bonded:

Al_2O_3	89.6 wt%
SiO_2	0.7
Fe_2O_3	0.05
MgO	3.4
Alkali	0.05
P_2O_5	6.2

(Resco Cast AA-22)

Samples were subjected to erosion by 100 g of 150 μm (100 mesh) SiC; particle velocity 72 m/s at 25 °C and 93 m/s at 1000 °C.

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE EROSION[b] OF MEDIUM-ALUMINA CASTABLE REFRACTORIES[22]



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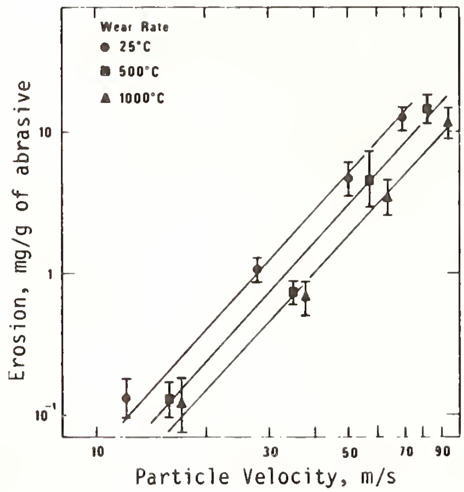
[a] Treatment consisted of placing specimens in a pressure vessel, heating to 310° C in a H_2O-saturated environment, holding for 65 hours, then raising the temperature to 610° C (when saturation temperature of 342° C was reached steam was vented to maintain vapor pressure at 15.0 MPa (2180 psi)), maintaining exposure conditions for 160 hours, cooling to 500° C and venting steam to ambient pressure, and finally allowing specimens to cool to ambient temperature.

[b] Specimens, both as-prepared and those treated hydrothermally as described in a, were subjected to erosion by 100 g of 150 μm (100 mesh) SiC at speeds of 57 m/s and 94 m/s, both at ambient temperature and 1000° C, impingement angle 90°.

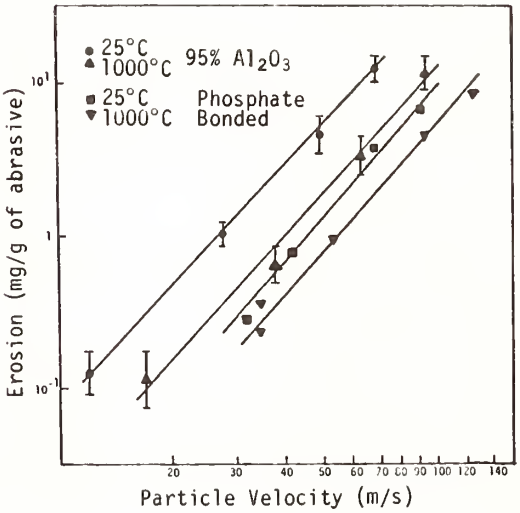
[c] A50 is an NBS-prepared medium-alumina castable refractory bonded with medium-purity calcium aluminate cement: 50.4 wt% Al_2O_3, 8.4 wt% CaO, 38.4 wt% SiO_2, 1.1 wt% Fe_2O_3, 0.1 wt% Na_2O, 1.6 wt% others and loss on ignition. Concrete batches of 2000 g were dry-mixed to homogeneity; water added slowly to "ball-in-hand" consistency (12.5 %); bars 75 x 15 x 7.5 mm were cast in gang molds with combination of vibration and tamping; after casting placed in 95+ % relative humidity at 22°-25° C for 24 hours; bars removed from molds and dried at 110° C for 48 hours.

[d] A56 is an NBS-prepared medium-alumina castable refractory bonded with high-purity calcium aluminate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3, 0.2 wt% Na_2O, 1.9 wt% others and loss on ignition. Specimens prepared as were those of A50 except that casting water was 11.0 %.

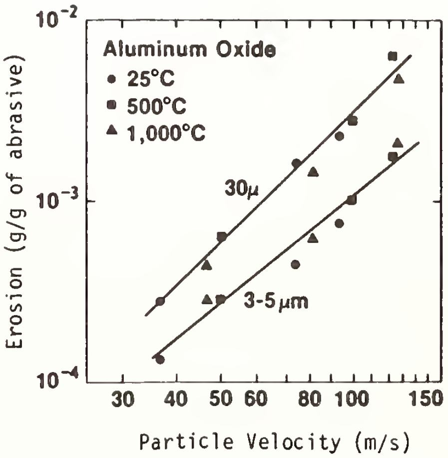
EFFECT OF TEMPERATURE AND PARTICLE VELOCITY ON THE EROSION[a] OF SEVERAL HIGH-ALUMINA REFRACTORIES[22]



Refractory is a high-purity tabular alumina bonded with calcium aluminat cement (Castolast G).



95% Alumina is a tabular alumina bonded with calcium aluminate cement (Castolast G); phosphate-bonded refractory is an extra-high alumina (Resco Cast AA-22).



Two different high-density alumina ceramics were tested, one having a nominal 30 μm grain size, one having 3-5 μm grain size; hot-pressed silicon nitride gives similar results.

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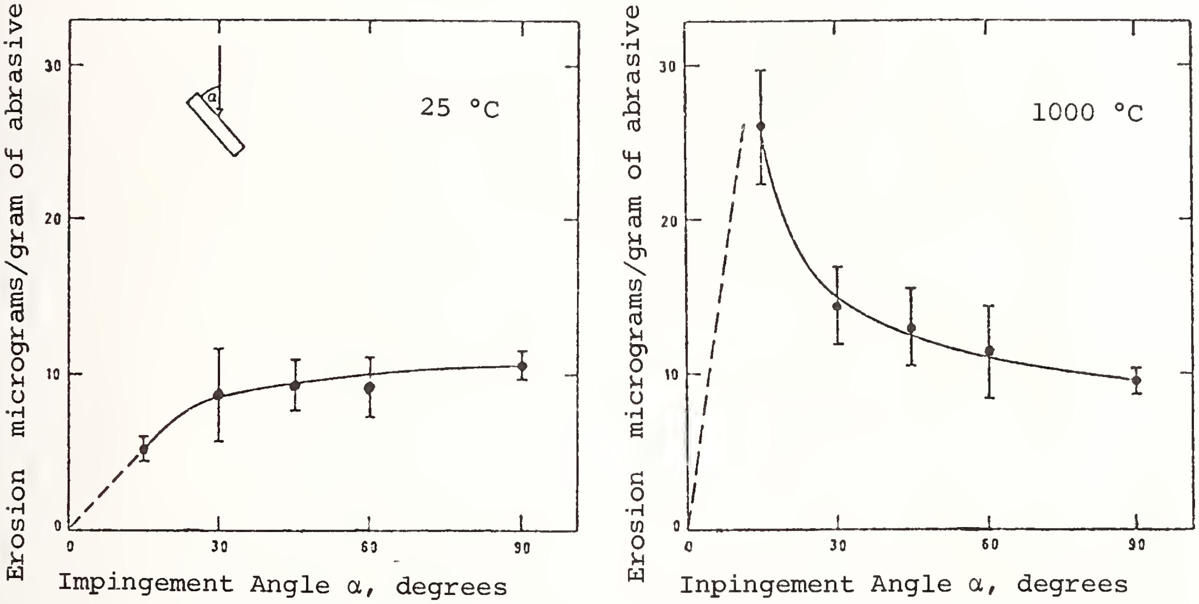
[a] Refractories were subjected to erosion by 100 g of 150 μm (100 mesh) SiC; angle of impingement 90°; erosion values based on weight loss of sample per weight of abrasive used.

EFFECT OF IMPINGEMENT ANGLE AND TEMPERATURE ON EROSION OF HIGH-ALUMINA CASTABLE AT LOW PARTICLE VELOCITY[22]



Specimens were subjected to erosion by 100 g of 150 μm of SiC; particle velocity 28 m/s at 25 °C and 39 m/s at 1000 °C; error bars are one standard deviation from the mean; the castable is a high-purity (95%) tabular alumina bonded with calcium aluminate cement (Castolast G).

EFFECT OF EXPOSURE[a] TO STEAM, HYDROGEN, AND CARBON MONOXIDE ON THE ABRASION RESISTANCE[b] OF VARIOUS REFRACTORIES [9]

Refractory	Brand Name Manufacturer	Cured & Dried[c]	Air Fired 1100° C 250 hr	Exposure Conditions[a]: Steam 1100° C 250 hr 1000 psi	Hydrogen 1100° C 250 hr 1000 psi	Carbon Monoxide 1100° C 125 hr 1000 psi
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	0.0049± 4	0.0205±50	0.0224	0.0249±88	0.0318±150
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	0.0066± 6	0.0424±48	0.0094	0.0346±39	0.0430± 94
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	0.0176±18	0.0530±46	0.0217	0.0478±34	0.0881± 90
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	0.0036± 4	0.0027± 3	0.0045	0.0051± 3	0.0042± 37
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	0.0029± 2	0.0063± 3	0.0093	0.0070±14	0.0104± 50
99% Al_2O_3 brick	99AD A. P. Green	0.0045± 5	0.0040±11	0.0038	0.0051±11	0.0052± 20
90% Al_2O_3 brick	Arco-90 General Refractories	0.0028± 2	0.0027± 1	0.0026	0.0038± 7	0.0039± 4
60% Al_2O_3 tar-impregnated brick	Ufala Tl Harbison-Walker	0.0025± 2	0.0048± 7	0.0033	0.0063±12	0.0074± 21
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	0.0058± 9	0.0063±12	0.0034	0.0076± 9	0.0079± 47

---

[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths of time. At least 5 samples tested; 95% confidence limits shown.

[b] Abrasion loss determined according to ASTM C-704-72, units are cc loss/g grit expended.

[c] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating

EFFECT OF EXPOSURE[a] TO CARBON DIOXIDE AND A MIXED GAS[b] ENVIRONMENT ON THE ABRASION RESISTANCE[c] OF VARIOUS REFRACTORIES[9]

				Exposure Conditions[a]	
Refractory	Brand Name Manufacturer	Cured & Dried[d]	Air Fired 1100° C 250 hr	Carbon Dioxide 1100° C 250 hr 800 psi	Mixed Gas[b] 1000° C 160 hr 1000 psi
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	0.0049± 4	0.0208±18	0.0230±38	0.0222±43
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	0.0066± 6	0.0374±43	0.0360±39	---
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	0.0176±18	0.0383±11	0.0485±28[e]	0.0312±28[e]
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories		0.0130±13	0.0212±59[e]	0.0056±64
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	0.0036± 4	0.0030± 2	0.0037± 4[e]	0.0034± 4
Dense 90% Al_2O_3 castable, phosphate bond	Resco Cast AA-22 Resco Products		0.0123±20	0.0110±19	0.0146±45
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	0.0029± 2	0.0075± 5	0.0098± 5[e]	0.0043±14[e]
99% Al_2O_3 brick	99AD A. P. Green	0.0045± 5	0.0066± 9	0.0087± 8[e]	0.0051± 8
90% Al_2O_3 brick	Arco-90 General Refractories	0.0028± 2	0.0031± 1	0.0041± 5[e]	0.0026±64
60% Al_2O_3 tar-impregnated brick	Ufala Tl Harbison-Walker	0.0025± 2	0.0062± 6	0.0067± 5	0.0087±46
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	0.0058± 9	0.0062± 7	0.0068± 7	0.0043±31

---

[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths of time. At least 5 samples tested; 95% confidence limits shown.

[b] Mixed gas composition: 24% hydrogen, 18% carbon monoxide, 12% carbon dioxide, 5% methane, 2% ammonia, 1% hydrogen sulfide, 38% steam.

[c] Abrasion loss determined according to ASTM C-704-72, units are cc loss/g grit expended.

[d] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, hled 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

[e] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF CERAMIC FIBER ADDITION ON ABRASION RESISTANCE OF A HIGH-ALUMINA CASTABLE REFRACTORY[a] [9]

Additions to Castable	Average Weight Loss[b], g
10.6% water	2.8
17% water	6.0
8% water + Hycol[c]	1.9
10% water + GP 2500[d]	2.6
2% AB-312 fiber[e] + 12% water	3.0
5% AB-312 fiber + 10.6% water	7.3
5% AB-312 fiber + 18% water	5.4
10% AB-312 fiber + 17% water	4.1
1% AB-312 fiber + 10% water + Hycol	1.2
2% AB-312 fiber + 10% water + GP 2500	1.9
5% Saffil fiber[f] + 11.3% water	18.0
5% Saffil fiber + 15% water	5.1

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[a] Castable used is Harbison-Walker's Castolast G, a high-purity tabular alumina, calcium aluminate bonded.

[b] Sample bars 1 in x 1 in x 3 1/2 in were abraded with 1000g of 36 grit SiC according to ASTM C-704; above values are the average of 3 separate samples of each preparation.

[c] Wetting agent from W. R. Grace Company, 6 ounces added per 100 pounds of cement to reduce amount of water.

[d] Wetting agent from Cresset Chemical Company, 6 ounces added per 100 pounds of cement to reduce amount of water.

[e] Ceramic fiber from 3M Company, high-alumina Al_2O_3-B_2O_3-SiO_2, 11 μm diameter. Fibers chopped in high-speed Waring blender, length varied 20-150 μm after chopping; castable, fibers, and water mixed in blender before casting, samples then moist cured for 24 h, oven dried for 24 h.

[f] Ceramic fiber from Imperial Chemical Industries, high-temperature 98% Al_2O_3-2% SiO_2, 3 μm diameter; treated as described in footnote e.

RELATIONSHIP BETWEEN EROSIVE WEAR[a] AND FLEXURAL STRENGTH[b] FOR HYDROTHERMALLY-TREATED[c] ALUMINA REFRACTORIES[23]

Material	Treatment Temperature[c] °C	Flexural Strength[b] MPa	Erosion[a] mg sample lost/ g abrasive used
Calcined Flint Clay[d] Castable	untreated	10.1	20.3
	110	13.9	13.3
	310	10.9	13.3
	410	15.2	16.0
	610	15.5	14.0
	710	15.2	16.0
	910	14.8	13.6
High-Purity Alumina[e] Castable	untreated	17.4	18.2
	110	23.4	9.6
	310	24.1	14.6
	410	27.1	15.2
	610	24.8	9.2
	710	25.1	10.2
	910	28.0	11.6

---

[a] Specimens were subjected to erosion by 100 mesh (150 μm) SiC at 25 °C; impingement angle 90°; particle velocity 72 m/s.

[b] Flexural strength as determined in four-point bend tests, loading rate 5×10^{-3} cm/min (2×10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperatures.

[c] Treatment consisted of sealing samples in a pressure chamber and heating to test temperature, then injecting steam to raise the pressure to 1000 psig.

[d] An NBS-prepared medium-alumina castable refractory bonded with high-purity calcium aluminate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3, 0.2 wt% Na_2O, 1.9 wt% others and loss on ignition.

[e] An NBS-prepared high-alumina castable bonded with high-purity calcium aluminate cement: 94.4 wt% Al_2O_3, 4.5 wt% CaO, 0.1 wt% SiO_2, 0.1 wt% Fe_2O_3, 0.2 wt% Na_2O.

EROSION/CORROSION MATERIAL LOSS[a] OF SOME REFRACTORIES IN COAL GASIFICATION ATMOSPHERE[b] [11]

Erodent		Coarse FMC char[c]					
Temperature, °F		-1800-			-1800-		
Pressure, psi		atmospheric			1000		
Velocity, ft/s		100			100		
Time, hr		100			100		
Volume % H_2S[b]		1.0			1.0		
Refractory	Brand Name	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments	Average[d] Corrosion mils	Maximum[e] Erosion/ Corrosion mils	Comments
90% Al_2O_3 castable, calcium aluminate bond	Castolast G	0	7.8	Localized binder removal E/C[f] surface	+1.4	2.5	Limited visible attack
60% Al_2O_3 castable, calcium aluminate bond	Super Brikcast A	-0.4	34.4	Localized loss of binder E/C surface	-0.4	23.6	Localized binder and particle loss E/C surface
54% Al_2O_3 castable, insulating, calcium aluminate bond	Litecast 75-28	-6.0	243.8	Specimen completely penetrated	-2.3	246.7	Specimen completely destroyed
85% Al_2O_3 brick, phosphate bond	Chemal 85 B	+2.0	17.6	Some binder removel E/C surface	+1.8	55.6	Major binder and particle loss E/C surface
90% Al_2O_3 brick, self-bond	Kricor	+1.5	5.4	Possible binder removal E/C surface	+1.9	26.6	Moderate binder loss E/C surface
77% Al_2O_3 insulating brick, vitreous bond	B&W Insalcor	0	7.0	No apparent attack	+4.7	49.2	Erosion area on E/C surface; corner of specimen broken near test
70% Al_2O_3 brick, mullite	Alumex 70-HD	+2.4	13.9	Some binder removal E/C surface	+0.7	45.7	Major binder loss E/C surface; three broken corners after test
60% Al_2O_3 brick, pitch impregnated	Ufala TI	-1.0	3.4	Possible binder removal E/C surface	+0.1	15.3	Light binder loss E/C surface
45% Al_2O_3 superduty fire brick	KX-99	+0.7	5.2	Possible binder removal E/C surface	-1.6	27.8	Moderate binder loss E/C surface
90% Al_2O_3-10% Cr_2O_3 brick	Ruby	+1.7	5.0	Possible binder removal E/C surface	+1.2	14.0	Light binder loss E/C surface

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[a] Refractory samples 2 x 2 x 3/4 in were subjected to erosion in coal gasification atmosphere under the indicated conditions, impingement angle 90°; values are for one specimen per test.

[b] Coal gasification atmosphere input gas: 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, either 0.1, 0.5 or 1.0% H_2S and the balance H_2O.

[c] Char from Western Kentucky coal prepared by COED process, -20 + 40 mesh (840 to 420 μm).

[d] Average corrosion of the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in uneroded area.

[e] Maximum effect on the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in eroded area and pits.

EROSION/CORROSION TESTING[a] OF REFRACTORIES[b][33]

actory	Initial Weight, g	Weight Change, g (±0.0005 g) During First 50 h	During Second 50 h	Total Change for 100 h	Physical Description after 100 h
Al_2O_3 fused cast brick nofrax A2; reference)	86.7751	-0.003	+0.002	-0.001	No visible erosion. Gray/black deposit on impinged surface.
Al_2O_3 fused cast brick nofrax A1)	92.8273	+0.023	+0.006	+0.029	No visible erosion. Gray/black deposit on impinged surface.
Al_2O_3 dense castable stolast G)	91.5132	-0.414	-0.062	-0.476	No visible erosion. Gray/black deposit on impinged surface.
Al_2O_3/10% Cr_2O_3 solid ution fired brick (CS 612)	102.0899	-0.062	-0.003	-0.065	No visible erosion. Gray/black deposit on impinged surface.
Si_2ON_2, ∿20% Si_3N_4, 0% SiC brick (SION)	68.6982	+2.721	+0.180	+2.901	No visible erosion. Light gray discoloration. Slight weight loss during first 50 h, which resulted from damage in handling.
Al_2O_3 phosphate bond mming mix (Brikram 90)	99.4256	-0.027	-0.012	-0.039	No visible erosion. Gray/black deposit on impinged surface.
% Al_2O_3 phosphate bonded stable (Resco Cast AA-22)	88.9209	-0.285	-0.085	-0.370	No visible erosion. Gray deposit with pink/yellow tint.
Al_2O_3, 23% SiO_2 brick lumex 70)	73.6872	-0.406	-0.094	-0.500	Some binder erosion. Black deposit with yellowish tint.
Al_2O_3 castable (AR 400)	78.9711	-1.319	-0.160	-1.479	Corners, edges, and binder show some erosion. Slight damage during first 50 h. Partial black deposit.
Al_2O_3 fire clay aggregate nning mix (Lo-Abrade GR)	63.8424	-0.955	-0.120	-1.075	Some binder erosion. Partial black deposit. Slight damage during first 50 h.
Al_2O_3 fused cast brick onofrax R)	125.0410	+0.042	+0.006	+0.048	No visible erosion. Black deposit with yellowish tint.
7% Al_2O_3 castable raxcast ES)	73.7900	-4.590[c]	-0.016	-4.606	No visible erosion. Black deposit with yellowish tint. Some weight loss during first 50 h, which resulted from damage in handling.
% Al_2O_3, 40% SiO_2 castable B&W Kaocrete HS)	57.9730	-1.963	-0.364	-2.327	Obvious erosion of binder over entire impinged surface. Partial black deposit.
% SiC, ∿18% Si_3N_4 bonded, ense fired brick (Refrax 20)	90.6470	+1.755	+0.097	+1.852	No visible erosion. Black deposit with yellowish tint.
% SiC, 14% Al_2O_3, ∿10% SiO_2 rick (Siltec)	78.6791	+0.060	+0.018	+0.078	No visible erosion. Black deposit with yellowish tint.

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est temperature was controlled at 980 °C (1800 °F), pressure was maintained at 240 KPa (35 psi), and char article velocity averaged 39 m/s (125 ft/s). Char used was FMC char from Western Kentucky coal. Gas omposition was close to the following with variations due to problems with ammonia and steam control: in vol %), 39 H_2O, 24 H_2, 12 CO_2, 18 CO, 5 CH_4, 1 NH_3, 1 H_2S. Total exposure time was 100 hr.

fter exposure, specimens were lightly brushed, air blown, and weighed after testing.

isual examination did not indicate any erosion or other damage to account for the high measured weight loss. Experimental error is suspected.

B.2.3 Coatings and Surface Treatments

BLE OF CONTENTS

EROSION TEST[a] DATA FOR VARIOUS COATINGS[1]

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	20° C, 90° imp[c]	700° C, 90° imp[c]
CVD[d] W pure coating		Rolla[e]		0.53	0.25
CVD[d] W on mild steel		Rolla		0.57	0.34
CVD[d] W on mild steel	550	Rolla		0.48	0.16
TiC coating on WC	Carboloy 523	Carboloy		0.31	0.72
CVD[d] TiC on unknown substrate			pen[f]	pen[f]	pen[f]
71.5WC-12TiC-10TaC-6.5Co	VR 73		pen	pen	
VR 73 + B_4C			pen	pen	
WC-11.5TaC-8TiC-8.5Co	GE 370		pen	pen	
GE 370 + 20NiTiB_2			pen	pen	
85WC-15Co	LW-IN40		pen	pen	
WC-10Ni-2.3W	2S5		pen	pen	
CVD[d] SiC pure coating			0.20[g]	0.05[g]	0
CVD[d] SiC on graphite cloth which had been converted to SiC			0.13[g]	0.06[g]	0
CVD[d] SiC on HIP[h] SiC and graphite	Lummus 1-8	MTC & Ceradyne	0	0	0[i]
SiC in Ni over Cu	Nye-Carb		pen	pen	
Si_3N_4 on graphite			pen	pen	pen
TiB_2 on nickel[j]		CPMRC[k]	0	0	0
TiB_2 on 310 SS[j]	18B-11	United Tech.	0	0	0[l]
TiB_2 on 310 SS[j]	19A-13	United Tech.	0	0	0[l]
TiB_2 on 410 SS[m]	BM5	Battelle NW	0	0	0[i,n]
TiB_2 on 410 SS[o]	BM6	Battelle NW	0	0	0[i,n]
TiB_2 CNTD[p]	168-179	Chemetal Corp.	0	0	0[i,n]
TiB_2 on Kovar[j]	115-115	Sandia Labs.	0	0	0[i,n]
CVD[d] Al_2O_3 on unknown substrate			pen	pen	pen
Cr_2O_3	LC-4		pen	pen	
Cr_2O_3-5SiO_2-3TiO_2		CWS Corp.	0.61	1.23	
0.5C-4Si-16Cr-4B-4Fe-2.4Cu-2.4Mo-2.4W-bal Ni[q]	Ni-Cr-B-Cu	CWS Corp.	0.98	1.32	2.79
35(WC+8Ni)-11Cr-2.5B-2.5Fe-2.5Si-0.5C-bal Ni[q]	NiWC	CWS Corp.	0.72	1.11	2.06
HfN sputtered on steel			pen	pen	

(Table Continued)

EROSION TEST[a] DATA FOR VARIOUS COATINGS[1]

(Table Continued)

Material	Brand Name or Other Designation	Source	Relative Erosion Factor[b] 20° C, 20° imp[c]	Relative Erosion Factor[b] 20° C, 90° imp[c]	Relative Erosion Factor[b] 700° C, 90° imp
88WC + 12Co on 440C SS[q]	Plasmalloy 702-E	Plasmadyne	pen	pen	pen
75Cr-C + 25Ni-Cr on 440C SS[q]	Plasmalloy 915-E	Plasmadyne	pen	pen	pen
Iron-base TiC on 440C SS[q]	FerroTiC	Plasmadyne	pen	pen	pen
CVD[d] TiC on unknown substrate			pen	pen	pen
CVD[d] TiN on unknown substrate			pen	pen	pen
CVD[d] TiCN on Ti-6Al-4V			0	pen[r]	
CVD[d] TiCN on Inconel 718			0	pen[r]	
CVD[d] TiCN on WC			pen[r]	pen[r]	

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[a] Erosion test conditions: 1/2-inch square specimens subjected to erosion by 27μ Al_2O_3 abrasive, 170 m/sec particle velocity, 3 minutes test duration, N_2 atmosphere, 5 g/min abrasive flow.

[b] Relative Erosion Factor = $\frac{\text{Volume loss of sample}}{\text{Volume loss of Stellite 6B}}$, volume loss calculated from weight loss and density data; Stellite 6B = 30Cr-4.5W-1.2C-bal Co.

[c] imp = angle of impingement. [d] CVD = chemical vapor deposition.

[e] Rolla = Rolla Metallurgy Research Center, Bureau of Mines.

[f] pen = coating penetrated. [g] Weight loss noted, but no visible crater.

[h] HIP = hot isostatic pressed.

[i] Also tested at 700°C, 20° impingement angle, with same results.

[j] Coating electrodeposited.

[k] CPMRC = College Park Metallurgy Research Center, Bureau of Mines.

[l] Electrodeposited TiB_2 showed excellent erosion resistance, even after testing for 8 minutes. There was, however, spalling of these samples at 700°C due to thermal expansion mismatching.

[m] 1.5-2.2 mils sputtered on at 700°C.

[n] Retesting at 20°C after tests at 700°C revealed some spalling.

[o] 1.5-2.2 mils sputtered on at 360°C.

[p] CNTD = controlled nucleation thermochemical deposition.

[q] Coating applied by plasma-gun process. The three Plasmadyne coatings ranked 702-E >FerroTiC > 915-E in terms of their relative erosion resistance as to which lasted longer during the test time period.

[r] Retarded penetration, coating 0.002in thick.

EROSION/CORROSION RESISTANCE OF CERAMIC-COATED ALLOYS[a][33]

Coating System		Exposure Time, hr	Weight, g±0.0003g			Remarks
ate	Coating		Initial	Final	Change	
	Al_2O_3	17	132.8574	132.6943	-0.162	Coating spalled from edges and back surface.
y 800	Al_2O_3	17	133.1391	131.9385	-1.201	Coating spalled from front and back surface and edges.
	Al_2O_3	17	134.3148	133.1853	-1.129	
	50% Al_2O_3 + 50% Cr_2O_3	17	137.5543	134.7110	-2.843	
y 800	50% Al_2O_3 + 50% Cr_2O_3	17	136.0418	133.6493	-2.392	
	50% Al_2O_3 + 50% Cr_2O_3	17	135.5464	132.3798	-3.167	
	Cr_2O_3	17	141.0624	135.2764	-4.786	
y 800	Cr_2O_3	17	138.5082	132.7282	-5.780	
	Cr_2O_3	17	138.2464	132.8629	-5.383	
	Al_2O_3	33	136.3926	136.0719	-0.321	Some coating spalled from front surface and edges.
y 800	Al_2O_3	33	132.9919	132.5560	-0.436	Coating spalled from front surface and edges, slight spalling on back surface.
	Al_2O_3	33	132.5076	131.5773	-0.939	Coating spalled from front and back surface and edges.
	50% Al_2O_3 + 50% Cr_2O_3	33	140.2884	137.4119	-2.876	
y 800	50% Al_2O_3 + 50% Cr_2O_3	33	135.6531	132.5551	-3.098	
	50% Al_2O_3 + 50% Cr_2O_3	33	133.2851	130.1555	-3.129	
	Cr_2O_3	33	138.4376	133.6509	-4.787	
y 800	Cr_2O_3	33	139.3122	133.1919	-6.120	
	Cr_2O_3	33	140.3091	134.1164	-6.193	
	cubic ZrO_2 stabilized with CaO	50	140.0531	135.6402	-4.413	Coating spalled from front surface and edges. Partial spalling on back surface.
y 800	cubic ZrO_2 stabilized with CaO	50	141.1302	138.6060	-2.524	Coating spalled from front surface only.
	cubic ZrO_2 stabilized with CaO	50	138.3660	135.9207	-2.445	
	cubic ZrO_2 stabilized with CaO	50	142.4890	140.1007	-2.388	75% of coating spalled from front surface starting at bend.
y 800	cubic ZrO_2 stabilized with CaO	50	141.3496	140.3997	-0.950	25% of coating spalled from front surface starting at bend.
	cubic ZrO_2 stabilized with CaO	50	140.9328	139.9837	-0.946	30% of coating spalled from front surface starting at bend.
	magnesium zirconate ($MgO \cdot ZrO_2$)	50	141.0876	141.3260	+0.238	No coating failure. Slight visible erosion. Uniform gray discoloration of impinged surface.
y 800	magnesium zirconate ($MgO \cdot ZrO_2$)	50	140.2687	140.4804	+0.212	
	magnesium zirconate ($MgO \cdot ZrO_2$)	50	135.2933	135.4402	+0.147	

(Table Continued)

EROSION/CORROSION RESISTANCE OF CERAMIC-COATED ALLOYS[a][33], Continued

Coating System		Exposure	Weight, g±0.0003g			
Substrate	Coating	Time, hr	Initial	Final	Change	Remarks
304 SS	magnesium zirconate ($MgO \cdot ZrO_2$)	first 50	141.8209		+0.149	No coating failure 50 hr. Spalling started at nose of after 100 hr. 8% c front surface spall
		second 50			-0.069	
		total 100			+0.081	
Incoloy 800	magnesium zirconate ($MgO \cdot ZrO_2$)	first 50	139.9400		+0.215	No coating failure. Slight visible eros Uniform gray discol ation of impinged s
		second 50			+0.040	
		total 100			+0.255	
310 SS	magnesium zirconate ($MgO \cdot ZrO_2$)	first 50	140.2760		+0.159	
		second 50			+0.026	
		total 100			+0.185	
310 SS	uncoated bare metal (reference)	first 50	19.9654		+0.056	No erosion visible. Uniform gray discol ation with yellowis tint.
		second 50			+0.009	
		total 100			+0.065	

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[a] Test temperature was controlled at 980 °C (1800 °F), pressure was maintained at 240 KPa (35 psi), and char part velocity averaged 39 m/s (125 ft/s). Char used was FMC char from Western Kentucky coal. Gas composition was c to the following with variations due to problems with ammonia and steam control: (in vol %), 39 H_2O, 24 H_2, 12 18 CO, 5 CH_4, 1 NH_3, 1 H_2S. Intended total exposure time was 100 hr consisting of 50 hr test durations. The 1 33 hr tests were the results of systems failures. Alumina, chromia, and stabilized zirconia coatings did not vive the runs, only magnesium zirconate lasted. The specimens were U-bends with plasma-sprayed coats (~250 μm with a base coat of 75Ni-24Cr-1Al. Specimens were lightly brushed, air blown, and weighed after testing.

EROSION/CORROSION[a] COATING LOSS OF CERAMIC-COATED ALLOYS[b][33]

Coating	Substrate	Coating Thickness[c], mm	
		Back Face	Front Face
Al_2O_3	Type 304 SS	0.07	0.11
	Incoloy 800	0.01	0
	Type 310 SS	0	0
$MgO-ZrO_2$	Type 304 SS	0.30	0.11
	Incoloy 800	0.30	0.07-0.27
	Type 310 SS	0.28	0.10-0.23
ZrO_2	Type 310 SS	0.27	0.08
Cr_2O_3	Type 310 SS	0.04	0.05
$Al_2O_3-Cr_2O_3$	Type 310 SS	0.06	0.03

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[a] Test temperature was controlled at 980 °C (1800 °F), pressure was maintained at 240 KPa (35 psi), and char particle velocity averaged 39 m/s (125 ft/s). Char used was FMC char from Western Kentucky coal. Gas composition was close to the following with variations due to problems with ammonia and steam control: (in vol %), 39 H_2O, 24 H_2, 12 CO_2, 18 CO, 5 CH_4, 1 NH_3, 1 H_2S. Intended total exposure time was 100 hr consisting of 50 hr test durations. The 17 and 33 hr tests were the results of systems failures. Alumina, chromia, and stabilized zirconia coatings did not survive the runs, only magnesium zirconate lasted. Compare Table B.2.3.2 for weight loss and description of specimens in this same test.

[b] The specimens were U-bends with plasma-sprayed coats (∿250 μm or ∿0.250 mm thick) with a base coat of 75Ni-24Cr-1Al.

[c] After exposure specimens were cut and mounted for microscopic examination.

B.3 Mechanical Properties Testing

B.3.1 Alloys

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EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON ROOM TEMPERATURE TENSILE STRENGTH[b] OF WELD OVERLAYS [8]

	Single Layer Overlay			Double Layer Overlay		
eld Overlay	As Welded MPa(psi)	Exposed[c] MPa(psi)	Change % Decrease	As Welded MPa(psi)	Exposed[c] MPa(psi)	Change % Decrease
WS-ER309 Filler n 304L SS--GMAW[d]	557(80,850)	471(68,250)	15.6	577(83,700)	515(74,650)	10.8
WS-ER309 Filler n 304L SS--SAW[d]	565(81,950)	496(71,900)	12.3	586(84,950)	521(75,500)	11.1
WS-ER309 Filler n 304L SS--GTAW-HW[d]	564(81,800)	522(75,750)	7.4	579(84,05)	528(76,550)	8.9
nconel Filler Metal 2[e] on 304L SS--GMAW	564(81,850)	408(59,150)	27.3	589(85,450)	414(60,000)	29.8
nconel Filler Metal 2 on 304L SS--SAW	561(82,400)	338(49,050)	40.5	566(82,150)	369(53,550)	34.8
nconel Filler Metal 2 on 304L SS--GTAW-HW	595(86,350)	382(55,450)	35.9	584(84,65)	378(54,900)	35.1
nconel Filler Metal 2 on 310 SS--GMAW	577(83,700)	432(62,600)	25.2	595(86,250)	439(63,650)	26.2
nconel Filler Metal 2 on 310 SS--SAW	582(84,400)	358(51,900)	38.5	596(86,500)	393(57,050)	34.0
nconel Filler Metal 2 on 310 SS--GTAW-HW	616(89,350)	375(54,550)	38.9	625(90,650)	414(60,050)	33.8
nconel Filler Metal 72 n Incoloy 800H--GMAW	573(83,150)	415(60,150)	27.7	588(85,300)	382(55,400)	35.0
nconel Filler Metal 72 n Incoloy 800H--SAW	571(82,750)	374(54,250)	34.4	573(83,150)	384(55,750)	33.0
nconel Filler Metal 72 n Incoloy 800H--GTAW-HW	602(87,350)	435(63,050)	27.8	615(89,200)	396(57,500)	35.6
139 Filler Metal[e] on 04L SS--GMAW	576(83,550)	393(57,000)	31.8	595(86,250)	457(66,250)	23.2
139 Filler Metal on 04L SS--SAW	503(86,050)	426(61,500)	28.2	578(83,800)	385(55,800)	33.4
139 Filler Metal on 04L SS--GTAW-HW	586(85,300)	432(62,700)	26.5	586(85,050)	393(57,000)	33.0
R139 Filler Metal on 310 SS--GMAW	585(84,850)	384(55,700)	34.4	615(89,150)	386(56,050)	37.1
R139 Filler Metal on 310 SS--SAW	587(85,200)	390(56,600)	33.6	598(86,750)	348(50,400)	41.9
R139 Filler Metal on 310 SS-GTAW-HW	599(86,900)	434(62,900)	27.6	591(85,750)	443(64,300)	25.0
R139 Filler Metal on Incoloy 800H--GMAW	577(83,650)	382(55,350)	33.8	597(86,600)	406(58,900)	32.0
R139 Filler Metal on Incoloy 800H--SAW	576(83,600)	407(59,000)	29.4	588(85,250)	385(55,900)	34.4
R139 Filler Metal on Incoloy 800H--GTAW-HW	573(83,150)	444(64,350)	22.6	588(85,300)	477(69,150)	18.9

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[a] Coal gasification atmosphere = 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, balance H_2O.

[b] Tensile tests were run according to ASTM-E8; two specimens were tested from each weld; tensile stress was applied in the direction of welding; weld overlay was on both sides of the test specimens; overlay surface was not machined before testing.

[c] Samples were exposed to the coal gasification atmosphere for 1000 hours at 982°C (1800°F).

[d] GMAW = Gas metal arc welding process, SAW = Submerged arc welding process, GTAW-HW = Gas tungsten arc with hot wire welding process.

[e] Inconel Filler Metal 72 is Ni-based with 44% Cr; R139 is Ni-based with 31% Cr, 15% Fe, 3% Al.

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON ROOM TEMPERATURE 0.2% YIELD STRENGTH[b] OF WELD OVERLAYS [8]

Weld Overlay	Single Layer Overlay		Double Layer Overlay	
	As Welded MPa(psi)	Exposed[c] MPa(psi)	As Welded MPa(psi)	Exposed[c] MPa(psi)
AWS-ER309 Filler on 304L SS--GMAW[d]	337(48,850)	186(26,950)	373(54,100)	195(28,250)
AWS-ER309 Filler on 304L SS--SAW[d]	344(49,950)	191(27,700)	368(53,350)	202(29,300)
AWS-ER309 Filler on 304L SS--GTAW-HW[d]	350(50,700)	192(27,850)	388(56,250)	201(29,200)
Inconel Filler Metal 72[e] on 304L SS--GMAW	333(48,300)	198(28,750)	372(54,000)	239(34,650)
Inconel Filler Metal 72 on 304L SS--SAW	333(48,250)	210(30,450)	347(50,400)	245(35,500)
Inconel Filler Metal 72 on 304L SS--GTAW-HW	365(53,000)	196(28,450)	378(54.900)	232(33,650)
Inconel Filler Metal 72 on 310 SS--GMAW	335(48,600)	236(34,250)	359(52,050)	238(34,500)
Inconel Filler Metal 72 on 310 SS--SAW	345(50,050)	214(31,000)	350(50,750)	223(32,400)
Inconel Filler Metal 72 on 310 SS--GTAW-HW	362(52,450)	231(33,500)	391(56,650)	266(38,550)
Inconel Filler Metal 72 on Incoloy 800H--GMAW	299(43,300)	220(31,850)	334(48,500)	245(35,500)
Inconel Filler Metal 72 on Incoloy 800H--SAW	299(43,400)	222(32,200)	336(48,750)	245(35,500)
Inconel Filler Metal 72 on Incoloy 800H--GTAW-HW	324(47,000)	218(31,600)	367(53,250)	230(33,350)
R139 Filler Metal[e] on 304L SS--GMAW	340(49,350)	231(33,550)	353(51,020)	287(41,650)
R139 Filler Metal on 304L SS--SAW	348(50,500)	225(32,650)	352(51,050)	273(39,650)
R139 Filler Metal on 304L SS-GTAW-HW	339(49,100)	219(31,700)	377(54,700)	285(41,300)
R139 Filler Metal on 310 SS--GMAW	339(49,200)	273(39,600)	371(53,750)	309(44,750)
R139 Filler Metal on 310 SS--SAW	315(45,700)	244(35,400)	359(52,050)	264(38,350)
R139 Filler Metal on 310 SS--GTAW-HW	344(49,900)	265(38,500)	367(53,300)	317(45,950)
R139 Filler Metal on Incoloy 800H--GMAW	304(44,100)	268(38,850)	339(49,200)	314(45,600)
R139 Filler Metal on Incoloy 800H--SAW	298(43,250)	259(37,500)	333(48,300)	303(43,900)
R139 Filler Metal on Incoloy 800H--GTAW-HW	309(44,750)	271(39,250)	342(49,650)	336(48,750)

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[a] Coal Gasification atmosphere = 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, balance H_2O.

[b] Tensile tests were run according to ASTM-E8; two specimens were tested from each weld; tensile stress was applied in the direction of welding; weld overlay was on both sides of the test specimens; overlay surface was not machined before testing.

[c] Samples were exposed to the coal gasification atmosphere for 1000 hours at 982°C (1800°F).

[d] GMAW = Gas metal arc welding process; SAW = Submerged arc welding process; GTAW-HW = Gas tungsten arc with hot wire welding process.

[e] Inconel Filler Metal 72 is Ni-based with 44% Cr; R139 is Ni-based with 31% Cr, 15% Fe, 3% Al.

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON ROOM TEMPERATURE % ELONGATION[b] OF WELD OVERLAYS [8]

Weld Overlay	Single Layer Overlay		Double Layer Overlay	
	As Welded	Exposed[c]	As Welded	Exposed[c]
AWS-ER309 Filler on 304L SS--GMAW[d]	57.0	47.0	57.0	50.7
AWS-ER309 Filler on 304L SS--SAW[d]	57.2	44.2	52.5	48.7
AWS-ER309 Filler on 304L SS--GTAW-HW[d]	53.2	64.0	51.0	49.7
Inconel Filler Metal 72[e] on 304L SS--GMAW	52.0	34.5	42.0	32.5
Inconel Filler Metal 72 on 304L SS--SAW	46.0	26.5	47.0	25.5
Inconel Filler Metal 72 on 304L SS--GTAW-HW	49.0	30.2	48.0	31.5
Inconel Filler Metal 72 on 310 SS--GMAW	48.0	12.0	50.5	18.0
Inconel Filler Metal 72 on 310 SS--SAW	37.0	20.0	40.0	15.5
Inconel Filler Metal 72 on 310 SS--GTAW-HW	44.0	20.5	40.0	12.5
Inconel Filler Metal 72 on Incoloy 800H--GMAW	50.0	20.2	49.5	20.5
Inconel Filler Metal 72 on Incoloy 800H--SAW	46.0	18.5	36.0	20.5
Inconel Filler Metal 72 on Incoloy 800H--GTAW-HW	49.0	25.2	45.0	20.2
R139 Filler Metal[e] on 304L SS--GMAW	54.5	56.2	50.5	51.5
R139 Filler Metal on 304L SS--SAW	47.0	50.0	38.0	39.5
R139 Filler Metal on 304L SS--GTAW-HW	55.0	46.7	50.5	38.0
R139 Filler Metal on 310 SS--GMAW	41.5	11.0	44.5	10.7
R139 Filler Metal on 310 SS-SAW	50.0	11.0[f]	49.0	9.7
R139 Filler Metal on 310 SS--GTAW-HW	53.0	14.0	46.5	10.7
R139 Filler Metal on Incoloy 800H--GMAW	50.0	16.5	48.5	18.2
R139 Filler Metal on Incoloy 800H--SAW	48.0	21.0	46.0	18.7
R139 Filler Metal on Incoloy 800H--GTAW-HW	48.5	18.2	50.0	18.2[f]

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[a] Coal gasification atmosphere = 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, balance H_2O.

[b] % Elongation in 5.08 cm (2.0 in); tensile tests were run according to ASTM-E8; two specimens were tested from each weld; tensile stress was applied in the direction of welding; weld overlay was on both sides of the test specimens; overlay surface was not machined before testing.

[c] Samples were exposed to the coal gasification atmosphere for 1000 hours at 982°C (1800°F).

[d] GMAW = Gas metal arc welding process; SAW = Submerged arc welding process; GTAW-HW = Gas tungsten arc with hot wire welding process.

[e] Inconel Filler Metal 72 is Ni-based with 44% Cr; R139 is Ni-based with 31% Cr, 15% Fe, 3% Al.

[f] One sample broke outside gage length.

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] EXPOSURE ON THE VICKERS HARDNESS[b] OF WELD OVERLAYS [8]

	Single Layer Overlay				Double Layer Overlay			
Weld Overlay	Location	As Welded	Exposed[c]	Change	Location	As Welded	Exposed[c]	Change
AWS-ER309 Filler on 304L SS--GMAW[d]	OV[e]	186	156	-30	UL[e]	196	163	-33
	HAZ[e]	179	151	-28	LL[e]	192	158	-34
	BM[e]	183	152	-31	HAZ	180	155	-25
					BM	179	150	-29
AWS-ER309 Filler on 304L SS--SAW[d]	OV	196	178	-18	UL	201	183	-18
	HAZ	172	150	-22	LL	201	180	-21
	BM	176	149	-27	HAZ	183	149	-34
					BM	178	151	-27
AWS-ER309 Filler on 304L SS--GTAW-HW[d]	OV	190	163	-27	UP	194	180	-14
	HAZ	172	157	-15	LL	180	159	-21
	BM	185	157	-28	HAZ	179	152	-27
					BM	196	158	-38
Inconel Filler Metal[f] 72 on 304L SS--GMAW	OV	174	219	+45	UL	194	242	+48
	HAZ	173	141	-32	LL	186	228	+42
	BM	172	146	-26	HAZ	175	134	-41
					BM	178	144	-34
Inconel Filler Metal 72 on 304L SS--SAW	OV	180	232	+42	UL	192	227	+35
	HAZ	170	140	-30	LL	187	216	+29
	BM	169	144	-25	HAZ	191	145	-46
					BM	191	142	-49
Inconel Filler Metal 72 on 304L SS--GTAW-HW	OV	177	221	+44	UL	189	250	+61
	HAZ	178	149	-29	LL	190	251	+61
	BM	179	143	-36	HAZ	179	136	-43
					BM	193	138	-55
Inconel Filler Metal 72 on 310 SS--GMAW	OV	188	266	+78	UL	200	249	+49
	HAZ	185	184	- 1	LL	193	239	+46
	BM	177	178	+ 1	HAZ	195	170	-25
					BM	194	168	-26
Inconel Filler Metal 72 on 310 SS--SAW	OV	194	254	+60	UL	189	250	+61
	HAZ	175	172	- 3	LL	193	232	+39
	BM	169	177	+ 8	HAZ	179	158	-21
					BM	176	150	-26
Inconel Filler Metal 72 on 310 SS--GTAW-HW	OV	189	256	+67	UL	200	250	+50
	HAZ	179	154	-25	LL	214	247	+33
	BM	178	158	-20	HAZ	179	166	-13
					BM	193	156	-37
Inconel Filler Metal 72 on Incoloy 800H--GMAW	OV	201	218	+17	UL	197	243	+46
	HAZ	181	143	-42	LL	206	208	+ 2
	BM	174	150	-24	HAZ	177	139	-38
					BM	177	150	-27
Inconel Filler Metal 72 on Incoloy 800H--SAW	OV	187	210	+33	UL	185	237	+52
	HAZ	162	136	-26	LL	197	209	+12
	BM	170	151	-19	HAZ	167	140	-27
					BM	170	153	-17
Inconel Filler Metal 72 on Incoloy 800H--GTAW-HW	OV	182	205	+23	UL	199	237	+38
	HAZ	169	141	-28	LL	190	186	- 4
	BM	166	148	-18	HAZ	170	146	-24
					BM	167	162	- 5
R139 Filler Metal[f] on 304L SS--GMAW	OV	196	322	+126	UL	206	337	+131
	HAZ	192	150	-42	LL	197	319	+122
	BM	192	152	-40	HAZ	195	144	-51
					BM	195	150	-45
R139 Filler Metal on 304L SS--SAW	OV	189	234	+45	UL	201	289	+88
	HAZ	171	144	-27	LL	203	239	+36
	BM	173	152	-21	HAZ	182	144	-38
					BM	178	149	-29
R139 Filler Metal on 304L SS--GTAW-HW	OV	181	248	+67	UL	180	303	+123
	HAZ	182	150	-32	LL	189	200	+111
	BM	184	149	-35	HAZ	185	146	-39
					BM	198	155	-43

(Table Continued)

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] EXPOSURE ON THE VICKERS HARDNESS[b] OF WELD OVERLAYS[8]

(Table Continued)

	Single Layer Overlay				Double Layer Overlay			
ld Overlay	Location	As Welded	Exposed[c]	Change	Location	As Welded	Exposed[c]	Change
39 Filler Metal on 0 SS--GMAW	OV	185	302	+117	UL	190	342	+152
	HAZ	182	162	-20	LL	189	286	+97
	BM	182	167	-15	HAZ	183	158	-25
					BM	176	162	-14
39 Filler Metal on 0 SS--SAW	OV	196	243	+47	UL	217	278	+61
	HAZ	188	166	-22	LL	214	211	- 3
	BM	193	167	-26	HAZ	214	159	-55
					BM	212	161	-51
39 Filler Metal on 0 SS--GTAW-HW	OV	189	286	+97	UL	201	320	+119
	HAZ	194	164	-30	LL	202	314	+112
	BM	187	170	-17	HAZ	205	163	-42
					BM	197	158	-39
39 Filler Metal on coloy 800H--GMAW	OV	197	305	+108	UL	200	322	+122
	HAZ	171	143	-28	LL	206	278	+72
	BM	179	152	-27	HAZ	176	145	-31
					BM	178	148	-30
39 Filler Metal on coloy 800H--SAW	OV	191	261	+70	UL	218	301	+83
	HAZ	175	142	-33	LL	212	248	+36
	BM	175	154	-21	HAZ	182	148	-34
					BM	181	154	-27
39 Filler Metal on coloy 800H--GTAW-HW	OV	178	287	+99	UL	187	321	+134
	HAZ	161	140	-21	LL	183	256	+73
	BM	166	150	-16	HAZ	166	146	-20
					BM	176	154	-22

oal gasification atmosphere = 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, balance H_2O.

ickers Hardness Numbers were determined on the surface ground and etched cross sections using a 10 kg oad and a 2/3 objective. Each value reported is the average of a minimum of 5 measurements made in he weld, heat affected zone, and substrate.

amples were exposed to the coal gasification atmosphere for 1000 hours at 982°C (1800°F).

MAW = Gas metal arc welding process, SAW = Submerged arc welding process, GTAW-HW = Gas tungsten arc ith hot wire welding process.

V = overlay, HAZ = heat-affected zone, BM = base metal, UL = upper layer (in double layer overlays), L = lower layer.

nconel Filler Metal 72 is Ni-based, 44% Cr; R139 is Ni-based with 31% Cr, 15% Fe, 3% Al.

ROOM TEMPERATURE BEND TEST[a] RESULTS[b] OF INCONEL FILLER METAL 72 WELD OVERLAYS ON VARIOUS ALLOYS[8]

Weld Process	Substrate	No. of Layers	Orientation[c]	Percent Elongation in 6.3 mm (0.25 in)	12.7 mm (0.50 in)	25.4 mm (1.0 in)
GMAW[d]	304L SS	1	Transverse	18	20	21
			Longitudinal	18	22	22
GMAW	304L SS	2	Transverse	24	23	22
			Longitudinal	22	22	22
SAW[d]	304L SS	1	Transverse	24	22	21
			Longitudinal	24	22	21
SAW	304L SS	2	Transverse	24	22	21
			Longitudinal	24	22	21
GTAW-HW[d]	304L SS	1	Transverse	24	22	21
			Longitudinal	24	22	21
GTAW-HW	304L SS	2	Transverse	24	22	21
			Longitudinal	24	22	21
GMAW	310 SS	1	Transverse	28	25	22
			Longitudinal	24	22	21
GMAW	310 SS	2	Transverse	24	23	22
			Longitudinal	24	22	21
SAW	310 SS	1	Transverse	24	22	21
			Longitudinal	24	22	21
SAW	310 SS	2	Transverse	24	22	21
			Longitudinal	24	22	21
GTAW-HW	310 SS	1	Transverse	24	22	21
			Longitudinal	24	22	21
GTAW-HW	310 SS	2	Transverse	24	22	21
			Longitudinal	24	22	21
GMAW	Incoloy 800H	1	Transverse	20	20	20
			Longitudinal	24	20	22
GMAW	Incoloy 800H	2	Transverse	20	20	21
			Longitudinal	28	21	21
SAW	Incoloy 800H	1	Transverse	21	24	21
			Longitudinal	18	21	22
SAW	Incoloy 800H	2	Transverse	20	19	20
			Longitudinal	19	21	21
GTAW-HW	Incoloy 800H	1	Transverse	22	21	20
			Longitudinal	20	20	21
GTAW-HW	Incoloy 800H	2	Transverse	20	22	21
			Longitudinal	20	21	20

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[a] Tests were made on specimens with overlay on both sides, machined longitudinal and transverse to the direction of welding; specimens were 127.0 mm(5 in) by 32-41 mm(1 1/4-1 5/8 in) by 9.5 mm(3/8 in); bend fixture had a 38 mm(1.5 in) roller and 60 mm(2.375 in) span, cross head speed 12.7 mm(0.5 in) per minute; test requirement is a 180° bend without formation of a crack greater than 3.2 mm(1/8 in).

[b] Values are the average of two tests per orientation.

[c] Relationship of long dimension of bend specimen to the welding direction.

[d] GMAW = Gas metal arc welding process; SAW = Submerged arc welding process; GTAW-HW = Gas tungsten arc welding with hot wire.

ROOM TEMPERATURE BEND TEST[a] RESULTS[b] OF R139 FILLER METAL WELD OVERLAYS ON VARIOUS ALLOYS[8]

Weld Process	Substrate	No. of Layers	Orientation[c]	Percent Elongation in 6.3 mm (0.25 in)	12.7 mm (0.50 in)	25.4 mm (1.0 in)
GMAW[d]	304L SS	1	Transverse	20	20	21
			Longitudinal	24	22	21
GMAW	304L SS	2	Transverse	20	20	20
			Longitudinal	26	22	21
SAW[d]	304L SS	1	Transverse	24[e]	23	21
			Longitudinal	24	22	21
SAW	304L SS	2	Transverse[f,g]	24	24	21
			Transverse[h]	20	18	14
			Longitudinal[f]	24	22	22
			Longitudinal[i]	20	16	16
GTAW-HW[d]	304L SS	1	Transverse	22	25	21
			Longitudinal	24	22	21
GTAW-HW	304L SS	2	Transverse	20	21	21
			Longitudinal[f]	24	22	21
			Longitudinal[j]	17	20	24
GMAW	310SS	1	Transverse	20	21	21
			Longitudinal	24	22	21
GMAW	310SS	2	Transverse	26	24	22
			Longitudinal	24	22	21
SAW	310SS	1	Transverse	20	24	22
			Longitudinal	24	22	21
SAW	310SS	2	Transverse	24	22	22
			Longitudinal	24	22	21
GTAW-HW	310SS[k]	1	Transverse	20	21	21
			Longitudinal	26	24	22
GTAW-HW	310SS[k]	2	Transverse	20	20	21
			Longitudinal	26	22	21
GMAW	Incoloy 800H	1	Transverse	21	22	21
			Longitudinal	24	22	21
GMAW	Incoloy 800H	2	Transverse	24	22	21
			Longitudinal	24	22	21
SAW	Incoloy 800H	1	Transverse	24	23	21
			Longitudinal	24	22	21
SAW	Incoloy 800H	2	Transverse[f,l]	14	12	9
			Transverse[m]	28	22	20
GTAW-HW	Incoloy 800H	1	Transverse	24	26	22
			Longitudinal	24	22	21
GTAW-HW	Incoloy 800H	2	Transverse	20	23	22
			Longitudinal	24	22	21

---

[a] Tests were made on specimens with overlay on both sides, machined longitudinal and transverse to the direction of welding; specimens were 127.0 mm(5 in) by 32-41 mm(1 1/4-1 5/8 in) by 9.5 mm(3/8 in); bend fixture had a 38 mm(1.5 in) roller and 60 mm(2.375 in) span, cross head speed 12.7 mm(0.5 in) per minute; test requirement is a 180° bend without formation of a crack greater than 3.2 mm(1/8 in).

[b] Values are the average of two tests per orientation.

[c] Relationship of long dimension of bend speciment to the welding direction.

[d] GMAW = Gas metal arc welding process; SAW = Submerged arc welding process; GTAW-HW = Gas tungsten arc welding with hot wire.

[e] Test discontinued when defect measured ∿3.2 mm(1/8 in).

[f] Values from duplicate samples are not averaged but reported separately.

[g] Test discontinued because a 3.2 mm crack opened at 70° bend at an overlay repair point in overlay on one side of specimen.

[h] Test discontinued as per footnote g at a 44° bend angle.

[i] Test discontinued as per footnote g at a 35° bend angle.

[j] Small defects were present before bending, test discontinued at 58° bend angle because a 3.2 mm crack formed.

[k] Laminations in center of substrate.

[l] Small defects were present before bending, test discontinued at 28° bend angle because a 3.2 mm crack formed.

[m] Small defects were present before bending, test discontinued at 109° bend angle because a 3.2 mm crack formed.

ROOM TEMPERATURE BEND TEST[a] RESULTS[b] OF AWS-ER309 WELD OVERLAYS ON 304L SS [8

Weld Process	No. of Layers	Orientation[c]	Percent Elongation in 6.3 mm(0.25 in)	12.7 mm(0.5 in)	25.4 mm(1.0 i
GMAW[d]	1	Transverse	24	23	20.5
		Longitudinal	20	19	21
GMAW	2	Transverse	24	24	20.5
		Longitudinal	18	21	20
SAW[d]	1	Transverse	22	24	21.5
		Longitudinal	22	23	20
SAW	2	Transverse	22	22	21.5
		Longitudinal	22	21	21
GTAW-HW[d]	1	Transverse	20	22	21.0
		Longitudinal	24	23	20
GTAW-HW	2	Transverse	22	24	21.5
		Longitudinal	24	21	20

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[a] Tests were made on specimens with overlay on both sides, machined longitudinal and transverse to the direction of welding; specimens were 152.4 mm(6 in) by 32-41 mm(1 1/4-1 5/8 in) by 9.5 mm(3/8 in); bend fixture had a 38 mm(1.5 in) roller and 60 mm(2.375 in) span, cross head speed 12.7 mm(0.5 in) per minute; test requirement is a 180° bend without formation of a crack greater than 3.2 mm(1/8 in).

[b] Values are the average of two tests per orientation.

[c] Relationship of long dimension of bend specimen to the welding direction.

[d] GMAW = Gas metal arc welding process; SAW = Submerged arc welding process; GTAW-HW = Gas tungsten arc welding with hot wire.

EFFECT OF TEST AND EXPOSURE TEMPERATURE AND COAL GASIFICATION ATMOSPHERE[a] ON TENSILE PROPERTIES[b] OF SOME WELDED ALLOYS [10]

ial tion/ eatment[c]	Test Condition[d]	Welded Incoloy 800H[e]					Welded Incoloy 800H Al[g,h]					Welded 310 SS[i]				
		YS ksi	UTS ksi	El. %	RA %	FL[f]	YS ksi	UTS ksi	El. %	RA %	FL[f]	YS ksi	UTS ksi	El. %	RA %	FL[f]
lded	80 °F	43.3	83.5	42.6	69.0	B	26.3	65.5	14.9	1.6	W	47.0	89.8	38.0	66.5[j]	B
	1800 °F	12.2	15.9	38.2	81.2	B	7.7	10.8	67.7	87.0	B	8.0	11.0	49.2	69.9[j,k]	BW[k]
°F, air	80 °F	52.8	77.4	6.6	7.4	W	28.2	60.8	6.8	7.8	W	42.8	89.7	34.3	58.6[j]	B
	1200 °F	38.2	65.0	18.3	34.6	B	24.5	54.2	28.1	36.6	B	23.8	54.0	27.8	54.2	B
°F, CGA[a]	80 °F	50.5	76.2	7.4	0.9	W						46.2	89.6	34.8	55.6	B
°F, air	80 °F	43.2	81.8	13.8	15.2	W	27.3	58.3	7.4	8.0	W	42.5	87.6	29.6	35.8	B
	1500 °F	22.6	30.6	37.4	50.0	B	15.2	31.2	27.2	19.6	W	16.4	27.6	14.7	9.4	W
°F, air	80 °F	27.1	55.0	9.8	10.5	W	25.8	43.2	5.2	5.7	W	27.8	85.1	36.4	43.5[j]	W
	1800 °F	7.8	9.6	75.1	80.4	B	7.4	10.3	64.3	78.4	B	7.1	10.9	61.6	64.8[j]	B

ial tion/ eatment[c]	Test Condition[d]	Welded RA 333[l]					Welded Haynes 188[m]					Welded INCO 657[o]				
		YS ksi	UTS ksi	El. %	RA %	FL[f]	YS ksi	UTS ksi	El. %	RA %	FL[f]	YS ksi	UTS ksi	El. %	RA %	FL[f]
lded	80 °F	54.8	110.2	33.3	44.1[j]	B	76.5	138.6	30.5	28.0	W	78.8	109.1	7.9	4.2	B
	1800 °F	10.9	16.2	50.4	78.9	B	21.6	27.9	49.5	72.8	B	13.7	20.6	20.1	44.5	BW[n]
°F, air	80 °F	59.8	111.6	25.8	34.2	B	83.0	146.7	23.8	15.2	W	F[p]	85.4	0.0	0.0	BW[n]
	1200 °F	39.8	80.2	30.7	39.4	B	55.4	111.2	27.2	31.0	BW[n]	106.3	129.2	0.9	0.9	B
°F, CGA	80 °F	57.5	101.8	18.0	17.3	B	82.6	149.6	32.4	30.9	B					
°F, air	80 °F	58.1	109.0	8.0	9.4	W	77.4	117.2	5.2	4.0	W	106.5	119.4	0.6	0.4	B
	1500 °F	26.2	46.5	50.9	63.4	B	45.9	69.2	38.6	39.6	BW[n]	34.4	55.2	15.5	24.1	BW[n]
°F, air	80 °F	39.4	72.4	7.6	10.4	W	65.0	124.4	19.9	21.4	W	71.8	91.9	1.6	2.5	W
	1800 °F	14.3	15.1	64.6	84.0	B	17.0	26.6	61.0	80.0	B	13.8	19.3	29.6	22.0	W

= coal gasification atmosphere; input gas at 450 °F in mole percent, 12% CO_2, 18% CO, 24 % H_2, 39.5% H_2O, 5% CH_4, 1% NH_3, 0.5% H_2S.

cimens are ASTM standard, 0.505 in diameter, 2-in long gauge section; values reported are for duplicate specimens except where otherwise ked; tests conducted on specimens with weldment in center of gauge length; properties shown are for base metal/weldment composite.

treatment consisted of exposure for 1,000 hours to high temperatures in air at 1 atm or in coal gasification atmosphere at 68 atm (1000 psi).

tests were performed in air at the indicated temperatures.

oloy 800H Heat No. HH7131A, 1-in. thick plate with double-V weld joint; root passes made with 1/8-in. dia. Metrode 50-50 Nb rod (Batch 030171D); subsequent passes made with 5/32-in. dia. Metrode 50-50 Nb rod (Batch No. 082671A).

= failure location; B = base metal, w = weld metal.

oloy 800H Heat No. HH7131A, 1-in. thick plate with double-V weld joint; root passes made with 1/8-in. dia. Metrode 50-50 Nb rod (Batch 030171D); subsequent passes made with 5/32-in. dia. Metrode 50-50 Nb rod (Batch No. 082671A). Aluminum coating applied by pack diffusion cess to tensile specimens by Alon Processing, Inc. (Alonized).

ld and Ultimate Tensile Strengths of aluminized samples calculated using diameter of uncoated specimen; reduction in area calculated ng diameter of uncoated specimen and final diameter of coated specimen less twice the coating thickness.

e 310 SS Heat No. 24569, 1-in. thick plate with double-V weld joint; root passes made with 1/8-in. dia. Type 310 rod (Heat No. 74707); sequent passes made with 3/16-in. dia. Type 310 rod (Heat No. 72733).

four properties are the average for three specimens.

one specimen most of necking occurred in base metal although failure location was in weld metal; reduction in area value is average the two specimens where failure occurred in base metal.

333 Heat No. 24777, 1-in. thick plate with double-V weld joint; all passes made with 5/32-in. dia. RA 333 rod (Heat No. 200-217617).

nes 188 Heat No. 1880-6-1531, 1-in. thick plate with double-V weld joint; root passes made with 1/16-in. dia. Haynes 188 wire (Heat No. 0-3-1668); subsequent passes made with 1/8-in. dia. Haynes 188 wire (Heat No. 1880-2-1408).

lure occurred in base metal in one specimen , in weld metal in other.

O 657 Heat No. 19-77-20, centrifugally cast pipe, 1-in. wall thickness, single-V weld joint; welded with 5/32-in. dia. Metrode 50-50 Nb (Batch No. 050761).

cimen failed without yielding.

EFFECT OF EXPOSURE[a] TO COAL GASIFICATION ATMOSPHERES ON THE UNIAXIAL TENSILE PROPERTIES[b] OF VARIOUS ALLOYS[7]

	As-Received Material[c]				Tested at Indicated Temperatures after Exposure at Indicated Temperatures and Pressures										
					Atmosphere 1, 34 atm[d]			Atmosphere 1, 102 atm[d]			Atmosphere 2, 34 atm[e]			Atmosphere 2,	
	Ambient	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F	1382°F	1600°F
0.2% YIELD STRENGTH[b]															
ALLOY USS 18-18-2[f]	331.2 (201.5)[c]	(113.1)[c]	57.2 (93.8)[c]	(40.0)[c]	141.9	76.3	52.1	130.2	68.3	36.4[g]	141.7[h]	77.1	52.2	161.7[i]	73.4
ALLOY INCOLOY 800[f]	332.4 (365.7)	175.1 (161.8)	72.4 (92.8)	(51.0)	143.0	75.2	41.1	142.4	75.2	37.4[g] 38.5[j]	142.0	80.0	43.7[h]	139.6	69.3
ALLOY 310 SS[f]	292.3 (268.4)	129.4 (119.4)	64.9 (87.6)	(59)	122.6	85.6	50.2	114.8	76.4	39.7[g]	121.9	85.1	43.6	133.1	77.9
ALLOY INCONEL 671[f]	563.5 (482.9)	260.9	90.1		250.6	108.1	52.6	242.9	103.2	48.7[g]	233.8	105.0	50.1	251.0	119.8
ULTIMATE TENSILE STRENGTH[b]															
ALLOY USS 18-18-2	588.7 (531.2)	(240.8)	79.0 (104.2)	(75.2)	193.7	101.7	72.2	186.1	91.6	47.9	187.8	97.2	63.6	447.6[i]	87.3
ALLOY INCOLOY 800	595.8 (620.9)	204.9 (231.5)	94.9 (120)	(65.9)	181.3	91.3	53.5	180.8	91.3	49.1 51.4[j]	178.3	91.7	53.9	187.5	92.9
ALLOY 310 SS	564.8 (563.4)	201.0 (269.1)	103.1 (158.7)	(89.7)	196.9	114.1	67.7	200.7	103.0	48.2	205.2	111.6	55.4	212.3	107.9
ALLOY INCONEL 671	848.7 (862.4)	313.4	141.7		288.8	136.0	67.7	282.6	131.8	64.7	278.5	132.3	62.2	291.1	143.1
% UNIFORM STRAIN[b] [% TOTAL ELONGATION]															
ALLOY USS 18-18-2	[68] ([63])	([46])	[71] ([55])	([74])	11.0 [44.1]	13.6 [60.2]	9.3 [55.9]	13.1 [52.5]	12.1 [49.3]	13.3 [50.6]	13.5 [61.6]	11.5 [50.8]	10.4 [93.4]	42.1[i] [47.9][i]	14.2 [48.0]
ALLOY INCOLOY 800	[46] ([38])	[89] ([46])	[122] ([119])	([113])	12.7 [59.8]	12.9 [99.3]	16.0 [74.1]	14.4 [85.8]	18.0 [73.4]	23.1,22.0[j] [93.5,88.1]	13.6 [100.4]	7.7 [82.3]	18.8 [68.7]	12.0 [54.5]	14.2 [67.8]
ALLOY 310 SS	[65] ([52])	[48] ([29])	[81] ([43])	([53])	14.2 [33.8]	11.5 [59.8]	11.2 [45.9]	16.7 [45.9]	14.3 [50.3]	16.8 [57.8]	18.9 [43.5]	11.9 [53.4]	13.0 [66.9]	14.1 [30.3]	12.0 [45.3]
ALLOY INCONEL 671	[45] ([25])	[64]	[156]		8.8 [33.4]	9.3 [73.5]	7.8 [35.5]	9.2 [62.1]	9.5 [84.4]	10.8 [50.6]	11.8 [85.9]	9.2 [110.9]	8.8 [54.1]	7.0 [33.8]	6.9 [43.5]

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[a] Specimens in as-machined condition were exposed to the coal gasification atmospheres given in footnotes d and e for 100 hours.

[b] Tensile specimens, with an overall length of 3.4 in and conforming to specifications of ASTM E-8, were tested on a standard laboratory tensile machine, crosshead speed 0.025 in/min, at ambient conditions and at the indicated temperatures. Tests at elevated temperatures were conducte dry, flowing argon; heating up (about 45 min) and cooling down (about 20 min) were under argon. Data for as-received samples are for single data for exposed samples are for duplicate specimens except where noted. Units for 0.2% Yield Strength and Ultimate Tensile Strength are in Both uniform and total percent elongation are given; the values for total percent elongation are in square brackets [].

[c] Values in parentheses are literature values quoted in the reports, not data generated by the authors.

[d] Composition of atmosphere no. 1:

	Input, 1 atm, 77°F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	(mole %)	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
CO	22.75	10.9	27.5	44.6	6.4	17.6	33.0
CO_2	30.20	18.9	12.9	6.3	20.7	16.9	11.1
H_2	25.47	16.0	25.8	34.3	10.2	17.3	25.2
H_2O		21.2	14.0	7.6	24.8	19.3	13.4
H_2S	1.96	1.6	1.5	1.5	1.7	1.6	1.6
CH_4	19.61	8.6	6.3	4.3	10.8	9.2	7.5
C		22.6	12.0	1.4	25.4	18.0	8.3

[e] Composition of atmosphere no. 2:

	Input, 1 atm, 77°F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	(mole %)	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
CO	33.42	10.4	26.4	42.7	6.2	16.9	31.7
CO_2	19.15	17.9	12.1	5.9	19.5	15.9	10.5
H_2	33.42	16.3	26.1	34.7	10.3	17.6	25.5
H_2O		21.1	13.9	7.6	24.7	19.2	13.3
H_2S	1.29	1.2	1.1	1.1	1.2	1.2	1.1
CH_4	12.85	9.1	6.6	4.5	11.3	9.7	7.8
C		24.0	13.7	3.5	26.7	19.5	10.1

Note: Equilibrium atmospheres do contain dispersed solid carbon.

[f] Alloy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, 0.06 C, 0.296 others, balance Fe; Incoloy 800 (A.M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; AISI 310 SS (Rolled Alloys), 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe; Inconel 671 (Huntington Alloys), 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 0.02 Mn, 0.357 others.

[g] Specimens were slightly deformed after exposure to corroding atmospheres.

[h] Data are for a single specimen.

[i] Tensile testing done at 754° F by mistake.

[j] Values for the two specimens given separately and not averaged.

CHANGE[a] IN UNIAXIAL TENSILE PROPERTIES OF ALLOYS RESULTING FROM COAL GASIFICATION EXPOSURES[b] [7]

oy[c]	Atmosphere No. 1[b]						Atmosphere No. 2[b]					
	34 atm			102 atm			34 atm			102 atm		
	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
% UNIFORM STRAIN[a]												
18-18-2	1.12	3.68	0.38	1.34	3.27	0.54	1.38	3.11	0.42	--	3.84	0.56
oloy 800	0.86	1.05	0.81	0.97	1.46	1.17	0.92	0.63	0.95	0.81	1.15	0.69
SS	1.92	0.92	0.51	2.26	1.14	0.76	2.55	0.95	0.59	1.91	0.96	0.52
onel 671	1.80	3.72	3.55	1.88	3.80	4.91	2.41	3.68	4.00	1.43	2.76	2.00
% TOTAL ELONGATION[a]												
18-18-2	0.52	1.07	0.40	0.62	0.88	0.36	0.73	0.91	0.67	--	0.86	0.44
oloy 800	0.66	0.82	1.16	0.94	0.61	1.46	1.10	0.68	1.07	0.60	0.56	0.87
SS	0.87	0.75	0.51	1.18	0.63	0.64	1.12	0.67	0.74	0.78	0.57	0.57
onel 671	0.33	0.26	0.24	0.61	0.30	0.34	0.84	0.39	0.37	0.33	0.15	0.22
ULTIMATE TENSILE STRENGTH (MPa)[a]												
18-18-2	1.02	1.07	1.54	0.98	0.97	1.02	0.99	1.02	1.32	--	0.92	1.11
oloy 800	0.89	0.92	1.06	0.89	0.92	1.02	0.88	0.92	1.07	0.92	0.93	1.17
SS	0.85	1.08	1.30	0.87	0.97	0.92	0.89	1.05	1.06	0.92	1.02	1.21
onel 671	1.15	1.45	1.20	1.12	1.41	1.14	1.11	1.41	1.10	1.16	1.53	1.53

s-machined specimens were exposed for 1000 hours in the coal gasification atmospheres at the indicated temperatures and ressures. Similar specimens were aged in vacuum for 1000 hours at the appropriate temperatures. All specimens were ensile tested on a standard laboratory tensile testing machinge, crosshead speed 0.025 in/min. Specimens conformed to ne specifications of ASTM E-8. Tests were performed at the indicated temperatures under dry, flowing argon; heating up about 45 min) and cooling down (20 min) were under argon. Data are for duplicate specimens. The values compare the roperties for the exposed specimens with the properties of the aged specimens; i.e. (% ELONGATION)$_{exposed}$ ÷ (ELON- ATION)$_{aged}$ and (ULTIMATE TENSILE STRENGTH)$_{exposed}$ ÷ (ULTIMATE TENSILE STRENGTH)$_{aged}$, therefore, the values for the aged pecimens = 1.0.

omposition of atmosphere no. 1:

	Input, 1 atm, 77°F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	(mole %)	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
CO	22.75	10.9	27.5	44.6	6.4	17.6	33.0
CO_2	30.20	18.9	12.9	6.3	20.7	16.9	11.1
H_2	25.47	16.0	25.8	34.3	10.2	17.3	25.2
H_2O		21.2	14.0	7.6	24.8	19.3	13.4
H_2S	1.96	1.6	1.5	1.5	1.7	1.6	1.6
CH_4	19.61	8.6	6.3	4.3	10.8	9.2	7.5
C		22.6	12.0	1.4	25.4	18.0	8.3

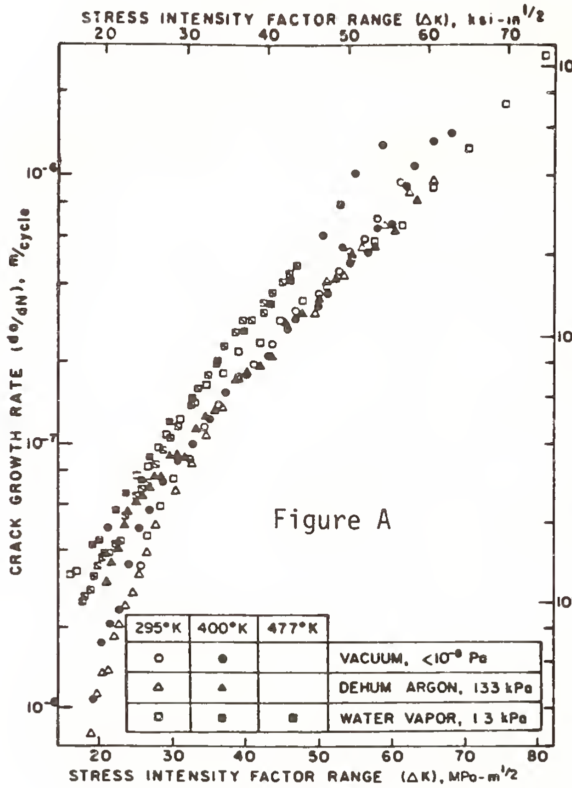
omposition of atmosphere no. 2:

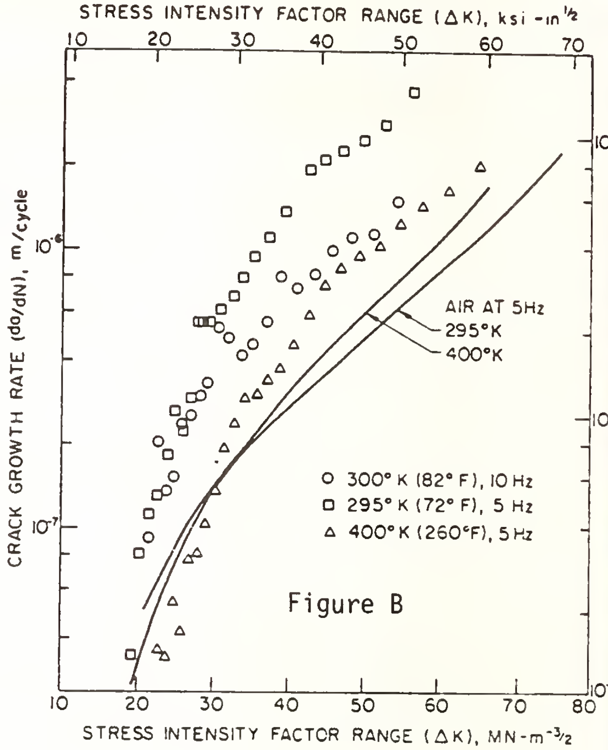
	Input, 1 atm, 77°F	Equilibrium at 34 atm			Equilibrium at 102 atm		
	(mole %)	1382°F	1600°F	1800°F	1382°F	1600°F	1800°F
CO	33.42	10.4	26.4	42.7	6.2	16.9	31.7
CO_2	19.15	17.9	12.1	5.9	19.5	15.9	10.5
H_2	33.42	16.3	26.1	34.7	10.3	17.6	25.5
H_2O		21.1	13.9	7.6	24.7	19.2	13.3
H_2S	1.29	1.2	1.1	1.1	1.2	1.2	1.1
CH_4	12.85	9.1	6.6	4.5	11.3	9.7	7.8
C		24.0	13.7	3.5	26.7	19.5	10.1

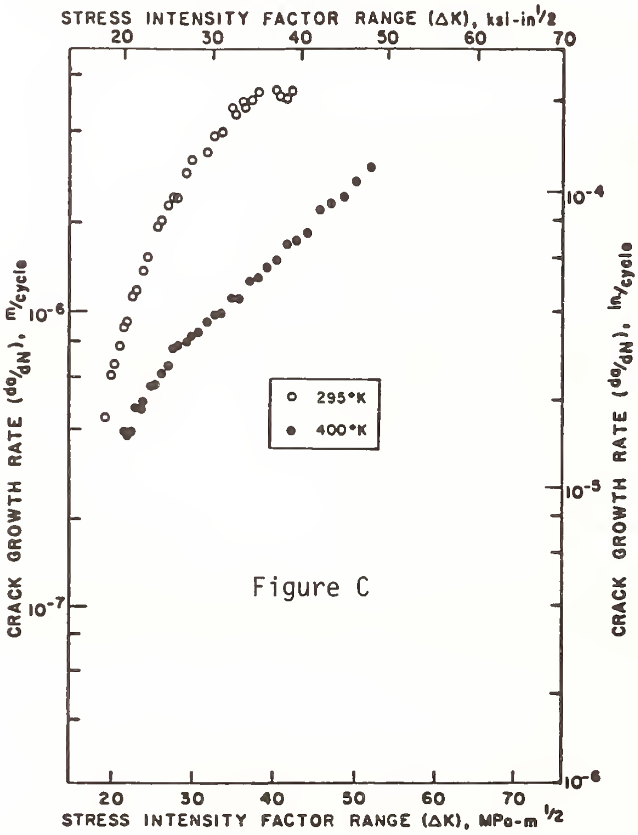
Note: Equilibrium atmospheres do contain dispersed solid carbon.

lloy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, o.06 C, 0.296 thers, balance Fe; Incoloy 800 (A. M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; ISI 310 SS (Rolled Alloys), 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 C, 0.504 others, balance Fe, Inconel 671 Huntington Alloys), 47.76 Cr, 51.78 Ni, 0.17 Fe, 0.18 Si, 0.06 C, 0.02 Mn, 0.357 others.

EFFECT OF TEMPERATURE ON FATIGUE CRACK GROWTH KINETICS[a] FOR 2-1/4 Cr-1 Mo STEEL (A542) IN VARIOUS ENVIRONMENTS[29]







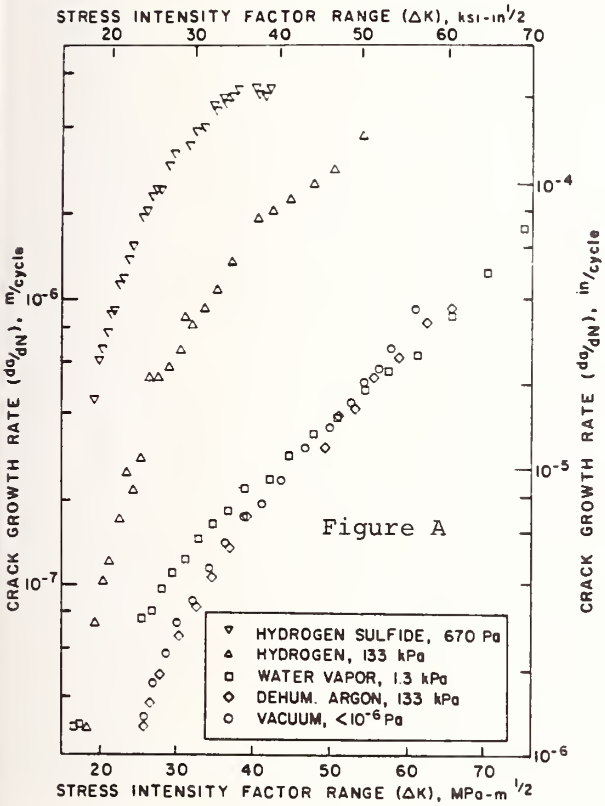
[a] Specimens fatigued at 5 Hz (except for 300 K data in Figure B) with a minimum-to-maximum stress ratio of R = 0.1.

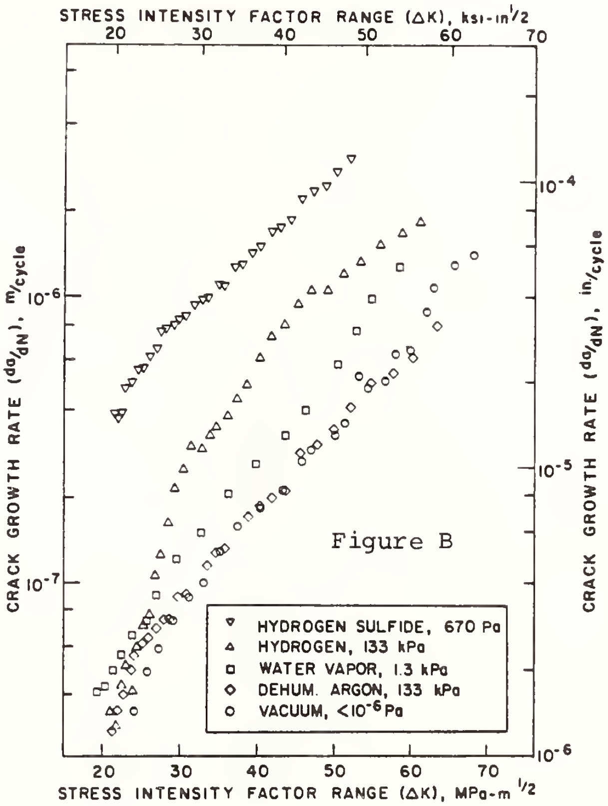
Figure A--Effect of temperature in vacuum, dehumidified argon and in water vapor.

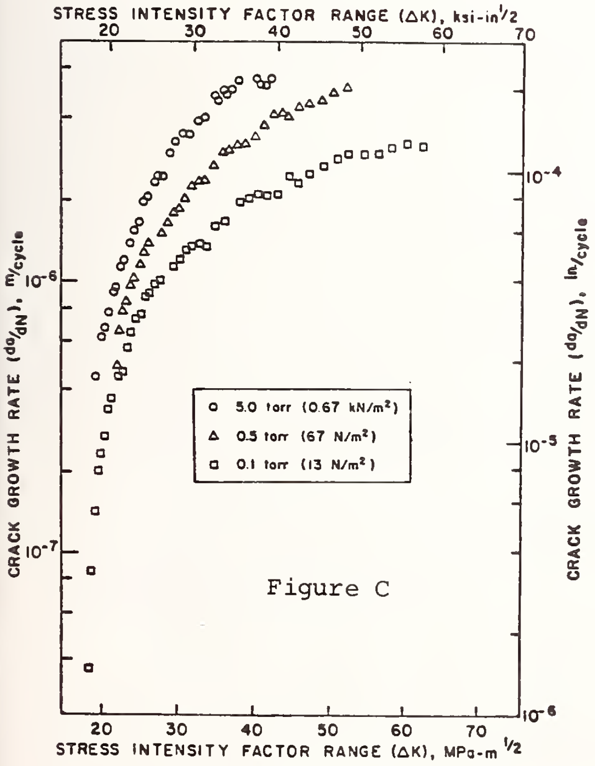
Figure B--Effect of temperature in 133 kN/m^2 (5 psig) dehumidified hydrogen at two frequencies.

Figure C--Effect of temperature in hydrogen sulfide (5 torr or 0.67 kN/m^2).

EFFECT OF ENVIRONMENT ON FATIGUE CRACK GROWTH KINETICS[a]
FOR 2-1/4 Cr-1 Mo STEEL (A542) [29]







[a] Specimens fatigued at 5 Hz with a minimum-to-maximum stress ratio of R = 0.1.

Figure A--Effect of environment at 295 K.

Figure B--Effect of environment at 400 K.

Figure C--Effect of pressure in hydrogen sulfide at 295 K.

STRESS RUPTURE TESTS[a] OF SOME WELDED ALLOYS IN AIR AND IN COAL GASIFICATION ATMOSPHERE[b](10)

Environment	Temperature °F	Stress ksi	Time (hours) to				Elong. %	RA %	Minimum Creep Rate[c] %/hr	FL[d]
			0.1% El.[c]	0.5% El.[c]	1.0% El.[c]	Rupture				
				WELDED INCOLOY 800H[e]						
air, 1 atm	1200	40.0	0.1	13.8	24.4	32.7	19.9	40.9	0.0224	B
	1200	26.0	1.7	131.6	--	575.5	1.8	2.2	0.00095	W
	1200	13.0	1600	--	--	6063.4[f]	--	--	0.000015	--
CGA[b], 68 atm	1200	35.0	--	--	--	3.0	29.5	55.7	--	B
	1200	25.0	--	--	--	917.4	8.4	5.1	--	B
air, 1 atm	1500	10.6	5.3	138	--	139.5	1.0	3.7	0.00196	B
	1500	8.4	42.2	--	--	571.3	1.8	2.4	0.00053	W
	1500	3.0	2250	--	--	6063.4[f]	--	--	0.000013	--
CGA, 68 atm	1500	9.5	--	--	--	28.5	19.9	47.8	--	W
	1500	7.6	--	--	--	352.5	--	--	--	HAZ
air, 1 atm	1800	3.45	17.6	63.8	72.1	75.6	2.3	4.5	0.00504	W
	1800	2.4	0.7	188	285	317.0	2.6	4.7	0.0015	W
	1800	0.9	15.1	3620	4730	6251.8[f]	--	--	0.000058	--
CGA, 68 atm	1800	3.0	--	--	--	1.6	31.2	68.8	--	B
	1800	2.5	9	79	152	251.0	0.3	2.3	0.0053	B
	1800	2.0	--	--	--	194.8	0.4	5.9	--	HAZ
				WELDED INCOLOY 800H, Al[g]						
air, 1 atm	1200	40.0	--	--	--	5.9	36.6	46.5	--	B
	1200	25.0	0.1	1.4	7.5	356.1	8.5	4.6	0.0099	W
	1200	13.0	43.5	--	--	3347.8[f]	--	--	0.000058	--
CGA, 68 atm	1200	25.0	--	--	--	129.5	13.0	26.7	--	HAZ
	1200	17.5	--	--	--	1022.0	24.8	16.5	0.002	W
	1200	13.0	7	30	45	667.5	30.5	29.2	0.012	HAZ
air, 1 atm	1500	10.6	0.1	0.3	0.6	26.9	37.1	10.2	0.399	W
	1500	7.7	0.4	2.4	5.1	161.5	25.6	9.5	0.129	HAZ
	1500	3.0	1.0	810	--	3516.0[f]	--	--	0.00012	--
CGA, 68 atm	1500	7.6	--	--	--	48.5	3.4	6.1	--	HAZ
	1500	5.5	16	162	182	226.0	7.1	8.0	0.0007	W
	1500	4.6	--	--	--	504.4	1.1	1.5	--	W
air, 1 atm	1800	3.45	5.7	40.0	56.0	57.9	2.0	2.3	0.0108	W
	1800	2.3	2.4	21.3	49.6	153.6	6.1	2.3	0.0182	W
	1800	0.9	250	1400	2320	3000.0	3.1	1.2	0.00034	W
CGA, 68 atm	1800	2.8	--	--	--	3.3	63.0	72.0	--	B
	1800	1.8	--	--	--	68.9[h]	--	--	--	W
	1800	1.4	--	--	--	73.7	4.1	3.8	--	W
				WELDED 310 STAINLESS STEEL[i]						
air, 1 atm	1200	22.5	1.0	8.1	18.7	86.4	4.6	9.3	0.046	W
	1200	18.0	2.0	34.4	78.2	328.1	4.6	2.5	0.011	W
	1200	15.0	9.8	131	315	706.6	2.5	1.9	0.002	W
CGA, 68 atm	1253	15.7	--	--	--	145.0	7.5	5.1	0.042	W
	1200	13.0	--	--	--	111.0	13.9	8.9	0.023	W
	1200	12.0	--	--	--	470.6	5.0	3.5	--	W
air, 1 atm	1500	6.7	1.8	15.5	30.5	57.6	2.6	3.0	0.031	W
	1500	5.2	1.9	8.7	72.2	116.7	3.0	2.1	0.012	W
	1500	3.5	24	207	299	336.3	1.5	1.6	0.002	W
	1500	3.0	64.3	341	482	538.0	1.9	2.2	0.00095	W
	1500	2.3	143	518	810	1233.4	4.6	4.0	0.00076	W
CGA, 68 atm	1500	4.0	--	--	--	118.0	9.1	2.3	0.0296	W
	1583	3.5	--	38	62	120.8	4.3	1.1	0.027	W
	1500	3.5	--	62	294	780.0	5.5	1.9	0.0018	W
air, 1 atm	1800	2.05	1.4	10.2	19.6	108.2	11.3	8.9	0.053	W
	1800	1.6	0.6	11.4	31.8	376.0	15.7	3.5	0.034	W
	1800	1.4	2.4	23.6	55.3	754.1	22.5	9.2	0.018	W
CGA, 68 atm	1800	1.5	--	2.0	4.0	55.0	48.0	60.9	0.196	B
	1800	1.0	--	--	--	130.3	--	--	--	B
	1800	0.5	--	--	--	633.4	47.7	35.8	--	W
				WELDED RA 333[j]						
air, 1 atm	1200	36.3	1.9	3.2	4.7	64.0	31.9	9.5	0.260	W
	1200	27.0	1.4	8.8	18.6	282.5	17.0	5.7	0.052	W
	1200	22.0	2.5	34	81.5	724.3	10.0	3.9	0.010	W
CGA, 68 atm	1253	29.5	--	--	--	94.8	25.9	58.3	0.315	B
	1253	20.0	--	24	48	365.0	10.8	2.0	0.012	W
	1200	18.0	--	50	89	564.0	7.6	2.3	0.0123	W
air, 1 atm	1500	10.1	0.2	4.1	10.5	60.9	5.7	1.9	0.066	W
	1500	8.1	1.8	21.2	49.7	154.9	3.8	2.5	0.007	W
	1500	6.0	13.3	127	342	898.7	3.9	1.9	0.0022	W
CGA, 68 atm	1583	20.0	--	--	--	1.7	58.0	81.1	--	B
	1583	7.0	--	--	--	209.2	7.3	1.9	0.013	W
	1500	6.0	--	40	75	434.3	9.4	10.5	0.0146	W
air, 1 atm	1800	2.81	1.1	9.9	20.3	158.2	28.3	6.5	0.060	W
	1800	2.5	1.7	15.1	28.3	223.0	30.8	37.7	0.032	B
	1800	1.8	1.5	36	77.5	765.7	26.7	28.7	0.016	B
CGA, 68 atm	1800	1.8	--	--	--	80.2	39.5	64.3	--	B
	1800	1.3	--	--	--	82.4	21.3	6.7	--	W
	1800	0.9	--	--	--	188.4	79.2	66.8	--	W

(Table Continued)

STRESS RUPTURE TESTS[a] OF SOME WELDED ALLOYS IN AIR AND IN COAL GASIFICATION ATMOSPHERE[b] [10]

(Table Continued)

WELDED HAYNES 188[k]										
air, 1 atm	1200	48.0	7.3	98.6	--	105.4	3.4	8.1	0.004	W
	1200	44.0	7.0	121	274	437.6	3.0	5.9	0.003	B
	1200	40.0	19.7	264	479	1301.9	5.4	6.7	0.002	W
CGA, 68 atm	1200	44.0	--	66	164	384.0	5.7	5.4	0.0142	W
	1200	40.0	--	--	--	49.0	2.0	1.9	--	B
	1200	36.0	--	--	--	1959.0	10.6	2.7	0.010	W
air, 1 atm	1500	30.0	0.1	0.5	1.0	10.5	12.2	6.8	0.950	W
	1500	20.0	0.5	2.8	6.3	160.0	33.4	45.8	0.117	B
	1500	18.0	1.1	5.9	13.1	294.9	32.1	41.9	0.0525	B
	1500	17.0	6.2	80	215	1086.2	18.6	31.0	0.012	B
CGA, 68 atm	1500	20.0	--	--	--	60.6	--	--	--	B
	1583	17.0	--	--	--	262.5	30.4	16.8	0.038	B
	1500	14.5	--	--	--	752.5	23.5	31.5	--	B
air, 1 atm	1800	6.0	1.8	12.6	19.8	121.6	14.1	4.0	0.056	W
	1800	4.2	7.5	60.1	108.3	452.1	13.0	16.9	0.020	W
	1800	3.0	17.0	264	430	1431.8	17.4	6.9	0.0022	W
CGA, 68 atm	1800	3.7	--	7.5	11.5	48.9	30.5	69.0	0.131	B
	1800	3.5	--	--	--	283.0	43.5	60.4	0.0125	B
	1800	3.0	--	--	--	518.9	48.1	61.4	--	B
WELDED INCO 657[l]										
air, 1 atm	1200	40.0	0.6	7.2	17.3	110.4	3.2	2.2	0.0144	B
	1200	31.0	1.5	16.2	41.1	396.8	3.0	1.9	0.00358	B
	1200	13.0	36.4	384	--	5605.1[f]	--	--	0.000050	--
CGA, 68 atm	1200	35.0	--	--	--	142.3	2.0	1.9	--	W
	1200	30.0	--	--	--	261.0	3.2	1.9	0.0086	B
air, 1 atm	1500	15.0	0.2	7.0	28.7	54.7	2.5	4.6	0.0212	W
	1500	10.6	1.9	83.6	252	302.7	3.0	1.8	0.00280	W
	1500	3.0	34.6	--	--	5605.0[f]	--	--	0.000019	--
CGA, 68 atm	1500	12.0	--	--	--	36.0	14.8	4.1	0.0955	W
	1500	10.0	--	--	--	347.8	--	--	--	W
	1500	9.0	--	--	--	558.7	4.4	7.0	--	W
air, 1 atm	1800	3.45	4.7	51.1	87.0	111.0	4.2	9.0	0.00840	W
	1800	2.6	22	241	385	440.5	4.8	4.2	0.00177	W
	1800	0.9	8.1	2420	4140	5572.3[f]	--	--	0.00012	--
CGA, 68 atm	1800	2.2	--	--	--	98.2	10.0	11.1	--	W
	1800	2.2	--	--	--	23.0	20.2	19.46	--	W
	1800	1.8	--	--	--	14.8	10.2	20.3	--	W
	1800	2.0	--	--	--	26.2	7.9	20.9	--	W

---

[a] Test specimens are ASTM standard, 0.505 in diameter, 2-in long gauge section; tests were conducted in air and in a simulated coal gasification environment as indicated; values are for single specimens; tests conducted on specimens with weldment in center of gauge length; properties shown are for base metal/weldment composite.

[b] CGA = coal gasification atmosphere; input gas at 450°F in mole percent, 12% CO_2, 18% CO, 24% H_2, 39.5% H_2O, 5% CH_4, 1% NH_3, 0.5% H_2S.

[c] Elongation in 2-in gauge length measured in air; crosshead displacement measured in coal gasification atmosphere.

[d] FL = failure location, B = base metal, W = weldment, HAZ = heat affected zone.

[e] Incoloy 800H Heat No. HH7131A, 1-in thick plate with double-V weld joint; root passes made with 1/8-in dia. Metrode 50-50 Nb rod (Batch No. 0301710); subsequent passes made with 5/32-in dia. Metrode 50-50 Nb rod (Batch No. 082671A).

[f] Test terminated before specimen ruptured.

[g] Incoloy 800H Heat No. 7131A, 1-in thick plate with double-V weld joint; root passes made with 1/8-in dia. Metrode 50-50 Nb rod (Batch No. 0301710); subsequent passes made with 5/32-in dia. Metrode 50-50 Nb rod (Batch No. 082671A). Aluminum coating applied by pack diffusion process to tensile specimens by Alon Processing, Inc. (Alonized).

[h] Specimen failed prematurely because of equipment problem.

[i] Type 310 SS Heat No. 24569, 1-in thick plate with double-V weld joint; root passes made with 1/8-in dia. Type 310 rod (Heat No. 74707); subsequent passes made with 3/16-in dia. Type 310 rod (Heat No. 72733).

[j] RA 333 Heat No. 24777, 1-in thick plate with double-V weld joint; all passes made with 5/32-in dia. RA 333 rod (Heat No. 200-217617).

[k] Haynes 188 Heat No. 1880-6-1531, 1-in thick plate with double-V weld joint; root passes made with 1/16-in dia. Haynes 188 wire (Heat No. 1880-3-1668); subsequent passes made with 1/8-in dia. Haynes 188 wire (Heat No. 1880-2-1408).

[l] INCO 657 Heat No. 19-77-20, centrifugally cast pipe, 1-in. wall thickness, single-V weld joint; welded with 5/32-in dia. Metrode 50-50 Nb rod (Batch No. 050761).

STRESS RUPTURE TESTS[a] OF SOME ALLOYS IN AIR AND IN COAL GASIFICATION ATMOSPHERE[b] [10]

Environment	Temperature °F	Stress ksi	Time (hours) to				Elong. %	RA %	Minimum Creep Rate[c] %/hr
			0.1% El.[c]	0.5% El.[c]	1.0% El.[c]	Rupture			
INCOLOY 800H[d]									
Air, 1 atm	1200	31.0	0.1	2.7	26.7	174.9	36.4	43.5	0.030
	1200	31.0	0.1	2.0	21.4	184.4	34.9	41.5	0.018
	1200	31.0	-	-	-	176.2	38.4	54.2	0.070
	1200	31.0	-	-	-	77.0	36.9	46.9	0.082
	1200	31.0	-	-	-	95.0	33.6	38.5	0.165
	1200	31.0	-	-	-	87.0	37.6	45.6	0.152
	1200	27.5	0.2	4.9	51	555.9	30.8	36.3	0.018
	1200	23.5	0.9	12.7	105	1659.1	24.2	30.2	0.003
CGA[b], 68 atm	1253	35.5	-	-	-	6.9	18.7	46.8	1.178
	1253	31.0	-	-	-	2.7	35.1	53.5	8.0
	1253	17.5	-	-	-	173.5	26.1	63.6	0.180
	1200	15.0	-	-	-	3780.6	33.2	45.9	-
	1200	13.0	-	-	-	3777.5[e]	32.4[e]	35.7[e]	-
Argon, 68 atm	1200	31.0	-	-	-	143.0	25.0	42.6	0.390
Air, 1 atm	1500	9.6	0.3	2.3	5.2	155.9	39.1	43.5	0.017
	1500	9.6	-	-	-	82.0	44.7	53.0	0.483
	1500	8.2	1.7	20.7	50.9	641.4	26.0	40.6	0.021
	1500	6.8	5.5	129	240	1739.8	24.9	35.9	0.005
CGA, 68 atm	1583	8.5	-	-	-	81.8	25.5	51.4	0.052
	1583	6.5	-	-	-	138.0	24.0	13.1	0.090
	1500	5.4	-	-	-	499.0	33.4	27.5	0.004
Air, 1 atm	1800	4.85	0.4	15.2	27.5	66.8	30.0	38.5	0.0215
	1800	3.5	19.5	260	306	432.9	11.0	21.2	0.001
	1800	2.75	269	633	738	1018.9	13.9	18.2	0.0007
	1800	2.31	210	1293	1630	2579.0	17.4	16.9	0.0002
	1800	1.9	370	5280	6820	9540.3[f]	-	-	0.000069
CGA, 68 atm	1800	2.0	-	10	15	37.5	33.0	48.8	0.0938
	1800	1.8	-	-	-	78.1	50.8	50.6	-
	1800	1.5	-	-	-	457.9	21.6	32.5	-
INCOLOY 800H, Al[g]									
Air, 1 atm	1200	28.5	0.1	0.6	1.5	101.2	53.8	54.5	0.155
	1200	25.0	0.2	1.5	4.5	356.4	54.2	56.0	0.0358
	1200	23.0	0.3	2.7	6.9	533.7	49.7	59.0	0.0199
CGA, 68 atm	1200	29.4	-	-	-	63.0	43.0	44.2	0.111
	1200	22.5	-	4.0	7.0	178.0	46.8	46.7	0.0794
	1200	17.5	-	-	-	975.0	39.3	40.4	0.00529
Air, 1 atm	1500	8.6	0.1	0.6	1.3	102.9	73.0	71.6	0.363
	1500	7.6	0.2	2.0	9.5	248.8	74.3	61.6	0.144
	1500	6.4	3.1	20.6	41.2	1350.4	52.6	55.6	0.0192
CGA, 68 atm	1500	8.6	-	-	-	59.2	51.7	55.0	-
	1500	7.6	-	-	-	191.4	38.1	60.8	0.188
	1500	6.5	-	-	-	524.0	28.7	44.6	-
Air, 1 atm	1800	3.4	7.5	38	58	180.6	13.8	22.5	0.012
	1800	2.8	0.3	6.1	13.6	194.6	28.8	27.9	0.0688
	1800	2.5	175	585	726	847.9	5.5	7.6	0.00039
CGA, 68 atm	1800	2.5	-	1.75	3.5	23.5	55.2	62.0	0.0741
	1800	1.8	-	-	-	50.8	34.8	35.2	-
	1800	0.8	-	-	-	94.7	66.3	58.3	-

(Table Continued)

STRESS RUPTURE TESTS[a] OF SOME ALLOYS IN AIR AND IN COAL GASIFICATION ATMOSPHERE[b] [10]
(Table Continued)

Environment	Temperature	Stress	Time (hours) to				Elong.	RA	Minimum Creep Rate[c]
	°F	ksi	0.1% El.[c]	0.5% El.[c]	1.0% El.[c]	Rupture	%	%	%/hr
310 STAINLESS STEEL[h]									
Air, 1 atm	1200	28.0	0.04	0.2	0.5	78.8	48.9	48.0	0.328
	1200	23.0	0.25	1.8	6.1	317.0	48.3	44.5	0.088
	1200	22.5	0.14	2.7	8.7	397.6	37.3	39.9	0.056
	1200	22.5	-	-	-	89.0	36.3	64.0	0.111
	1200	18.0	1.4	21.6	47.1	1074.8	31.0	32.9	0.0156
CGA, 68 atm	1253	15.7	-	-	-	48.0	27.8	69.9	0.3[i]
	1253	10.0	-	-	-	378.2	52.4	57.3	0.07[i]
	1200	8.8	-	-	-	3240.0	41.5	39.5	-
	1200	8.0	-	-	-	2184.0	49.7	50.9	-
Air, 1 atm	1500	8.0	0.25	1.5	3.5	110.0	75.4	53.5	0.216
	1500	8.0	-	-	-	67.0	45.6	62.2	0.313
	1500	6.7	0.3	4.2	9.5	221.1	49.0	45.0	0.080
	1500	6.7	-		-	331.0	38.3	36.6	0.105
	1500	5.2	1.3	17.1	40.4	612.9	42.1	42.6	0.024
	1500	4.8	4.2	33.2	68.5	813.1	46.4	36.7	0.015
CGA, 68 atm	1500	6.7	-	-	-	155.0	52.1	33.4	0.119
	1500	5.2	-	-	-	316.0	46.4	41.2	0.031
	1583	3.5	-	-	-	285.0	-	-	-
	1500	3.5	-	-	-	599.7	28.1	29.0	-
Air, 1 atm	1850	2.6	0.1	0.4	0.9	38.9	73.0	48.3	0.793
	1800	2.4	0.4	2.6	6.0	115.2	53.0	43.2	0.182
	1800	2.05	0.9	5.5	11.0	186.7	41.9	33.5	0.105
	1800	2.0	0.7	4.7	8.6	162.3	46.5	33.8	0.163
	1800	1.5	1.55	16.7	34	517.8	43.9	32.9	0.032
	1800	0.9	3.4	69.7	154	2424.8	53.5	20.9	0.0098
CGA, 68 atm	1800	1.5	-	2.5	4.5	89.0	70.4	65.6	0.3704
	1800	1.0	-	-	-	73.0	54.8	43.6	-
	1800	0.5	-		-	78.1	83.4	57.1	-
RA 333[j]									
Air, 1 atm	1200	36.3	0.1	0.6	1.8	66.3	56.7	54.4	0.373
	1200	29.5	0.5	3.2	6.8	213.3	66.2	54.5	0.128
	1200	28.5	-	-	-	147.0	76.0	57.0	0.104
	1200	28.5	-	-	-	242.0	86.3	60.5	0.120
	1200	22.0	6.3	28.9	55.4	1670.4	70.2	56.0	0.016
CGA , 68 atm	1253	29.5	-	-	-	23.0	47.2	66.0	0.333
	1200	26.0	-	-	-	144.0	56.0	63.2	-
	1200	22.0	-	22	80	967.0	44.9	58.5	0.0126
	1200	22.0	-	55	90	1267.0	48.3	60.4	0.0042
	1253	20.0	-	-	-	1028.0	75.1	69.4	0.025
Air, 1 atm	1500	11.0	0.3	1.5	3.7	104.1	92.7	82.8	0.268
	1500	10.1	0.4	3.0	7.0	200.0	78.4	78.9	0.109
	1500	9.5	-	-	-	210.0	64.2	67.1	0.054
	1500	8.6	-	-	-	238.0	62.4	70.9	0.063
	1500	8.4	0.8	9.4	24.9	722.9	69.1	67.7	0.022
CGA, 68 atm	1583	11.5	-	-	-	17.0	40.4	84.8	0.970
	1500	7.4	-	1	7	226.5	56.5	59.5	0.068
	1500	6.5	-	-	-	888.5	44.1	61.6	-
Air, 1 atm	1800	3.4	0.2	2.2	5.2	76.9	46.9	40.0	0.195
	1800	2.81	0.8	6.1	12.9	172.6	48.2	33.9	0.093
	1800	2.6	0.1	3.4	9.1	205.0	43.7	33.5	0.090
	1800	1.8	1.9	26.5	61.4	807.2	46.0	29.6	0.021
CGA, 68 atm	1800	1.8	-	6	12	119.0	71.4	62.1	0.1076
	1800	1.5	-	-	-	59.2	47.9	59.0	-
	1800	1.3	-	-	-	131.5[e]	-	-	-
HAYNES 188[k]									
Air, 1 atm	1200	70.0	-	4.7	8.7	166.6	31.6	29.2	0.099
	1200	60.0	1.4	12.5	25.2	419.4	32.5	29.8	0.045
	1200	48.0	5.0	65	141	2061.0	28.3	29.0	0.014
CGA, 68 atm	1253	48.0	-	-	-	67.3	29.1	26.3	-
	1200	45.0	-	-	-	261.1	17.1	17.7	-
	1200	38.0	-	-	-	1686.0	26.5	21.4	0.01058
Air, 1 atm	1500	28.0	-	0.6	1.2	29.4	65.4	60.6	0.776
	1500	19.5	0.6	3.6	8.6	283.5	37.7	42.6	0.072
	1500	17.0	17.0	1.1	8.1	791.2	29.8	37.3	0.016
CGA, 68 atm	1583	21.0	-	-	-	60.8	49.2	45.9	0.407
	1500	18.5	-	-	-	51.4	53.9	57.6	0.1556
	1500	13.0	-	-	-	619.7	38.9	36.9	0.032
Air, 1 atm	1800	4.2	1.2	9.3	17.7	132.0	68.2	52.8	0.067
	1800	4.0	0.3	5.9	14.7	216.7	77.0	61.3	0.0654
	1800	3.9	9.1	89	143	712.2	41.5	39.5	0.006
	1800	3.7	7.6	95	163	794.0	45.4	46.6	0.006
CGA, 68 atm	1800	3.7	-	-	-	64.8	62.1	64.9	-
	1800	3.5	-	-	-	141.4	30.8	33.8	-
	1800	1.0	-	-	-	567.1	70.4	58.4	-

(Table Continued)

STRESS RUPTURE TESTS[a] OF SOME **ALLOYS IN AIR AND** IN COAL GASIFICATION ATMOSPHERE[b] [10]
(Table Continued)

Environment	Temperature °F	Stress ksi	Time (hours) to				Elong. %	RA %	Minimum Creep Rate[c] %/hr
			0.1% El.[c]	0.5% El.[c]	1.0% El.[c]	Rupture			
INCO 657[l]									
Air, 1 atm	1200	40.0	0.05	0.3	1.0	192.8	7.5	6.4	0.0099
	1200	31.0	-	-	-	244.0	6.0	3.9	0.007
	1200	30.0	3.2	26.0	43.7	556.0	4.1	2.9	0.003
	1200	25.0	8.5	42.0	71.0	1317.9	3.9	2.9	0.001
CGA, 68 atm	1200	40.0	-	-	-	141.0	7.3	5.8	0.018
	1200	30.0	-	-	-	432.2	3.6	3.5	0.004
	1200	20.0	-	-	-	1564.0	5.8	3.9	0.001
Air, 1 atm	1500	16.0	0.2	3.4	12.1	60.6	8.2	11.2	0.0424
	1500	10.6	0.6	22.0	220	448.2	3.4	4.5	0.002
	1500	8.0	2.0	184	865	1200.3	3.0	2.5	0.007
CGA, 68 atm	1583	14.3	-	-	-	52.5	25.0	37.7	0.25[i]
	1500	12.5	-	-	-	69.5	9.6	20.0	0.045
	1583	9.0	-	-	-	444.0	10.7	11.1	0.015
	1500	9.0	-	-	-	380.0	6.5	10.8	0.007
	1500	7.5	-	-	-	564.7	-	-	-
Air, 1 atm	1800	4.7	2.2	22.2	43.1	69.7	5.0	5.5	0.0199
	1800	3.45	2.3	76	155	270.8	8.7	5.9	0.006
	1800	2.3	3.4	124	405	973.8	10.5	8.9	0.002
CGA, 1 atm	1800	2.2	-	-	-	106.4	8.9	9.8	-
	1800	1.8	-	-	-	672.2	12.0	7.1	-
	1800	2.0	-	-	-	200.0	13.5	19.7	-
HK-40 STAINLESS STEEL[m]									
Air, 1 atm	1200	32.9	0.08	2.5	23.2	121.5	3.5	4.4	0.0025
	1200	30.0	0.09	5.9	34.5	392.4	2.4	3.5	0.00162
	1200	26.0	1.2	32.5	313	982.2	1.9	1.9	0.0007
	1200	19.5	16.6	575	-	6063.0[f]	-	-	0.000064
CGA, 68 atm	1200	32.9	-	-	-	110.2	3.1	4.3	0.007
	1200	30.0	-	-	-	240.0	5.8	2.4	0.006
	1200	26.0	-	-	-	882.0	6.7	4.3	0.0035
Air, 1 atm	1500	11.3	0.5	31.5	-	89.9	3.0	3.6	0.0057
	1500	9.5	2.8	202	-	246.9	1.3	1.7	0.001
	1500	7.8	1.5	308	-	701.6	1.0	1.2	0.0005
CGA, 68 atm	1500	9.5	-	-	-	12.0	4.4	4.3	-
	1500	7.0	-	-	-	783.8	3.9	1.6	-
	1500	5.5	-	-	-	1189.7[e]	-	-	-
Air, 1 atm	1800	5.3	7.0	102	-	109.9	2.0	3.0	0.0027
	1800	3.75	39	328	-	333.9	1.0	1.6	0.0008
	1800	2.85	120	850	-	870.7	0.8	1.0	0.0003
CGA, 68 atm	1800	3.0	-	-	-	23.0	-	-	-
	1800	1.8	-	-	-	272.1	7.8	10.4	-
	1800	1.65	-	-	-	417.2	6.8	2.0	-
STELLITE 6B[n]									
Air, 1 atm	1200	80.0	-	-	-	FOL[o]	53.3	68.1	-
	1200	70.0	0.25	5.6	34	223.3	7.8	8.0	0.016
	1200	56.0	1.6	114	240	1147.3	6.1	6.0	0.003
	1200	50.0	15	194	357	2027.6	5.9	6.9	0.001
CGA, 68 atm	1200	70.0	-	-	-	117.3	10.9	10.7	0.043
	1200	65.0	-	-	-	94.1	7.6	10.7	-
	1200	56.0	-	-	-	591.0	8.2	8.6	-
Air, 1 atm	1500	35.0	0.05	0.28	1.0	40.3	17.3	27.9	0.245
	1500	24.0	0.3	5.6	34.2	496.8	4.9	3.8	0.004
	1500	19.8	2.3	23.6	187	973.6	5.1	4.0	0.002
CGA, 68 atm	1500	33.0	-	-	-	17.1	14.5	23.6	-
	1500	30.0	-	-	-	188.9	8.4	8.9	-
	1500	22.0	-	-	-	322.9	4.4	3.5	-
Air, 1 atm	1800	11.0	11.0	0.26	3.1	105.0	19.1	20.0	0.066
	1800	8.1	0.8	17	54.7	379.9	14.7	15.0	0.014
	1800	6.5	1.5	24.3	96.4	869.7	14.9	11.4	0.006
CGA, 68 atm	1800	10.0	-	-	-	31.3	-	-	-
	1800	6.0		-	-	537.7	6.2	3.5	-

(Table Continued)

STRESS RUPTURE TESTS[a] OF SOME ALLOYS IN AIR AND IN COAL GASIFICATION ATMOSPHERE[b][10]

(Table Continued)

Environment	Temperature °F	Stress ksi	Time (hours) to				Elong. %	RA %	Minimum Creep Rate[c] %/hr
			0.1% El.[c]	0.5% El.[c]	1.0% El.[c]	Rupture			
SUPERTHERM T63WC[p]									
Air, 1 atm	1200	42.0	-	-	0.3	58.5	12.1	14.0	0.075
	1200	36.3	0.05	1.4	25	263.4	14.1	17.5	0.021
	1200	33.0	0.18	54.7	125	886.3	10.8	13.5	0.007
CGA, 68 atm	1200	36.3	-	-	-	13.0	21.9	18.1	0.332
	1200	25.0	-	-	-	1174.0	7.0	11.0	-
Air, 1 atm	1500	16.5	0.4	7.0	28.6	143.8	11.9	20.5	0.019
	1500	13.0	1.0	33.4	205	668.8	8.9	14.2	0.0025
	1500	12.2	1.1	81.5	484	1033.7	6.5	8.5	0.0013
CGA, 68 atm	1500	13.0	-	-	-	96.0	15.6	28.4	0.037
	1500	11.0	-	-	-	429.0	25.1	41.0	-
	1500	10.0	-	-	-	373.0	17.4	9.7	-
Air, 1 atm	1800	6.6	5.0	51.4	79	150.1	12.2	20.0	0.009
	1800	5.7	14.5	242	308	448.3	7.5	9.0	0.0018
	1800	5.0	12.0	504	832	1143.6	5.0	12.9	0.0007
CGA, 68 atm	1800	4.0	-	-	-	72.0	17.0	49.2	0.0889
	1800	3.5	-	-	-	115.6	13.2	37.4	-
	1800	2.5	-	-	-	367.1	22.2	43.2	-
RA 330[q]									
Air, 1 atm	1200	26.0	0.1	0.5	1.8	59.6	82.1	68.8	0.302
	1200	22.0	0.4	3.6	7.1	167.1	64.7	69.3	0.150
	1200	18.7	1.5	11.5	24.4	633.4	63.2	72.7	0.046
	1200	17.5	565.8	-	-	1902.3[f]	-	-	0.00013
CGA, 68 atm	1200	18.7	-	-	-	131.0	60.5	51.3	0.085
	1200	16.5	-	-	-	262.7	70.9	70.3	-
	1200	14.5	-	-	-	387.6	52.7	63.0	-
Air, 1 atm	1500	8.0	0.2	1.6	3.4	90.7	51.2	47.6	0.311
	1500	6.0	1.1	8.8	18.4	381.4	37.2	37.6	0.044
	1500	5.0	2.6	25.4	56.4	791.6	42.7	37.6	0.018
CGA, 68 atm	1500	6.0	-	-	-	127.0	47.1	46.0	0.122
	1500	5.0	-	-	-	371.8	3.6	18.1	0.006
	1500	4.5	-	-	-	597.8	47.8	42.5	-
Air, 1 atm	1800	2.4	0.7	4.9	8.9	94.4	46.6	40.2	0.168
	1800	1.74	2.8	19.0	32.9	301.0	54.6	37.0	0.063
	1800	1.3	1.6	42.8	83.7	1016.3	51.2	23.8	0.015
CGA, 68 atm	1800	1.3	-	-	-	66.3	40.5	45.3	0.1371
	1800	0.9	-	-	-	23.4	38.7	48.3	-
	1800	0.5	-	-	-	206.7	31.3	45.3	-

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[a] Test specimens are ASTM standard, 0.505 in diameter, 2-in long gauge section; tests were conducted in air and in a simulated coal gasification environment as indicated; values are for single specimens.

[b] CGA = coal gasification atmosphere; input gas at 450°F in mole percent, 12% CO_2, 18% CO, 24% H_2, 39.5% H_2O, 5% CH_4, 1% NH_3, 0.5% H_2S.

[c] Elongation in 2-in gauge length measured in air; crosshead displacement measured in coal gasification atmosphere.

[d] Incoloy 800H Heat No. HH7131A, 1-in thick plate.

[e] Specimen failed prematurely because of equipment problem.

[f] Test terminated before specimen ruptured.

[g] Incoloy 800H Heat No. 7131A, 1-in thick plate. Aluminum coating applied by pack diffusion process to tensile specimens by Alon Processing, Inc. (Alonized).

[h] Type 310 SS Heat No. 24569, 1-in thick plate.

[i] Faulty data recording. Value shown is estimated.

[j] RA 333 Heat No. 24777, 1-in thick plate.

[k] Haynes 188 Heat No. 1880-6-1531, 1-in thick plate.

[l] INCO 657 Heat No. 19-77-20, centrifugally cast pipe, 1-in wall thickness.

[m] HK-40 stainless steel Heat No. B-387-A, centrifugally cast pipe, 1-in wall thickness.

[n] Stellite 68 Heat No. 6-1026, 1-in thick plate.

[o] Specimen failed on loading.

[p] Supertherm T63WC Heat J2403, centrifugally cast pipe, 1-in wall thickness.

[q] Ra 330 Heat No. 19726, 1-in thick plate.

COMPARISON AND RANKING[a] OF ALLOY PERFORMANCE BASED ON STRESS RUPTURE DATA IN AIR (1 ATM) AND CGA (68 ATM)[10]

Alloy	1,000-hr Rupture Stress (ksi) Air (σ_A)	CGA (σ_C)	σ_C/σ_A (%)	CGA Rupture Life (t_c) at σ_A (hrs)	t_c/1,000 (%)	Alloy Rank[b] Air	CGA
1200 °F Data							
Incoloy 800H	25.2	16.5	65.5	29.6	3.0	6	6
Incoloy 800H(W)[c]	23.9	24.0	100.4	1,096.6	109.7	6	6
Incoloy 800H(Al)[d]	21.6	17.1	79.2	284.8	28.5	7	8
Incoloy 800H(W-Al)	22.2	14.8	66.7	176.6	17.7	7	8
310 SS	18.7	9.5	50.8	10.3	1.0	10	10
310 SS(W)	14.2	11.3	79.6	121.1	12.1	10	10
RA333	23.7	22.2	93.7	444.8	44.5	8	7
RA333(W)	20.7	15.2	73.4	333.8	33.4	8	7
Haynes 188	53.3	39.9	74.9	19.3	1.9	2	2
Haynes 188(W)	40.8	39.1	95.8	709.0	70.9	2	2
Inco 657	26.5	23.0	86.8	612.7	61.3	5	5
Inco 657(W)	25.6	21.3	83.2	487.2	48.7	5	5
HK-40 SS	26.3	25.6	97.3	789.5	79.0	4	3
Stellite 6B	56.2	53.4	95.0	606.2	60.6	1	1
Supertherm T63WC	32.5	25.3	77.8	49.4	4.9	3	4
RA330	17.4	11.9	68.4	186.8	18.7	9	9
1500 °F Data							
Incoloy 800H	7.5	4.5	60.0	107.9	10.8	5	7
Incoloy 800H(W)	7.7	6.9	89.6	304.2	30.4	5	7
Incoloy 800H(Al)	6.6	6.0	90.9	501.6	50.2	8	9
Incoloy 800H(W-Al)	5.6	4.0	71.4	203.7	20.4	8	9
310 SS	4.6	2.8	60.9	361.1	36.1	10	10
310 SS(W)	2.3	3.3	143.5	1.2x10^{5}	1.2x10^{4}	10	10
RA333	8.0	6.2	77.5	179.4	17.9	7	6
RA333(W)	5.8	5.0	86.2	502.4	50.2	7	6
Haynes 188	16.3	12.2	74.8	125.6	12.6	2	2
Haynes 188(W)	16.7	14.1	84.4	266.1	26.6	2	2
Inco 657	8.5	7.0	82.4	445.5	44.6	4	4
Inco 657(W)	8.3	8.7	104.8	1,688.8	168.9	4	4
HK-40 SS	7.3	6.2	84.9	182.2	18.2	6	5
Stellite 6B	20.4	21.8	106.9	1,857.8	185.8	1	1
Supertherm T63WC	12.2	9.2	75.4	143.3	14.3	3	3
RA330	4.8	4.1	85.4	437.8	43.8	9	8
1800 °F Data							
Incoloy 800H	2.8	1.4	50.0	1.8	0.2	6	--
Incoloy 800H(W)[c]	1.8	---	----	---	---	6	--
Incoloy 800H(Al)[d]	2.4	---	----	---	---	8	--
Incoloy 800H(W-Al)	1.3	---	----	---	---	8	--
310 SS	1.2	---	----	---	---	10	--
310 SS(W)	1.3	0.4	30.8	66.2	6.6	10	--
RA333	1.7	---	----	---	---	7	--
RA333(W)	1.7	---	----	---	---	7	--
Haynes 188	3.7	0.8	21.6	84.9	8.5	3	--
Haynes 188(W)	3.3	3.0	90.9	271.2	27.1	3	--
Inco 657	2.3	1.7	73.9	62.9	6.3	5	--
Inco 657(W)	2.2	---	----	---	---	5	--
HK-40 SS	3.0	1.4	46.7	3.0	0.3	4	--
Stellite 6B	6.3	5.4	85.7	409.8	41.0	1	--
Supertherm T63WC	5.1	1.9	37.3	31.2	3.1	2	--
RA330	1.3	---	----	---	---	8	--

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[a] Based on rupture stresses and rupture lives calculated from equations fitted (least-squares) to data given in preceding table.

[b] Ranking based on 1,000-hr rupture stresses in air and CGA; for alloys with welds ranking is based on base metal or weldment strength, whichever is lower.

[c] W - indicates tests performed on specimens with weldments at center of gauge length.

[d] Al - indicates tests performed on aluminum-coated specimens; coating applied by pack diffusion process by Alon Processing, Inc. (Alonized).

LOW-CYCLE FATIGUE DATA[a] OBTAINED IN AIR ON SELECTED ALLOYS[10]

Alloy	Test Temperature °F	Tension Hold Time min	Cycles to Failure
Type 310 SS[b]	1500	0	375
	1500	10	286
	1500	30	253
	1500	53	150
	1800	0	170
	1800	10	97
	1800	30	75
	1800	53	62
Incoloy 800H[c]	1500	0	400
	1500	10	319
	1500	30	235
	1500	53	127
	1800	0	285
	1800	10	130
	1800	30	123
	1800	53	116
Inco 657[d]	1500	0	7
	1500	10	326
	1500	30	40
	1500	53	4
	1800	0	59
	1800	10	130
	1800	30	100
	1800	53	77

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[a] Tested at a total strain range of 1.5% (0.75% compressive to 0.75% tensile); continuous cycling tests conducted as well as tests with hold times at the peak tensile strain in each cycle of 10, 30, and 53 minutes; mean strain rate during cyclic portion of tests (between hold times) is about 0.1% per minute; values are for single specimens.

[b] Type 310 SS Heat NO. 24569, 1-in. thick plate.

[c] Incoloy 800H Heat No. HH7131A, 1-in. thick plate.

[d] Inco 657 Heat No. 19-77-20, centrifugally cast pipe, 1-in. wall thickness.

VICKERS HARDNESS OF ALLOYS BEFORE AND AFTER EXPOSURE TO COARSE FMC CHAR ERODENT[a] IN COAL GASIFICATION ATMOSPHERE[b][11]

		Hardness Impression Dimensions, mm				Corrosion Surface		Average Hardness, VPN
		1st Impression		2nd Impression				
Alloy	Exposure	Diagonal	Depth	Diagonal	Depth	Diagonal	Depth	
Incoloy 800	Before	0.96[c]	0.14[d]	1.11	0.16	1.09	0.16	173
	After	0.98[c]	e	1.10		1.09		ND[f]
Incoloy 800 (Al)[g]	Before	1.03	0.15	1.04	0.15	1.14	0.16	164
	After	1.01		1.03		1.07		ND
Inconel 601	Before	1.11	0.16	1.10	0.16	1.09	0.16	154
	After	1.12		1.10		1.03		ND
310 SS	Before	1.03	0.15	1.03	0.15	1.03	0.15	175
	After	1.04		1.01		1.01		ND
310 SS (Al)[g]	Before	0.97	0.14	0.97	0.14	0.99	0.14	196
	After	0.89		0.87		0.98		ND
RA-333	Before	0.94	0.13	0.95	0.14	0.94	0.13	208
	After	0.98		0.98		0.95		ND
309 SS	Before	1.08	0.15	1.06	0.15	1.05	0.15	166
	After	1.06		1.03		1.03		ND
446 SS	Before	0.99	0.14	0.99	0.14	0.99	0.14	190
	After	0.94		0.92		0.97		ND
Inconel 671	Before	0.83	0.12	0.84	0.12	0.83	0.12	267
	After	0.82		0.82		0.82		ND
Crutemp 25	Before	1.12	0.16	1.10	0.16	1.11	0.16	151
	After	1.10		1.07		1.08		ND
Haynes 188	Before	0.87	0.12	0.88	0.13	0.87	0.12	245
	After	0.87		0.88		0.86		ND

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[a] Char from Western Kentucky coal prepared by COED process, -20 + 40 mesh (840 to 420 μm).

[b] Alloy samples 1 x 1 x 1/4 in were subjected to erosion in coal gasification atmosphere at 1500 °F, gas velocity 100 fps, for 50 hr, at atmospheric pressure; input gas composition in volume %, 12% CO_2, 18 % CO, 24% H_2, 5% CH_4, 1% NH_3, 1.0% H_2S, balance H_2O.

[c] Average of both diagonals.

[d] Calculated by dividing average diagonal by 7.

[e] Computation of depth after exposure from the exposed hardness impression diagonals would not be meaningful and is not made.

[f] [illegible]

[g] [illegible]

EFFECT OF TEMPERATURE AND COAL GASIFICATION ATMOSPHERE[a] ON THE ROCKWELL HARDNESS[b] OF SOME ALLOYS[10]

erial dition/ treatment[c]	Base Metal[d] Average Hardness	Base Metal[d] Hardness Range	Weld Metal[e] Average Hardness	Weld Metal[e] Hardness Range	Base Metal[d] Average Hardness	Base Metal[d] Hardness Range	Weld Metal[e] Average Hardness	Weld Metal[e] Hardness Range
	INCOLOY 800H[f]				INCOLOY 800H Al[g]			
Received & Welded	71 B	60-82 B	25 C	21-27 C	72 B	69-77 B	78 B	73-81 B
, 1200 °F	83 B	81-86 B	48 C	46-50 C	78 B	76-81 B	32 C	22-35 C
[a], 1200 °F	74 B	50-86 B	47 C	41-51 C				
, 1500 °F	78 B	72-84 B	31 C	24-37 C	75 B	68-82 B	28 C	24-31 C
, 1800 °F	70 B	66-74 B	89 B	82-94 B	75 B	68-86 B	25 C	23-27 C
	310 STAINLESS STEEL[h]				RA 333[i]			
Received & Welded	74 B	66-79 B	83 B	71-88 B	87 B	85-91 B	90 B	83-92 B
r, 1200 °F	77 B	65-83 B	93 B	89-97 B	88 B	83-92 B	98 B	94-100 B
A, 1200 °F	82 B	80-87 B	96 B	95-99 B	93 B	92-95 B	22 C	20-24 C
r, 1500 °F	83 B	78-85 B	95 B	95-96 B	98 B	97-98 B	99 B	99-100 B
r, 1800 °F	74 B	73-75 B	82 B	80-84 B	88 B	80-90 B	88 B	87-90 B
	HAYNES 188[j]				INCO 657[k]			
Received & Welded	22 C	92 B-27 C	21 C	20-22 C	21 C	20-22 C	27 C	19-31 C
r, 1200 °F	27 C	95 B-30 C	27 C	26-30 C	47 C	43-51 C	53 C	50-55 C
A, 1200 °F	30 C	26-33 C	30 C	27-32 C	48 C	44-50 C	50 C	42-53 C
r, 1500 °F	31 C	30-35 C	34 C	34-35 C	38 C	34-41 C	41 C	38-42 C
r, 1800 °F	24 C	24-24 C	22 C	20-24 C	96 B	85-99 B	23 C	21-25 C

GA = coal gasification atmosphere; input gas at 450 °F in mole percent, 12% CO_2, 18% CO, 24% H_2, 39.5% H_2O, % CH_4, 1% NH_3, 0.5% H_2S.

ll tests were conducted at ambient temperature on charpy impact specimens.

retreatment consisted of exposure to high temperatures for 1000 hours in air at 1 atm or in CGA at 68 atm (1000 psi).

welve measurements made per alloy condition (2 each on 3 base metal specimens and 2 each on base metal portions f specimens containing weldments).

ix measurements made per alloy condition (2 each on weld metal portion of specimens containing weldments).

ncoloy 800H Heat No. HH7131A, 1-in thick plate with double-V weld joint; root passes made with 1/8-in dia. etrode 50-50 Nb rod (Batch No. 030171D); subsequent passes made with 5/32-in dia. Metrode 50-50 Nb rod (Batch o. 082671A).

ncoloy 800H Heat No. HH7131A, 1-in thick plate with double-V weld joint; root passes made with 1/8-in dia. etrode 50-50 Nb rod (Batch No. 030171D); subsequent passes made with 5/32-in dia. Metrode 50-50 Nb rod (Batch o. 082671A). Aluminum coating applied by pack diffusion process to notched impact specimens by Alon Processing, nc. (Alonized).

ype 310 SS Heat No. 24569, 1-in thick plate with double-V weld joint; root passes made with 1/8-in dia. Type 310 od (Heat No. 74707); subsequent passes made with 3/16-in dia. Type 310 rod (Heat No. 72733).

A 333 Heat No. 24777, 1-in thick plate with double-V weld joint; all passes made with 5/32-in. dia. RA 333 rod Heat No. 200-217617).

aynes 188 Heat No. 1880-6-1531, 1-in thick plate with double-V weld joint; root passes made with 1/16-in dia. aynes 188 wire (Heat No. 1880-3-1668); subsequent passes made with 1/8-in. dia. Haynes 188 wire (Heat No. 880-2-1408).

NCO 657 Heat No. 19-77-20, centrifugally cast pipe, 1-in wall thickness, single-V weld joint; welded with 5/32-in ia. Metrode 50-50 Nb rod (Batch No. 050761).

CHARPY V-NOTCH IMPACT TEST[a] RESULTS FOR ALLOYS SUBJECTED TO HIGH TEMPERATURE AND COAL GASIFICATION ATMOSPHERE[b][10]

Material Condition/ Pretreatment[c]	INCOLOY 800H[d]		INCOLOY 800H Al[e]		310 SS[f]	
	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in
As Received	204 +[g]	0.093[g]	173.3	0.061	88.3	0.070
Air, 1200 °F	134.0	0.076	117.5	0.059	76.8	0.065
CGA[b], 1200 °F	117.3	0.076			74.5	0.061
Air, 1500 °F	166.0	0.069	106.3	0.051	24.7	0.019
Air, 1800 °F	74.0	0.062	134.5	0.061	87.2	0.060

	RA 333[h]		HAYNES 188[i]		INCO 657[j]	
	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in
As Received	43.3	0.040	68.2	0.049	8.7	0.007
Air, 1200 °F	19.5	0.019	30.7	0.025	1.2	0.000
CGA, 1200 °F	20.7	0.019	32.2	0.024	1.0	0.000
Air, 1500 °F	7.5	0.005	7.5	0.004	1.5	0.000
Air, 1800 °F	47.8	0.037	47.2	0.027	2.0	0.002

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[a] Tests conducted in air at 1 atm and 80 °F; values are the average of results for three specimens.

[b] CGA = coal gasification atmosphere; input gas at 450 °F in mole percent, 12% CO_2, 18% CO, 24% H_2, 39.5% H_2O, 5% CH_4, 1% NH_3, 0.5% H_2S.

[c] Pretreatment consisted of exposure to high temperatures for 1,000 hours in air at 1 atm or in coal gasification atmosphere at 68 atm (1000 psi).

[d] Incoloy 800H Heat No. HH7131A, 1-in thick plate.

[e] Incoloy 800H Heat No. HH7131A, 1-in thick plate. Aluminum coating applied by pack diffusion process to notched impact specimens by Alon Processing, Inc. (Alonized).

[f] Type 310 SS Heat No. 24569, 1-in thick plate.

[g] Specimens did not break.

[h] RA 333 Heat No. 24777, 1-in thick plate.

[i] Haynes 188 Heat No. 1880-6-1531, 1-in thick plate.

CHARPY V-NOTCH IMPACT TEST[a] RESULTS FOR WELDED ALLOYS SUBJECTED TO HIGH TEMPERATURE AND COAL GASIFICATION ATMOSPHERE[b] [10]

	WELDED 800H[d]		WELDED 800H Al[e]		WELDED 310 SS[f]	
Material Condition/ Pretreatment[c]	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in
As Welded	3.8	0.002	2.7	0.001	69.3	0.064
Air, 1200 °F	1.3	0.001	2.7	0.002	28.3	0.030
CGA[b], 1200 °F	3.5	0.004	---	-----	16.2	0.013
Air, 1500 °F	2.7	0.002	2.5	0.001	3.3	0.003
Air, 1800 °F	3.2	0.004	2.0	0.002	23.0	0.023

	WELDED RA 333[g]		WELDED HAYNES 188[h]		WELDED INCO 657[i]	
Material Condition/ Pretreatment	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in	Impact Energy ft. lbs	Lateral Expansion in
As Welded	63.2	0.051	81.8	0.064	4.0	0.001
Air, 1200 °F	26.0	0.019	33.0	0.019	1.3	0.000
CGA, 1200 °F	22.5	0.015	38.2	0.024	1.0	0.001
Air, 1500 °F	4.2	0.002	4.7	0.004	1.3	0.000
Air, 1800 °F	14.2	0.016	20.7	0.016	2.5	0.001

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[a] Tests conducted in air at 1 atm and 80 °F; tests conducted on specimens with notch in weldment, parallel to weldment centerline; values are the average of results for three specimens.

[b] CGA = coal gasification atmosphere; input gas at 450 °F in mole percent, 12% CO_2, 18% CO , 24% H_2, 39.5% H_2O, 5% CH_4, 1% NH_3, 0.5% H_2S.

[c] Pretreatment consisted of exposure to high temperature for 1000 hours in air at 1 atm or in coal gasification atmosphere at 68 atm (1000 psi).

[d] Incoloy 800H Heat No. HH7131A, 1-in. thick plate with double-V weld joint; root passes made with 1/8-in. dia. Metrode 50-50 Nb rod (Batch No. 030171D); subsequent passes made with 5/32-in. dia. Metrode 50-50 Nb rod (Batch No. 082671A).

[e] Incoloy 800H Heat No. HH7131A, 1-in. thick plate with double-V weld joint; root passes made with 1/8-in. dia. Metrode 50-50 Nb rod (Batch No. 030171D); subsequent passes made with 5/32-in. dia. Metrode 50-50 Nb rod (Batch No. 082671A). Aluminum coating applied by pack diffusion process to notched impact specimens by Alon Processing, Inc. (Alonized).

[f] Type 310 SS Heat No. 24569, 1-in. thick plate with double-V weld joint; root passes made with 1/8-in. dia. Type 310 rod (Heat No. 74707); subsequent passes made with 3/16-in dia. Type 310 rod (Heat No. 72733).

[g] RA 333 Heat No. 24777, 1-in. thick plate with double-V weld joint; all passes made with 5/32-in. dia. RA 333 rod (Heat No. 200-217617).

[h] Haynes 188 Heat No. 1880-6-1531, 1-in. thick plate with double-V weld joint; root passes made with 1/16-in. dia. Haynes 188 wire (Heat No. 1880-3-1668); subsequent passes made with 1/8-in. dia. Haynes 188 wire (Heat No. 1880-2-1408).

[i] INCO 657 Heat No. 19-77-20, centrifugally cast pipe, 1-in. wall thickness, single-V weld joint; welded with 5/32-in. dia. Metrode 50-50 Nb rod (Batch No. 050761).

EFFECT OF TEST AND EXPOSURE TEMPERATURE[a] AND COAL GASIFICATION ATMOSPHERE[b] ON TENSILE PROPERTIES[c] OF SOME ALLOYS[10]

Material Condition/ Pretreatment[d]	Test Condition[e]	Incoloy 800H[f]				Incoloy 800H Al[g]				310 SS[h]			
		YS ksi	UTS ksi	El. %	RA %	YS ksi	UTS ksi	El. %	RA %	YS ksi	UTS ksi	El. %	R
as received	80 °F	31.1	83.1	48.0	71.9[i]	27.3	79.0	41.4	55.1	38.1	92.6	46.5	6
	1800 °F	8.7	11.2	94.2	86.8[i]	8.0	10.4	89.4	81.8	6.7	10.1	78.3	7
1200 °F, air	80 °F	35.1	90.3	34.7	47.4[i]	32.1	78.4	33.4	48.4	33.5	87.2	44.6	6
	1200 °F	26.7	60.2	31.2	37.2	20.7	54.3	32.0	30.8	23.3	52.1	39.8	5
1200 °F, CGA[b]	80 °F	40.8	93.0	31.0	36.2					33.4	86.6	33.8	5
1500 °F, air	80 °F	30.2	82.6	39.6	52.6	27.5	77.6	33.1[j]	45.4	32.6	86.2	34.9	3
	1500 °F	18.0	27.0	71.2	68.2	16.6	28.2	60.6	51.3	14.4	26.6	54.4	4
1800 °F, air	80 °F	24.6	81.3	37.7	41.9	26.4	74.1	18.6[j]	14.7[j]	27.6	84.5	40.4	4
	1800 °F	6.7	9.8	84.9	83.2	7.4	10.1	82.8	74.0	7.0	10.8	72.1	6

Material Condition/ Pretreatment[d]	Test Condition[e]	RA 333[k]				Haynes 188[l]				INCO 657[m]			
		YS ksi	UTS ksi	El. %	RA %	YS ksi	UTS ksi	El. %	RA %	YS ksi	UTS ksi	El. %	R
as received	80 °F	47.2	105.7	40.7	47.2[i]	67.6	147.1	52.0	54.3[i]	55.4	111.8	22.3	1
	1800 °F	10.3	15.6	89.0	78.4	19.6	28.6	71.5	79.0	15.3	20.2	31.9	4
1200 °F, air	80 °F	52.2	110.0	35.8	33.6	81.6	150.2	37.8	38.8	F[m]	125.1	0.0	
	1200 °F	34.4	77.0	42.7	46.8	52.6	114.6	40.3	39.7	99.2	136.2	1.4	
1200 °F, CGA	80 °F	63.2	103.5	19.4	21.2	76.6	142.4	31.4	26.8	F[m]	99.5	0.0	
1500 °F, air	80 °F	52.6	109.3	19.6	15.6	71.4	153.3	24.8	25.8	104.4	131.3	1.0	
	1500 °F	25.8	40.8	73.0	71.8	44.4	65.7	52.3	67.0	36.6	53.4	23.4	2
1800 °F, air	80 °F	38.0	94.9	34.2	26.0	60.4	142.2	42.2	45.4	71.4	112.2	4.9	
	1800 °F	11.3	14.2	89.6	82.7	17.4	25.6	56.0	79.7	14.6	18.8	33.0	3

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[a] Limited metallographic examination of fractured surfaces indicated that as-received specimens were in solution anne condition with little or no grain boundary precipitation. Massive grain boundary precipitates formed at 1200 and 1500°F during pretreatment; at 1800°F fewer precipitates formed and specimens approached the annealed condition.

[b] CGA = coal gasification atmosphere; input gas at 450 °F in mole percent, 12% CO_2, 18% CO, 24% H_2, 39.5% H_2O, 5% CH 1% NH_3, 0.5% H_2S.

[c] Specimens are ASTM standard, 0.505 in diameter, 2-in long gauge section; values reported are the average for duplic specimens except where otherwise marked.

[d] Pretreatment consisted of exposure for 1,000 hours to high temperatures in air at 1 atm or in coal gasification atmosphere at 68 atm (1000 psi).

[e] All tests were performed in air at the indicated temperatures.

[f] Incoloy 800H, 1-in thick plate, heat no. HH7131A.

[g] Incoloy 800H, 1-in thick plate, heat no. HH7131A; Al = aluminized coating applied by pack diffusion process to tens specimen by Alon Processing, Inc. (Alonized).

[h] Type 310 stainless steel, 1-in thick plate, heat no. 24569.

[i] All four properties are the average for three specimens.

[j] These values are for one specimen either because other specimen was damaged or because fracture occurred outside o gauge length.

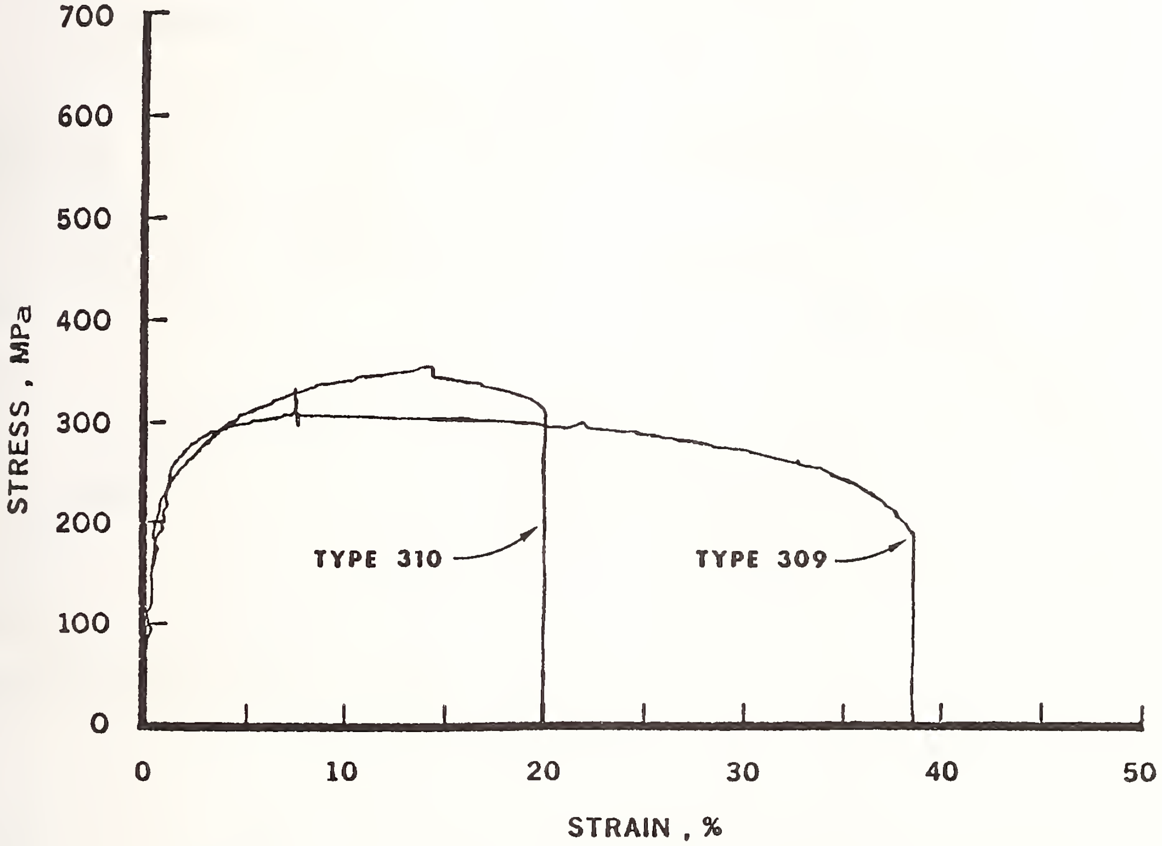
[k] RA 333, 1-in thick plate, heat no. 24777.

[l] Haynes 188, 1-in thick plate, heat no. 1880-6-1531.

[m] INCO 657, centrifugally cast pipe, 1-in wall thickness, heat no. 19-77-20.

[n] Specimen failed without yielding.

COMPARISON OF STRESS-STRAIN DATA[a] OF TYPES 309 AND 310 SS[25]



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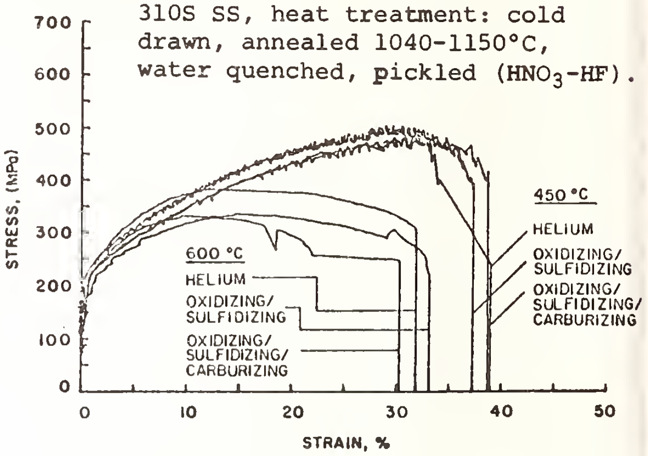
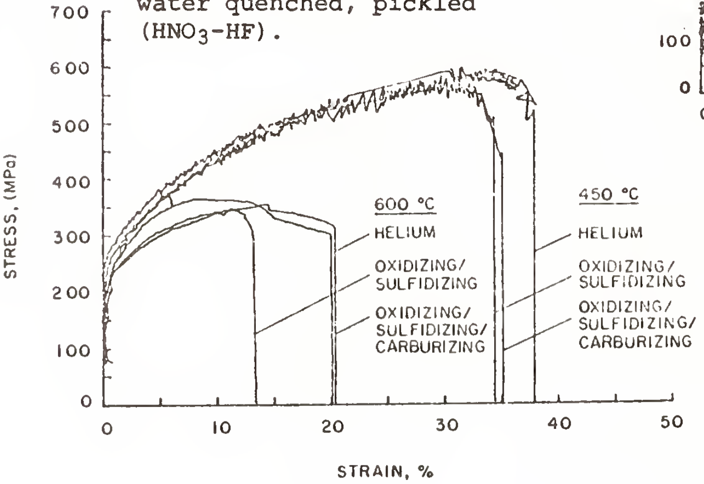
[a] Strain rate 1 x 10^{-6}/s; temperature 600°C (1100°F); atmosphere helium; alloy specimens were 9.5 mm diameter rods 58 cm long threaded to attach to universal couplings outside the test cell; central gauge section was 2.5 cm long and 4 mm in diameter, produced by machining, then polished with SiC papers and Crocus cloth , rinsed with acetone and alcohol and dried. Gas was introduced into the test cell and the temperature raised to the test value.

STRESS-STRAIN CURVES FOR VARIOUS ALLOYS TESTED[a] IN INERT AND COAL GASIFICATION ENVIRONMENTS[b] [25]

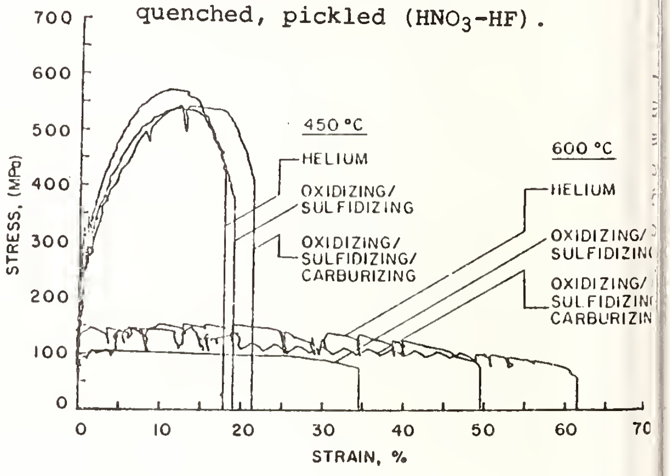
310S SS, heat treatment: cold drawn, annealed 1040-1150°C, water quenched, pickled (HNO_3-HF).



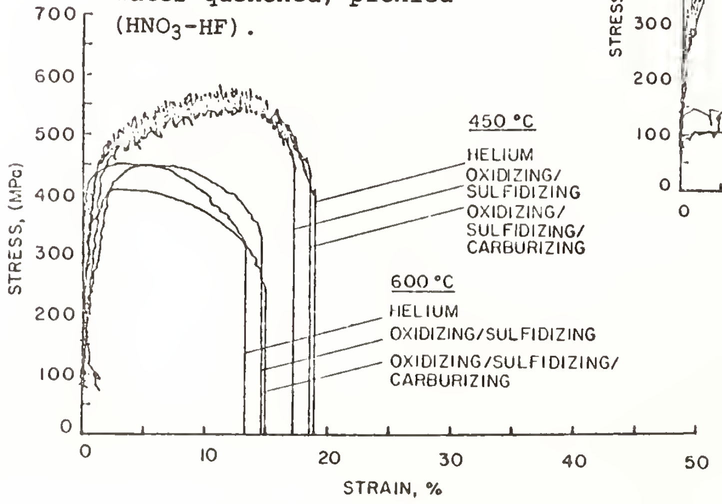
310 SS, heat treatment: cold drawn, annealed 1040-1150°C, water quenched, pickled (HNO_3-HF).



446 SS, heat treatment: cold drawn, annealed 790-870°C, water quenched, pickled (HNO_3-HF).



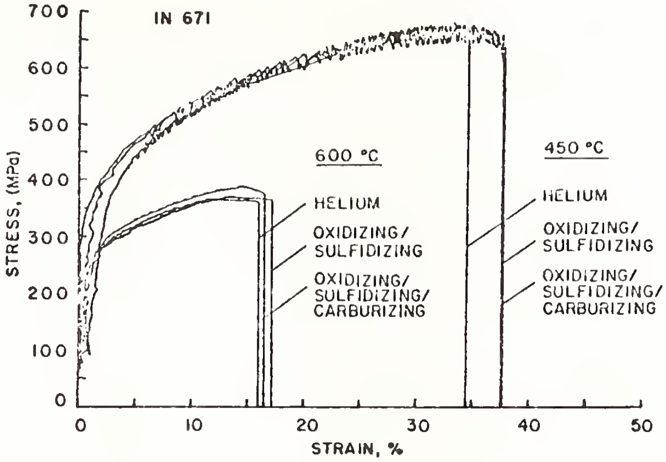
347 SS, heat treatment: cold drawn, annealed 980-1090°C, water quenched, pickled (HNO_3-HF).



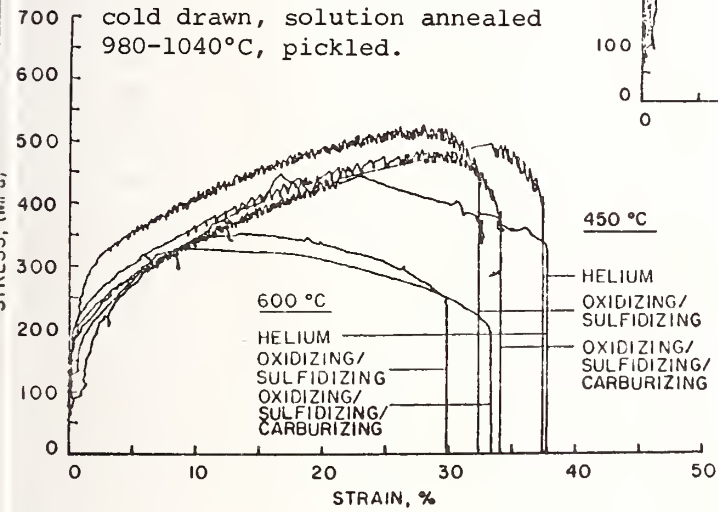
(Data Continued)

STRESS-STRAIN CURVES FOR VARIOUS ALLOYS TESTED[a] IN INERT AND COAL GASIFICATION ENVIRONMENTS[b] [25], Data Continued

Inconel 671, heat treatment:
cold drawn, solution annealed →
1150°C, pickled.



Incoloy 800, heat treatment:
cold drawn, solution annealed
980-1040°C, pickled.



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[a] Strain rate 1 x 10^{-6}/s, temperatures 450°C (850°F) and 600°C (1100°F); alloy specimens were 9.5 mm diameter rods 58 cm long threaded to attach to universal couplings outside the test cell; central gauge section was 2.5 cm long and 4 mm in diameter, produced by machining, then polished with SiC papers and Crocus cloth, rinsed with acetone and alcohol and dried.

[b] Gases were introduced into the test cell and the temperature raised to the test value; inert environment: helium; coal gasification environments:

	Oxidizing/Sulfidizing			Oxidizing/Sulfidizing/Carburizing		
	Input	Equilibrium		Input	Equilibrium	
	25 °C	450 °C	600 °C	25 °C	450 °C	600 °C
CO	11.6	1.2	9.2	26.0	1.1	12.5
CO_2	15.4	24.9	20.6	14.8	22.0	20.0
H_2	13.0	16.0	36.3	26.0	12.8	32.7
CH_4	10.0	12.5	2.9	10.0	11.2	5.5
H_2S	1.0	1.0	0.9	1.0	1.0	0.9
H_2O	49.0	44.4	30.3	22.2	34.3	19.4
C	--	--	--	--	17.6	9.0
log P_{O_2}		-28.995	-23.919		-29.026	-24.216
log P_{S_2}		-10.260	- 8.878		-10.086	- 8.751
log a_c		- 0.043	- 0.288		+ 0.017	+ 0.038

Pressure 1 atm for all environments.

MECHANICAL PROPERTIES OF ALLOYS TESTED AT VARIOUS STRAIN RATES AT 540°C (1000°F) IN HYDROGEN SULFIDE ATMOSPHERES[25]

Material	Strain Rate	Ultimate Tensile Strength[a]	Elongation[a]	Reduction in Area[a]	Environment
	s^{-1}	ksi	%	%	
310 SS[b,e]	1.3×10^{-4}	82	33.8	63.2[b]	H_2O/H_2S[c]
	7.8×10^{-5}	73	32.9	55.9	wet H_2S[d]
	5.5×10^{-5}	76	33.4	62.8	H_2O/H_2S
	7.2×10^{-6}	68.5	22.5	33.1	H_2O/H_2S
	3.9×10^{-6}	70	12.9	25.4	wet H_2S
	3.6×10^{-6}	69	23.7	30.2	H_2O/H_2S
	1.1×10^{-6}	68	17.2	18.4	wet H_2S
	8.4×10^{-7}	68	18.7	17.5	H_2O/H_2S
	1.9×10^{-7}	--	9.0	14.4	wet H_2S
310S SS[e]	1.3×10^{-4}	71.5	33.6	63.0	wet H_2S
	1.5×10^{-5}	71.6	34.5	62.6	wet H_2S
	7.3×10^{-6}	69	35.9	62.3	wet H_2S
	8.4×10^{-7}	63.1	34.8	50.1	wet H_2S
	1.2×10^{-7}	--	27.0	36.5	wet H_2S
347 SS[e]	1.3×10^{-4}	78.8	17.4	62.0	wet H_2S
	3.7×10^{-5}	78.1	15.5	63.1	wet H_2S
	7.3×10^{-6}	71.6	15.1	64.3	wet H_2S
	8.4×10^{-7}	75.6	14.5	55.4	wet H_2S
	8.4×10^{-7}	75.4	17.1	61.4	H_2O/H_2S
	1.2×10^{-7}	--	8.6	48.8	wet H_2S
Incoloy 800[b,e]	1.3×10^{-4}	--	32.8	68.8[b]	wet H_2S
	3.7×10^{-5}	--	33.5	65.3	wet H_2S
	7.3×10^{-6}	--	34.2	55.2	wet H_2S
	8.4×10^{-7}	--	32.0	49.9	wet H_2S
	1.7×10^{-7}	--	35.9	55.0	wet H_2S

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[a] Alloy specimens were 9.5 mm rods 58 cm long threaded to attach to universal couplings outside the test cell; central gauge sections were 2.5 cm long and 4 mm in diameter, produced by machining, then polished with SiC papers and Crocus cloth, rinsed with acetone and alcohol and dried; elongation was determined after fracture by gauge marks on the reduced section of the specimen.

[b] Heavy duplex oxide-sulfide scale formed on these alloys; because of the scale, the reduction in area values were calculated by determining the amount of metal lost on the surface of specimen outside of the reduced area and adding this amount to the diameter of unreacted metal in the reduced area remaining after the test.

[c] The gas was H_2S plus steam; gases were introduced into the test cell and the temperature raised to the test value.

[d] H_2S saturated at room temperature with water vapor.

[e] Heat treatments: 310 SS and 310S SS, cold drawn, annealed 1040-1150°C, water quenched, pickled (HNO_3-HF); 347 SS, cold drawn, annealed 980-1090°C, water quenched, pickled (HNO_3-HF); Incoloy 800, cold drawn, solution annealed 980-1040°C, pickled.
SEM examination of 310 SS: many surface cracks observed in the gauge section, approximately perpendicular to the stress axis, central region of primary fracture surface was ductile with flat outer rim corresponding to intergranular surface cracks, failure at the higher strain rates occurred by ductile shear, secondary shear cracks formed near the primary failure; 310S SS and 347 SS showed no intergranular cracking over the entire strain rate range.

BIAXIAL STRESS RUPTURE DATA[a] FOR TUBULAR ALLOY SPECIMENS IN AIR AND IN SIMULATED COAL GASIFICATION ATMOSPHERE[b][14]

Environment	Temperature K	Temperature °F	Hoop Stress[c] MPa	Hoop Stress[c] ksi	Hours to Rupture	Percent Strain Failure[d]	Percent Strain Maximum[e]
310 STAINLESS STEEL[f]							
Air, 1 atm	922	1200	188	27.3	3.9	2.1	-
	922	1200	122	16.2	158.9	2.6	2.8
	922	1200	124	18.0	99.1	2.0	-
CGA[b], 68 atm	922	1200	126	18.1	334.8	4.0	-
Air, 1 atm	1089	1500	62	9.1	11.7	2.5	-
	1089	1500	37	5.4	105.9	1.2	-
	1089	1500	38	5.5	99-166	1.9	-
	1089	1500	39	5.7	95.0	1.2	1.6
CGA, 68 atm	1072	1470	38.4	5.5	165	1.5	1.9
Air, 1 atm	1255	1800	13	1.8	106.2	3.2	3.8
	1255	1800	13	1.9	32.1	1.3	-
CGA, 68 atm	1255	1800	12.5	1.8	29.9	5	6.8
INCOLOY 800H[g]							
Air, 1 atm	922	1200	270	39.1	1.3	6.8[h]	-
	922	1200	227	32.9	55.8	3.2	4.1
	922	1200	234	34.0	66.6	1.4	-
	922	1200	217	31.5	110.7	2.5	-
CGA, 68 atm	922	1200	218	31.3	450.2	0.7	-
Air, 1 atm	1089	1500	101	14.6	12.6	11.2[h]	-
	1089	1500	68	9.8	474.0	2.3	-
CGA, 68 atm	1104	1530	87.3	12.5	9.0	0.8	-
Air, 1 atm	1255	1800	25	3.6	126.4	0.5	-
	1255	1800	26	3.7	207.6	0.5	-
CGA, 68 atm	1255	1800	17.7	2.5	16.0	1.6	2.3
INCOLOY 800H, Al[i]							
Air, 1 atm	922	1200	181	26.3	2.2	2.1	5.6
	922	1200	192	27.9	15.7	6.0	6.9
CGA, 68 atm	922	1200	183	26.2	7.8	3.9	-
Air, 1 atm	1089	1500	89.6	13.0	1.0	2.3	-
	1063	1455	71.7	10.4	232.7	6.0	7.3
	1063	1455	48.9	7.1	1201.5	2.0	3.1
CGA, 68 atm	1089	1500	62.6	9.0	29.8	3.4	-
Air, 1 atm	1255	1800	24.8	3.6	61.3	1.2	-
	1255	1800	23.5	3.4	49.7	2.1	-
CGA, 68 atm	1255	1800	22.8	3.3	14.0	3.2	-
INCO 657[j]							
Air, 1 atm	922	1200	201	29.2	112.7	1.0	-
	922	1200	208	30.1	64.9	1.0	-
CGA, 68 atm	922	1200	247	35.4	102.7	0.2	-
Air, 1 atm	1089	1500	139	20.2	4.6	2.6	-
	1089	1500	70.0	10.0	148.8	0.9	-
	1089	1500	76.5	11.7	74.9	1.0	-
CGA, 68 atm	1077	1480	78.9	11.3	87.9	1.0	-
Air, 1 atm	1255	1800	27.0	3.9	59.0	0.8	-
	1255	1800	24.4	3.5	79.2	0.8	-
CGA, 68 atm	1255	1800	>24.4[k]	3.5	13.9	1.1	1.8

(Table Continued)

BIAXIAL STRESS RUPTURE DATA[a] FOR TUBULAR ALLOY SPECIMENS IN AIR
AND IN SIMULATED COAL GASIFICATION ATMOSPHERE[b][14]

(Table Continued)

Environment	Temperature K	Temperature °F	Hoop Stress[c] MPa	Hoop Stress[c] ksi	Hours to Rupture	Percent Strain Failure[d]	Percent Strain Maximum[e]
HAYNES 188[l]							
Air, 1 atm	977	1300	305	44.3	67.0	11.3	13.8
	977	1300	291	42.2	113.3	17.9	18.9
CGA, 68 atm	1005	1350	237	33.9	45.3	1.0	6.5
Air, 1 atm	1089	1500	179	26.0	53.7	18.2	-
	1089	1500	159	23.1	122.7	14.2	-
CGA, 68 atm	1071	1470	166	23.8	35.3	5.0	-
Air, 1 atm	1255	1800	46	6.7	67.7	10.8	-
	1255	1800	49	7.1	74.5	12.0	12.7
CGA, 68 atm	1255	1800	38.6	5.5	13.2	0.3	-

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[a] Tubular specimens, approximately 1 cm in diameter by 11 cm long with the outside diameter of the central 7 c portion reduced to form a gauge section, were pressurized to measure the hundred-hour biaxial stress rupture strength. The stress imposed on the specimens by the greater internal pressure was calculated using the formula for thick-walled tubes. Argon was used to provide the internal pressure in the specimens and ruptur was measured by sensing a significant drop in specimen argon pressure.

[b] CGA = coal gasification atmosphere, input gas composition to the test pressure vessel, 12% CO_2, 18% CO, 24% 5% CH_4, 1% NH_3, 0.5% H_2S, balance H_2O; gas was added continuously to the reactor at the rate of ∿10 reactor volumes per hour.

[c] Maximum hoop stress at inner tube surface calculated for thick-wall tube.

[d] Diametric strain.

[e] Reported if maximum strain is greater than failure strain by 0.3%.

[f] Type 310 stainless steel, Heat No. 24569, Rolled alloys, 25.4 mm (1 in.) plate, hot rolled, annealed and pic Tensile Strength 586 MPa (85,000 psi), Yield Strength (0.2%) 259 MPa (37,600 psi), % Elong. 51, % RA 64, Hardness BHN 179. Metallographic examination showed that the rupture hole was in an area of banding (lower content) in the wall in the as-received plate; it is not possible to characterize the pinhole cracks as eith intergranular or transgranular.

[g] Incoloy 800H, Heat No. 1HH7131A3 - Lot P 90380, Huntington Alloys, 25.4 mm (1 in.) plate, hot rolled, descal solution annealed; Hardness R_B 84. Rupture was always a longitudinal irregular crack. At 1089 K and below the rupture usually finished as a transgranular crack with high local strain; at 1255K it remained intergran Sulfidation in high temperature CGA test shortened rupture life by reducing tube wall thickness.

[h] Local ballooning.

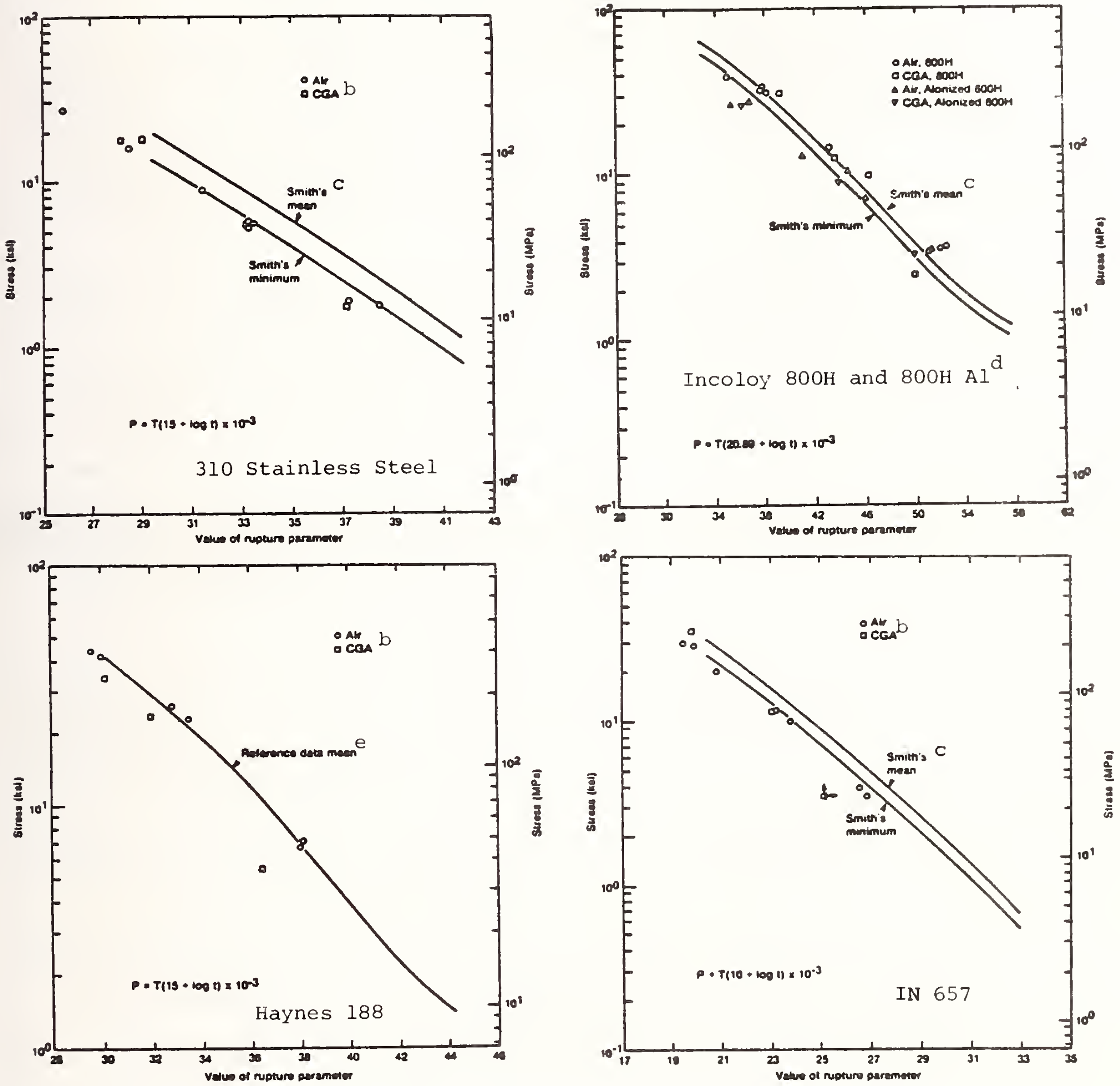
[i] Incoloy 800H alonized; aluminum coating applied to the outside diameter of the gauge section of specimens by diffusion process by Alon Processing Inc. Cause of data scatter was apparently the variation in coating thi metallographic examination showed two external surface layers; outer layer was very brittle, with cracks whi not penetrate the inner layer.

[j] Inconel 657, Heat No. 19-77-20, Duraloy Blaw-Knox, pipe, 6-5/8 in OD x 4-5/8 in ID as-cast; specimen prepare from the center of the pipe wall, specimen axis parallel to pipe axis. Some interdendritic porosity found i specimen walls; specimens often failed at more than one location.

[k] During the last 4.5 hours of test the stress gradually increased to approximately 32 MPa due to pressure dro outside the specimen.

[l] Haynes 188, Heat No. 1880-6-1531, Stellite Division, Cabot, 25 mm (1 in.) plate, hot rolled, solutionized; Yi Strength (0.2%) 490 MPa (71,000 psi), Tensile Strength 1020 MPa (148,000 psi), % Elong. in 4D 50.0.

VARIATION OF BIAXIAL STRESS RUPTURE[a] PARAMETER FOR SEVERAL ALLOYS IN AIR AND IN COAL GASIFICATION ATMOSPHERE[b] [14]



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[a] Biaxial stress rupture data plotted are those data reported in the preceding table. The rupture parameter is an empirical approach developed to treat stress-to-rupture which is dependent on both time and temperature. The rupture parameter, P, equals the absolute temperature (in °R) multiplied by a constant plus the log of the rupture time in hours.

[b] CGA = coal gasification atmosphere; see the footnotes in the preceding table.

[c] Lines drawn are average and minimum values from plots of the available uniaxial stress rupture from several heats of each alloy. The minimum lines show the statistical value above which 95% of the available data were located (G.V. Smith, "The Elevated Temperature Yield, Tensile and Rupture Strengths of Nine Alloys of Interest for Coal Gasification," Draft to Metal Properties Council Phase V Task Force Members, January 1977).

[d] Aluminum coating applied by pack diffusion process by Alon Processing Inc. (Alonized).

[e] The mean line is from limited uniaxial data compiled by R.M. Horton.

ALLOYS AND ENVIRONMENTAL CONDITIONS REQUIRED FOR CRACKING AS DETECTED BY SLOW STRAIN RATE TECHNIQUE[a] [25]

Alloy	Heat Treatment	Conditions and Results
Inconel 671	Cold drawn, solution annealed 1150°C, pickled.	At 450°C: in inert[b] atmospheres, no cracking; in CGA[c], shallow secondary cracking seen near primary fracture. At 600°C: no reactive environment needed; in inert and CGA, brittle fracture, internal cracking, many within an α-Cr phase or at the interface of α-Cr and matrix; α-Cr phase was temperature- and strain-induced.
310 SS	Cold drawn, annealed 1040-1150°C, water quenched, pickled (HNO_3-HF).	At 450°C: in inert (ultra-pure He) or reactive (CGA) atmospheres, no cracking. At 540°C: in helium, in vacuum, and in H_2, numerous intergranular cracks formed. At 600°C: minimal reactive environment needed; in He, CGA, and H_2S atmospheres, failure occurred through surface initiated intergranular cracking.
310S SS	Cold drawn, annealed 1040-1150°C, water quenched, pickled (HNO_3-HF).	At 450°C: in inert or reactive atmospheres, no cracking. At 540°C: in He and in vacuum, numerous intergranular cracks; in H_2S atmosphere, no cracks. At 600°C: minimal reactive environment needed; in He, CGA, and H_2S atmospheres, failure occurred through surface initiated intergranular cracking.
347 SS	Cold drawn, annealed 980-1090°C, water quenched, pickled (HNO_3-HF).	At 450°C: in inert or reactive atmospheres, no cracking. At 600°C: in He and oxidizing-sulfidizing-carburizing CGA, small shallow surface cracks at necked region of sample and next to fracture surface; in oxidizing-sulfidizing CGA, no cracks.
Incoloy 800	Cold drawn, solution annealed 980-1040°C, pickled.	At 450°C: in inert or reactive atmospheres, no cracking. At 600°C: reactive environment needed for cracking; in He, no cracking; in CGA shallow surface cracking occurred.

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[a] Alloy specimens were 9.5 mm rods 58 cm long threaded to attach to universal couplings outside the test cell; central gauge sections were 2.5 cm long and 4 mm in diameter, produced by machining, then polished with SiC papers and Crocus cloth, rinsed with acetone and alcohol and dried; strain rate $1x\ 10^{-6}/s$.

[b] Inert atmosphere usually helium, 310 SS also tested in argon; gases apparently had very small amounts of oxygen and/or water included.

[c] CGA = coal gasification atmosphere; gases were introduced into the test cell and the temperature raised to the test value:

	Oxidizing/Sulfidizing			Oxidizing/Sulfidizing/Carburizing		
	Input	Equilibrium		Input	Equilibrium	
	25 °C	450 °C	600 °C	25 °C	450 °C	600 °C
CO	11.6	1.2	9.2	26.0	1.1	12.5
CO_2	15.4	24.9	20.6	14.8	22.0	20.0
H_2	13.0	16.0	36.3	26.0	12.8	32.7
CH_4	10.0	12.5	2.9	10.0	11.2	5.5
H_2S	1.0	1.0	0.9	1.0	1.0	0.9
H_2O	49.0	44.4	30.3	22.2	34.3	19.4
C	--	--	--	--	17.6	9.0
log P_{O_2}		-28.995	-23.919		-29.026	-24.216
log P_{S_2}		-10.260	- 8.878		-10.086	- 8.751
log a_C		- 0.043	- 0.288		+ 0.017	+ 0.038

Pressure 1 atm for all environments.

EFFECT OF EXPOSURE[a] TO A HIGH VOLATILE BITUMINOUS A COAL[b] FLUE GAS ON THE HARDNESS OF SOME ALLOYS[17]

Material	Average Temperature °F	Midwall Hardness HRB	Midwall Hardness HRC
316 SS	As-received	89	
	1100	90	
	1150	96	
	1200	89	
	1330	84	
	1340	89	
310 SS	As-received	88	
	1000	86	
	1100	87	
	1110	88	
	1150	83	
	1200	89	
	1390	84	
	1420	86	
12R72	As-received	83	
	1150	84	
	1200	85	
	1240	88	
	1360	81	
	1370	79	
	1580	78	
Incoloy 802	As-received	87	
	1450	80	
	1600	78	
Inconel 617	As-received	94	
	1410	99	
	1625	92	
Haynes 188	As-received	99	
	1425	100	
	1617	96	
	1700	96	
Inconel 671 clad on Incoloy 800		Base	Clad
	As-received	77	40
	1170	83	42
	1200	87	36
	1400	75	36
	1440	72	36
	1600	66	33
	1700	54	31

---

[a] Exposure was for 300 hours in the high temperature superheater section of a laboratory solid fuel burning test facility. Sample pipe sections (1 in long, 1.5 in diameter, 0.25 in wall thickness) were threaded and tandem mounted to form an air-cooled probe.

[b] Eastern bituminous high volatile A coal, nominal HHV 12280, ash 18%, sulfur 1%, and moisture 0.4% by weight.

EFFECT OF EXPOSURE[a] TO THE FLUE GASES OF SEVERAL COALS ON THE HARDNESS OF SEVERAL ALLOYS[17]

		Exposure Conditions		Exposure Effects		
				Depth of Attack	Midwall Hardness	
Material	Coal Feedstock[b]	Temperature (°F)[c]	Hours	Mils	HRB	HRC
316 SS	(not exposed)	ambient	0	0	78	
	Subbitum. C	1258	3144	3.1	80	
		1037	3672	1.0	87	
	HV Bitum. C	1310	3672	2.5	73	
		1264	4104	2.8	73	
	HV Bitum. A	1195	3720	1.7	83	
		1098	7008	2.7	86	
	Lignite A	1258	4180	1.7	82	
		1290	4680	2.0	79	
310 SS	(not exposed)	ambient	0	0	89	
	Subbitum. C	1344	3144	2.2	84	
		1000	3672	None	85	
		1215	7368	1.5	74	
		800	7368	2.0	74	
	HV Bitum. A	960	3552	0.4	89	
		1188	3720	0.6	90	
		873	6504	1.2	92	
		1089	7008	0.4	91	
	HV Bitum. C	1131	2905	0.7	90	
		1254	4104	0.5	85	
		1302	7008	1.9	84	
	Lignite A	1272	4180	1.1	85	
		1290	4680	1.7	85	
12R72	(not exposed)	ambient	0	0	80	
	Subbitum. C	1300	3144	Excessive	68	
		1170	3672	5.0	78	
	HV Bitum. C	1302	4104	Excessive	68	
	HV Bitum. A	1151	3720	2.3	83	
		1125	7008	3.1	83	
	Lignite A	1249	4180	2.5	74	
		1477	4680	5.5	68	
Incoloy 800	(not exposed)	ambient	0	0	72	
	Subbitum. C	1277	3144	4.3	75	
		1343	3144	2.6	71	
		1145	3672	2.0	77	
		7368	7368	4.5	72	
	HV Bitum. A	995	3552	0.7	71	
		1209	3720	1.7	77	
		974	6504	0.9	82	
		1115	8081	4.0	76	
	HV Bitum. C	1463	2350	2.5	71	
		1115	2350	2.5	72	
		1284	4104	4.0	65	
	Lignite A	1001	600	2.0	74	
		1001	4180	1.4	67	
		1365	4680	1.3	72	
Inconel 617	(not exposed)	ambient	0	0	89	
	Subbitum. C	1280	7368	2.7	83	
		700	7368	1.2	90	
		1188	7368	12.5	84	
		1138	7368	9.0	86	
	HV Bitum. A	933	3552	0.1	95	
		933	3552	0.9	99	
		994	3552	0.5	98	
		956	6478	0.4		26
	HV Bitum. C	1261	2950	2.7	91	
		1211	3672	0.4		24
	Lignite A	953	600	0.9	96	
Haynes 188	(not exposed)	ambient	0	0		23
	Subbitum. C	700	7368	0.6		27
		1293	7368	3.0		27
		1141	7368	2.5		29
		1201	7368	5.0		25
	HV Bitum. A	973	3552	0.5		34
		993	3552	0.7		32
		907	6478	6.7		32
	HV Bitum. C	671	1849	1.0		27
	Lignite A	1180	840	1.0		33
		1343	840	1.7		31

(Table Continued)

EFFECT OF EXPOSURE[a] TO THE FLUE GASES OF SEVERAL COALS ON THE HARDNESS OF SEVERAL ALLOYS[17]

(Table Continued)

		Exposure Conditions		Exposure Effects		
				Depth of Attack	Midwall Hardness	
Material	Coal Feedstock[b]	Temperature (°F)[c]	Hours	Mils	HRB	HRC
Inconel 671 Clad on Incoloy 800	(not exposed)	ambient	0	0		33
	Subbitum. C	1337	3672	severe		27
		1000	3672	severe		31
		1130	7368	severe		29
		1162	7368	severe, the clad/base metal interface also showed deterioration		11-27
	HV Bitum. A	1000	3552	0.4		35
		1000	3553	0.4		35
		1177	3720	1.1		31
		974	6478	0.2		30
	HV Bitum. C	1342	2950	3.5		35
		1230	3144	4.0		27
		1350	3144	4.0		26
		1166	3672	2.0		31
	Lignite A	1176	4180	0.1		29
		1243	4180	5.0		30
		1236	4180	Attack: 9.0 mil; cracks extending from surface to clad base interface, interface very irregular		32
		1440	4680	severe		30

---

[a] Tests consisted of exposure of 28 pipe sections, 2 in O.D. x 1.5 in long, threaded into each other to form a probe. The exterior surface of the probe was exposed to combustion products and the interior surface temperature was controlled with air. The exposures were carried out in coal-fired commercial steam generators.

[b] Subbitum. C = Western subbituminous C coal, nominal HHV 7780, 24.5% ash, 0.4% sulfur and 7.2% moisture by weight; HV Bitum. A = Eastern bituminous high volatile A coal, nominal HHV 12280, 18% ash, 1% sulfur, and 0.4% moisture by weight; HV Bitum. C = Illinois No. 6 bituminous high volatile C coal, nominal HHV 10430, 10.7% ash, 3% sulfur and 15.9% moisture by weight; Lignite A = Texas Lignite A, nominal HHV 7010, 9.8% ash, 0.7% sulfur and 33.8% moisture by weight.

[c] Average value of temperature in the range to which the samples were exposed.

HARDNESS OF SEVERAL WELD/BASE METAL COMBINATIONS AFTER EXPOSURE[a] TO THE FLUE GASES OF FOUR COALS[17]

Weld Composition		Coal Feedstock[b]	Exposure Conditions		Weld Hardness		Weld Quality[c]
Base Metals Joined	Weld Material		Avg. Temp. °F	Time Hrs.	HRB	HRC	
316 SS/ Inconel 800	Inconel 82 & Inconel 617[d]	Subbitum. C	1000	3672	87		
		HV Hitum. A	1106	8081	88		[Lack of peneti at root]
		HV Bitum. C	1202	4680	84		
		Lignite A	1244	4180	86		[Lack of peneti at root]
Incoloy 800/ Inconel 617	Inconel 82 & Inconel 617[d]	Subbitum. C	1280	7468		26	[Lack of penetr at root]
		HV Bitum. A	994	3552		26	[Lack of penetr at root]
Incoloy 800/ Inconel 617	Inconel 82	Subbitum. C	800	7368		28	[Lack of peneti at root]
		HV Bitum. A	956	6478	92		[Lack of penetr at root]
Inconel 671 clad on Incoloy 800/ Incoloy 800	Inconel 82	HV Bitum. C	1230	4680	89		porosity and co shuts, [lack of tration at root
		Lignite A	1244	4180	88		porosity and co shuts, [crack at
		Subbitum. C	1240	3672	86		porosity and co shuts
		HV Bitum. A	1122	8081	84		porosity and co shuts, [lack of tration at root
Incoloy 800/ Haynes 188	Inconel 82	Subbitum. C	800	7368		24	[Lack of penetra at root]
		HV Bitum. A	947	6478	96		[Lack of penetra at root]

[a] Tests consisted of exposure of 28 pipe sections, 2 in O.D. x 1.5 in long, threaded into each other to form a probe. The exterior surface of the probe was exposed to combustion products and the interior surface temperature was controlled with air. The exposures were carried out in coal-fired commercial steam generators.

[b] Subbitum. C = Western subbituminous C coal, nominal HHV 7780, 24.5% ash, 0.4% sulfur and 7.2% moisture by weight; HV Bitum. A = Eastern bituminous high volatile A coal, nominal HHV 12280, 18% ash, 1% sulfur, and 0.4% moisture by weight; HV Bitum. C = Illinois No. 6 bituminous high volatile C coal, nominal HHV 10430, 10.7% ash, 3% sulfur and 15.9% moisture by weight; Lignite A = Texas Lignite A, nominal HHV 7010, 9.8% ash 0.7% sulfur and 33.8% moisture by weight.

[c] Observations made on sections after exposure.

[d] Both used as the weld metal in one weld.

EFFECT OF COAL GASIFICATION ENVIRONMENTS[a] AND TEMPERATURE ON THE MECHANICAL PROPERTIES[b] AND FRACTURE MODE OF ALLOYS TESTED BY SLOW STRAIN RATE TECHNIQUE[c] [25]

RIAL	Helium[d]		Oxidizing-Sulfidizing Gas[a]		Oxidizing-Sulfidizing-Carburizing Gas[a]	
	450°C(840°F)	600°C(1100°F)	450°C(840°F)	600°C(1100°F)	450°C(840°F)	600°C(1100°F)
Stainless Steel[e]						
S (MPa)	602	368	581	347	598	362
(ksi)	87.3	53.4	84.2	50.3	87.6	52.5
long. %	37.9	19.9	35.4	14.0	35.6	19.9
%	64.6	28.8	55.1	21.6	60.2	23.4
racture Mode	ductile failure	intergranular secondary cracking	ductile failure	intergranular secondary cracking	ductile failure	intergranular secondary cracking
S Stainless Steel[e]						
TS (MPa)	518	437	519	376	513	336
(ksi)	75.1	63.4	75.2	54.5	74.4	48.7
long. %	38.9	31.9	38.6	32.8	38.8	30.3
A %	65.1	42.8	65.1	43.9	69.9	33.8
racture Mode	ductile failure	intergranular secondary cracking	ductile failure	intergranular secondary cracking	ductile failure	intergranular secondary cracking
Stainless Steel[f]						
TS (MPa)	568	451	591	460	590	426
(ksi)	82.3	65.3	85.7	66.6	85.5	61.7
long. %	18.8	13.4	17.0	14.5	18.4	14.8
A %	65.2	52.2	60.2	46.0	59.7	58.3
racture Mode	ductile failure	secondary cracking, path not determined	ductile failure	ductile failure	ductile failure	secondary cracking, path not determined
Stainless Steel[e]						
TS (MPa)		334				--
(ksi)		48.4				--
long. %		37.7				36.5
RA %		69.2				62.7
racture Mode		secondary cracking, path not determined[g]				secondary cracking, path not determined[g]
Stainless Steel[h]						
UTS (MPa)	586	152	552	109	574	160
(ksi)	85.0	22.0	80.0	15.8	83.2	23.2
Elong. %	17.3	62.0	19.3	34.7	21.0	49.5
RA %	57.0	86.2	61.4	88.3	58.0	83.3
Fracture Mode	ductile failure	secondary cracking, path not determined	secondary cracking, path not determined[g]	secondary cracking, path not determined[i]	secondary cracking, path not determined[g]	secondary cracking, path not determined[i]
coloy 800[j]						
UTS (MPa)	526	467	544	368	551	353
(ksi)	76.2	67.7	78.9	53.4	79.8	51.1
Elong. %	37.3	37.1	32.6	29.4	34.3	32.7
RA %	72.1	60.1	65.8	49.4	70.5	61.7
Fracture Mode	ductile failure	secondary cracking, path not determined	ductile failure	secondary cracking, path not determined	ductile failure	secondary cracking, path not determined

(Table Continued)

EFFECT OF COAL GASIFICATION ENVIRONMENTS[a] AND TEMPERATURE ON THE MECHANICAL PROPERTIES[b] AND FRACTURE MODE OF ALLOYS TESTED BY SLOW STRAIN RATE TECHNIQUE[c] [25]

(Table Continued)

MATERIAL	Helium[d]		Oxidizing-Sulfidizing Gas[a]		Oxidizing-Sulfidizing-Carburizing	
	450°C(840°F)	600°C(1100°F)	450°C(840°F)	600°C(1100°F)	450°C(840°F)	600°C(1100
Inconel 671[k]						
UTS (MPa)	680	416	670	397	676	448
(ksi)	98.6	60.3	97.1	57.6	97.9	64.9
Elong. %	32.8	16.1	38.6	17.5	38.0	16.3
RA %	37.7	16.3	45.3	20.7	39.3	16.8
Fracture Mode	ductile failure	secondary cracking, path not determined[l]	secondary cracking, path not determined[m]	secondary cracking, path not determined[l]	secondary cracking, path not determined[m]	secondary cracking, path not determined[l]

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[a] Gases were introduced into the test cell and the temperature raised to the test value:

	Oxidizing/Sulfidizing Gas			Oxidizing/Sulfidizing/Carburizing Gas		
	Input	Equilibrium		Input	Equilibrium	
	1 atm, 25 °C	1 atm, 450 °C	1 atm, 600 °C	1 atm, 25 °C	1 atm, 450 °C	1 atm, 600 °C
CO	11.6	1.2	9.2	26.0	1.1	12.5
CO_2	15.4	24.9	20.6	14.8	22.0	20.0
H_2	13.0	16.0	36.3	26.0	12.8	32.7
CH_4	10.0	12.5	2.9	10.0	11.2	5.5
H_2S	1.0	1.0	0.9	1.0	1.0	0.9
H_2O	49.0	44.4	30.3	22.2	34.3	19.4
C	--	--	--	--	17.6	9.0
$\log P_{O_2}$		-28.995	-23.919		-29.026	-24.216
$\log P_{S_2}$		-10.260	- 8.878		-10.086	- 8.751
$\log a_c$		- 0.043	- 0.288		+ 0.017	+ 0.038

[b] Alloy specimens were 9.5 mm rods 58 cm long threaded to attach to universal couplings outside the test cell; cer gauge sections were 2.5 cm long and 4 mm in diameter, produced by machining, then polished with SiC papers and C cloth, rinsed with acetone and alcohol and dried; elongation was determined after fracture by gauge marks on the duced section of the specimen.

[c] Strain rate for these data 1 x 10^{-6}/s.

[d] Tests performed in helium to provide a base line value.

[e] Heat treatment: cold drawn, annealed 1040-1150°C, water quenched, pickled (HNO_3-HF). Results of tests at strain 1 x 10^{-6}/s: in helium, 540°C (1000°F), UTS 414 MPa (50 ksi), RA 18%, intergranular cracking occurred; in air, 8 (1500°F), UTS 173 MPa (25 ksi), Elong. 11%, RA 14.5%, intergranular secondary cracking; in air, 1040°C (1900°F), 76 MPa (11 ksi), Elong. 41%, RA 21%, brittle fracture, many intergranular secondary cracks.

[f] Heat treatment: cold drawn, annealed 980-1090°C, water quenched, pickled (HNO_3-HF).

[g] Shallow cracking observed.

[h] Heat treatment: cold drawn, annealed 790-870°C, water quenched, pickled (HNO_3-HF).

[i] Cracks formed a mosaic pattern.

[j] Heat treatment: cold drawn, solution annealed 980-1040°C, pickled.

[k] Heat treatment: cold drawn, solution annealed 1150°C, pickled.

[l] Cracking shallow, primary fracture ductile.

[m] α-Cr phase found, apparently strain- and temperature-induced.

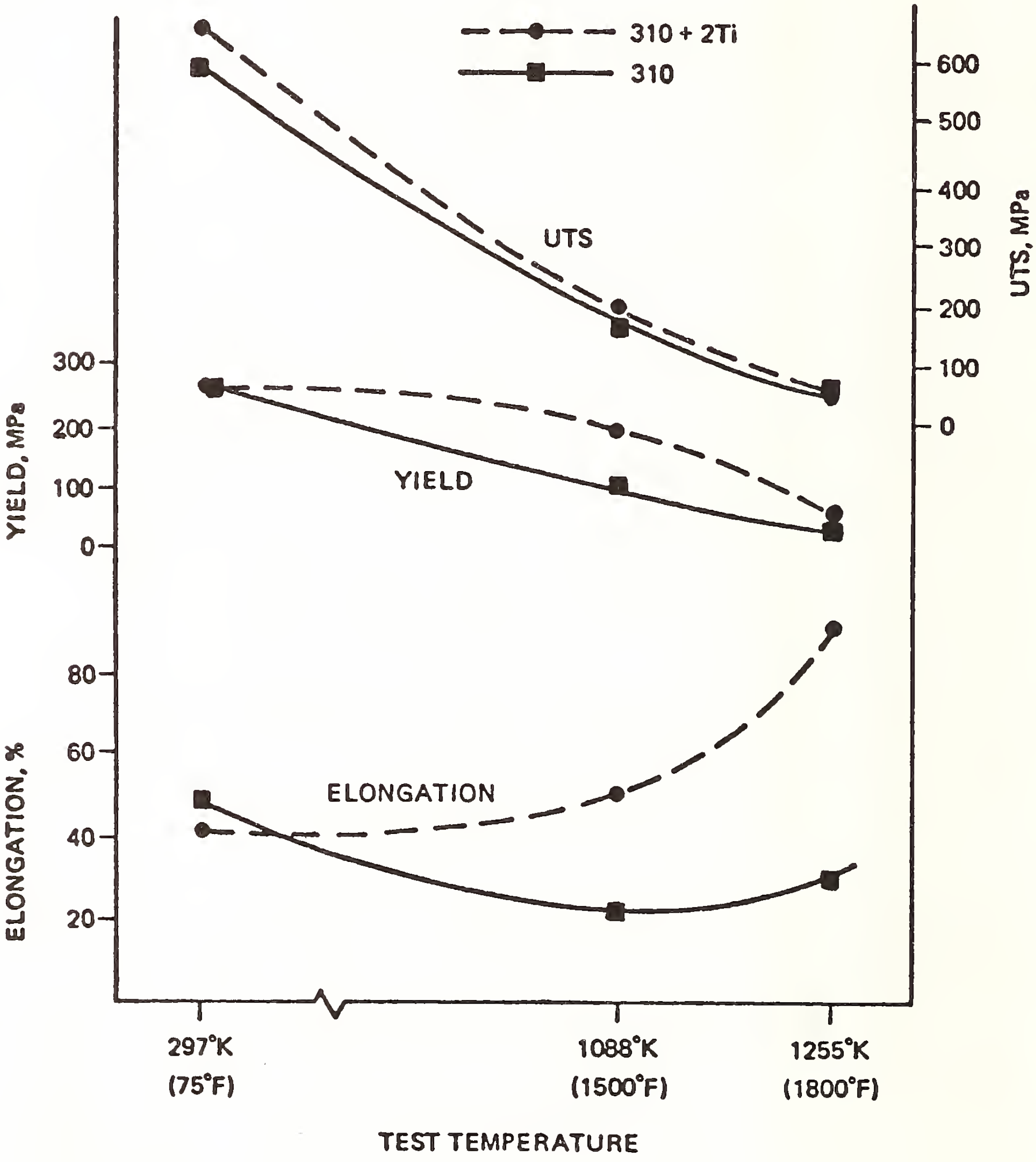
TENSILE PROPERTIES OF ALLOYS AFTER ELEVATED TEMPERATURE EXPOSURE[a] [31]

	Yield Strength, ksi			Ultimate Strength, ksi			Total Elongation, %			Reduction in Area, %		
Exposure--	none	1500 °F	1800 °F	none	1500 °F	1800 °F	none	1500 °F	1800 °F	none	1500 °F	1800 °F
Alloy[b]												
310 SS	46.7	46.5	37.7	75.9	86.4	70.1	14	15	14	28	14	22
Fe-25Cr-20Ni-3Ti	55.9	110	88.5	86.3	110	157.2	10	<1	24	4	0	24
233 (Fe-22Cr-23Ni-3Ti)	47.9	68.4	100.5	103.3	112.9	157.7	37	2	17	24	1	16
310 SS + 3Ti	66.1	96.0	102	87.4	112.8	121	8	<1	4	2	<1	<1
233 MS (Fe-23Ni-22Cr-3Ti-Mn-Si)	53.3	71.3	114.5	109.9	118.5	147.6	37	1	6	29	1	4
Nimonic 81 (M313)	65.6	62.3	70.9	124.7	127.7	130.0	40	33	30	27	24	25
Ni-30Cr-4Ti	120.5	90.2	88.3	181.5	149.0	155.0	24	11	23	21	10	21
Ni-30Cr-4Al	93.8	93.5	91.3	144.2	153.0	142.0	41	33	31	28	23	25

[a] Test procedure: Starting material, 0.5 in. x 0.5 in. x 3.0 in. blanks of each alloy were exposed at the indicated temperatures for 1000 hours in stagnant air. Tensile specimens with an 0.25 in. gauge diameter were machined from the blanks. All tensile tests performed in air at ambient temperatures.

[b] Experimental alloys prepared by addition to the indicated base alloy. 233 and 233 MS are modified versions of 310 SS.

EFFECT OF Ti ADDITION TO TYPE 310 STAINLESS STEEL[a] ON TENSILE PROPERTIES[b][31]



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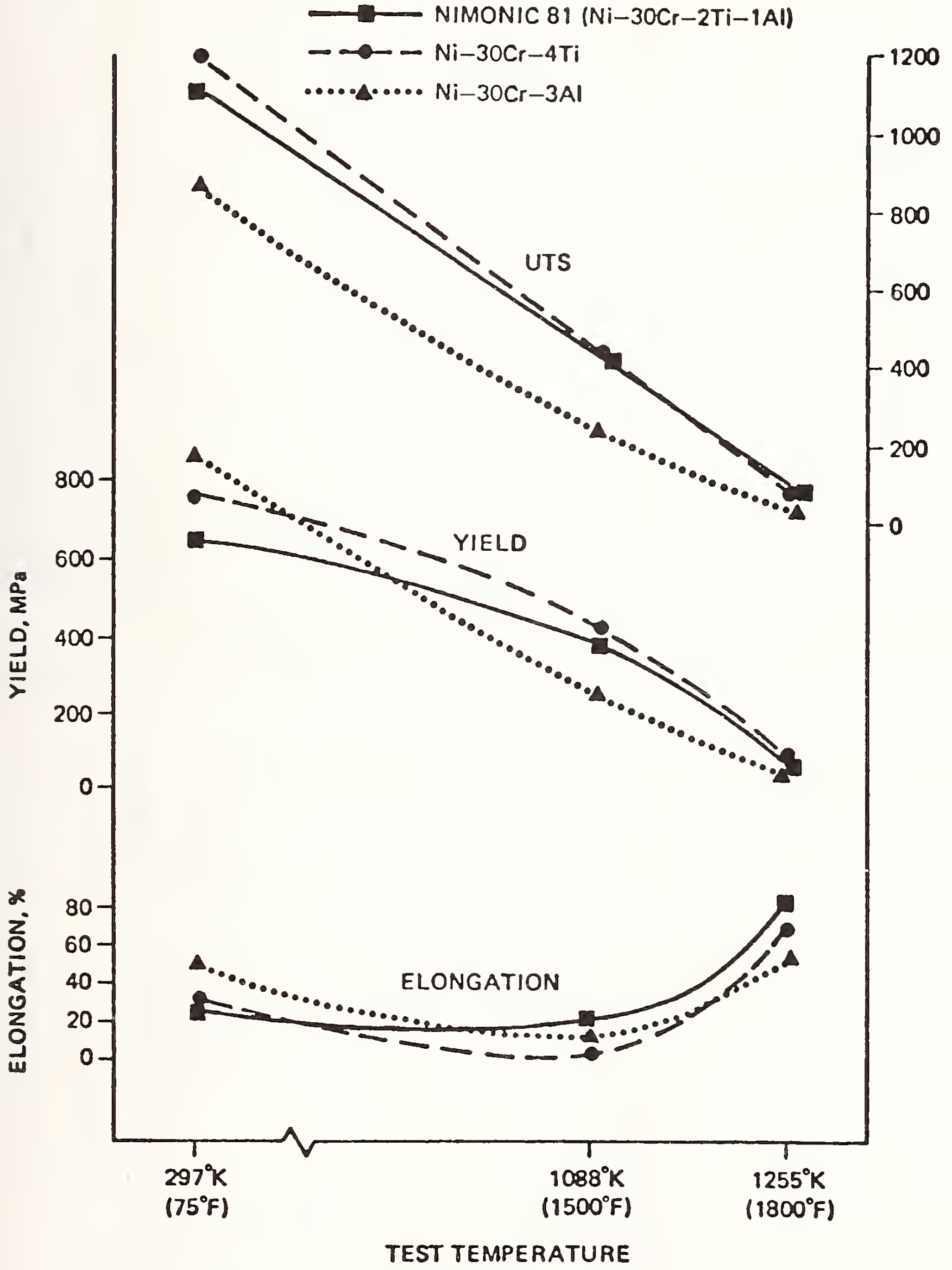
[a] Commercial 310 SS and an experimental alloy prepared by melting the commercial stock and the 2% Ti plus enough Cr to maintain the Cr-content of the original material.

[b] Ultimate tensile strength, yield strength, and total elongation were measured.

EFFECT OF Ti AND Al ADDITION TO Ni-30Cr BASE ALLOY[a] ON TENSILE PROPERTIES[b] [31]



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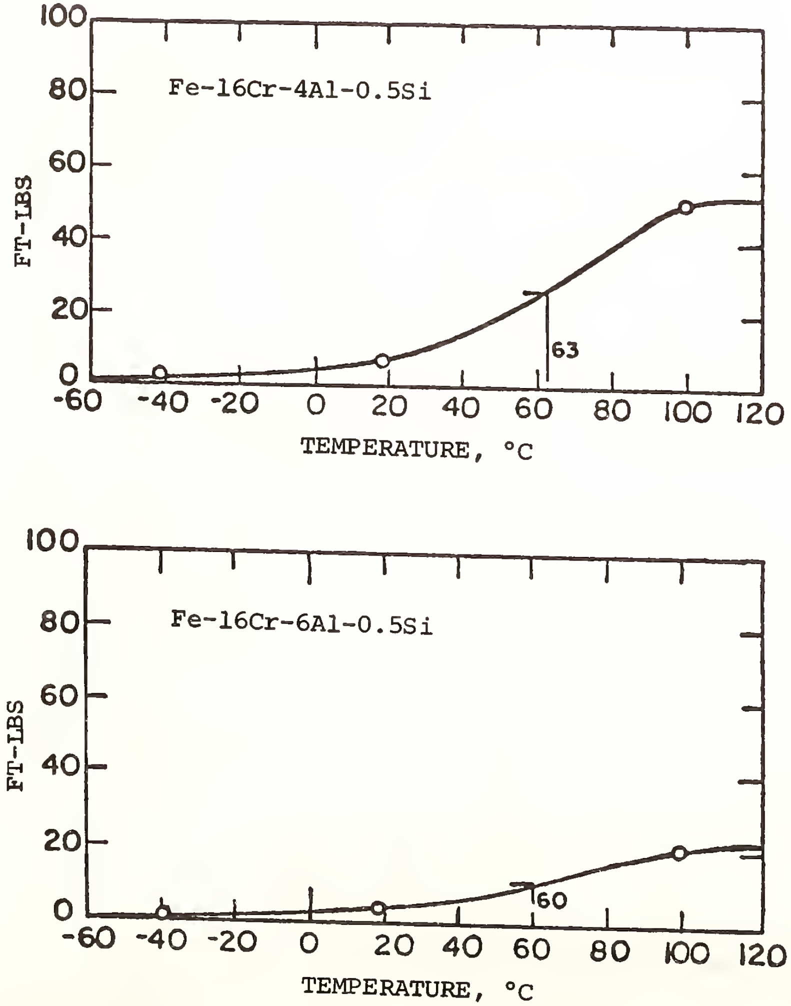
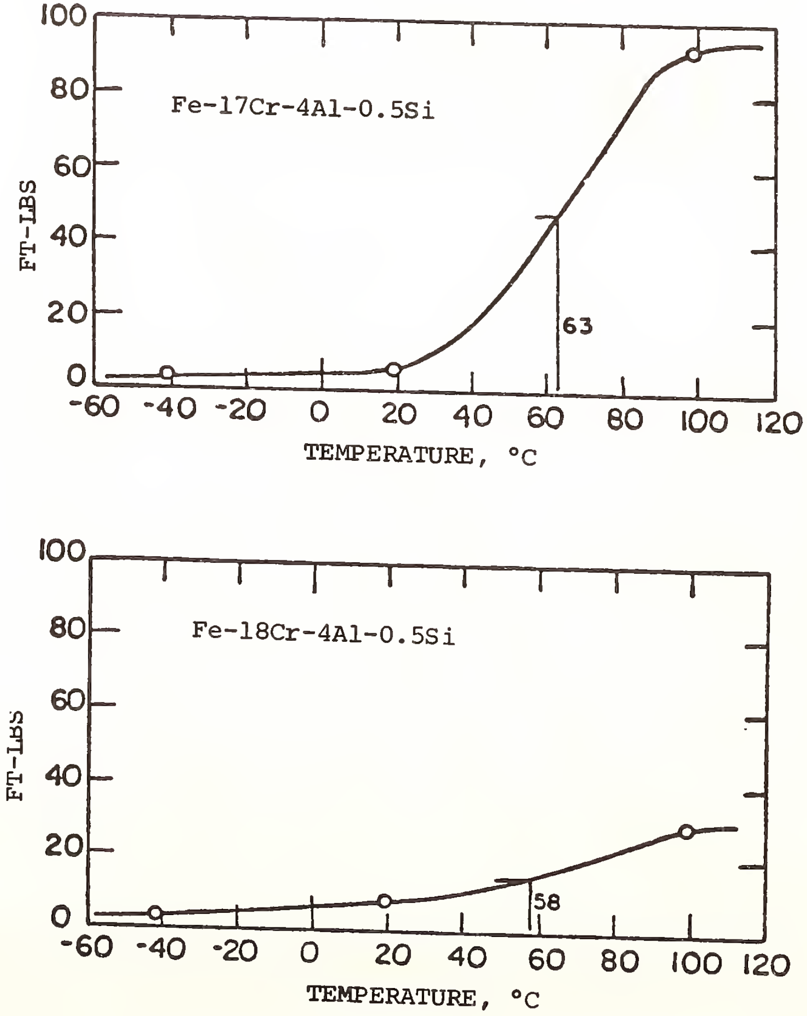
[a] Experimental alloys prepared from Nickel 200, Cr, and the modifying element, and a commercially available alloy with the desired composition.

[b] Ultimate tensile strength, yield strength, and total elongation were measured.

DUCTILE-BRITTLE TRANSITIONS IN IMPACT[a] FOR SOME EXPERIMENTAL ALLOYS[b][34]

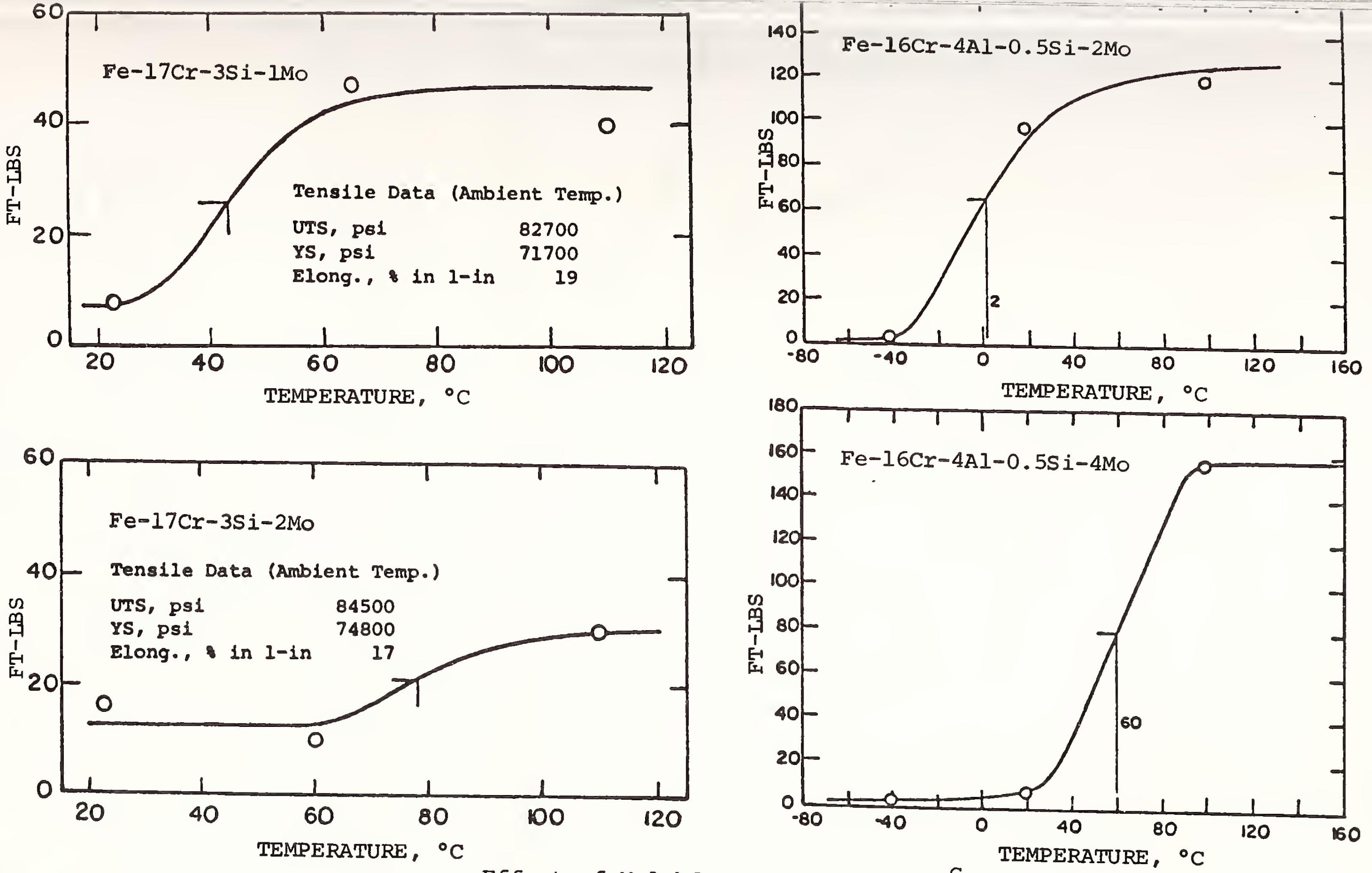


Effect of Increasing Aluminum[c]



Effect of Increasing Chromium[c]

(Data Continued)



Effect of Molybdenum Concentration[c]

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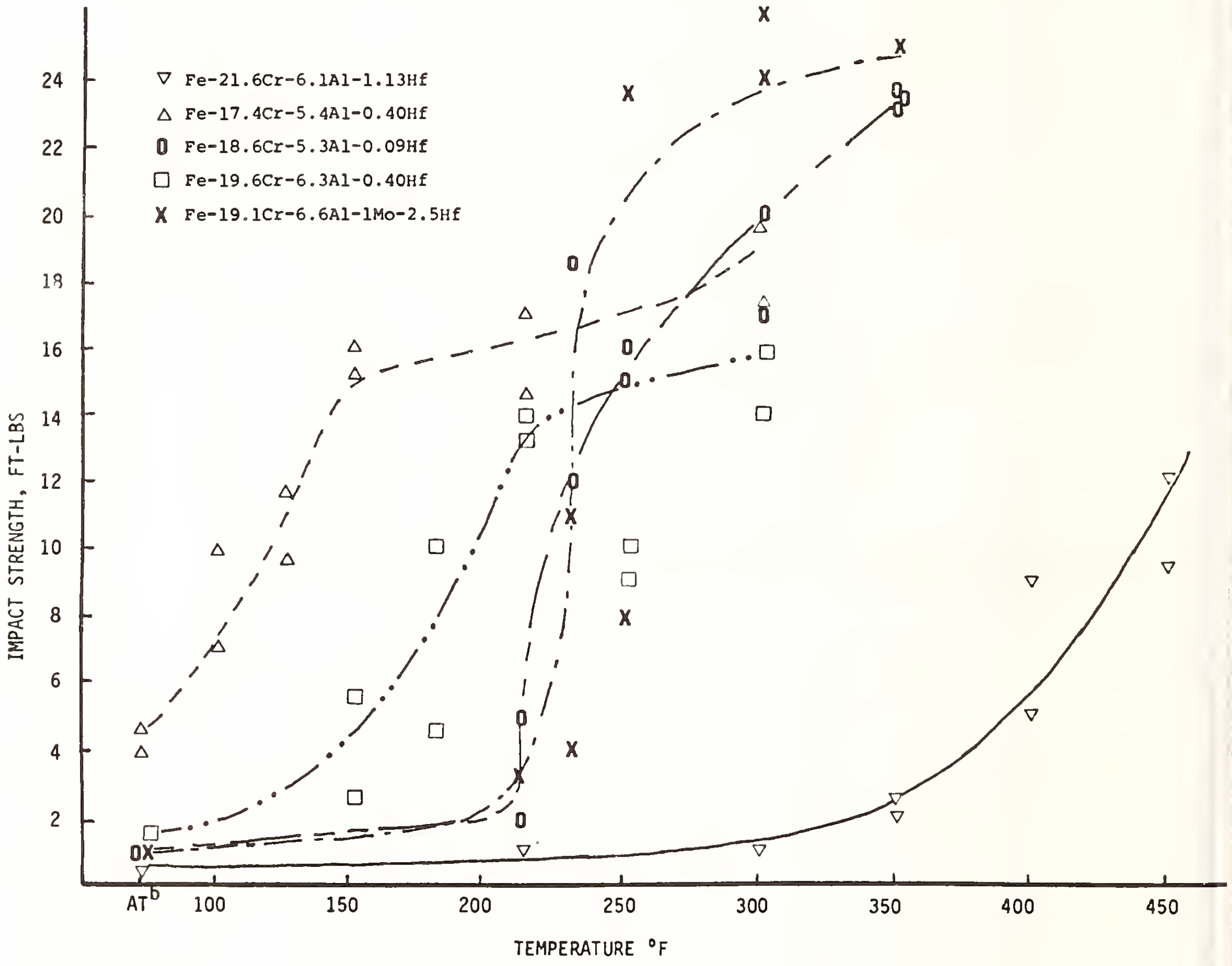
[a] Charpy V-Notch.

[b] Alloys were vacuum induction melted, homogenized, forged, and rolled to plate and bar.

[c] Indicated value is nominal percent added and the actual values have not been determined.

DUCTILE-BRITTLE TRANSITION[a] OF FeCrAlHfMo EXPERIMENTAL ALLOYS[34]



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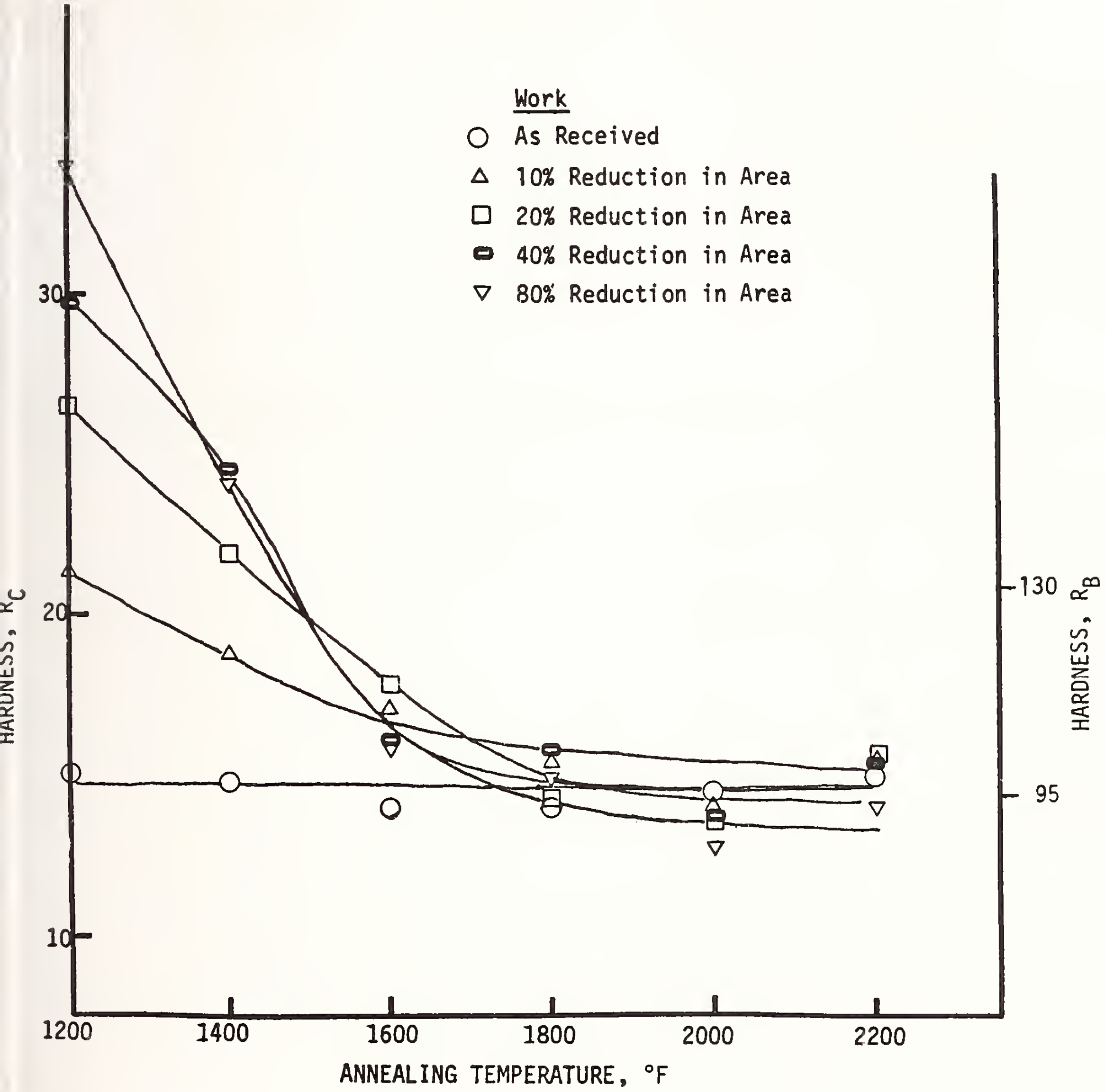
[a] Alloys tested in high strain rate, unnotched bend tests.

EFFECT OF COLD WORKING AND RECRYSTALLIZATION ANNEALING[a] ON THE HARDNESS OF A CLADDING ALLOY[b][34]



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[a] Samples were held at temperature one hour.

[b] Fe-18Cr-6Al-1Mo-0.6Hf, LM-1866; cast and rolled by Allegheny Ludlum.

EFFECT OF COMPOSITION AND HEAT TREATMENT ON IMPACT BEHAVIOR OF Fe-Cr-Al EXPERIMENTAL ALLOYS[a] [34]

Alloy[b]	Impact Strength[c] - ft.-lb.						
	Solution Treated[d]	Aged 425 °C		Aged 475 °C		Aged 5	
		1 hr	10 hr	1 hr	10 hr	1 hr	
17Cr-4Al-0.5Si-bal Fe	5.8	3.5	4.4	7.1	2.1	2.5	
18Cr-4Al-0.5Si-bal Fe	7.3	15.6	3.2	2.5	2.3	2.7	
16Cr-4Al-2Mo-0.5Si-bal Fe	97.0	121.6	8.9	66.9	12.2	--	1
16Cr-4Al-4Mo-0.5Si-bal Fe	7.3	9.0	5.8	5.2	4.0	5.3	
18Cr-6Al-0.5Si-bal Fe	3.0	3.3	2.8	3.6	2.6	5.3	
16Cr-6Al-0.5Si-bal Fe	3.5	3.1	2.8	3.5	2.0	2.7	

---

[a] Alloys were vacuum induction melted, homogenized, forged, and rolled to plate bar.

[b] Composition in weight percent.

[c] Charpy V-notch.

[d] 1800 °F/ 1/2-hr/ water quenched.

TENSILE TEST DATA OF EXPERIMENTAL ALLOYS[a] FOR USE IN COAL GASIFICATION ENVIRONMENTS[34]

Alloy[b]	Room Temperature 0.2% YS ksi	Room Temperature UTS ksi	Room Temperature % Elong.	1600 °F 0.2% YS ksi	1600 °F UTS ksi	1600 °F % Elong.	1800 °F 0.2% YS ksi	1800 °F UTS ksi	1800 °F % Elong.
17Cr-4Al-0.5Si-bal Fe	61.7	76.6	25.9	4.7	4.8	77.3	2.3	2.3	168
18Cr-4Al-0.5Si-bal Fe	62.3	76.4	27.1	4.0	4.7	128.5	2.1	2.1	63.3
16Cr-4Al-0.5Si-2Mo-bal Fe	65.3	82.1	29.4	5.4	5.9	90.3	2.6	2.6	81
16Cr-4Al-0.5Si-4Mo-bal Fe	75	93.1	25.7	7.0	7.3	113.3	2.7	2.7	107
18Cr-6Al-0.5Si-bal Fe	64.6	88.4	27.4	5.5	5.8	76	2.2	2.3	89
16Cr-4Al-0.5Si-0.5Y-bal Fe	66.1	79.3	24.4	4.7	5.2	126.5	2.0	2.1	115
16Cr-6Al-0.5Si-bal Fe	67.1	85.6	24.4	4.6	5.1	114.6			
ARMCO 18SR[c]	60-70	80-90	25-30	3.2	4.8			2.0	
AISI 446SS[d]	51.5	83	25		$\sim$6				
AISI 310SS[d]	40	92	47		20	28-60		10	24-65

[a] Alloys were vacuum induction melted, homogenized, forged and rolled to plate and bar.

[b] Composition by weight percent.

[c] Data from ARMCO product information data sheet.

[d] Data from Metals Handbook, Vol. I, American Society for Metals, Ohio.

STRESS RUPTURE DATA OF EXPERIMENTAL ALLOYS[a] FOR USE IN COAL GASIFICATION ENVIRONMENTS[34]

Alloy[b]	Test Temp. (°F)	Stress (psi)	Time To Rupture (hrs)	Estimated Elongation (%)	Estima 100-h Ruptu Stres
17Cr-4Al-0.5Si-bal Fe	1600	978	>74.4[c]	---	100
	1600	1216	37.7	147	
	1600	1408	2.8	123	
	1800	384	31.4	156	28
	1800	608	5.0	195	
	1800	802	3.2	199	
18Cr-4Al-0.5Si-bal Fe	1600	1010	43.1	152	80
	1600	1200	36.5	68	
	1600	1389	11.3	81	
	1800	410	10.3	145	6
	1800	600	5.0	196	
	1800	789	> 4.5[c]	---	
16Cr-4Al-0.5Si-2Mo-bal Fe	1600	1389	24.4	94	
	1800	410	122.4	126	45
	1800	600	12.5	121	
16Cr-4Al-0.5Si-4Mo-bal Fe	1600	1010	>171.7[c]	---	120
	1600	1168	>32.1[c]	---	
	1600	1389	45.6	187	
	1800	410	206.9	128	50
	1800	600	42.9	165	
	1800	789	10.0	172	
18Cr-6Al-0.5Si-bal Fe	1600	1010	60.4	106	90
	1600	1389	28.2	161	
	1800	600	27.4	166	42
	1800	789	5.5	123	
16Cr-4Al-0.5Si-0.5Y-bal Fe	1600	992	55.2	118	
	1800	382	>43.3[c]	---	35
	1800	600	13.6	158	
	1800	802	3.8	114	
16Cr-6Al-0.5Si-bal Fe	1600	1010	40.1	150	85
	1600	1200	15.7	175	
	1600	1389	16.9	169	
	1800	410	75.1	169	35
	1800	600	11.8	210	
	1800	789	> 4.2[c]	---	
AISI 446 SS[d]	1600				130
	1800				70
AISI 310 SS[d]	1800				380

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[a] Alloys were vacuum induction melted, homogenized, forged, and rolled to plate and bar

[b] Composition in weight percent.

[c] Machine was shut down due to extensive elongation.

[d] Data obtained from Metals Handbook, vol. 1, American Society for Metals, Ohio.

TENSILE PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEEL[b] AT TWO TEST TEMPERATURES AFTER AUSTENITIZING AS AFFECTED BY COOLING RATE[c] AND HEAT TREATMENT[d][35]

rgical on[d]	Cooling Rate[c]		Test Temperature		Stresses, MPa (ksi)		Total[e] Elongation, %		Reduction in Area
	K/s	°R/s	°C	°F	0.2% Offset Yield	Ultimate	L/D=7	L/D=4	%
			Austenitized at 927 °C (1700 °F) for 1 hr						
	0.3	0.6	24	75	537 (77.9)	762 (110)	14.1		47
	0.3	0.6	343	650	582 (84.5)	865 (125)	10.0		36
	3	5	24	75	779 (113)	1007 (146)	11.5		57
	3	5	343	650	879 (127)	1090 (158)	11.2		50
	0.3	0.6	22	72	419 (60.8)	582 (84.4)	16.5		68
	0.3	0.6	343	650	401 (58.2)	538 (78.1)	12.6		65
	3	5	22	72	532 (77.1)[f]	645 (93.5)	15.5		67
	3	5	343	650	479 (69.5)	595 (86.3)	12.5		63
SR (40 h)	0.3	0.6	22	72	385 (55.9)	552 (80.0)	18.4		68
SR (40 h)	0.3	0.6	343	650	343 (52.6)	515 (74.7)	13.4		65
SR (40 h)	3	5	24	75	455 (66.2)[f]	568 (82.4)	17.2		72
SR (40 h)	3	5	343	650	421 (61.0)	538 (77.8)	12.3		66
SR (120 h)	0.3	0.6	24	76	363 (52.7)	518 (75.1)	19.8	27.1	71
SR (120 h)	0.3	0.6	343	650	328 (47.6)	490 (71.0)	13.3	18.4	63
SR (120 h)	3	5	22	72	426 (61.8)[f]	543 (78.8)	18.8		72
SR (120 h)	3	5	343	650	381 (55.3)	506 (73.4)	13.6		65
SR (40 h),A(1000 h)	0.3	0.6	24	76	365 (53.1)	520 (75.5)	20.3	27.6	71
SR (40 h),A(1000 h)	0.3	0.6	343	650	333 (48.4)	492 (71.4)	14.2	19.2	61
SR (40 h),A(1000 h)	3	5	24	76	472 (68.5)	586 (85.0)	17.7	24.9	71
SR (40 h),A(1000 h)	3	5	343	650	415 (60.3)	533 (77.4)	13.2	18.6	65
			Austenitized at 1038°C (1900°F) for 1 h						
	0.3	0.6	24	75	710 (103)	928 (135)	11.5		54
	0.3	0.6	343	650	790 (114)	1048 (152)	11.1		41
	3	5	22	72	759 (110)	980 (143)	11.5		58
	3	5	343	650	869 (126)	1064 (154)	11.0		50
	0.3	0.6	24	75	533 (77.3)	651 (94.4)	14.1		66
	0.3	0.6	343	650	484 (70.2)	603 (87.5)	11.8		63
	3	5	22	72	534 (77.4)[f]	645 (93.6)	15.4		72
	3	5	343	650	483 (70.0)	596 (86.4)	12.1		66
SR (40 h)	0.3	0.6	24	75	469 (68.0)	588 (85.3)	16.3	22.9	69
SR (40 h)	0.3	0.6	345	650	436 (63.2)	548 (79.6)	12.2	17.3	62
SR (40 h)	3	5	22	72	543 (78.8)[f]	647 (93.8)	14.0	20.0	71
SR (40 h)	3	5	343	650	485 (70.4)	582 (84.4)	11.5	16.8	64
SR (120 h)	0.3	0.6	22	72	408 (59.3)	540 (78.3)	19.2	26.7	73
SR (120 h)	0.3	0.6	345	650	379 (55.0)	506 (73.4)	13.9	19.3	63
SR (120 h)	3	5	22	72	423 (61.4)[f]	543 (78.8)	17.5		72
SR (120 h)	3	5	343	650	385 (55.9)	510 (73.9)	13.8		67
SR (40 h),A(1000 h)	0.3	0.6	22	71	458 (66.5)	579 (84.0)	16.0	22.4	70
SR (40 h),A(1000 h)	0.3	0.6	345	650	428 (62.1)	550 (79.8)	12.3	17.5	63
SR (40 h),A(1000 h)	3	5	22	72	451 (65.4)	571 (82.8)	18.0	25.1	71
SR (40 h),A(1000 h)	3	5	345	650	402 (58.3)	528 (76.6)	14.1	19.5	65

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e of two specimens. All heat treatments were performed in air on 0.13 m (5 in) long x 13 mm (0.5 in) square each bar provided two test specimen blanks. .

', gr. 22.

g rate 3K/s (5 °R/s) simulates that at the surface of thick (0.25-0.3 m or 10-12 in) steel plate during ing after being austenitized; cooling rate 0.3 K/s (0.6 °R/s) simulates that at the 1/4-thickness depth.

ce called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific depth ons in thick steel plates that have been annealed or quenched by subjecting a steel bar up to 25.4 mm (1 in) to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; cooling is by gas g directly on the specimen while additional radiant "make-up heat" maintains the desired cooling rate. tes quench rate simulated by DATA TRAK; T denotes temper at 704 °C (1300 °F) for 1 h followed by air g; SR denotes stress relief at 677 °C (1250 °F) for 40 or 120 h, followed by air cooling; A denotes aging at 343 °C (650 °F) for 1000 h. Cooling after each additional heat treatment was on firebrick in still air.

of gauge length (L) to gauge diameter (D) is 7; strain rate is 0.016/min. L/D=4 data are calculated from D=7 data.

are lower yield values.

FRACTURE TOUGHNESS DATA FOR A543 CLASS 1 STEEL THICK PLATE[a][35]

Plate Depth[b]	Specimen Orientation	54 J (40 ft-lb) Transition Temperature °C	54 J (40 ft-lb) Transition Temperature °F	Upper Shelf Energy J	Upper Shelf Energy ft-lb
Surface	Longitudinal - parallel to rolling direction	-96	-140	140	103
	Transverse - perpendicular to rolling direction	-84	-120	112	82
1/4-thickness	Longitudinal	-73	-100	122	90
∿63.5 mm (2.5 in)	Transverse	-62	-80	114	84
Midthickness	Longitudinal	-26	-15	106	78
∿127 mm (5 in)	Transverse	-21	-5	91	67

Toughness Values, MPa$\sqrt{m}$ (ksi$\sqrt{in}$)

Plate Depth[b]	Test Temperature °C	Test Temperature °F	Precracked Charpy V-Notch, K_{Icd} by Equivalent Energy: RW[c]	Precracked Charpy V-Notch, K_{Icd} by Equivalent Energy: WR[d]	0.394T (10-mm Thick) Compact Tension in WR[c] Orientation: K_{Icd} by Equivalent Energy	0.394T (10-mm Thick) Compact Tension in WR[c] Orientation: $K_{(J)}$ by J-Integral
Surface	-129	-200	69 (63)	103 (94)		
	-73	-100		208 (189)		
	-18	0	229 (208)	229 (208)		
	38	100		225 (205)		
	93	200	225 (205)			
	149	300		202 (184)		
	260	500	203 (185)	192 (175)		
1/4 thickness	-184	-300			38 (35)	38 (35)
∿63.5 mm	-129	-200	90 (82)	110 (100)	103 (94)	104 (95)
(2.5 in)	-101	-150			156 (142)	157 (143)
	-73	-100		202 (184)	166 (151)	169 (154)
	-18	0	223 (203)	225 (205)	200 (182)	202 (184)
	38	100		199 (181)		
	93	200	216 (197)			
	176	350	193 (176)	185 (168)		
	260	500	196 (178)	169 (154)		
Mid-thickness	-129	-200	48 (44)	59 (54)		
∿127 mm (5 in)	-73	-100		102 (93)		
	-18	0	215 (196)	191 (174)		
	38	100		185 (168)		
	93	200	202 (184)			
	176	350	199 (181)			
	260	500	146 (133)	176 (160)		

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[a] 254 mm (10 in) thick plate.

[b] A device called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of spe depth locations in thick steel plates that have been annealed or quenched by subjecting a steel bar 25.4 mm (1 in) square to a preselected thermal cycle. Tungsten filament quartz lamps are the heat cooling is by gas flowing directly on the specimen while additional radiant "make-up heat" maintain desired cooling rate.

[c] RW - specimen orientation: specimen axis parallel to rolling direction (RD); fracture propagation transverse to RD.

[d] WR - specimen orientation: specimen axis transverse to rolling direction (RD); fracture propagatio parallel to RD.

TENSILE TEST RESULTS FOR HEAT TREATED[a] CANDIDATE 2-1/4 Cr-1 Mo (SA-387, Grade 22) STEEL[b] FOR PRESSURE VESSELS[35]

Treatment Code[c]	Test Temperature °C	°F	Tensile Properties, MPa (ksi) 0.2% Offset Yield (YS)	Ultimate (UTS)	Ductility, % Elongation	Reduction in Area (RA)
	20	68	239.9 (34.8)	479.1 (69.5)	23.6	71
	482	900	179.3 (26.0)	391.6 (56.8)	23.6	75.6
	20	68	235.1 (34.1)	487.4 (70.7)	23.2	52.9[d]
	482	900	190.3 (27.6)	406.1 (58.9)	20.7	75.3
	20	68	249.6 (36.2)	510.9 (74.1)	23.0	65.0
	482	900	224.7 (32.6)	472.2 (68.5)	15.5	66.1
[d]	20	68	249.6 (36.2)	484.7 (70.3)	23.3	52.9[d]
	482	900	177.9 (25.8)	397.8 (57.7)	21.3	73.8
	20	68	251.6 (36.5)	478.4 (69.3)	27.7	71.3
	482	900	179.3 (26.0)	386.1 (56.0)	19.4	76.2
	20	68	245.4 (35.6)	479.1 (69.5)	24.6	73.0
	482	900	179.3 (26.0)	373.0 (54.1)	18.5	76.5
	20	68	235.1 (34.1)	475.0 (68.9)	25.6	72.2
	482	900	179.3 (26.0)	371.6 (53.9)	21.5	72.2
	20	68	251.0 (36.4)	484.0 (70.2)	22.5	71.0
	482	900	193.8 (28.2)	408.2 (59.2)	20.5	75.9
	20	68	251.0 (36.4)	488.8 (70.9)	24.3	71.0
	482	900	195.9 (28.4)	402.0 (58.3)	20.5	75.4
	20	68	241.3 (35.0)	480.3 (69.7)	24.7	72.6
	482	900	185.5 (26.9)	288.2 (56.3)	22.7	76.3
	20	68	239.3 (34.7)	481.2 (69.8)	24.7	71.7
	482	900	191.0 (27.7)	386.8 (56.1)	20.9	76.4
	20	68	224.7 (32.6)	477.1 (69.2)	23.2	72.6
	482	900	180.7 (26.2)	377.8 (54.8)	23.5	75.8
[d]	20	68	239.9 (34.8)	492.9 (71.5)	22.8	52.0[d]
	482	900	208.2 (30.2)	433.0 (62.8)	19.0	70.6
	20	68	241.3 (35.0)	490.2 (71.1)	23.4	70.6
	482	900	206.8 (30.0)	409.6 (59.4)	19.6	73.4
	20	68	235.1 (34.1)	482.0 (69.9)	22.7	73.0
	482	900	199.3 (28.9)	382.6 (55.5)	21.2	75.6
	20	68	214.4 (31.9)	470.9 (68.3)	23.4	72.9
	482	900	184.1 (26.7)	366.8 (53.2)	23.8	72.8
	20	68	635.0 (92.1)[e]	895.6 (129.9)	13.0	51.4
	20	68	573.0 (83.1)[e]	878.4 (127.4)	12.1	51.4

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evice called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific th locations in thick steel plates that have been annealed or quenched by subjecting a steel bar up to 4 mm (1 in) square to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; ling is by gas flowing directly on the specimen while additional radiant "make-up heat" maintains the ired cooling rate.

the simulated anneal heat treatments meet the Class 1 requirements for SA 387 Grade 22 [206 MPa (30Ksi) 413 MPa (60Ksi) minimum yield and ultimate strengths, respectively]. The simulated quench heat atment was used to achieve an ASTM A542 Class 1 steel (accelerated cooling from austenitizing perature).

(Data Continued)

TENSILE TEST RESULTS FOR HEAT TREATED[a] CANDIDATE 2-1/4 Cr-1 Mo (SA-387, Grade 22) STEEL[b] FOR PRESSURE VESSELS[35], Continued

Footnotes continued

[c] Heat treatments simulated by the DATA TRAK device:

Heat Treatment Code*	Heat Treatment Represented	Plate Depth Simulated	Austenitizing Temperature °C	Austenitizing Temperature °F	Isothermal Hold Temperature °C	Isothermal Hold Temperature °F	Cooling Rate to Hold Temperature K/sec	Cooling Rate to Hold Temperature °F/sec	Cooling Rate to Ambient K/sec	Cooling Rate to Ambient °F/sec	Temper Temp. °C	Temper Temp. °F	Time hr
A1	Anneal	All	899	1650	None				0.008	0.014	None		
A2	Anneal	All	927	1700	None				0.008	0.014	None		
A3	Anneal	All	954	1750	None				0.008	0.014	None		
IA1(X)	Isothermal Anneal	All	899	1650	704	1300	0.015	0.028	0.015	0.028	None		
IA2(X)	Isothermal Anneal	All	927	1700	704	1300	0.015	0.028	0.015	0.028	None		
IA3(X)	Isothermal Anneal	All	954	1750	704	1300	0.015	0.028	0.015	0.028	None		
Q1	Quench	Midthick	899	1650	None		None		0.26	0.46	None		
Q2	Quench	Midthick	927	1700	None		None		0.26	0.46	None		
Q3	Quench	Midthick	954	1750	None		None		0.26	0.46	None		
Q1T	Quench & temper	Midthick	899	1650	None		None		0.26	0.46	704	1300	1
Q2T	Quench & temper	Midthick	927	1700	None		None		0.26	0.46	704	1300	1
Q3T	Quench & temper	Midthick	954	1750	None		None		0.26	0.46	704	1300	1

*(X) in IA series denotes isothermal hold time. For example, IA24 identifies a specimen austenitized at 927 °C and isothermally held (at 704 °C) for 4 hr.

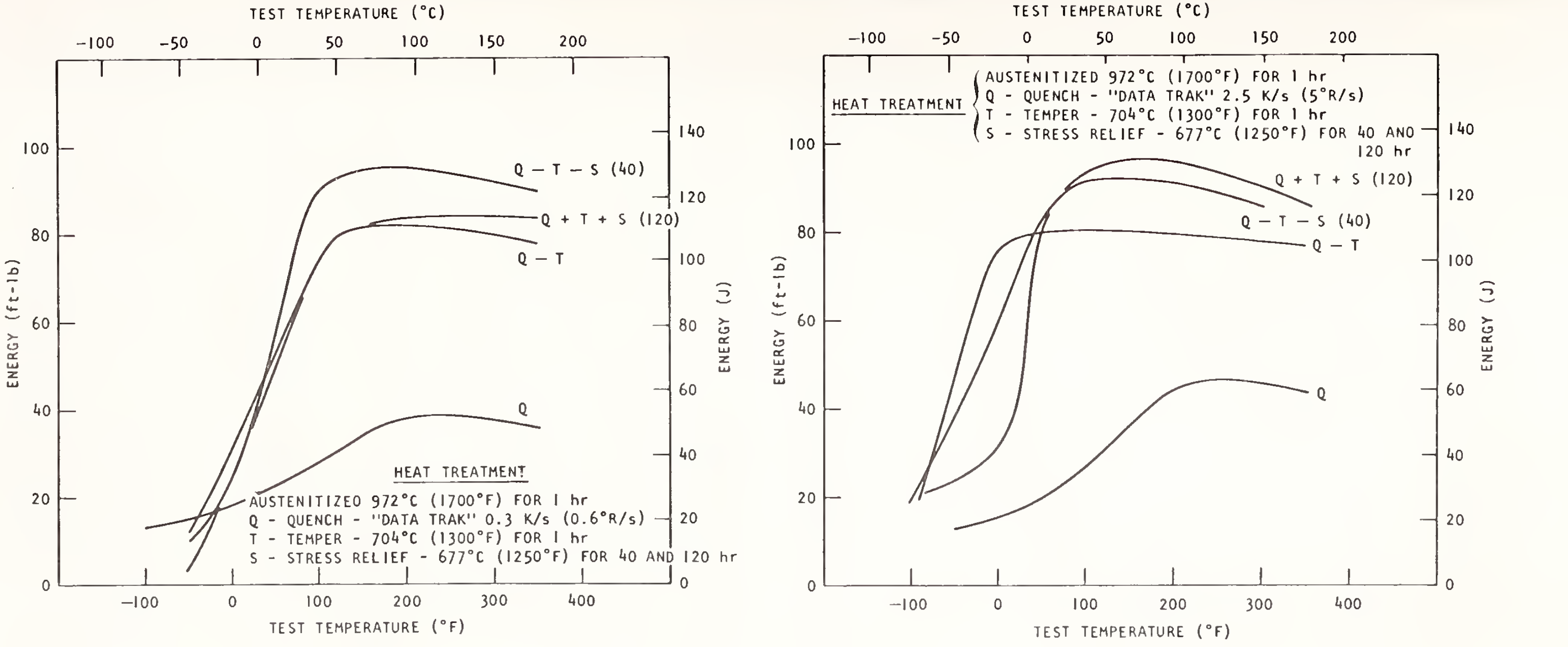
[d] Heat treatments A2, IA11, IA31, had RA values near 50%. The RA measurement is useful for predicting toughness, as low RA values suggest low toughness; these anneal treatments may need to be explored further.

[e] Specimen Q2 did not achieve the minimum yield strength [586 MPa(85Ksi)] required for A542 Class 1 steel in the as-quenched condition. Charpy V-notch (C_V) data indicate a toughness value [50J (37 ft-lb)] that is unacceptable to the industry:

Charpy V-Notch Results for 2-1/4 Cr-1 Mo Steel Specimens Quenched From Austenitizing Temperature 927 °C (1700 °F at Cooling Rate 0.26 K/sec (0.46 °F/sec), heat treatment code Q2.

Test Temperature °C	Test Temperature °F	Absorbed Energy J	Absorbed Energy ft-lb	Lateral Expansion mm	Lateral Expansion in
20	68	25.2	18.5		
65.6	150	46.9	34.5	0.068	0.027
93.3	200	53.0	39	0.079	0.031
121.1	250	51.7	38	0.081	0.032

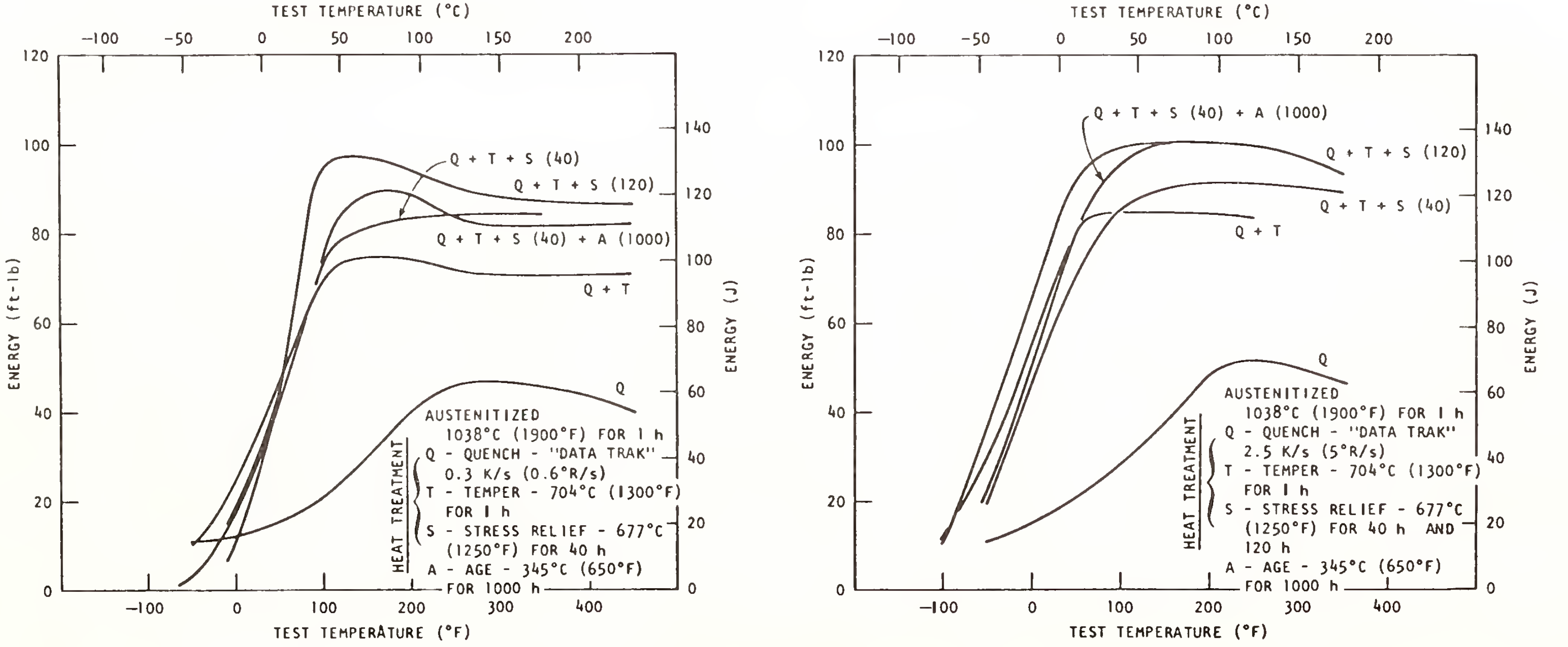
ALLOY STEEL PLATE AFTER ADDITIONAL HEAT TREATMENTS[b][35]



(Data Continued)

[Note added in proof: 927 °C = 1700 °F, not 972 °C.]

VARIATION OF CHARPY-V IMPACT ENERGY WITH TEST TEMPERATURE FOR 2 1/4 Cr-1 Mo (SA-387, GR. 22)[a] ALLOY STEEL PLATE AFTER ADDITIONAL HEAT TREATMENTS[b][35], Continued



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[a] 76 mm (3 in) thick plate.

[b] A device, DATA TRAK, was used to obtain specimens whose thermal exposure simulates that of specific depth locations in thick steel plates that have been annealed or quenched by subjecting steel bars to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; cooling is by gas flowing directly on the specimen while additional radiant "make-up heat" maintains the desired cooling rate.

TENSILE PROPERTIES AT VARIOUS DEPTH LOCATIONS IN ASTM A543 CLASS 1 STEEL THICK PLATE[a] [35]

Depth[b]	Test Temperature		Strength[c], MPa (ksi)		Total Elongation[d], %		Reduction in Area (%)
	°C	°F	0.2% Yield	Ultimate	L/D = 7	L/D = 4	
			R-Oriented[e] Specimens				
0.03	23	74	726 (106)	813 (118)	15.7	22.5	73
0.03	345	650	611 (88.7)	692 (100)	12.1	18.1	68
0.25	-29	-20	743 (107)	852 (123)	16.7	23.5	68
0.25	23	74	710 (103)	806 (117)	14.6	20.8	70
0.25	345	650	594 (86.2)	679 (98.6)	11.2	16.7	68
0.25	480	900	531 (77.1)	565 (82.1)	14.6	24.0	77
0.50	26	78	710 (103)	809 (117)	14.4	20.6	67
0.50	345	650	607 (88.1)	699 (101)	11.0	16.3	63
			W-Oriented[f] Specimens				
0.03	23	74	727 (105)	809 (117)	15.7	22.4	68
0.03	345	650	615 (89.3)	699 (101)	11.7	17.2	62
0.25	-29	-20	743 (108)	854 (124)	15.5	21.7	66
0.25	23	74	696 (101)	792 (115)	14.8	21.1	66
0.25	345	650	592 (85.9)	679 (98.5)	10.8	16.1	64
0.25	480	900	527 (76.5)	566 (82.2)	14.2	23.4	75
0.50	26	79	723 (105)	823 (119)	13.8	19.4	64
0.50	345	650	610 (88.5)	703 (102)	10.7	14.8	62

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[a] 248 mm (9 3/4 in) thick plate.

[b] Fraction of wall thickness: 0.03, near surface; 0.25, quarter-thickness; 0.50, mid-thickness.

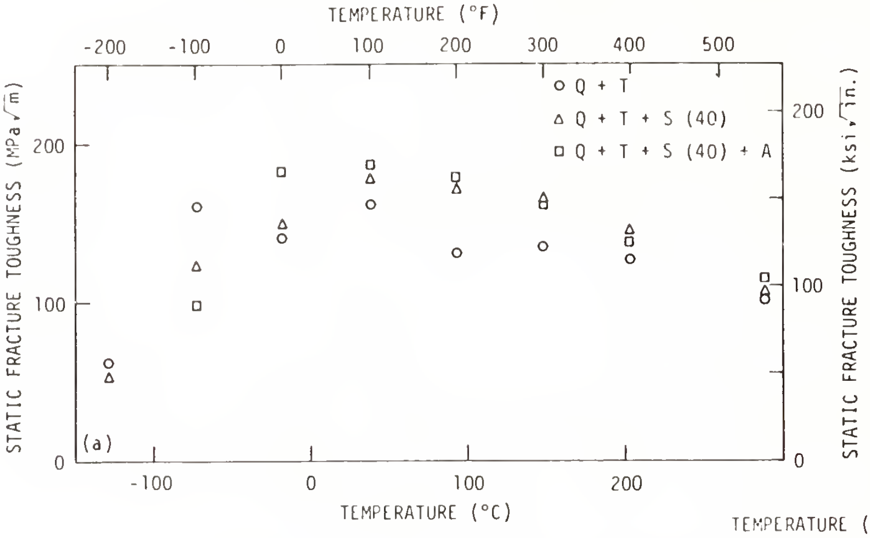
[c] 4.48-mm gauge diameter specimen, average of two specimens, speed 0.41/min.

[d] Gauge length to gauge diameter ratio $L/D = 4$ calculated from $L/D = 7$ data.

[e] Specimen orientation: specimen axis parallel to the rolling direction (RD).

[f] Specimen orientation: specimen axis transverse to RD.

EFFECT OF HEAT TREATMENT[a] ON THE STATIC FRACTURE TOUGHNESS[b] OF 2 1/4 Cr-1 Mo STEEL PLATE[c] AFTER AUSTENITIZATION[35]

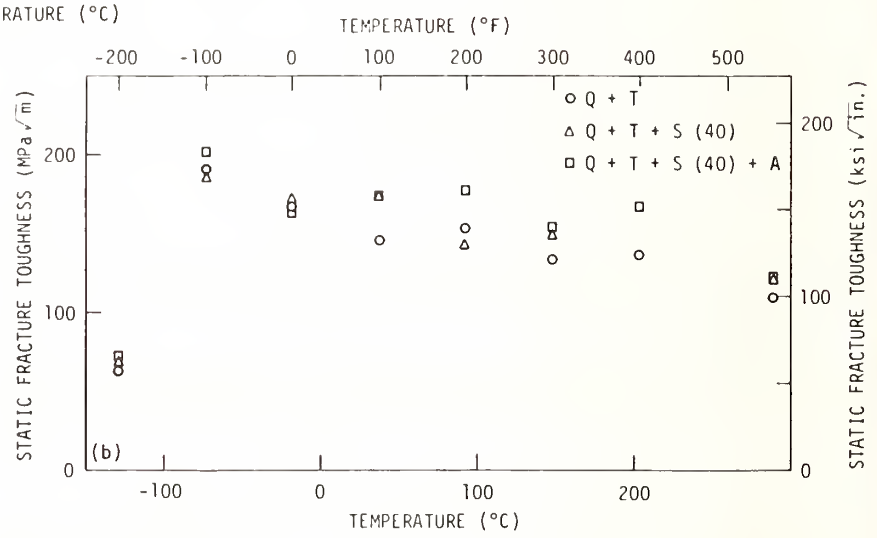


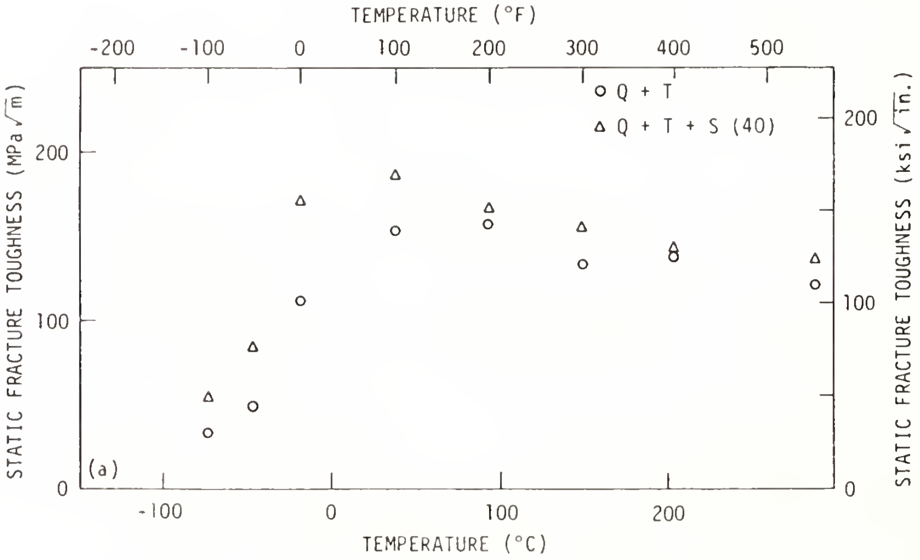
HEAT TREATMENT[a]

AUSTENITIZED
972°C (1700°F) 1 h
QUENCH (DATA TRAK)
0.3 K (0.6°R)/s
TEMPER
704°C (1300°F) 1 h
STRESS RELIEF
677°C (1250°F) 40 h
AGED
343°C (650°F) 1000 h

HEAT TREATMENT[a]

AUSTENITIZED
972°C (1700°F) 1 h
QUENCH (DATA TRAK)
2.5 K (5°R)/s
TEMPER
704°C (1300°F) 1 h
STRESS RELIEF
677°C (1250°F) 40 h
AGED
343°C (650°F) 1000 h



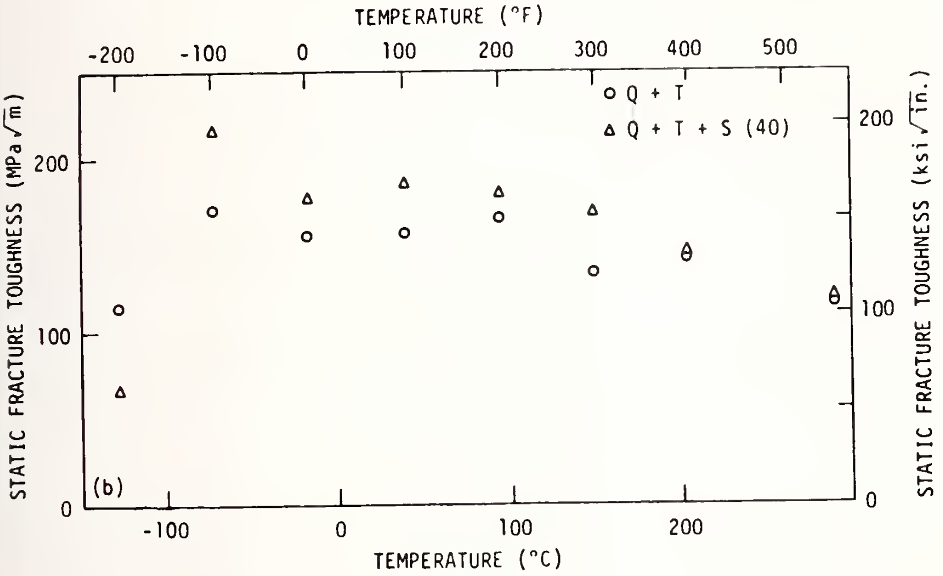


HEAT TREATMENT[a]

AUSTENITIZED
1038°C (1900°F) 1 h
QUENCH (DATA TRAK)
0.3 K (0.6°R)/s
TEMPER
704°C (1300°F) 1 h
STRESS RELIEF
677°C (1250°F) 40 h

(Data Continued)

EFFECT OF HEAT TREATMENT[a] ON THE STATIC FRACTURE TOUGHNESS[b] OF 2 1/4 Cr-1 Mo STEEL PLATE[c] AFTER AUSTENITIZATION[35], Continued



HEAT TREATMENT[a]
AUSTENITIZED
1038°C (1900°F) 1 h
QUENCH (DATA TRAK)
2.5 K (5°R)/s
TEMPER
704°C (1300°F) 1 h
STRESS RELIEF
677°C (1250°F) 40 h

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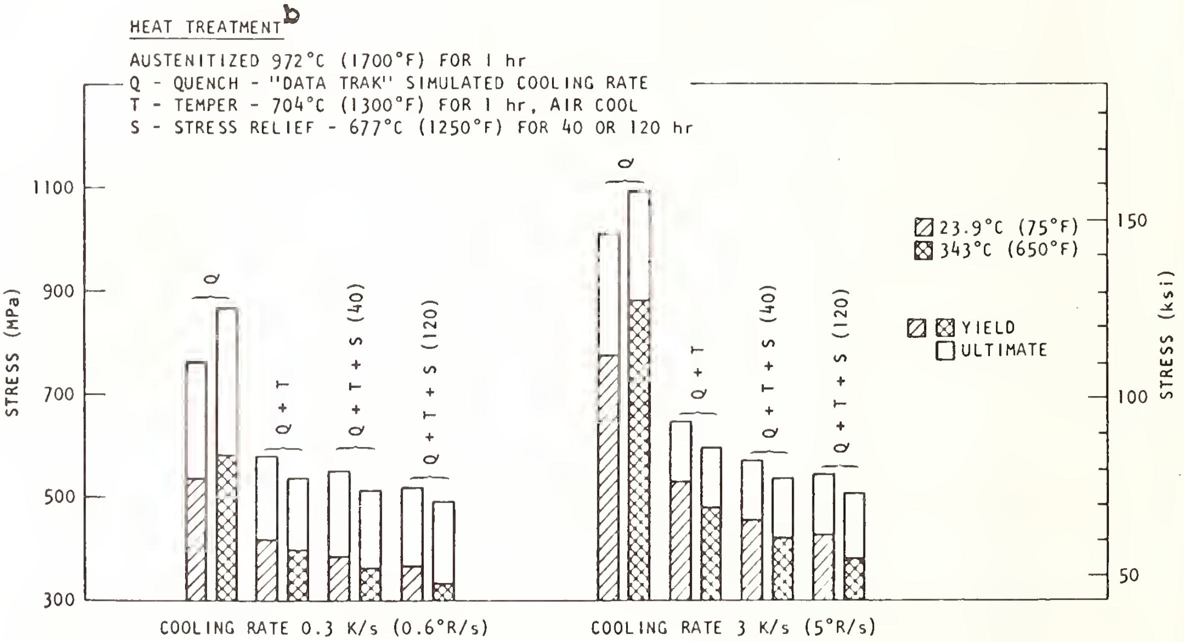
[a] A device called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific depth locations in thick steel plates that have been annealed or quenched by subjecting a steel bar up to 25.4 mm (1 in) square to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; cooling is by gas flowing directly on the specimen while additional radiant "make-up heat" maintains the desired cooling rate. Cooling rate 2.5 K/s (5 °R/s) simulates the surface of 0.25-0.3 m (10-12 in) thick plate; rate 0.3 K/s (0.6 °R/s) simulates the 1/4-thickness depth.

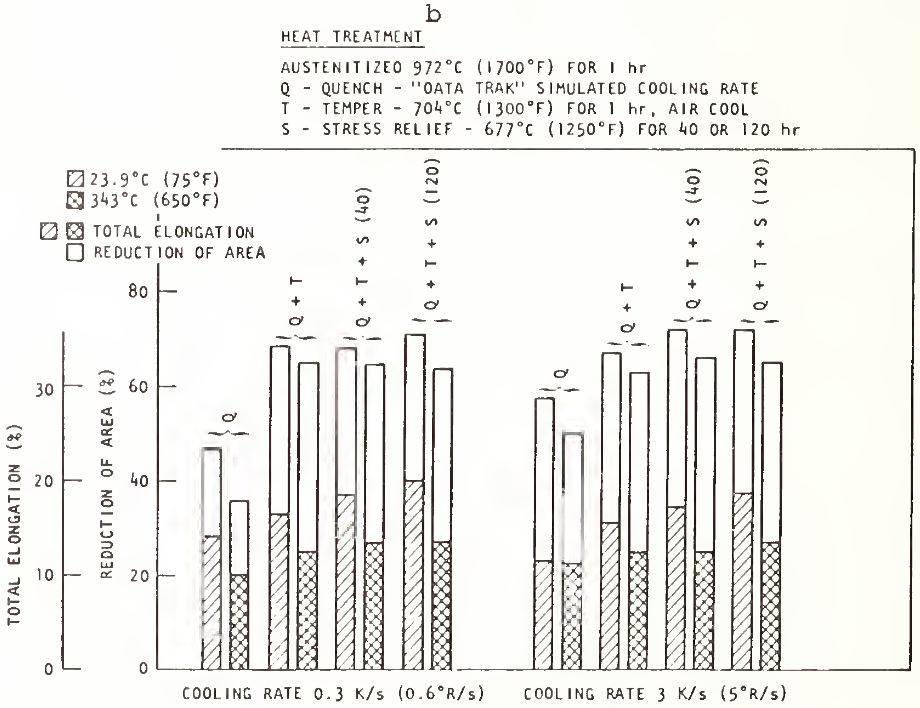
[b] Pre-cracked Charpy V-Notch.

[c] SA-387, gr. 22.

[Note added in proof: 927 °C = 1700 °F, not 972 °C.]

EFFECT OF COOLING RATE[a] AND HEAT TREATMENT[b] ON THE TENSILE PROPERTIES[c] OF 2 1/4 Cr-1 Mo STEEL[d] AT TWO TEST TEMPERATURES AND AFTER AUSTENITIZING AT TWO TEMPERATURES[35]



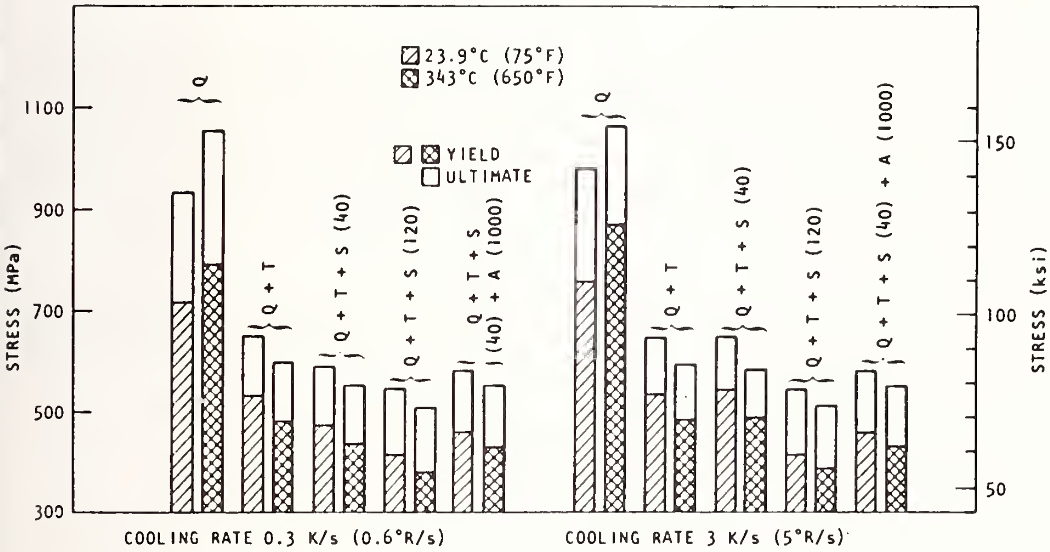


(Data Continued)

EFFECT OF COOLING RATE[a] AND HEAT TREATMENT[b] ON THE TENSILE PROPERTIES[c] OF 2 1/4 Cr-1 Mo STEEL[d] AT TWO TEST TEMPERATURES AND AFTER AUSTENITIZING AT TWO TEMPERATURES[35], Continued

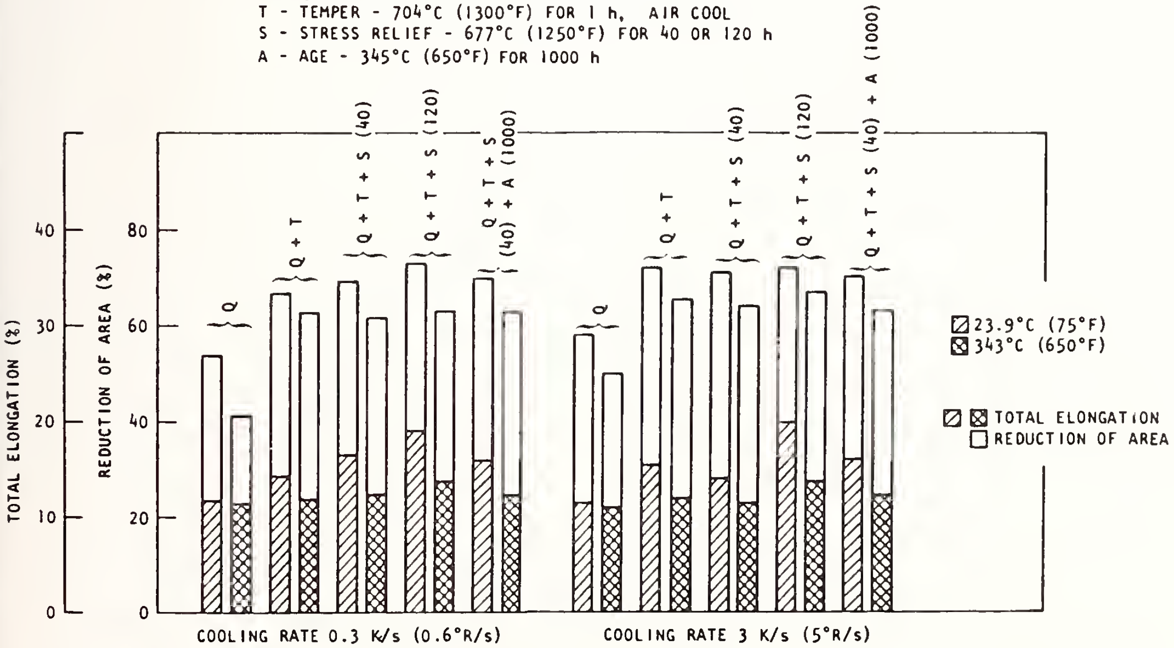
HEAT TREATMENT[b]

AUSTENITIZED 1038°C (1900°F) FOR 1 h
Q - QUENCH - "DATA TRAK" SIMULATED COOLING RATE
T - TEMPER - 704°C (1300°F) FOR 1 h, AIR COOL
S - STRESS RELIEF - 677°C (1250°F) FOR 40 OR 120 h
A - AGED - 345°C (650°F) FOR 1000 h



HEAT TREATMENT[b]

AUSTENITIZED 1038°C (1900°F) FOR 1 h
Q - QUENCH - "DATA TRAK" SIMULATED COOLING RATE
T - TEMPER - 704°C (1300°F) FOR 1 h, AIR COOL
S - STRESS RELIEF - 677°C (1250°F) FOR 40 OR 120 h
A - AGE - 345°C (650°F) FOR 1000 h



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(Data Continued)

EFFECT OF COOLING RATE[a] AND HEAT TREATMENT[b] ON THE TENSILE PROPERTIES[c] OF 2 1/4 Cr-1 Mo STEEL[d] AT TWO TEST TEMPERATURES AND AFTER AUSTENITIZING AT TWO TEMPERATURES[35], Continued

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[a] Cooling rate 3 K/s (5 °R/s) simulates that at the surface of thick (0.25-0.3 m or 10-12 in) steel plate during quenching after being austenitized; cooling rate 0.3 K/s (0.6 °R/s) simulates that at the 1/4-thickness depth.

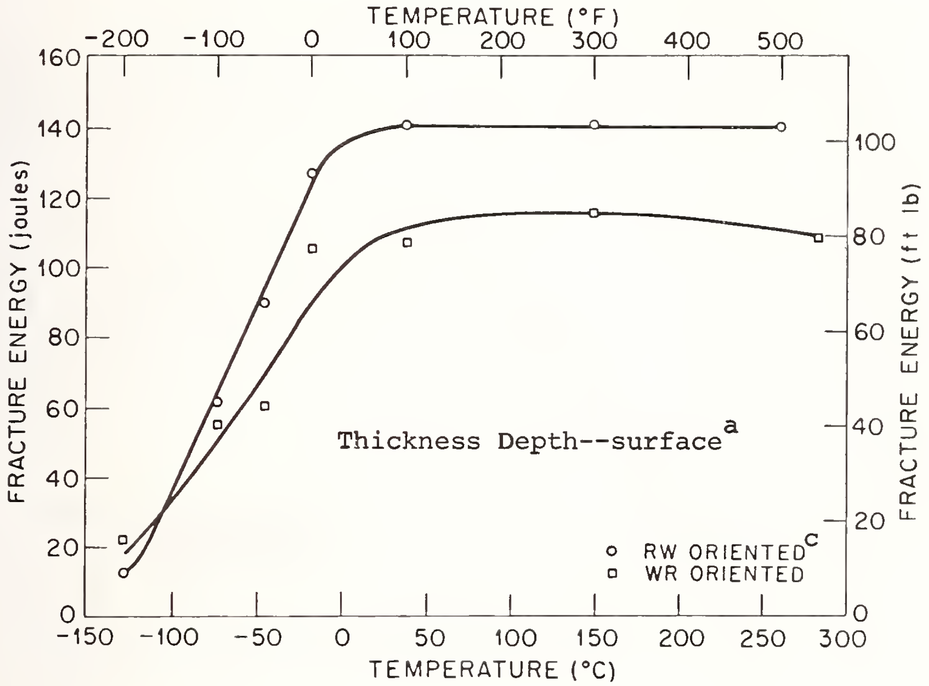
[b] A device called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific depth locations in thick steel plates that have been annealed or quenched by subjecting a steel bar up to 25.4 mm (1 in) square to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; cooling is by gas flowing directly on the specimen while additional radiant "make up heat" maintains the desired cooling rate.

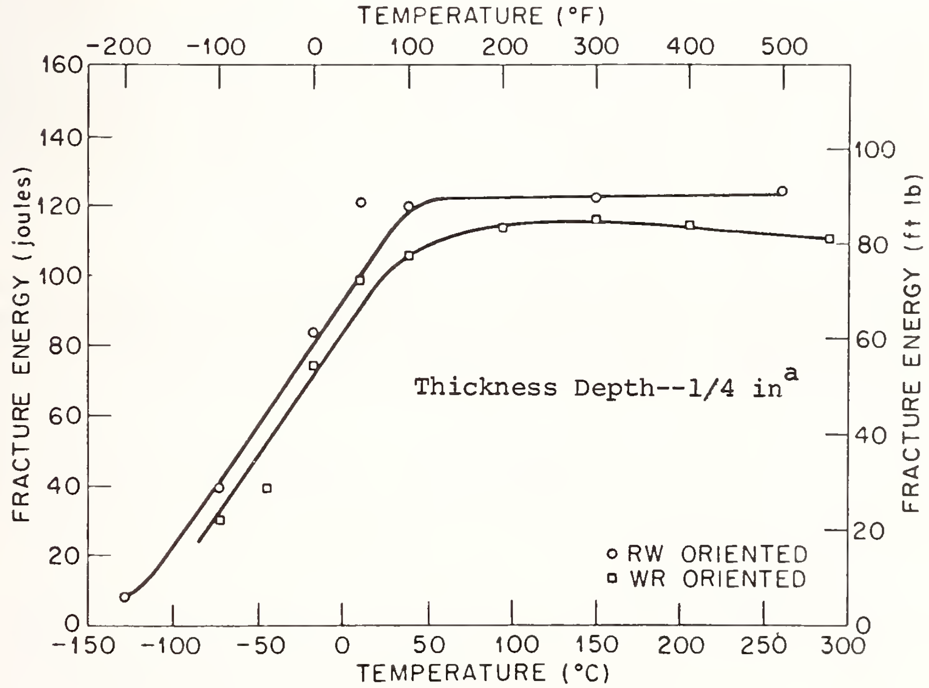
[c] Average of two specimens. All heat treatments were performed in air on 0.13 m (5 in) long x 13 mm (0.5 in) square bars; each bar provided two test specimen blanks.

[d] SA-387, gr. 22.

[Note added in proof: 927 °C = 1700 °F, not 972 °C.]

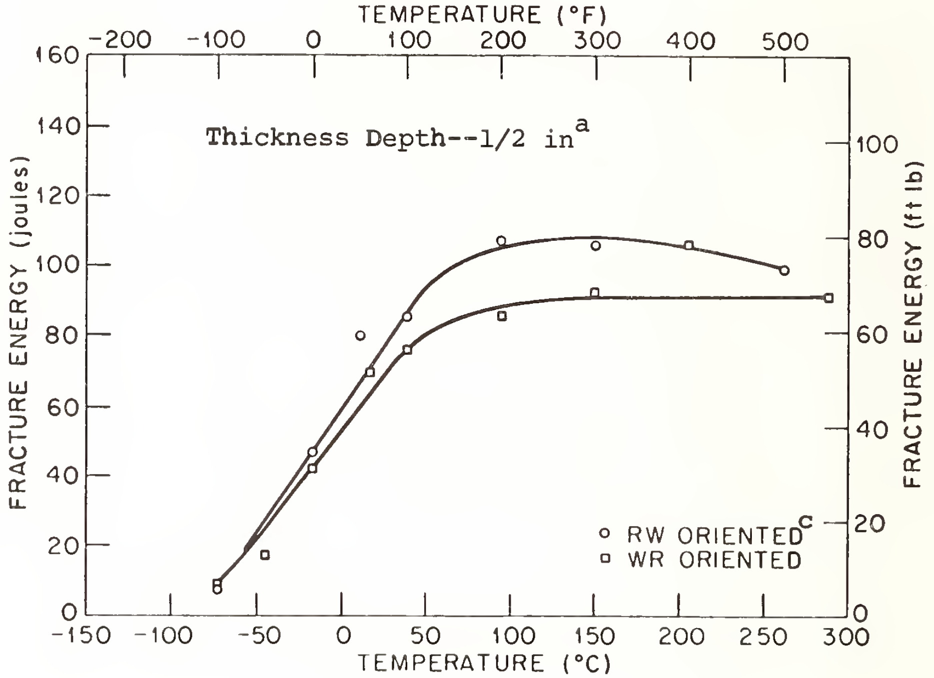
VARIATION OF CHARPY-V IMPACT ENERGY WITH TEMPERATURE AND THICKNESS DEPTH[a] FOR ASTM A543 CLASS 1 STEEL PLATE[b][35]





(Data Continued)

VARIATION OF CHARPY-V IMPACT ENERGY WITH TEMPERATURE AND THICKNESS DEPTH[a] FOR ASTM A543 CLASS 1 STEEL PLATE[b] [35], Continued



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[a] A device called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific depth locations in thick steel plates that have been annealed or quenched by subjecting a steel bar up to 25.4 mm (1 in) square to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; cooling is by gas flowing directly on the specimen while additional radiant "make-up heat" maintains the desired cooling rate.

[b] 254 mm (10 in) thick quenched and tempered plate.

[c] Specimen orientation: RW--specimen axis parallel to rolling direction (R fracture propagation transverse to RD; WR--specimen axis transverse to rolling direction, fracture propagation parallel to RD.

Heat[b] Treatment	Test Temperature (°C)	Test Temperature (°F)	Strength Properties, MPa (ksi) 0.2% Yield		Strength Properties, MPa (ksi) Ultimate		Total Elongation ($L/D = 7$) (%)	Reduction in Area (%)
					R-Oriented			
A	23	74	717	(104)	806	(117)	13.2	68
A	23	74	703	(102)	806	(117)	16.1	71
B	21	70	671	(97.4)	779	(113)	16.2	69
B	21	70	672	(97.5)	772	(112)	15.6	72
B	150	300	595	(86.4)	689	(100)	13.9	72
A	345	650	595	(86.4)	677	(98.2)	10.7	69
A	345	650	593	(86.1)	682	(99.0)	11.7	67
B	345	650	577	(83.8)	675	(98.0)	12.3	67
					W-Oriented			
A	23	74	696	(101)	792	(115)	14.3	65
A	23	74	696	(101)	792	(115)	15.3	68
B	21	70	673	(97.7)	779	(113)	15.5	68
A	345	650	594	(86.2)	681	(98.9)	11.0	65
A	345	650	590	(85.6)	677	(98.2)	10.7	64
B	345	650	575	(83.4)	678	(98.4)	13.0	66

[a] 248 mm (9 3/4 in) thick plate; specimens were removed from the 1/4-thickness depth.

[b] A - as received plus
Austenitized: 900 °C (1650 °F) for 7.5 h, water quenched;
Tempered: 620 °C (1150 °F) for 10 h;
Stress Relieved: 565 °C (1050 °F) for 58 h;
Retempered: 640 °C (1180 °F) for 10 h.

B - as received plus Stress Relief: 610 °C (1130 °F) for 40 h.

EFFECT OF COOLING RATE AND HEAT TREATMENT[a] ON THE CHARPY V-NOTCH TOUGHNESS OF 2 1/4 Cr-1 Mo (SA-387, Gr22) STEEL AFTER AUSTENITIZING[35]

Metallurgical Condition[a]	Cooling Rate[b]		41-J (30-ft-lb) Transition Temperature		Upper Shelf Energy	
	K/s	°R/s	°C	°F	J	ft-lb
Austenitized at 927 °C (1700 °F) for 1 h						
Q	0.3	0.6	46	115	52	38
Q+T	0.3	0.6	-21	-5	112	82
Q+T+SR(40)	0.3	0.6	-12	10	129	95
Q+T+SR(120)	0.3	0.6	-12	10	114	84
Q+T+SR(40)+A(1000)	0.3	0.6	-21	-5	125	92
Q	3	5	49	120	63	46
Q+T	3	5	-59	-75	109	80
Q+T+SR(40)	3	5	-57	-70	125	92
Q+T+SR(120)	3	5	-21	-5	131	96
Q+T+SR(40)+A(1000)	3	5	-34	-30	110	81
Austenitized at 1038 °C (1900°F) for 1 h						
Q	0.3	0.6	66	150	64	47
Q+T	0.3	0.6	-9	15	102	75
Q+T+SR(40)	0.3	0.6	-1	30	114	84
Q+T+SR(120)	0.3	0.6	-1	30	132	97
Q+T+SR(40)+A(1000)	0.3	0.6	-4	25	122	90
Q	3	5	43	110	69	51
Q+T	3	5	-34	-30	116	85
Q+T+SR(40)	3	5	-34	-30	124	91
Q+T+SR(120)	3	5	-54	-65	136	100
Q+T+SR(40)+A(1000)	3	5	-46	-50	136	100

Metallurgical Condition[c]	Charpy V-Notch Energy [J (ft-lb)] at Indicated Temperature -29°C(-20°F)	-12°C(+10°F)	24°C(75°F)	66°C(150°F)	121°C(250°F)
Quenched from 923 °C			27 (20)	46 (34)	52 (38)
Quenched and tempered 1 hr at 704 °C		24 (17.5)	85 (62.5)	133 (97.5)	136 (100)
Quenched and tempered and postweld heat-treated 40 hr at 677 °C	20 (15)	41 (30)	129 (95)	150 (110)	150 (110)

(Table Continued)

EFFECT OF COOLING RATE AND HEAT TREATMENT[a] ON THE CHARPY V-NOTCH OUGHNESS OF 2 1/4Cr-1 Mo (SA-387, Gr 22) STEEL AFTER AUSTENITIZING[35],

Continued

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device called DATA TRAK was used to obtain specimens whose thermal exposure mulates that of specific depth locations in thick steel plates that have been nealed or quenched by subjecting a steel bar up to 25.4 mm (1 in) square to a eselected thermal cycle. Tungsten filament quartz lamps are the heat source; oling is by gas flowing directly on the specimen while additional radiant ake-up heat" maintains the desired cooling rate. Q denotes DATA TRAK simulated ench rate. T denotes temper at 704 °C (1300°F) for 1 h; air cooled. SR denotes ress relief at 677 °C (1250°F) for 40 or 120 h; air cooled. A(1000) denotes ing at 343 °C (650°F) for 1000 h.

ese treatments simulated the surface (cooling rate 3K/s (5°R/s)) and the 1/4 ickness depth (cooling rate 0.3K/s (0.6 °R/s)) of 0.25 - 0.3 m (10-12 in) thick ate.

oled in the DATA TRAK device to simulate the 1/4-thickness depth location in 4- to 305-mm thick plate.

METAL HARDNESS[a] DATA OF ALLOYS[b] BEFORE AND AFTER EXPOSURE IN A FLUIDIZED BED COAL COMBUSTOR [c][37]

Alloy[b]	Exposure Temperature		Knoop Hardness[a]			
			As	Exposure Times		
	°F	°C	Received	10 Hours	500 Hours	1500 Hours
P9(Fe-8.9Cr-1Mo-0.7Si)	--	--	222^{+18}_{-11}			
	1245	674				236^{+10}_{-23}
304 SS(Fe-18.5Cr-8Ni-2Mn)	--	--	150^{+15}_{-12}			
	1546	841		165^{+9}_{-16}		
	1485	807				198^{+18}_{-15}
310 SS(Fe-24.5Cr-21.7Ni-1.7Mn-0.2Mo-0.4Si)	--	--	181^{+7}_{-13}			
	1487	808		153^{+15}_{-11}		
	1470	796			159^{+20}_{-13}	
	1460	793				202^{+11}_{-12}
Inconel 671(47.2Cr-52.2Ni-014Fe-0.2Si)	--	--	218^{+19}_{-19}			
	1495	813		352^{+24}_{-27}		
	1530	832				346^{+24}_{-12}
FSX414(Co-29.8Cr-0.9Fe-10.7Ni-7W-1Si-0.7Mn)	--	--	399^{+125}_{-87}			
	1490	810			395^{+111}_{-75}	
	1475	802				421^{+103}_{-82}
18-18-2(Fe-18.4Cr-18Ni-1.9Si-1.5Mn)	--	--	176^{+7}_{-4}			
	1435	779				272^{+15}_{-20}
347 SS(Fe-17.7Cr-11.7Ni-0.7Si-1.4Mn)	--	--	233^{+10}_{-7}			
	1465	796				180^{+8}_{-10}
Fe-Cr-Al Coating[d,e]						
Outer layer			365^{+69}_{-131}			
Inner layer	--	--	176^{+10}_{-10}			
Outer layer					393^{+1}_{-3}	
Inner layer	1480	804			164^{+10}_{-7}	
Outer layer						373^{+54}_{-29}
Inner layer	1505	808				153^{+5}_{-4}
Al/Cr Coating[d,f]						
Outer layer			566^{+32}_{-33}			
Inner layer	--	--	445^{+35}_{-18}			
Outer layer						524^{+1}_{-1}
Inner layer	1442	783				491^{+6}_{-3}

(Table Continued)

METAL HARDNESS[a] DATA OF ALLOYS[b] BEFORE AND AFTER EXPOSURE IN A FLUIDIZED BED COAL COMBUSTOR[c][37]

-Continued-

Alloy[b]	Exposure Temperature °F	Exposure Temperature °C	Knoop Hardness[a] As Received	Knoop Hardness[a] Exposure Times 10 Hours	Knoop Hardness[a] Exposure Times 500 Hours	Knoop Hardness[a] Exposure Times 1500 Hours
Pack Aluminized[d,g] Coating						
Outer layer			864^{+31}_{-83}			
Inner layer	--	--	632^{+100}_{-100}			
Outer layer[h]						570^{+162}_{-60}
Inner layer	1620	882				411^{+29}_{-17}

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[a] Knoop pyramid hardness, 100 gram load.

[b] Test specimens were machined from tube or bar stock to 1.25 in (3.17cm) OD, 1.00 in (2.54cm) ID, and 0.97 in (2.46cm) long. FSX414 obtained as cast rods from which specimens were machined. As machined specimens were solvent rinsed before exposure. Twenty-one specimens were used to make up a tube probe for exposure in the combustion facility.

[c] Facility consists of a 24 in diameter refractory-lined fluidized-bed combustor charged with Illinois No. 6 coal, +8 to -200 mesh and limestone from Greer Quarry, West Virginia, < 8 mesh. Combustor operated at atmospheric pressure.

[d] All layered coatings were applied to 304SS substrate, the average hardness of which varied between 150 and 200 Knoop before and after exposure. Coated specimens were wire brushed and/or hand abraded with emery cloth and solvent rinsed before exposure.

[e] This (Fe-15Cr-10Al-8Ni-1Mo-1Si) coating consists of two 3.5 mil plasma sprayed layers, the first of which was anneal bonded (Union Carbide).

[f] HI 35, duplex coating of Al over a chromized 304SS with a case depth of 10 mil (Alloy Surfaces).

[g] Diffused Al case; five hours 1700 °F in 15% Al-12Si + 2.5% NH_4Cl + 82.5% Al_2O_3 (Battelle).

[h] Exposure for this specimen was actually 1000 hours, not 1500 hours.

HARDNESS[a] AND BEND TEST[b] DATA FOR EXPERIMENTAL ALLOYS[c] [34]

Alloy Composition[c]								Solution treated 15 min, 1800 °F, followed by					Solution treated 30 min, 1800 °F, followed by						
								air cool	air cool, age 2 hr, 480 °F		air cool, age 200 hr, 885 °F		air cool	hot water quench		slow cool		air cool + 290 hr, 475	
Fe	Cr	Al	Mn	Si	Hf	Mo	Y	R_A[a]	R_A[a]	angle[b] (°)	R_A[a]	angle[b] (°)	R_A[a]	R_A[a]	angle[b] (°)	R_A[a]	angle[b] (°)	R_A[a]	angle[b] (°)
bal	5	6						59	56	79[d]	56	69							
bal	5	8						56	58	69	57	8							
bal	5	8	2.5					61	62	50	63	58							
bal	5	10						59	59	36	58	32							
bal	5	10	2.5					55	55	51	55	6							
bal	5	10	5					57	57	27	58	14							
bal	5	12	2.5					60	60	18	61	14							
bal	7.5	6						52	52	77[d]	52	29							
bal	10	8						57	58	31	58	78							
bal	10	10						58	57	12	56	22							
bal	10	10	2.5					59	57	27	58	43							
bal	10	10	5					56	57	20	56	19							
bal	10	12	2.5					55	55	18	54	20							
bal	14	5					0.5						47.6	46.9	170[e]	48.3	170[e]	58.9	170[e]
bal	15	3						48	47	88[d]	48	86							
bal	15	4						50	49	80[d]	50	86[d]							
bal	15	6						53	55	78[d]	54	85[d]							
bal	15	10						56	56	11	55	28							
bal	15	10	5					56	56	8	56	14							
bal	16	4.5												49.5	170	48.7	170		
bal	16	4.5					0.5						47.9	47.9	170[e]	51.0	170[e]	57.0	60
bal	16	4.5				0.75								48.8	170	49.6	170		
bal	16	4.5				2	0.5						51.6	50.5	170[e]	53.3	115	55.6	11
bal	16	4.5				4	0.5						53.9	52.5	170[e]	55.7	34	51.8	11
bal	16	4.5			0.5								48.3	45.4	170[e]	51.3	170[e]	61.0	170[e]
bal	16	4.5		0.25										49.2	170	50.5	137		
bal	16	4.5		0.5										51.0	170	54	170		
bal	16	4.5		1										53.5	170	54.7	85		
bal	16	4.5	0.75	0.5										51.9	170	52.3	88		
bal	16	4.5	1.5	1										55.1	170	55	42		
bal	16	5			1	2								52.7	170	55.8	170		
bal	17			3										53.8	170	52.5	170		
bal	17			3										53.4	170[e]	54.7	170[e]		
bal	17			3		2								56.5	170	57.7	153		
bal	17			3	1	1								54.8	170	54.8	170		
bal	17	3												43.8	170[e]	46.9	170[e]		
bal	18			2										50.3	170[e]	50.8	170[e]		
bal	18	1		1										43.8	170[e]	48.8	170[e]		
bal	18	2												42.3	170[e]	44.7	170[e]		
bal	18	4					0.5						48.2	46.0	170[e]	50.0	170[e]	56.6	17
bal	18	4		1										54.5	170	54.5	64		
bal	18	5			1	1								54.4	170	56.2	170		
bal	18	5		0.5										54.4	170	53.7	53		
bal	18	5		0.5		2								54.5	170	56.0	93		
bal	18	6												53.0	170[e]	53.9	170[e]		
bal	18	6		0.5										48.8	65	55.5	--		
bal	18	6		1										53.2	90	56.8	68		
bal	18	6		2										58.5	15	59.2	13		
bal	19			1										41.3	170[e]	47.3	170[e]		
bal	19	1												38.4	170[e]	42.7	170[e]		
bal	20													44.9	170[e]	--	--		

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[a] Rockwell Hardness at ambient temperature.

[b] Coupons (0.055 in. x 0.75 in. x 1.5 in.) were bent 170° over a 2t radius or to a lesser angle at which failure by cracking was observed.

[c] Alloys were arc melted and drop cast by the nonconsumable electrode process under argon at 1.5 atm. Cast structure broken up by extrusion from 2000 °F (canned in stainless steel) and hot rolling from 1600 °F (10 percent reduction in thickness per pass and reheated between passes) to 0.1 in. thickness. The 0.1 in. strips were rerolled at 2000 °F to 0.07 in. thick sheets. Surfaces conditioned by grit blasting.

[d] Did not fail.

[e] No cracking observed.

HARDNESS AND CHARPY V-NOTCH ENERGY OF EXPERIMENTAL SECONDARY HARDENING MARTENSITIC STEELS[a] AS FUNCTIONS OF TEMPERING TEMPERATURES AND ALLOY ELEMENT MODIFICATION[41]

Alloy[a]	Tempering Temperature[c] °C	Hardness R_c	Charpy V-Notch Energy (ft-lbs)
Base Alloy[b] (0.36C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, balance Fe)	as quenched	56.5	14
	200	52.2	30
	300	48.5	18
	400	46.5	18
	500	47.0	24
	550	47.5	31
	600	46.5	31
Base + 2 Si (0.38C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, 1.96Si, balance Fe)	as quenched	56.0	14
	200	54.5	21
	300	54.3	18
	400	54.3	14
	500	54.0	9
	550	53.8	13
	600	50.3	3
Base + 3 Si (0.38C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, 1.96Si, balance Fe)	as quenched	60.5	15
	200	55.5	21
	300	55.8	24
	400	55.6	21
	500	57.0	6
	550	55.4	12
	600	51.6	5
Base + 2Si + .25V (0.36C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, 2.05Si, 0.25V, balance Fe)	as quenched	57.0	14
	200	54.8	21
	300	54.5	16
	400	54.4	13
	500	55.1	10
	550	53.0	15
	600	48.0	4
Base + 2Si + 0.4V[d] (0.35C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, 2.15Si, 0.40V, balance Fe)	as quenched	56.9	14
	200	54.3	24
	300	53.7	18
	400	54.3	13
	500	54.7	11
	550	55.1	15
	600	53.1	3
Base + 1Al + 1Si + 0.25V (0.37C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, 0.89Al, 1.07Si, 0.25V, balance Fe)	as quenched	58.5	12
	200	54.3	22
	300	54.2	15
	400	54.1	12
	500	55.1	8
	550	54.7	16
	600	53.6	9
	650	50.3	6

(Table Continued)

HARDNESS AND CHARPY V-NOTCH ENERGY OF EXPERIMENTAL SECONDARY HARDENING MARTENSITIC STEELS[a] AS FUNCTIONS OF TEMPERING TEMPERATURES AND ALLOY ELEMENT MODIFICATION[41]

continued

Alloy[a]	Tempering Temperature[c] °C	Hardness R_c	Charpy V-Notch Energy (ft-lbs)
Base + 1Al +	as quenched	55.5	15
1Si + 0.4V	200	54.0	23
(0.37C, 0.5Mn	300	54.2	14
1.0Cr, 3.0Ni,	400	54.1	13
2.0Mo, 0.82Al,	500	55.0	12
1.11Si, 0.40V,	550	55.0	17
balance Fe)	600	54.5	10
	650	51.5	14

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[a] Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests were obtained from the bars. Indicated heat treatment (austenitization under argon, quenching or isothermal transformation, tempering, etc.) was applied to the specimen blanks.

[b] Base alloy is a developmental material derived from prior screening. Nomina compositions in wt. %. Values for C, Al and Si from chemical analysis.

[c] Unless specified differently the samples were austenitized at 1050 °C for 1 hour followed by oil quenching. Tempered samples were then held at indicated temperatures for one hour followed by air or water quench.

[d] Austenitization temperature was 1100 °C for this composition.

TENSILE PROPERTIES OF EXPERIMENTAL SECONDARY HARDENING MARTENSITIC TEELS[a] AS FUNCTIONS OF TEMPERING TEMPERATURE AND ALLOY ELEMENT MODIFICATION[41]

y[a]	Tempering Temperature[c] °C	0.2 % Yield Strength(ksi)	Ultimate Tensile Stress(ksi)	Total Elongation (%)
Alloy[b]	as quenched	220	335	5.9
6C, 0.5Mn, 1.0Cr,	200	206	265	8.3
n, 2.0Mo, balance	300	198	240	7.8
	400	190	228	7.6
	500	187	223	10.7
	550	194	225	13.3
	600	198	219	13.0
+ 2 Si	as quenched	242	346	4.5
8C, 0.5Mn, 1.0Cr,	200	240	300	6.7
i, 2.0Mo, 1.96Si,	300	248	293	7.5
nce Fe)	400	243	280	8.0
	500	233	289	6.1
	550	235	270	10.4
	600	240	-	-
+ 3 Si	as quenched	-	-	-
38C, 0.5Mn, 1.0Cr	200	260	312	-
Ni, 2.0Mo, 2.95 Si,	300	263	307	9.3
ance Fe)	400	270	308	9.6
	500	266	312	3.8
	550	266	287	4.2
	600	-	-	-
+ 2 Si + 0.25V	as quenched	254	356	4.3
36C, 0.5Mn, 1.0Cr,	200	233	296	7.4
Ni, 2.0Mo, 2.05Si,	300	239	290	7.5
5V, balance Fe)	400	244	286	6.4
	500	240	290	7.8
	550	247	290	9.5
	600	-	-	-
+ 2 Si + 0.4V[d]	as quenched	247	337	4.0
35C, 0.5Mn, 1.0Cr,	200	225	293	6.8
Ni, 2.0Mo, 2.15Si,	300	230	283	6.5
0V, balance Fe)	400	240	278	5.9
	500	242	295	4.0
	550	251	294	5.0
	600	255	-	-
e + 1 Al + 1 Si+.25V	as quenched	241	334	5.0
37C, 0.5Mn, 1.0Cr,	200	234	291	7.5
Ni, 2.0Mo, 0.89Al	300	237	284	7.0
7Si, 0.25V, balance Fe)	400	242	287	6.3
	500	246	295	7.1
	550	243	293	9.5
	600	252	283	8.3
	650	230	246	-

(Table Continued)

TENSILE PROPERTIES OF EXPERIMENTAL SECONDARY HARDENING MARTENSITIC STEELS[a] AS FUNCTIONS OF TEMPERING TEMPERATURE AND ALLOY ELEMENT MODIFICATION[41]

continued

Alloy[a]	Tempering Temperature[c] °C	0.2% Yield Strength(ksi)	Ultimate Tensile Stress(ksi)	Total Elongation (%)
Base + 1Al+1Si+0.4V (0.37C, 0.5Mn, 1.0Cr, 3.0Ni, 2.0Mo, 0.82Al, 1.11Si, 0.40V, balance Fe)	as quenched	226	320	5.5
	200	235	289	8.5
	300	238	280	8.5
	400	244	277	7.8
	500	236	281	8.4
	550	251	295	10.5
	600	256	288	10.2
	650	243	258	8.1

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[a] Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests were obtained from the bars. Indicated heat treatment (austenitization under argon, quenching or isothermal transformation, tempering, etc.) was applied to the specimen blanks.

[b] Base alloy is a developmental material derived from prior screening. Nominal compositions in wt %. Values for C, Al and Si from chemical analysis.

[c] Unless specified differently the samples were austenitized at 1050 °C for 1 hour followed by oil quenching. Tempered samples were then held at indicated temperatu for one hour followed by air or water quench.

[d] Austenitization temperature was 1100 °C for this composition.

EFFECT OF HEAT TREATMENT ON HARDNESS AND CHARPY V-NOTCH ENERGY OF EXPERIMENTAL BAINITIC SECONDARY HARDENING STEELS[a][41]

loy[a]	Tempering Temperature, °C	Hardness (Rockwell C)			Charpy V-Notch Energy (ft-lbs)		
		HT1[b]	HT2[b]	HT3[b]	HT1	HT2	HT3
.se (0.39C,	as quenched	54.0	38.0	49.0	-	3.0	16.0
1Mo, 0.3V	300	-	38.0	-	-	-	-
5Mn, balance	400	49.0	39.0	46.8	-	4.0	18.0
)	450	48.5	38.5	-	23.5	-	-
	500	49.0	28.0	46.2	20.3	3.5	15.5
	550	48.6	41.2	48.1	25.0	4.5	13.0
	600	50.8	46.2	49.3	21.3	2.0	9.0
	650	48.3	-	-	10.0	-	-
se + 2 Cr	as quenched	56.0	49.0	52.0	-	7.0	13.5
.4C, 1.98 Mo,	300	-	48.0	49.5	-	7.0	14.4
.3V, 0.5Mn,	400	50.0	48.0	50.0	19.0	5.0	8.5
.03Cr, balance	450	49.0	47.5	50.1	19.0	-	10.2
)	500	51.0	47.0	51.2	22.0	3.8	7.5
	550	51.8	49.0	51.6	27.0	4.0	8.0
	600	49.5	48.0	50.6	17.0	4.9	8.5
ase + 2 Cr +	as quenched	57.5	52.0	54.0	-	18.0	28.6
Ni (0.39C,	300	-	51.0	50.7	-	18.0	28.5
.93Mo, 0.3V,	400	50.6	51.0	51.0	24.0	18.0	22.5
.5Mn, 1.93Cr,	450	50.0	50.5	51.0	24.5	-	24.0
.06Ni, balance	500	50.5	51.0	51.2	24.5	15.0	24.0
e)	550	52.8	52.7	52.9	35.0	10.5	31.0
	600	51.0	51.5	51.3	36.5	15.0	35.0

Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests were obtained from the bars. Indicated heat treatment (austenitization under argon, quenching or isothermal transformation, tempering, etc.) was applied to the specimen blanks.

Heat Treatments

HT1 = austenitized 1000 °C (1 hr), oil quench, temper (1 hr).
HT2 = austenitized 1000 °C (1 hr), isothermally transformed (1 hr) (base 315 °C, base + 2 Cr 300 °C, base + 2 Cr + 3 Ni 280 °C) above M_s temperature, oil quench, temper (1 hr).
HT3 = austenitized 1000 °C (1 hr), isothermally transformed (1 hr) (base 300 °C, base + 2 Cr 250 °C, base + 2 Cr + 2 Ni 225 °C) below M_s temperature, oil quench, temper (1 hr).

EFFECT OF HEAT TREATMENT ON TENSILE PROPERTIES OF EXPERIMENTAL BAINITIC SECONDARY HARDENING STEELS[a] [41]

Alloy[a]	Tempering Temperature °C	0.2% Yield Strength (ksi)			Ultimate Tensile Strength (ksi)			Elongation (%)		
		HT1[b]	HT2[b]	HT3[b]	HT1	HT2	HT3	HT1	HT2	HT3
Base (0.39C, 2.1Mo, 0.3V, 0.5Mn, balance Fe)	as quenched	219	136	161	296	167	191	12.2	16.1	16.
	500	205	-	150	227	-	180	15.8	-	17.
	550	217	138	135	233	172	168	7.6	21.3	18.
	600	215	171	188	240	194	207	9.0	17.9	19.
	650	214	-	-	217	-	-	12.1	-	-
Base + 2 Cr (0.4C, 1.98Mo, 0.3V, 0.5Mn, 2.03Cr, balance Fe)	as quenched	225	188	199	305	228	258	8.8	14.1	9.
	400	194	185	194	239	224	244	9.4	12.2	11.
	500	211	183	185	244	224	238	15.4	18.5	14.
	550	202	194	210	245	229	243	17.2	18.5	14.
	600	206	192	204	237	224	241	18.6	18.4	17.
Base + 2Cr + 3Ni (0.39C, 1.93Mo, 0.3V, 0.5Mn, 1.93Cr, 3.06Ni, balance Fe)	as quenched	222	196	204	296	289	299	5.3	8.5	8.
	400	196	180	191	246	236	238	10.4	11.8	16.
	500	207	178	195	254	255	256	16.6	13.8	19.
	550	211	215	217	256	254	254	17.7	12.0	17.
	600	214	210	215	248	244	242	16.8	15.3	18.

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[a] Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests were obtained from the bars. Indicated heat treatment (austenitization under argon, quenching or isothermal transformation, tempering, etc.) was applied to the specimen blanks.

[b] Heat Treatments

HT1 = austenitized 1000 °C (1 hr), oil quench, temper (1 hr).

HT2 = austenitized 1000 °C (1 hr), isothermally transformed (1 hr) (base 315 °C, base + 2 Cr 300 °C, base + 2 Cr + 3 Ni 280 °C) above M_s temperature, oil quench, temper (1 hr).

HT3 = austenitized 1000 °C (1 hr), isothermally transformed (1 hr) (base 300 °C, base + 2 Cr 250 °C, base + 2 Cr + 2 Ni 225 °C) below M_s temperature, oil quench, temper (1 hr).

HARDNESS AND TOUGHNESS OF EXPERIMENTAL MATRIX STEELS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b] [41]

Alloy[a]	Tempering Temperature[b]	Hardness Rockwell C	Charpy V-Notch Energy	Plane Strain Fracture Toughness
Alloy 1[c]	As quenched	56.0	7.5 ft-lb	25.0 ksi√in
(0.46C-	200 °C	53.5	7.8	29.5
4.11Cr-2.8Mo-	300	54.0	9.5	30.7
1.62W-1.38V-	400	52.8	6.8	30.6
balance Fe)	450	51.2	---	----
	500	53.3	6.8	27.8
	550	54.5	5.8	25.1
	600	52.0	7.0	35.2
	650	43.5	9.3	38.1
Alloy 2	As quenched	57.0	14.5	30.3
(0.47C-	200	56.5	15.0	35.2
4.20Cr-2.2Mo-	300	53.5	18.0	37.2
0.70W-1.43V-	400	53.0	14.0	34.9
balance Fe)	450	52.5	----	----
	500	54.5	16.0	30.8
	550	54.5	16.5	31.3
	600	52.0	14.5	38.1
	650	45.5	16.5	44.2
Alloy 3	As quenched	60.5	9.0	25.5
(0.52C-	200	59.5	12.0	30.1
4.30Cr-2.2Mo-	300	54.0	16.0	31.4
1.68W-0.67V-	400	55.5	16.5	29.8
balance Fe)	450	55.5	----	----
	500	56.0	15.0	27.0
	550	55.5	14.5	24.2
	600	54.0	14.5	31.3
	650	45.5	17.0	36.2
Alloy 4	As quenched	57.0	22.5	--
(0.38C-	200	56.0	27.0	--
4.40Cr-2.0Mo-	300	53.0	27.5	--
0.49W-0.43V-	400	52.5	25.5	--
balance Fe)	450	51.5	25.0	--
	500	52.5	27.5	--
	550	52.5	40.0	--
	600	50.5	43.5	--
	650	44.5	55.5	--

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[a] Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests were obtained from the bars. Indicated heat treatment was applied to the specimen blanks.

[b] All samples austenitized one hour at 1000 °C, oil quenched, and tempered one hour at indicated temperature.

[c] Composition corresponds to commercial VASCO MA steel.

EFFECT OF HEAT TREATMENT ON HARDNESS AND TOUGHNESS OF AN EXPERIMENTAL MATRIX STEEL[a,b,c][41]

	Hardness (Rockwell C)			Charpy V-Notch Energy (ft-lbs)		
Austenitization Temperature →	1000 °C	1050 °C	1100 °C	1000 °C	1050 °C	1100 °C
Tempering Temperature						
as quenched	57.0	59.5	60.5	22.5	8.0	8.0
200 °C	56.0	57.5	58.0	27.0	17.0	15.0
300	53.0	53.5	54.8	27.5	14.5	14.0
400	52.5	52.0	53.0	25.5	16.5	12.5
450	51.5	53.0	53.5	25.0	19.5	14.0
500	52.5	54.5	56.0	27.5	21.5	15.5
550	52.5	54.5	56.0	40.0	36.5	16.0
600	50.5	52.5	53.0	43.5	53.0	16.5
650	44.5	46.0	47.5	55.0	14.0	8.5

---

[a] Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw materials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and forged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests were obtained from the bars. Indicated heat treatment (austenitization under argon, quenching or isothermal transformation, tempering, etc.) was applied to the specimen blanks.

[b] Composition in wt %: 0.38C, 4.40Cr, 2.0Mo, 0.49W, 0.43V, balance Fe. Designated as B17 in original reports.

[c] Samples austenitized for one hour at indicated temperature and oil quenched. Tempering time was onehour followed by a water quench.

TENSILE PROPERTIES OF EXPERIMENTAL MATRIX STEELS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b][41]

loy[a]	Tempering Temperature[b] °C	0.2% Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)
loy 1[c]	as quenched	235	290	1.0
.46C, 4.11 Cr,	200	250	273	3.3
3Mo, 1.62W,	300	234	267	6.7
38V, balance	400	229	262	5.0
)	500	225	272	9.5
	550	233	280	10.5
	600	230	271	12.0
	650	173	205	14.0
loy 2	as quenched	246	242	2.5
.47C, 4.20Cr,	200	259	328	4.6
2Mo, 0.70W,	300	242	282	8.2
43V, balance Fe)	400	236	280	6.6
	500	228	284	7.7
	550	244	287	10.1
	600	242	276	13.1
	650	185	218	13.4
loy 3	as quenched	271	342	1.0
.52C, 4.30Cr,	200	284	351	2.0
2Mo, 1.68W,	300	274	320	4.2
67V, balance	400	255	310	7.2
)	500	271	317	5.2
	550	234	313	7.8
	600	260	293	10.0
	650	189	223	12.1

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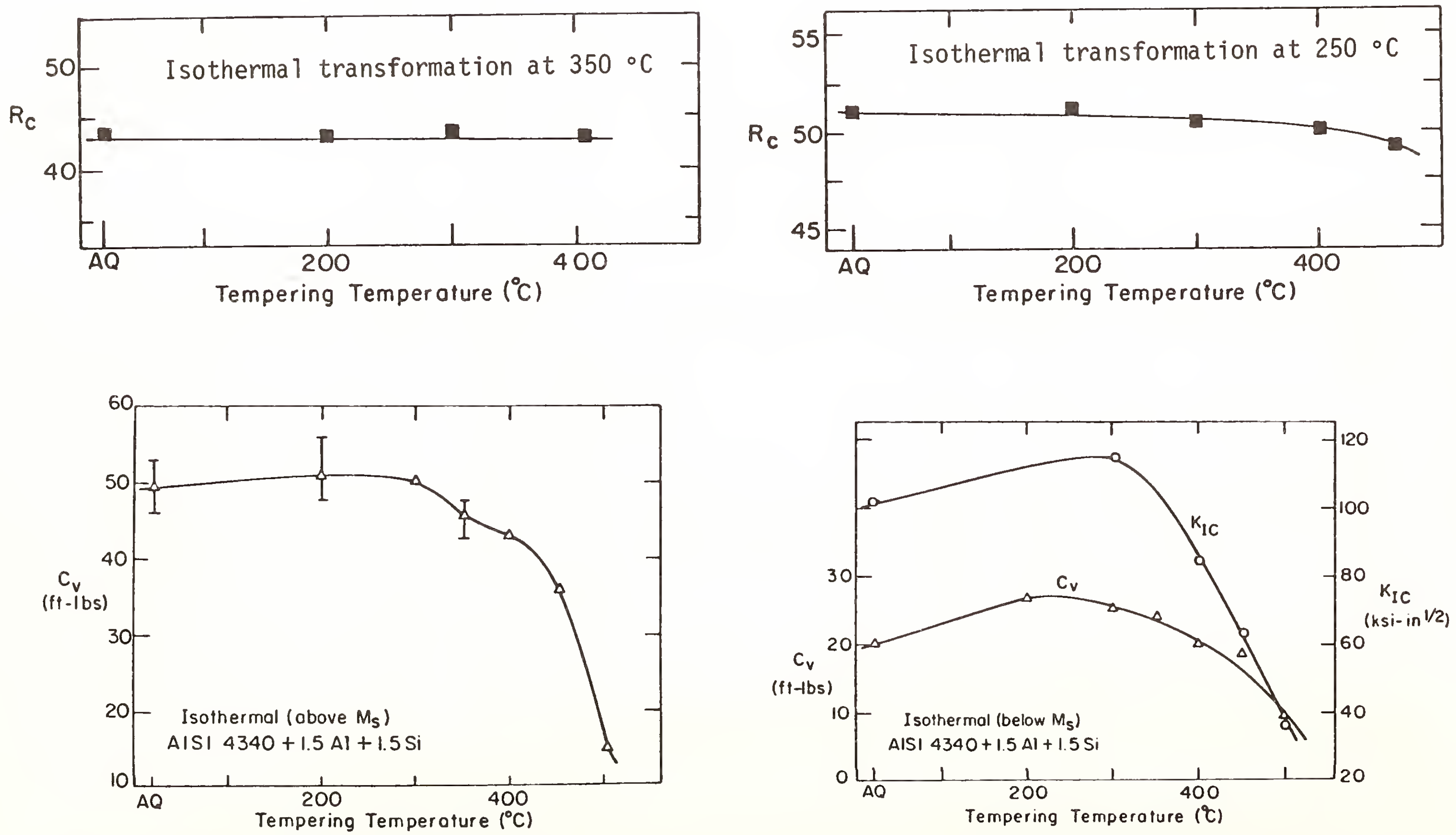
repared as 11.3 kg ingots in an induction furnace under argon atmosphere. Raw aterials were 99.9% pure. Ingots were homogenized at 1200 °C for 24 hours and orged at 1200 °C to bars about 2.5 cm thick. Specimen blanks for various tests re obtained from the bars. Indicated heat treatment (austenitization under rgon, quenching or isothermal transformation, tempering, etc.) was applied to he specimen blanks.

ll samples austenitized one hour at 1000 °C, oil quenched, and tempered one our at indicated temperature.

omposition corresponds to commercial VASCO MA steel.

EFFECT OF HEAT TREATMENT ON HARDNESS AND TOUGHNESS OF A MODIFIED AISI 4340 STEEL[a] [41]



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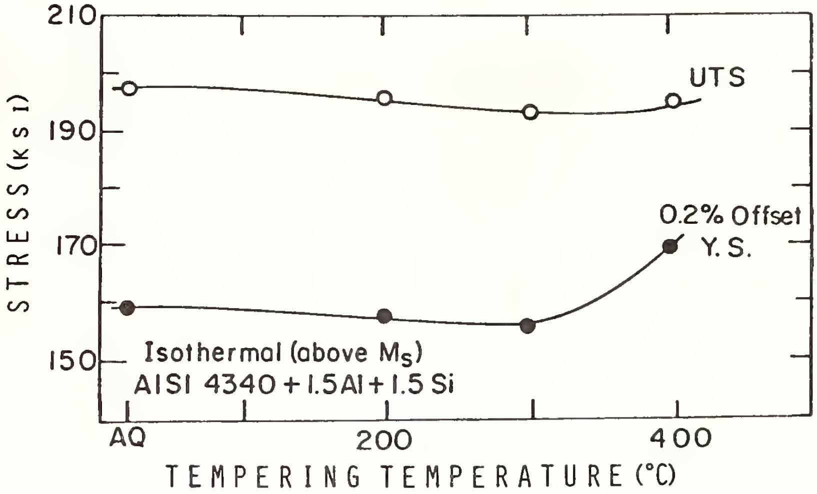
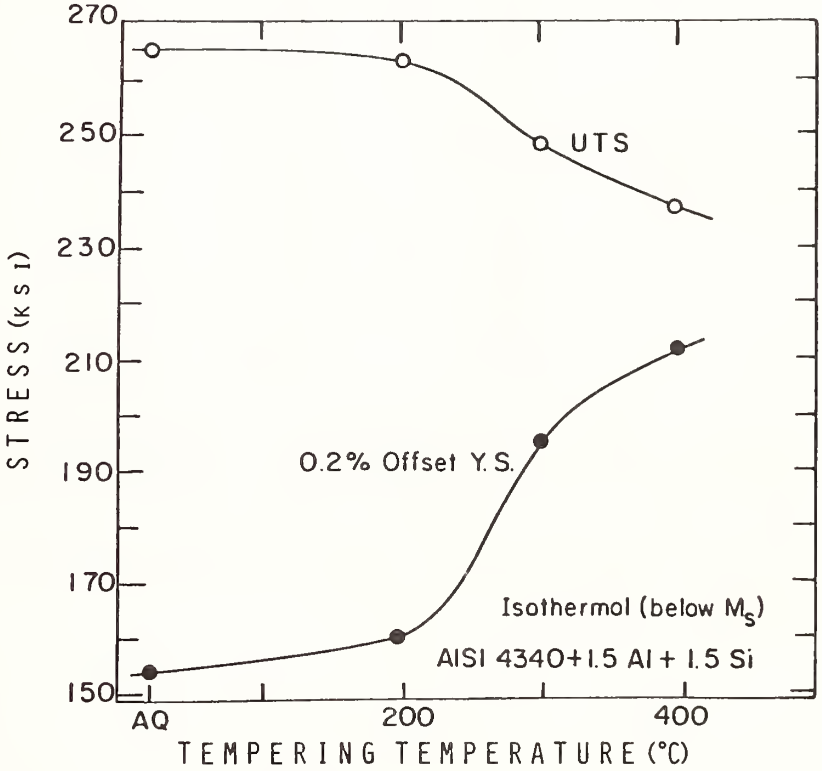
[a] Remelted commercial 4340 steel plus added 1.5% Al and 1.5% Si; austenitized at 1000 °C for 1 hour, isothermally transformed for 1 hour at the indicated temperature, quenched, tempered 1 hour and quenched. M_s temperature = 300 °C.

EFFECT OF HEAT TREATMENT ON THE TENSILE PROPERTIES OF A MODIFIED AISI 4340 STEEL[a][41]

Isothermal transformation at 350 °C for one hour



Isothermal transformation at 250 °C for one hour



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[a] Remelted commercial 4340 steel plus added 1.5% Al and 1.5% Si; austenitized at 1000 °C for 1 hour, isothermally transformed for 1 hour at the indicated temperature, quenched, tempered one hour and quenched. M_s temperature = 300 °C.

HARDNESS AND TOUGHNESS PROPERTIES OF EXPERIMENTAL Cr-Si-Mo STEELS[a][41]

Alloy[a]	Tempering Temperature[b] °C	Hardness (R_c)	Charpy V-Notch Energy (ft-lbs)		Work to Fai KSI·$\frac{IN}{IN}$
			Ambient Temp.	-40 °C	
0.3C, 2.0Cr, 1.5Si, 0.3Mo, balance Fe[c]	as quenched	52.7	19	12	32.3
	100	53.4	17	-	36.0
	150	53.8	20	18	36.3
	200	53.1	23	17	33.9
	250	52.7	23	19	34.1
	300	51.8	17	-	29.3
	400	52.0	12	-	30.9
	500	58.0	18	-	29.1
0.4C, 2.0Cr, 1.5Si, 0.3Mo, balance Fe	as quenched	58.9	6	6	14.0
	100	58.0	6	-	13.6
	150	58.6	12	9	21.4
	200	57.1	13	12	29.3
	250	56.0	16	10	28.2
	300	54.7	8	-	27.1
	400	54.7	10	-	23.9
	500	49.3	14	-	29.7
0.3C, 3.0Cr, 1.5Si, 0.3Mo, balance Fe	as quenched	52.8	17	16	39.9
	100	54.8	21	-	40.4
	150	54.7	22	22	37.2
	200	53.0	29	27	39.4
	250	52.7	31	24	37.9
	300	53.2	21	-	34.9
	400	52.4	22	-	37.1
	500	49.4	18	-	37.2

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[a] Prepared as 11.3 kg cast ingots, in an argon atmosphere, using an induction furnace and 99.9% purity raw materials.

[b] Austenitized at 900 °C (1 hr), oil quenched, tempered 1 hr.

[c] Stated to correspond to a commercial ESCO steel which was not identified further.

TENSILE PROPERTIES OF EXPERIMENTAL Cr-Si-Mo STEELS[a] [41]

loy[a]	Tempering Temperature[b] °C	0.2% Yield Strength, ksi	Ultimate Tensile Strength, ksi	Reduction in Area %	Elongation %
3C, 2.0Cr, 5Si, 0.3Mo, lance Fe[c]	as quenched	203	300	15.3	8.3
	100	202	298	19.0	9.1
	150	213	294	21.9	9.6
	200	221	285	23.9	9.0
	250	237	290	28.0	13.0
	300	230	277	28.4	8.1
	400	216	249	34.3	9.6
	500	205	230	33.0	10.3
4C, 2.0Cr, 5Si, 0.3Mo, lance Fe	as quenched	251	331	3.8	2.2
	100	242	331	3.0	3.0
	150	253	344	6.9	2.8
	200	256	322	11.3	1.1
	250	264	315	16.3	5.9
	300	263	313	16.7	10.2
	400	256	291	16.0	-
	500	215	246	27.4	10.0
3C, 3.0Cr, 5Si, 0.3Mo, lance Fe	as quenched	211	304	26.0	8.8
	100	213	304	31.7	12.0
	150	220	298	27.5	7.3
	200	212	284	35.7	12.9
	250	231	276	47.0	12.6
	300	232	281	37.0	14.8
	400	232	268	48.2	14.3
	500	196	240	39.2	13.3

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repared as 11.3 kg cast ingots, in an argon atmosphere, using an induction urnace and 99.9% purity raw materials.

ustenitized at 900 °C (1 hr), oil quenched, tempered 1 hour.

tated to correspond to a commercial ESCO steel which was not identified further.

TENSILE PROPERTIES OF COMMERCIAL AND HEAT-TREATED AND COMPOSITION-MODIFIED Cr-Mo STEELS FOR USE AS PRESSURE VESSEL SHELLS[40]

	Heat Treatment[b]							
Alloy[a]	Austenitization	Tempering	Plate Location[c]	Cooling Process	0.2% Yield Strength ksi	Ultimate Tensile Strength, ksi	Elongation (1 in) %	Red in
A387 grade 22 Commercial 6 in plate reheat treated	1000 °C	650 °C	8 in 1/4T		81.4	95.4	23.7	
A387 developmental ingot	900 °C	625 °C	8 in 1/4T		81.4 77.8	114.6 110.4	18.5 20.3	
A542, small ingots			8 in 1/4T	air cool	81.9 77.8	114.6 110.4	18.5 20.3	
A542, small ingot			12 in 1/4T	accelerated cool	58.5 60.2	100.6 104.3	19.9 19.0	
A542, reheat treated	1000 °C, 1 hr	650 °C, 4 h	8 in 1/4T		81.4 81.9 77.9	95.4[d] 114.6 110.4	23.7 18.5 20.3	
A542 base +0.5% Ni	1000 °C	650 °C 4 h	8 in 1/4T	immersion quench	94.0	111.5	21.4	
A542 base +0.5% Ni	1000 °C	650 °C, 4 h	8 in 1/4T	air cool	94.4	112.5	22.5	
A542 base +1% Ni	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	103.1 98.9	120.7 116.8	22.1 22.3	
A542 base +1% Ni grain refined	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	99.3 100.4	115.2 116.1	22.2 21.6	
A542 base +0.5% Mn	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	95.0	112.2	19.4	
A542 base +0.5% Mn	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	air cool	95.5	112.7	19.1	
A542 base +0.5% Mn grain refined	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	98.2 99.3	113.8 115.8	22.4 23.7	
A542 base +0.5% Cr	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	94.2	111.8	23.1	
A542 base +0.5% Cr	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	air cool	90.7	108.7	19.7	
A542 base +0.5% Mo	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	101.8	118.3	20.2	
A542 base +0.5% Mo	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	air cool	93.8	114.3	21.0	
A542 base +0.5% Ni +0.5% Mn	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	88.9 88.2	108.3 107.8	23.6 23.1	
A542 base +1% Ni +0.5% Mn grain refined	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	102.2	118.4	21.6	
A542 base +1% Ni +0.5% Mn +0.75% Cr grain refined	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	90.2 90.4	111.4 110.6	24.5 23.0	
A542 base +1% Ni +1% Mn +1% Si	1000 °C, 1 h	650 °C, 4 h	8 in 1/4T	immersion quench	98.6 101.8	122.5 125.4	18.4 20.5	
A542 base +0.5% Ni	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	immersion quench	94.0	112.3	21.9	
A542 base +0.5% Mn	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	immersion quench	92.8	110.5	22.5	
A542 base +0.5% Cr	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	immersion quench	93.6	110.3	18.1	
A542 base +0.5% Mo	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	immersion quench	95.6	119.5	17.0	

(Table Continued)

TENSILE PROPERTIES OF COMMERCIAL AND HEAT-TREATED AND COMPOSITION-MODIFIED Cr-Mo STEELS FOR USE AS PRESSURE VESSEL SHELLS[40]

-Continued-

	Heat Treatment[b]							
loy[a]	Austenitization	Tempering	Plate Location[c]	Cooling Process	0.2% Yield Strength ksi	Ultimate Tensile Strength, ksi	Elongation (1 in) %	Reduction in Area %
se +1% Mn	900 °C	625 °C	10 in		--	115.0	22.1	67.8
			1/4T		102.9	117.1	24.4	65.9
se +1% Mn	900 °C	625 °C	10 in		99.2	112.7	22.7	70.6
			1/4T		101.9	115.9	21.6	69.8
ade 22	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	spray quench	80.8	96.4	22.1	67.4
se	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	spray quench	59.4[e]	102.4[e]	21.5[e]	69.5[e]
ase +1% Mn	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	spray quench	85.8[e]	103.2[e]	25.0[e]	72.8[e]
ase +0.5% Ni Mn	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	spray quench	89.2[e]	106.9[e]	24.1[e]	70.0[e]
ase +0.5% Ni Mn grain ed	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	spray quench	91.5[e]	107.8[e]	25.9[e]	69.8[e]
ase +1% Ni Mn	1000 °C, 1 h	650 °C, 4 h	12 in	spray quench	89.47	107.32	24.5	69.5
			1/4T		91.55	108.92	23.9	64.2
ase +1% Ni Mn +0.75% Cr	1000 °C, 1 h	650 °C, 4 h	12 in 1/4T	spray quench	89.9[e]	103.5[e]	26.0[e]	72.3[e]
ase	1000 °C, 1 h	700 °C, 4 h	12 in 1/4T	spray quench	72.4[e]	92.8[e]	24.9[e]	71.9[e]
ase +1% Mn	1000 °C, 1 h	700 °C, 4 h	12 in 1/4T	spray quench	72.2[e]	93.3[e]	22.8[e]	64.3[e]
ase +0.5% Ni Mn	1000 °C, 1 h	700 °C, 4 h	12 in 1/4T	spray quench	70.4[e]	91.6[e]	23.8[e]	69.9[e]
ase +0.5% Ni Mn grain ed	1000 °C, 1 h	700 °C, 4 h	12 in 1/4T	spray quench	75.5[e]	94.2[e]	25.2[e]	69.4[e]
ase +1% Ni Mn	1000 °C, 1 h	700 °C, 4 h	12 in 1/4T	spray quench	70.1[e]	91.9[e]	28.7[e]	70.9[e]
ase +1% Ni Mn +0.75% Cr	1000 °C, 1 h	700 °C, 4 h	12 in	spray quench	72.4[e]	93.3[e]	27.1[e]	69.7[e]

---

oximate base composition for A387 is $\sim$2.25 Cr, $\sim$1 Mo, $\sim$0.4 Mn, $\sim$0.2 Si, $\sim$0.1 C, balance Fe, and for A542 is $\sim$2.25 Cr, $\sim$1 Mo, Mn, $\sim$0.3 Si, 0.15 C, 0.1 Ni, balance Fe.

l ingots of commercial and composition-modified steels were reheat treated in an induction furnace. The furnace was programmed controlled to provide small ingots with the heat treatments and cooling rates characteristic of specific location in thick slabs.

means the 1/4 thickness location within the plate thickness designated.

a 0.10% C heat.

es are those for the average of three tests.

TENSILE PROPERTIES OF COMMERCIAL AND HEAT-TREATED AND COMPOSITION-MODIFIED Mn-Mo-Ni STEELS FOR USE AS PRESSURE VESSEL SHELLS[40]

	Heat Treatment[b]							
Alloy[a]	Austenitization	Tempering	Plate Location[c]	Cooling Process	0.2% Yield Strength ksi	Ultimate Tensile Strength, ksi	Elongation (1 in) %	Reduction in Area %
A533B, Commercial 6 in plate steel	925 °C	680 °C	6 in 1/2T		66.0 66.4	89.3 89.5	25.7 25.3	68.6 69.7
A533B, reheat treated[d] 6 in plate	900 °C	625 °C	6 in 1/2T		69.4 77.6	93.3 100.0	24.5 24.3	65.4 63.4
A508[e] class 2 Commercial forging steel, 14 in thick	895 °C	670 °C (stress relieved 625 °C)	14 in 1/4T		59.3 58.7	83.3 82.7	26.8 28.4	70.3 73.3
A508, reheat treated[d] 14 in plate	900 °C	625 °C	14 in 1/4T		71.4 73.3	93.2 94.4	22.6 22.9	61.9 58.9
A533B, small ingot, simulated 8 in plate, treated			8 in 1/4T	immersion quench	89.4 90.0	108.3 109.3	22.9 22.6	68.6 69.1
A533B, small ingot, simulated 12 in plate treated			12 in 1/4T	immersion quench	89.3 88.9	107.4 107.3	22.5 22.8	66.8 67.9
A533B, As-received 9 in plate					68.7	88.0	25.0	61.7
A533B, reheat treated, 8 in plate	900 °C, 5 h	normalized	8 in 1/4T	immersion quench	66.1 68.5	89.6 91.4	22.2 22.2	65.5 62.1
A533B, reheat treated 8 in plate	925 °C, 1 h	675 °C, 4 h	8 in 1/4T	air cool	67.3 64.9	88.7 87.5	25.2 25.3	55.0 61.0
A533B base +1%Si	900 °C, 1/2 h	625 °C, 1 h	8 in 1/4T	immersion quench	98.4 98.0	126.5 131.1	18.2 19.3	55.4 50.7
A533B base +2%Si	900 °C, 1/2 h	625 °C, 1 h	8 in 1/4T	immersion quench	87.5 86.8	118.3 116.8	20.5 23.8	51.9 58.3
A533B base +1%Si grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	70.2 73.3	92.2 94.4	26.7 23.8	61.9 61.6
A533B base +2%Si grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	79.8 86.6	104.6 108.4	24.5 24.1	61.4 60.7
A533B base +1%Cr grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	86.6 85.1	104.0 103.7	21.6 25.3	69.5 74.2
A533B base +0.5% Mn grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	75.2 72.9	94.4 86.9	23.0 24.5	60.9 65.0
A533B base +1.0% Mn grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	72.7 67.0	98.7 93.8	25.4 23.9	61.4 60.9
A533B base +1%Cr +0.75% Mn grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	89.6 91.0	109.4 109.8	24.6 23.7	71.5 70.5
A533B base +1%Cr +0.75% Si grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immmersion quench	94.5 93.8	118.0 117.4	21.6 22.6	67.8 68.1
A533B base +1%Cr +0.75% Mn +0.75% Si grain refined	925 °C, 1/2 h	675 °C, 4 h	8 in 1/4T	immersion quench	97.6 98.1	119.4 119.9	21.6 24.7	68.9 68.1
A533B, Commercial (base) 12 in plate	925 °C, 1 h	675 °C, 8 h	12 in 1/4T	spray quench	63.8 70.3	87.2 90.0	23.6 25.9	65.0 75.0
A533B base +1%Cr	925 °C, 1 h	675 °C, 8 h	12 in 1/4T	spray quench	78.8 79.5	96.4 97.7	26.9 24.3	65.2 64.4
A533B base +0.7% Mn	925 °C, 1 h	675 °C, 8 h	12 in 1/4T	spray quench	77.6	102.7	26.1	61.6
A533B base +1% Cr +0.7% Mn	925 °C, 1 h	675 °C, 8 h	12 in 1/4T	spray quench	81.9 79.8	105.9 104.5	27.0 26.0	64.0 69.4
A533B base +1%Cr +0.7% Mn +0.7%Si	925 °C, 1 H	675 °C, 8 H	12 in 1/4T	spray quench	85.6 88.5	109.2 111.0	22.2 26.3	62.1 62.2

(Continued)

TENSILE PROPERTIES OF COMMERCIAL AND HEAT-TREATED AND COMPOSITION-MODIFIED Mn-Mo-Ni STEELS FOR USE AS PRESSURE VESSEL SHELLS[40]

-Continued-

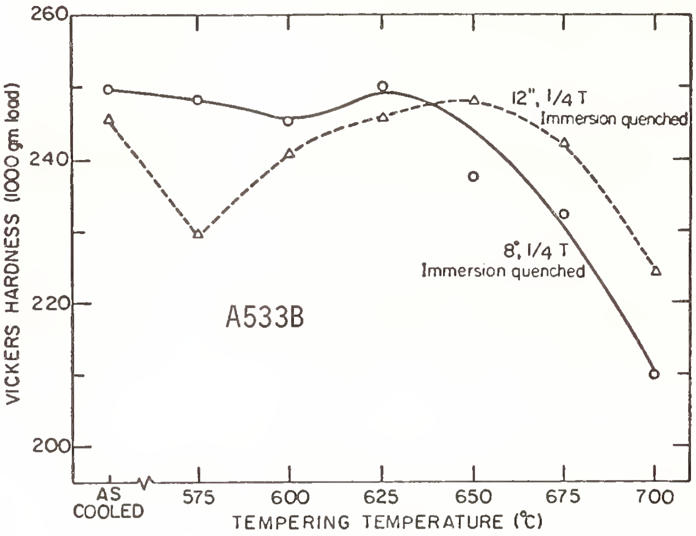
composition of A533B is ∿1.3 Mn, ∿0.5 Mo, ∿0.5 Ni, 0.2C, ∿0.2 Si, balance Fe and of A508 is ∿0.7 Mn, ∿0.6 Mo, ∿0.7 Ni, 0.2C, Cr, ∿0.3 Si, balance Fe. Data for as-received commercial alloys were obtained at appropriate locations in the thick slabs.

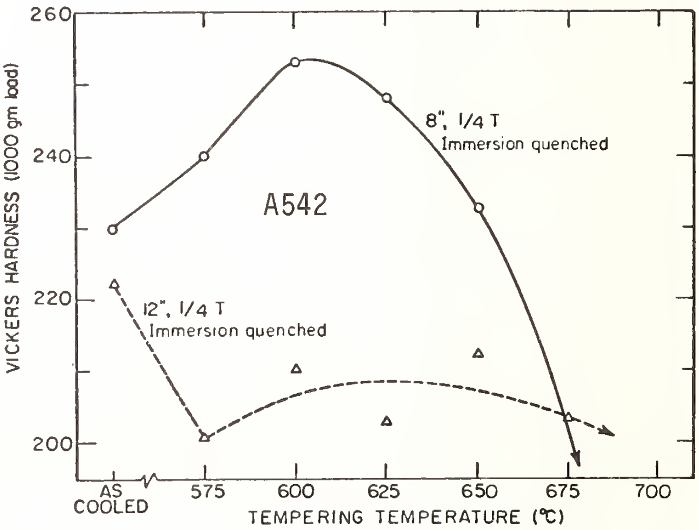
l ingots of commercial and composition-modified steels were reheat treated in an induction furnace. The furnace was programmed controlled to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick s.

means the 1/2 thickness location within the plate thickness designated; 1/4T means the 1/4 thickness location.

reheat treated values are the baseline values for the alloy, rather than the as-received plate, for comparison with other heat tments and compositions.

TEMPERING RESPONSE OF TWO STEELS[a] FOLLOWING IMMERSION QUENCHING FOR THICK PLATE[b] [40]





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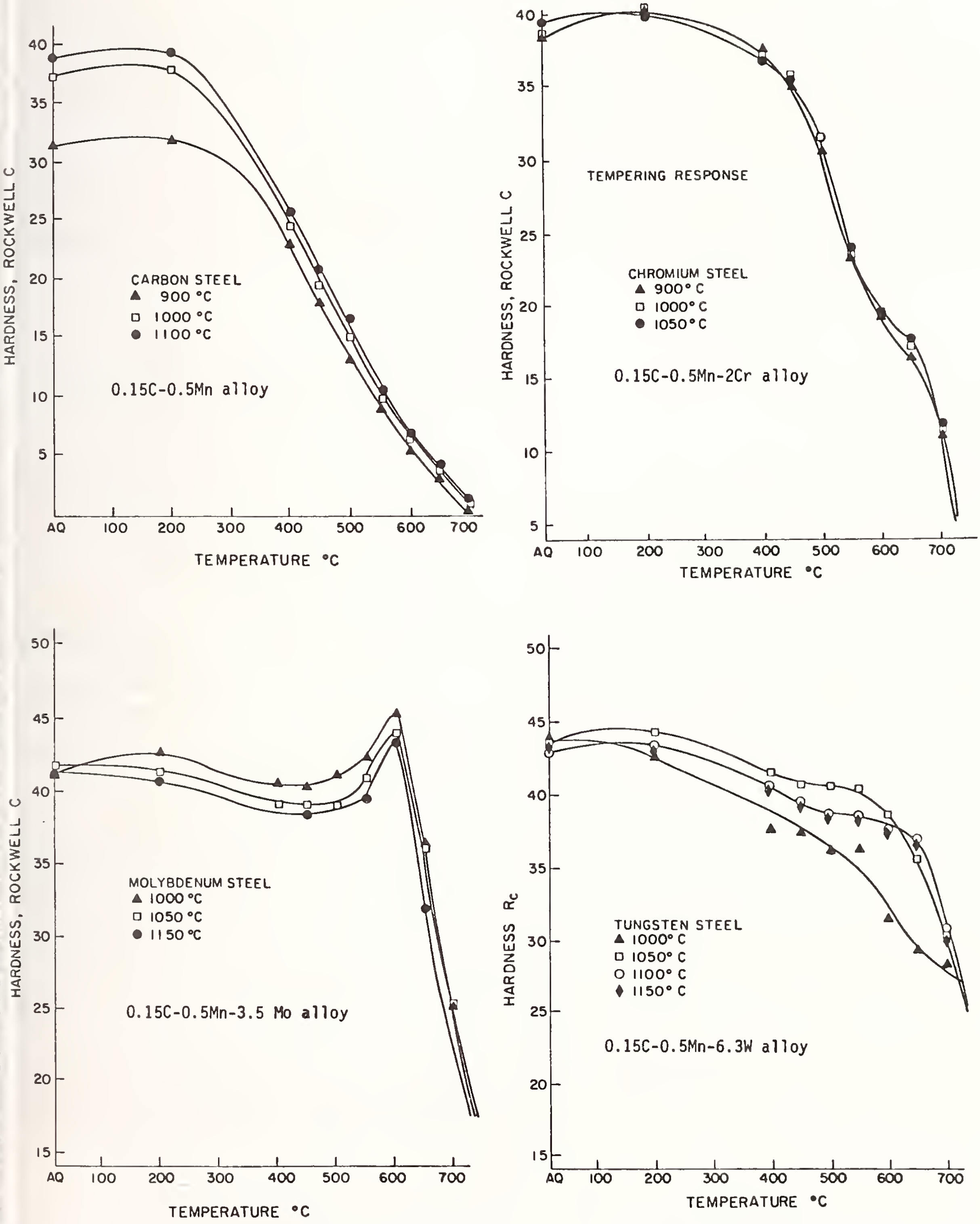
[a] Approximate compositions--A533B: ∿1.3 Mn, ∿0.5 Mo, ∿0.5 Ni, ∿0.2 C, ∿0.2 Si, balance Fe; A542: ∿2.25 Cr, ∿1 Mo, ∿0.4 Mn, ∿0.3 Si, 0.2C, balance Fe.

[b] Ingots of steel were reheat treated in a programmed and controlled induction furnace to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick plate. The plate thickness is specified in inches and the location as a fraction of the thickness of the plate, i.e. 1/4 T is 1/4 of the plate thickness.

EMPERING RESPONSE[a] OF CARBON STEEL AND MODIFICATIONS AFTER AUSTENITIZATION AT SEVERAL TEMPERATURES[40]



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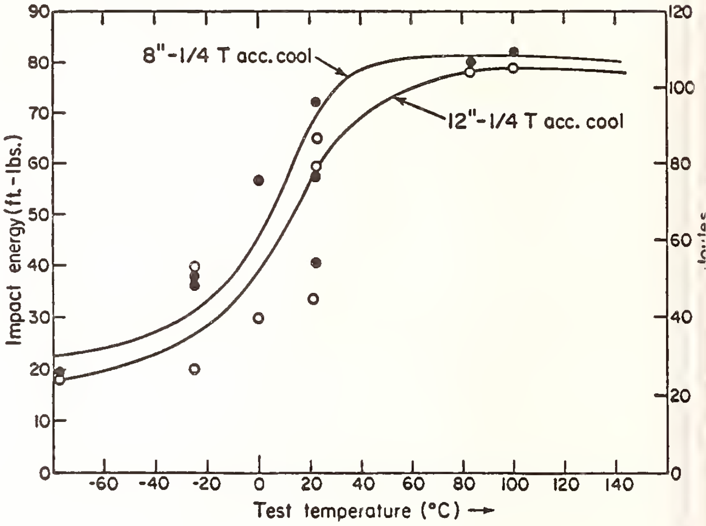
[a] As measure by Rockwell C hardness versus tempering temperature. AQ = as quenched condition.

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Cr-Mo THICK PLATE STEELS[40]

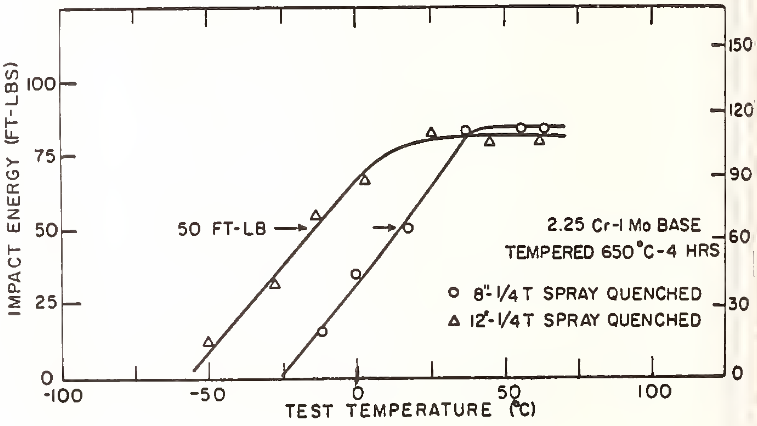
A387 commercial 6 inch plate; austenitized at 1000 °C; heat treated to simulate[a] 8 in plate, 1/4 thickness location, immersion quenched; tempered at 650 °C for 4 hours

(0.10C, 0.41Mn, 1.06Mo, 2.28Cr, 0.21Si, 0.019S, 0.008P, 0.003Cu)



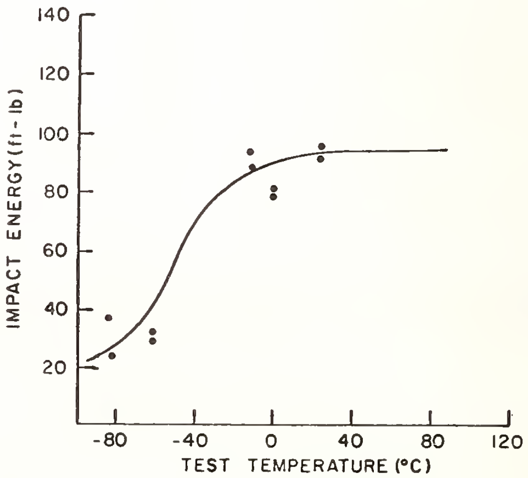
A542 commercial ingot; austenitized at 1000 °C for 1 hour; treated to simulate[a] 8 in and 12 in plate, 1/4 thickness location, spray quenched; tempered at 650 °C for 4 hours

(0.15C, 0.42Mn, 0.91Mo, 0.10Ni, 2.18Cr, 0.30Si, 0.009S, 0.015P, 0.019Al)



A543 commercial 10 in plate, as received condition, 1/4 thickness location

(0.17C, 0.33Mn, 0.57Mo, 3.40Ni, 1.65Cr, 0.25Si, 0.014S, 0.019P, 0.02V, 0.019Al, 0.16Cu)

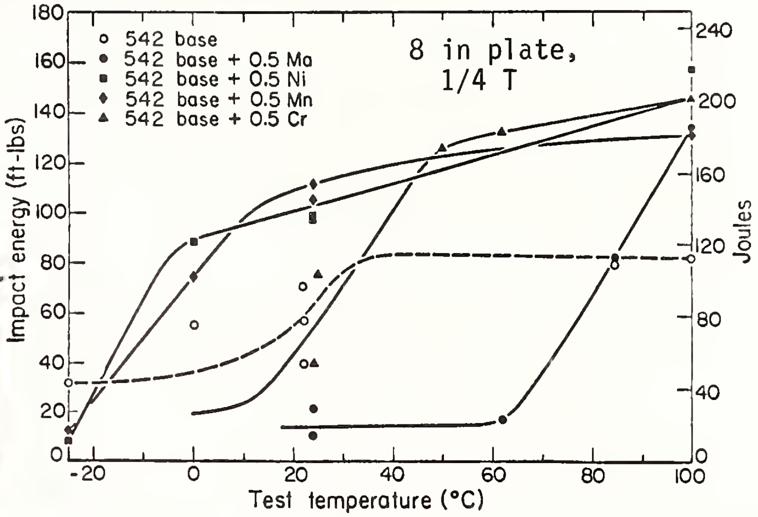


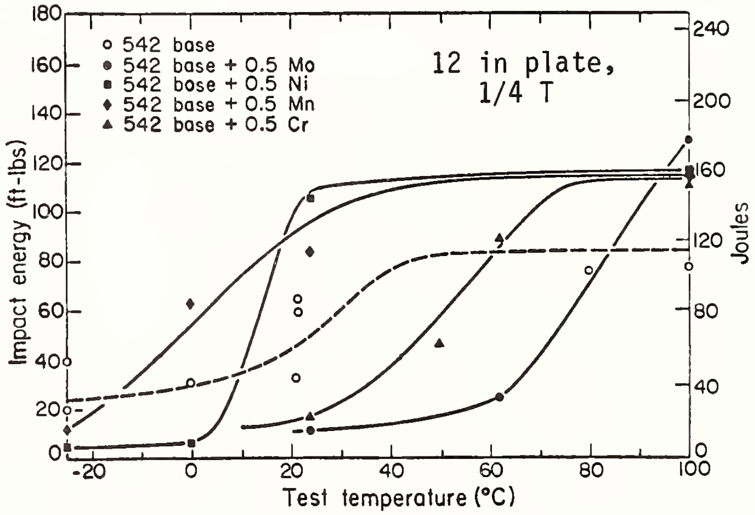
(Data Continued)

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Cr-Mo THICK PLATE STEELS[40], Continued

A542 steel modified with Mo, Ni, Mn, and Cr; austenitized at 1000 °C; treated to simulate[a] 8 in and 12 in plate, 1/4 thickness location, immersion quenched; tempered at 650 °C for 4 hours

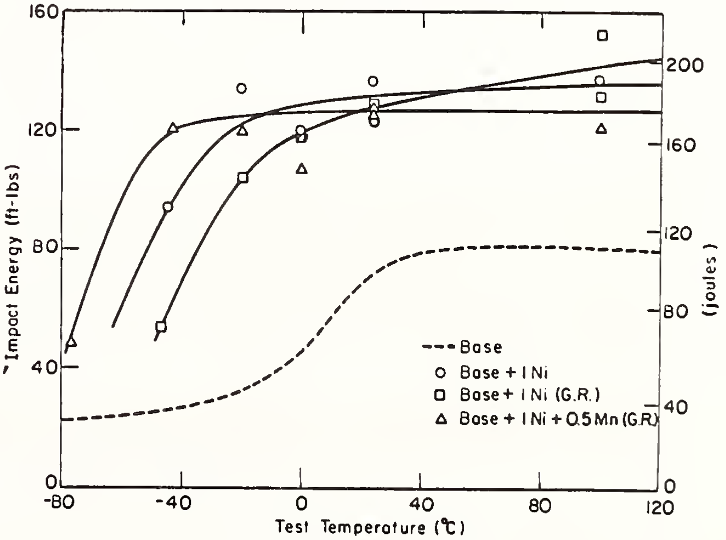
0.5 Mo[b] (0.19C, 0.44Mn, 1.13Mo, 2.44Cr, 0.48Si)
0.5 Ni[b] (0.16C, 0.47Mn, 0.84Mo, 0.49Ni, 2.35Cr, 0.44Si)
0.5 Mn[b] (0.20C, 0.92 Mn, 0.90Mo, 2.52Cr, 0.44Si)
0.5 Cr[b] (0.17C, 0.44Mn, 0.92Mo, 3.15Cr, 0.41Si)





A542 steel modified with Ni, and with Ni + Mn; austenitized at 1000 °C; treated to simulate[a] 8 in plate, 1/4 thickness, immersion quenched; tempered at 650 °C for 4 hours

1 Ni[c] (0.20C, 0.37Mn, 1.0Mo, 1.04Ni, 2.10Cr, 0.50Si)
1 Ni[c] (GR, 0.18C, 0.43Mn, 0.94Mo, 0.95Ni, 2.07Cr, 0.45Si)
1 Ni + 0.5 Mn[c] (GR, 0.18C, 0.90Mn, 0.94Mo, 0.99Ni, 2.16Cr, 0.48Si)

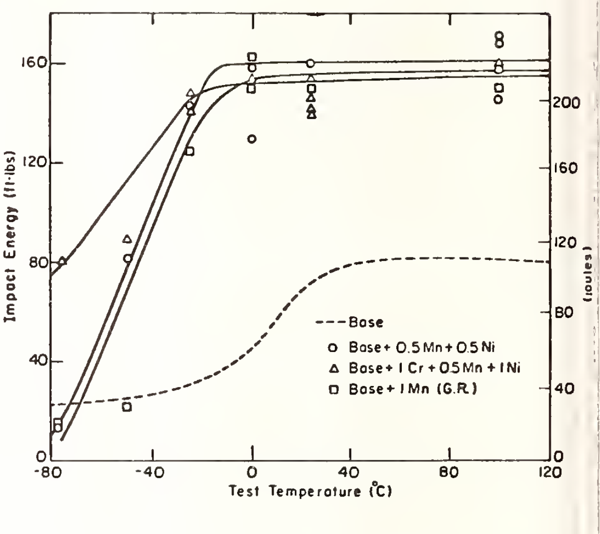


(Data Continued)

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Cr-Mo THICK PLATE STEELS[40], Continued

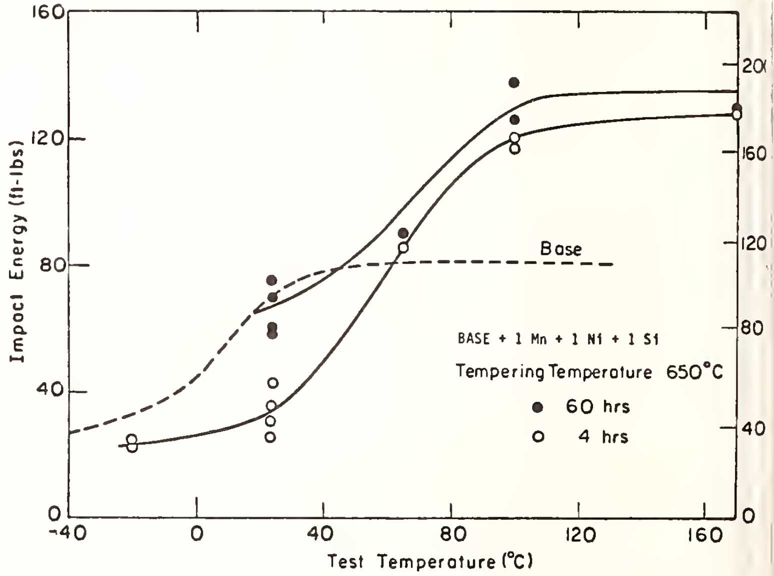
A542 steel modified with Mn + Ni, Cr + Mn + Ni, and Mn; austenitized at 1000 °C; treated to simulate[a] 8 inch plate, 1/4 thickness location, immersion quenched; tempered at 650 °C for 4 hours

0.5 Mn + 0.5 Ni[c] (0.18C, 0.82Mn, 0.92Mo, 0.49Ni, 2.16Cr, 0.45Si)
1 Cr + 0.5 Mn + 1 Ni[c] (GR, 0.18C, 0.93Mn, 0.92Mo, 0.98Ni, 3.09Cr, 0.45Si)
1 Mn[c] (GR, 0.19C, 1.41Mn, 0.94Mo, 2.15Cr, 0.48Si)



A542 steel modified with Mn + Ni + Si; austenitized at 1000 °C; treated to simulate[a] 8 in plate, 1/4 thickness location, immersion quenched; tempered at 650 °C for 4 hours

1 Mn + 1 Ni + 1 Si[b] (0.18C, 1.35Mn, 0.94Mo, 1.0Ni, 2.13Cr, 1.42Si)



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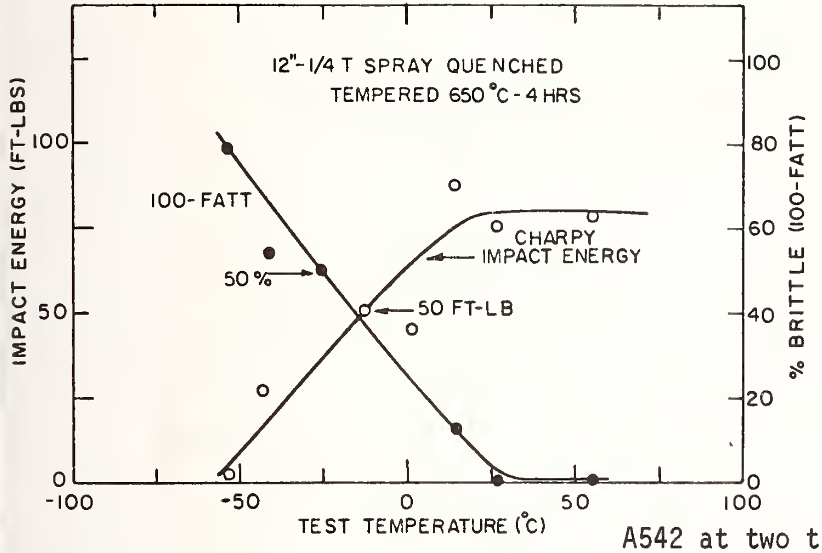
[a] Steels were reheat treated in a programmed and controlled induction furnace to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick plate.

[b] These preparations also contained a maximum of 0.01 S, and a maximum of 0.01 P.

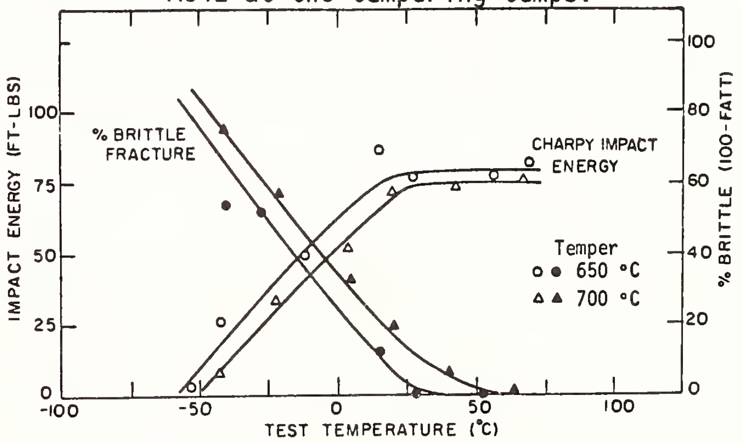
[c] These preparations also contained a maximum of 0.01 S, and a maximum of 0.01 P. They were also grain refined with Al and Nb.

CHARPY V-NOTCH IMPACT ENERGY AND FRACTURE APPEARANCE TRANSITION TEMPERATURE (FATT) FOR COMMERCIAL AND COMPOSITION MODIFIED Cr-Mo THICK PLATE STEELS[a][40]

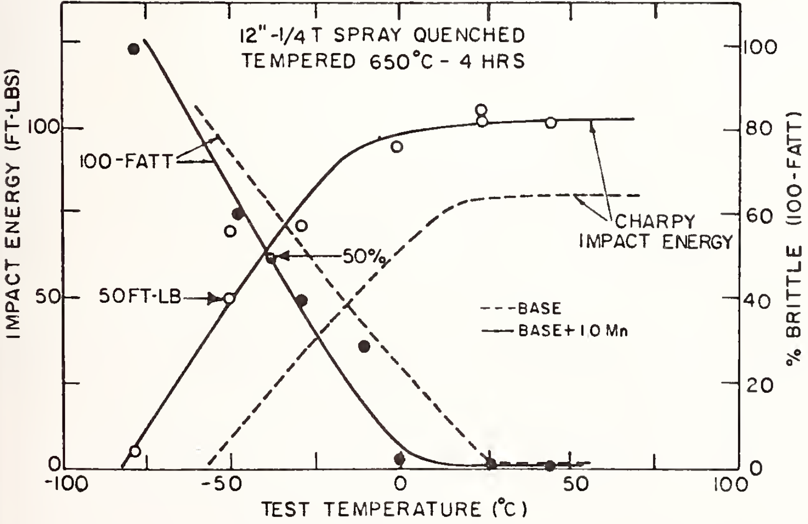
A542 (2.25 Cr-1 Mo)



A542 at two tempering temps.



A542 + 1% Mn

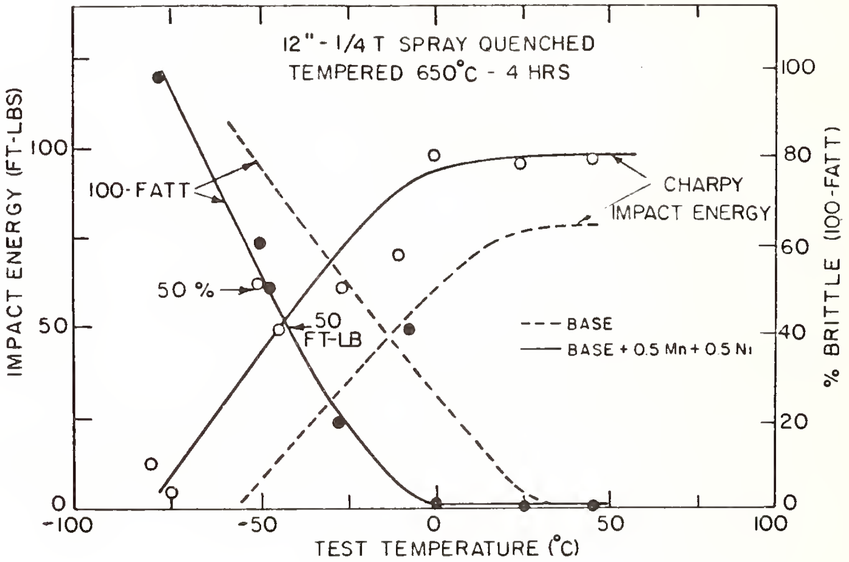


(Data Continued)

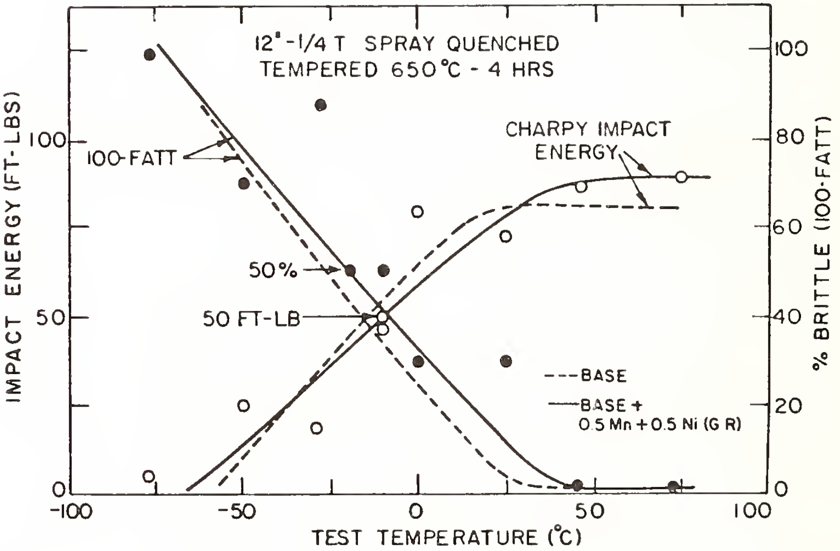
CHARPY V-NOTCH IMPACT ENERGY AND FRACTURE APPEARANCE TRANSITION TEMPERATURE (FATT) FOR COMMERCIAL AND COMPOSITION-MODIFIED Cr-Mo THICK PLATE STEELS[a][40]

(Data Continued)

A542 + 0.5% Mn + 0.5% Ni



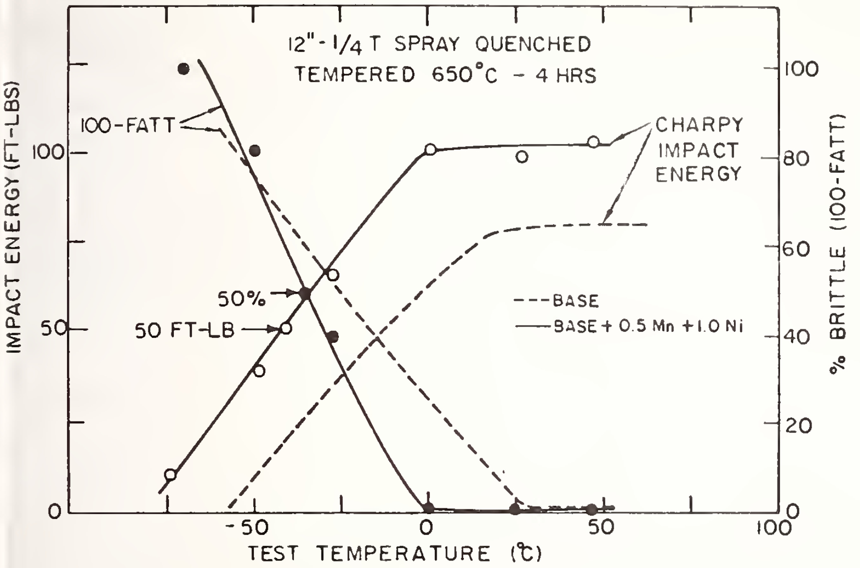
A542 + 0.5% Mn + 0.5% Ni (grain refined)



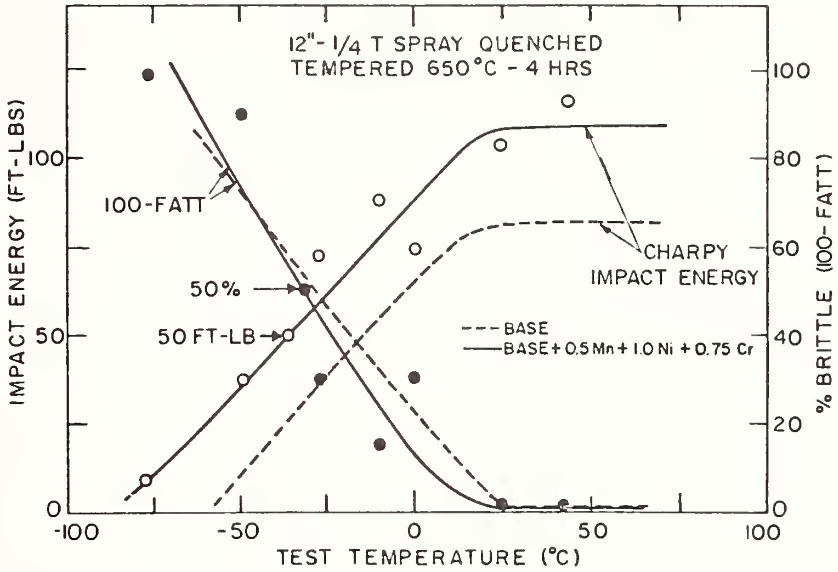
(Data Continued)

CHARPY V-NOTCH IMPACT ENERGY AND FRACTURE APPEARANCE TRANSITION TEMPERATURE FATT) FOR COMMERCIAL AND COMPOSITION-MODIFIED Cr-Mo THICK PLATE STEELS[a] [40]
(Data Continued)

A542 + 0.5% Mn + 1% Ni



A542 + 0.5% Mn + 1% Ni +0.75% Cr



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[a] Approximate composition for the A542 (A387) base material: ∿2.25 Cr, ∿1 Mo, ∿0.4 Mn, ∿0.2 Si, ∿0.1 C, balance Fe. Composition modifications effected by addition of the indicated amounts of elements to the base composition. Steels were reheat treated in a programmed and controlled induction furnace to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick plate. The treatment for all of these steels corresponded to that for the 1/4 thickness location in 12 inch plate, spray quenched; the steels were tempered at 650 °C for 4 hours; one specimen was tempered at 700 °C.

CHARPY V-NOTCH IMPACT PROPERTIES OF 2 1/4Cr-1 Mo THICK PLATE STEELS[a][40]

Alloy[a]	Transition Temperature		Impact Energy	
	50 ft-lb °C	FATT[b] (50% Brittle) °C	25 °C ft-lb	Upper Shelf ft-lb
2.25 Cr-1 Mo base alloy	-12	-30	78	80
Base + 1% Mn	-50	-38	105	105
Base + 0.5% Mn + 0.5% Ni	-45	-50	98	98
Base + 0.5% Mn + 0.5% Ni[c]	-10	-20	78	83
Base + 0.5% Mn + 1% Ni	-40	-35	103	103
Base + 0.5% Mn + 1% Ni + 0.75% Cr	-36	-33	110	110

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[a] Approximate composition for the A542 (A387) base material: ∿2.25 Cr, ∿1 Mo, ∿0.4 Mn, ∿0.2 Si, ∿0.1 C, balance Fe. Composition modifications effected by addition of the indicated amounts of elements to the base composition. Steels were reheat treated in a programmed and controlled induction furnace to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick plate. The treatment for all these steels corresponded to that for the 1/4 thickness location in 12 inch plate, spray quenched; the steels were tempered at 650 °C for 4 hours.

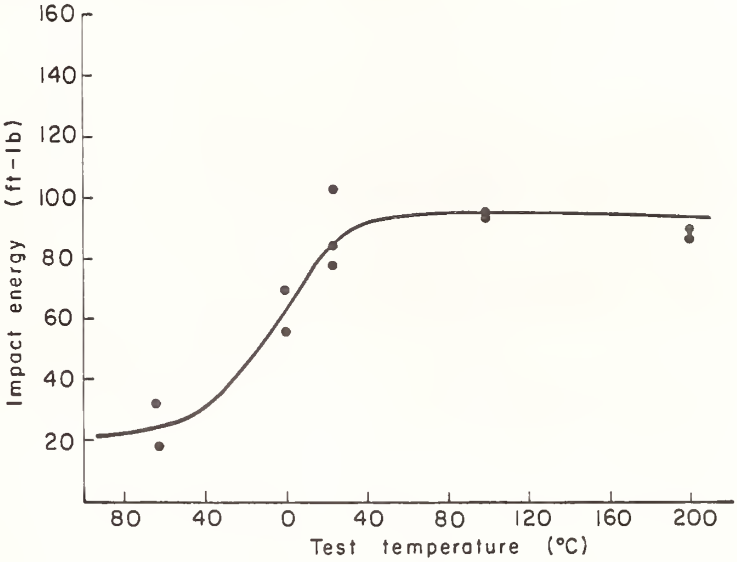
[b] FATT = Fracture Appearance Transition Temperature.

[c] Grain refined.

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[40]

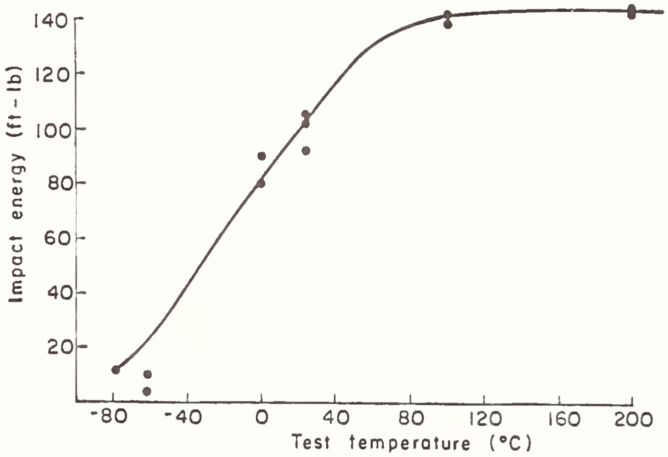
Nominal A533B commercial 6 in plate, 1/2 thickness location; as received condition, quenched and tempered

(0.2C, 1.30Mn, 0.54Mo, 0.61Ni, 0.17Si, 0.015S, 0.010P)



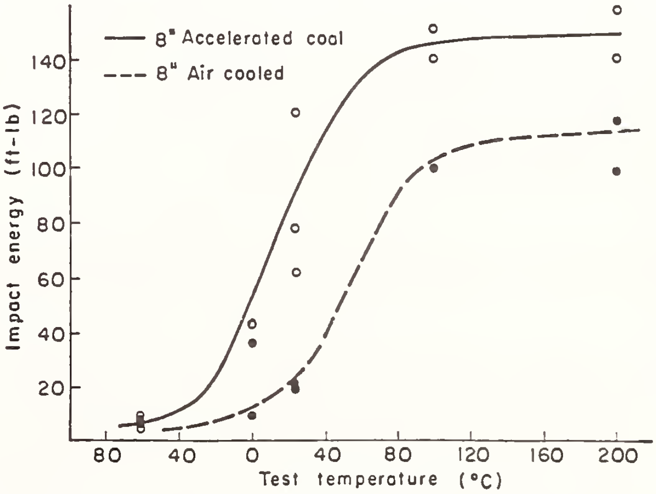
Commercial A508 Class 2 steel, 14 in thick plate, 1/2 thickness location; as received condition, quenched, tempered, and stress-relieved

(0.21C, 0.67Mn, 0.63Mo, 0.74Ni, 0.33Cr, 0.29Si, 0.010S, 0.007P, 0.04Al,0.10Cu)



Developmental A533B ingot, simulated thick plate heat treated[a], 8 inch plate, 1/4 thickness location, immersion quenched and air cooled

(0.24C, 1.19Mn, 0.59Mo, 0.44Ni, 0.07Cr, 0.23Si, 0.005S, 0.021P)

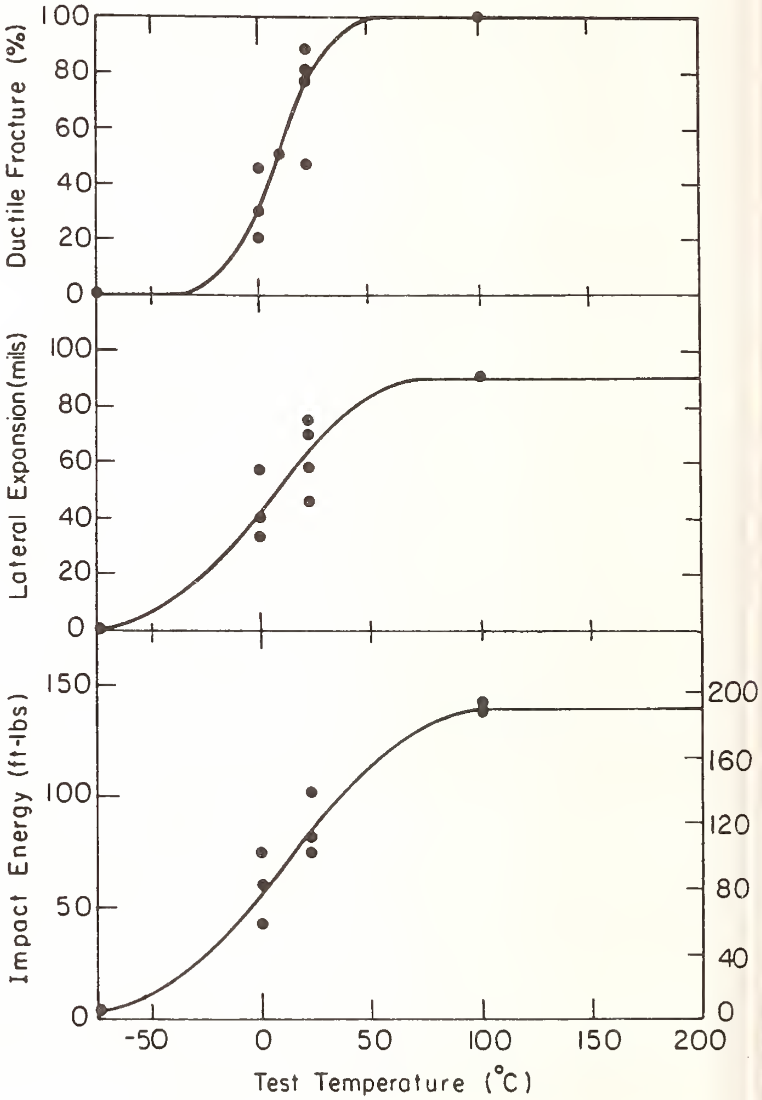


(Data Continued)

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[40], Continued

Commercial A533B 9 in plate **normalized**; austenitized at 925 °C for 1 hour; treated to simulate[a] 8 in plate, 1/4 thickness location, spray quenched; tempered at 675 °C for 4 hours

(0.22C, 1.32Mn, 0.57Mo, 0.65Ni, 0.20Si, 0.007S, 0.009P, 0.036Al, 0.07Cu)



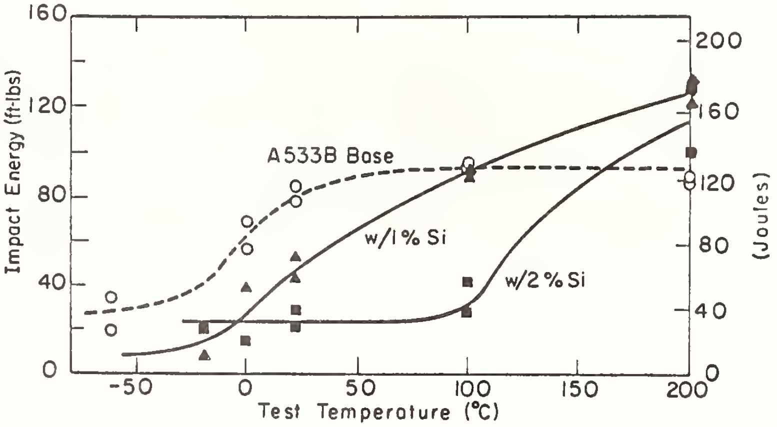
(Data Continued)

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[40], Continued

A533B steel modified with Si; austenitized at 925 °C, 1/2 hour; treated to simulate[a] 8 in plate, 1/4 thickness location, immersion quenched; tempered at 675 °C for 4 hours

1% Si[b] (0.22C, 0.64Mn, 0.51Mo, 0.6Ni, 0.92Si)

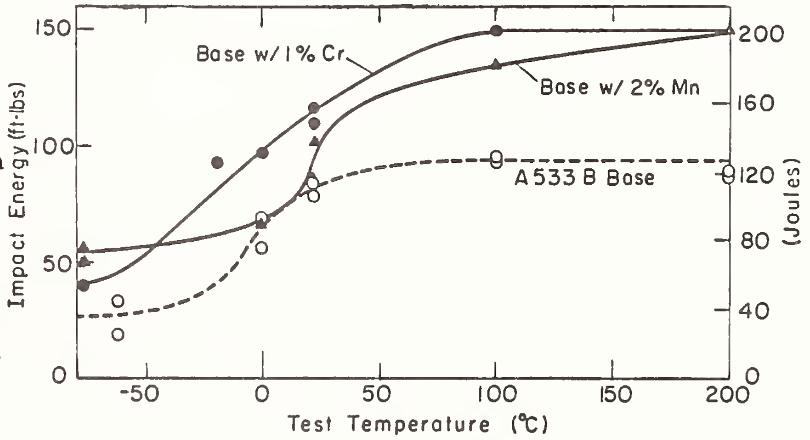
2% Si[b] (0.22C, 1.40Mn, 0.6Mo, 0.6Ni, 1.91Si)



A533B steel modified with Cr and Mn; austenitized at 925 °C, 1/2 hour; treated to simulate[a] 8 in plate, 1/4 thickness location, immersion quenched; tempered at 675 °C for 4 hours

1% Cr[b] (0.22C, 1.42Mn, 0.6Mo, 0.6Ni, 1.01Cr, 0.25Si)

2% Mn[b] (0.20C, 2.02Mn, 0.6Mo, 0.6Ni, 0.25 Si)

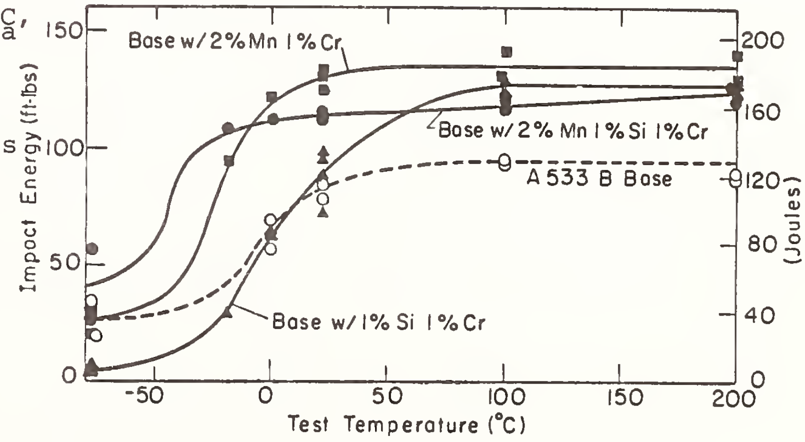


A533B modified with Mn, Cr, and Si; austenitized at 925 °C, 1/2 hour; treated to simulate[a] 8 in plate, 1/4 thickness location, immersion quenched; tempered at 675 °C for 4 hours

1% Si 1% Cr[b] (0.23C, 1.33Mn, 0.6Mo, 0.6Ni, 1.04Cr, 0.97Si)

2% Mn 1% Cr[b] (0.22C, 1.92Mn, 0.6Mo, 0.6Ni, 1.01Cr, 0.26Si)

2% Mn 1% Si 1% Cr[b] (0.22C, 1.87Mn, 0.6Mo, 0.6Ni, 0.99Cr, 1.05Si)



(Data Continued)

CHARPY IMPACT ENERGY FOR COMMERCIAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[40], Continued

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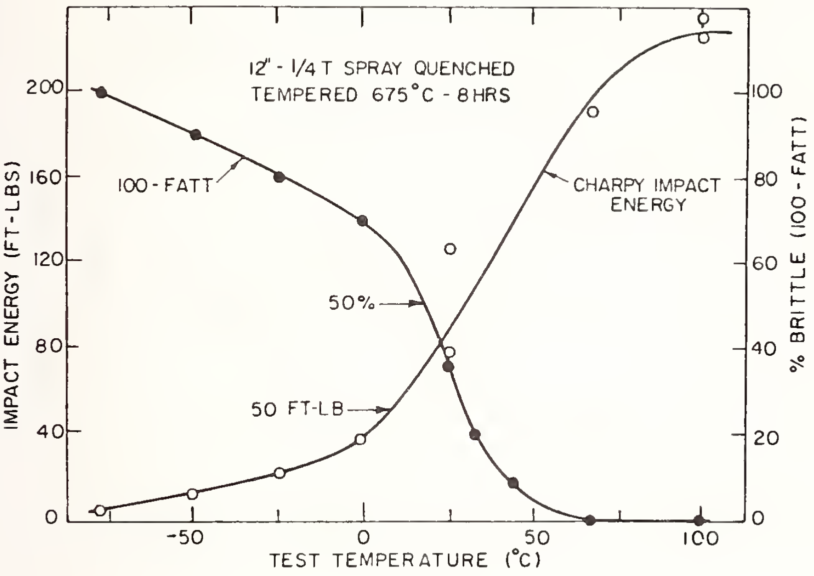
[a] Steels were reheat treated in a programmed and controlled induction furnace to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick plate.

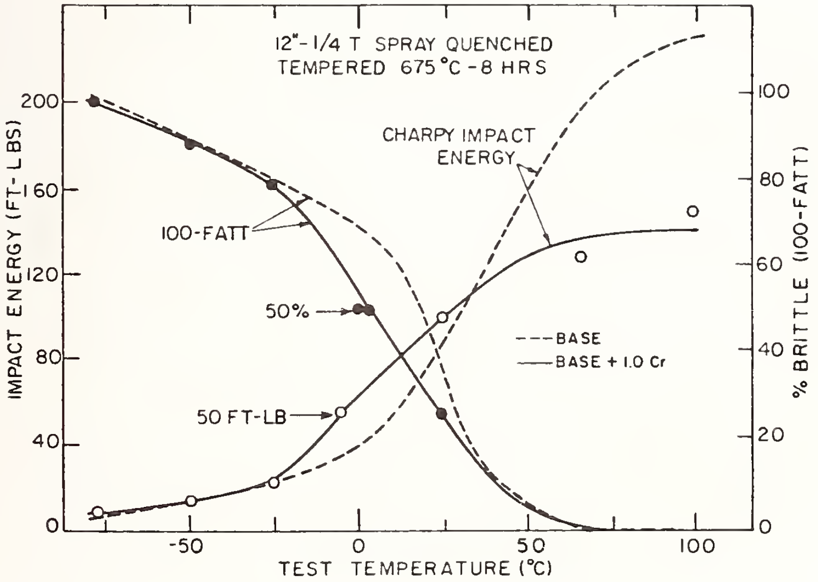
[b] All of these preparations also contained a maximum of 0.01 S, and a maximum of 0.01 P. All were grain refined with 0.02 Al and 0.03 V.

HARPY V-NOTCH IMPACT ENERGY AND FRACTURE APPEARANCE TRANSITION TEMPERATURE TT) FOR COMMERCIAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[a][40]

Commercial A533B



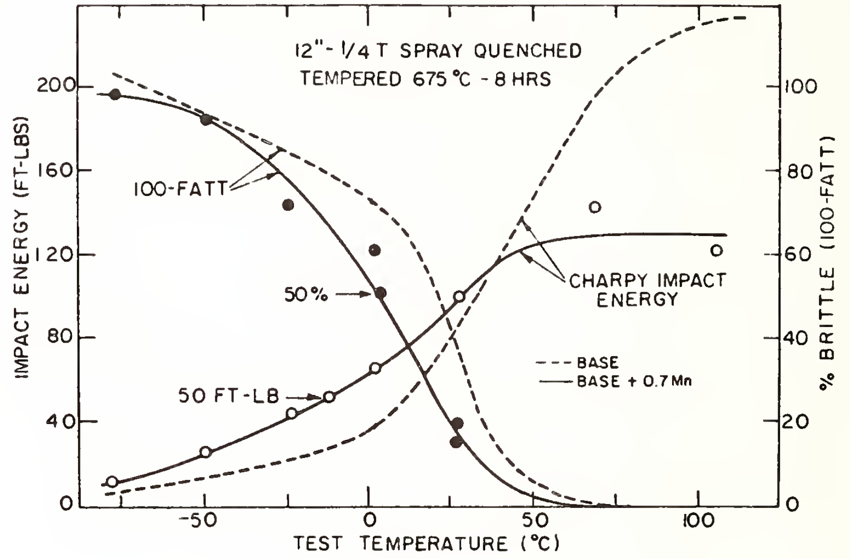
A533B + 1% Cr



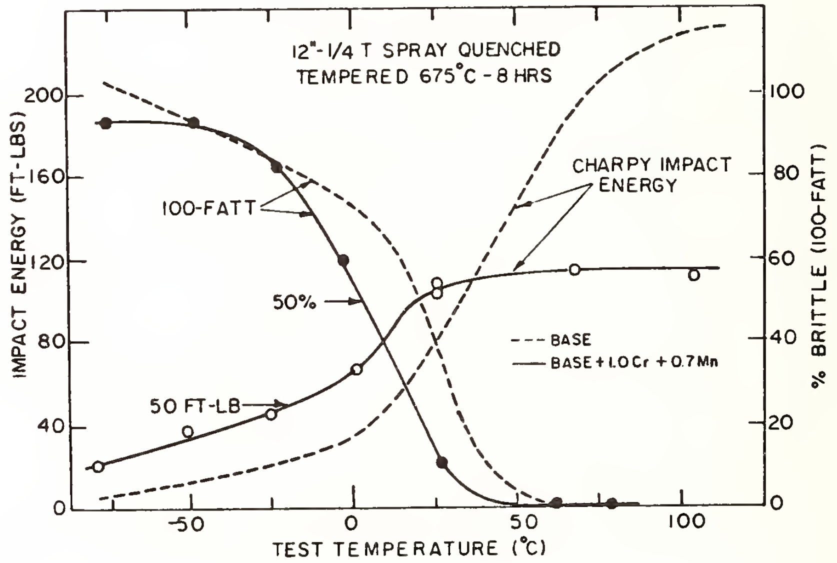
(Data Continued)

CHARPY V-NOTCH IMPACT ENERGY AND FRACTURE APPEARANCE TRANSITION TEMPERATURE (FATT) FOR COMMERCIAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[a][4

(Data Continued)



A533B + 0.7% Mn

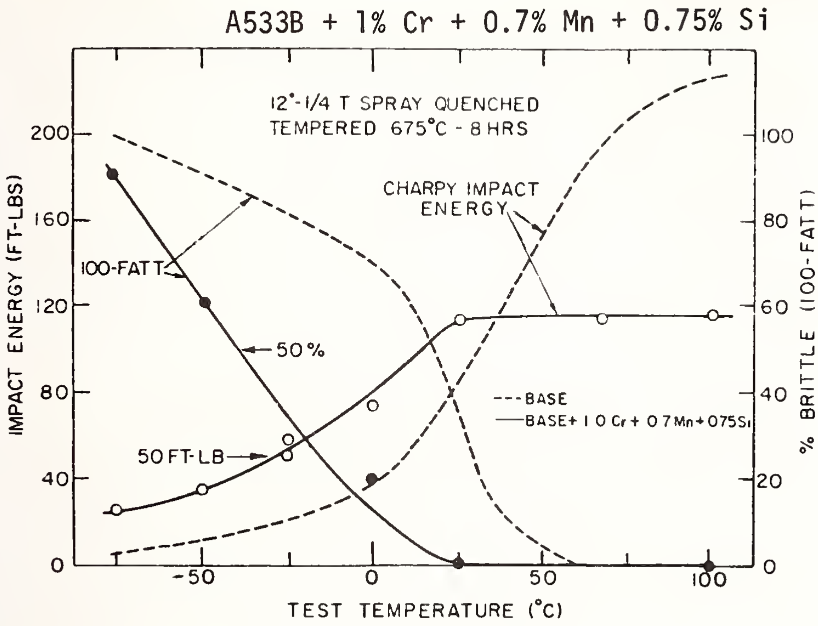


A533B + 1% Cr + 0.7% Mn

(Data Continued)

IARPY V-NOTCH IMPACT ENERGY AND FRACTURE APPEARANCE TRANSITION TEMPERATURE
TT) FOR COMMERICAL AND COMPOSITION-MODIFIED Mn-Mo-Ni THICK PLATE STEELS[a][40]

(Data Continued)



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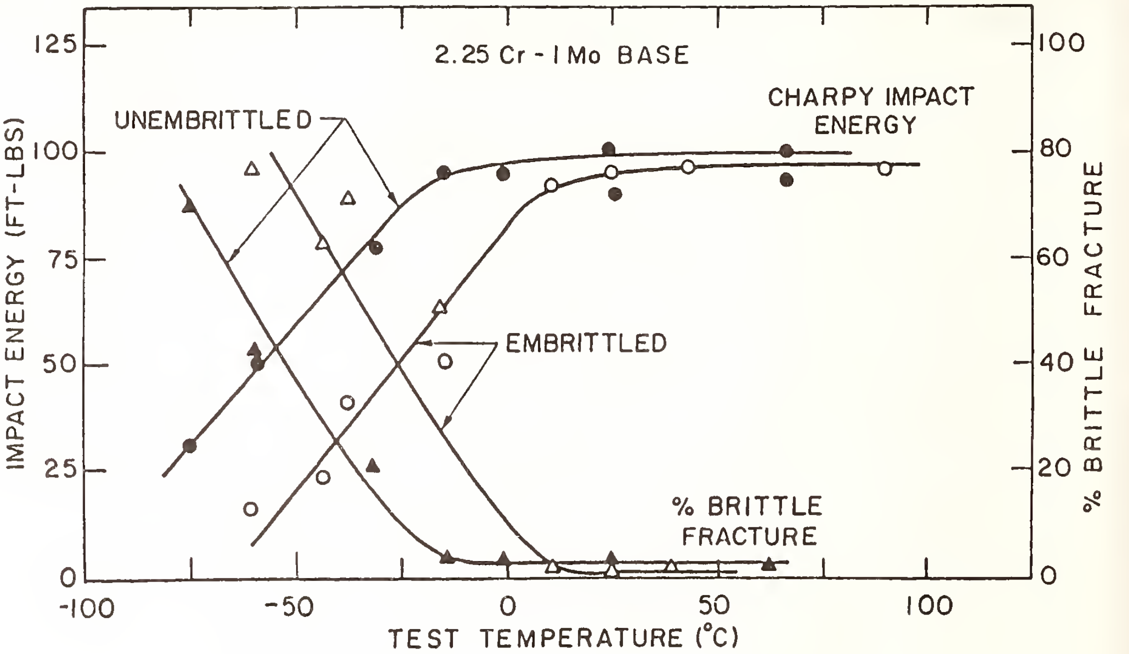
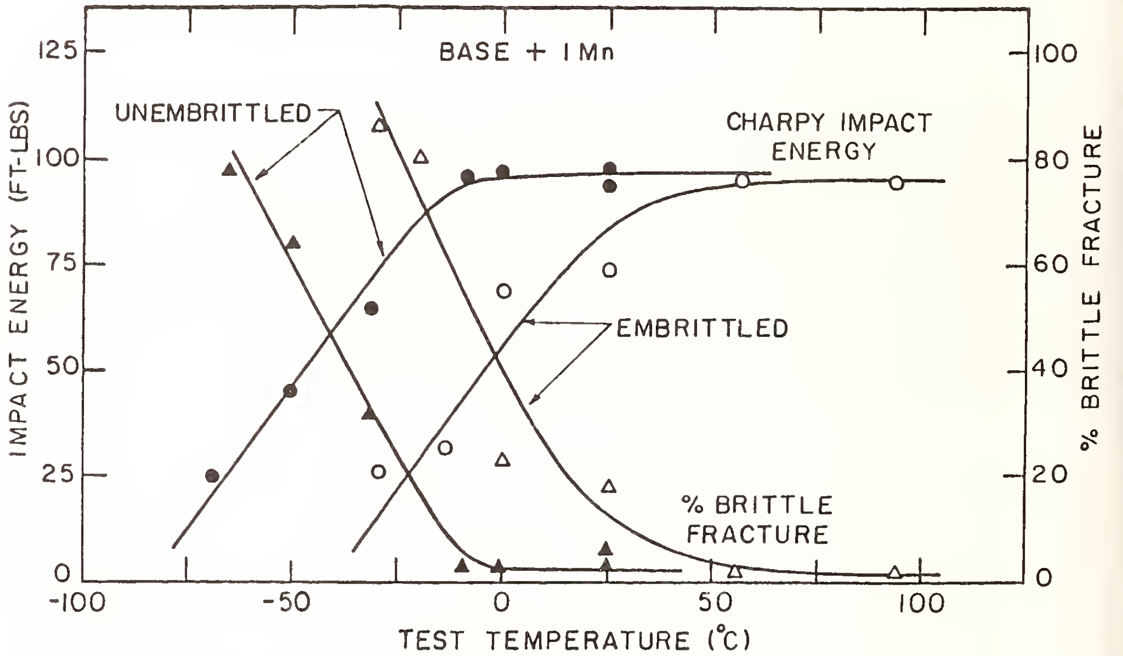
[a]Approximate composition for A533B base material: ~1.3 Mn, ~0.5 Mo, ~0.5 Ni, 0.2 C, ~0.2 Si, balance Fe. Composition modifications effected by addition of the indicated amounts of elements to the base composition. Steels were reheat treated in a programmed and controlled induction furnace to provide small ingots with the heat treatments and cooling rates characteristic of specific locations in thick plate. The treatment for all of these steels corresponded to that for the 1/4 thickness location in 12 in plate, spray quenched; the steels were tempered at 675 °C for 8 hours.

CHARPY IMPACT ENERGY AND FRACTURE DATA FOR EMBRITTLED Cr-Mo STEELS[a] [40]





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[a] Base alloy composition: ~2.25 Cr, ~1 Mo, ~0.4 Mn, ~0.2 Si, ~0.1 C, balance Fe. Unembrittled alloys were austenitized at 1000 °C for 1 hour, agitated oil quenched, then tempered at 650 °C for 4 hours. Embrittled alloys were austenitized at 1000 °C for 1 hour, agitated oil quenched, tempered at 650 °C for 4 hours, aged isothermally at 483 °C (900 °F) for 1000 hours, and oil quenched.

EFFECT OF TEMPER EMBRITTLEMENT ON Cr-Mo STEELS[a][40]

	Unembrittled[b] Value/Embrittled[c] Value				Shift in Transition Temperature	
Alloy[a]	Hardness Rockwell C	50 ft-lb Temp. °C	FATT[d] 50%	Upper Shelf Energy, ft-lb	50 ft-lb ΔT, °C	ΔFATT[d] °C
2.25 Cr-1 Mo base steel	26/26	-63/-23	-61/-30	98/96	40	31
Base + 1% Mn	27/26.5	-47.5/-5	-42/-5	97/93	42.5	37
Base + 0.5% Mn + 0.5% Ni	26/26.6	-70/-22	-58/-26	106/100	48	32

---

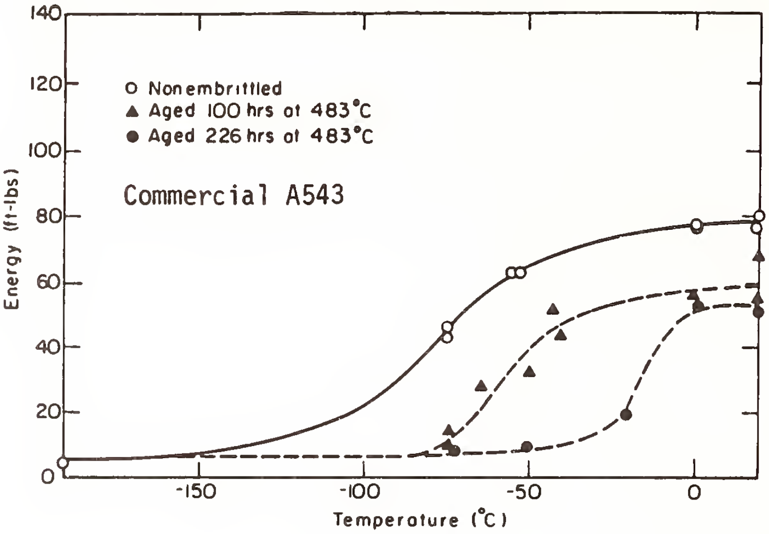
[a] Base alloy composition: ∿2.25 Cr, ∿1 Mo, ∿0.4 Mn, ∿0.2 Si, ∿0.1 C, balance Fe.

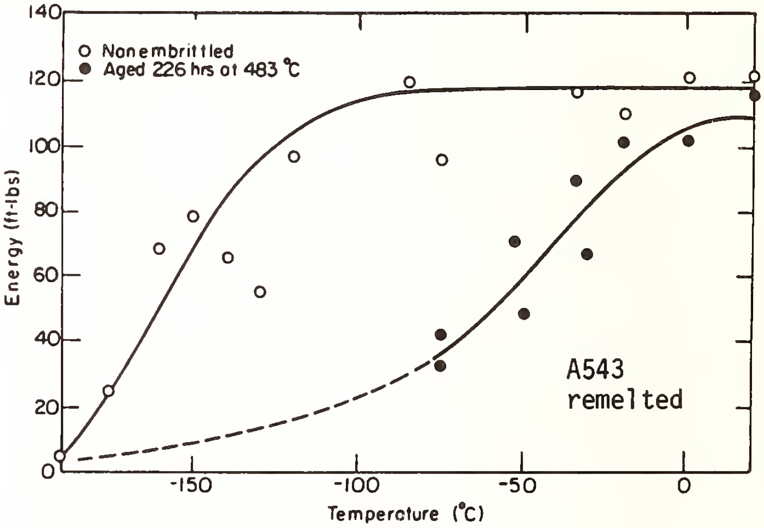
[b] Unembrittled alloys were austenitized at 1000 °C for 1 hour, agitated oil quenched to ambient temperature, then tempered at 650 °C for 4 hours.

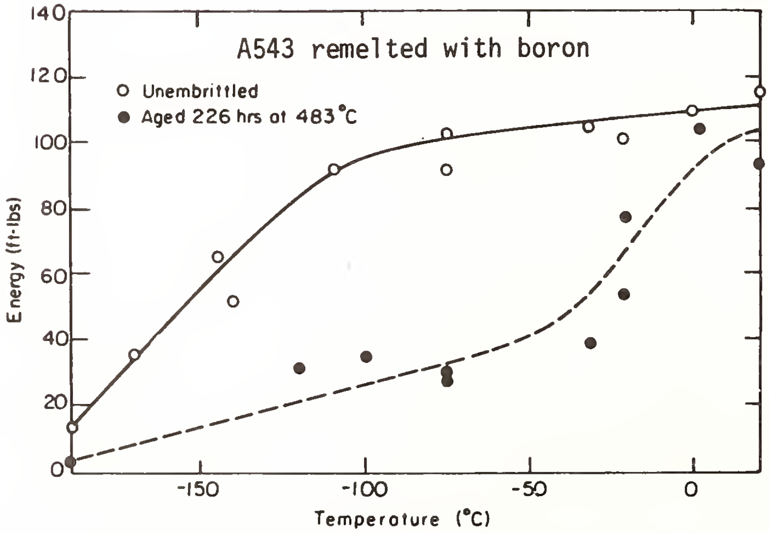
[c] Embrittling treatment: austenitization at 1000 °C for 1 hour, agitated oil quenching to ambient temperature, tempering at 650 °C for 4 hours, isothermal aging at 483 °C (900 °F) for 1000 hours, oil quenching to ambient temperature.

[d] FATT = Fracture Appearance Transition Temperature.

CHARPY IMPACT TESTS OF A543 ALLOY[a] SUBJECTED TO ISOTHERMAL EMBRITTLEMENT[b][40]



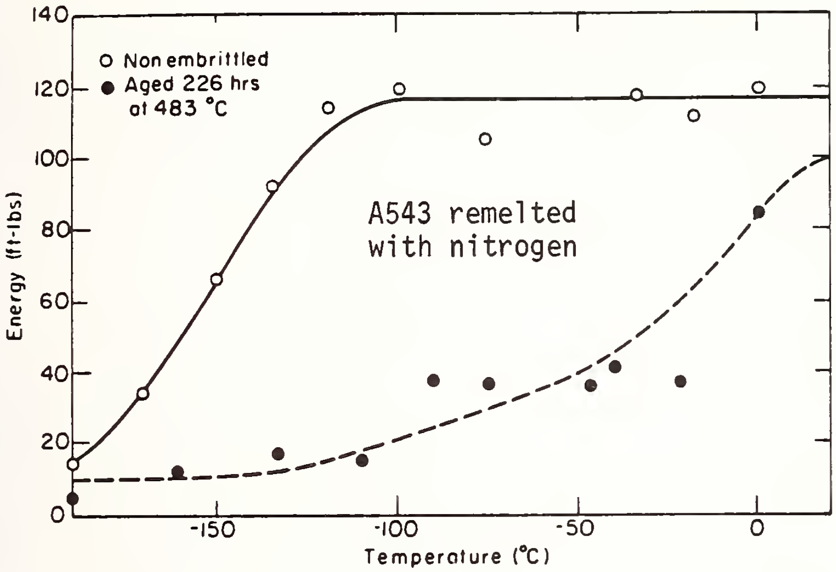




(Data Continued)

ARPY IMPACT TESTS OF A543 ALLOY[a] SUBJECTED TO ISOTHERMAL EMBRITTLEMENT[b][40]

(Continued)



Composition of A543: 0.33 Mn, 3.4 Ni, 0.57Mo, 1.65 Cr, 0.17 C, 0.014 S, 0.019 P, 0.019 Al, balance Fe. For remelt with boron: 0.005 B. For remelt with nitrogen: 0.015 N.

Embrittling treatment: austenitization at 900 °C for 2 hours, agitated oil quenching, tempering at 625 °C for 3.5 hours, agitated oil quenching, aging at 483 °C (determined to be the knee of the isoembrittlement curve) for up to 226 hours, water quenching with agitation.

TENSILE PROPERTIES OF C-V-MN DEVELOPMENTAL STEELS[a][40]

Alloy[a]	Isothermal Transformation Temperature[b], °C	Yield Strength ksi	Ultimate Tensile Strength, ksi	Elongation %	Reduction in Area %
AUSTENITIZED[c] at 1000 °C					
0.1C-0.5V -0.5MN(0.1C base alloy)	750 (TD)	55	85	21	84
	700 (TD)	60	86	20	78
	650 (TD)	60	88	20	76
	600 (TD)	73	95	20	78
	550 (B)	120	130[d]	9	0
0.1C base + 3Ni	750 (M)	130	158	12	36
	700 (M)	138	162	10	28
	650 (TD)	80	112	21	76
	600 (TD)	95	118	22	61
	550 (B)	125	141	20	38
0.2C-1V- 0.5Mn (0.2C base alloy)	750 (TD)	55	73	27	84
	650 (TD)	76	104	20	76
	550 (B)	105	130	10	35
0.2C base + 1.5Ni	780 (M)	162	190	12	30
	700 (TD)	70	98	20	79
	625 (TD)	95	125	18	70
	550 (B)	125	151	16	45
0.2C base + 3Ni	700 (M)	152	188	14	32
	650 (TD)	90	118	22	80
	600 (TD)	104	132	18	65
	550 (B)	132	165	15	38
AUSTENITIZED[c] at 1200 °C					
0.2C base	750 (TD)	80	108	16	35
	650 (TD)	136	151[d]	2	0
	550 (B)	-	155[d]	2	0
0.2C base + 1.5Ni	780 (M)	172	195	8	12
	700 (TD)	114	141	12	25
	625 (TD)	-	165[d]	2	0
	550 (B)	-	186[d]	2	0
0.2C base + 3Ni	700 (M)	158	196	7	10
	650 (TD)	-	150[d]	2	0
	550 (B)	-	167[d]	2	0

---

[a] Approximate composition of non-ferrous elements given, balance of alloy is Fe.

[b] Holding time 1 hour. TD = total decomposition product through the upper transformation C-curve. M = Martensite formed through quenching after ausaging (isothermal holding in the austenite range before transformation). B = Bainite formed through the lower transformation regime.

[c] Austenitized for 1 hour prior to isothermal holding.

[d] Fracture stress.

HARDNESS AND IMPACT TOUGHNESS OF C-V-MN DEVELOPMENTAL STEELS[a] [40]

Alloy[a]	Isothermal Transformation Temperature[b], °C	Rockwell Hardness Scale	Charpy V-Notch Impact Energy ft-lb
AUSTENITIZED[c] at 1000 °C			
0.1C-0.5V -0.5Mn (0.1C base alloy)	750(TD)	52 A	18
	700(TD)	53 A	27
	650(TD)	55 A	6
	600(TD)	60 A	4
	550(B)	58 A	2
0.1C base + 3Ni	750(M)	63 A	45
	700(M)	68 A	52
	650(TD)	57 A	58
	600(TD)	56 A	6
	550(B)	63 A	4
0.2C-1V-0.5Mn (0.2C base alloy)	750(TD)	51 A	∿240
	650(TD)	55 A	8
	550(B)	61 A	5
0.2C base +1.5 Ni	780(M)	72 A	40
	700(TD)	53 A	38
	625(TD)	60 A	4
	550(B)	64 A	4
0.2C base + 3Ni	700(M)	66 A	57
	650(TD)	58 A	130
	600(TD)	60 A	4
	550(B)	64 A	6
AUSTENITIZED[c] at 1200 °C			
0.2C base	750(TD)	18 C	2
	650(TD)	37 C	2
	550(B)	40 C	2
0.2C base + 1.5 Ni	780(M)	40 C	20
	700(TD)	26 C	6
	625(TD)	35 C	3
	550(B)	45 C	2
0.2C base + 3Ni	700(M)	40 C	28
	650(TD)	35 C	2
	550(B)	44 C	2

---

[a] Approximate compositions of non-ferrous elements given, balance of alloy is Fe.

[b] Holding time 1 hour. TD = total decomposition product through the upper transformation C-curve. M = Martensite formed through quenching after ausaging (isothermal holding in the austenite range before transformation). B = Bainite formed through the lower transformation regime.

[c] Austenitized for 1 hour prior to isothermal holding.

B.3 Mechanical Properties Testing

B.3.2 Refractories

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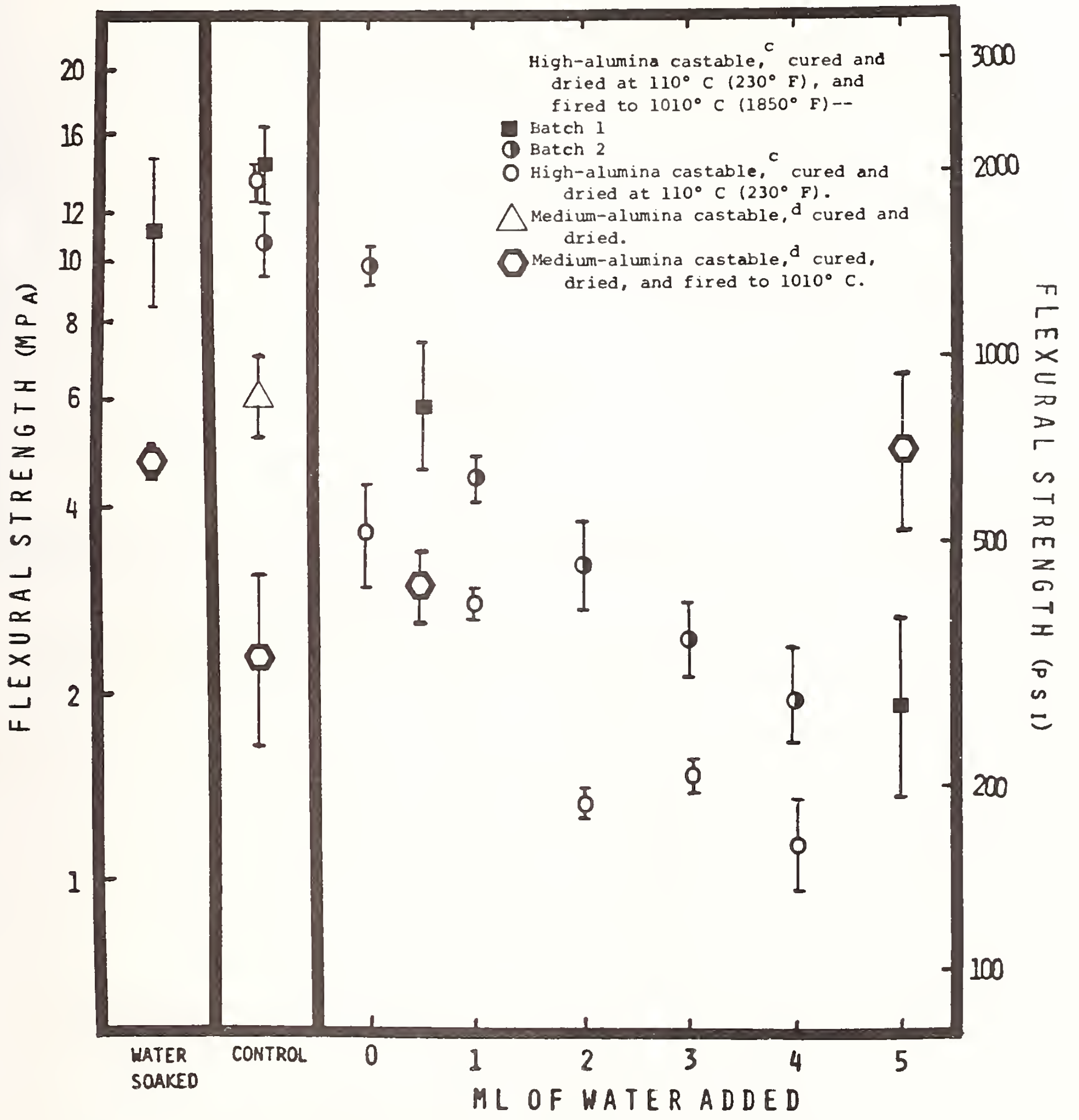
EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE FLEXURAL STRENGTH[b] OF ALUMINA CASTABLE REFRACTORIES[23]



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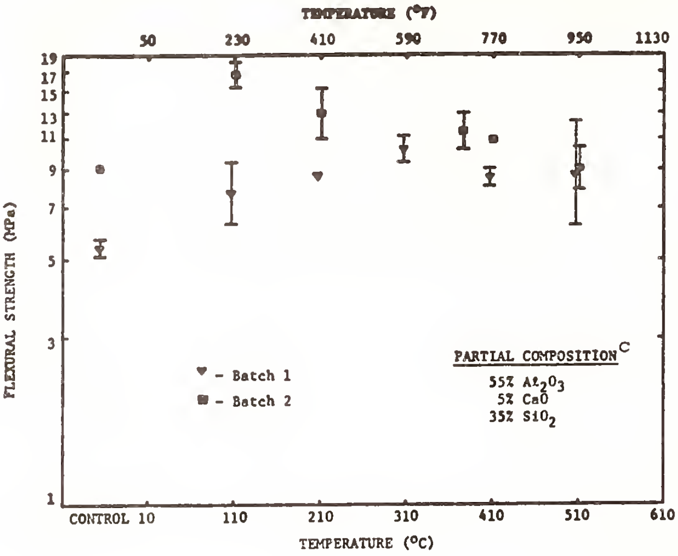
[a] Treatment consisted of sealing specimens (specimen volume 7 cc) in a 21 cc pressure chamber with varying amounts of water (0 to 5 ml) and raising the temperature to 510 °C (950 °F). Control specimens were not subjected to any treatment. "Water soaked" specimens were soaked in water at ambient temperature for about 5 hours.

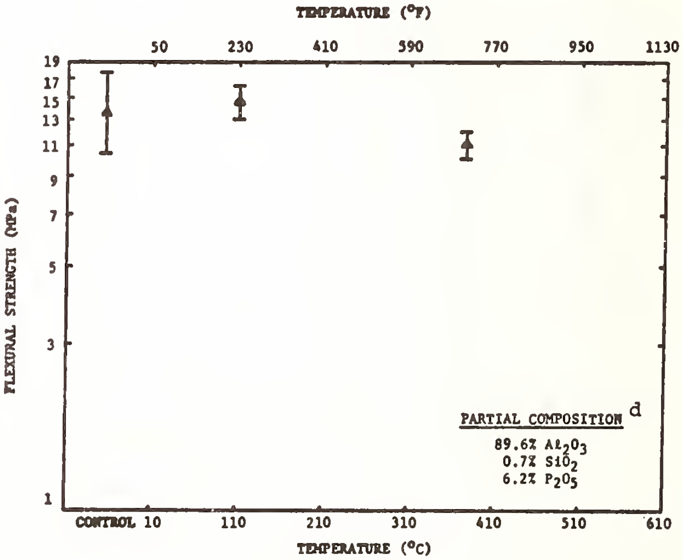
[b] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; each point represents the average of the logarithm of the breaking stress, the error bars are the standard deviations for those values.

[c] A high-purity (95%) tabular alumina bonded with calcium aluminate cement (Castolast G).

[d] A medium-purity (55%) alumina, calcined flint clay, mullite, bonded with calcium aluminate cement (Lo-Abrade).

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE FLEXURAL STRENGTH[b] OF ALUMINA CASTABLE REFRACTORIES[23]





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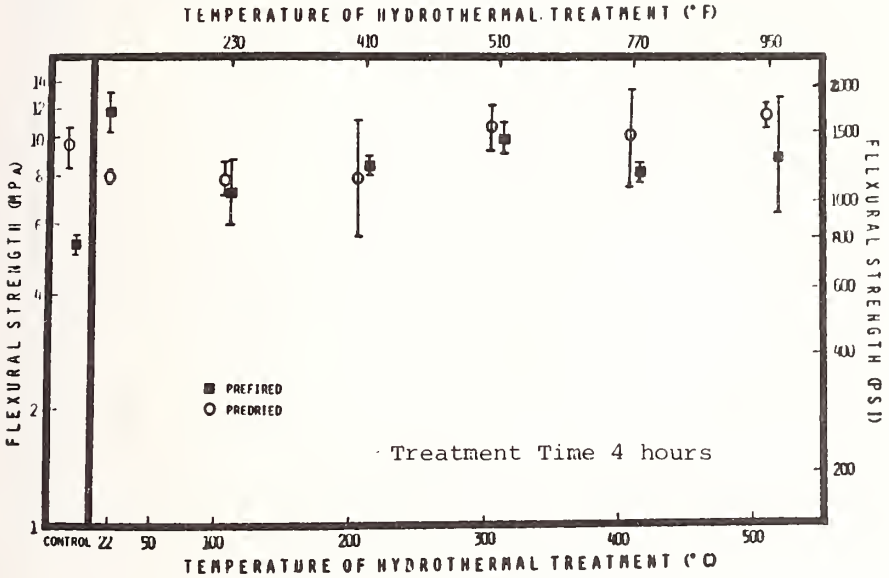
[a] Treatment consisted of sealing specimens (specimen volume 7 cc) in a 21 cc pressure chamber with water (3 ml for the 55% Al_2O_3 refractory and 5 ml for the 89.6% Al_2O_3 refractory) and raising the temperature to produce high-pressure steam; treatment time 20 hours; control specimens not subjected to steam treatment.

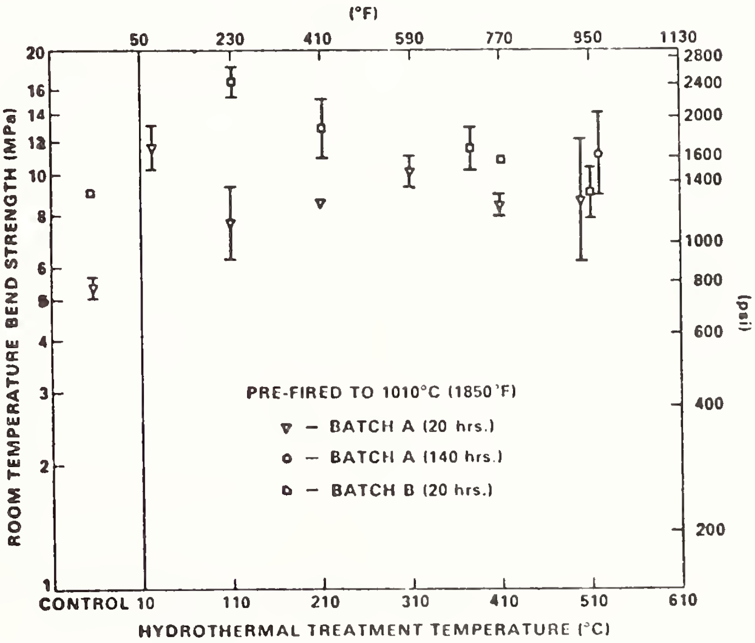
[b] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; each point represents the average of the logarithm of the breaking stress, error bars are standard deviations for those values.

[c] Refractory is a calcined flint clay aggregate with calcium aluminate bond, prefired to 1010° C (1850° F); Batch 1 was mixed by hand, Batch 2 was mixed in a commercial mixer with a lesser amount of water.

[d] Refractory is a tabular alumina aggregate with phosphate bond, prefired to 1010° C (1850° F).

EFFECT OF HYDROTHERMAL TREATMENT[a] AT VARYING TEMPERATURES ON THE FLEXURAL STRENGTH[b] OF MEDIUM-ALUMINA CASTABLE REFRACTORY[c] [23]





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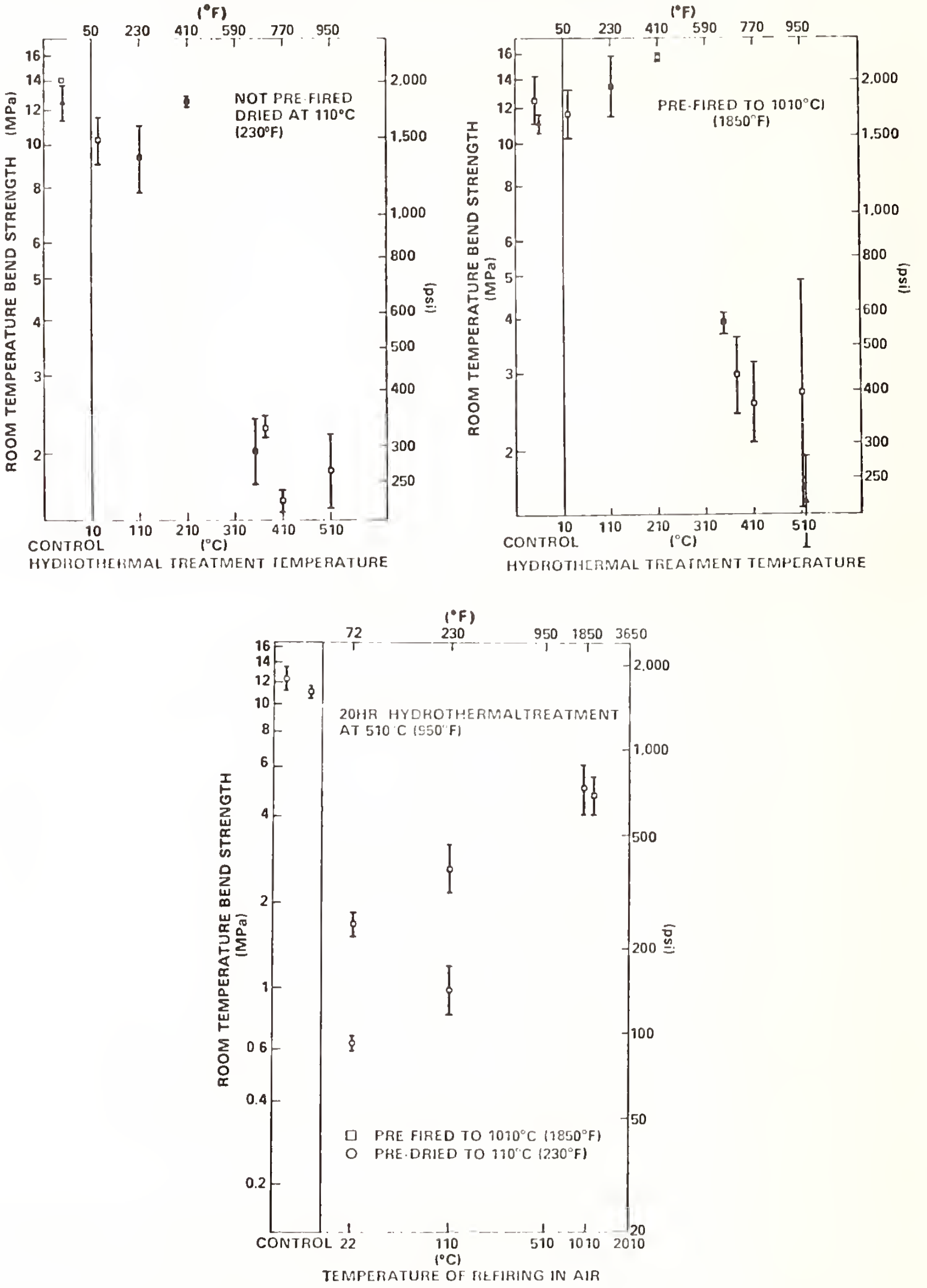
[a] Treatment consisted of sealing specimens (specimen volume 7 cc) in a 21 cc pressure chamber with 3 ml water and raising the temperature to produce high-pressure steam; treatment time as indicated; control specimens not subjected to steam.

[b] Flexural strength as determined in four-point bend tests, loading rate 5×10^{-3} cm/min (2×10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; each point represents the average of the logarithm of the breaking stress, error bars are standard deviations for those values.

[c] A medium-purity (55%) alumina, calcined flint clay, mullite, bonded with calcium aluminate cement (Lo-Abrade).

EFFECT OF HYDROTHERMAL TREATMENT[a] AND REFIRING[b] OF TREATED SPECIMENS ON THE FLEXURAL STRENGTH[c] OF HIGH-ALUMINA CASTABLE REFRACTORY[d][23]



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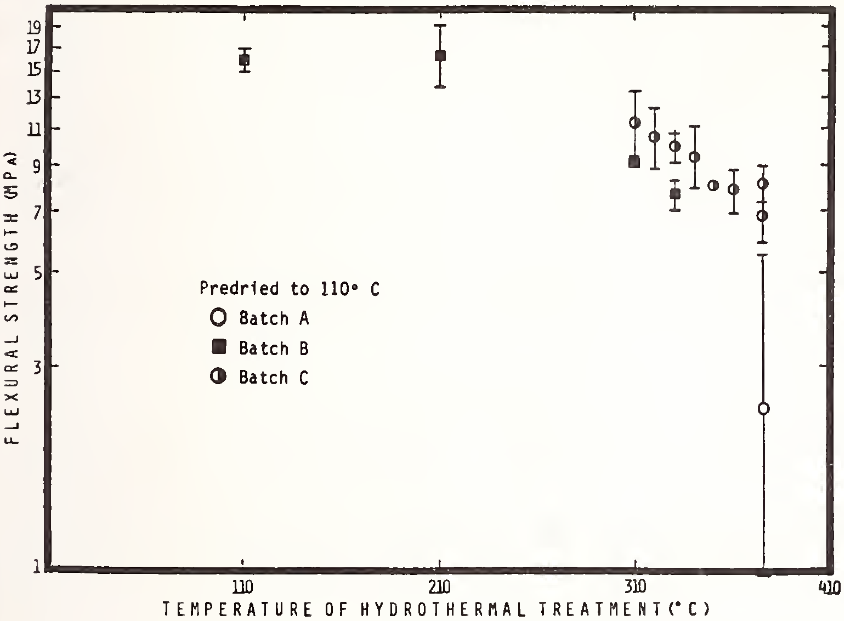
[a] Treatment consisted of sealing specimens (specimen volume 7 cc) in a 21 cc pressure chamber with 3 ml water and raising the temperature to produce high-pressure steam; treatment time 4 hours; control specimens not subjected to steam treatment.

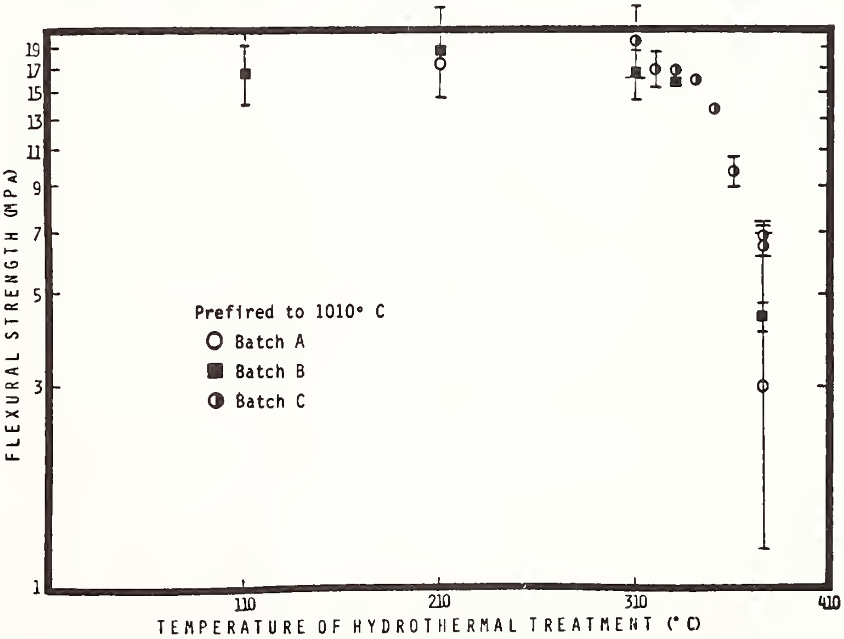
[b] Castable specimens were given treatment outlined in footnote a for 20 hours at 510 °C and then refired at various temperatures.

[c] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; each point represents the average of the logarithm of the breaking stress, the error bars are the standard deviations for those values.

[d] A high-purity (95%) tabular alumina bonded with calcium aluminate cement (Castolast G).

EFFECT OF HYDROTHERMAL TREATMENT[a] AT VARYING TEMPERATURES ON THE FLEXURAL STRENGTH[b] OF CALCIUM ALUMINATE CEMENT[c] [23]





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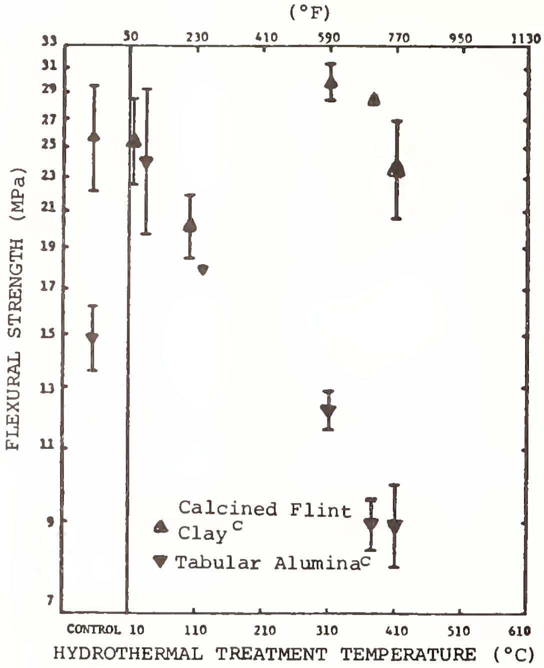
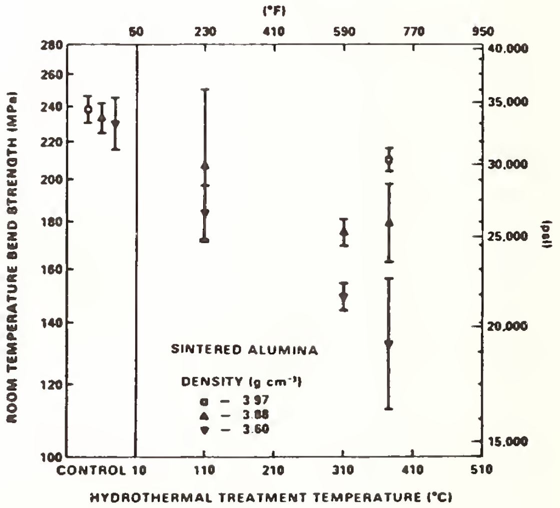
[a] Treatment consisted of sealing specimens (specimen volume 7 cc) in a 21 cc pressure chamber with 5 ml water and raising the temperature to produce high-pressure steam; treatment time 20 hours.

[b] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; each point represents the average of the logarithm of the breaking stress, error bars are the standard deviation for those values.

[c] A high-purity calcium aluminate cement (65% $CaO \cdot Al_2O_3$, 25% $CaO \cdot 2Al_2O_3$, 10% fine unreacted Al_2O_3); cement was cast into bars 5 x 10 x 50 mm, then dried at 110 °C for 20 hours; some of the dried bars were then fired at 1010 °C for 20 hours.

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE FLEXURAL STRENGTH[b] OF THE BONDING MATRIX AND OF THE AGGREGATE OF ALUMINA REFRACTORIES[23]





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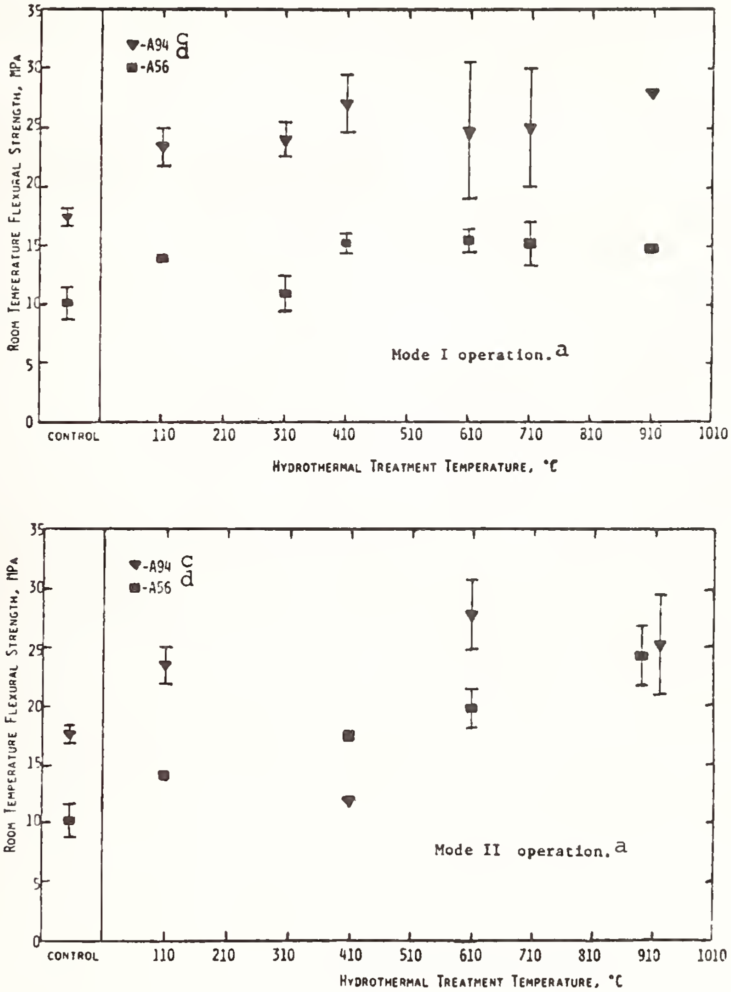
[a] Treatment consisted of sealing specimens (specimen volume 7 cc) in a 21 cc pressure chamber with 3 ml of water and raising the temperature to produce high-pressure steam; treatment time 20 hours; control specimens were not subjected to steam.

[b] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; each point represents the average of the logarithm of the breaking stress, error bars are standard deviations for those values.

[c] The calcined flint clay refractory is a medium-purity (55%) alumina, mullite, bonded with calcium aluminate cement (Lo-Abrade); the tabular alumina refractory is a high-purity (95%) alumina bonded with calcium aluminate cement (Castolast G); the aggregate mix of both castables was sized and only the -150 mesh fraction was used in preparing specimens for the above test.

EFFECT OF VARYING MODE OF HYDROTHERMAL TREATMENT[a] ON THE FLEXURAL STRENGTH[b] OF CASTABLE REFRACTORIES[23]



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[a] Treatment consisted of exposing specimens to high-pressure steam at varying temperatures under two modes of operation. Mode I: vessel is heated to final test temperature and steam is then injected to bring the vessel to operating pressure (1000 psi). Mode II: water is injected so that during heating of vessel the pressure and temperature follow the saturated vapor curve; when operating pressure (1000 psi) is reached, steam is vented to maintain 1000 psi as the temperature is raised to the final test temperature.

[b] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperature; error bars are standard deviations.

[c] A94 is an NBS-prepared high-alumina castable bonded with calcium aluminate cement: 94.4 wt% Al_2O_3, 4.5 wt% CaO, 0.1 wt% SiO_2, 0.1 wt% Fe_2O_3, 0.2 wt% Na_2O.

[d] A56 is an NBS-prepared medium-alumina, calcined flint clay castable bonded with calcium aluminate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3, 0.2 wt% Na_2O.

EFFECT OF HIGH-BTU GAS EXPOSURE[a] ON THE COMPRESSIVE STRENGTH[b] OF MISCELLANEOUS REFRACTORIES[9]

Refractory	Air Fired 250 h, 980 °C	High-Btu Gas[a] 250 h, 980 °C, 1000 psi
40-45% Al_2O_3 castable/gunnable, medium-purity calcium aluminate bond	3,090±330	7,200±1280[c]
50% Al_2O_3 gunnable, high-purity calcium aluminate bond	2,270±110	4,620± 560[c]
40% Al_2O_3castable/gunnable, medium-purity calcium aluminate bond	390± 50	440± 30
Magnesium aluminate spinel ramming mix, chromate bonded	7,180±940	9,880± 430[c]

---

[a] All samples were prefired in air at 980 °C for 24 h, then either air fired for 250 h, or exposed to the gas mixture for 250 h. Feed gas composition: 25% H_2, 21% CO, 13% CO_2, 5% CH_4, 36% H_2O.

[b] ASTM C-133-72, specimens were 1 in x 1 in x 2 in; 95% confidence intervals are given; units are psi.

[c] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF FLOWING HIGH-BTU GAS[a] ON THE COMPRESSIVE STRENGTH[b] OF AN ALUMINA-SILICA REFRACTORY[c] [9]

Exposure Time	Compressive Strength[b]	
hr	Air Fired, 980° C	High-Btu Gas[a], 980° C, 1000 psi
0[d]	3,180±300	3,180±300
50	2,925±240	4,950±660
100	2,450±180	4,100±420
150	2,510±280	5,750±560
200	2,320±160	3,750±360
250	2,080±160	5,970±440

[a] Steam-gas mixture composition: 45% H_2O, 55% high-Btu gas composed of 39.5% H_2, 30.9% CO, 21.0% CO_2, 8.6% CH_4. An average of 6 scf/h of the mixture passed into the reaction vessel; superficial velocity was calculated to be 0.04 ft/min in the vessel.

[b] ASTM C-133-72, specimens were 1 in x 1 in x 2 in; values given are 95% confidence intervals; units are psi.

[c] Refractory is a dense 55% Al_2O_3-fireclay calcine aggregate (A. P. Green's Lo-Abrade) with intermediate-purity calcium aluminate cement (Universal Atlas Cement's Refcon).

[d] All samples were prefired in air at 980° C for 24 hr, then exposed.

EFFECT OF THERMAL SHOCK[a] ON THE MODULUS OF RUPTURE[b] OF SOME ALUMINA REFRACTORIES[2]

Composition	Brand Name	Manufacturer	MOR (Ambient) PSI	MOR After Thermal Shock PSI	MOR (2000 PSI
96% Al_2O_3	Plicast 40	Plibrico	797(42)[c]	98(±55)[d]	516
94.6% Al_2O_3-0.5% SiO_2	Alfrax B-57	Carborundum	111(16)[e]	no test	no tes
94.5% Al_2O_3-0.15% SiO_2	Greencast-94	A. P. Green	1054(280)[c]	no test	538(2
93.7% Al_2O_3-0.1% SiO_2	Castolast G	Harbison-Walker	849(61)[c]	242(±154)[d]	no tes
93.7% Al_2O_3	Taycor 414-FH	Taylor	1875(193)[c]	133(±82)[d]	966(6
93% Al_2O_3	Kao-Phos 30	Babcock & Wilcox	2063(125)[c]	150(±108)[d]	no tes
92.6% Al_2O_3-6.8% CaO-0.4% SiO_2	H-W Lt.Wt. 33	Harbison-Walker	78(46)[f]	no test	no tes
89.6% Al_2O_3-0.7% SiO_2	Resco-Cast AA-22	Resco Products	1789(120)[c]	345(±278)[d]	499(8
over 87% Al_2O_3	Alfrax 66	Carborundum	722(100)[c]	181(±120)[d]	no tes

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[a] Thermal shock test: samples heated rapidly to temperatures ranging from 1700°F to 2000°F, soaked for 2 to 5 hours, and rapidly cooled to ambient temperatures.

[b] Modulus of rupture (MOR) test complied with ASTM Specification C-268-70.

[c] Standard deviation based on 5 samples.

[d] Variation of two samples tested.

[e] Standard deviation based on 3 samples.

[f] Standard deviation based on 4 samples.

EFFECT OF EXPOSURE[a] TO SEVERAL ENVIRONMENTS ON THE MODULUS OF RUPTURE[b] OF VARIOUS REFRACTORIES[9]

			Exposure Conditions[a]					
				Steam		Hydrogen		Carbon Dioxide
actory	Brand Name Manufacturer	Cured & Dried[c]	Air Fired 1100 °C 250 hr	1100 °C 250 hr 1000 psi	Air Fired 1100 °C 250 hr	1100 °c 250 hr 1000 psi	Air Fired 1100 °C 250 hr	1100 °C 250 hr 800 psi
e 95% Al_2O_3 able, cal- aluminate	Castolast G Harbison-Walker	1,380±210	695	295	695± 90	590± 165	745± 45	745± 250
e 55% Al_2O_3 able, cal- aluminate	Lo-Abrade A. P. Green	740± 40	450	1385	450± 55	440± 40	425± 45	535± 290[d]
tweight 50% 3 insulating able, calcium inate bond	Litecast 75-28 General Re-fractories	770± 50	465	1015	465±190	650± 100	580± 35	590± 100
e 45% Al_2O_3 able, cal- aluminate	H.S. Brikcast BF General Re-fractories						1,235± 80	1,015± 125[d]
Al_2O_3 ram- mix, phos- e bond	Brikram 90R General Re-fractories	2,373±270	4180	3600	4,180±435	5,035±1205	4,735±310	4,525±1065
e 90% Al_2O_3 able, phos- e bond	Resco Cast AA-22 Resco Products						2,550±155	2,910± 380[d]
ium alumin- neat cement Al_2O_3)	CA-25 Alcoa	560±180	380	575	380±210	310± 105	505±160	395± 100
Al_2O_3 brick	99AD A. P. Green	2,720± 90	3365	2760	3,365±700	3,930± 175	3,410±195	3,145± 635
Al_2O_3 brick	Arco-90 General Re-fractories	2,960±370	4055	4940	4,055±365	4,005± 635	4,605±360	4,830±1030
Al_2O_3 tar- regnated ck	Ufala T1 Harbison-Walker	3,290±450	2555	3665	2,555±390	2,310± 730	2,990±540	2,910± 115
Al_2O_3 fired er duty brick	KX-99 A. P. Green	1,140±300	1620	2625	1,620±190	1,860± 315	2,750±365	2,790± 630

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nples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths time.

TM C-583-67, test bars 1 in x 1 in x 7 in; values given are 95% confidence intervals; units are psi.

nples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramng mix was taken as received, pressed at 1000 psi in sample mold, dried at 250 °F 28 hr, heated at 50 °F/hr to 500 °F, held hr, heated at 50 °F/hr to 1000 °F, held 24 hr, cooled slowly back to ambient temperature, and the resulting samples sawed to ze; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230 °F, cooled in a moisture-proof ntainer, stored at 75 °F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25 °C water to give ball-in-hand consistency, oweled into molds on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90 °F and 100% relative midity, removed from molds and dried 24 hr at 230 °F.

hese values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF ALKALI-GAS EXPOSURE[a]
ON THE HOT MODULUS OF RUPTURE[b] OF SOME REFRACTORIES [9]

Refractory	Brand Name Manufacturer	Hot Modulus of Rupture[b] after Treatment[a] A 50% soln, Air Fired	 B 50% soln, Mixed Gas	 C 25% soln, Air Fired	 D 25% sol Mixed G
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	2,180	940	1,680	1,450
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	620	500	460	720
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories	630	650	410	730
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	510	500	820	630
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	1,150	1,370	1,420	2,780
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	3,330	2,880	2,690	3,040

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[a] All samples were fired in air for 24 hr at 980° C. Identical samples were then expo
to one of the following treatments:

A--Samples were soaked for 24 hr in a 50% by weight solution of KOH-NaOH, then air
fired at 980° C for 250 hr.

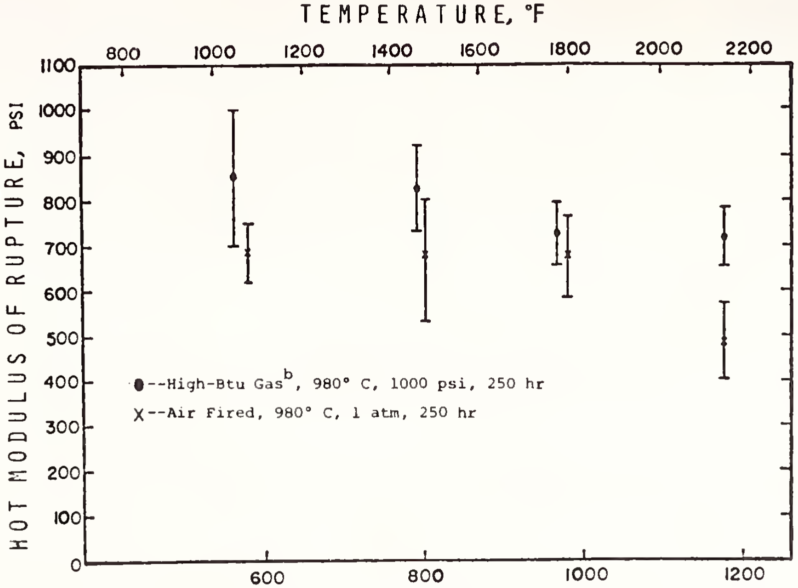
B--Samples were soaked for 24 hr in a 50% by weight solution of KOH-NaOH, then exp
to a mixed gas atmosphere at 980° C for 250 hr at 1000 psi. [Feed gas presumed
be 25% H_2, 21% CO, 13% CO_2, 5% CH_4, 36% H_2O.]

C--Samples were soaked for 24 hr in a 25% by weight solution of KOH-NaOH, then air
fired at 980° C for 250 hr.

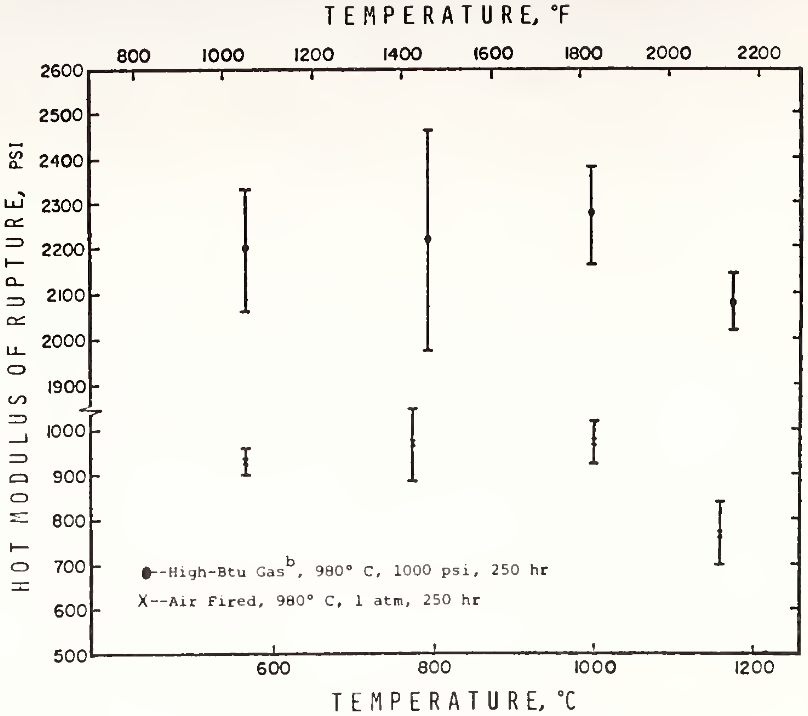
D--Samples were soaked for 24 hr in a 25% by weight solution of KOH-NaOH, then exp
to a mixed gas atmosphere as in B.

[b] ASTM C-583-67, 1 in x 1 in x 7 in specimens used.

EFFECT OF EXPOSURE[a] TO HIGH-BTU GAS[b] ON THE HOT MODULUS OF RUPTURE[c] OF INTERMEDIATE-ALUMINA REFRACTORIES[9]



Hot Modulus of Rupture of Intermediate-Alumina Refractory Containing High-Purity Cement[d]



Hot Modulus of Rupture of Intermediate-Alumina Refractory Containing Intermediate-Purity Cement[e]

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[a] Identical samples were either fired in air or exposed to the gas atmosphere at the stated temperatures and pressures for the stated lengths of time.

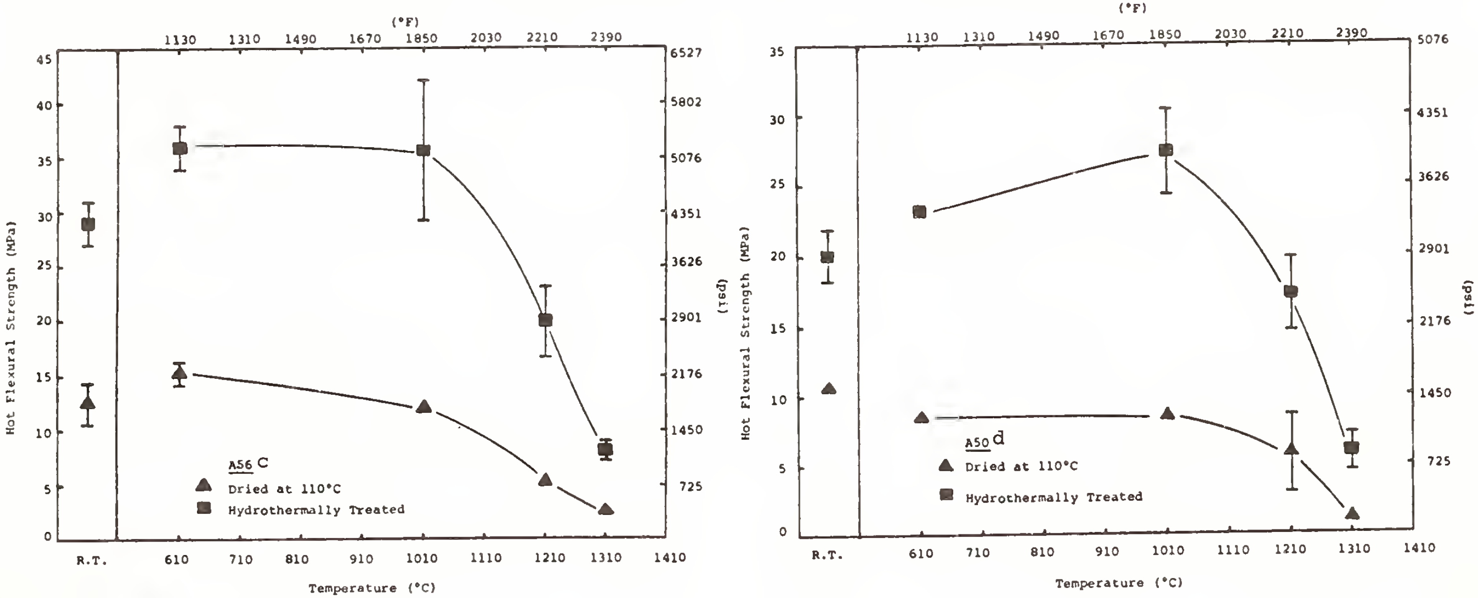
[b] Gas composition (feed gas): 24% H_2, 18% CO, 12% CO_2, 5% CH_4, 2% NH_3, 1% H_2S, 38% H_2O.

[c] ASTM C-583-67, test bars 1 in x 1 in x 6 in; values given are 95% confidence intervals; units are psi.

[d] Dense 55% Al_2O_3 castable (Lo-Abrade from A. P. Green), calcium aluminate bonded (CA-25 Calcium Aluminate Cement, high-purity with 0.15% SiO_2, 0.3% Fe_2O_3, from Alcoa).

[e] Dense 45% Al_2O_3 castable (H.S. Brikcast BF from General Refractories), calcium aluminate bonded (Refcon, intermediate-purity with 6% SiO_2, 1.8% Fe_2O_3, from Universal Atlas Cement).

EFFECT OF HYDROTHERMAL TREATMENT[a] ON THE HOT FLEXURAL STRENGTH[b] OF MEDIUM-ALUMINA CASTABLE REFRACTORIES[23]



Appearance of Fractured Surfaces

Normally-Cured Specimens: Crack propagation and fracture occurred predominantly in the cement matrix, circumventing the aggregate grains.

Hydrothermally-Treated Specimens: Transgranular gracture of aggregate grains occurred as cracks propagated.

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[a] Treatment consisted of placing specimens in a pressure vessel, heating to 310 °C in a water-saturated environment, holding for 65 hours, then raising the temperature to 610 °C (when saturation temperature of 342 °C was reached steam was vented to maintain vapor pressure at 15.0 MPa (2180 psi)), maintaining exposure conditions for 160 hours, cooling to 500 °C and venting steam to ambient pressure, and finally allowing specimens to cool to ambient temperature.

[b] Hot flexural strength as determined in four-point bend tests on a universal testing machine; constant crosshead displacement rate of 5 x 10^{-2} mm/min; all specimens, untreated and hydrothermally treated, were heated to the test temperature at ∿5 °C/min and held at temperature for 15 hours before testing.

[c] A56 is an NBS-prepared medium-alumina castable refractory bonded with high-purity calcium aluminate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3, 0.2 wt% Na_2O, 1.9 wt% others and loss on ignition. Concrete batches of 2000 g were dry-mixed to homogeneity; water added slowly to "ball-in-hand" consistency (11.0%); bars 75 x 15 x 7.5 mm were cast in gang molds with combination of vibration and tamping; after casting placed in 95+% relative humidity at 22-25 °C for 24 hours; bars were removed from molds and dried at 110 °C for 48 hours.

[d] A50 is an NBS-prepared medium-alumina castable refractory bonded with medium-purity calcium aluminate cement: 50.4 wt% Al_2O_3, 8.4 wt% CaO, 38.4 wt% SiO_2, 1.1wt% Fe_2O_3, 0.1 wt% Na_2O, 1.6 wt% others and loss on ignition. Specimens prepared the same way as for A56 except that the casting water was 12.5%.

STRENGTH OF SOME ALUMINA REFRACTORIES[2]

Composition	Brand Name[a]	Crushing Strength (ambient)	Crushing Strength (2000 °F)	Shear Strength (ambient)	Mechanical Shock[b] (ambient)
		psi	psi	psi	in-lb/in^2
96% Al_2O_3	Plicast 40	5633(374)[c]	6208(584)[d]	2661(454)[c]	8.4(0)[c]
94.6% Al_2O_3-0.5% SiO_2	Alfrax B-57	465(32)[c]	no test	279(118)[c]	no test
94.5% Al_2O_3-0.15% SiO_2	Greencast-94	7571(118)[c]	4815(464)[c]	7227(74)[c]	56.4(44)[c]
93.7% Al_2O_3-0.1% SiO_2	Castolast G	5668(380)[c]	4358(1215)[d]	2799(731)[c]	16.8(6.7)[c]
93.7% Al_2O_3	Taycor 414-FH	13685(469)[c]	9438(1682)[d]	4893(1381)[c]	9.6(1.2)[c]
93% Al_2O_3	Kao-Phos 30	5274(607)[c]	2355(±331)[e]	926(70)[c]	no test
92.6% Al_2O_3-6.8% CaO-0.4% SiO_2	H-W Lt.Wt. 33	7751(465)[c]	2720(763)[c]	4478(746)[c]	15.2(11)[c]
89.6% Al_2O_3-0.7% SiO_2	Resco Cast AA-22	3927(±83)[e]	3565(306)[d]	2132(179)[c]	10.4(5)[c]
over 87% Al_2O_3	Alfrax 66	745(40)[c]	no test	400(93)[c]	no test

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[a] See Section B.3.2.10 for manufacturers.

[b] Mechanical shock test involved the use of the Tinius-Olson Charpy impact tester.

[c] Standard deviation based on 3 samples.

[d] Standard deviation based on 4 samples.

[e] Variation of two samples tested.

EFFECT OF ALKALI-GAS EXPOSURE[a] ON THE COMPRESSIVE STRENGTH[b] OF SOME REFRACTORIES[9]

Refractory	Brand Name Manufacturer	Compressive Strength[b] after Treatment[a]			
		A High-Btu Gas	B Alkali-Gas	C Solution, Air Fired	D Solution, Alkali-Gas
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	6,880±1310	7,480± 390	9,030	8,020
Dense 90% Al_2O_3 castable, calcium aluminate bond	DOE 90 Generic Preparation	5,360± 280	5,970± 880	9,950	11,770
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	4,540± 720	7,650±1200	3.060	3,170
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	3,130± 260	2,720	1,740	1,700
Dense 45% Al_2O_3 castable, calcium aluminate bond	B&W Kaocrete D Babcock & Wilcox	7,290± 500	7,280±1170	1,600	2,100
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories	10,960±1440	11,170±5640	2,940	3,830
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	12,690±2100	11,510±4300	14,300	23,070
Dense 90% Al_2O_3 castable, phosphate bond	Resco Cast AA-22 Resco Products	5,040± 320	3,610	7,100	2,090
60% Al_2O_3 ramming mix, phosphate bond	HW 23-75 Harbison-Walker	11,430± 780	10,100±1530	9,430	12,040
90% Al_2O_3 brick	Arco-90 General Refractories	20,410±1900	21,750±6370	26,650	24,740
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	13,880±1900	13,170	13,930	10,630

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[a] All samples were fired in air at 980° C for 24 hr and then given one of the following treatments:

A--Samples were exposed to a high-Btu gas for 250 hr at 980° C and 1000 psi. Feed gas composition: 26% H_2, 21% CO, 14% CO_2, 5% CH_4, 34% H_2O.

B--A 2:1 mixture by weight of KOH/NaOH was placed in a Pt crucible and surrounded by test specimens in the reaction vessel. Feed gas composition was the same as in A. The specimens were subjected to the resulting atmosphere for 200 hr at 980° C and 1000 psi. At the end of the test the alkali had been reduced about 50% and the KOH/NaOH ratio was 1.58 in the crucible.

C--Samples were soaked for 24 hr in a solution of 500g KOH and 250g NaOH in 600 ml water, oven dried at 125° C for 24 hr, and then air fired at 980° C for 200 hr.

D--Samples were soaked and dried as in C, and then subjected to the same alkali-gas atmosphere described in B.

[b] ASTM C-133-72, specimens were 1 in x 1 in x 2 in; values given are 95% confidence intervals; units are psi.

EFFECT OF EXPOSURE[a] TO A MIXED GAS[b] ON THE COMPRESSIVE STRENGTH[c] OF VARIOUS REFRACTORIES [9]

ctory	Manufacturer	Cured & Dried[d]	Air Fired 1100° C 160 hr	Mixed Gas[b] 980° C 160 hr 1000 psi	Air Fired 980° C 1000 hr	Mixed Gas[b] 980° C 1000 hr 1000 psi
95% Al_2O_3 ble, cal- aluminate	Castolast G Harbison-Walker	2,670± 330[e] 5,790± 70[f]	3,480± 590	2,520± 80[g]	3,660± 540 9,710±1710[i]	2,460± 250[g] 7,650±1240[g,i]
55% Al_2O_3 ble, cal- aluminate	Lo-Abrade A. P. Green	2,030± 330	1,500± 190	2,360± 140[g,h]	1,530± 80	3,740± 880[g,h]
weight 50% insulating ble, calcium nate bond	Litecast 75-28 General Refractories	1,300± 260	1,880± 270	2,710± 170[g]	1,010± 110	3,050± 430[g]
45% Al_2O_3 ble, cal- aluminate	H.S. Brikcast BF General Refractories		4,440± 200	10,860±1030[g,h]	3,340± 260	12,740±1560[g,h]
l_2O_3 ram- mix, phos- bond	Brikram 90R General Refractories	13,790± 840	19,080±4390	15,940±4170	15,860±2090	14,200±5380
90% Al_2O_3 ble, phos- bond	Resco Cast AA-22 Resco Products		6,060± 860	5,180±1000[h]	6,590± 790	3,840± 560[g,h]
um alumin- eat cement Al_2O_3)	CA-25 Alcoa	13,600±1610	9,420±3130	9,450±1280	10,960±1710	9,950±2910
Al_2O_3 brick	99AD A. P. Green	7,700±3200	7,250±1820	10,280±1480[g]	8,160±2500	8,510±1780
Al_2O_3 brick	Arco-90 General Refractories	18,400±5270	25,530±3820	27,340±6410	24,150±1770	25,530±4150
Al_2O_3 tar- egnated	Ufala Tl Harbison-Walker	17,370±8860	9,480±2660	11,480±2080	16,140±3380	15,860±4460
Al_2O_3 fired r duty brick	KX-99 A. P. Green	6,240±2150	10,960±1890	13,070±5560[g]	10,710±4320	14,110±2140

les were fired in air then exposed to the mixed gas environment at the temperature and pressure indicated for the ed length of time.

ed gas composition (feed gas): 24% hydrogen, 18% carbon monoxide, 12% carbon dioxide, 5% methane, 2% ammonia, 1% ogen sulfide, 38% steam.

C-133-72, 1 x 1 x 2 inch specimens cut from test bar; values are 95% confidence intervals; units are psi.

les were prepared in the following ways: Fired brick was taken as received and cut to sample size with a dia- saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at F/he to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient tempera- , and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven ed for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mix- (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating e for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from s and dried 24 hr at 230° F.

-inch cubes cut from larger test bars.

-inch cubes cast in molds.

se values were labelled as differing from the air-fired values by a statistically significant amount.]

se values were labelled as differing from the other mixed-gas values by a statistically significant amount.]

e values were obtained using specimens prepared from a new batch of the castable.

EFFECT OF STEAM EXPOSURE[a] ON THE COMPRESSIVE STRENGTH[b] OF VARIOUS REFRACTORIES [9]

Refractory	Brand Name Manufacturer	Cured & Dried[c]	Air Fired 815° C 250 hr	Steam 815° C 250 hr 1000 psi	Air Fired 980° C 250 hr	Steam 980° C 250 hr 1000 ps
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	2,670± 330[d] 5,790± 70[e]	8,710±2725	7,475± 360	9,810±1590	7,595±4
Dense 90% Al_2O_3 castable, calcium aluminate bond	DOE 90 Generic Preparation		5,210± 835	7,330± 840[f]	6,285± 485	5,555±3
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	2,030± 330	1,607± 270	5,660± 380[f]	1,920± 280	2,675±3
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	1,300± 260	1,865± 200	2,925± 390[f]		
Dense 45% Al_2O_3 castable, calcium aluminate bond	B&W Kaocrete D Babcock & Wilcox		2,870±1090	9,540± 545[f]		
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories		3,280± 290	11,550± 620[f]	3,090± 270	10,790±7
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	13,790± 840	14,940±4680	12,795± 970		
Dense 90% Al_2O_3 castable, phosphate bond	Resco Cast AA-22 Resco Products		6,910±1680	4,880± 400[f]		
60% Al_2O_3 ramming mix, phosphate bond	HW 23-75 Harbison-Walker		9,150±1405	8,135±1165		
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	13,600±1610	9,195±1300	10,860±1260	10,355± 810	8,220±7
90% Al_2O_3brick	Arco-90 General Refractories	18,400±5270	24,780±4035	24,325±2540		
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	6,240±2150	8,370±2740	14,205±3155[f]		

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[a] Samples were fired in air, then exposed to steam at the temperature and pressure indicated for the stated lengtl of time.

[b] ASTM C-133-72, one-inch cube specimens used; values given are 95% confidence intervals, units are psi.

[c] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a di mond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated a 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient tempera ture, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mi er (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed fr molds and dried 24 hr at 230° F.

[d] One-inch cubes cut from larger test bars.

[e] One-inch cubes cast in molds.

[f] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

Refractory	Manufacturer	Cured & Dried[c]	Exposure Conditions[a]					
			Air Fired 1100° C 250 hr	Hydrogen 1100° C 250 hr 1000 psi	Air Fired 1100° C 125 hr	Carbon Monoxide 1100° C 125 hr 1000 psi	Air Fired 1100° C 250 hr	Carbon Dioxide 1100° C 250 hr 1000 psi
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	2,670± 330[d] 5,790± 70[e]	3,370± 520	2,200± 260	3,060± 700	3,960± 2320	3,480± 590	2,910± 350
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	2,030± 330	1,470± 130	1,890± 200	1.330± 130	1890	1,500± 190	2,270± 240[f]
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	1,300± 260	1,360± 90	2,110± 140	1,110± 110	---	1,880± 270	1,680± 250
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories						4,440± 200	3,390± 440[f]
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	13,790± 840	20,590±3520	19,250±3740	15,400±4630	15,760±11200	19,080±4390	16,330±4200
Dense 90% Al_2O_3 castable, phosphate bond	Resco Cast AA-22 Resco Products						6,060± 860	6,520± 500
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	13,600±1610	11,510±2440	8,820±1570	7,880±1220	---	9,420±3130	9,020±1110
99% Al_2O_3 brick	99AD A. P. Green	7,700±3200	8,440±3140	12,090±2920	8,440±3140	11,140±9290	7,250±1820	8,680±1690
90% Al_2O_3 brick	Arco-90 General Refractories	18,400±5270	21,160±7280	20,530±7900	21,160±7280	22,640±2660	25,530±3820	22,750±8360
60% Al_2O_3 tar-impregnated brick	Ufala T1 Harbison-Walker	17,370±8860	10,680±4090	5,690±3480	10,680±4090	10,560±9070	9,480±2660	8,490±1830
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	6,240±2150	6,750±1920	4,050±1020	6,750±1920	7,580±2250	10,960±1890	12,400±1440

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[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths of time.

[b] ASTM C-133-72, one-inch cube specimens used; values given are 95% confidence intervals; units are psi.

[c] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

[d] One-inch cubes cut from larger test bars.

[e] One-inch cubes cast in molds.

[f] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF EXPOSURE[a] TO STEAM AND A HIGH-BTU GAS[b] ON THE COMPRESSIVE STRENGTH[c] OF SOME REFRACTORIES FOR POSSIBLE USE IN SLAGGING GASIFIERS[9]

Refractory[d]	Brand Name Manufacturer	Air Fired 980°C 250 hr	Steam 980° C 250 hr 1000 psi	Air Fired 980° C 250 hr	High-Btu 980° 250 1000
Al_2O_3(90)-Cr_2O_3(10) Sintered brick	Ruby Harbison-Walker	11,550± 380	11,190± 970	12,470±1030	11,810±1
Al_2O_3(60)-Cr_2O_3(27)-MgO(6)-Fe_2O_3(4) Fused-cast brick	Monofrax K-3 Carborundum Co.	25,460±3940	26,380±3850	24,540±5300	26,800±2
MgO(61)-Cr_2O_3(17)-Fe_2O_3(11)-Al_2O_3(8) Sintered brick	Guidon Harbison-Walker	9,810±2060	8,130± 790	8,680±1240	7,270±1
Cr_2O_3(80)-MgO(8)-Fe_2O_3(6) Fused-cast brick	Monofrax E Carborundum Co.	24,940±3840	20,730±2550	20,140±2910	22,820±4
SiC(73)-Si_3N_4(21)-Al_2O_3(3)-SiO_2(3) Sintered brick	Refrax 20 Carborundum Co.	23,360±7740	Disintegrated[e]	20,570±3420	Disintegr
Al_2O_3(85)-Cr_2O_3(10)-P_2O_5(2)-SiO_2(2) Ramming plastic, chemically bonded	Shamrock 888	11,240±2530	12,900±1150	11,010±1530	14,840±1
Cr_2O_3(40)-Fe_2O_3(23)-Al_2O_3(21)-MgO(10) Ramming plastic, chemically bonded	Kemram C-E Refractories	14,620±1510	5,710±1020[e]	15,250± 870	9,180±1
Al_2O_3(88)- Cr_2O_3(10)-P_2O_5(1) Chemically bonded brick	Serv-M (852Z) Taylor Refractories/NL Industries	23,810±3550	24,000±2170	20,470±3630	22,280±2
MgO(53)-Cr_2O_3(20)-Al_2O_3(17)-Fe_2O_3(8) Sintered brick	Dibond 50 General Refractories	8,310±1760	7,690±1330		
MgO(59)-Cr_2O_3(19)-Al_2O_3(13)-Fe_2O_3(7) Sintered brick	GR-200 General Refractories	8,040±1650	7,110± 440		
MgO(64)-Cr_2O_3(15)-Al_2O_3(13)-Fe_2O_3(6) Sintered brick	Nucon 60 Harbison-Walker	5,670± 900	4,570±4570		

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[a] Identical samples of each material were exposed to steam or were air fired. For the tests involving the H Btu Gas, identical samples were prefired for 24 hours in air and then either exposed to the gas or air fir

[b] Gas composition (feed gas): 25% H_2, 13% CO_2, 21% CO, 5% CH_4, 36% H_2O.

[c] ASTM C-133-72, specimens were 1 in x 1 in x 2 in; values given are 95% confidence intervals; units are psi

[d] The numbers in parentheses indicate the percent of the constituent present.

[e] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF EXPOSURE[a] TO GASIFICATION ATMOSPHERES[b] ON THE COMPRESSIVE STRENGTH[c] OF VARIOUS REFRACTORIES[9]

fractory	Manufacturer	Cured & Dried[d]	Air Fired 980° C 250 hr	Low-BTU Gas[b] 980° C 250 hr 400 psi	Air Fired 810° C 250 hr	High-BTU Gas[b] 760° C 160 hr 1000 psi
nse 95% Al_2O_3 stable, cal- um aluminate nd	Castolast G Harbison-Walker	2,670± 330[e] 5,790± 70[f]	9,810±1590	9,660± 550	8,710±2725	7,290±1670
nse 90% Al_2O_3 stable, cal- um aluminate nd	DOE 90 Generic Preparation		6,285± 485	5,839±1120	5,210± 835	4,315±2060
nse 55% Al_2O_3 stable, cal- um aluminate nd	Lo-Abrade A. P. Green	2,030± 330	1,920± 280	2,495± 220	1,607± 270	5,280± 415[g]
ghtweight 50% $_2O_3$ insulating stable, calcium uminate bond	Litecast 75-28 General Refractories	1,300± 260	1,280± 125	2,490± 790[g]	1,865± 200	2,475± 460[g]
nse 45% Al_2O_3 stable, cal- um aluminate ond	B&W Kaocrete D Babcock & Wilcox		2,285± 295	6,945±2425[g]	2870±1090	7,940± 615[g]
nse 45% Al_2O_3 astable, cal- ium aluminate ond	H.S. Brikcast BF General Refractories		3,090± 270	7,025± 700[g]	3,280± 290	8,570±2010[g]
0% Al_2O_3 ram- ing mix, phos- nate bond	Brikram 90R General Refractories	13,790± 840	19,145±1980	15,615±5305	14,940±4680	15,420±2765
ense 90% Al_2O_3 astable, phos- hate bond	Resco Cast AA-22 Resco Products		8,105± 630	6,550±1750	6,910±1680	5,025± 575[g]
0% Al_2O_3 ram- ing mix, phos- hate bond	HW 23-75 Harbison-Walker		13,150±3035	11,150± 740	9,150±1405	8,115±1735
alcium alumin- te neat cement 78% Al_2O_3)	CA-25 Alcoa	13,600±1610	10,355± 810	9,185±1300	9,195±1300	8,780±2040
0% Al_2O_3brick	Arco-90 General Refractories	18,400±5270	18,110±12340	25,100±8470	24,780±4035	20,470±5670
5% Al_2O_3 fired super duty brick	KX-99 A. P. Green	6,240±2150	12,715±4810	11,110±1280	8,370±2740	14,265±6160[g]

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[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lenths of time.

[b] Composition of feed gases: Low-BTU gas--17.3% hydrogen, 12.9% carbon monoxide, 8.7% carbon dioxide, 3.7% methane, 42.5% nitrogen, 1% hydrogen sulfide, 2% ammonia, 12% steam; High-BTU Gas--24% hydrogen, 18% carbon monoxide, 12% carbon dioxide, 5% methane, 2% ammonia, 1% hydrogen sulfide, 38% steam.

[c] ASTM C-133-72; values given are 95% confidence intervals; units are psi.

[d] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

[e] One-inch cubes cut from larger bars.

[f] One-inch cubes cast in molds.

[g] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF EXPOSURE[a] TO MIXED GASES ON THE COMPRESSIVE STRENGTH[b]
OF REFRACTORIES REINFORCED WITH STEEL FIBERS[9]

Refractory	Brand Name Manufacturer	Type Fiber	Wt% Fiber[c]	Fiber Length[d]	Air Fired 980° C 500 hr	Low-Btu Gas[e] 980° C 500 hr 400 psi	Air Fired 980° C 250 hr	High- 98 25 100
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	430 SS	2	1 3/8	6,320	5,400		
		430 SS	2	---			7,680	6,
		446 SS	2	1 3/8	7,150	6,020[g]		
		446 SS	2	---			8,385	6,
		446 SS,C[h]	2	1 3/8	6,650	5,920		
		446 SS,C	2	---			7,540	6,
		310 SS	2	1 3/8	6,280	5,610		
		310 SS	2	---			7,280	5,
Dense 90% Al_2O_3 castable, calcium aluminate bond	DOE 90 Generic Preparation	430 SS	2	---			6,870	6,
		446 SS	2	---			5,135	5,
		446 SS,C	2	1 3/8	5,540	4,880		
		446 SS,C	2	---			5,920	6,
		310 SS	2	1 3/8	5,680	4,520[g]		
		310 SS	2	---			6,855	5,
		304 SS	4	3/4	5,370	5,930		
		HT[i]	4	3/4	5,170	9,000[g]		
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories	430 SS[j]	4	3/4	3,570	10,410[g]		
		430 SS	2	---			3,025	10,
		446 SS	4	3/4	4,100	8,560[g]		
		446 SS	2	---			4,130	11,
		446 SS,C	4	3/4	3,890	10,580[g]		
		446 SS,C	2	---			4,130	12,
		310 SS	4	3/4	3,370	9,750[g]		
		310 SS	2	---			4,150	12,
		304 SS	4	3/4	3,720	9,960[g]		
		HT[i]	4	3/4	3,930	10,220[g]		
Dense 50% Al_2O_3 castable, calcium aluminate bond	Mix 36-C Generic Preparation	430 SS	4	3/4	4,130	12,790[g]		
		446 SS	4	3/4	5,300	11,410[g]		
		446 SS,C	4	3/4	4,260	14,120[g]		
		310 SS	4	3/4	4,190	12,530[g]		
		304 SS	4	3/4	4,200	10,100[g]		
		HT[i]	4	3/4	4,570	12,620[g]		
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	446 SS	4	3/4	1,530	2,840[g]		
		304 SS	4	3/4	1,300	2,290[g]		

---

[a] Identical samples were subjected to firing in air or to the gas atmosperes under the stated conditions.

[b] ASTM C-133-72; values are the average of at least 4 specimens; units are psi.

[c] Wt % based on the castable dry weight.

[d] Units are inches; fibers are 0.02 in diameter; dimensions of fibers not given for exposures to high-Btu gas.

[e] Low-Btu gas contains H_2S. Feed gas composition: 17% H_2, 15% CO, 9% CO_2, 4% CH_4, 46% N_2, 2% NH_3, 1% H_2S, 6% H_2O.

[f] High-Btu gas (feed gas) composition: 25% H_2, 21% CO, 13% CO_2, 5% CH_4, 36% H_2O.

[g] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

[h] This material was a coated 446 SS.

[i] This material is a commercial, but proprietary stainless steel containing ~17% Cr, with some Al and Ti.

[j] Metallographic examination made of fibers removed from Brikcast samples exposed to the H_2S-containing low-Btu gas
dicated that the coated 446 SS fibers had corroded the least. All other fibers were about equally corroded with
304 SS showing the most corrosion. Fibers from all materials exposed to the high-Btu gas showed no degradation o
red within samples but there was some degradation where fibers extended to the surface of the sample.

EFFECT OF STEAM EXPOSURE[a] ON THE COMPRESSIVE STRENGTH[b] OF A REFRACTORY CONCRETE[c] WITH AND WITHOUT VARIOUS ADDITIVES[d] [9]

Sample Composition				Compressive Strength[b]	
Material	Additive	Wt %	Wt % Water	Air Fired 980° C 250 hr	Steam 980° C 250 hr 1000 psi
0[c]/CA-25[e]			8.6	6,285±485	5,555±365[g]
0/Refcon[f]			8.6	6,245±675	5,105±355[g]
0/CA-25	Cabosil[d]	0.5	8.8	5,060±290	3,445±155[g]
		2.5	15.8	1,725±190	625±140[g]
		5.0	22.2	695±170	245± 80[g]
0/CA-25	Silica flour[d]	0.5	8.0	5,600±495	4,060±270[g]
		2.5	8.7	4,470±290	2,195±100[g]
		5.0	8.8	3,840±205	3,235±240[g]
0/CA-25	kyanite[d] (calcined)	0.5	8.6	4,915±270	4,510±230
		2.5	8.7	4,270±370	3,075±115[g]
		5.0	8.9	3,630±230	2,335±100[g]

---

les were fired in air, then exposed to steam at the temperature and pressure in-
ted for the stated lenth of time.

C-133-72, 1 in x 1 in x 2 in cast bars used; values given are 95% confidence
rvals; units are psi.

e 90% Al_2O_3 castable, calcium aluminate bonded; a generic preparation.

tives are reactive silica (minus 325 mesh) added to the DOE 90 before casting.

5 Calcium Aluminate Cement, a high-purity calcium aluminate (0.15% SiO_2, 0.3%
3), from Alcoa.

on is a medium purity calcium aluminate (6% SiO_2, 1.8% Fe_2O_3), from Universal
s Cement.

se values were labelled as differing from the air-fired values by a statisti-
y significant amount.]

EFFECT OF CASTING WATER AND PLASTICIZER CONTENT ON THE COLD CRUSHING STRENGTH OF A HIGH-ALUMINA CASTABLE REFRACTORY[a] [9]

Water Content %	Polyvinyl Alcohol Content %	Crushing Strength Pipe[b] lb/linear ft	Crushing Strength Cubes[c] lb/square in
11	0	1520	4850
11	0.25	1010	2990
11	0.5	1100	3490
12	0	1080	4300
12	0.25	870	3050
12	0.5	950	2080

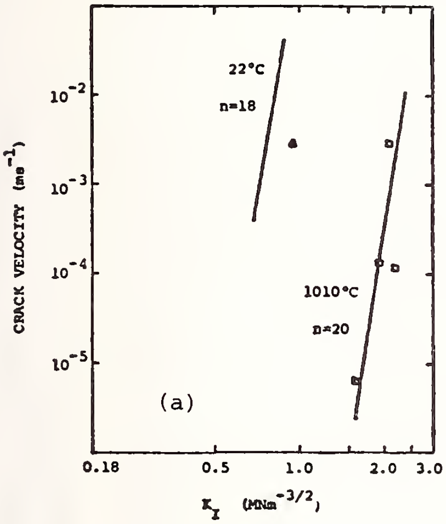
---

[a] Castable used is Harbison-Walker's Castolast G, a high-purity tabular alumina, calcium aluminate bonded.

[b] Pipe casting: Casting water and castable mix conditioned 24 hr at ambient temperatures; stirred in Hobart mixer 2 min; pipe mold is charged while slowly rotating and the walls smoothed; castable is "set-up" by rotating mold at over 1000 rpm several minutes; pipe removed and placed in sealed plastic bag (humidity >90%) and cured 24 hr at 40° C; dried 24 hr at 120° C; pipe dimensions 4 in OD and 6 in long.

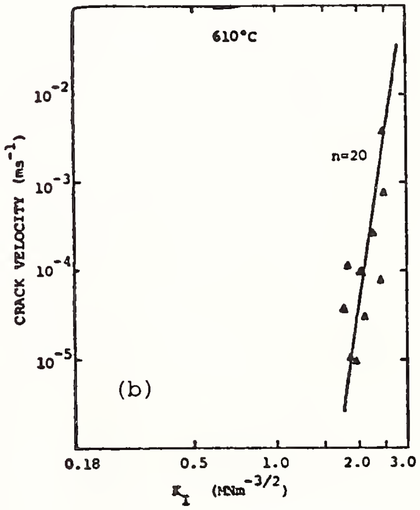
[c] Size of cubes not specified, nor casting procedure.

EFFECT OF TEMPERATURE AND SMALL AGGREGATE SIZE ON CRACK GROWTH IN A HIGH-ALUMINA CASTABLE REFRACTORY[23]

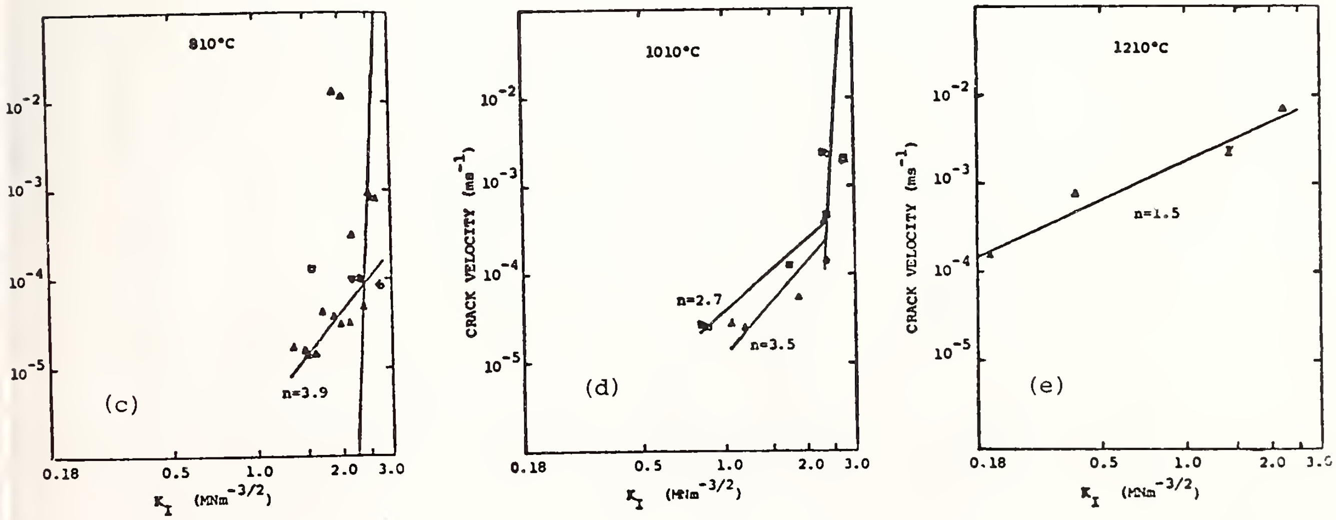


Slow crack growth data versus stress intensity factor; test temperatures as indicated. n is the slope.

(a) Material cast as-received; high-purity, 95%, tabular alumina bonded with calcium aluminate (Castolast G).

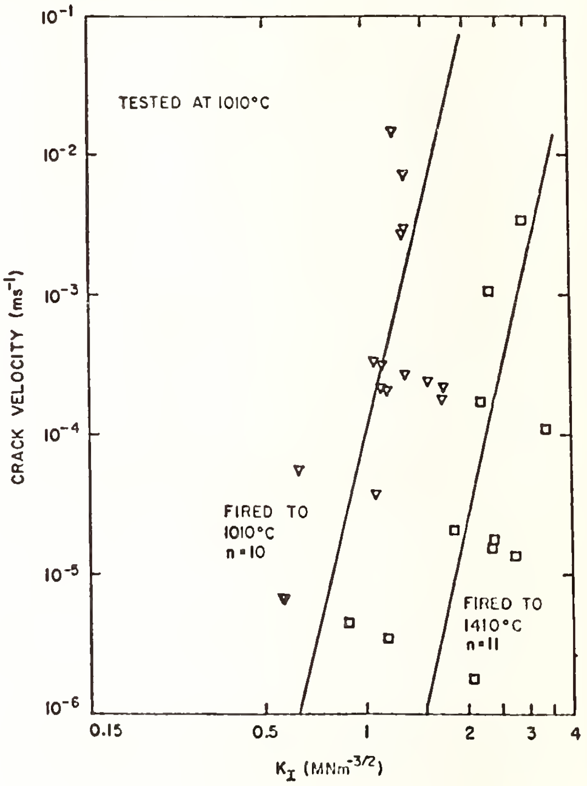


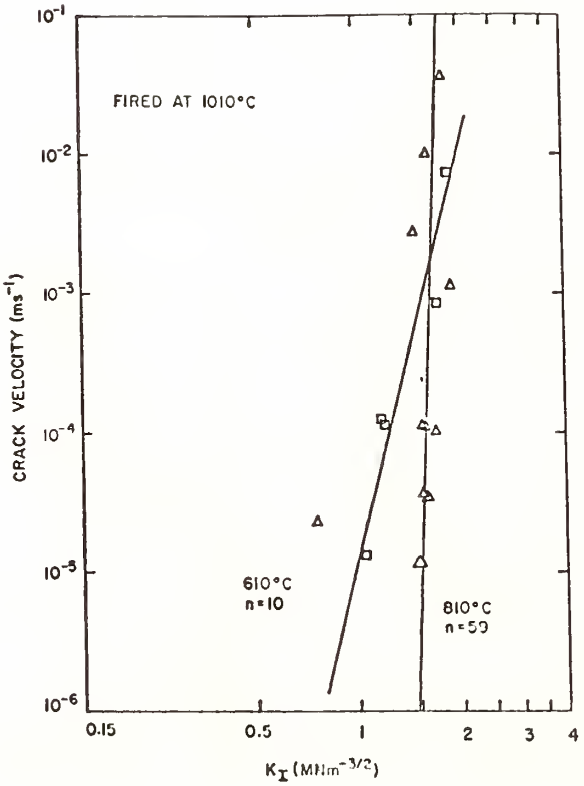
(b,c,d,e) Tests performed on same refractory; aggregate mix sieved before casting to remove particles larger than #14 Tyler mesh so as to obtain a higher cement to aggregate ratio.

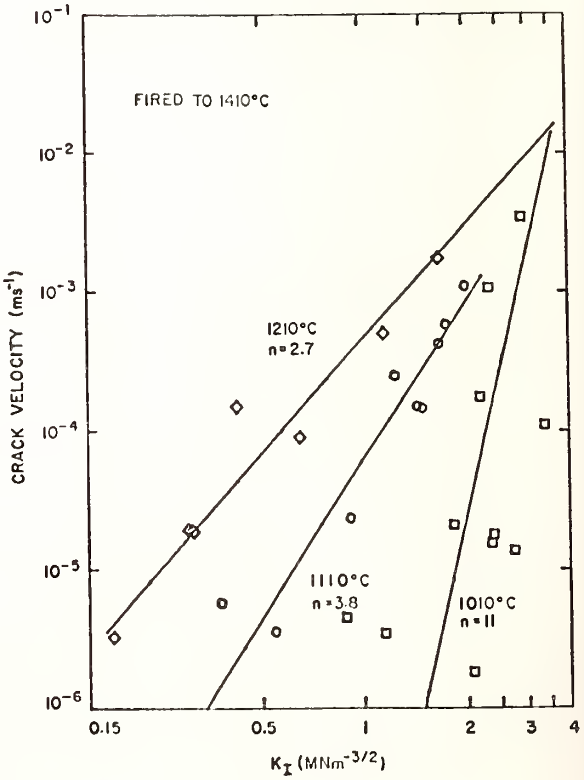


EFFECT OF FIRING TEMPERATURE AND TEST TEMPERATURE ON CRACK GROWTH IN A MEDIUM-ALUMINA CASTABLE REFRACTORY[23]

Slow crack growth rate versus stress intensity factor; refractory is 55% alumina calcined flint clay, mullite, bonded with calcium aluminate cement (Lo-Abrade); firing and test temperatures as indicated; n is the slope.







EFFECT OF HEAT TREATMENT[a] ON COMPRESSIVE STRENGTH, PHASE ASSEMBLAGE AND POROSITY OF A HIGH-ALUMINA CASTABLE REFRACTORY[b][9]

Maximum Cure Temperature, °C	Compressive Strength[c], psi		Phases[d] Present as Determined by X-ray Diffraction							Pore Diameter[e] Micrometers
	Lot A	Lot B	α-Al_2O_3	CA	CA_2	C_3AH_6	$C_{12}A_7$	$Al(OH)_3$	β-$NaAl_{11}O_{17}$	
120		8,860±550	X	X		X		X		0.04
600	7,430±140	7,990±350	X	X	X				X	
800	12,720±830	8,750±640	X	X	X		X			0.17
1,000	10,140±720	7,850±610	X	X	X		X			0.23
1,200	12,780±1390	6,960±760	X	X	X					
1,400		7,870±610	X	X	X				X	0.80

---

[a] Heat treatment consisted of raising temperature at the rate of 30 °C/h from ambient to 540 °C, holding for 6 hours, then raising at 60 °C/h to the "maximum cure" temperature. Samples soaked at the cure temperature for 8 hours, and then the furnace and contents cooled naturally to ambient conditions.

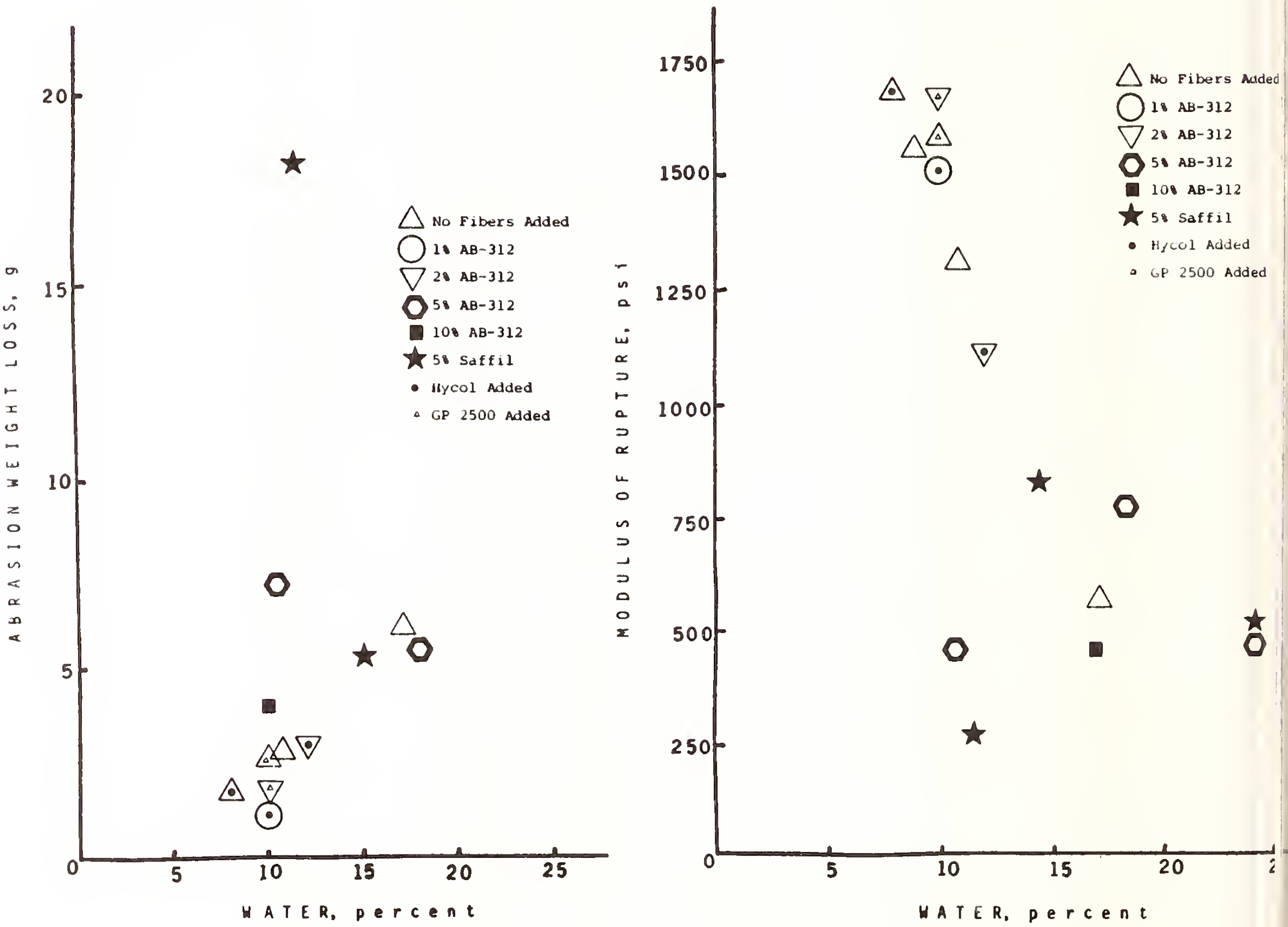
[b] Castable used is Harbison-Walker Castolast G, a high-purity tabular alumina, calcium aluminate bonded. Samples were prepared from two different commercial lots in the form of 2-inch cubes. 10 ml H_2O per 100 g dry refractory was mixed with a Hobart mixer for 1 minute, cured under 100% relative humidity and 29 °C for 24 h, and dried at 120 °C for 24 h.

[c] 95% confidence interval.

[d] Cement notation used to abbreviate phase designations: $A = Al_2O_3$, $C = CaO$, $H = H_2O$.

[e] Diameter of smallest surface-connected pores which mercury must enter in order to reach a degree of penetration equal to 0.05 cc/g.

EFFECT OF CERAMIC FIBER[a] ADDITION ON ABRASION RESISTANCE[b] AND MODULUS OF RUPTURE[c] OF A HIGH-ALUMINA CASTABLE REFRACTORY[d] [9]



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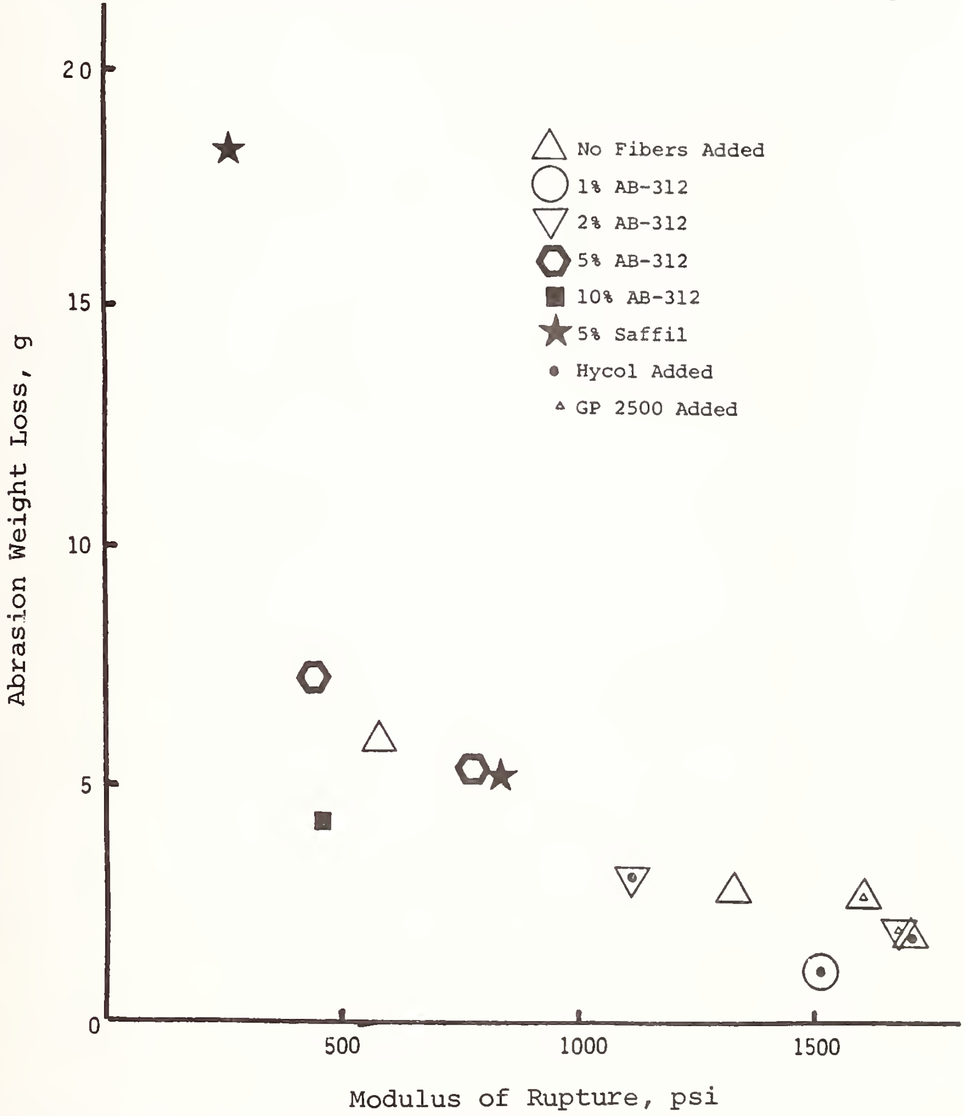
[a] Fibers used were AB-312 from 3M Company, high-alumina Al_2O_3-B_2O_3-SiO_2, 11 µm diameter and Saffil from Imperial Chemical Industries, high-temperature 98% Al_2O_3-2% SiO_2, 3 µm diameter. Fibers were chopped in high-speed Waring blender length after chopping varied 20-150 µm; castable, fibers, and water mixed in blender before casting; cast samples were moist cured for 24 hr, oven dried fo 24 hr. Wetting agents were used to reduce the amount of water necessary, 6 ounces added per 100 pounds of cement: Hycol from W. R. Grace Company and GP 2500 from Cresset Chemical Company.

[b] Sample bars 1 in x 1 in x 3 1/2 in were abraded with 1000g of 36 grit SiC according to ASTM C-704; above values are the average of 3 separate samples of each preparation.

[c] Modulus of Rupture measured using bars 1 in x 1 in x 7 in, test method and loa not specified; each point is the average of 2 specimens.

[d] Castable used is Harbison-Walker's Castolast G, a high-purity tabular alumina, calcium aluminate bonded.

EFFECT OF CERAMIC FIBER[a] ADDITION ON CORRELATION OF ABRASION HT LOSS[b] WITH MODULUS OF RUPTURE[c] OF A HIGH-ALUMINA CASTABLE REFRACTORY[d] [9]



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Sample bars 1 in x 1 in x 3 1/2 in were abraded with 1000g of 36 grit SiC according to ASTM C-704; above values are the average of 3 separate samples of each preparation.

Modulus of Rupture measured using bars 1 in x 1 in x 7 in, test method and load not specified; each point is the average of 2 specimens.

Castable used is Harbison-Walker's Castolast G, a high-purity tabular alumina, calcium aluminate bonded.

EFFECT OF TEMPERATURE CYCLING ON LENGTH OF ALUMINA REFRACTORY SAMPLES[2]

Composition	Brand Name[a]	Average Percent Change in Length at Ambient Temperature after Cycling to 2000 °F					
		Fired[b]	Cycle 1[c]	Cycle 2[c]	Cycle 3[c]	Cycle 4[c]	Cycle 5[c]
96% Al_2O_3	Plicast 40	+0.25	-0.01	-0.01	-0.01	-0.01	-0.01
94.6% Al_2O_3-0.5% SiO_2	Alfrax B-57	-0.04					
94.5% Al_2O_3-0.15% SiO_2	Greencast-94	+0.11					+0.07
93.7% Al_2O_3-0.1% SiO_2	Castolast G	+0.57	+0.01	0	+0.02	-0.01	-0.01
93.7% Al_2O_3	Taycor 414-FH	-1.5	0	0	0	0	0
93% Al_2O_3	Kao-Phos 30	-0.63					
92.6% Al_2O_3-6.8% CaO-0.4% SiO_2	H-W Lt.Wt. 33	-0.52	-0.02	-0.07	-0.07	-0.07	-0.07
89.6% Al_2O_3-0.7% SiO_2	Resco Cast AA-22	-0.02					
Over 87% SiO_2	Alfrax 66	-0.23					

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[a] See Section B.3.2.10 for manufacturers.

[b] Length compared to length of unfired sample.

[c] Length after each cycle compared to length of fired sample.

EFFECT OF THERMAL SHOCK[a] ON CONDITION OF ALUMINA REFRACTORY SAMPLES[2]

osition	Brand Name[b]	Sample Condition 1700-1800°F	 1800-2000°F	 2000°F
Al_2O_3	**Plicast 40**	No cracking or pitting		Deep cracks after cycle 1 on one sample
% Al_2O_3- 5% SiO_2	**Alfrax B-57**			
% Al_2O_3- 15% SiO_2	**Greencast-94**			
% Al_2O_3- 1% SiO_2	**Castolast G**	No cracking or pitting		Small surface cracks after cycle 1, no further changes
% Al_2O_3	**Taycor 414-FH**	No cracking or pitting		Slight cracks on surface after cycle 1, no further changes
Al_2O_3	**Kao-Phos 30**		Cracked after cycles 3 and 5	
% Al_2O_3-6.8% -0.4% SiO_2	**H-W Lt.Wt. 33**		Cracked after cycle 5	
% Al_2O_3- 7% SiO_2	**Resco-Cast AA-22**			Crack through after cycle 1, no further changes
87% Al_2O_3	**Alfrax 66**			

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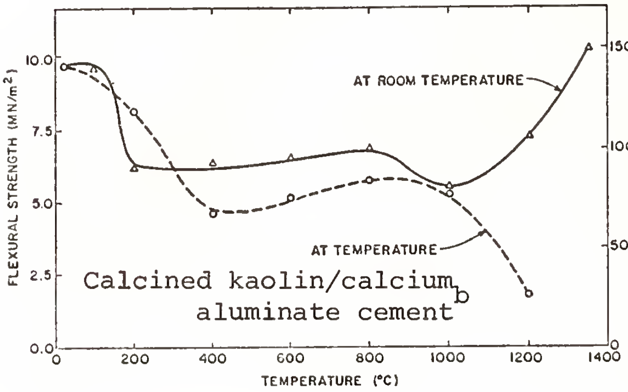
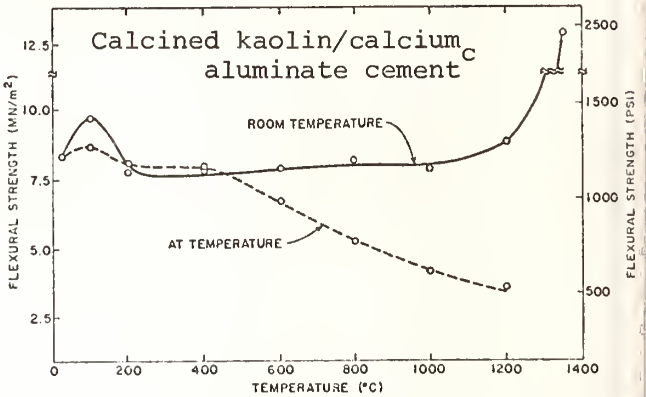
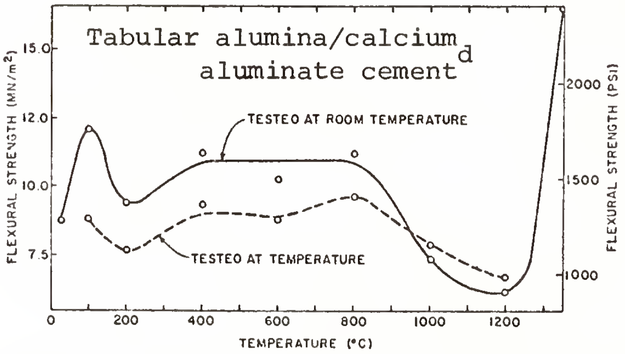
mal shock test consisted of heating rapidly to the indicated temperature, soaking 2-5 hours, and rapidly cooling to ambient temperature. Each sample was subjected such cycles.

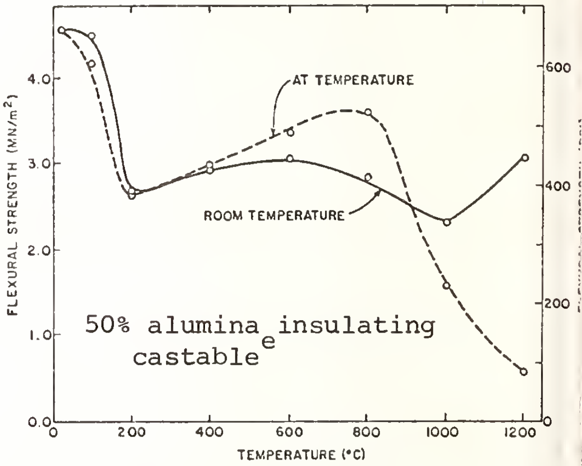
preceding tables for manufacturers.

EFFECT OF TEMPERATURE ON THE FLEXURAL STRENGTH[a] OF SEVERAL ALUMINA REFRACTORIES[16]









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[a] Flexural strength was measured in three-point bending, crosshead speed 0.05 in/min, span 6 in. Samples 1 in x 1 in x 7 in were cast, vibrated one minute cured sealed in plastic 24 h at ambient temperature, cured in air 24 h at ambient temperature, cured in air 24 h at 100 °C, fired at 60 °C/h to 200, 400, 600, 800, 1000, 1200 and 1350 °C and soaked at temperature 5 h, furnace coole to ambient temperature. One set of samples tested at ambient temperature (so id line), second set heated in a globar furnace and tested at firing temperatures when samples reached thermal equilibrium (dashed line).

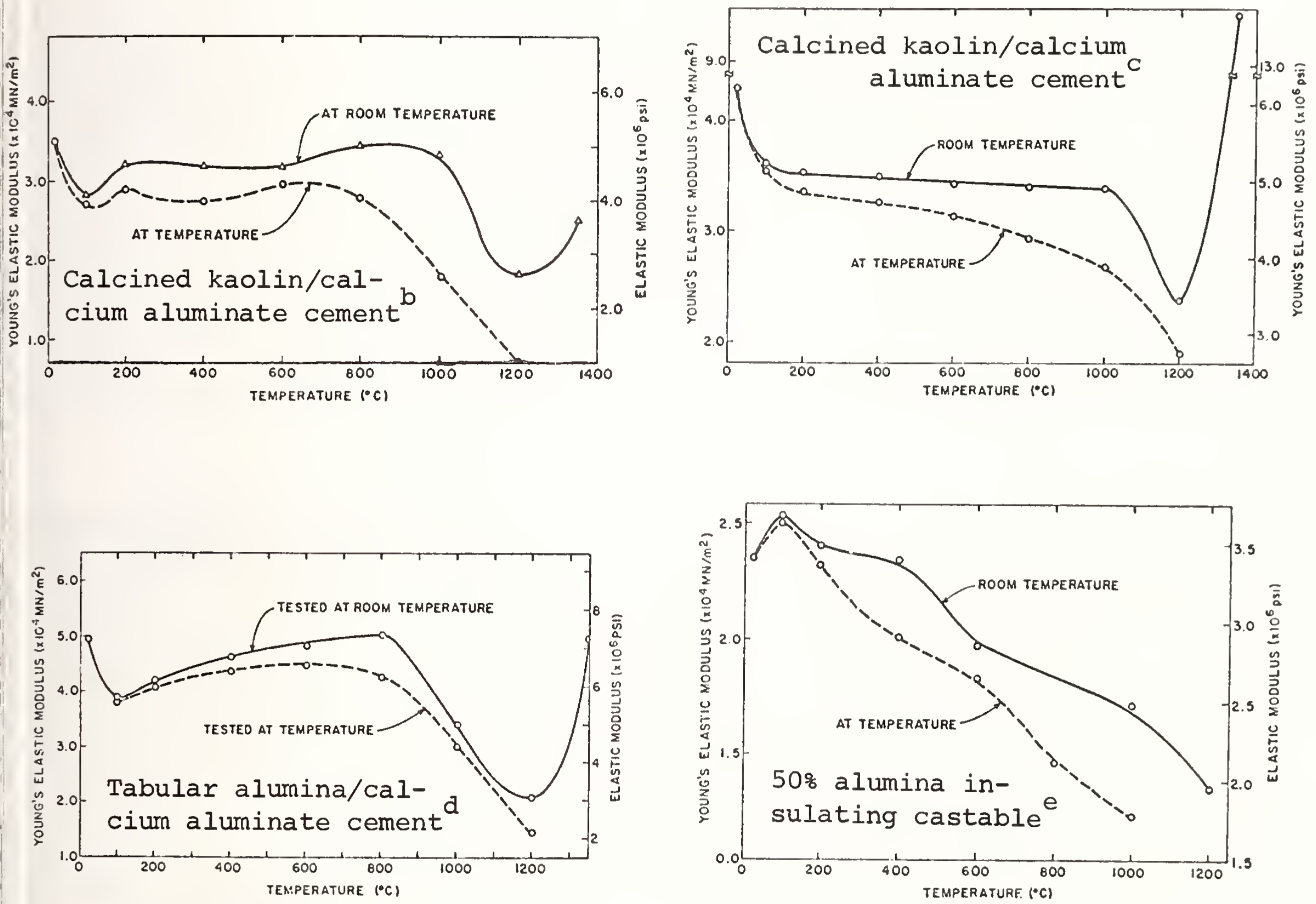
[b] 75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement) water added to ball-in-hand consistency, 13.5% of aggregate and cement.

[c] 75% Mulcoa M-47 aggregate, 25% Calcium Aluminate Cement CA-25 (Alcoa), water ball-in-hand consistency, 11.3% of aggregate and cement.

[d] 75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-ha consistency, 10.4% of aggregate and cement.

[e] Litecast 75-28 (General Refractories), a lightweight insulating castable, calcium aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF TEMPERATURE ON THE YOUNG'S MODULUS[a] OF SEVERAL ALUMINA REFRACTORIES[16]



Young's modulus measured by flexural resonance; three-point bend testing at crosshead speed 0.05 in/min, span 6 in. Samples 1 in x 1 in x 7 in were cast, vibrated one minute, cured sealed in plastic 24 h at ambient temperature, cured in air 24 h at ambient temperature, cured in air 24 h at 100 °C, fired at 60 °C/h to 200, 400, 600, 800, 1000, 1200 and 1350 °C and soaked at temperature 5 h, furnace cooled to ambient temperature. One set of samples tested at ambient temperature (solid line), second set heated in a globar furnace and tested at firing temperatures when samples reached thermal equilibrium (dashed line).

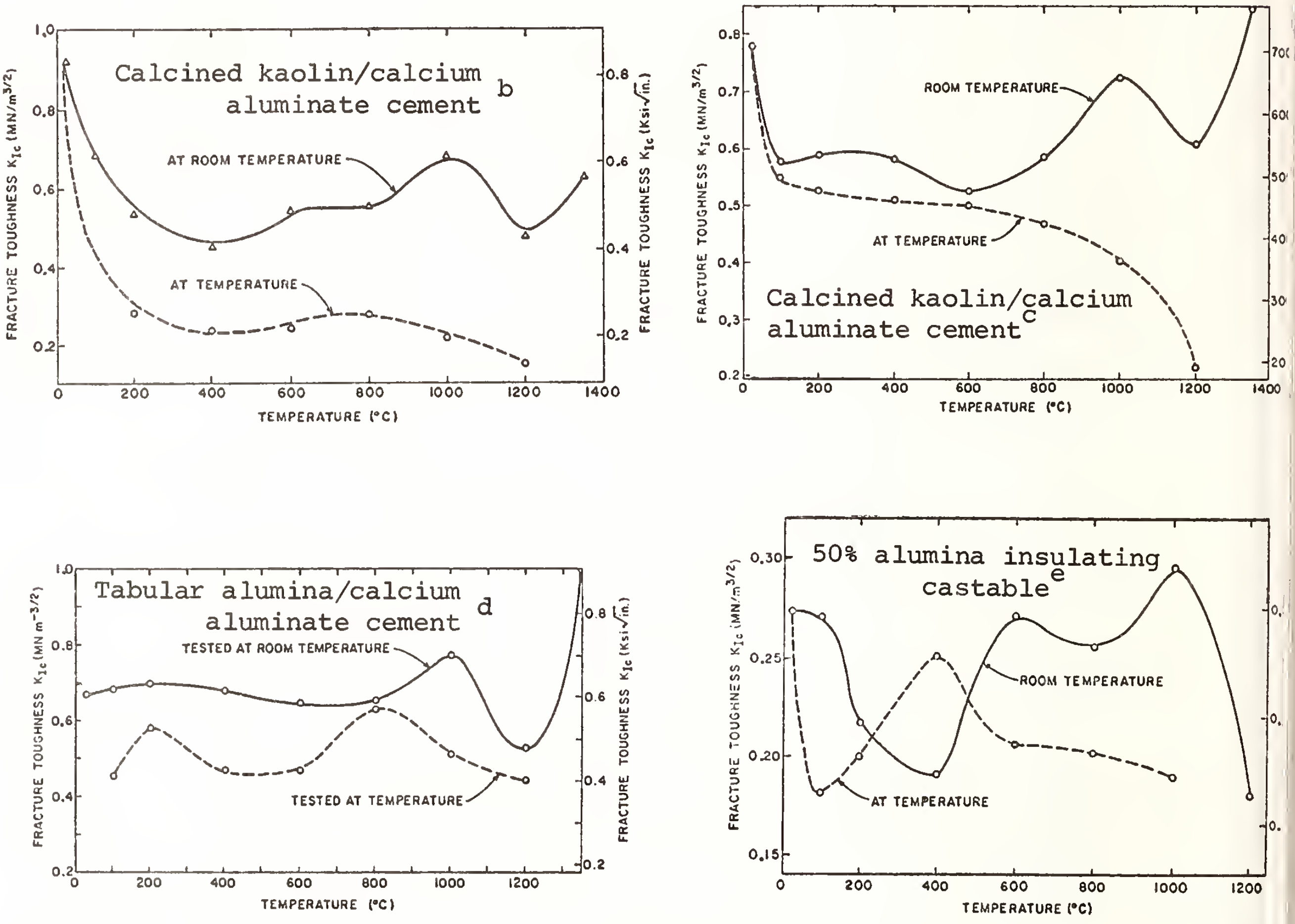
75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement), water added to ball-in-hand consistency, 13.5% of aggregate and cement.

75% Mulcoa M-47 aggregate, 25% Calcium Aluminate Cement CA-25 (Alcoa), water to ball-in-hand consistency, 11.3% of aggregate and cement.

75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-hand consistency, 10.4% of aggregate and cement.

Litecast 75-28 (General Refractories), a lightweight insulating castable, calcium aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF TEMPERATURE ON THE FRACTURE TOUGHNESS[a] OF SEVERAL ALUMINA REFRACTORIES[16]



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[a] Fracture toughness measured by single edge notched beam method, notch was saw to depth of 1/2 specimen thickness, average notch width about 0.032 in; tested three-point bending, crosshead speed 0.05 in/min. Samples 1 in x 1 in x 7 in were cast, vibrated one minute, cured sealed in plastic 24 h at ambient temper ture, cured in air 24 h at ambient temperature, cured in air 24 h at 100 °C, f at 60 °C/h to 200, 400, 600, 800, 1000, 1200 and 1350 °C and soaked at tempera 5 h, furnace cooled to ambient temperature. One set of samples tested at ambi temperature (solid line), second set heated in a globar furnace and tested at firing temperatures when samples reached thermal equilibrium (dashed line).

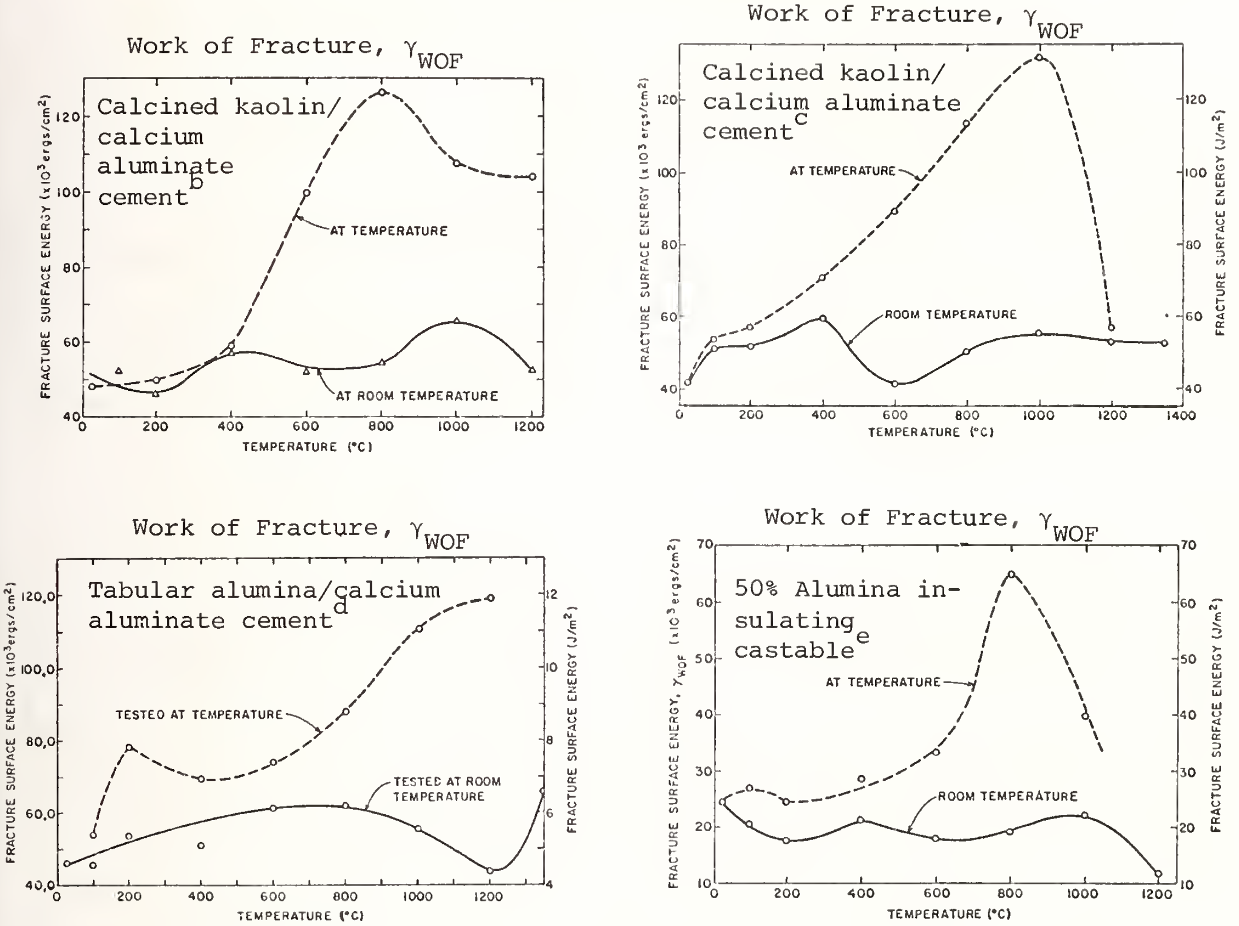
[b] 75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement), water added to ball-in-hand consistency, 13.5% of aggregate and cement.

[c] 75% Mulcoa M-47 aggregate, 25% Calcium Aluminate Cement CA-25 (Alcoa), water ball-in-hand consistency, 11.3% of aggregate and cement.

[d] 75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-ha consistency, 10.4% of aggregate and cement.

[e] Litecast 75-28 (General Refractories), a lightweight insulating castable, cal aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF TEMPERATURE ON THE WORK OF FRACTURE[a] OF SEVERAL ALUMINA REFRACTORIES[16]



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[a] Fracture measurements by single edge notched beam method; notch was saw cut so that one fourth of the cross sectional area remained, average notch width about 0.32 in; tested in three-point bending, crosshead speed 0.05 in/min. Samples 1 in x 1 in x 7 in were cast, vibrated one minute, cured sealed in plastic 24 h at ambient temperature, cured in air 24 h at ambient temperature, cured in air 24 h at 100 °C, fired at 60 °C/h to 200, 400, 600, 800, 1000, 1200 and 1350 °C and soaked at temperature 5 h, furnace cooled to ambient temperature. One set of samples tested at ambient temperature (solid line), second set heated in a globar furnace and tested at firing temperatures when samples reached thermal equilibrium (dashed line). γ_{WOF} was then measured as the area under the load-displacement curve divided by twice the fracture surface area.

[b] 75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement), water added to ball-in-hand consistency, 13.5% of aggregate and cement.

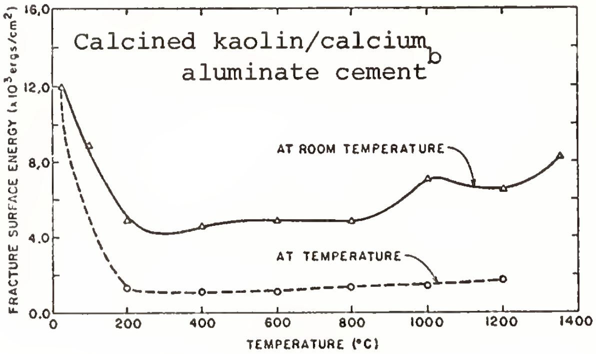
[c] 75% Mulcoa M-47 aggregate, 25% Calcium Aluminate Cement CA-25 (Alcoa), water to ball-in-hand consistency, 11.3% of aggregate and cement.

[d] 75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-hand consistency, 10.4% of aggregate and cement.

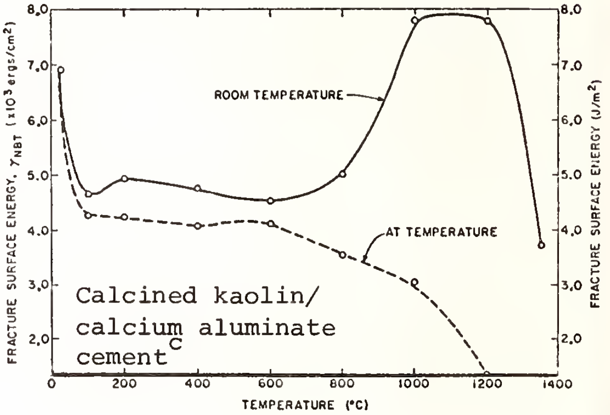
[e] Litecast 75-28 (General Refractories), a lightweight insulating castable, calcium aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF TEMPERATURE ON NOTCH BEAM TEST RESULTS[a] OF SEVERAL ALUMINA REFRACTORIES[16]

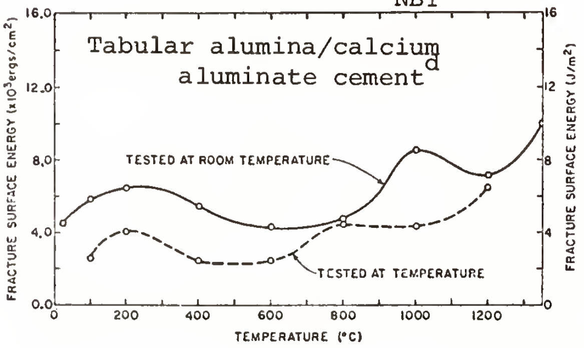
Notch Beam Test, γ_{NBT}



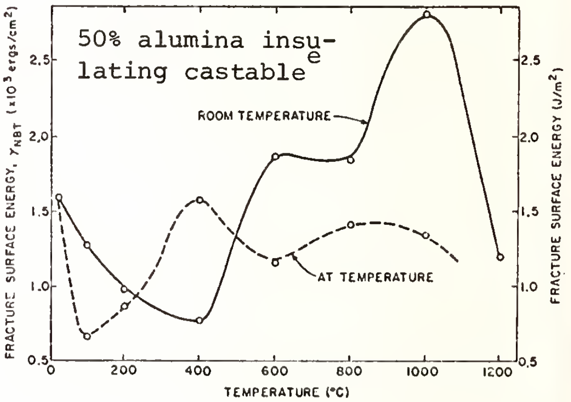
Notch Beam Test, γ_{NBT}



Notch Beam Test, γ_{NBT}



Notch Beam Test, γ_{NBT}



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[a] Fracture toughness measured by single edge notched beam method; notch was saw cut to depth of 1/2 specimen thickness, average notch width about 0.032 in; tested in three-point bending, crosshead speed 0.05 in/min. Samples 1 in x 1 in x 7 in were cast, vibrated one minute, cured sealed in plastic 24 h at ambient temperature, cured in air 24 h at ambient temperature, cured in air 24 h at 100 °C, fired at 60 °C/h to 200, 400, 600, 800, 1000, 1200 and 1350 °C and soaked at temperature 5 h, furnace cooled to ambient temperature. One set of samples tested at ambient temperature (solid line), second set heated in a globar furnace and tested at firing temperatures when samples reached thermal equilibrium (dashed line). γ_{NBT} was then calculated from an equation relating fracture toughness and Young's modulus.

[b] 75% Mulcoa M-47 (C-E Minerals) aggregate, 25% Refcon (Universal Atlas Cement), water added to ball-in-hand consistency, 13.5% of aggregate and cement.

[c] 75% Mulcoa M-47 aggregate, 25% Calcium Aluminate Cement CA-25 (Alcoa), water to ball-in-hand consistency, 11.3% of aggregate and cement.

[d] 75% Tabular alumina (Alcoa) aggregate, 25% CA-25 (Alcoa), water to ball-in-hand consistency, 10.4% of aggregate and cement.

[e] Litecast 75-28 (General Refractories), a lightweight insulating castable, calcium aluminate bonded, water to ball-in-hand consistency, 24% of mix.

EFFECT OF TEMPERATURE ON THE CRUSHING STRENGTH OF PHOSPHATE-BONDED REFRACTORIES

			45% Al_2O_3[a]	90% Al_2O_3[b]	90-95% Al_2O_3[c]
Bulk Density, lb/ft^3					
Cured at ambient temp.			150	194	182
Dried 24 hrs. at 450 °F			142.5	185	172
Linear Shrinkage, %					
Cured length relative to dried length			0.3	0.2	0.2
Hot Crushing Strength, Psi (MPa)					
	°F	°C			
	72	22	2480±345 (17.0)	2680±385 (18.4)	3490±1050 (24.0)
	500	260	3480±715 (24.0)	4830±545 (33.2)	3740±1825 (25.8)
	1000	538	5205±480 (35.9)	6670±800 (46.0)	6770±2330 (46.6)
	1500	816	6080±1100 (41.9)	8000±630 (55.1)	6840±2030 (47.1)
	1750	954	8080±455 (55.6)	6370±710 (43.9)	4160±980 (28.6)
	2000	1098	3640±640 (25.0)	1530±540 (10.5)	1260±405 (8.7)

[a] Generic preparation: 45% Al_2O_3 phosphate-bonded ramming mix.

[b] Generic preparation: 90+% Al_2O_3 phosphate-bonded ramming mix.

[c] Commercial material: 90-95% Al_2O_3 phosphate-bonded ramming mix (90 Ram H.S. from C-E Refractories).

CREEP AND HOT LOAD DEFORMATION FOR VARIOUS CASTABLE ALUMINA REFRACTORIES[26]

			Percent Deformation									
Material			50% Al_2O_3[a]		Modified 90+% Al_2O_3[b]			Standard 50% Al_2O_3[c]	Modified 50% Al_2O_3[d]	40-60% Al_2O_3[e]	50% Al_2O_3[f]	45% Al_2O_3 Ram[g]
Casting Water, %			21	24	7.75	8.5	9.0	10	10	11	7.5	
Test Conditions psi	°F	hr										
100	2000	11	3.9	--	0.0	0.1	0.0	0.3	--	0.5	0.3(0.4)	0.6
200	2000	11	failed[i]	--	0.1	0.1	0.1	--	--	0.8	0.4(0.5)	0.8
1000	2000	10[h]	--	--	--	--	0.6	failed after 1 hr at 1500 psi	--	--	1.7(1.0)	--
1500	2000	10	--	--	1.4	--	--	--	--	--	--	--
2000	2000	10	--	--	--	2.4	3.7	--	--	--	--(2.7)	--
2500	2000	10	--	--	2.3	--	--	--	--	--	--(3.4)	--
3300	2000	10	--	--	3.8	5.0	5.6[j]	--	--	--	--	--
100	1800	11	1.4	1.9	--	--	--	0.2	0.2	--	--	--
200	1800	11	3.3	5.8	--	--	--	--	0.3	--	--	--
1000	1800	10	--	--	--	--	--	--	--	--	--	0.2
1500	1800	10	--	--	--	--	--	1.0	1.4	1.6	--	--
2000	1800	10	--	--	--	--	--	--	--	--	--	0.4
2500	1800	10	--	--	--	--	--	1.7	failed in 1.25 hr	--	--	--
100	1500	11	0.3	--	--	--	--	0.1	--	0.2	--	--
700	1500	10	1.7	2.9	--	--	--	--	--	0.4	--	--
1000	1500	10	3.1	--	--	--	--	--	--	--	--	--
1500	1500	10	5.0	5.4[k]	--	--	--	--	--	1.6	--	--

[a] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

[b] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] Generic preparation: 75% calcined kaolin (60% to -20 mesh, 15% ball milled fines, 50% less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[d] Generic preparation: 75% calcined kaolin (70% 6 to -20 mesh, 5% ball milled fines, 50% less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[e] Commercial dense castable, calcium aluminate bonded (Lo-Abrade, A. P. Green).

[f] Coarse grain size, high strength 50% alumina prototype castable (B&W 36C, Babcock & Wilcox); data are for two separate batches.

[g] Generic preparation: 45% alumina phosphate-bonded ramming mix.

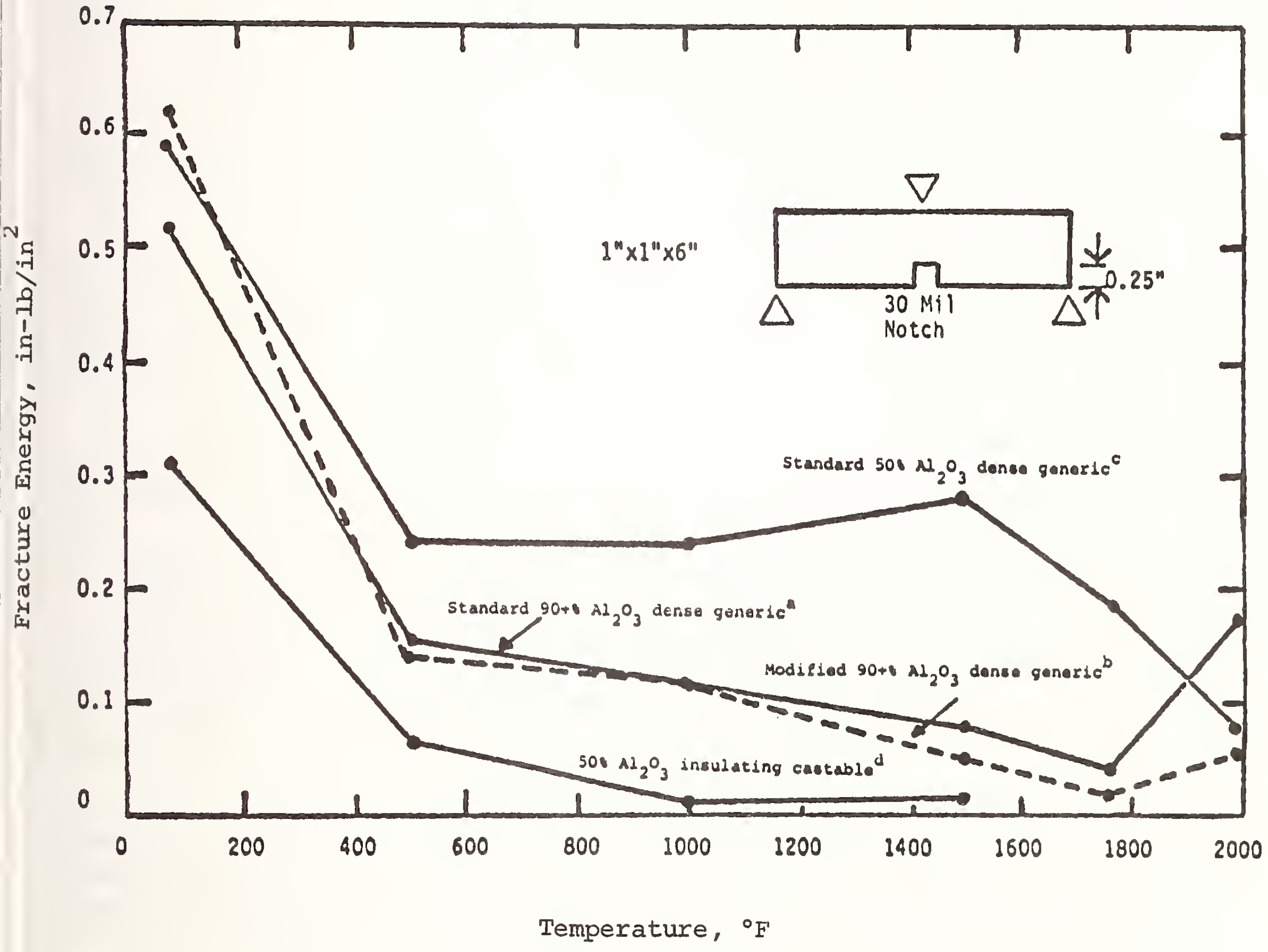
[h] In ten hour tests, samples at temperature 11 hr, but tested for only 10 hr.

[i] Samples from three batches failed, one at 1900°F, a second after 3 hours, a third after 5 hours.

[j] Sample began to fail after 7 hr, test was stopped.

[k] Sample began to fail after 3 hr, test was stopped.

EFFECT OF TEMPERATURE ON THE FRACTURE ENERGY OF SOME ALUMINA REFRACTORIES[26]



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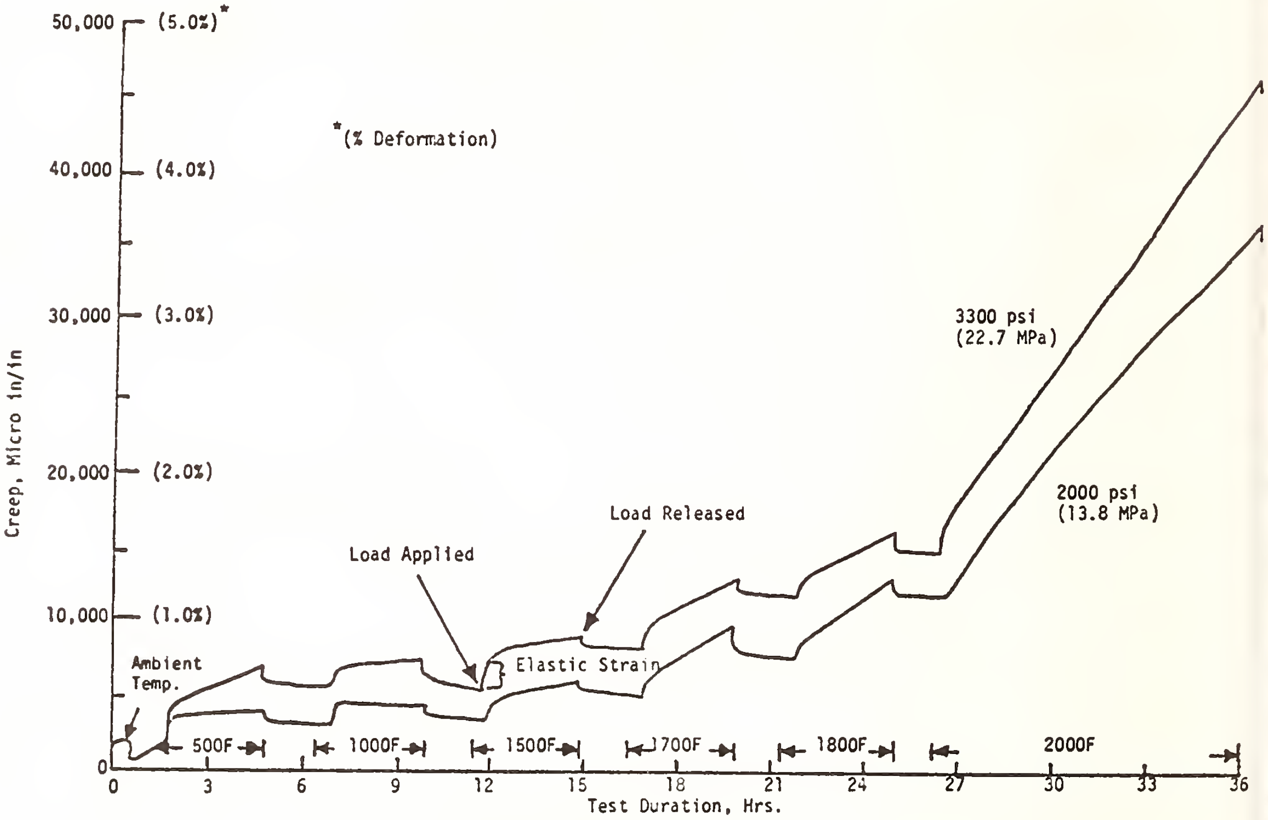
[a] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

[b] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] Generic preparation: 75% calcined kaolin (60% 6 to -20 mesh, 15% ball milled fines, 50% of these being less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[d] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

EFFECT OF STRESS LEVELS AND TEMPERATURE ON THE CREEP[a] OF A HIGH-ALUMINA CASTABLE[b] [26]



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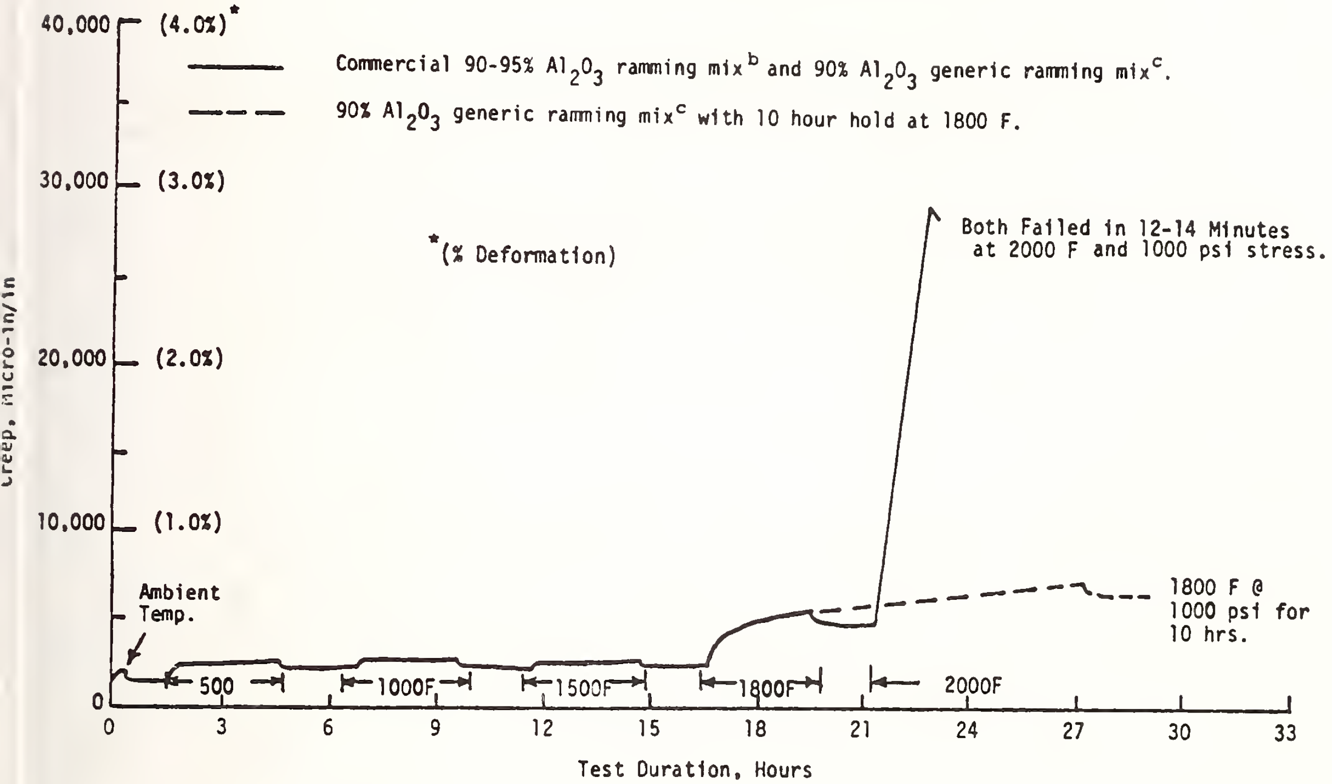
[a] A modified creep test at two stress levels and seven test temperatures: the stress level was held constant throughout the test while the temperature was progressively increased; specimens were soaked for one hour at each test temperature before the indicated stress was applied; stress was removed after three hours except for the highest temperature at which stress was removed after ten hours; specimens were six inches (15.24 cm) long.

[b] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge); specimen density 173 lb/ft^3 (2.75 g/cc).

EFFECT OF INCREASING TEMPERATURE ON CREEP BEHAVIOR[a] AT CONSTANT STRESS OF HIGH-ALUMINA RAMMING MIXES[26]



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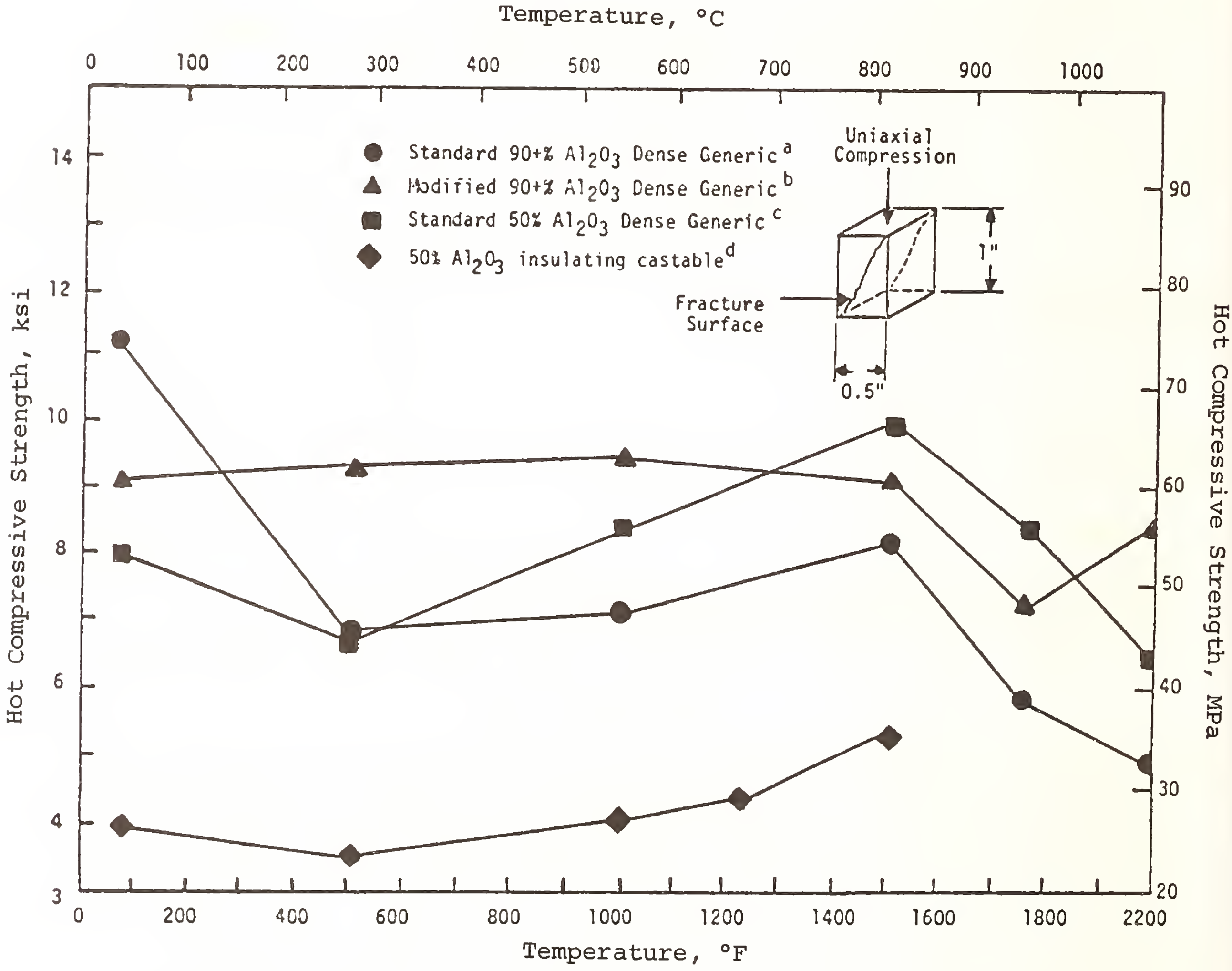
[a] A modified creep test: the stress level was held constant throughout the test while the temperature was progressively increased; specimens were soaked for one hour at each test temperature before stress (1000 psi) was applied; stress was removed after three hours except for the highest temperature at which stress was removed after ten hours.

[b] 90 Ram H.S. from C-E Refractories; density of specimen, 181 lb/ft^3.

[c] Generic preparation, 90+% alumina, phosphate bonded; density of specimens: 188 lb/ft^3 for specimen which failed at high temperature, 187 lb/ft^3 for specimen with 10 hour hold at 1800 °F.

EFFECT OF TEMPERATURE ON THE COMPRESSIVE STRENGTH OF SOME ALUMINA REFRACTORIES[26]



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[a] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

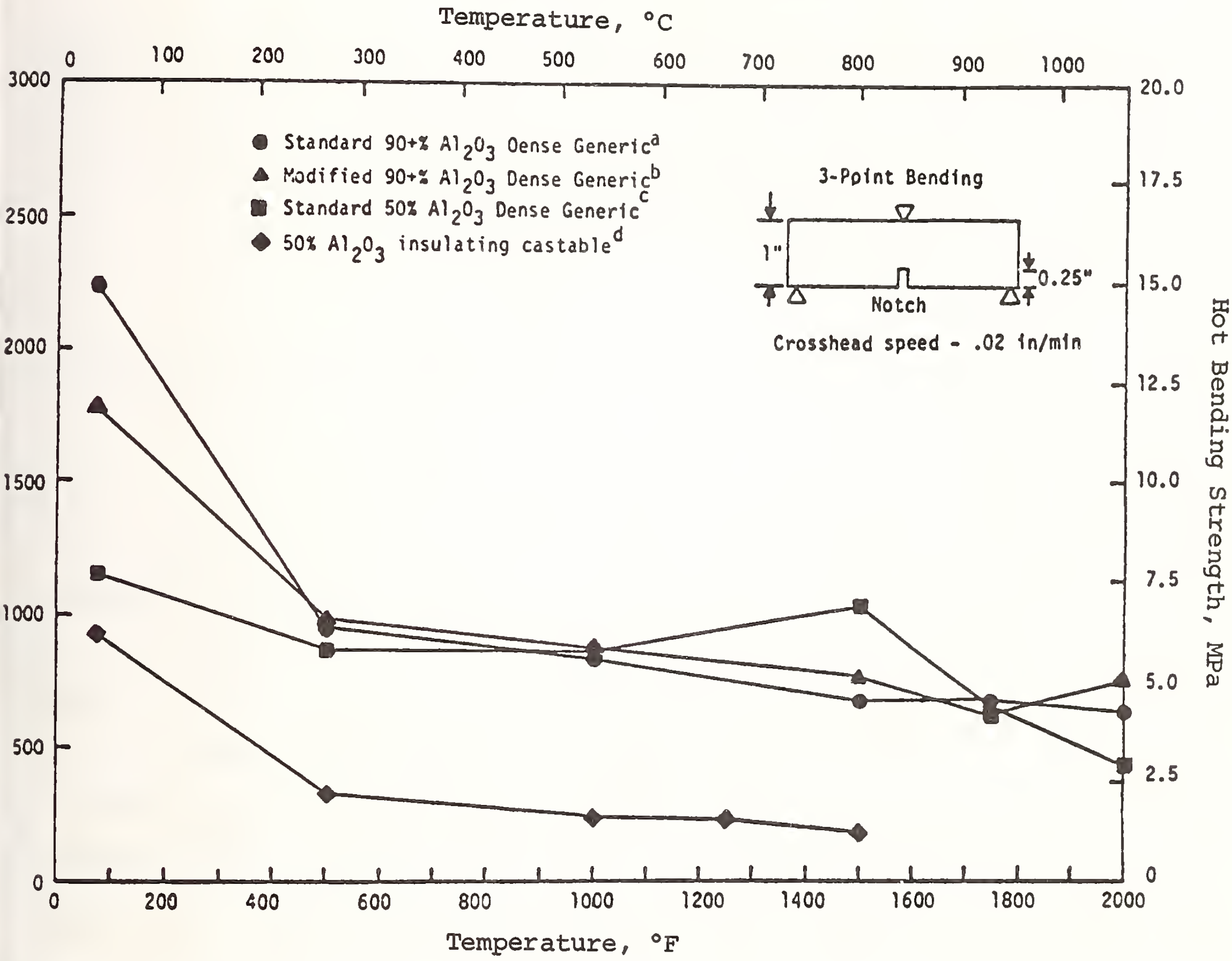
[b] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] Generic preparation: 75% calcined kaolin (60% 6 to -20 mesh, 15% ball milled fines, 50% of which are less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[d] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

[Note: Temperature value 2200 on graph as given by authors should read 2000.]

EFFECT OF TEMPERATURE ON THE MODULUS OF RUPTURE OF SOME ALUMINA REFRACTORIES [26]



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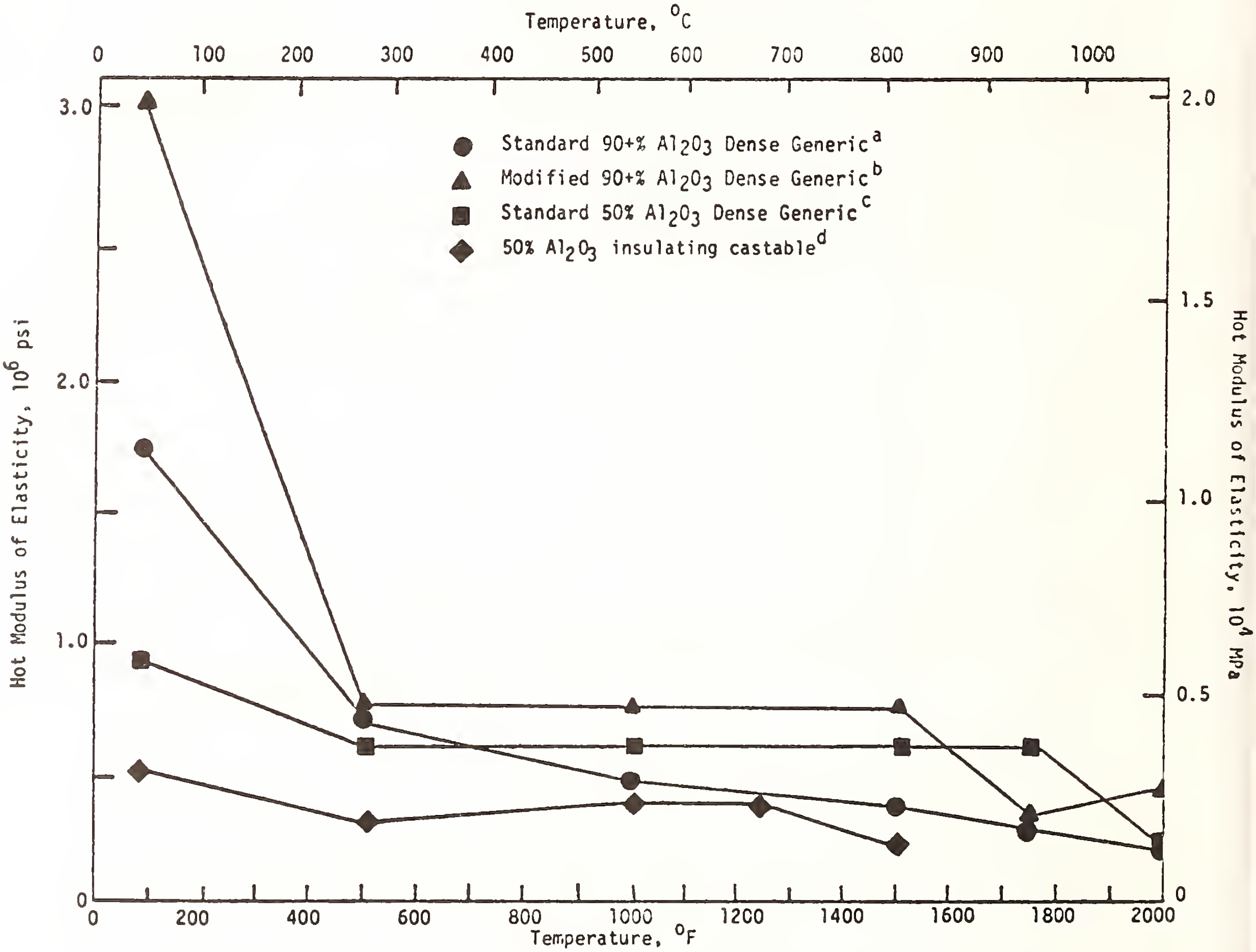
[a] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

[b] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] Generic preparation: 75% calcined kaolin (60% 6 to -20 mesh), 15% ball milled fines, 50% of these were less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[d] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF SOME ALUMINA REFRACTORIES[26]



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[a] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

[b] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] Generic preparation: 75% calcined kaolin (60% 6 to -20 mesh, 15% ball milled fines, 50% less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[d] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

EFFECT OF TEMPERATURE ON THE RESULTS OF RADIAL COMPRESSION TESTS[a] OF SOME SILICON CARBIDE TUBES[15]

MATERIAL					Failure Rate %		
perature °C(°F)	Mean Strength ksi	Characteristic Stress (ksi)[b]	Weibull Slope[c]	Number Tested	1.0	0.5	0.1
					Failure Stress (ksi)		
SINTERED SILICON CARBIDE[d]							
mbient	26.4	29.0	9.30	30	17.68	16.4	13.79
16(1500)	22.7	25.0	6.51	8	12.33	11.08	8.65
26(1700)	31.4	33.0	8.88	4	19.65	18.17	15.16
37(1900)	26.6	28.0	8.92	4	16.71	15.46	12.91
60(2300)	26.3	28.0	8.30	4	16.08	14.79	12.18
71(2500)	16.4	17.8	9.14	4	10.76	9.97	8.36
REACTION-BONDED SILICON CARBIDE[e]							
mbient	35.775	42.0	5.80	30	19.00	16.85	12.76
16(1500)	39.045	41.0	8.65	8	24.10	22.22	18.45
26(1700)	33.043	33.0	8.20	4	18.83	17.29	14.21
37(1900)	42.099	44.0	11.92	4	29.91	28.21	24.65
60(2300)	36.301	37.0	11.94	4	25.16	23.74	20.75
71(2500)	15.445	15.0	7.23	4	7.93	7.21	5.77
SINTERED SILICON CARBIDE[f]							
mbient	29.014	30.5	5.97	32	14.1	12.6	9.6
16(1500)	22.263	23	27.8	4	19.5	19.0	17.9
26(1700)	28.641	31	6.08	5	14.5	13.0	10.0
37(1900)	28.782	32	5.66	5	14.2	12.6	9.4
60(2300)	37.285	41	5.67	5	18.2	16.1	12.1

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truded tubes, 1.905 cm(0.75 in) outer diameter, 1.27 cm (0.5 in) inner diameter, and
27 cm (0.5 in) long, were loaded between two flat plates in the radial direction. Tests
ambient temperature were tested using compliant layers (4 sheets of 0.0127 cm thick
ad) to prevent point loading. High temperature tests were made with induction heating
a a SiC susceptor, radial compression was applied with the sample between alumina blocks.

aracteristic stress is the stress corresponding to 62.3% cumulative failures in a plot of
mber of failures versus stress.

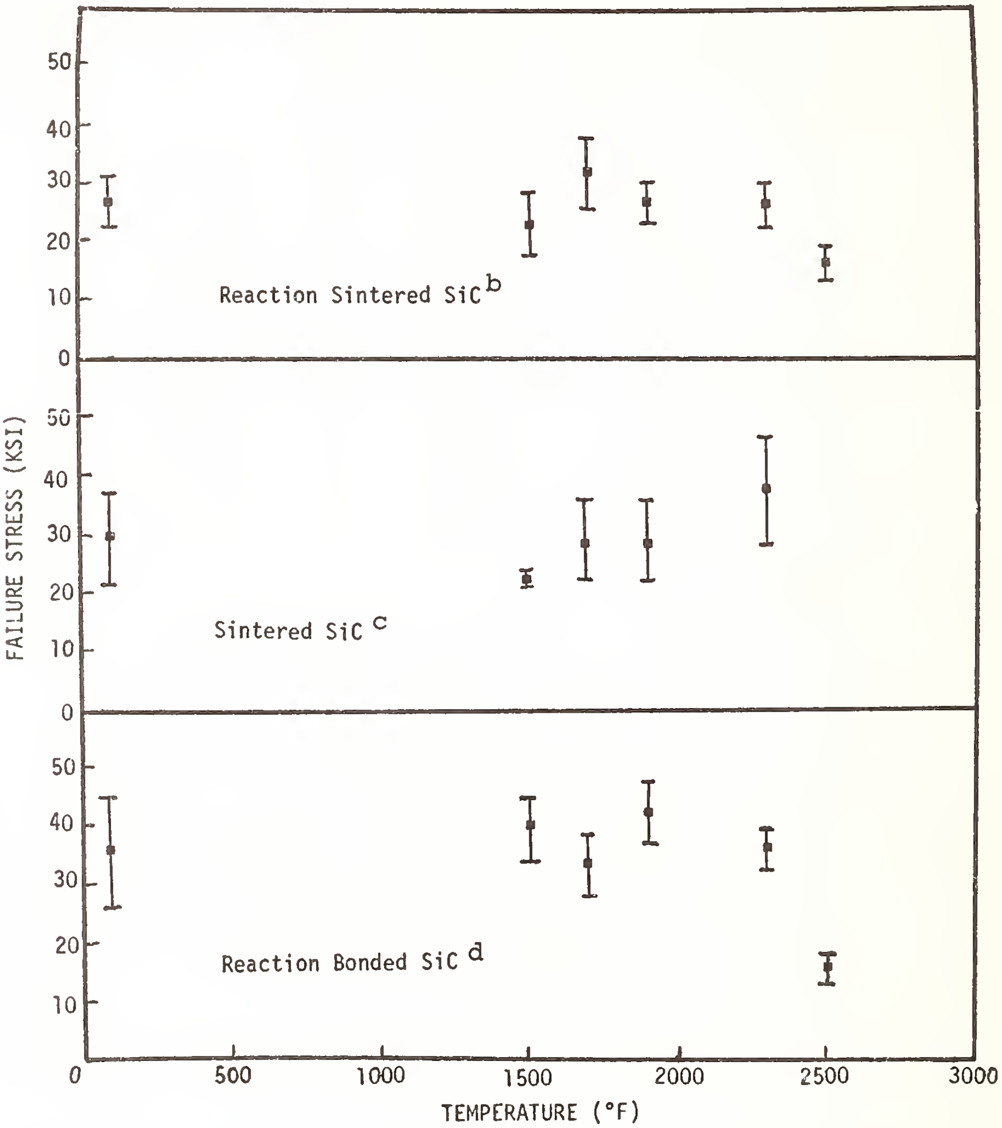
ibull slope or modulus is the slope of a failure distribution curve, i.e. number of fail-
es versus stress.

-430 from Norton.

per-KT SiC from Carborundum.

ntered alpha SiC from Carborundum; testing stopped because specimens had irregularities,
ternal circumferential cracks or voids and some microscopic radial cracks.

FAILURE STRESS[a] AS A FUNCTION OF TEMPERATURE FOR SILICON CARBIDE REFRACTORIES[15]



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[a] Stress measured by loading extruded tubes between two flat plates in the radial direction. Tubes samples were 1.905 cm (0.75 in) outer diameter, 1.27 cm (0.5 in) inner diameter, and 1.27 cm (0.5 in) long. Tests at ambient temperature were tested using compliant layers (4 sheets of 0.0127 cm thick lead) to prevent point loading. High temperature tests were made with induction heating via a SiC susceptor, radial compression was applied with the sample between alumina blocks.

[b] NC-430 from Norton.

[c] Sintered alpha SiC from Carborundum; testing stopped because specimens had irregularities, internal circumferential cracks or voids and some microscopic radial cracks.

[d] Super-KT SiC from Carborundum.

EFFECT OF EXPOSURE TO VARIOUS GASES AND CONDITIONS ON THE STRENGTH OF A MEDIUM-ALUMINA REFRACTORY[a][23]

Gas vironment	Temperature °C	Pressure MPa (psi)	Time h	Flexural Strength[b] MPa (psi)	Compressive Strength MPa
ntrol, red for 5 hr 1000°C				(1,300±350)	
rbon dioxide	610	(1000)	65	(1,200±220)	
% CO_2 and 0% H_2O	610	(1000)	20	(2,170±380)	
% CO_2 and 0% H_2O	610	(1000)	165	(2,180±440)	
ntrol				9.6±2.1 (1,400±300)	
eam[c]	{400 620	2.07 4.14	17} 100	13.1±1.5 (1,900±200)[d]	
ntrol				10.9±1.9	34.5±3.5
% H_2O and 30% CO_2[e]	510	7.5	90	11.9±3.1	39.5±2.5
	510	15.0	90	13.75±.96	48.6±12.9
	710	7.5	90	14.2±3.7	59.6±3.4
	710	15.0	90	14.54±.48	41.0±12.5
	910	7.5	90	16.39±.02	56.2±8.2
	910	15.0	90	20.28±.03	43.6±5.5

---

n NBS-prepared medium-alumina castable refractory bonded with high-purity calcium aluinate cement: 55.6 wt% Al_2O_3, 4.5 wt% CaO, 37.0 wt% SiO_2, 0.8 wt% Fe_2O_3, 0.2 wt% Na_2O, .9 wt% others and loss on ignition.

lexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min 2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower oading span 40 mm; tests at ambient temperatures.

he pressure chamber was initally evacuated and 150 ml water was metered into the chamer; the chamber was then heated and held at the temperatures and pressures for the times iven which are bracketed together; tests were performed *in situ* after the 117 hour peiod; values are the median and standard deviation for four specimens.

hese are *in situ* values.

pecimens were first heated in argon at ambient pressure; when temperature equilibrium eached water and carbon dioxide were metered into the chamber; after 90 hour exposure he specimens were cooled to 500°C and the gases slowly vented.

EFFECT OF EXPOSURE TO VARIOUS GASES AND CONDITIONS ON THE FLEXURAL STRENGTH OF A HIGH-ALUMINA REFRACTORY[a][23]

Gas Environment	Temperature °C	Pressure MPa (psi)	Time h	Flexural Strength[b] MPa (psi)
Control, fired for 5 hr at 1010°C				19.0±1.2 (2,750±180)
Steam	910	7 (∿1000)	330.5	29.2±6.7 (4,240±970)
Steam	410 610 910	7 7 7	46 43 335 [c]	31.0±7.5 (4,490±1,090)
Control				14.8±1.8 (2,150±260)
Steam	410	4.55	110	10.9±0.3[d] (1.590±50)
Steam	510	4.86	90	11.2±1.2[d] (1.630±170)
Control				15.6±0.7 (2,262±102)
70% H_2O and 30% CO_2[e]	610	7	42	20.5±1.5 (2,973±218)
Control				14.8±1.8 (2,150±260)
Coal Gasification Atmosphere[f]	510	7.5 (∿1090)	90	13.4±2.4 (1.950±340)
	710	7.5 (∿1090)	90	16.1±0.4 (2,340±60)
	910	7.5 (∿1090)	90	14.8±1.3 (2,150±190)

---

[a] An NBS-prepared high-alumina castable bonded with high-purity calcium aluminate cement: 94.4 wt% Al_2O_3, 4.5 wt% CaO, 0.1 wt% SiO_2, 0.1 wt% Fe_2O_3, 0.2 wt% Na_2O.

[b] Flexural strength as determined in four-point bend tests, loading rate 5 x 10^{-3} cm/min (2 x 10^{-3} in/min); rectangular specimens 5 x 10 x 50 mm; upper loading span 10 mm, lower loading span 40 mm; tests at ambient temperatures except where noted.

[c] The total set of bracketed conditions were those to which the specimens were subjected before the specimens were tested.

[d] These measurements were made *in situ*.

[e] Specimens were first heated in argon at ambient pressure; when temperature equilibrium reached, water and carbon dioxide were metered into the chamber; after the 42 hour exposure the specimens were cooled to 500°C and the gases slowly vented.

[f] Tests were run as described in footnote e except that the gases metered into the pressure chamber were 40 vol% H_2O, 20 vol% CO, 15 vol% CO_2, 25 vol% H_2 which provides a gaseous environment of H_2O, CO, CO_2, H_2 and CH_4 at the temperature-pressure exposure conditions.

EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY[a] OF SOME CASTABLE REFRACTORIES[26]

Temperature		Hot Modulus of Elasticity[a], 10^6 psi (MPa)			
°F	°C	Standard 50% Al_2O_3[b]	Standard 90+% Al_2O_3[c]	Modified 90+% Al_2O_3[d]	50% Al_2O_3[e]
72	22	0.9±0.5 (6200)	1.7±0.8 (11710)	3.0±1.5 (20670)	0.6±0.3 (4130)
500	260	0.6±0.3 (4130)	0.7±0.3 (4820)	0.8±0.3 (5510)	0.4±0.1 (2065)
1000	538	1.0±0.4 (6890)	0.5±0.2 (3445)	0.8±0.3 (5510)	0.4±0.2 (2755)
1250	677	--	--	--	0.4±0.2 (2755)
1500	816	0.6±0.2 (4130)	0.4±0.1 (2755)	0.7±0.3 (4820)	0.2±0.1 (1380)
1750	954	0.6±0.3 (4130)	0.3±0.1 (2065)	0.4±0.1 (2755)	--
2000	1098	0.2±0.1 (1380)	0.2±0.1 (1380)	0.4±0.2 (2755)	--

[a] Values are the average of five samples tested at each temperature.

[b] Generic preparation: 75% calcined kaolin (60% to -20 mesh, 15% ball milled fines, with 50% of these less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

[d] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[e] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

EFFECT OF TEMPERATURE ON THE COMPRESSIVE STRENGTH[a] OF SOME CASTABLE REFRACTORIES [26]

Temperature		Hot Compressive Strength[a], psi (MPa)			
		Standard 50% Al_2O_3[b]	Standard 90+% Al_2O_3[c]	Modified 90+% Al_2O_3[d]	50% Al_2O_3[e]
°F	°C				
72	22	8020 ±880 (55.2)	11120±1030 (76.6)	9100±1750 (62.7)	3945±350 (27.2)
500	260	6705 ±850 (46.2)	6830 ±605 (47.0)	9220±580 (63.5)	3490±180 (24.0)
1000	538	8570 ±910 (59.0)	7200 ±570 (49.6)	9690±1040 (66.8)	3940±340 (27.1)
1250	677	--	--	--	4245±740 (29.2)
1500	816	10130±490 (69.8)	8330 ±580 (57.4)	9130±1480 (62.9)	5330±430 (36.7)
1750	954	8690 ±390 (59.9)	5915 ±115 (40.8)	7300±1160 (50.3)	--
2000	1098	6300 ±1020 (43.4)	5010 ±425 (34.7)	8455±420 (58.3)	--

[a] Values are the average of five samples tested at each temperature.

[b] Generic preparation: 75% calcined kaolin (60% to -20 mesh, 15% ball milled fines, with 50% of these less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

[d] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[e] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

EFFECT OF TEMPERATURE ON THE MODULUS OF RUPTURE[a] OF SOME CASTABLE REFRACTORIES[26]

Temperature		Modulus of Rupture[a], psi (MPa)			
		Standard 50% Al_2O_3[b]	Standard 90+% Al_2O_3[c]	Modified 90+% Al_2O_3[d]	50% Al_2O_3[e]
°F	°C				
72	22	1125±140 (7.8)	2325±170 (16.0)	1790±330 (12.3)	855±65 (5.9)
500	260	860 ±85 (5.9)	950 ±150 (6.5)	980 ±150 (6.8)	320±30 (2.2)
1000	538	890 ±50 (6.1)	840 ±320 (5.8)	890 ±170 (6.1)	225±55 (1.6)
1250	677	--	--	--	220±25 (1.5)
1500	816	1030±150 (7.1)	685 ±90 (4.7)	865 ±55 (6.0)	185±115 (1.3)
1750	954	660 ±85 (4.5)	690 ±225 (4.8)	610 ±210 (4.2)	--
2000	1098	435 ±90 (3.0)	615 ±205 (4.2)	760 ±320 (5.2)	--

[a] Hot Bending Strength, values are the average of five samples tested at each temperature.

[b] Generic preparation: 75% calcined kaolin (60% to -20 mesh, 15% ball milled fines, with 50% of these less than 325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[c] DOE 90 generic preparation: 65% tabular alumina (6 to -20 mesh), 10% calcined alumina (-325 mesh), 25% calcium aluminate cement (Secar 250, Lone Star Lafarge).

[d] Modified DOE 90 generic preparation: 70% tabular alumina (-48 mesh), 5% calcined alumina (-325 mesh), 25% calcium aluminate cement (Casting Grade CA-25, Alcoa).

[e] Commercial lightweight insulating castable, calcium aluminate bonded (Litecast 75-28, General Refractories).

COMPRESSIVE STRENGTH[a] AND WEIGHT LOSS DATA FOR REFRACTORIES EXPOSED TO CARBON MONOXIDE AT 500 °C AND 600 PSI FOR 100 HOURS[27]

Added Dopant	Wt% Fe	Compressive Strength, psi[a]	Ratio wt. After to Wt. Before	No. of Samples	Average Streng After Exposure One Atmosphere
DOE 90 GENERIC CASTABLE[c]					
none	0.0	7,675±500	0.999	4	7,150±2,050
Fe	0.5	0±0[g]	0.000[g]	3	
Fe_2O_3	2.0	9,725±600	1.007	3	
DOE 50% Al_2O_3 GENERIC CASTABLE[d]					
none	0.0	5,400±1,025	0.999	4[e]	4,825±1,250
Fe	0.5	0±0[g]	0.000[g]	3	
Fe_2O_3	2.0	7,850±325	1.011	3	
DOE PHOSPHATE-BONDED RAMMING MIX[f]					
none	0.0	6,900±950	1.000	4[e]	10,050±3,750
Fe	0.5	0±0[g]	0.000[g]	3	
Fe_2O_3	1.0	6,775±2,200	1.006	3	

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[a] Compressive strength was measured on a universal testing machine with a crosshead speed of 0.1 in/min.

[b] The average value for 44 samples of each refractory which had been exposed to a v riety of CO-containing atmospheres for 100 hours each.

[c] DOE 90 generic castable: 65 wt% tabular alumina (25 wt% 6 to 10 mesh, 20 wt% 10 t 20 mesh, 20 wt% less than 20 mesh), 10 wt% calcined alumina (less than 325 mesh), 25 wt% calcium aluminate cement (Casting Grade CA-25 cement), all Alcoa materials Materials were dry mixed for 2 min, then water added with continued mixing to bal in-hand consistency (∿605 ml); refractory then poured into 2 in x 2 in x 2 in alu minum molds, vibrated for 5 min, sealed in plastic for 24 hr, then fired for 5 hr in air at 1100 °C.

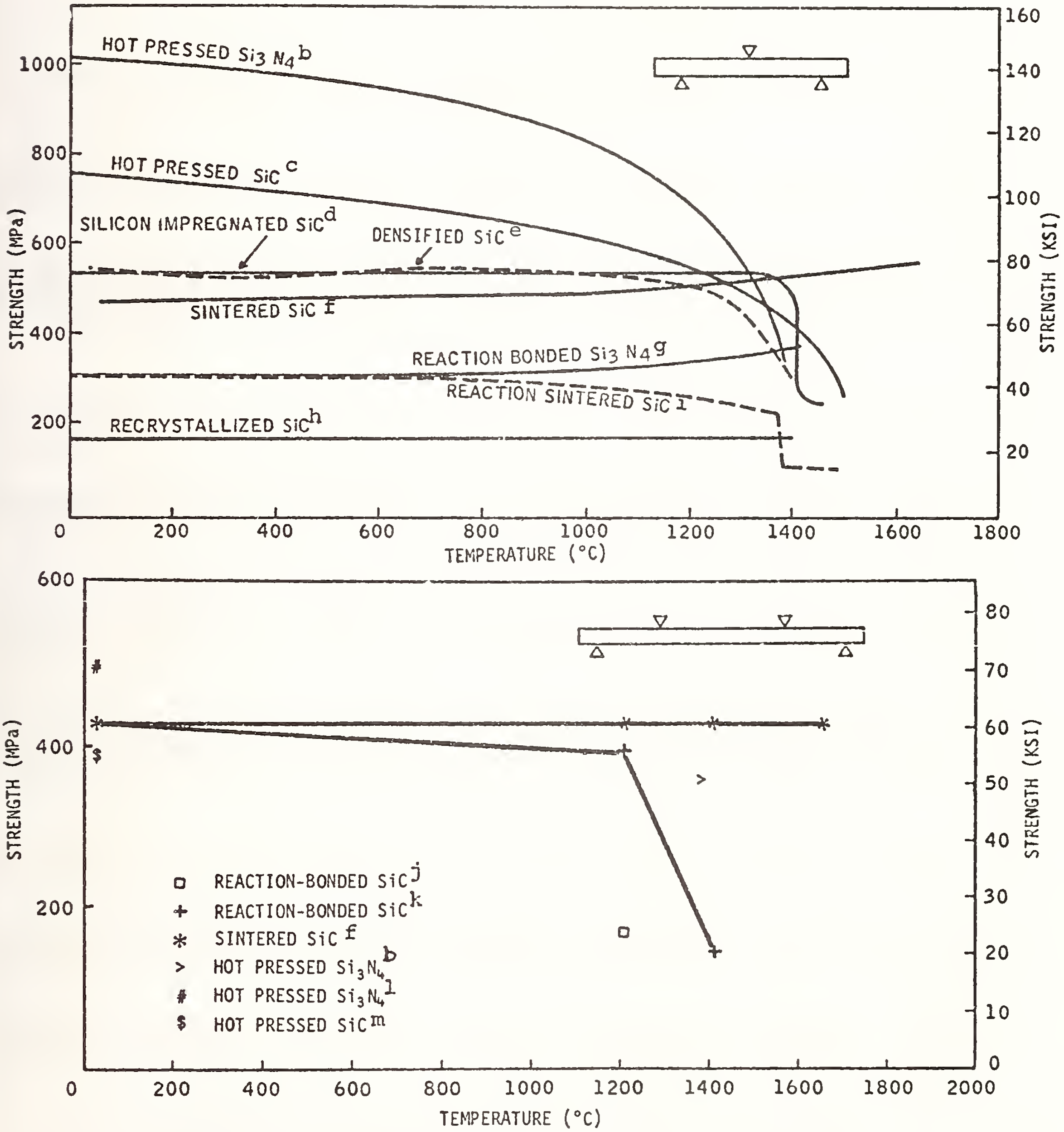
[d] DOE generic castable: 75 wt% calcined kaolin (25 wt% 6 to 10 mesh, 20 wt% 10 to 2 mesh, 15 wt% less than 20 mesh, 20 wt% less than 200 mesh), 25 wt% calcium aluminate cement (Casting Grade CA-25, Alcoa). Samples were prepared as described in footnote c except that the water used was ∿700 ml.

[e] Only three samples were used in strength testing.

[f] DOE generic ramming mix: 82 wt% tabular alumina (30 wt% 6 to 10 mesh, 20 wt% 10 t 20 mesh, 15 wt% less than 20 mesh, 17 wt% less than 48 mesh), 15 wt% calcined alu mina (less than 325 mesh), 3 wt% bentonite; to this was added 1 wt% hydrated alum na, 6 wt% phosphoric acid (85%), and 0.25 wt% water. Dry materials were mixed ar then hand mixed in plastic bags with the liquids; mixture was aged for 18 hr; sam ples formed by die pressing at 500 psi, curing at 250 °C in air for 12 hr, then firing at 1100 °C for 5 hr.

[g] Samples disintegrated.

EFFECT OF TEMPERATURE ON THE FLEXURAL STRENGTH OF SILICON-CONTAINING REFRACTORIES[a] [15]



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[a] Authors included data from various sources; strengths are mean values, do not fully represent true statistical strengths.

[b] NC-132 (Norton). [c] NC-203 (Norton). [d] Refel self-bonded SiC. [e] NC-435 (Norton).

[f] Alpha SiC (Carborundum). [g] NC-350 (Norton). [h] NC-400 (Norton).

[i] NC-430 (Norton). [j] KT SiC (Carborundum). [k] Super-KT SiC (Carborundum).

[l] Ceradyne material; # represents lowest value of range given, 70 to 120 ksi.

[m] Ceradyne material; $ represents lowest value of range given, 55 to 100 ksi.

COMPRESSIVE STRENGTH[a] OF IRON-DOPED REFRACTORIES AFTER EXPOSURE[b] TO MIXTURES OF CARBON MONOXIDE AND OTHER GASES [27]

		DOE 90 Generic Composition[c]				DOE 50% Al_2O_3 Generic Composition[d]				DOE Generic Ramming Mix[e]			
Added Dopant	Wt% Fe	Compressive Strength, psi[a]	Ratio Doped to Undoped Strength	Ratio Wt. After to Wt. Before	No. of Samples	Compressive Strength, psi[a]	Ratio Doped to Undoped Strength	Ratio Wt. After to Wt. Before	No. of Samples	Compressive Strength, psi[a]	Ratio Doped to Undoped Strength	Ratio Wt. After to Wt. Before	No. of Samples
FEED GAS COMPOSITION: 99.99% CO													
None	0.0	10,325 ±1,250		1.000	5	6,750 ±1,450		1.000	5	13,750 ±2,475		.985	4
Fe	0.5	5,800 ±2,725	.562	.949	5	5,125 ±900	.759	.987	5	9,875 ±3,175	.718	.977	4
Fe	1.0	3,475 ±2,250	.337	.774	5	0 ±0	0	0	5	9,600 ±1,325	.698	.980	4
Fe	1.5	3,350 ±2,150	.325	.529	5	75 ±200	.011	.024	5	6,475 ±2,175	.471	.965	4
Fe	2.0	2,475 ±3,350	.240	.303	5	125 ±275	.019	.050	5	9,775 ±1,650	.711	.972	4
Fe_2O_3	0.5	13,300 ±1,225	1.288	1.000	5	6,300 ±1,175	.933	1.000	5	13,000 ±2,650	.945	.950	4
Fe_2O_3	1.0	12,775 ±950	1.237	1.000	5	5,575 ±1,075	.827	1.000	5	14,675 ±2,100	1.067	.970	4
Fe_2O_3	1.5	13,075 ±750	1.266	1.000	5	7,675 ±375	1.137	1.000	5	11,625 ±1,950	.845	.965	4
Fe_2O_3	2.0	12,650 ±500	1.225	1.000	5	7,275 ±975	1.078	1.000	5	9,375 ±1,900	.682	.955	4
FEED GAS COMPOSITION: 95% CO-5% CO_2													
None	0.0	5,800 ±2,750		1.001	4	4,450 ±1.075		1.000	4	8,075 ±2,675		1.000	4
Fe	0.5	7,600 ±925	1.310	.999	4	3,150 ±2,150	.708	.729	4	8,650 ±3,575	1.071	1.000	4
Fe	1.0	5,925 ±900	1.022	.954	4	0 ±0	0	0	4	7,650 ±5,875	.947	1.004	4
Fe	1.5	4,650 ±3,550	.802	.736	4	0 ±0	0	0	4	8,975 ±3,875	1.111	.999	3
Fe	2.0	4,350 ±3,925	.750	.714	4	1,950 ±2,575	.438	.493	4	8,050 ±3,700	.997	.987	4
Fe_2O_3	0.5	8,875 ±300	1.530	.999	4	6,175 ±1,450	1.388	1.000	4	11,300 ±300	1.399	.999	4
Fe_2O_3	1.0	7,600 ±1,300	1.310	.987	4	4,700 ±1,500	1.056	1.000	4	11,900 ±3,000	1.474	1.000	4
Fe_2O_3	1.5	7,000 ±750	1.207	1.000	4	5,750 ±2,325	1.292	1.001	4	11,800 ±4,425	1.461	.999	4
Fe_2O_3	2.0	8,200 ±3,275	1.414	1.000	4	3,725 ±1,550	.837	1.003	4	2,475 ±4,950	.307	.748	4
FEED GAS COMPOSITION: 85% CO-15% CO_2													
None	0.0	7,025 ±1,100		1.000	4	4,425 ±725		1.011	4	11,625 ±2,150		1.007	4
Fe	0.5	8,750 ±600	1.246	.935	4	5,350 ±525	1.209	1.008	4	10,625 ±1,400	.914	1.008	4
Fe	1.0	8,000 ±2,000	1.139	.999	4	5,150 ±1,000	1.164	1.006	4	8,375 ±3,325	.720	.900	4
Fe	1.5	6,125 ±1,675	.872	.963	4	4,925 ±1,525	1.113	1.009	4	4,750 ±700	.409	.561	4
Fe	2.0	7,300 ±1,725	1.039	1.002	4	6,125 ±1,550	1.384	1.008	4	6,750 ±2,750	.581	.844	3
Fe_2O_3	0.5	7,050 ±600	1.004	1.006	4	4,825 ±550	1.090	1.011	4	11,750 ±3,450	1.011	1.007	4
Fe_2O_3	1.0	6,225 ±1,875	.886	1.008	4	4,650 ±175	1.051	1.010	4	10,500 ±4,725	.903	1.002	4
Fe_2O_3	1.5	6,650 ±925	.947	1.008	4	5,125 ±800	1.158	1.010	4	6,075 ±2,475	.523	.702	4
Fe_2O_3	2.0	8,600 ±550	1.224	1.008	4	5,500 ±825	1.243	1.009	4	4,975 ±4,300	.428	.755	3
FEED GAS COMPOSITION: 99.8% CO-0.2% NH_3													
None	0.0	6,100 ±1,100		1.007	4	4,875 ±1,250		.999	4	14,950 ±1,825		.998	4
Fe	0.5	5,275 ±3,725	.865	.999	4	4,650 ±875	.954	1.000	4	11,500 ±2,275	.769	.999	4
Fe	1.0	4,750 ±1,150	.779	.982	4	3,800 ±1,250	.779	.999	4	5,250 ±1,850	.351	.630	4
Fe	1.5	2,300 ±2,125	.377	.641	4	1,350 ±1,600	.277	.403	4	9,150 ±4,300	.612	.864	4
Fe	2.0	3,200 ±2,125	.525	.850	4	100 ±225	.021	.099	4	7,225 ±3,650	.483	.914	4
Fe_2O_3	0.5	4,075 ±550	.668	.999	4	5,250 ±650	1.077	.999	4	14,650 ±3,600	.980	.999	4
Fe_2O_3	1.0	5,859 ±1,750	.959	.999	4	4,775 ±475	.979	.999	4	13,400 ±1,775	.896	1.000	4
Fe_2O_3	1.5	6,175 ±925	1.012	.999	4	4,125 ±850	1.051	1.003	4	11,150 ±4,900	.746	1.001	4
Fe_2O_3	2.0	6,800 ±3,175	1.115	.999	4	5,750 ±850	1.179	1.004	4	8,750 ±1,800	.585	1.002	4
FEED GAS COMPOSITION: 99.2% CO-0.8% NH_3													
None	0.0	6,350 ±1,500		1.001	4	3,925 ±800		1.000	4	12,150 ±3,025		1.000	4
Fe	0.5	5,750 ±1,375	.906	.958	4	5,225 ±1,350	1.331	1.050	4	10,725 ±1,125	.883	1.000	4
Fe	1.0	4,300 ±2,725	.677	.910	4	75 ±150	.019	.399	4	4,750 ±3,625	.391	.723	4
Fe	1.5	4,700 ±1,975	.740	.827	4	575 ±675	.146	.307	4	6,725 ±2,525	.553	.849	4
Fe	2.0	6,975 ±3,225	1.098	.946	4	1,750 ±1,025	.446	.444	4	7,450 ±2,350	.613	.981	4
Fe_2O_3	0.5	7,000 ±1,125	1.102	1.001	4	5,950 ±525	1.516	.999	4	12,700 ±4,275	1.045	.999	4
Fe_2O_3	1.0	5,975 ±1,125	.941	1.001	4	4,550 ±475	1.159	1.000	4	11,350 ±3,800	.934	1.000	4
Fe_2O_3	1.5	9,225 ±1,676	1.453	1.001	4	5,275 ±525	1.344	1.004	4	10,975 ±1,325	.903	1.001	4
Fe_2O_3	2.0	8,925 ±2,000	1.406	1.001	4	5,625 ±200	1.433	.918	4	11,150 ±1,525	.918	1.001	4
FEED GAS COMPOSITION: 99.8% CO-0.2% H_2S													
None	0.0	7,200 ±1,250		0.999	4	4,375 ±1,050		.999	4	8,250 ±975		.999	4
Fe	0.5	7,000 ±2,750	0.972	0.999	4	1,575 ±475	.360	.996	4	6,000 ±650	.727	.990	4
Fe	1.0	5,375 ±3,000	0.747	0.999	4	0 ±0	0	.515	4	5,000 ±1,150	.606	.971	4
Fe	1.5	7,000 ±2,350	0.972	0.988	4	0 ±0	0	.239	4	5,325 ±1,750	.645	.986	4
Fe	2.0	6,300 ±3,525	0.875	0.968	4	2,850 ±2,650	.651	.692	4	5,250 ±1,675	.636	.987	4
Fe_2O_3	0.5	8,550 ±400	1.188	0.999	4	4,925 ±775	1.131	.999	4	9,525 ±2,550	1.155	.999	4
Fe_2O_3	1.0	8,575 ±1,250	1.191	1.000	4	4,950 ±875	1.131	.999	4	9,325 ±2,050	1.130	.997	4
Fe_2O_3	1.5	7,775 ±600	1.080	1.000	4	4,650 ±1,650	1.063	.999	4	1,725 ±2,075	.209	.644	4
Fe_2O_3	2.0	8,725 ±1,225	1.212	1.000	4	4,275 ±725	.977	.998	4	2,275 ±2,225	.276	.690	4

(Tabled Continued)

COMPRESSIVE STRENGTH[a] OF IRON-DOPED REFRACTORIES AFTER EXPOSURE[b] TO MIXTURES OF CARBON MONOXIDE AND OTHER GASES[27], Table Continued

		DOE 90 Generic Composition[c]				DOE 50% Al_2O_3 Generic Composition[d]				DOE Generic Ramming Mix[e]			
Added Dopant	Wt% Fe	Compressive Strength, psi[a]	Ratio Doped to Undoped Strength	Ratio Wt. After to Wt. Before	No. of Samples	Compressive Strength, psi[a]	Ratio Doped to Undoped Strength	Ratio Wt. After to Wt. Before	No. of Samples	Compressive Strength, psi[a]	Ratio Doped to Undoped Strength	Ratio Wt. After to Wt. Before	No. of Samples
FEED GAS COMPOSITION: 99.2% CO-0.8% H_2S													
None	0.0	7,475 ±675		0.998	4	5,450 ±200		.996	4	5,700 ±3,025		.998	4
Fe	0.5	8,075 ±1,350	1.080	0.990	4	3,975 ±1,275	.729	.996	4	6,100 ±2,075	1.070	.997	4
Fe	1.0	9,100 ±475	1.217	0.996	4	2,625 ±1,925	.482	.962	4	9,700 ±3,425	1.702	.987	4
Fe	1.5	7,775 ±2,200	1.040	0.999	4	500 ±625	.092	.986	4	9,625 ±4,175	1.689	.934	4
Fe	2.0	4,125 ±4,775	0.552	0.683	4	4,900 ±3,950	.899	.737	4	8,475 ±2,675	1.489	.931	4
Fe_2O_3	0.5	7,850 ±2,100	1.050	1.000	4	5,825 ±1,100	1.069	1.000	4	6,850 ±2,450	1.202	.999	4
Fe_2O_3	1.0	8,900 ±950	1.191	0.999	4	5,200 ±1,125	.954	1.000	4	2,550 ±3,550	.447	.678	4
Fe_2O_3	1.5	7,150 ±550	0.957	0.999	4	5,975 ±2,775	1.096	1.000	4	0 ±0	0	.706	4
Fe_2O_3	2.0	7,925 ±2,950	1.060	1.000	4	5,225 ±725	.959	1.001	4	675 ±950	.118	.131	4
FEED GAS COMPOSITION: 80% CO-20% H_2O													
None	0.0	6,775 ±2,325		1.005	4	3,475 ±575		.999	4	6,725 ±2,225		1.000	4
Fe	0.5	8,425 ±1,825	1.244	1.004	4	3,225 ±1,825	.928	.999	4	6,375 ±1,675	.948	.998	4
Fe	1.0	9,825 ±4,325	1.450	1.004	4	4,425 ±1,200	1.273	.998	4	4,825 ±1,625	.717	.999	4
Fe	1.5	10,450 ±2,275	1.542	1.002	4	5,325 ±1,300	1.532	.998	4	7,725 ±850	1.149	.999	4
Fe	2.0	9,725 ±2,900	1.435	1.001	4	4,850 ±100	1.396	.997	4	8,075 ±1,775	1.201	.999	4
Fe_2O_3	0.5	9,050 ±1,600	1.336	1.003	4	4,400 ±750	1.266	.999	4	8,100 ±2,750	1.204	.999	4
Fe_2O_3	1.0	11,350 ±4,025	1.675	1.002	4	4,075 ±600	1.173	1.000	4	10,450 ±3,025	1.554	.999	4
Fe_2O_3	1.5	17,700 ±1,550	2.613	1.004	4	6,125 ±2,225	1.763	.999	4	10,500 ±2,900	1.561	.999	4
Fe_2O_3	2.0	16,750 ±3,775	2.472	1.003	4	4,325 ±475	1.245	1.000	4	5,975 ±2,800	.888	.999	4
FEED GAS COMPOSITION: 60% CO-40% H_2O													
None	0.0	8,700 ±2,800		1.005	4	4,775 ±1,250		1.002	4	6,900 ±2,175		.999	4
Fe	0.5	8,150 ±1,200	0.937	1.005	4	4,325 ±975	.906	1.000	4	5,125 ±2,000	0.743	.999	4
Fe	1.0	9,075 ±1,500	1.043	1.003	4	4,275 ±1350	.895	.999	4	8,525 ±3,175	1.236	.998	4
Fe	1.5	8,550 ±2,025	0.983	1.002	4	4,550 ±550	.953	.999	4	4,900 ±975	.710	.999	4
Fe	2.0	7,775 ±1,300	0.894	1.003	4	3,150 ±875	.660	.998	4	8,625 ±2,225	1.250	.998	4
Fe_2O_3	0.5	8,750 ±725	1.006	1.000	4	3,850 ±1,325	.806	1.000	4	9,375 ±3,025	1.359	.999	4
Fe_2O_3	1.0	9,250 ±475	1.063	1.001	4	3,975 ±875	.832	1.001	4	7,775 ±3,150	1.127	.997	4
Fe_2O_3	1.5	10,625 ±750	1.221	1.001	4	4,175 ±950	.874	1.000	4	10,600 ±2,450	1.536	.998	4
Fe_2O_3	2.0	12,100 ±3,050	1.391	1.001	4	4,250 ±675	.890	1.000	3	11,550 ±3,500	1.674	.999	4
FEED GAS COMPOSITION: 80% CO-20% H_2													
None	0.0	5,325 ±900		0.998	4	5,100 ±600		.998	4	12,000 ±3,250		.999	4
Fe	0.5	6,000 ±850	1.126	0.996	4	5,750 ±1,050	1.127	.996	4	9,900 ±1,400	.825	.997	4
Fe	1.0	11,125 ±1,225	2.089	0.997	4	10,425 ±1,325	2.044	.996	4	10,775 ±2,875	.898	.996	4
Fe	1.5	10,800 ±1,150	2.028	0.996	4	12,150 ±2,125	2.382	.995	4	11,400 ±750	.950	.959	4
Fe	2.0	4,875 ±1,100	0.915	0.765	4	11,525 ±1,475	2.260	.969	4	12,500 ±2,100	1.042	.968	4
Fe_2O_3	0.5	9,950 ±950	1.869	0.998	4	6,000 ±1,850	1.176	.996	4	15,100 ±2,500	1.258	.998	4
Fe_2O_3	1.0	7,625 ±575	1.432	0.998	4	11,050 ±1,300	2.167	.995	4	15,925 ±1,300	1.327	.995	4
Fe_2O_3	1.5	11,050 ±1,825	2.075	0.997	4	13,175 ±1,600	2.583	.995	4	11,925 ±2,375	.994	.994	4
Fe_2O_3	2.0	8,025 ±3,350	1.507	0.997	4	11,625 ±2,650	2.279	.994	4	8,250 ±750	.688	.992	4
FEED GAS COMPOSITION: 60% CO-40% H_2													
None	0.0	6,975 ±875		1.000	4	5,125 ±650		.997	4	10,450 ±3,375		.999	4
Fe	0.5	6,775 ±550	0.971	0.968	4	4,075 ±775	.795	.997	4	8,650 ±2,475	.828	.997	4
Fe	1.0	9,775 ±425	1.401	1.031	4	5,725 ±850	1.117	.996	4	10,300 ±1,900	.986	.996	4
Fe	1.5	8,075 ±925	1.158	0.897	4	5,150 ±400	1.005	.996	4	10,925 ±2,275	1.045	.996	4
Fe	2.0	9,000 ±1,325	1.290	0.997	4	5,100 ±1,125	.995	.996	4	10,925 ±1,225	1.045	.996	4
Fe_2O_3	0.5	7,875 ±1,275	1.129	0.999	4	4,875 ±1,075	.951	.998	4	10,675 ±1,725	1.022	.997	4
Fe_2O_3	1.0	8,050 ±1,750	1.154	0.999	4	5,275 ±375	1.029	.997	4	9,625 ±1,900	.921	.996	4
Fe_2O_3	1.5	8,775 ±2,200	1.258	0.999	3	4,250 ±875	.829	.997	4	11,050 ±950	1.057	.996	4
Fe_2O_3	2.0	8,200 ±2,400	1.176	0.998	4	6,275 ±800	1.224	.997	4	10,400 ±3,375	.995	.995	4

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[a] The compressive strength was measured on a universal testing machine with a crosshead speed of 0.1 in/min.

[b] Exposure was for 100 hr at 500 °C and 1 atmosphere pressure of the gases.

[c] DOE generic castable: 65 wt% tabular alumina (25 wt% 6 to 10 mesh, 20 wt% 10 to 20 mesh, 20 wt% less than 20 mesh), 10 wt% calcined alumina (less than 325 mesh), 25 wt% calcium aluminate cement (Casting Grade CA-25 cement), all Alcoa materials. Materials were dry mixed for 2 min, then water added with continued mixing to ball-in-hand consistency (~605 ml); refractory then poured into 2 in x 2 in x 2 in aluminum molds, vibrated for 5 min, sealed in plastic for 24 hr, then fired for 5 hr in air at 1100°C.

[d] DOE generic castable: 75 wt% calcined kaolin (25 wt% 6 to 10 mesh, 20 wt% 10 to 20 mesh, 15 wt% less than 20 mesh, 20 wt% less than 200 mesh), 25 wt% calcium aluminate cement (Casting Grade CA-25, Alcoa). Samples were prepared as described in footnote c except that the water used was ~700 ml.

[e] DOE generic ramming mix: 82 wt% tabular alumina (30 wt% 6 to 10 mesh, 20 wt% 10 to 20 mesh, 15 wt% less than 20 mesh, 17 wt% less than 48 mesh), 15 wt% calcined alumina (less than 325 mesh), 3 wt% bentonite; to this was added 1 wt% hydrated alumina, 6 wt% phosphoric acid (85%), and 0.25 wt% water. Dry materials were mixed and then hand mixed in plastic bags with the liquids; mixture was aged for 18 hr; samples formed by die pressing at 500 psi, curing at 250°C in air for 12 hr, then firing at 1100°C for 5 hr.

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE MODULUS OF RUPTURE[b] OF VARIOUS ALUMINA REFRACTORIES[c] [39]

Treatment Conditions[a]				Modulus of Rupture[b], psi			
Atmosphere	Temperature °F	Pressure psi	Time[d]	94% Al_2O_3[e]	93% Al_2O_3[f]	90-95% Al_2O_3[g]	90-95% Al_2O_3[h]
. . . . . DENSE HIGH-ALUMINA CASTABLES							
Air (dried)	230	ambient	24h	2870±290	2500±140	3080±240	3300±370
Air (fired)	500	ambient	18h	1940±130	1185±180	2510±190	2410±260
Air (fired)	1000	ambient	18h	1880± 55	1380±150	2650± 90	2220±350
CGA exposure	500	500	10d	3030±190	2510±330	2880±260	3120±760
	500	500	20d	1950±180	1630±210	2520±190	2580±470
	500	500	30d	2760±420	2610±170	2690±400	2990±380
CGA exposure	1000	1000	10d	1270±230	735± 80	1460±150	1780±300
	1000	1000	20d	1240±140	740± 65	1470±160	1500±200
	1000	1000	30d	1300±130	750± 60	1570± 55	1720±270
CGA,H_2O saturated[i]	447	1000	30d	4240±130	1984	not tested	4860±380
H_2O/CO,H_2O saturated	390	465	10d	4470±160	2320±150	4870±320	4780±620
H_2O/CO	500	465	10d	2390±260	2230±150	3270±370	3520±220
	1000	465	10d	1175±170	860± 80	1560±210	1580±240
. . . . . DENSE HIGH-ALUMINA CASTABLES (GENERIC PREPARATIONS)							
				93% Al_2O_3[j]	91% Al_2O_3[k]	91% Al_2O_3[l]	
Air (dried)	230	ambient	24h	2850±190	2930±340	2370±300	
Air (fired)	500	ambient	18h	2220±170	970±180	1700±300	
Air (fired)	1000	ambient	18h	2200±140	1810±290	970±230	
CGA exposure	500	500	10d	2640±870	2930±340	2260±560	
	500	500	20d	2440±420	1800±210	1870±220	
	500	500	30d	2860±600	3120±160	2740±230	
CGA exposure	1000	1000	10d	1820±210	700± 75	1290±120	
	1000	1000	20d	1920± 30	640± 65	1260±170	
	1000	1000	30d	1800±200	660± 80	1250±140	
CGA,H_2O saturated[i]	447	1000	30d	6630± 35	not tested	2650±450	
H_2O/CO,H_2O saturated	390	465	10d	4830±330	3310±270		
H_2O/CO	500	465	10d	2530± 60	3040±280		
	1000	465	10d	1620±190	1211±150		
CGA with H_2S	1000	1000	10d	1720±100	1125±150		
	1000	1000	20d	1750± 95	880±185		
	1000	1000	30d	2020±160	1035±130		
CGA with H_2S, H_2O saturated	447	1000	30d	4870±210	4050±560		
. . . . . INTERMEDIATE-ALUMINA DENSE AND INSULATING CASTABLES							
				54-57% Al_2O_3[m]	57% Al_2O_3[n]	59% Al_2O_3[o]	54% Al_2O_3[p]
Air (dried)	230	ambient	24h	2030±560	2200±240	650±100	970±120
Air (fired)	500	ambient	18h	1870±340	1570±230	460± 50	790± 80
Air (fired)	1000	ambient	18h	1760±180	1390±100	480± 35	940± 40
CGA exposure	500	500	10d	2810±310	2770±900	570±100	890±190
	500	500	20d	2270±310	2000±310	440± 80	670± 65
	500	500	30d	2700±450	2130±340	460± 50	710± 60
CGA exposure	1000	1000	10d	2160±450	2390±170	530± 20	1160± 40
	1000	1000	20d	2510±370	2730±240	580± 35	1090± 70
	1000	1000	30d	2540±330	2450±320	650± 55	1090± 90
CGA,H_2O saturated[i]	447	1000	30d	3540± 90	3330±830	930± 10	960±270
H_2O/CO,H_2O saturated	390	465	10d	2880±210	3280±400	860±140	870± 55
H_2O/CO	500	465	10d	2280±200	3280±180	610± 80	850± 70
	1000	465	10d	2020±130	1760± 28	490± 55	1094±210
CGA with H_2S	1000	1000	10d		2245±200		865± 90
	1000	1000	20d		2140±140		895± 65
	1000	1000	30d		2340±190		900± 65
CGA with H_2S, H_2O saturated	447	1000	30d		3920±385		560± 70

(Table Continued)

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE MODULUS OF RUPTURE[b] OF VARIOUS ALUMINA REFRACTORIES[c][39]

(continued)

Treatment Conditions[a]				Modulus of Rupture[b], psi		
Atmosphere	Temperature °F	Pressure psi	Time[d]	96% Al_2O_3[q]	96% Al_2O_3[r]	90% Al_2O_3[s]
PHOSPHATE-BONDED RAMMING MIXES						
Air (fired)	1000	ambient	18h	3190±320	3410±250	2650±600
CGA exposure	500	500	10d	3320±270	2420±520	1260±620
	500	500	20d	3960±450	2970±280	2370±560
	500	500	30d	4040±380	3120±38	2520±510
CGA exposure	1000	1000	10d	3340±420	3240±410	1810±390
	1000	1000	20d	3190±390	2930±440	2680±450
	1000	1000	30d	3610±570	3010±410	1610±640
CGA,H_2O saturated[i]	447	1000	30d	1620±320	470±40	440±60
H_2O/CO,H_2O saturated	390	465	10d	1290±650		540±170
H_2O/CO	500	465	10d	2640±220		2800±400
	1000	465	10d	2960±210		2090±180
CGA with H_2S	1000	1000	10d	2350±245		
	1000	1000	20d	2175±305		
	1000	1000	30d	2240±420		
CGA with H_2S, H_2O saturated	447	1000	30d	1100±120		

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[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18CO, $12CO_2$, $24H_2$, $41H_2O$, and $5CH_4$, another CGA with 40% H_2O and 1% H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (vol %). Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] Modulus of rupture from 3-point bending tests, ASTM C268-70 with a span of 2 in and a crosshead speed of 0.5 cm/min. All values are averages for seven specimens except where noted.

[c] All cement-bonded castables were cast in molds either 12 x 3 x 1/2 in or 3 x 3/4 x 3/4 in, cured 24 hr in air at 100 percent humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12 x 3 x 1/2 in slabs were then cut to 3 x 1/2 x 1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3 x 3/4 x 3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[d] Time units are given, either h for hours or d for days.

[e] 94% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Greencast-94, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[f] 93% alumina dense castable, calcium aluminate (72% alumina, 25% calcia) bonded (B&W Kao-Tab 93, Babcock & Wilcox; C-3 cement, Babcock & Wilcox).

[g] 90-95% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Castolast G, Harbison-Walker; CA-25 Calcium Aluminate Cement, Alcoa).

[h] 90-95% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Purotab, Kaiser Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[i] Data are for two specimens only.

[j] 93% alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

[k] 91% alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox)

[l] 91% alumina dense castable, UMR-3 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; C-3, a 72% alumina-25% calcia cement, Lone Star Lafarge).

[m] 54-57% alumina, 34-37% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (Lo-Abrade, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[n] 57% alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[o] 59% alumina, 33% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Kast-O-Lite 30, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[p] 54% alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[q] 96% alumina dense phosphate-bonded ramming mix (Greenpak-90P, A. P. Green).

[r] 96% alumina dense phosphate-bonded ramming mix (90 Ram H.S., C-E Refractories).

[s] 90% alumina dense phosphate-bonded ramming mix (Brikram 90R, General Refractories).

EFFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE MODULUS OF RUPTURE[c] OF CASTABLE ALUMINA REFRACTORIES[d][39]

Treatment Conditions[a]					Modulus of Rupture,[c] psi			
Environment		Temperature °F	Pressure psi	Time[e]	DENSE CASTABLES			
					93% Alumina[f]	87% Alumina[g]	64% Alumina[h]	58% Alumina[i]
Air (dried)		230	ambient	24 h	2850± 90	2260±170	---	2370±210
Air (fired)		500	ambient	18 h	2220± 70	1620±170	1770± 50	1290±120
Air (fired)		1000	ambient	18 h	2200±140	1490±170	1995±180	1290± 70
Saturated steam	vapor	447	410	10 d	4320±330	2460±270	4250±270	2710±210
	liquid	447	410	10 d	3900±380	2090±160	4180±460	2620±160
CGA with H_2S, saturated	vapor	447	1000	44 d	3920±450	2970±325	4670±945	2340±480
	liquid	447	1000	44 d	6180±380	not tested	5530±435	---
CGA with H_2S, saturated[j]		465	1000	5 d	1860±660	3980±370	2450±180	3040±125
followed by firing in air[k]		1000	ambient	18 h	1730± 85	3900±150	2130±250	2720±170
Cycling tests--repeat of preceding exposure followed by air firing								
1 cycle					1190±130	3980±270	4220±615	3440±365
2 cycles					1130±245	3830±255	4015±200	3460±300
3 cycles					1430±180	3570±355	3890±280	3050±300
4 cycles					1260±160	4070±750	3270±265	2645±275
5 cycles					1360±720	3510±410	3940±283	3420±350

Environment		Temperature °F	Pressure psi	Time[e]	INSULATING CASTABLES		
					54% Alumina[l]	47% Alumina[m]	35% Alumina[n]
Air (dried)		230	ambient	24 h	970± 20	440± 90	145
Air (fired)		500	ambient	18 h	795± 80	195± 35	120± 10
Air (fired)		1000	ambient	18 h	940± 40	210± 50	100± 20
Saturated steam	vapor	447	410	10 d	670± 50	380± 60	60± 4
	liquid	447	410	10 d	640± 70	430± 50	90± 20
CGA with H_2S, saturated	vapor	447	1000	44 d	790±110	440± 85	220± 65
	liquid	447	1000	44 d	1580± 95	not tested	580± 30
CGA with H_2S, saturated[j]		465	1000	5 d	790± 60	1065±130	190± 40
followed by firing in air[k]		1000	ambient	18 h	975±120	1060±140	130± 35
Cycling tests--repeat of preceding exposure followed by air firing							
1 cycle					990± 40	965±140	160± 10
2 cycles					965±125	975± 0	150± 25
3 cycles					1000± 90	1050± 70	130± 25
4 cycles					990± 80	760± 85	130± 20
5 cycles					945± 50	990± 75	160± 25

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[a] Samples were exposed in a steam generator, both in vapor and in the liquid in the bottom of the vessel. After placement of samples, the vessel was heated to the desired steam pressure and where tests included other gases, these were then added so as to obtain the desired overall concentrations. The overall composition of the coal gasification atmosphere (CGA) is (in vol %) 18 CO, 12 CO_2, 24 H_2, 40 H_2O, 5 CH_4, and 1 H_2S. A gaseous flow rate was maintained so as to provide one complete change in atmosphere every 24 hours. The vapor was 85% steam saturated in these tests.

[b] Other tests showed that boehmite formation occurred in steam-saturated atmospheres and resulted in very large increases in the flexural strength. These cycling tests were designed to investigate the effect of repetitive formation and decomposition of boehmite on the properties of the refractories.

[c] Modulus of Rupture from 3-point bending tests, ASTM C268-70 with a span of 2 in and a crosshead speed of 0.5 cm/min. All values are averages for seven specimens.

[d] After casting, specimens were cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hours. Specimens were stored at 230 °F until tested.

[e] Time units are given, h for hours, d for days.

[f] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

(Table Continued)

FFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE MODULUS OF RUPTURE[c] OF CASTABLE ALUMINA REFRACTORIES[d][39], Continued

otnotes continued

7.4% Alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Refcon, 58% alumina + titania-33% calcia, Universal Atlas Cement).

53.8% Alumina, 28.3% silica castable, UMR-8 generic preparation (75% calcined kaolin aggregate +25% calcium aluminum cement) (Mulcoa 60 and Mulgrain M47, C-E Minerals; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

58.6% Alumina, 29.6% silica castable, UMR-5 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement) (Mulcoa 60 and Mulgrain M47, C-E Minerals; Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

5% steam saturated; this exposure is the one forming the first step in the cycling tests, forming boehmite.

The firing step, following the saturated CGA exposure, completed one cycle, decomposing the boehmite.

54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

34.5% Alumina, 52.5% silica insulating castable (VSL-50, A.P. Green).

EFFECT OF EXPOSURE[a] TO CARBON-MONOXIDE/STEAM IN SATURATED VAPOR OR LIQUID ON THE MODULUS OF RUPTURE[b] OF VARIOUS ALUMINA REFRACTORIES[c][39]

Refractory[c]	CO/H_2O=0.1 (532 °F) MOR[d], psi	CO/H_2O=1.0 (466 °F) MOR[d], psi	CO/H_2O=3.0 (400 °F) MOR[d], psi
DENSE HIGH-ALUMINA CASTABLES			
93% Alumina[e]	4660 (4610)	2910 (4720)	3320 (3590)
91% Alumina[f]	2290 (4710)	2000 (3770)	1930 (2030)
87% Alumina[g]	2450 (1750)	3120 (3570)	1410 (3100)
88% Alumina[h]	Not Tested	3300 (3330)	3990 (3950)
84% Alumina[i]	Not Tested	3540 (3190)	3980 (4210)
DENSE INTERMEDIATE-ALUMINA CASTABLES			
57% Alumina, 34% silica[j]	4470 (3960)	4610 (3880)	4060 (3570)
50% Alumina, 38% silica[k]	3740 (1580)	3280 (3700)	3920 (3030)
INSULATING CASTABLES			
54% Alumina, 40% silica[l]	490 (250)	1230 (1190)	1100 (1440)
46% Alumina, 40% silica[m]	520 (520)	1000 (880)	785 (1010)
35% Alumina, 53% silica[n]	120 (170)	300 (420)	280 (390)
PHOSPHATE-BONDED RAMMING MIX			
96% Alumina[o]	920 (1080)	1920 (1910)	1760 (1550)

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[a] Samples were exposed in a steam generator to provide saturated vapor conditions. After placing samples, the vessel was heated to the desired steam pressure and the other gas was then added so as to obtain the concentrations specified in the table. A gaseous flow rate was maintained so as to provide one complete change in atmosphere every 24 hours. Time of exposure was 20 days.

[b] Modulus of rupture from 3-point bending tests, ASTM C268-70 with a span of 2 in and a crosshead speed of 0.5 cm/min. All values are averages for seven specimens except where noted.

[c] All cement bonded castables were cast in molds either 12x3x1/2 in or 3x3/4x3/4 in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12x3x0.5 in slabs were then cut to 3x1/2x1/2 in bars. Phosphate-bonded specimens were prepared by hard ramming in 3x3/4x3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[d] Numbers without parentheses are for samples exposed to saturated vapor, average of seven samples. Adjacent numbers in parentheses are for samples immersed in liquid (water) under the same exposure conditions, average of two samples.

EFFECT OF EXPOSURE[a] TO CARBON-MONOXIDE/STEAM IN SATURATED VAPOR OR LIQUID ON THE MODULUS OF RUPTURE[b] OF VARIOUS ALUMINA REFRACTORIES[c][39]

(Continued)

[e] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

[f] 91% Alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[g] 87.4% Alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Refcon, 58% Alumina + titania-33% calcia, Universal Atlas Cement).

[h] 88% Alumina dense castable, UMR-6 generic preparation (generic preparation UMR-1 with 5% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[i] 84% Alumina dense castable, UMR-7 generic preparation (generic preparation UMR-1 with 10% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[j] 57% Alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[k] 50.4% Alumina, 38.4% silica castable, UMR-5 generic preparation (75% Mulcoa + Mulgrain M-60, C-E Minerals; 25% Refcon, a 58% Alumina + titania-33% cement, Universal Atlas Cement).

[l] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75; C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[m] 46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

[n] 34.5% Alumina, 52.5% silica insulating castable (VSL-50, A.P. Green).

[o] 96% Alumina dense phosphate-bonded ramming mix (Greenpak-90P, A.P. Green).

EFFECT OF EXPOSURE TO AN UNSATURATED AND STEAM-SATURATED SIMULATED COAL GASIFICATION ENVIRONMENT[a] ON THE MODULUS OF RUPTURE[b] OF VARIOUS ALUMINA REPRACTORIES[c] [39]

Refractory[c]	Unsaturated (700 °F) MOR, psi	Saturated (447 °F)[d] MOR, psi
DENSE HIGH-ALUMINA CASTABLES		
94% Alumina[f]	1230	2790 (3210)
93% Alumina[g]	1750	4610 (5190)
91% Alumina[h]	1580	3600 (2420)
91% Alumina[i]	2110	1670 (2010)
88% Alumina[j]	nt[e]	nt[e] (4290)
84% Alumina[k]	nt	nt (4980)
DENSE INTERMEDIATE-ALUMINA CASTABLES		
57% Alumina[l]	3560	3560 (4260)
50% Alumina[m]	nt	3570 (nt)
INSULATING CASTABLES		
54% Alumina, 40% silica[n]	1050	480 (1340)
46% Alumina, 40% silica[o]	nt	510 (nt)
PHOSPHATE-BONDED RAMMING MIXES		
96% Alumina[p]	nt	1600 (nt)
90% Alumina[q]	nt	1520 (nt)

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[a] Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and other gases were then added so as to obtain the concentrations specified. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours. The simulated coal gasification atmosphere composition is (in vol %) 18CO, 12CO$_2$, 24H$_2$, 5CH$_4$, 40H$_2$O and 1H$_2$S. The samples were exposed at the temperatures indicated in the table at 1000 psia for 60 days.

[b] Modulus of Rupture from 3-point bending tests, ASTM C268-70 with a span of 2 in and a crosshead speed of 0.5 cm/min. All values are averages for seven specimens except where noted.

[c] All cement bonded castables were cast in molds either 12x3x1/2 in or 3x3/4x3/4in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12x3x0.5 in slabs were then cut to 3x1/2x1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3x3/4x3/4 in molds, immediately drying for 24 hr at 230 °F and then fixing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

FECT OF EXPOSURE TO AN UNSATURATED AND STEAM-SATURATED SIMULATED COAL GASIFICATION ENVIRONMENT[a] ON THE MODULUS OF RUPTURE[b] OF VARIOUS ALUMINA REFRACTORIES[c] [39]

(Continued)

[d] Numbers without parentheses are for samples exposed to saturated vapor. Adjacent number in parentheses is for samples immersed in liquid (water), average of two samples.

[e] nt represents samples not tested in that exposure condition.

[f] 94% Alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Greencast-94, A.P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[g] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

[h] 91% Alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[i] 91% Alumina dense castable, UMR-3 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; C-3, a 72% alumina-25% calcia cement, Lone Star Lafarge).

[j] 88% Alumina dense castable, UMR-6 generic preparation (generic preparation UMR-1 with 5% SiO_2, added as 99.9% pure, bone dry Wedron silica flour).

[k] 84% Alumina dense castable, UMR-7 generic preparation (generic preparation UMR-1 with 10% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[l] 57% Alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[m] 50.4% Alumina, 38.4% silica castable, UMR-5 generic preparation (75% Mulcoa + Mulgrain M-60, C-E Minerals: 25% Refcon, a 58% Alumina + titania-33% calcia cement, Universal Atlas Cement).

[n] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75; C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[o] 46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

[p] 96% Alumina dense phosphate-bonded ramming mix (Greenpak-90P, A. P. Green).

[q] 90% Alumina dense phosphate-bonded ramming mix (Brikram 90R, General Refractories).

RESULTS OF THERMAL-SHOCK TESTING[a] FOR SPALLING RESISTANCE OF VARIOUS COATING-SUBSTRATE SYSTEMS[33]

ing	Intermediate Layer(s)	Bond Coat	Substrate	Deposition Technique	No. of Cycles Before Spalling
)$_3$	--	--	304 SS	PS	1
	--	--	304 SS	IP	1^c
	--	--	310 SS	PS	1
	--	--	316 SS	PS	1
	--	--	Incoloy 800	PS	1
	--	--	1020 steel	PS	2^d
	--	Al (∿ 60 μm)	304 SS	PS	1
	--	Al (1-3 μm)	304 SS	IP	4^e
	--	Hf (1-3 μm)	304 SS	IP	4^e
	--	Cr (∿ 60 μm)	304 SS	PS	1
	--	NiCr (∿ 60 μm)	304 SS	PS	2-3
	--	NiCrAl^f (60-80 μm)	304 SS	PS	5^e,3^e (two tests)
	--	NiCrAl (60-80 μm)	310 SS	PS	5^e
	--	NiCrAl (60-80 μm)	316 SS	PS	5^e
	--	NiCrAl (60-80 μm)	Incoloy 800	PS	5^e
	--	Stellite 12	304 SS	PS	1-3
	--	Stellite 12	316 SS	PS	1-3
	--	Stellite 12	Incoloy 800	PS	1-3
	--	CoCrNi	304 SS	PS	1-3
	--	CoCrNi	316 SS	PS	1-3
	--	CoCrNi	Incoloy 800	PS	1-3
	--	Amdry 348	304 SS	PS	1
	--	Amdry 348	310 SS	PS	3^g
	--	Amdry 348	Incoloy 800	PS	2^g
	50Al$_2$O$_3$-50Co	Co	304 SS	PS	1
	50Al$_2$O$_3$-50Co	Co	310 SS	PS	1
	50Al$_2$O$_3$-50Co	Co	Incoloy 800	PS	1
	50Al$_2$O$_3$-50Triboloy 800	Triboloy 800	304 SS	PS	1
	50Al$_2$O$_3$-50Triboloy 800	Triboloy 800	310 SS	PS	1
	50Al$_2$O$_3$-50Triboloy 800	Triboloy 800	Incoloy 800	PS	1
	50Al$_2$O$_3$-50NiCrAl	NiCrAl	304 SS	PS	2
	50Al$_2$O$_3$-50NiCrAl	NiCrAl	310 SS	PS	1^h
	50Al$_2$O$_3$-50NiCrAl	NiCrAl	Incoloy 800	PS	2^h
	(70Al$_2$O$_3$-30NiCrAl) + (30Al$_2$O$_3$-70NiCrAl)	NiCrAl	304 SS	PS	3^g
	(70Al$_2$O$_3$-30NiCrAl) + (30Al$_2$O$_3$-70NiCrAl)	NiCrAl	310 SS	PS	4^g
	(70Al$_2$O$_3$-30NiCrAl) + (30Al$_2$O$_3$-70NiCrAl)	NiCrAl	Incoloy 800	PS	4^g
	ZrO$_2$	NiCrAl	304 SS	PS	5^g
	ZrO$_2$	NiCrAl	310 SS	PS	5^g
O$_3$	ZrO$_2$	NiCrAl	Incoloy 800	PS	5^g
$\cdot$Al$_2$O$_3$	--	--	304 SS	PS	1
	--	--	310 SS	PS	1
	--	--	316 SS	PS	1
	--	--	Incoloy 800	PS	1
	--	--	1020 steel	PS	1
	--	Stellite 12	304 SS	PS	1-3
	--	Stellite 12	316 SS	PS	1-3
	--	Stellite 12	Incoloy 800	PS	1-3
	--	CoCrNi	304 SS	PS	1-3
	--	CoCrNi	316 SS	PS	1-3
	--	CoCrNi	Incoloy 800	PS	1-3
	--	Amdry 348	304 SS	PS	1
	--	Amdry 348	310 SS	PS	2^g
	--	Amdry 348	Incoloy 800	PS	2^g
	50MgO$\cdot$Al$_2$O$_3$-50Co	Co	304 SS	PS	1
	50MgO$\cdot$Al$_2$O$_3$-50Co	Co	310 SS	PS	1
	50MgO$\cdot$Al$_2$O$_3$-50Co	Co	Incoloy 800	PS	1
	50MgO$\cdot$Al$_2$O$_3$-50Triboloy 800	Triboloy 800	304 SS	PS	1
	50MgO$\cdot$Al$_2$O$_3$-50Triboloy 800	Triboloy 800	310 SS	PS	1
	50MgO$\cdot$Al$_2$O$_3$-50Triboloy 800	Triboloy 800	Incoloy 800	PS	1
	ZrO$_2$	NiCrAl	304 SS	PS	5^g
	50MgO$\cdot$Al$_2$O$_3$-50Triboloy 800	NiCrAl	310 SS	PS	5^g
	50MgO$\cdot$Al$_2$O$_3$-50Triboloy 800	NiCrAl	Incoloy 800	PS	5^g
	(70MgO$\cdot$Al$_2$O$_3$-30NiCrAl) + (30MgO$\cdot$Al$_2$O$_3$-70NiCrAl)	NiCrAl	304 SS	PS	1
	(70MgO$\cdot$Al$_2$O$_3$-30NiCrAl) + (30MgO$\cdot$Al$_2$O$_3$-70NiCrAl)	NiCrAl	310 SS	PS	4^e
$\cdot$Al$_2$O$_3$	(70MgO$\cdot$Al$_2$O$_3$-30NiCrAl) + (30MgO$\cdot$Al$_2$O$_3$-70NiCrAl)	NiCrAl	Incoloy 800	PS	4^e

(Table Continued)

RESULTS OF THERMAL-SHOCK TESTING[a] FOR SPALLING RESISTANCE OF VARIOUS COATING-SUBSTRATE SYSTEMS[33]
(Continued)

Coating	Intermediate Layer(s)	Bond Coat	Substrate	Deposition Technique	No. of Cycles Before Spalling
$50Al_2O_3-50Cr_2O_3$	--	--	304 SS	PS	1
	--	--	316 SS	PS	1
	--	--	Incoloy 800	PS	1
	--	--	1020 steel	PS	1^d
	$50(Al_2O_3-Cr_2O_3)$ + 50Triboloy 800	Triboloy 800	304 SS	PS	1
	$50(Al_2O_3-Cr_2O_3)$ + 50Triboloy 800	Triboloy 800	310 SS	PS	1
	$50(Al_2O_3-Cr_2O_3)$ + 50Triboloy 800	Triboloy 800	Incoloy 800	PS	1
	$50(Al_2O_3-Cr_2O_3)$ + 50Co	Co	304 SS	PS	1
	$50(Al_2O_3-Cr_2O_3)$ + 50Co	Co	310 SS	PS	1
	$50(Al_2O_3-Cr_2O_3)$ + 50Co	Co	Incoloy 800	PS	2^g
	$[70(Al_2O_3-Cr_2O_3)-30NiCrAl]$ + $[50(Al_2O_3-Cr_2O_3)-50NiCrAl]$	NiCrAl	304 SS	PS	4^d
	$[70(Al_2O_3-Cr_2O_3)-30NiCrAl]$ + $[50(Al_2O_3-Cr_2O_3)-50NiCrAl]$	NiCrAl	310 SS	PS	4^d
$50Al_2O_3-50Cr_2O_3$	$[70(Al_2O_3-Cr_2O_3)-30NiCrAl]$ + $[50(Al_2O_3-Cr_2O_3)-50NiCrAl]$	NiCrAl	Incoloy 800	PS	4^d
ZrO_2	--	--	304 SS	PS	$4^{d,e}$
	--	--	Incoloy 800	PS	4^e
	--	--	1020 steel	PS	4^e
	--	Stellite 12	304 SS	PS	1-3
	--	Stellite 12	316 SS	PS	1-3
	--	Stellite 12	Incoloy 800	PS	1-3
	--	CoCrNi	304 SS	PS	1-3
	--	CoCrNi	316 SS	PS	1-3
	--	CoCrNi	Incoloy 800	PS	1-3
	--	Amdry 348	304 SS	PS	$1,2^g$ (two t s)
	--	Amdry 348	310 SS	PS	$2^g,1$ (two t s)
	--	Amdry 348	Incoloy 800	PS	2^g
	$50ZrO_2-50Co$	Co	304 SS	PS	1
	$50ZrO_2-50Co$	Co	310 SS	PS	1
	$50ZrO_2-50Co$	Co	Incoloy 800	PS	1
	$50ZrO_2$-50Triboloy 800	Triboloy 800	304 SS	PS	1
	$50ZrO_2$-50Triboloy 800	Triboloy 800	310 SS	PS	1
	$50ZrO_2$-50Triboloy 800	Triboloy 800	Incoloy 800	PS	1
	$50ZrO_2-50NiCrAl$	NiCrAl	304 SS	PS	4^g
	$50ZrO_2-50NiCrAl$	NiCrAl	310 SS	PS	4^g
ZrO_2	$50ZrO_2-50NiCrAl$	NiCrAl	Incoloy 800	PS	4^g
$MgO \cdot ZrO_2$	--	--	Incoloy 800	PS	4^e
	--	--	1020 steel	PS	2^d
	--	Stellite 12	304 SS	PS	1-3
	--	Stellite 12	316 SS	PS	1-3
	--	Stellite 12	Incoloy 800	PS	1-3
	--	CoCrNi	304 SS	PS	1-3
	--	CoCrNi	316 SS	PS	1-3
	--	CoCrNi	Incoloy 800	PS	1-3
	--	CoCrAl(Y)	304 SS	PS	8^e
	--	CoCrAl(Y)	310 SS	PS	8^e
	--	CoCrAl(Y)	Incoloy 800	PS	8^e
	--	Amdry 348	304 SS	PS	1
	--	Amdry 348	310 SS	PS	4^e
	--	Amdry 348	Incoloy 800	PS	4^e
	$50MgO \cdot ZrO_2-50Co$	Co	304 SS	PS	1^g
	$50MgO \cdot ZrO_2-50Co$	Co	310 SS	PS	4^e
	$50MgO \cdot ZrO_2-50Co$	Co	Incoloy 800	PS	4^e
	$50MgO \cdot ZrO_2$-50Triboloy 800	Triboloy 800	304 SS	PS	1
	$50MgO \cdot ZrO_2$-50Triboloy 800	Triboloy 800	310 SS	PS	1
$MgO \cdot ZrO_2$	$50MgO \cdot ZrO_2$-50Triboloy 800	Triboloy 800	Incoloy 800	PS	1
$75Al_2O_3-25ZrO_2$	--	NiCrAl	304 SS	PS	6^e
$75Al_2O_3-25ZrO_2$	--	NiCrAl	310 SS	PS	6^e
$75Al_2O_3-25ZrO_2$	--	NiCrAl	Incoloy 800	PS	6^e
$50Al_2O_3-50ZrO_2$	$50(Al_2O_3-ZrO_2)$ + 50Triboloy 800	Triboloy 800	304 SS	PS	1
	$50(Al_2O_3-ZrO_2)$ + 50Triboloy 800	Triboloy 800	310 SS	PS	1
	$50(Al_2O_3-ZrO_2)$ + 50Triboloy 800	Triboloy 800	Incoloy 800	PS	1
	$50(Al_2O_3-ZrO_2)$ + 50NiCrAl	NiCrAl	304 SS	PS	2
	$50(Al_2O_3-ZrO_2)$ + 50NiCrAl	NiCrAl	310 SS	PS	2
	$50(Al_2O_3-ZrO_2)$ + 50NiCrAl	NiCrAl	Incoloy 800	PS	2
	$[70(Al_2O_3-ZrO_2)-30NiCrAl]$ + $[30(Al_2O_3-ZrO_2)-70NiCrAl]$	NiCrAl	304 SS	PS	2^g
	$[70(Al_2O_3-ZrO_2)-30NiCrAl]$ + $[30(Al_2O_3-ZrO_2)-70NiCrAl]$	NiCrAl	310 SS	PS	1
$50Al_2O_3-50ZrO_2$	$[70(Al_2O_3-ZrO_2)-30NiCrAl]$ + $[30(Al_2O_3-ZrO_2)-70NiCrAl]$	NiCrAl	Incoloy 800	PS	2^g

(Table Continued)

RESULTS OF THERMAL-SHOCK TESTING[a] FOR SPALLING RESISTANCE OF VARIOUS COATING-SUBSTRATE SYSTEMS[33]
(Continued)

oating	Intermediate Layer(s)	Bond Coat	Substrate	Deposition Technique	No. of Cycles Before Spalling
r_2O_3	--	Stellite 12	304 SS	PS	1-3
↑	--	Stellite 12	316 SS	PS	1-3
	--	Stellite 12	Incoloy 800	PS	1-3
	--	CoCrNi	304 SS	PS	1-3
	--	CoCrNi	316 SS	PS	1-3
	--	CoCrNi	Incoloy 800	PS	1-3
	ZrO_2	NiCrAl	304 SS	PS	1
	ZrO_2	NiCrAl	310 SS	PS	1
	ZrO_2	NiCrAl	Incoloy 800	PS	1
	$50Cr_2O_3$-50NiCrAl	NiCrAl	304 SS	PS	1
↓	$50Cr_2O_3$-50NiCrAl	NiCrAl	310 SS	PS	1
r_2O_3	$50Cr_2O_3$-50NiCrAl	NiCrAl	Incoloy 800	PS	1
$_2O_3$	$50Y_2O_3$-50NiCrAl	NiCrAl	304 SS	PS	4[g]
$_2O_3$	$50Y_2O_3$-50NiCrAl	NiCrAl	310 SS	PS	4[g]
$_2O_3$	$50Y_2O_3$-50NiCrAl	NiCrAl	Incoloy 800	PS	4[g]
rO_2 + NiCrAl	--	NiCrAl	304 SS	PS	7[g]
rO_2 + NiCrAl	--	NiCrAl	310 SS	PS	12[g]
rO_2 + NiCrAl	--	NiCrAl	Incoloy 800	PS	12[g]
$gO\cdot Al_2O_3$-NiCrAl	--	NiCrAl	304 SS	PS	4[g]
$gO\cdot Al_2O_3$-NiCrAl	--	NiCrAl	310 SS	PS	4[g]
$gO\cdot Al_2O_3$-NiCrAl	--	NiCrAl	Incoloy 800	PS	4[g]
$gO\cdot ZrO_2$-NiCrAl	--	NiCrAl	304 SS	PS	11[g]
$gO\cdot ZrO_2$-NiCrAl	--	NiCrAl	310 SS	PS	14[g]
$gO\cdot ZrO_2$-NiCrAl	--	NiCrAl	Incoloy 800	PS	14[g]
oCrAl(Y)	--	--	304 SS	PS	7[e]
oCrAl(Y)	--	--	310 SS	PS	7[e]
oCrAl(Y)	--	--	Incoloy 800	PS	7[e]
r_3C_2(Ni-Al)	--	--	304 SS	PS	4[e]
↑	--	--	Incoloy 800	PS	4[e]
	--	--	1020 steel	PS	4[e]
	--	NiCrAl	304 SS	PS	6[g]
↓	--	NiCrAl	310 SS	PS	6[g]
r_3C_2(Ni-Al)	--	NiCrAl	Incoloy 800	PS	6[g]
$75Cr_3C_2$-25NiCr	--	NiCrAl	304 SS	PS	4[g]
$75Cr_3C_2$-25NiCr	--	NiCrAl	310 SS	PS	4[g]
$75Cr_3C_2$-25NiCr	--	NiCrAl	Incoloy 800	PS	4[g]

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[a] A single thermal-shock test cycle consisted of soaking at 980 °C for at least 0.5 hr and quenching to ambient temperatures by air cooling on a copper block (or asbestos sheet). Temperature change from 980 °C to 50 °C occurred in ∿ 10 minutes on copper block (asbestos provides a slower quench rate).

[b] PS = plasma-sprayed (coat 200-250 μm thick, IP = ion-plated (∿ 30 μm thick).

[c] When quenched on asbestos, specimen had not spalled in four cycles and test was discontinued.

[d] Asbestos-quenched.

[e] No spalling occurred, test discontinued.

[f] 75Ni-24Cr-1Al.

[g] Spalling developed at edges of specimen, test discontinued.

[h] Spalling developed at one edge only, test discontinued.

B.4 Physical Properties Testing

B.4.2 Refractories

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EFFECT OF EXPOSURE[a] TO STEAM, HYDROGEN, AND CARBON MONOXIDE ON THE BULK DENSITY[b] OF VARIOUS REFRACTORIES[9]

Refractory	Brand Name Manufacturer	Cured & Dried[c]	Air Fired 1100° C 250 hr	Exposure Conditions[a]: Steam 1100° C 250 hr 1000 psi	Hydrogen 1100° C 250 hr 1000 psi	Carbon Monoxide 1000° C 125 hr 1000 psi
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	172	163±1	169	164±1	166±1
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	133	128±1	131	129±1	131±3
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	91	86±3	81	87±1	87±1
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	188	187±2	182	181±3	190±2
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	134	113±2	116	116±1	115±2
99% Al_2O_3 brick	99AD A. P. Green	192	192±4	195	194±2	197±1
90% Al_2O_3 brick	Arco-90 General Refractories	193	194±1	193	194±1	195±2
60% Al_2O_3 tar-impregnated brick	Ufala Tl Harbison-Walker	168	161±3	156	160±2	165±1
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	144	143±5	141	143±2	145±3

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[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths of time.

[b] Bulk density determined according to ASTM C-20-73, units are lb/ft^3.

[c] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

EFFECT OF EXPOSURE[a] TO CARBON DIOXIDE AND A MIXED GAS[b] ENVIRONMENT ON THE BULK DENSITY[c] OF VARIOUS REFRACTORIES [9]

Refractory	Brand Name Manufacturer	Cured & Dried[d]	Air Fired 1100° C 250 hr	Exposure Conditions[a]	
				Carbon Dioxide 1100° C 250 hr 800 psi	Mixed Gas[b] 1000° C 160 hr 1000 psi
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	172	165± 1	163±1[e]	167±2
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	133	132± 3	129±3	128±2
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	91	86± 3	84±2	88±2
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories		132± 7	131±4	131±2
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	188	189±1	187±2[e]	185±3[e]
Dense 90% Al_2O_3 castable, phosphate bond	Resco Cast AA-22 Resco Products		173±1	173±3	172±3
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	134	114±1	111±1[e]	109±4[e]
99% Al_2O_3 brick	99AD A. P. Green	192	192±2	190±2	192±7
90% Al_2O_3 brick	Arco-90 General Refractories	193	193±1	192±1	196±2[e]
80% Al_2O_3 tar-impregnated brick	Ufala Tl Harbison-Walker	168	163±2	160±2	162±1
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	144	146±2	145±1	145±2

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[a] Samples were fired in air, then exposed to the individual gases at the temperature and pressure indicated for the stated lengths of time.

[b] Mixed gas composition: 24% hydrogen, 18% carbon monoxide, 12% carbon dioxide, 5% methane, 2% ammonia, 1% hydrogen sulfide, 38% steam.

[c] Bulk density determined according to ASTM C-20-73, units are lb/ft^3.

[d] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, hled 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

[e] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF EXPOSURE[a] TO A HIGH-BTU GAS[b] ON THE BULK DENSITY[c] AND APPARENT POROSITY[d] OF VARIOUS REFRACTORIES[9]

		Bulk Density[c]			Apparent Porosity[d]	
Refractory	Brand Name Manufacturer	Cured & Dried[e]	Air Fired 810° C 250 hr	High-Btu Gas[b] 760° C 160 hr 1000 psi	Air Fired 810° C 250 hr	High-Btu Gas[b] 760° C 160 hr 1000 psi
Dense 95% Al_2O_3 castable, calcium aluminate bond	Castolast G Harbison-Walker	172	171.4± 5.8	166.8±0.9	30.4±2.8	29.7±1.2
Dense 90% Al_2O_3 castable, calcium aluminate bond	DOE 90 Generic Preparation		167.6± 4.5	163.9±1.8	29.1±1.5	29.9±1.2
Dense 55% Al_2O_3 castable, calcium aluminate bond	Lo-Abrade A. P. Green	133	133.6±12.3	125.8±2.2	32.7±3.7	27.2±0.9
Lightweight 50% Al_2O_3 insulating castable, calcium aluminate bond	Litecast 75-28 General Refractories	91	89.2± 2.8	87.1±0.3	51.7±2.8	47.3±0.5[f]
Dense 45% Al_2O_3 castable, calcium aluminate bond	B&W Kaocrete D Babcock & Wilcox		123.3± 3.0	122.1±2.4	34.2±1.8	29.6±0.4[f]
Dense 45% Al_2O_3 castable, calcium aluminate bond	H.S. Brikcast BF General Refractories		127.6± 1.4	127.9±4.1	31.1±1.8	23.9±1.5[f]
90% Al_2O_3 ramming mix, phosphate bond	Brikram 90R General Refractories	188	186.6± 2.3	184.3±4.9	14.1±0.9	13.4±1.6
Dense 90% Al_2O_3 castable, phosphate bond	Resco Cast AA-22 Resco Products		181.5± 3.8	165.7±5.2[f]	25.8±1.6	21.7±0.9[f]
60% Al_2O_3 ramming mix, phosphate bond	HW 23-75 Harbison-Walker		155.7± 9.2	148.7±5.1	19.5±5.1	16.9±2.4
Calcium aluminate neat cement (78% Al_2O_3)	CA-25 Alcoa	134	115.8± 2.4	109.6±1.1[f]	57.9±1.1	56.9±1.1
90% Al_2O_3 brick	Arco-90 General Refractories	193	190.8± 0.8	190.9±2.5	14.1±0.4	11.4±1.3[f]
45% Al_2O_3 fired super duty brick	KX-99 A. P. Green	144	148.3± 1.8	146.8±2.4	10.9±1.0	10.4±0.9

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[a] Identical samples (1 in x 1 in x 2 in bars) were exposed to air firing and to High-Btu Gas under the conditions noted.

[b] High-Btu Gas (feed composition): 24% H_2, 18% CO, 12% CO_2, 5% CH_4, 2% NH_3, 1% H_2S, 38% H_2O.

[c] ASTM C-20-73; values given are 95% confidence intervals; units are lb/ft^3.

[d] Values are 95% confidence intervals; unit is per cent.

[e] Samples were prepared in the following ways: Fired brick was taken as received and cut to sample size with a diamond saw; Ramming mix was taken as received, pressed at 1000 psi in sample mold, dried at 250° F 28 hr, heated at 50° F/hr to 500° F, held 24 hr, heated at 50° F/hr to 1000° F, held 24 hr, cooled slowly back to ambient temperature, and the resulting sample sawed to size; Castables were thoroughly mixed and stored in plastic bags, oven dried for 24 hr at 230° F, cooled in a moisture-proof container, stored at 75° F for 24 hr, mixed in a Hobart mixer (144 rpm) with 25° C water to give ball-in-hand consistency, troweled into molds and vibrated on a vibrating table for 3 min, covered with plastic sheets and cured for 24 hr at 90° F and 100% relative humidity, removed from molds and dried 24 hr at 230° F.

[f] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

EFFECT OF EXPOSURE[a] TO HIGH-BTU GAS[b] ON THE BULK DENSITY[c] AND APPARENT POROSITY[d] OF REFRACTORIES REINFORCED WITH STEEL FIBERS[9]

Refractory	Brand Name Manufacturer	Type Fiber[e]	Bulk Density[c] Air Fired 980° C 250 hr	Bulk Density[c] High-Btu Gas[b] 980° C 250 hr 1000 psi	Apparent Porosity[d] Air Fired 980° C 250 hr	Apparent Porosity[d] High-Btu Gas[b] 980° C 250 hr 1000 psi
Dense 95% Al_2O_3	Castolast G	430 SS	166.1	162.3	34.7	28.9
castable, cal-	Harbison-	446 SS	166.7	166.7	33.6	30.8
cium aluminate	Walker	446 SS,C[f]	165.4	163.6	34.1	31.0
bond		310 SS	163.6	163.6	34.9	32.2
Dense 90% Al_2O_3	DOE 90	430 SS	167.3	165.4	32.5	29.4
castable, cal-	Generic	446 SS	166.7	164.8	34.2	31.3[g]
cium aluminate	Preparation	446 SS,C	167.9	167.3	32.4	30.0
bond		310 SS	167.3	168.5	31.5	30.9
Dense 45% Al_2O_3	H.S. Brikcast BF	430 SS	130.5	131.7	29.4	25.0[g]
castable, cal-	General Re-	446 SS	131.1	133.0	28.4	25.5
cium aluminate	fractories	446 SS,C	131.7	133.6	28.2	25.7[g]
bond		310 SS	133.0	135.5	28.2	24.8

[a] Identical samples were fired in air or exposed to the gas under the stated conditions.

[b] High-Btu Gas composition (feed gas): 25% H_2, 21% CO, 13% CO_2, 5% CH_4, 36% H_2O.

[c] ASTM C-20-73; units are lb/ft^3.

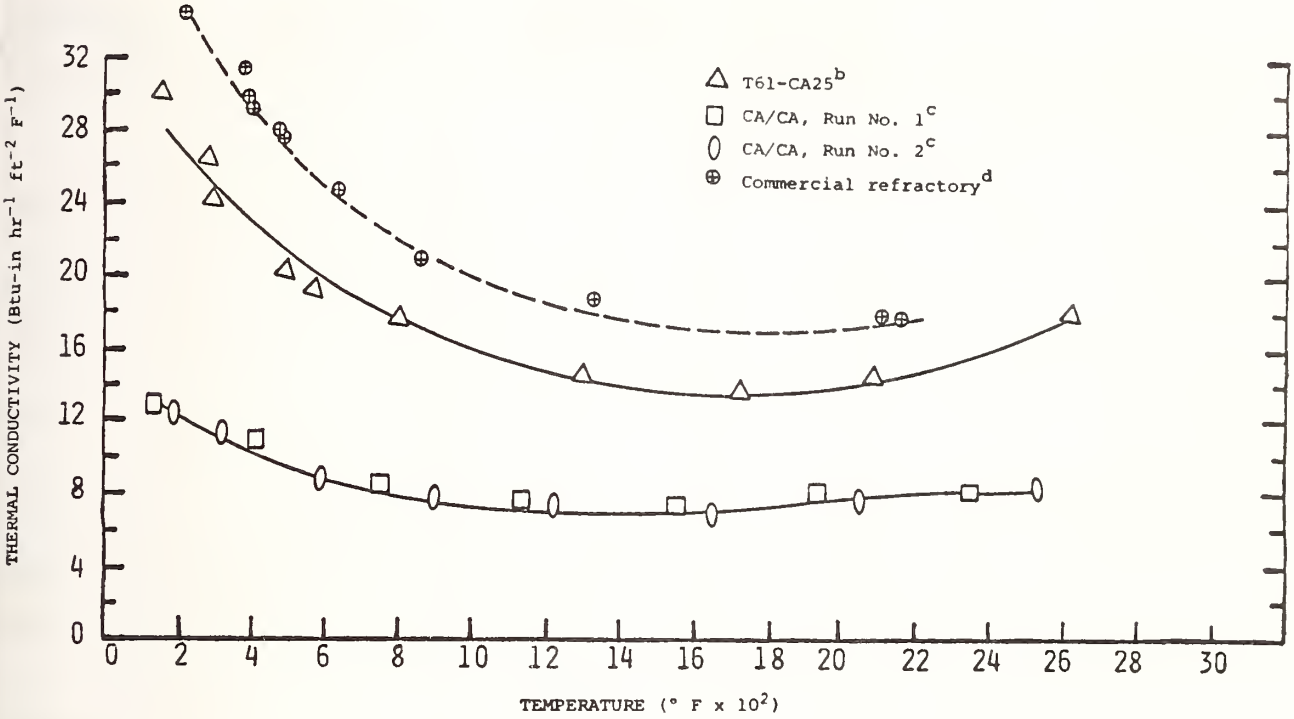
[d] Unit is per cent.

[e] 2 wt% of fiber (based on the castable dry weight) was added.

[f] This material was a coated 446 SS.

[g] [These values were labelled as differing from the air-fired values by a statistically significant amount.]

COMPARISON OF THERMAL CONDUCTIVITY[a] FOR HIGH-ALUMINA REFRACTORIES[9]



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[a] Duplicate determinations were made of each composition at each temperature.

[b] T61-CA25 is a 95% alumina refractory concrete, a generic preparation; bulk density 157-163 lb/ft^3.

[c] CA/CA is a 78% alumina refractory concrete, prepared by Tuscaloosa Metallurgy Research Center; bulk density 132 lb/ft^3; aggregate is made from sintered calcium aluminate cement.

[d] The commercial refractory is 95% alumina refractory concrete; bulk density 157-163 lb/ft^3. All of the above refractories had about the same cement/aggregate ratio and the same aggregate size distributions.

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12]

Two exposures in gasifier off-gas (SYNTHANE); reducing gas, H_2O, CO_2, CO, H_2, H_2S, ash and char (small amounts); ∿1290 °F, 1000 psi, exposure time not given.

Material (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a] %	Apparent Porosity[a] % change	Apparent Specific Gravity[a]	Apparent Specific Gravity[a] % change	Bulk Density[a] g/cm³	Bulk Density[a] % change
90+% Al_2O_3 dense castable CA bond[e] (Castolast G)	U		27.5		3.63		2.62	
	E1	+0.4	27.7	+ 0.7	3.59	- 1.1	2.59	- 1.1
	U		29.9		3.69		2.59	
	E2	-5.0	28.7	- 4.0	3.66	- 0.8	2.61	- 0.8
60% Al_2O_3 dense castable, CA bond (Mizzou Castable)	U		25.1		3.00		2.25	
	E1	-0.4	27.7	+10.4	3.11	+ 3.7	2.27	+ 0.9
	U		25.1		3.04		2.28	
	E2	-1.5	24.4	- 2.8	3.07	+ 1.0	2.32	+ 1.8
90+% Al_2O_3 light castable, CA bond (Purolite 30)	U		46.6		2.65		1.42	
	E1	-3.3	Disintegrated - could not be tested					
90+% Al_2O_3 light castable, CA bond (Greencast-97L)	U		49.9		2.82		1.41	
	E1	+2.0	54.9	+10.0	3.17	+12.4	1.43	+ 1.4
54% Al_2O_3 dense castable, CA bond (Super Brikcast A)	U		24.7		2.88		2.17	
	E2	-1.8	25.34	+ 2.6	2.94	+ 2.1	2.19	+ 0.9
54% Al_2O_3 light insulating castable, CA bond (Litecast 75-28)	U		37.9		2.36		1.51	
	E1	-1.4	55.0	+45.1	3.18	+34.8	1.43	- 5.3
	U		40.7(24.7)[f]		1.98(2.88)[f]		1.17(2.17)[f]	
	E2	-5.3	61.3	+50.6(+148)[f]	3.12	+57.6(+8.3)[f]	1.21	+ 3.4(-44.
70% Al_2O_3 (Mullite), Vitreous bond high fired brick (Mul-8)	U		17.2		3.05		2.53	
	E1	-0.2	19.1	+11.0	3.08	+ 1.0	2.49	- 1.6
	U		18.9		3.07		2.49	
	E2	-1.1	19.9	+ 5.8	3.10	+ 1.0	2.48	- 0.4
85% Al_2O_3 phosphate bond, dense fired brick (Chemal 85 B)	U		15.7		3.36		2.83	
	E1	0	16.8	+ 7.0	3.51	+ 4.5	2.91	+ 2.8
	U		16.6		3.43		2.83	
	E2	-0.9	19.7	+18.7	3.49	+ 1.8	2.80	- 1.1
90+% Al_2O_3 self-bonded dense fired brick (Kricor)	U		16.7		3.54		2.95	
	E1	-0.2	18.7	+12.0	3.58	+ 1.1	2.91	+ 1.4
	U		17.5		3.55		2.93	
	E2	-0.7	19.2	+ 9.7	3.58	+ 2.3	2.88	- 1.7
99+% Al_2O_3 self-bonded dense fired brick (H-W Corundum)	U		19.0		3.74		3.03	
	E1	+0.2	20.2	+ 6.3	3.80	+ 1.6	3.03	0
	U		20.3		3.77		3.02	
	E2	-0.6	21.7	+ 6.9	3.83	+ 1.6	2.94	- 1.0
77% Al_2O_3 self-bonded light insulating fired brick (B&W Insalcor)	U		46.5		2.81		1.53	
	E1	+0.4	61.4	+32.0	1.31	-53.4	1.29	-15.7
98+% Al_2O_3 self-bonded light insulated fired brick (Alfrax B 101)	U		60.7		3.74		1.47	
	E1	+1.3	59.4	- 2.1	2.84	-24.1	1.56	+ 6.1
99+% Al_2O_3 self-bonded dense fused cast brick (Monofrax A)	U		0.8		3.86		3.83	
	E1	-0.3	4.7	+488[g]	3.89	+ 0.8	3.71	- 3.1
	U		.09		3.82		3.79	
	E2	-0.2	3.14	+3388[g]	3.87	+ 1.3	3.75	- 1.1
SiC, silicon nitride bonded, dense fired brick (Refrax 20)[h]	U		15.1		3.12		2.64	
	E1	+3.1	19.2	+27.2	2.88	- 7.7	2.07	-21.6
	U		14.9		3.18		2.67	
	E2	-1.3	18.16	+21.9	2.88	- 9.4	2.36	-11.6
Alumina-Zirconia-Silica fused cast brick (AZS)	U		0.09		3.88		3.85	
	E2	-1.1	11.58	+12,767[g]	3.95	+ 1.8	3.49	- 9.4

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

rial (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a] %	Apparent Porosity[a] % change	Apparent Specific Gravity[a]	Apparent Specific Gravity[a] % change	Bulk Density[a] g/cm³	Bulk Density[a] % change
Two Exposure in gasifier off-gas (SYNTHANE) . . . . continued								
Al_2O_3 tar-impregnated Vitreous fired k (Ufala TI)	U		14.2		2.70		2.69	
	E2	-0.5	15.84	+11.6	2.98	+10.4	2.50	- 7.1
refired Ufala TI[i]	U		14.5		2.96		2.53	
	E2	-0.6	16.6	+14.5	2.98	+ 0.7	2.49	- 1.6
0% Al_2O_3 clay vitreous bond, high d super duty brick (KX-99)	U		12.3		2.52		2.29	
	E2	-0.9	16.5	+34.2	2.70	+ 7.1	2.26	- 1.3
refired KX-99[i]	U		11.5		2.62		2.32	
	E2	-0.7	15.0	+30.4	2.80	+ 3.1	2.30	- 0.9
Al_2O_3 phosphate bonded mortar mal 111)	U		--		--		--	
	E1	+0.2	--		--		--	
Al_2O_3 phosphate bond ramming mix p #60)	U		14.6		3.08		2.63	
	E1	-1.4	21.2	+45.2	2.84	- 7.8	2.24	-14.8
Al_2O_3 phosphate bond ramming mix kram 90)	U		16.3		3.52		2.95	
	E1	-1.9	15.6	- 4.3	3.44	- 2.3	2.90	+ 1.7
	U		14.6		3.50		2.99	
	E2	-0.8	17.2	+17.8	3.56	+ 1.7	2.95	- 1.3
Al_2O_3 light castable, CA bond ecast 80)	U		34.6		2.57		1.68	
	E1	-0.1	48.7	-40.8	3.24	+26.1	1.66	- 1.2
Al_2O_3 vitreous fired brick (Hi Lumite)	U		24.3		3.14		2.34	
	E1	-2.0	26.8	+10.3	3.27	+ 4.1	2.39	+ 2.1
Al_2O_3 phosphate bonded fired brick ex 85-B)	U		12.0		3.36		2.96	
	E1	-0.2	17.1	+42.5	3.51	+ 4.5	2.91	- 1.7
	U		12.0		3.36		2.96	
	E2	-0.7	21.65	+80.4	3.53	+ 5.1	2.76	- 6.8
Al_2O_3 phosphate bonded fired brick mex P-8)	U		13.8		3.32		2.86	
	E1	-0.1	21.8	+58.0	3.51	+ 5.7	2.74	- 4.2
	U		13.8		3.32		2.86	
	E2	-0.8	18.25	+32.3	3.37	+ 1.5	2.76	- 3.5
Al_2O_3 phosphate bonded castable co Cast AA-22)	U		23.9		3.53		2.69	
	E1	--	26.6	+11.3	3.09	-12.5	2.27	-15.6
	U		23.6		3.47		2.66	
	E2	-2.2	27.3	+15.7	3.65	+ 5.2	2.65	- 0.4
oxynitride bond, coupons/bricks stolon 63)	U		15.6		3.04		2.55	
	E2	-1.4	19.8	+26.9	2.98	- 2.0	2.39	- 6.3
Al_2O_3 chemical bond ramming mix Ram)	U		18.2		3.07		2.52	
	E2	-1.3	20.68	+13.6	3.16	+ 3.0	2.51	- 0.4
Al_2O_3 chemical bond ramming mix Ram H.S.)	U		21.9		3.12		2.44	
	E2	-1.8	21.92	+ 0.1	3.11	- 0.3	2.43	- 0.4
One exposure in the fluidized bed of the gasifier (SYNTHANE), reducing gas as in above plus coal fines, ash and char, 1800 °F, 1000 psi, exposure time not given								
Al_2O_3 dense castable CA bond[e] tolast G)	U		30.0		3.73		2.61	
	E	-5.2	27.6	- 8.0	3.65	- 2.1	2.70	+ 3.5
Al_2O_3 dense castable, CA bond (Mizzou able)	U		25.3		3.08		2.30	
	E	-1.2	25.7	+ 1.6	3.07	- 0.3	2.28	- 0.9
Al_2O_3 light castable, CA bond encast-97L)	U		49.6		2.78		1.40	
	E	-3.8	61.0	+23.1	3.74	+34.5	1.46	+ 4.3

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

Material (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a] %	Apparent Porosity[a] % change	Apparent Specific Gravity[a]	Apparent Specific Gravity[a] % change	Bulk Density[a] g/cm^3	Bulk Density[a] % change
One exposure in the fluidized bed of the gasifier (SYNTHANE) . . . . continued								
54% Al_2O_3 light insulating castable, CA bond (Super Brikcast A)	U		24.9		2.87		2.16	
	E	-0.8	25.4	+ 2.0	2.94	+ 2.43	2.20	+ 1.9
54% Al_2O_3 light insulating castable, CA bond (Litecast 75-28)	U		44.7		--		1.24	
	E	-3.2	58.7	+31.3	3.14	+40.0	1.30	+ 4.8
70% Al_2O_3 (Mullite), Vitreous bond high fired brick (Mul-8)	U		18.0		3.06		2.51	
	E	-0.6	19.8	+ 6.1	3.09	+ 1.0	2.48	- 1.2
85% Al_2O_3 phosphate bond, dense fired brick (Chemal 85 B)	U		16.2		3.43		2.87	
	E	-0.2	19.2	+18.5	3.45	+ 0.6	2.78	- 3.1
90+% Al_2O_3 self-bonded dense fired brick (Kricor)	U		17.1		3.53		3.03	
	E	-0.7	17.8	+ 4.1	3.59	+ 1.7	2.95	- 2.6
99+% Al_2O_3 self-bonded dense fired brick (H-W Corundum)	U		19.9		3.77		3.02	
	E	-0.3	20.9	+ 5.0	3.79	+ 0.5	3.00	- 0.7
77% Al_2O_3 self-bonded light insulating fired brick (B&W Insalcor)	U		47.5		2.81		1.47	
	E	-1.8	54.5	+14.5	3.22	+14.6	1.47	0
98+% Al_2O_3 self-bonded light insulating fired brick (Alfrax B 101)	U		60.4		3.75		1.48	
	E	-0.5	59.0	- 2.3	3.88	+ 3.5	1.56	+ 5.4
99+% Al_2O_3 self-bonded dense fused cast brick (Monofrax A)	U		0.9		3.84		3.80	
	E	-0.03	3.8	+322.	3.96	+ 3.1	3.81	+ 0.3
SiC, silicon nitride bonded, dense fired brick (Refrax 20)	U		15.6		3.14		2.65	
	E	-1.1	30.8	+33.3 [j]	2.78	-11.5	1.92	-27.6
Zirconium silicate, vitreous bond coupon	U		16.2		4.59		3.85	
	E	-0.1	16.9	+ 4.3	4.61	+ 0.4	3.83	- 0.5
60% Al_2O_3 tar-impregnated vitreous fired brick (Ufala TI), refired[i]	U		14.2		2.70		2.69	
	E	-0.2	15.65	+10.2	2.97	+10.0	2.58	- 4.1
45-50% Al_2O_3 high fired super duty brick (KX-99)	U		11.6		2.61		2.31	
	E	-0.5	14.9	+28.5	2.70	+ 3.5	2.30	- 0.4
60% Al_2O_3 phosphate bond ramming mix (Wasp #60)	U		18.0		2.91		2.38	
	E	-1.4	21.5	+23.9	2.81	- 3.4	2.24	- 5.9
90% Al_2O_3 phosphate bond ramming mix (Brikram 90)	U		15.4		3.55		2.92	
	E	-0.3	13.3	-13.6	3.50	- 1.4	3.03	+ 3.8
70+% Al_2O_3 vitreous fired brick (Hi Lumite 70 D)	U		21.5		2.77		2.17	
	E	-1.3	26.2	+26.5	2.75	- 0.7	2.03	- 6.5
85% Al_2O_3 phosphate bonded fired brick (Altex 85-B)	U		16.3		3.45		2.89	
	E	-0.2	21.3	+30.8	3.51	+ 2.0	2.76	- 4.5
80+% Al_2O_3 phosphate bonded fired brick (Alumex P-8)	U		15.8		3.34		2.81	
	E	-1.5	17.9	+13.3	3.35	+0.3	2.94	(4.6)
							(2.76)	1.8
90+% Al_2O_3 phosphate bonded castable (Resco Cast AA-22)	U		27.2		3.54		2.58	
	E	-0.5	23.4	-14.0	3.65	+ 3.1	2.80	+ 8.5
SiC, oxynitride bond, coupons/bricks (Crystolon 63)	U		14.7		3.05		2.60	
	E	-0.4	31.1	+111.7	2.86	- 6.2	2.19	-15.8

(Table Continued)

PHYSICAL PROPEPTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

rial (Brand Name)	Expo-sure[d]	% Weight change	Apparent Porosity[a]		Apparent Specific Gravity[a]		Bulk Density[a]	
			%	% change		% change	g/cm^3	% change
Three exposures in gasifier off-gas (Conoco, CO_2 Acceptor), $48H_2$, $23H_2O$, $12CH_4$, 8.5CO , $6CO_2$, $2.5N_2$ (vol. %); 1500 °F, 150 psig, ~800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3)								
Al_2O_3 dense castable CA bond[e]	U		27.5		3.63		2.62	
tolast G)	E1	-1.0	27.5	0	3.64	+ 0.3	2.64	+ 0.8
	U		27.5		3.63		2.62	
	E2	-0.33	31.7	+15.	3.83	+ 5.5	2.61	- 0.4
	U		31.2		3.82		2.64	
	E3	-0.32	25.6	-18.	3.49	- 8.6	2.60	- 1.5
Al_2O_3 dense castable, CA bond	U		25.1		3.00		2.25	
zou Castable)	E1	-1.2(-1.6)	22.3	-11	2.98	- 0.7	2.31	+ 2.7
	U		25.1		3.00		2.35	
	E2	+0.02	23.7	- 5.5	2.98	- 0.7	2.28	+ 2.7[j]
	U		24.6		2.98		2.25	
	E3	-0.84	26.5	+ 8.	3.06	+ 2.7	2.25	0
Al_2O_3 light castable, CA bond	U		46.6		2.65		1.42	
olite 30)	E1	-4.5	52.9	+14.	3.05	+15.	1.42(1.43)	0(+0.7)
	U		44.6		2.65		1.42	
	E2	-2.1	55.6	+24.	3.04	+15.	1.35	- 5.0
Al_2O_3 light castable, CA bond	U		49.9		2.82		1.41	
encast-97L)	E1	-0.9	30.1	-40.	2.04	-27.	1.43(1.94)	+ 0.7[j] (+37.6)
	U		49.9		2.82		1.41	
	E2	+1.15	51.5	+ 3.2	2.99	+ 6.0	1.45	+ 2.8
	U		50.8		2.69		1.26	
	E3	-4.1	61.1	+20.	3.74	+39.	1.41	+12.
Al_2O_3 dense castable, CA bond	U		25.5		2.85		2.18	
er Brikcast A)	E3	-0.74	28.0	+10.	2.91	+ 2.1	2.13	- 2.3
Al_2O_3 light insulating castable, CA	U		41.3		2.33		1.37	
(Litecast 75-28)	E1	-2.1	52.0	+25.9	3.04(3.10)	+30.5(+33.0)	1.46	+ 6.6
	U		37.9		2.36		1.51	
	E2	-0.60	51.6	+36.	3.00	+27.	1.45	- 3.9
	U		48.9		2.34		1.20	
	E3	-1.6	60.5	+24.	3.01	+29.	1.19	- 0.8
Al_2O_3 (Mullite), vitreous bond high	U		17.2(18.2)		3.05(3.06)		2.53(2.50)	
d brick (Mul-8)	E1	-0.2	19.2	+12.(+5.5)	3.09	+ 1.3(+1.0)	2.50	- 1.2(0)
	U		17.2		3.05		2.53	
	E2	+0.05	17.1	- 0.6	3.00	- 1.6	2.53	0
	U		19.0		3.07		2.49	
	E3	-0.16	19.6	+ 3.2	3.08	+ 0.3	2.48	- 0.4
Al_2O_3 phosphate bond, dense fired	U		15.7(17.6)		3.36(3.44)		2.83(2.84)	
k (Chemal 85 B)	E1	-0.3(-0.2)	16.0	+ 1.9(-9.1)	3.50	+ 4.2(+1.7)	2.94	+ 3.9(+3.5)
	U		15.7		3.36		2.83	
	E2	-0.07	14.5	- 7.6	3.48	+ 3.6	2.64	- 6.7
	U		15.0		3.45		2.94	
	E3	-0.21	16.2	+ 8.0	3.49	+ 1.2	2.92	- 0.7
Al_2O_3 self-bonded dense fired brick	U		16.7(15.1)		3.54(3.51)		2.95(2.99)	
ccr)	E1	0(-0.3)	17.6(16.7)	+ 5.4(+10.6)	3.55	+ 0.3(+1.1)	2.96(2.95)	+ 0.3(-1.3)
	U		16.7		3.54		2.95	
	E2	-0.5	17.8	+ 6.6	3.53	- 0.3	2.91	- 1.3
Al_2O_3 self-bonded dense fired brick	U		19.0		3.74(3.64)		3.03(2.95)	
Corundum)	E1	-0.1(-0.3)	20.3	+ 6.8	3.77	+ 0.8(+3.6)	3.00	- 1.0(+1.7)
	U		19.0		3.74		3.03	
	E2	+0.11	20.6	+ 8.4	3.78	+ 1.1	3.00	- 1.0
	U		24.3		3.76		3.00	
	E3	-0.12	21.0	-13.	3.77	+ 0.3	2.98	- 0.7

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

Material (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a]		Apparent Specific Gravity[a]		Bulk Density[a]	
			%	% change		% change	g/cm^3	% change
Three exposures in gasifier off-gas (Conoco, CO_2 Acceptor) . . . . . continued								
77% Al_2O_3 self-bonded light insulating fired brick (B&W Insalcor)	U		46.5(50.5)		2.81(2.77)		1.53(1.35)	
	E1	-10.9 (- 1.24) (- 1.0)	54.6(56.1)	+17.4(+11.1)	2.82(2.94)	+ 0.4(+5.1)	1.28(1.29) (1.30)	-16.3(-4.4
	U		46.5		2.81		1.53	
	E2	+0.85	55.2	+19.	2.82	+ 0.4	1.23	-20.
	U		48.7		2.81		1.44	
	E3	-1.34	55.7	+14.	3.28	+17.	1.45	+ 0.7
98+% Al_2O_3 self-bonded light insulating fired brick (Alfrax B 101)	U		60.7(57.7)		3.74(3.70)		1.47(1.57)	
	E1	-0.1(-1.2)	57.4(52.5)	- 5.4(-9.0)	3.75(3.02)	+ 0.3(-18.4)	1.59(1.43)	+ 5.4(-8.9
	U		60.7		3.74		1.47	
	E2	+1.1	59.2	- 2.5	3.76	+ 0.6	1.53	+ 4.1
	U		59.9		3.68		1.47	
	E3	+0.17	60.0	+ 0.2	3.68	0	1.52	+ 3.4
99+% Al_2O_3 self-bonded dense fused cast brick (Monofrax A)	U		0.8		3.86		3.83	
	E1	-0.10	0.4	-50.	3.90	+ 1.0	3.89	+ 1.6
	U		0.8		3.86		3.83	
	E2	-0.06	1.33	+66.	3.82	- 1.0	3.77	- 1.6
	U		0.9		3.85		3.80	
	E3	+0.05	1.85	+106	3.93	+ 2.1	3.78	- 0.5
SiC, silicon nitride bonded, dense fired brick (Refrax 20)	U		15.1(14.6)		3.12(3.10)		2.64(2.65)	
	E1	+0.29	16.1	+ 6.6(+10.3)	3.10	- 0.7(0)	2.60	- 0.9[j](-1
	U		15.1		3.12		2.64	
	E2	corroded	20.5	+36.	2.86	- 8.3	2.28	-14.
	U		17.3		3.16		2.61	
	E3	+0.11	20.9	+21.	2.92	-39.	2.30	-12
70% Al_2O_3 (Mullite) vitreous dense fired brick (Alumex 70-HD)	U		20.7		3.25		2.58	
	E3	-0.46	20.6	- 0.4	3.25	0	2.57	- 0.4
Zirconium sulfate vitreous bond coupon	U		16.2		4.58		3.84	
	E3	-0.39	16.5	+ 1.8	4.60	+ 0.4	3.83	- 0.3
60% Al_2O_3 tar-impregnated vitreous fired brick (Ufala TI)	U		0.9		2.70		2.68	
	E3	-6.8	15.3	+960.	2.95	+ 9.3	2.50	- 6.7
45-50% Al_2O_3 high fired super duty brick (KX-99)	U		12.3		2.62		2.30	
	E3	-0.62	14.2	+15.	2.67	+ 1.9	2.29	- 0.4
60% Al_2O_3 phosphate bond ramming mix (Wasp #60)	U		14.6(20.1)		3.08(2.82)		2.63(2.25)	
	E1	Specimen cracked						
	U		14.6		3.08		2.63	
	E2	fractured	20.8	+42.	2.86	- 7.1	2.26	-14.
	U		19.7		2.82		2.26	
	E3	-2.5	19.9	+ 1.0	2.82	0	2.26	0
90% Al_2O_3 phosphate bond ramming mix (Brikram 90)	U		16.3		3.52		2.95	
	E1	Specimen cracked						
	U		16.3		3.52		2.95	
	E2	+0.07	16.2	- 0.6	3.49	- 0.9	2.93	- 0.7
	U		19.5		3.62		2.92	
	E3	-0.19	16.5	-15.	3.50	- 3.3	2.92	0
52% Al_2O_3 light castable, CA bond (Litecast 80)	U		37.3		2.66		1.67	
	E1	-3.5	46.3	+24.1	2.94	+10.5	1.57	- 6.0
	U[f]		34.6		2.57		1.68	
	E1[f]	Specimen cracked						
	U		34.6		2.57		1.68	
	E2	-2.8	46.7	+35.	3.13	+30.	1.64	- 0.6
90+% Al_2O_3 dense castable, CA bond (Greencast-97)	U		27.7(31.2)		3.65(3.78)		2.64(2.61)	
	E1	-0.86	30.5	+10.(-2.2)	3.82	+ 4.9(+1.1)	2.65(2.66)	+ 0.4(+1.

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

rial (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a]		Apparent Specific Gravity[a]		Bulk Density[a]	
			%	% change		% change	g/cm^3	% change
Three exposures in gasifier off-gas (Conoco, CO_2 Acceptor) . . . . . . continued								
Al_2O_3 vitreous fired brick (Hi	U		24.3(21.2)		3.14(2.68)		2.34(2.11)	
e 70 D)	E1	-6.6	26.7	+ 9.9(+25.9)	3.25	+ 3.2(+21.3)	2.38	+ 1.7(+12.8)
	U		24.3		3.14		2.34	
	E2	-0.89	25.9	+ 6.6	3.25	+ 3.5	2.31	+ 3.0
l_2O_3 phosphate bonded fired brick	U		12.0(15.2)		3.36(3.44)		2.96(2.90)	
x 85-B)	E1	-0.20	16.7	+39.(+9.9)	3.50	+ 3.9(+1.7)	2.92	- 1.3(+0.7)
Al_2O_3 phophate bonded fired brick	U		13.8(15.2)		3.32(3.33)		2.86(2.82)	
ex P-8)	E1	-0.02 (-0.2)	15.2(15.1)	+10.(-0.7)	3.36(3.35)	+ 1.2(+0.6)	2.85	- 0.3(+1.1)
	U		13.8		3.36		2.86	
	E2	+0.07	15.4	+12.	3.33	- 0.9	2.82	- 1.4
l_2O_3/10% Cr_2O_3 solid solution	U		17.4		3.82		3.15	
brick (CS 612)	E1	-1.0(-0.3)	18.6(18.7)	+ 6.9(+7.5)	3.84	+ 0.5	3.12	- 1.0
Al_2O_3 phosphate bonded castable	U		23.7		3.53		2.69	
o Cast AA-22)	E3	-0.38	24.9	+ 5.0	3.53	0	2.68	- 0.4
oxynitride bond, coupon/bricks	U		14.2		3.08		2.64	
tolon 63)	E3	-18.1	20.0	+41.	2.97	- 3.6	2.38	- 9.8
Three exposures in dolomite regenerator off-gas (Conoco, CO_2 Acceptor); $70N_2$, $27CO_2$, 3CO, H_2S trace (vol %); 1850 °F, 150 psi, ~800 hr (exposure 1), 1000-2400 hr (exposure 2), 740-1450 hr (exposure 3)								
Al_2O_3 dense castable CA bond	U		27.5		3.63		2.62	
olast G)	E1	-1.2	31.2	+13.5	3.72	+ 2.2[j]	2.56	- 2.3
	U		27.5		3.63		2.62	
	E2	0	31.8	+16.	3.74	+ 3.0	2.55	- 2.6
	U		32.3		3.80		2.58	
	E3	+0.45	27.0	-16.	3.50	- 7.9	2.55	- 1.2
l_2O_3 dense castable, CA bond	U		25.1		3.00		2.25	
ou Castable)	E1	-2.1	23.2	- 4.7[j]	2.96	- 1.3	2.27	+ 0.9
	U		25.1		3.00		2.35(2.25)	
	E2	-1.9	25.8	+ 2.8	3.02	+ 0.7	2.24	- 4.7(-0.4)
	U		27.8		3.13		2.26	
	E3	+1.3	25.5	- 8.	3.06	- 2.2	2.28	+ 0.9
Al_2O_3 light castable, CA bond	U		46.6(44.6)		2.65		1.42	
lite 30)	E1	-9.0(-5.5)	53.0	+14.(-19)	3.03	+14.	1.43	+ 0.7
	U		44.6		2.65		1.42	
	E2	-34.	54.3	+22.	2.97	+12.	1.36	- 4.2
Al_2O_3 light castable, CA bond	U		49.9		2.82		1.41	
ncast-97L)	E1	-3.3	44.5	-11.	2.56	- 9.2	1.42	+ 0.7
	U		49.9		2.82		1.41	
	E2	+1.8	54.5	+ 9.2	3.12	+11.	1.42	+ 0.6
	U		45.9		2.57		1.39	
	E3	+3.2	60.8	+33	3.57	+39	1.40	+ 0.7
l_2O_3 dense castable, CA bond	U		26.4		2.94		2.13	
Brikcast A)	E3	+2.3	26.0	- 1.5	2.92	- 0.7	2.16	+ 1.4
l_2O_3 light insulating castable, CA	U		41.3(37.9)		2.33(2.36)		1.37(1.51)	
(Litecast 75-28)	E1	-1.3(-1.5)	49.8	+20.6(+9.6)	2.85(2.87)	+22.3(+21.6)	1.45	+ 5.8(-4.0)
	U		37.9		2.36		1.51	
	E2	+1.1	62.0	+64.	2.93	+24.	1.77	+17.
	U		48.4		2.34		1.19	
	E3	-0.34	57.5	+19.	2.91	+24	1.24	+ 4.2
$_2O_3$ (Mullite), Vitreous bond high	U		17.2(18.2)		3.05		2.53(2.50)	
brick (Mul-8)	E1	+0.3(+0.4)	17.9(18.0)	+ 4.1(-1.1)	3.06	+ 0.3	2.51	- 0.8(+0.4)
	U		17.2		3.05		2.53	
	E2	+2.2	17.0	- 1.2	3.05	0	2.53	0

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

Material (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a]		Apparent Specific Gravity[a]		Bulk Density[a]	
			%	% change		% change	g/cm^3	% chan
Three exposures in dolomite regenerator off-gas (Conoco, CO_2 Acceptor) . . . . continued								
85% Al_2O_3 phosphate bond, dense fired brick (Chemal 85 B)	U		15.7(17.6)		3.36(3.44)		2.83(2.84)	
	E1	+0.4	16.4(17.4)	+ 4.5(-1.1)	3.47	+ 3.3(+0.9)	2.90	+ 2.5(
	U		15.7		3.36		2.83	
	E2	-0.8	20.5	+31.	3.49	+ 3.9	2.77	- 2.1
	U		18.1		3.46		2.84	
	E3	+0.73	22.6	+25.	3.48	+ 0.6	2.84	0
90+% Al_2O_3 self-bonded dense fired brick (Kricor)	U		15.1(16.7)		3.51(3.54)		2.99(2.95)	
	E1	+0.4	16.7	+10.6(0)	3.53	+ 0.6(-0.3)	2.94	- 1.7(
	U[f]		16.7		3.54		2.95	
	E1[f]	0	16.6	- 0.6	3.52	- 0.6	2.94	- 0.3
	U		16.7		3.54		2.95	
	E2		Specimen not recovered					
	U		18.2		3.60		2.94	
	E3	+1.05	17.9	- 1.6	3.55	- 1.4	2.96	+ 0.7
99+% Al_2O_3 self-bonded dense fired brick (H-W Corundum)	U		19.0		3.64(3.74)		2.95(3.03)	
	E1	-0.8(0)	21.4(21.0)	+12.6(+10.5)	3.77(3.76)	+ 3.6(+0.6)	2.96(2.97)	+ 0.3(
	U		19.0		3.74		3.03	
	E2	+0.23	21.9	+15.	3.76	+ 0.6	2.84	- 6.3
	U		20.2		3.78		3.00	
	E3	+0.71	20.2	0	3.78	0	3.02	0
77% Al_2O_3 self-bonded light insulating fired brick (B&W Insalcor)	U		46.5		2.81		1.53	
	E1	-1.2 (+10.9)	56.0	+20.4	2.94	+ 4.6	1.30	-13.1
	U[f]		50.5		2.77		1.35	
	E1[f]	+1.0	54.8(54.6)	+ 8.5(+8.1)	2.89(2.82)	+ 4.3(+1.8)	1.28	- 5.2
	U		46.5		2.81		1.53	
	E2	+5.3	54.5	+17.	2.85	+ 1.4	1.30	-15.
	U		49.0		2.83		1.44	
	E3	+5.4	54.4	+11.	3.26	+15.	1.47	+ 2.1
98+% Al_2O_3 self-bonded light insulating fired brick (Alfrax B 101)	U		60.7(57.7)		3.74(3.70)		1.47(1.57)	
	E1	-0.15 (+2.0)	57.2	- 5.8(-0.9)	3.67	- 1.9(-0.8)	1.59	+ 5.4[j]
	U		60.7		3.74		1.47	
	E2	+2.2	57.9	- 4.6	3.77	+ 0.8	1.54	+ 4.8
	U		60.6		3.83		1.51	
	E3	+5.1	45.5	-25.	3.04	-21.	1.66	+10.
99+% Al_2O_3 self-bonded dense fused cast brick (Monofrax A)	U		0.8		3.86		3.83	
	E1	-0.15 (+0.2)	0.7(0.6)	-13.(-25)	3.83(3.89)	- 0.8(+0.8)	3.80(3.87)	- 0.8(
	U		0.8		3.86		3.83	
	E2	0	1.1	+38	3.82	- 1.0	3.78(3.82)	- 1.3(
	U		1.05		3.82		3.78	
	E3	+0.56	1.41	+34	3.82	0	3.76	- 0.5
SiC, silicon nitride bonded, dense fired brick (Refrax 20)	U		15.1(14.6)		3.12(3.10)		2.64(2.65)	
	E1	+3.1	8.5(9.4)	-44(-35.6)	2.97	- 4.8(-4.2)	2.72(2.71)	+ 3.0(
	U		15.1		3.12		2.64	
	E2	+3.7	6.5	-57.	2.85	- 8.7	2.67	+ 1.1
	U		15.4		3.15		2.67	
	E3	+0.33	7.9	-48.	2.97	- 5.1	2.74	+ 2.6
70% Al_2O_3 (Mullite) vitreous dense fired brick (Alumex 70-HD)	U		20.1		3.26		2.60	
	E3	+1.9	20.4	+ 1.5	3.23	- 0.9	2.57	- 1.2
60% Al_2O_3 tar-impregnated vitreous fired brick (Ufala TI)	U		1.1		2.79		2.76	
	E3	-4.2	12.1	+1000.	2.96	+ 6.1	2.60	- 5.8
45-50% Al_2O_3 high fired super duty brick (KX-99)	U		13.3		2.63		2.28	
	E3	+1.4	13.2	- 0.7	2.67	+ 1.5	2.31	+ 1.3

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS !121 (Continued)

ial (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a] %	Apparent Porosity[a] % change	Apparent Specific Gravity[a]	Apparent Specific Gravity[a] % change	Bulk Density[a] g/cm³	Bulk Density[a] % change
Three exposures in dolomite regenerator off-gas (Conoco, CO_2 Acceptor) . . . . continued								
l_2O_3 phosphate bond ramming mix #60)	U		14.6(20.1)		3.08(2.82)		2.63(2.25)	
	E1	Specimen cracked						
	U		14.6		3.08		2.63	
	E2	+1.7	19.2	+31.	2.78	- 9.7	2.24	-15.
	U		19.9		2.82		2.26	
	E3	+2.5	19.0	- 4.7	2.78	- 1.4	2.25	- 0.4
l_2O_3 phosphate bond ramming mix ram 90)	U		16.3		3.52		2.95	
	E1	-0.52 (+0.4)	16.8(17.0)	+ 3.1(+4.3)	3.46	- 1.7	2.88	- 2.6[j]
	U		16.3		3.52		2.95	
	E2	-0.20	17.2	+ 5.5	3.44	- 2.3	2.98(2.85)	+ 1.0(-3.4)
	U		19.6		3.63		2.92	
	E3	+1.6	14.8	-25.	3.44	-12.	2.93	+ 0.3
l_2O_3 light castable, CA bond cast 80)	U		37.3		2.66		1.67	
	E1	-1.3	46.0	+23.3	2.91	+ 9.4	1.56	- 6.6
	U[f]		34.6		2.57		1.68	
	E1[f]	-2.2	42.6	+23.	2.78	+ 8.2	1.60	- 4.8
	U		34.6		2.57		1.68	
	E2	+1.1	46.2	+34.	3.56(3.12)	+39.(+21)	1.67	- 0.6
Al_2O_3 dense castable, CA bond encast-97)	U		27.7(31.2)		3.65(3.78)		2.64(2.61)	
	E1	-0.16	25.7	- 7.8[j](-18)	3.56(3.55)	- 2.5(-6.1)	2.64	0(-1.1)
Al_2O_3 vitreous fired brick Lumite 70 D)	U		21.2(24.3)		2.68(3.14)		2.11(2.34)	
	E1	-0.14 (+0.5)	24.1(23.8)	+13.7(-2.1)	3.02(3.22)	+12.7(+2.3)	2.45(2.45)	+16.1(+4.7)
	U		24.3		3.14		2.34	
	E2	-0.18	16.9	-30.	2.58	-18.	2.15	- 8.1
Al_2O_3 phosphate bonded fired brick ex 85-B)	U		12.0(15.2)		3.36(3.44)		2.96(2.90)	
	E1	+0.07 (+0.7)	16.2(15.3)	+35.(+0.6)	3.48(3.48)	+ 3.6(+1.2)	2.91	- 1.7(+0.3)
Al_2O_3 phosphate bonded fired brick mex P-8)	U		13.8(15.2)		3.32(3.33)		2.86(2.82)	
	E1	-0.04 (+0.4)	17.2(16.4)	+25.(+7.9)	3.33	+ 0.3(0)	2.78	- 2.8(-1.4)
	U		13.8		3.36		2.86	
	E2	-0.16	19.5	+41.	3.33	- 0.9	2.68	- 6.3
Al_2O_3/10% Cr_2O_3 solid solution fired k (CS 612)	U		17.4		3.82		3.15	
	E1	+0.05 (+0.1)	18.4(18.8)	+ 5.8(+2.3)[j]	3.83(3.84)	+ 0.3(+0.5)	3.12	- 1.0
Al_2O_3 phosphate bonded castable co Cast AA-22)	U		24.1		3.53		2.68	
	E3	+1.8	26.6	+14.	3.59	+ 1.7	2.63	- 1.9
oxynitride bond, coupons/bricks stolon 63)	U		14.9		3.07		2.61	
	E3	+1.2	9.4	-37.	2.92	- 4.9	2.65	+ 1.5
One exposure in gasifier off-gas (Bi-Gas); H_2O, CO_2, CO, H_2, N_2, CH_4, H_2S, ash and char (entrained); 1800 °F , 750 psi, exposure time not given								
Al_2O_3 dense castable, CA bond er Brikcast A)	U		24.8[l]		2.87[l]		2.17[l]	
	E	-8.4	26.1	+ 5.2	2.89	+ 0.7	2.13	- 1.8
Al_2O_3 light insulating castable, CA (Litecast 75-28)	U		37.9[l]		2.36[l]		1.51[l]	
	E	-10.4	62.2	+64.	3.06	+30.	1.15	-24.
Al_2O_3 phosphate bond, dense fired ck (Chemal 85 B)	U		15.7[l]		3.36[l]		2.83[l]	
	E	-2.55	15.9	+ 1.3	3.36	0	2.83	0
Al_2O_3 (Mullite) vitreous dense fired ck (Alumex 70-HD)	U		19.2		3.23		2.61	
	E	-1.04	19.4	+ 1.0	3.29	+ 1.9	2.65	+ 1.5

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

Material (Brand Name)	Exposure[d]	% Weight change	Apparent Porosity[a]		Apparent Specific Gravity[a]		Bulk Density[a]	
			%	% change		% change	g/cm^3	ch
One exposure in gasifier off-gas (BI-GAS) . . . . continued								
90+% Al_2O_3 phosphate bonded castable (Resco Cast AA-22)	U		23.9[1]		3.53[1]		2.69[1]	
	E	+0.03	25.2	+ 5.4	3.60	+ 2.0	2.71	+ 0.
One exposure in gasifier off-gas (BATTELLE); 1800 °F, 100 psi, ∿50 hr exposure								
60% Al_2O_3 dense castable, CA bond (Mizzou Castable)	U		28.2		3.14		2.25	
	E	-16.4	27.5	- 2.5	3.07	- 2.2	2.23	- 0.
70% Al_2O_3 (Mullite), Vitreous bond high fired brick (Mul-8)	U		17.5		3.07		2.53	
	E	-0.04	17.8	+ 1.8	3.08	+ 0.3	2.53	0
85% Al_2O_3 phosphate bond, dense fired brick (Chemal 85 B)	U		14.5		3.38		2.90	
	E	+0.01	14.9	+ 2.8	3.41	+ 0.9	2.90	0
Silicon carbide, clay bonded	U		16.6		3.06		2.55	
	E	+0.36	17.2	+ 3.6	3.08	+ 0.7	2.55	0
90% Al_2O_3 phosphate bonded ramming mix (Brikram 90)	U		12.3		2.98		2.61	
	E	+0.04	12.3	0	2.98	0	2.62	+ 0.
80+% Al_2O_3 phosphate bonded ramming mix (Alumex P-8)	U		14.7		3.33		2.84	
	E	0.0	15.6	+ 6.1	3.37	+ 1.2	2.84	0
90+% Al_2O_3 phosphate bonded castable (Resco Cast AA-22)	U		29.6		3.55		2.50	
	E	-0.19	28.2	- 4.7	3.56	+ 0.3	2.56	+ 2.
One exposure in combuster off-gas (BATTELLE); 2000 °F, >100 psi, ∿50 hr exposure								
60% Al_2O_3 dense castable, CA bond (Mizzou Castable)	U		30.6		3.20		2.21	
	E	-38.5	27.0	-12.	3.10	- 3.1	2.26	+ 2
Silicon Carbide, clay bonded	U		16.7		3.05		2.54	
	E	+0.13	19.5	-17.	3.07	+ 0.7	2.48	- 2
60% Al_2O_3 tar-impregnated vitreous fired brick (Ufala TI)	U		0.2[1]		2.70[1]		2.69[1]	
	E	-5.8	15.1	+7450	3.05	+13.	2.59	- 3
45-50% Al_2O_3 high fired super duty brick (KX-99)	U		11.35		2.62		2.32	
	E	0.0	11.5	+ 1.3	2.67	+ 2.7	2.33	+ 0
90% Al_2O_3 phosphate bond ramming mix (Brikram 90)	U		13.2		3.46		3.00	
	E	+0.08	13.0	- 1.5	3.46	0	3.01	- 0
90+% Al_2O_3 phosphate bonded castable (Resco Cast AA-22)	U		26.0		3.55		2.63	
	E	-3.3	25.7	- 1.2	3.58	+ 0.8	2.66	+ 1

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

erial (Brand Name)	Exposure[d]	Brick[k] Portion	% Weight change	Apparent Porosity[a]		Apparent Specific Gravity[a]		Bulk Density[a]	
				%	% change		% change	g/cm³	% change
Three exposures in gasifier off-gas of high-temperature reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char; ∿1250 °F, 900-1100 psi, exposure time for 1 and 2 not given, exposure >1355 hr.									
-% Al_2O_3 dense castable CA bond stolast G)	U			27.5		3.63		2.62	
	E1	hot face	-3.2	25.8	- 6.2	3.51	- 3.3	2.64	+ 0.8
		cold face		27.8	+ 1.1	3.58	- 1.4	2.58	- 1.5
	U	whole[l]		27.5		3.63		2.62	
	E2	whole	+0.5						
		hot face		28.2	+ 2.5	3.63	0	2.61	- 0.4
		cold face		27.5	0	3.60	- 0.8	2.61	- 0.4
Al_2O_3 dense castable, CA bond zzou Castable)	U	whole		25.1		3.00		2.25	
	E2	hot face	+0.4	22.6	-10.	2.99	- 0.3	2.31	+ 2.7
		cold face		23.0	- 8.4	2.99	- 0.3	2.30	+ 2.2
o specimens in exposure 2)									
		hot face	+0.7	22.2	-12.	2.97	- 1.0	2.31	+ 2.7
		cold face		22.8	- 9.2	2.98	- 0.7	2.30	+ 2.2
	U	whole[l]		25.1		3.00		2.25	
	E3	whole	+0.7						
		hot face		23.2	- 7.6	3.01	+ 0.3	2.31	+ 2.7
		cold face		24.0	- 4.4	3.03	+ 1.0	2.30	+ 2.2
Al_2O_3 dense castable, CA bond per Brikcast A) bricks)	U	whole[l]		24.8		2.87		2.17	
	E3	whole (1)	+1.1						
		whole (2)	+0.9						
		hot face (1)		20.5	-17.	2.62	- 8.7	2.22	+ 2.3
		hot face (2)		20.2	-19.	2.85	- 0.7	2.21	+ 1.8
		cold face (1)		21.9	-12.	2.83	- 1.4	2.21	+ 1.8
		cold face (2)		21.0	-15.	2.84	- 1.0	2.23	+ 2.2
Al_2O_3 light insulating castable, bond (Litecast 75-28)	U	whole[l]		37.9		2.36		1.51	
	E3	whole	-0.3						
		hot face		63.8	+68.	3.03	+28.	1.10	-27.
		cold face		62.2	+64.	3.04	+29.	1.15	-24.
Al_2O_3 (Mullite), vitreous bond h fired brick (Mul-8)	U	whole		17.2		3.05		2.53	
	E1	hot face	+0.3	20.2	+17.	3.09	+ 1.3	2.47	- 2.4
		cold face		19.1	+11.	3.08	+ 1.0	2.49	- 1.6
	U	whole		17.2		3.05		2.53	
	E2	hot face	+0.5	22.0	+28.	3.12	+ 2.3	2.43	- 4.0
		cold face		20.8	+21.	3.11	+ 2.0	2.46	- 2.8
	U	whole[l]		17.2		3.05		2.53	
	E3	whole	+0.3						
		hot face		20.5	+19.	3.09	+ 1.3	2.40	- 5.1
		cold face		18.2	+ 6	3.09	+ 1.3	2.51	- 0.8
Al_2O_3 phosphate bond, dense ed brick (Chemal 85 B)	U	whole		15.7		3.36		2.83	
	E1	hot face	0.0	17.6	+12.	3.46	+ 3.0	2.88	+ 1.8
		cold face		18.8	+20.	3.48	+ 3.6	2.83	0
	U	whole		15.7		3.36		2.83	
	E2	hot face	+0.8	18.2	+16.	3.45	+ 2.7	2.82	- 0.4
		cold face		16.4	+ 4.5	3.43	+ 2.1	2.87	+ 1.4
	U	whole[l]		15.7		3.36		2.83	
	E3	whole	+1.1						
		hot face		19.9	+27.	3.43	+ 2.1	2.74	- 3.2
		cold face		18.6	+18.	3.42	+ 1.8	2.70	- 4.6
% Al_2O_3 self-bonded dense ed brick (Kricor)	U	whole		16.7		3.54		2.95	
	E1	hot face	-0.7	17.5	+ 4.8	3.54	0	2.92	- 1.0
		cold face		15.1	- 9.6	3.50	- 1.1	2.97	+ 0.7
	U	whole		16.7		3.54		2.95	
	E2	hot face	-0.1	16.6	- 0.6	3.57	+ 0.8	2.97	+ 0.7
		cold face		17.5	+ 4.8	3.54	0	2.92	- 1.0
	U	whole[l]		16.7		3.54		2.95	
	E3	whole	+2.0						
		hot face		17.8	+ 6.6	3.54	0	2.91	- 1.4
		cold face		15.2	- 9.0	2.51	- 0.8	2.98	+ 1.0

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS [12] (Continued)

Material (Brand Name)	Exposure[d]	Brick[k] Portion	% Weight change	Apparent Porosity[a] %	Apparent Porosity[a] % change	Apparent Specific Gravity[a]	Apparent Specific Gravity[a] % change	Bulk Density[a] g/cm^3	Bulk Density[a] % chan
Three exposures in gasifier off-gas of high-temperature reactor (HYGAS) . . . . continued									
99+% Al_2O_3 self-bonded dense fired brick (H-W Corundum)	U	whole		19.0		3.74		3.03	
	E1	hot face	+0.3	19.0	0	3.77	+ 0.8	3.06	+ 1.0
		cold face		19.5	+ 2.6	3.76	+ 0.5	3.03	0
	U	whole		19.0		3.74		3.03	
	E2	hot face	+0.96	19.7	+ 3.7	3.78	+ 1.1	3.03	0
		cold face		20.9	+10.	3.81	+ 1.9	3.01	- 0.7
	U	whole[l]		19.0		3.74		3.03	
	E3	whole	-0.02						
		hot face		20.5	+ 7.9	3.77	+ 0.8	3.00	- 1.0
		cold face		21.4	+13.	3.78	+ 1.1	2.98	- 1.7
77% Al_2O_3 self-bonded light insulating fired brick (B&W Insalcor)	U	whole		46.5		2.81		1.53	
	E1	hot face	-1.3	56.4	+21.	2.87	+ 2.1	1.26	-18.
		cold face		57.6	+24.	2.98	+ 6.0	1.27	-17.
98+% Al_2O_3 self-bonded light insulating fired brick (Alfrax B 101)	U	whole		60.7		3.74		1.47	
	E1	hot face	-0.15	57.7	- 4.9	3.72	- 0.5	1.57	+ 6.8
		cold face		56.7	- 6.6	3.61	- 3.5	1.56	+ 6.1
70% Al_2O_3 (Mullite) vitreous dense fired brick (Alumex 70-HD)	U	whole[l]		19.2		3.23		2.61	
	E3	whole	+0.7						
		hot face		19.1	- 0.5	3.24	+ 0.3	2.62	+ 0.4
		cold face		19.6	+ 2.1	3.27	+ 1.2	2.63	+ 0.8
60% Al_2O_3 tar-impregnated vitreous fired brick (Ufala TI)	U	whole[l]		0.2		2.70		2.69	
	E3	whole	-5.1						
		hot face		12.7	+6250	2.95	+ 9.3	2.58	- 4.1
		cold face		11.5	+5650	2.95	+ 9.3	2.61	- 3.0
45-50% Al_2O_3 high fired super duty brick (KX-99)	U	whole[l]		12.3		2.62		2.29	
	E3	whole	-0.9						
		hot face		21.1	+72.	2.72	+ 3.8	2.15	- 6.1
		cold face		14.4	+17.	2.66	+ 1.5	2.28	- 0.4
90% Al_2O_3 phosphate bond ramming mix (Brikram 90)	U	whole		16.3		3.52		2.95	
	E2	hot face	+0.6	17.3	+ 6.1	3.54	+ 0.6	2.93	- 0.7
		cold face		17.2	+ 5.5	3.53	+ 0.3	2.93	- 0.7
(two specimens in exposure 2)		hot face	+0.01	16.6	+ 1.8	3.56	+ 1.1	2.97	+ 0.7
		cold face		16.0	- 1.8	3.54	+ 0.6	2.98	+ 1.0
	U	whole[l]		16.3		3.52		2.95	
	E3	whole	+0.6						
		hot face		14.7	- 9.8	3.47	- 1.4	2.91	- 1.4
		cold face		21.9	+34.	3.64	+ 3.4	2.84	- 3.7
90+% Al_2O_3 dense castable, CA bond (Greencast-97)	U	whole		27.7		3.65		2.64	
	E2	hot face	-1.46	27.9	+ 0.7	3.66	+ 0.3	2.64	0
		cold face		27.4	- 1.1	3.67	+ 0.5	2.67	+ 1.1
70+% Al_2O_3 vitreous fired brick (Hi Lumite 70 D)	U	whole		24.3		3.14		2.34	
	E1	hot face	-0.03	27.1	+12.	3.27	+ 4.1	2.39	+ 2.1
		cold face		24.7	+ 1.6	3.24	+ 3.2	2.44	+ 4.
	U	whole		24.3		3.14		2.34	
	E2	hot face	-0.67	22.6	- 7.0	3.12	- 0.6	2.43	+ 3.
		cold face		20.8	-14.	3.11	- 1.0	2.46	+ 5.
85% Al_2O_3 phosphate bonded fired brick (Altex 85-B)	U	whole		12.0		3.36		2.96	
	E1	hot face	+0.09	15.3	+28.	3.48	+ 3.6	2.94	- 0.
		cold face		15.8	+32.	3.47	+ 3.3	2.93	- 1.
	U	whole		12.0		3.36		2.96	
	E2	hot face	+0.40	16.2	+35.	3.49	+ 3.9	2.92	- 1.
		cold face		15.1	+26.	3.49	+ 3.9	2.97	+ 0.
80+% Al_2O_3 phosphate bonded fired brick (Alumex P-8)	U	whole		13.8		3.32		2.86	
	E1	hot face	--	14.4	+ 4.3	3.23	- 2.7	2.76	- 3.
		cold face		16.3	+18.	3.33	+ 0.3	2.79	- 2.
	U	whole		13.8		3.32		2.86	
	E2	hot face	+0.18	18.3	+33.	3.38	+ 1.8	2.76	- 3.
		cold face		17.7	+28.	3.40	+ 2.4	2.72	- 4.

(Table Continued)

PHYSICAL PROPERTIES[a] OF REFRACTORIES[b] EXPOSED TO THE CONDITIONS[c] IN COAL GASIFICATION PILOT PLANTS[12] (Continued)

es

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t porosity, specific gravity and bulk density measured by liquid immersion method according to ASTM C20-46, using kerosine as the
ing medium; specimens were first evacuated 2 hr, kerosine introduced and the evacuation continued for 3 to 4 hr. Values are for
cimen.

pecimens were prepared by diamond saw sectioning of commercial refractories supplied by manufacturers. Castables were mixed with
of distilled water recommended by manufacturers, poured into 9 in straights in wooden molds, cured in 100% humidity for 48 hr, then
, fired to 1500 °F and cooled. All refractories were fired to 1500 °F for 4 hr in air before all testing both before and after
e. Sample sizes varied for different pilot plants: Synthane and Conoco, 4 x 2 x 1 in; Hygas, 9 x 2 1/2 x 4 1/2 in brick; Bi-Gas,
1 in; Battelle 1.6 x 1.6 x 1 in.

nditions to which the refractories were subjected were not specified. Time periods, when given, are only approximate.

xposed, E1 = first exposure, E2 = second exposure, etc.

= calcium aluminate bond.

in parentheses or values given on separate lines for same exposure are conflicting values for same data reported in different tables
set of reports.

ncreases in values seen for fused cast materials due to development of a network of hairline cracks caused by thermal shock.

ly disintegrated fragments were weighed together.

ns were refired to 2640°F for 4 hr before exposure.

eported is not consistent with the unexposed and exposed values but it is not possible to determine which of the three values is
.

amples, 9 x 2 1/2 x 4 1/2 in bricks, were placed so that the 2 1/2 x 4 1/2 in face was exposed to the gasifier conditions. Slices
t from each end, one in thick, for tests.

properties of all unexposed specimens evaluated in this exposure.

te: Footnote h should appear on SiC (Refrax 20) entries in the first
umn of the table on pages 3, 5, and 7.]

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE WEIGHT AND DIMENSIONS OF SAMPLES OF ALUMINA REFRACTORIES[b][39]

Treatment Conditions[a]							
Atmosphere	Temperature °F	Pressure psi	Time[c]	Weight Change, %/Dimensional Change, %[d]			
DENSE HIGH ALUMINA CASTABLES							
				94% Al_2O_3[e]	93% Al_2O_3[f]	90-95% Al_2O_3[g]	90-95% Al_2O_3[h]
Air (dried)	230	ambient	24h	--	--	--	--
Air (fired)	500	ambient	18h	-3.1/-0.1	-2.9/-0.3	-2.3/nil	-3.0/-0.2
Air (fired)	1000	ambient	18h	-4.5/-0.1	-4.7/-0.4	-3.9/-0.1	-4.1/nil
CGA exposure	500	500	10d	-0.4/nil	-0.8/+0.2	+0.2/nil	+0.4/+0.2
	500	500	20d	-1.5/-0.2	-2.1/-0.4	-0.7/nil	-0.6/-0.3
	500	500	30d	-0.2/-0.2	-0.6/-0.4	nil/-0.3	+0.6/-0.3
CGA exposure	1000	1000	10d	-2.6/+0.2	-4.3/-0.4	-1.1/-0.3	+0.4/-0.1
	1000	1000	20d	-1.9/-0.3	-3.2/-0.6	-1.0/nil	-1.4/-0.1
	1000	1000	30d	-1.9/-0.4	-3.7/-1.1	-0.9/-0.2	-1.4/-0.3
CGA,H_2O saturated[i]	447	1000	30d	+0.1/+0.4	-1.6/-0.1	not tested	+2.0/-0.3
H_2O/CO, saturated	390	465	10d	-0.5/-0.1	-0.1/nil	+0.1/-0.2	-0.4/-0.1
H_2O/CO	500	465	10d	+0.3/-0.1	+1.5/-0.2	+0.3/-0.1	+0.6/nil
	1000	465	10d	-2.5/-0.2	-3.8/-0.4	-1.9/-0.1	-2.0/-0.1
CGA with H_2S	1000	1000	10d	-2.3/-0.1	-2.5/-0.3	-1.7/-0.1	-1.8/-0.1
DENSE HIGH ALUMINA CASTABLES (GENERIC PREPARATIONS)							
				93% Al_2O_3[j]	91% Al_2O_3[k]	91% Al_2O_3[l]	
Air (dried)	230	ambient	24h	--	--	--	
Air (fired)	500	ambient	18h	-3.2/-0.6	-4.3/-0.2	-3.0/-1.2	
Air (fired)	1000	ambient	18h	-5.0/-0.3	-5.0/-0.1	-4.0/-0.3	
CGA exposure	500	500	10d	-0.4/+0.1	nil/nil	+1.0/-0.2	
	500	500	20d	-1.6/-0.6	-1.8/nil	-1.4/-0.5	
	500	500	30d	-0.4/-0.3	-0.1/-0.2	+0.2/-0.4	
CGA exposure	1000	1000	10d	-2.5/-0.1	-3.7/-0.1	-5.0/-0.5	
	1000	1000	20d	-1.8/-0.4	-3.3/-0.4	-3.5/-1.0	
	1000	1000	30d	-2.0/-0.2	-3.6/-0.5	-3.8/-0.9	
CGA,H_2O saturated[i]	447	1000	30d	+0.2/+0.1		-1.7/+0.3	
H_2O/CO,H_2O saturated	390	465	10d	-0.2/-0.2	-1.4/-0.1	+0.7/-0.1	
H_2O/CO	500	465	10d	-0.2/-0.1	+0.7/-0.1	+2.5/-0.2	
	1000	465	10d	-2.6/-0.2	-4.8/-0.2	-4.8/-0.3	
CGA with H_2S	1000	1000	10d	-2.0/-0.2	-4.2/-0.2	-2.5/-0.2	
	1000	1000	20d	-2.2/-0.2	-4.2/-0.2		
	1000	1000	30d	-1.2/-0.2	-4.0/-0.2		
CGA with H_2S, H_2O saturated	447	1000	30d	+0.5/+0.3	-2.4/+0.3		
INTERMEDIATE-ALUMINA DENSE AND INSULATING CASTABLES							
				54-57% Al_2O_3[m]	57% Al_2O_3[n]	59% Al_2O_3[o]	54% Al_2O_3[p]
Air (dried)	230	ambient	24h	--	--	--	--
Air (fired)	500	ambient	18h	-3.0/nil	-3.2/-0.1	-3.4/nil	-2.1/-0.3
Air (fired)	1000	ambient	18h	-4.7/-0.2	-5.0/-0.2	-5.0/+0.1	-3.5/nil
CGA exposure	500	500	10d	-0.1/nil	-0.8/-0.1	-1.5/-0.1	-1.0/+0.3
	500	500	20d	-1.8/nil	-2.2/nil	-2.0/-0.4	-1.5/+0.1
	500	500	30d	-0.8/-0.3	-1.1/-0.3	-1.7/-0.1	-1.1/+0.2
CGA exposure	1000	1000	10d	-4.2/nil	-4.0/-0.1	-4.2/-0.2	-2.9/+0.1
	1000	1000	20d	-3.8/nil	-4.2/nil	-4.7/-0.1	-3.1/nil
	1000	1000	30d	-4.2/nil	-4.4/-0.1	-5.0/-0.2	-3.2/+0.1
CGA,H_2O saturated[i]	447	1000	30d	-4.2/+0.1	-5.2/nil	-5.0/nil	-1.9/-0.1
H_2O/CO,H_2O saturated	390	465	10d	-1.5/nil	-1.6/+0.1	-2.7/nil	-2.3/+0.3
H_2O/CO	500	465	10d	-1.6/nil	-0.1/+0.1	-2.1/nil	-1.3/+0.5
	1000	465	10d	-4.5/-0.2	-4.5/-0.1	-4.1/-0.2	-4.7/-0.2
CGA with H_2S	1000	1000	10d	-4.0/-0.1	-4.5/-0.2	-4.7/-0.2	-2.9/-0.1
	1000	1000	20d		-4.0/-0.2		-2.7/nil
	1000	1000	30d		-4.1/+0.1		-2.9/nil
CGA with H_2S, H_2O saturated	447	1000	30d		-2.7/+0.2		+1.4/+0.6

(Table Continued)

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE WEIGHT AND DIMENSIONS OF SAMPLES OF ALUMINA REFRACTORIES[b][39]
(continued)

Treatment Conditions[a]						
Atmosphere	Temperature °F	Pressure psi	Time[c]	Weight Change, %/Dimensional Change, %[d]		
PHOSPHATE-BONDED RAMMING MIXES						
				96% Al_2O_3[q]	96% Al_2O_3[r]	90% Al_2O_3[s]
Air (fired)	1000	ambient	18h	--	--	--
CGA exposure	500	500	10d	+0.1/-0.3	+0.2/-0.2	-1.1/nil
	500	500	20d	+0.1/-0.1	nil/nil	-0.1/-0.1
	500	500	30d	nil/nil	+0.1/nil	-0.1/nil
CGA exposure	1000	1000	10d	-0.1/nil	+0.4/nil	-0.7/-0.1
	1000	1000	20d	-0.2/nil	-0.1/nil	-0.3/-0.1
	1000	1000	30d	-0.1/nil	+0.2/nil	-0.1/nil
CGA,H_2O saturated[i]	447	1000	30d	+0.2/+0.2	+1.0/+0.1	-3.3/nil
H_2O/CO,H_2O saturated	390	465	10d	-1.0/-0.1	-0.4/-0.1	-2.5/-0.1
H_2O	500	465	10d	+0.1/nil	+0.1/-0.1	+0.1/-0.2
	1000	465	10d	-0.3/-0.1	nil/-0.1	-0.6/nil
CGA with H_2S	1000	1000	10d	-0.3/-0.1	-0.2/nil	-0.4/nil
	1000	1000	20d	-0.3/+0.2		
	1000	1000	30d	-0.3/+0.2		
CGA with H_2S, H_2O saturated	447	1000	30d	+2.0/+0.3		

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[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18CO, $12CO_2$, $24H_2$, $41H_2O$, and $5CH_4$, another CGA with 40 percent H_2O and 1 percent H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (in vol %). Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours,

[b] All cement bonded castables were cast in molds either 12 x 3 x 1/2 in or 3 x 3/4 x 3/4 in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12 x 3 x 1/2 in slabs were then cut to 3 x 1/2 x 1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3 x 3/4 x 3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[c] Time units are given, either h for hours or d for days.

[d] Data are the averages for seven specimens except where noted. Change in weight or dimension is with as-dried value as initial value; + indicates increase, - indicates decrease.

[e] 94% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Greencast-94, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[f] 93% alumina dense castable, calcium aluminate (72% alumina, 25% calcia) bonded (B&W Kao-Tab 93, Babcock & Wilcox; C-3 cement, Babcock & Wilcox).

[g] 90-95% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Castolast G, Harbison-Walker; CA-25 Calcium Aluminate Cement, Alcoa).

[h] 90-95% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Purotab, Kaiser Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[i] Data for two specimens only.

[j] 93% alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

[k] 91% alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[l] 91% alumina dense castable, UMR-3 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; C-3, a 72% alumina-25% calcia cement, Lone Star Lafarge).

[m] 54-57% alumina, 34-37% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (Lo-Abrade, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[n] 57% alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[o] 59% alumina, 33% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Kast-O-Lite 30, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[p] 54% alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[q] 96% alumina dense phosphate-bonded ramming mix (Greenpak-90P, A. P. Green).

[r] 96% alumina dense phosphate-bonded ramming mix (90 Ram H.S., G-E Refractories).

[s] 90% alumina dense phosphate-bonded ramming mix (Brikram 90R, General Refractories).

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE DENSITY AND POROSITY OF VARIOUS ALUMINA REFRACTORIES[b][39]

Treatment Conditions[a]							
Atmosphere	Temperature °F	Pressure psi	Time[c]	Density (g/cc)/Apparent Porosity (%)[d]			
DENSE HIGH ALUMINA CASTABLES							
				94% Al_2O_3[e]	93% Al_2O_3[f]	90-95% Al_2O_3[g]	90-95% Al_2O_3[h]
Air (dried)	230	ambient	24h	2.77/14	2.62/19	2.85/14	2.88/14
Air (fired)	500	ambient	18h	2.75/20	2.56/25	2.81/17	2.84/17
Air (fired)	1000	ambient	18h	2.67/25	2.59/28	2.74/20	2.78/22
CGA exposure	500	500	10d	2.81/19	2.59/25	2.87/19	2.87/19
	500	500	20d	2.78/21	2.59/26	2.85/19	2.88/20
	500	500	30d	2.81/20	2.63/24	2.88/19	2.90/18
CGA exposure	1000	1000	10d	2.77/24	2.57/28	2.85/21	2.87/21
	1000	1000	20d	2.75/24	2.58/28	2.85/21	2.85/22
	1000	1000	30d	2.75/24	2.57/28	2.85/21	2.87/21
CGA,H_2O saturated[i]	447	1000	30d	2.79/13	2.53/29		2.94/6
H_2O/CO,H_2O saturated	390	465	10d	2.78/5	2.54/27	2.87/4	/4
H_2O/CO	500	465	10d		2.67/23	2.89/17	/18
	1000	465	10d	2.83/20	2.56/27	2.84/21	/21
DENSE HIGH ALUMINA ASTABLES (GENERIC PREPARATIONS)							
				93% Al_2O_3[j]	91% Al_2O_3[k]	91% Al_2O_3[l]	
Air (dried)	230	ambient	24h	2.75/16	2.66/16	2.47/23	
Air (fired)	500	ambient	18h	2.71/20	2.58/24	2.45/25	
Air (fired)	1000	ambient	18h	2.68/23	2.52/28	2.35/31	
CGA exposure	500	500	10d	2.74/23	2.70/22	2.50/27	
	500	500	20d	2.76/22	2.62/23	2.47/29	
	500	500	30d	2.75/21	2.68/22	2.52/27	
CGA exposure	1000	1000	10d	2.73/24	2.61/26	2.46/31	
	1000	1000	20d	2.74/24	2.60/27	2.44/31	
	1000	1000	30d	2.73/26	2.59/27	2.44/32	
CGA,H_2O saturated[i]	447	1000	30d	2.75/11		2.44/28	
H_2O/CO,H_2O saturated	390	465	10d	2.72/5	2.61/7		
H_2O/CO	500	465	10d	2.74/22	2.70/21		
	1000	465	10d	2.73/24	2.58/26		
CGA with H_2S	1000	1000	10d	2.70/26	2.59/27		
	1000	1000	20d	2.76/24	2.61/26		
	1000	1000	30d	2.78/23	2.60/27		
CGA with H_2S, H_2O saturated	447	1000	30d	2.73/15	2.58/18		
INTERMEDIATE-ALUMINA DENSE AND INSULATING CASTABLES							
				54-57% Al_2O_3[m]	57% Al_2O_3[n]	59% Al_2O_3[o]	54% Al_2O_3[p]
Air (dried)	230	ambient	24h	2.33/13	2.31/16	1.53/43	1.58/39
Air (fired)	500	ambient	18h	2.29/17	2.27/19	1.52/46	1.55/41
Air (fired)	1000	ambient	18h	2.26/20	2.21/23	1.46/49	1.54/42
CGA exposure	500	500	10d	2.32/18	2.30/19	1.50/48	1.55/45
	500	500	20d	2.30/19	2.28/21	1.50/49	1.51/44
	500	500	30d	2.32/18	2.30/20	1.50/48	1.52/44
CGA exposure	1000	1000	10d	2.26/21	2.24/22	1.48/52	1.53/50
	1000	1000	20d	2.27/20	2.25/22	1.48/52	1.53/51
	1000	1000	30d	2.25/21	2.25/22	1.49/52	1.53/52
CGA,H_2O saturated[i]	447	1000	30d	2.24/12	2.15/22	1.45/54	1.54/52
H_2O/CO,H_2O saturated	390	465	10d	2.24/18	2.31/11	1.47/51	1.52/48
H_2O/CO	500	465	10d	2.32/19	2.34/17	1.51/49	1.55/45
	1000	465	10d	2.27/20	2.24/23	1.49/51	1.54/47
CGA with H_2S	1000	1000	10d		2.24/22		1.54/51
	1000	1000	20d		2.25/22		1.54/51
	1000	1000	30d		2.24/22		1.54/51
CGA with H_2S, H_2O saturated	447	1000	30d		2.26/17		1.59/45

(Table Continued)

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE DENSITY AND POROSITY OF VARIOUS ALUMINA REFRACTORIES[b][39]
(continued)

Treatment Conditions[a]				Density (g/cc)/Apparent Porosity (%)[d]		
Atmosphere	Temperature °F	Pressure psi	Time[c]			
PHOSPHATE-BONDED RAMMING MIXES						
				96% Al_2O_3[q]	96% Al_2O_3[r]	90% Al_2O_3[s]
Air (fired)	1000	ambient	18h	2.95/17	2.92/20	2.96/17
CGA exposure	500	500	10d	2.91/19	2.90/20	2.90/20
	500	500	20d	2.97/18	2.94/20	2.95/18
	500	500	30d	2.97/18	2.94/20	2.94/18
CGA exposure	1000	1000	10d	2.90/18	2.91/18	2.94/16
	1000	1000	20d	2.94/18	2.94/19	3.00/15
	1000	1000	30d	2.95/18	2.96/19	3.00/16
CGA,H_2O saturated[i]	447	1000	30d	2.96/21	2.94/21	2.93/21
H_2O/CO,H_2O saturated	390	465	10d	2.87/21	2.89/21	3.02/17
H_2O/CO	500	465	10d	2.87/26	2.94/20	3.08/14
	1000	465	10d	2.90/19	2.90/20	3.04/15
CGA with H_2S	1000	1000	10d	2.87/20		
	1000	1000	20d	2.88/20		
	1000	1000	30d	2.87/20		
CGA with H_2S, H_2O saturated	447	1000	30d	2.90/21		

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[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18 CO, $12CO_2$, $24H_2$, $41H_2O$, and $5CH_4$, another CGA with 40% H_2O and 1% H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (vol %). Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] All cement bonded castables were cast in molds either 12 x 3 x 1/2 in or 3 x 3/4 x 3/4 in, cured 24 hours in air at 100 percent humidity at ambient temperature, and dried at 230 °F for 24 hours. The 12 x 3 x 1/2 in slabs were then cut to 3 x 1/2 x 1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3 x 3/4 x 3/4 in molds, immediately drying for 24 hours at 230 °F and then firing at 1000 °F for 18 hours. All specimens were stored at 230 °F until tested.

[c] Time units are given, either h for hours or d for days.

[d] Data are the average for seven specimens except where noted.

[e] 94% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Greencast-94, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[f] 93% alumina dense castable, calcium aluminate (72% alumina, 25% calcia) bonded (B&W Kao-Tab 93, Babcock & Wilcox; C-3 cement, Babcock & Wilcox).

[g] 90-95% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Castolast G, Harbison-Walker; CA-25 Calcium Aluminate Cement, Alcoa).

[h] 90-95% alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Purotab, Kaiser Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[i] Data are for two specimens only.

[j] 93% alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

[k] 91% alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[l] 91% alumina dense castable, UMR-3 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; C-3, a 72% alumina-25% calcia cement, Lone Star Lafarge).

[m] 54-57% alumina, 34-37% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (Lo-Abrade, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[n] 57% alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[o] 59% alumina, 33% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Kast-O-Lite 30, A. P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[p] 54% alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[q] 96% alumina dense phosphate-bonded ramming mix (Greenpak-90P, A. P. Green).

[r] 96% alumina dense phosphate-bonded ramming mix (90 Ram H.S., G-E Refractories).

[s] 90% alumina dense phosphate-bonded ramming mix (Brikram 90R, General Refractories).

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE WEIGHT AND DIMENSIONS OF SAMPLES OF CALCIUM ALUMINATE CEMENTS[39]

Treatment Conditions[a]				Initially Dry[b]	Hydrated[b]	
Atmosphere	Temperature °F	Pressure psi	Time[c]	Weight Change,[d] %	Weight Change,[d] %	Dimensional Change,[d] %
			79% ALUMINA, 18% CALCIA CEMENT[e]			
Air (dried)	230	ambient	24h	--	--	--
CGA exposure	500	500	10d	+16.5		
	500	500	20d	+ 8.8	nil	-4.3
	500	500	30d	+16.0		
CGA exposure	1000	1000	10d	+12.5	-2.2	+0.6
	1000	1000	20d	+11.3	-1.1	-1.3
	1000	1000	30d	+13.0	-1.6	-0.3
CGA,H_2O saturated[f]	447	1000	30d	+18.3	+2.0	+0.7
H_2O/CO,H_2O saturated	390	465	10d	+ 9.5	+5.4	-0.6
H_2O/CO	500	465	10d	+20.3	+7.3	+1.1
	1000	465	10d	+ 5.9	-2.3	-0.9
CGA with H_2S	1000	1000	10d	+12.6	-4.0	-1.2
			72% ALUMINA, 26% CALCIA CEMENT[g]			
Air (dried)	230	ambient	24h	--	--	--
CGA exposure	500	500	10d	+16.3		
	500	500	20d	+ 5.2	+ 3.7	-0.6
	500	500	30d	+16.2		
CGA exposure	1000	1000	10d	+16.9	+ 2.4	+0.7
	1000	1000	20d	+19.9	- 1.8	-1.2
	1000	1000	30d	+18.0	+ 5.4	-0.3
CGA,H_2O saturated[f]	447	1000	30d	not tested	+ 5.5	+0.7
H_2O/CO,H_2O saturated	390	465	10d	+25.7	+ 6.7	+0.7
H_2O/CO	500	465	10d	+ 6.4	+13.5	+0.6
	1000	465	10d	+ 4.3	- 6.6	-1.7
CGA with H_2S	1000	1000	10d	+ 8.4	- 5.3	-1.5
			72% ALUMINA, 25% CALCIA CEMENT[h]			
Air (dried)	230	ambient	24h	--	--	--
CGA exposure	500	500	10d	+19.3		
	500	500	20d	+ 6.4	+ 4.8	-3.1
	500	500	30d	+19.5		
CGA exposure	1000	1000	10d	+11.7	- 6.3	+0.6
	1000	1000	20d	+13.8	- 2.3	-1.7
	1000	1000	30d	+11.8	- 2.9	-0.2
CGA,H_2O saturated[f]	447	1000	30d	+18.7	- 4.2	+2.0
H_2O/CO,H_2O saturated	390	465	10d	+ 2.3	+10.3	+2.4
H_2O/CO	500	465	10d	+31.1	+16.5	nil
	1000	465	10d	- 0.7	- 5.5	-1.0
CGA with H_2O	1000	1000	10d	+11.5	- 6.1	-1.5

(Table Continued)

EFFECT OF HEAT TREATMENT AND GASEOUS ENVIRONMENT[a] ON THE WEIGHT AND DIMENSIONS OF SAMPLES OF CALCIUM ALUMINATE CEMENTS[39]
(continued)

Treatment Conditions[a]					Hydrated[b]	
Atmosphere	Temperature °F	Pressure psi	Time[c]	Initially Dry[b] Weight Change,[d] %	Weight Change,[d] %	Dimensional Change,[d] %
. . . . 58% ALUMINA + TITANIA, 33% CALCIA CEMENT[i]						
Air (dried)	230	ambient	24h	--	--	--
CGA exposure	500	500	10d			
	500	500	20d	+ 7.6	+ 1.0	-0.6
	500	500	30d			
CGA exposure	1000	1000	10d	+12.8	- 5.0	-0.2
	1000	1000	20d	+17.0	- 4.7	-1.0
	1000	1000	30d	+12.1	+ 0.7	nil
CGA,H_2O saturated[f]	447	1000	30d		+ 4.3	+1.0
H_2O/CO,H_2O saturated	390	465	10d	+15.1	+ 2.4	+0.8
H_2O/CO	500	465	10d	+32.2	+10.6	+4.6
	1000	465	10d	- 1.9	- 7.1	-1.1
CGA with H_2S	1000	1000	10d		- 6.3	-1.2
. . . . 44% ALUMINA + TITANIA, 36% CALCIA CEMENT[j]						
Air (dried)	230	ambient	24h	--	--	--
CGA exposure	500	500	10d			
	500	500	20d	+ 7.1	+1.5	-0.8
	500	500	30d			
CGA exposure	1000	1000	10d		-2.3	-0.7
	1000	1000	20d	+13.8	-4.2	-1.3
	1000	1000	30d		-1.5	+0.5
CGA,H_2O saturated[f]	447	1000	30d		+1.8	+1.4
H_2O/CO,H_2O saturated	390	465	10d	+14.4	-3.0	+1.0
H_2O/CO	500	465	10d	+24.8	+4.9	-0.1
	1000	465	10d	- 0.5	-8.0	-2.0
CGA with H_2S	1000	1000	10d		-6.1	-1.5

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[a] Environments included a simulated coal gasification atmosphere (CGA) with an overall composition (in vol %) of 18 CO, $12CO_2$, $24H_2$, $41H_2O$, and $5CH_4$, another CGA with 40% H_2O and 1% H_2S, and a CO-steam atmosphere which is 47.5 H_2O and 52.5 CO (vol %). Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified above. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours.

[b] Cements were tested as initially dry powders and as neat cement specimens. Hydrated neat cement samples (water/cement ratio of ∿ 0.3) were cast as 1/2-in cubes, cured in air at 100% humidity for 24 hr, and dried at 230 °F for 24 hr. Samples were stored at 230 °F until tested.

[c] Time units are given, either h for hours or d for days.

[d] Data are for seven samples except where noted. Change in weight or dimension is with as-dried value as the initial value; + indicates increase, - indicates decrease. No data are given for the fired condition.

[e] 79% alumina, 18% calcia cement (CA-25 Calcium Aluminate Cement, Alcoa).

[f] Data for two samples only.

[g] 72% alumina, 26% calcia cement (Secar 71(250), Lone Star Lafarge).

[h] 71.5 to 72.5% alumina, 24 to 25% calcia cement (C-3, Babcock & Wilcox).

[i] 58% alumina + titania, 33% calcia cement (Refcon, Universal Atlas Cement).

[j] 44% alumina + titania, 36% calcia cement (Lumnite, Universal Atlas Cement).

EFFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE WEIGHT AND DIMENSIONS OF CASTABLE ALUMINA REFRACTORY SPECIMENS[c] [39]

Treatment Conditions[a]					Weight Change, %/Dimensional Change, %[e]			
					-DENSE CASTABLES-			
Environment		Temperature °F	Pressure psi	Time[d]	93% Alumina[f]	87% Alumina[g]	64% Alumina[h]	58% Alumina
Air (dried)		230	ambient	24 h	--/--	--/--	--/--	--/--
Air (fired)		500	ambient	18 h	-3.2/-0.6	-4.6/nil	-3.0/-0.1	-4.2/nil
Air (fired)		1000	ambient	18 h	-5.0/-0.3	-5.8/-0.1	-3.8/-0.1	-4.7/nil
Saturated steam	vapor	447	410	10 d	-0.2/+0.1	-0.7/+0.1	-1.8/+0.1	-0.8/+0.2
	liquid	447	410	10 d	+0.5/+0.2	-0.5/+0.3	-1.5/+0.4	-1.2/+0.3
CGA with H_2S, saturated	vapor	447	1000	44 d	+0.7/+0.5	+1.7/+0.5	-1.6/nil	nil/nil
	liquid	447	1000	44 d	+1.3/+0.1	nt/nt[o]	+0.1/nil	nt/nt[o]
CGA with H_2S, saturated[j]		465	1000	5 d	+0.4/+0.3	+2.3/nil	+0.5/+0.1	+2.1/nil
followed by firing in air[k]		1000	ambient	18 h	-2.7/+0.4	-1.3/nil	-2.1/-0.2	-1.1/-0.1
Cycling tests--repeat of preceding exposure followed by air firing								
1 cycle					-2.4/-0.1	-1.0/nil	-2.0/-0.3	-1.1/-0.1
2 cycles					-2.2/-0.1	-0.7/-0.1	-2.0/-0.2	-0.8/-0.1
3 cycles					-2.2/nil	-1.3/-0.2	-2.3/-0.1	-1.4/-0.1
4 cycles					-2.3/nil	-0.9/-0.2	-2.4/-0.1	-2.3/-0.2
5 cycles					-1.8/+0.2	-0.5/-0.1	-2.1/nil	-1.2/-0.1

Environment		Temperature °F	Pressure psi	Time[d]	54% Alumina[l]	47% Alumina[m]	35% Alumina[n]
Air (dried)		230	ambient	24 h	--/--	--/--	--/--
Air (fired)		500	ambient	18 h	-2.1/-0.3	-5.4/nil	-4.5/nil
Air (fired)		1000	ambient	18 h	-3.6/nil	-6.4/nil	-5.6/-0.4
Saturated steam	vapor	447	410	10 d	-1.6/+0.3	-1.6/+0.7	-4.6/+0.5
	liquid	447	410	10 d	-2.3/+0.5	-3.6/+0.2	-5.3/+0.7
CGA with H_2S, saturated	vapor	447	1000	44 d	+0.8/+0.4	-3.5/+0.2	-2.3/+0.7
	liquid	447	1000	44 d	+9.1/-0.3	nt/nt	+9.1/+0.1
CGA with H_2S, saturated[j]		465	1000	5 d	+0.2/+0.4	+1.2/+0.2	+0.3/nt
followed by firing in air[k]		1000	ambient	18 h	-1.6/nt	-3.4/nt	-4.8/nt
Cycling tests--repeat of preceding exposure followed by air firing							
1 cycle					-2.2/+0.4	-3.9/+0.1	-4.7/+1.0
2 cycles					-2.0/+0.4	-3.9/+0.2	-4.3/+1.0
3 cycles					-2.2/+0.1	-2.7/nil	-4.2/+0.5
4 cycles					-2.5/+0.1	-4.2/-0.1	-5.6/+0.4
5 cycles					-2.7/+0.3	-3.8/nil	-4.6/+0.1

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[a] Samples were exposed in a steam generator, both in vapor and in the liquid in the bottom of the vessel. Afte placement of samples, the vessel was heated to the desired steam pressure and where tests included other gase these were then added so as to obtain the desired overall concentrations. the overall composition of the coa gasification atmosphere (CGA) is (in vol %) 18 CO, 12 CO_2, 24 H_2, 40 H_2O, 5 CH_4, and 1 H_2S. A gaseous flow rate was maintained so as to provide one complete change in atmosphere every 24 hours. The vapor was 85% ste saturated in these tests.

[b] Other tests showed that boehmite formation occurred in steam-saturated atmospheres and resulted in very large increases in the flexural strength. These cycling tests were designed to investigate the effect of repetitiv formation and decomposition of boehmite on the properties of the refractories.

[c] After casting, specimens were cured 24 hours in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hours. Specimens were stored at 230 °F until tested.

[d] Time units are given, either h for hours or d for days.

[e] Values are averages for seven samples. Change in weight or dimension is with as-dried value as the initial value; + indicates increase, - indicates decrease.

[f] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

(Table Continued)

EFFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE WEIGHT AND DIMENSIONS OF CASTABLE ALUMINA REFRACTORY SPECIMENS[c][39], Continued

ootnotes continued

37.4% Alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Refcon, 58% alumina + titania-33% calcia, Universal Atlas Cement).

53.8% Alumina, 28.3% silica castable, UMR-8 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement) (Mulcoa 60 and Mulgrain M47, C-E Minerals; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

58.6% Alumina, 29.6% silica castable, UMR-5 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement) (Mulcoa 60 and Mulgrain M47, C-E Minerals; Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

35% steam saturated; this exposure is the one forming the first step in the cycling tests, forming boehmite.

The firing step, following the saturated CGA exposure, completed one cycle, decomposing the boehmite.

54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

34.5% Alumina, 52.5% silica insulating castable (VSL-50, A.P. Green).

nt = not tested.

EFFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE DENSITY AND POROSITY OF CASTABLE ALUMINA REFRACTORIES[c] [39]

Treatment Conditions[a]				Density(g/cc)/Porosity(%)[e]			
				-DENSE CASTABLES-			
Environment	Temperature °F	Pressure psi	Time[d]	93% Alumina[f]	87% Alumina[g]	64% Alumina[h]	58% Alumina
Air (dried)	230	ambient	24 h	2.74/ 7.1	2.62/18.6	2.47/12.0	2.41/13.5
Air (fired)	500	ambient	18 h	2.69/22.5	2.58/23.4	2.38/16.5	2.44/16.3
Air (fired)	1000	ambient	18 h	2.66/26.2	2.54/27.0	2.38/19.9	2.37/18.9
Saturated steam vapor	447	410	10 d	2.68/17.9	2.53/25.5	2.33/13.4	2.32/17.0
Saturated steam liquid	447	410	10 d	2.67/18.8	2.52/25.5	2.35/15.2	2.32/16.3
CGA with H_2S, saturated vapor	447	1000	44 d	2.69/10.3	2.64/ 3.8	2.41/10.2	2.33/12.4
CGA with H_2S, saturated liquid	447	1000	44 d	2.73/18.3	nt/nt[o]	2.41/10.3	nt/nt[o]
CGA with H_2S, saturated[j]	465	1000	5 d	2.68/20.3	2.67/13.1	2.44/11.7	2.45/12.4
followed by firing in air	1000	ambient	18 h	2.60/24.7	2.57/20.3	2.40/16.1	2.39/16.1
Cycling tests--repeat of preceding exposure followed by air firing							
1 cycle				2.69/25.7	2.59/24.8	2.42/18.3	2.38/17.9
2 cycles				2.69/25.3	2.62/24.5	2.41/19.0	2.38/17.9
3 cycles				2.70/25.7	2.62/24.5	2.42/17.6	2.37/17.7
4 cycles				2.68/26.2	2.63/24.4	2.42/18.9	2.38/17.9
5 cycles				2.69/25.1	2.62/24.6	2.43/19.4	2.39/17.7

				-INSULATING CASTABLES-		
Environment	Temperature °F	Pressure psi	Time[d]	54% Alumina[l]	47% Alumina[m]	35% Alumina[n]
Air (dried)	230	ambient	24 h	1.52/43.0	1.22/48.2	0.93/56.0
Air (fired)	500	ambient	18 h	1.53/44.8	1.16/52.8	0.90/61.8
Air (fired)	1000	ambient	18 h	1.53/45.9	1.13/54.4	0.90/62.9
Saturated steam vapor	447	410	10 d	1.45/52.5	1.13/57.8	0.86/67.1
Saturated steam liquid	447	410	10 d	1.47/52.6	1.11/59.8	0.85/63.9
CGA with H_2S, saturated vapor	447	1000	44 d	1.57/30.9	1.20/56.5	0.97/63.7
CGA with H_2S, saturated liquid	447	1000	44 d	1.68/24.7	nt/nt	1.13/57.7
CGA with H_2S, saturated[j]	465	1000	5 d	1.58/44.3	1.28/51.9	1.04/59.5
followed by firing in air	1000	ambient	18 h	1.55/46.7	1.24/53.9	0.95/64.5
Cycling tests--repeat of preceding exposure followed by air firing						
1 cycle				1.56/48.5	1.21/56.4	0.97/64.3
2 cycles				1.55/48.0	1.21/55.7	0.96/64.5
3 cycles				1.56/48.1	1.22/54.1	0.98/62.7
4 cycles				1.56/49.3	1.24/56.0	0.98/63.8
5 cycles				1.52/51.0	1.23/56.9	0.97/63.7

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[a] Samples were exposed in a steam generator, both in vapor and in the liquid in the bottom of the vessel. After placement of samples, the vessel was heated to the desired steam pressure and where tests included other gases these were then added so as to obtain the desired overall concentrations. The overall composition of the coal gasification atmosphere (CGA) is (in vol%) 18 CO, 12 CO_2, 24 H_2, 20 H_2O, 5 CH_4, and 1 H_2S. A gaseous flow rat was maintained so as to provide one complete change in atmosphere every 24 hours. The vapor was 85% steam saturated in these tests.

[b] Other tests showed that boehmite formation occurred in steam-saturated atmospheres and resulted in very large - creases in the flexural strength. These cycling tests were designed to investigate the effect of repetitive f- mation and decomposition of boehmite on the properties of the refractories.

[c] After casting, specimens were cured 24 hours in air at 100% humidity at ambient temperature, and dried at 230 for 24 hr. Specimens were stored at 230 °F until tested.

[d] Time units are given, h for hours and d for days.

[e] Values are averages for seven samples.

[f] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Ta ular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

(Table Continued)

FFECT OF SATURATED VAPOR AND LIQUID AND EXPOSURE[a] TO PRESSURE-TEMPERATURE CYCLING CAUSING BOEHMITE FORMATION AND DECOMPOSITION[b] ON THE DENSITY AND POROSITY OF CASTABLE ALUMINA REFRACTORIES[c][39], Continued

otnotes continued

37.4% Alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Refcon, 58% alumina + titania-33% calcia, Universal Atlas Cement).

53.8% Alumina, 28.3% silica castable, UMR-8 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement) (Mulcoa 60 and Mulgrain M47, C-E Minerals; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

58.6% Alumina, 29.6% silica castable, UMR-5 generic preparation (75% calcined kaolin aggregate + 25% calcium aluminate cement) (Mulcoa 60 and Mulgrain M47, C-E Minerals; Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

35% Steam saturated; this exposure is the one forming the first step in the cycling tests, forming boehmite.

The firing step, following the saturated CGA exposure, completed one cycle, decomposing the boehmite.

54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75, C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

34.5% Alumina, 52.5% silica insulating castable (VSL-50, A.P. Green).

nt = not tested.

EFFECT OF EXPOSURE[a] TO CARBON-MONOXIDE/STEAM IN SATURATED VAPOR OR LIQUID ON THE DENSITY AND POROSITY OF VARIOUS ALUMINA REFRACTORIES[b] [39]

Refractory[b]	$CO/H_2O=0.1$ (532°F)		$CO/H_2O=1.0$ (466°F)		$CO/H_2O=3.0$ (400°F)	
	Density[c] gm/cc	Porosity[c] %	Density[c] gm/cc	Porosity[c] %	Density[c] gm/cc	Porosity[c] %
DENSE HIGH-ALUMINA CASTABLES						
93% Alumina[d]	2.76 (2.77)	13 (13)	2.64 (2.67)	26 (20)	2.69 (2.53)	22 (26)
91% Alumina[e]	2.65 (2.63)	15 (14)	2.51 (2.55)	22 (22)	2.61 (2.38)	22 (33)
87% Alumina[f]	2.60 (2.66)	19 (17)	2.52 (2.59)	26 (22)	2.58 (2.46)	23 (28)
88% Alumina[g]	Not Tested		2.60 (2.53)	23 (18)	2.65 (2.56)	8 (24)
84% Alumina[h]	Not Tested		2.53 (2.62)	18 (20)	2.54 (2.51)	6 (22)
DENSE INTERMEDIATE-ALUMINA CASTABLES						
57% Alumina, 34% silica[i]	2.26 (2.29)	17 (16)	2.32 (2.26)	18 (20)	2.29 (2.15)	9 (22)
50% Alumina, 38% silica[j]	2.39 (2.41)	16 (14)	2.38 (2.38)	17 (16)	2.46 (2.33)	13 (18)
INSULATING CASTABLES						
54% Alumina, 40% silica[k]	1.51 (1.51)	52 (52)	1.57 (1.68)	51 (35)	1.53 (1.51)	51 (52)
46% Alumina, 40% silica[l]	1.19 (1.31)	56 (51)	1.24 (1.33)	57 (45)	1.22 (1.14)	56 (60)
35% Alumina, 53% silica[m]	0.86 (0.93)	68 (64)	0.84 (0.90)	70 (67)	0.89 (0.87)	67 (69)
PHOSPHATE-BONDED RAMMING MIX						
96% Alumina[n]	2.84 (2.84)	23 (22)	2.87 (2.97)	21 (19)	2.84 (2.88)	22 (22)

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[a] Samples were exposed in a steam generator to provide saturated vapor conditions. After placing samples, the vessel was heated to the desired steam pressure and the other gas was then added so as to obtain the concentrations specified in the table. A gaseous flow rate was maintained so as to provide one complete change in atmosphere every 24 hours. The specimens were exposed at the temperatures specified in the table at 1000 psia for 20 days.

[b] All cement bonded castables were cast in molds either 12 x 3 x 1/2 in for 3 x 3/4 x 3/4 in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12 x 3 x 0.5 in slabs were then cut to 3 x 1/2 x 1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3 x 3/4 x 3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[c] Numbers without parentheses are for samples exposed to saturated vapor, average of seven samples. Adjacent numbers in parentheses are for samples immersed in liquid (water) under the same exposure conditions, average of two samples.

[d] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

[e] 91% Alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement)(Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[f] 87.4% alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Refcon, 58% alumina + titania -33% calcia, Universal Atlas Cement).

[g] 88% alumina dense castable, UMR-6 generic preparation (generic preparation UMR-1 with 5% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[h] 84% Alumina dense castable, UMR-7 generic preparation (generic preparation UMR-1 with 10% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[i] 57% Alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[j] 50.4% Alumina, 38.4% silica castable, UMR-5 generic preparation (75% Mulcoa + Mulgrain M-60, C-E Minerals; 25% Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

[k] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75; C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[l] 46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

[m] 34.5% Alumina, 52.5% silica insulating castable (VSL-50, A. P. Green).

[n] 96% Alumina dense phosphate-bonded ramming mix (Greenpak-90P, A. P. Green).

EFFECT OF CARBON MONOXIDE-STEAM AND HYDROGEN SULFIDE EXPOSURE[a] ON THE WEIGHT OF VARIOUS ALUMINA REFRACTORIES[b][39]

	Weight Change,[c] %					
	$CO/H_2O=0.1$ + 1 Vol% H_2S		$CO/H_2O=1.0$ + 1 Vol% H_2S		$CO/H_2O=3.0$ + 1 Vol% H_2S	
Refractory[b]	1000°F Unsaturated	532°F Saturated[d]	1000°F Unsaturated	466°F Saturated[d]	1000°F Unsaturated	400°F Saturated[d]
DENSE HIGH-ALUMINA CASTABLES						
93% Alumina[e]	-2.1	+1.9 (+4.1)	-2.3	-2.9 (-2.2)	-2.0	-1.0 (-5.5)
91% Alumina[f]	-3.6	+2.4 (+1.4)	-3.8	+0.7 (-3.9)	-4.0	+1.7 (-9.5)
87% Alumina[g]	-2.4	+3.0 (+2.0)	-3.5	-0.3 (-1.4)	-3.3	+3.8 (-5.2)
88% Alumina[h]	Not Tested		-4.2	-3.2 (+0.7)	-3.4	-0.6 (-3.1)
84% Alumina[i]	Not Tested		-4.1	-0.9 (+0.6)	-3.6	-0.5 (-3.8)
DENSE INTERMEDIATE-ALUMINA CASTABLES						
57% Alumina, 35% silica[j]	-5.1	-2.8 (+1.6)	-3.8	-1.3 (-4.7)	-3.5	-0.3 (-5.3)
50% Alumina, 38% silica[k]	-5.0	-1.1 (-0.7)	-4.0	-0.4 (-3.1)	-2.7	+0.8 (-3.0)
INSULATING CASTABLES						
54% Alumina, 40% silica[l]	-3.2	-0.6 (+3.1)	-2.7	+0.5 (+5.5)	-2.6	-0.1 (-1.1)
46% Alumina, 40% silica[m]	-6.7	-1.6 (+5.5)	-6.2	+0.4 (+7.3)	-6.2	+1.4 (-4.6)
35% Alumina, 53% silica[n]	-7.0	-7.7 (-5.2)	-6.1	-6.2 (-4.6)	-6.5	-6.6 (-4.6)
PHOSPHATE-BONDED RAMMING MIX						
96% Alumina[o]	-0.2	-0.7 (+0.6)	-0.2	-0.4 (+3.2)	-0.2	-0.4 (+2.0)

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[a] Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and the other gases were then added so as to obtain the concentrations specified in the table. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. Tests specified as unsaturated occurred in this vessel. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours. The specimens were exposed at the temperatures specified in the table at 1000 psia for 20 days.

[b] All cement bonded castables were cast in molds either 12 x 3 x 1/2 in or 3 x 3/4 x 3/4 in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12 x 3 x 0.5 in slabs were then cut to 3 x 1/2 x 1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3 x 3/4 x 3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[c] Referenced to as-cast and dried (230 °F) weight. Data are average values for seven samples except for values in parentheses (see footnote d).

[d] Numbers without parentheses are for samples exposed to saturated vapor, average of seven samples. Adjacent numbers in parentheses are for samples immersed in liquid (water) under the same exposure conditions, average of two samples.

[e] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, 79% alumina-18% calcia, Alcoa).

[f] 91% Alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[g] 87.4% Alumina dense castable, UMR-4 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Refcon, 58% alumina + titania-33% calcia, Universal Atlas Cement).

[h] 88% Alumina dense castable, UMR-6 generic preparation (generic preparation UMR-1 with 5% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[i] 84% Alumina dense castable, UMR-7 generic preparation (generic preparation UMR-1 with 10% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[j] 57% Alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[k] 50.4% Alumina, 38.4% silica castable, UMR-5 generic preparation (75% Mulcoa + Mulgrain M-60, C-E Minerals; 25% Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

[l] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75; C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[m] 46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

[n] 34.5% Alumina, 52.5% silica insulating castable (VSL-50, A. P. Green).

[o] 95% Alumina dense phosphate-bonded ramming mix (Greenpak-90P, A. P. Green).

EFFECT OF EXPOSURE TO AN UNSATURATED AND STEAM-SATURATED SIMULATED COAL GASIFICATION ENVIRONMENT[a] ON THE WEIGHT, DENSITY, AND POROSITY OF VARIOUS ALUMINA REFRACTORIES[b][39]

Refractory[b]	Unsaturated (700 °F)			Saturated (447 °F)[c]		
	Wt. Change[d] %	Density gm/cc	Porosity %	Wt. Change[d] %	Density gm/cc	Porosity %
DENSE HIGH-ALUMINA CASTABLES						
94% Alumina[e]	-1.9	2.72	26	-1.4 (+4.5)	2.69 (2.72)	23 (18)
93% Alumina[f]	-1.9	2.71	27	+1.0 (+7.3)	2.72 (2.78)	21 (6)
91% Alumina[g]	-2.5	2.58	29	-1.5 (+4.4)	2.54 (2.60)	23 (24)
91% Alumina[h]	-0.6	2.44	31	-2.0 (+10.2)	2.35 (2.53	32 (24)
88% Alumina[i]	nt[k]	nt[k]	nt[k]	nt[k] (+4.2)	nt[k] (2.77)	nt[k] (16)
84% Alumina[j]	nt	nt	nt	nt (+6.0)	nt (2.72)	nt (14)
DENSE INTERMEDIATE-ALUMINA CASTABLES						
57% Alumina[l]	-2.3	2.32	20	-1.2 (+5.2)	2.28 (2.38)	19 (13)
50% Alumina[m]	nt	nt	nt	-2.2 (nt)	2.40 (nt)	17 (nt)
INSULATING CASTABLES						
54% Alumina, 40% silica[n]	-1.4	1.51	52	+1.2 (+19.6)	1.54 (1.78)	50 (37)
46% Alumina, 40% silica[o]	nt	nt	nt	-2.1 (nt)	1.19 (nt)	57 (nt)
PHOSPHATE-BONDED RAMMING MIXES						
96% Alumina[p]	nt	nt	nt	+1.3 (nt)	2.89 (nt)	21 (nt)
90% Alumina[q]	nt	nt	nt	-0.8 (nt)	2.84 (nt)	22 (nt)

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[a] Samples were exposed in two pressure vessels. One vessel was a steam generator and tests which specify saturated conditions occurred in this vessel. After placing samples, the vessel was heated to the desired steam pressure and other gases were then added so as to obtain the concentrations specified. The second vessel was connected to the steam generator and after samples were placed and the vessel heated to the test temperature, the vessel was pressurized with the steam/gas mixture from the steam generator. A gaseous flow rate for both vessels was maintained so as to provide one complete change in atmosphere every 24 hours. The simulated coal gasification atmosphere composition is (in vol%) 18 CO, 12 CO_2, 24 H_2, 40 H_2O and 1 H_2S. The samples were exposed at the temperatures indicated in the table at 1000 psia for 60 days.

[b] All cement bonded castables were cast in molds either 12x3x1/2 in or 3x3/4x3/4 in, cured 24 hr in air at 100% humidity at ambient temperature, and dried at 230 °F for 24 hr. The 12x3x0.5 in slabs were then cut to 3x1/2x1/2 in bars. Phosphate-bonded specimens were prepared by hand ramming in 3x3/4x3/4 in molds, immediately drying for 24 hr at 230 °F and then firing at 1000 °F for 18 hr. All specimens were stored at 230 °F until tested.

[c] Numbers without parentheses are for samples exposed to saturated vapor, average of seven samples. Adjacent numbers in parentheses are for samples immersed in liquid (water) under the same exposure conditions, average of two samples.

[d] Referenced to as-cast and dried (230 °F) weight.

[e] 94% Alumina dense castable, calcium aluminate (79% alumina, 18% calcia) bonded (Greencast-94, A.P. Green; CA-25 Calcium Aluminate Cement, Alcoa).

[f] 93% Alumina dense castable, UMR-1 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; CA-25 Calcium Aluminate Cement, Alcoa).

[g] 91% Alumina dense castable, UMR-2 generic preparation (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; Secar 71(250), a 72% alumina-26% calcia cement, Babcock & Wilcox).

[h] 91% Alumina dense castable, UMR-3 generic prepration (70% tabular alumina + 30% calcium aluminate cement) (Tabular Alumina T-61, Alcoa; C-3, a 72% alumina-25% calcia cement, Lone Star Lafarge)

[i] 88% Alumina dense castable, UMR-6 generic preparation (generic preparation UMR-1 with 5% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[j] 84% Alumina dense castable, UMR-7 generic preparation (generic preparation UMR-1 with 10% SiO_2 added as 99.9% pure, bone dry Wedron silica flour).

[k] nt represents samples not tested in that exposure condition.

[l] 57% Alumina, 34% silica castable, calcium aluminate (79% alumina, 18% calcia) bonded (RC-3, General Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[m] 50.4% Alumina, 38.4% silica castable, UMR-5 generic preparation (75% Mulcoa + Mulgrain M-60, C-E Minerals; 25% Refcon, a 58% alumina + titania-33% calcia cement, Universal Atlas Cement).

[n] 54% Alumina, 40% silica insulating castable, calcium aluminate (79% alumina, 18% calcia) bonded (Cer-Lite #75; C-E Refractories; CA-25 Calcium Aluminate Cement, Alcoa).

[o] 46.7% Alumina, 40.2% silica insulating castable (Litecast 60-25, General Refractories).

[p] 96% Alumina dense phosphate-bonded ramming mix (Greenpak-90P, A.P. Green).

[q] 90% Alumina dense phosphate-bonded ramming mix (Brikram 90R, General Refractories).

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Many entries refer to A sections, B sections, and then A sections again. This is not due to a reorganization of the alphabet. The first A and B references are to data listings which include the specific material and property. Any A references which follow a B reference indicate discussion sections in which one or more of the B sections are explicitly mentioned. Please note that this does not mean a specific material is discussed in that section, but only that that material is included in a data set which is referred to in that section.

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. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This book, Construction Materials for Coal Conversion--Performance and Properties Data, provides a central source of materials information needed for the fossil fuel industry. Data have been collected and evaluated from Department of Energy-sponsored projects. The focus is on construction materials for coal gasification use. The book is organized so that the information is given both with respect to the various component areas of a coal gasification plant and with respect to the properties or possible failure mechanisms, e.g., corrosion, erosion, mechanical properties, and physical properties.

. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

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National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NBS under the authority of the National Standard Data Act (Public Law 90-396).

NOTE: The principal publication outlet for the foregoing data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

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