Prepared for:
U.S. Department of Energy
Laramie Energy Technology Center

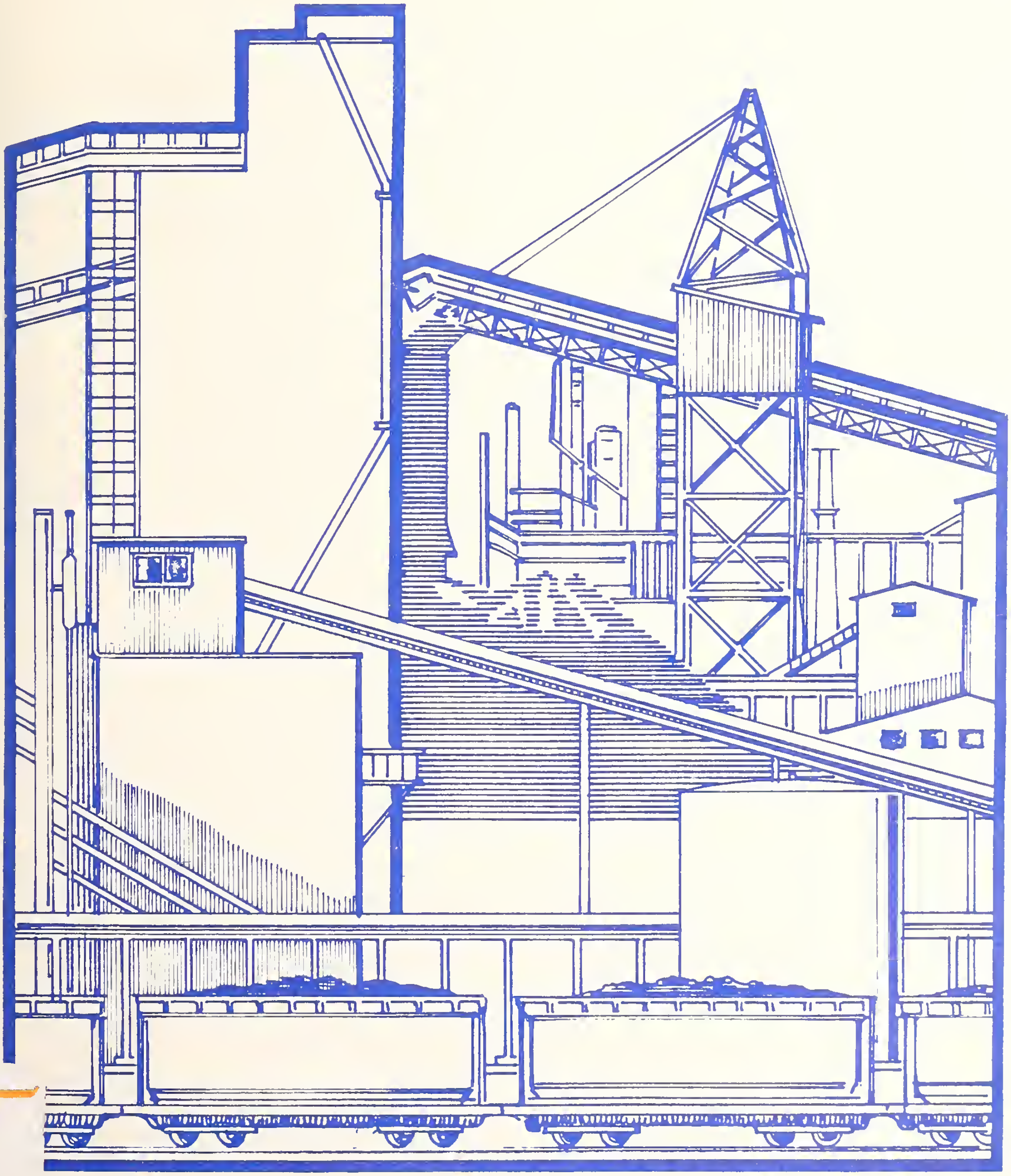
Prepared by:
U.S. Department of Commerce
National Bureau of Standards

NBS Special Publication 642, Suppl. 1

Construction Materials for Coal Conversion

Performance and Properties Data

Supplement 1



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Construction Materials for Coal Conversion

Performance and Properties Data

Supplement 1

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Issued December 1983

Library of Congress Catalog Card Number: 82-600610

National Bureau of Standards Special Publication 642, Suppl. 1
Natl. Bur. Stand. (U.S.), Spec. Publ. 642, Suppl.1, 774 pages (Dec. 1983)
CODEN: XNBSAV

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U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1983

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402

PREFACE TO SUPPLEMENT 1

Special Publication 642, published in 1982, was the first book issued in this set of publications. This 1983 publication, Supplement 1, contains revisions to SP 642 as well as many new pages of data, but is not a complete volume by itself. The pages of Supplement 1 are intended to be merged with the pages of SP 642 according to the instructions given below. The first book, SP 642, is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, stock number 003-003-02442-2, price $16.00 (add 25% for other than U.S. mailing).

For the 1982 publication, the cutoff dates for the data varied with each project reviewed since the reports on hand at the time the data were abstracted varied for each project. This 1983 Supplement brings the coverage of data for metals and alloys up-to-date through December 31, 1982. A projected second supplement (due in 1984) will bring the refractory data to a more current date. Since publication of SP 642, plans for the projected supplements changed with respect to the coverage and contents of the volumes. These changes are reflected in the revised Introduction and Tables of Contents.

The combined publications, SP 642 and Supplement 1, include data generated in about 70 projects carried out by approximately 40 organizations. Both books are bound so as to permit easy removal and insertion of pages and are three-hole punched to fit any standard ring binder. All pages in both books are dated so the most current version of updated pages can be identified easily. Pages in Supplement 1 carrying a 1981 or 1982 date are included in order to provide a complete recto and verso leaf to merge with the pages of SP 642 and have not been revised or changed in any way. A 1983 date on a page implies new or revised data have been printed.

In order to have a single volume containing the updated book sections simply substitute and add the Supplement I pages to the SP 642 pages according to the following:

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INTRODUCTION

Background

The nationwide program initiated in the 1970's by the U.S. Department of Energy and its predecessor agencies to foster development of a viable coal conversion industry featured a strong effort in materials testing and development. The data base for construction materials existing in the 1970's was inadequate for satisfactory materials selection for some component areas of advanced coal conversion plants, e.g., 1) valves and piping exposed to high-velocity, high-temperature streams of coal char and ash in turbulent flow, 2) metal components inside gasifier pressure vessels containing corrosive sulfide gases and operating at high temperatures and pressures, 3) vessels exposed to corrosive coal liquids and erosive slurries at high temperatures and pressures, and gas-quench waters at more moderate temperatures, and 4) pressure vessels larger than any in existence.

To expand the necessary data base, candidate materials were tested in controlled laboratory experiments, in coal gasification and liquefaction pilot plants and, in a few cases, in commercial coal-fired utility plants. About forty organizations including industrial, university, and government laboratories, and non-profit research institutions were involved in generating the materials properties and data reported in this compilation. Some materials evaluations were obtained from diagnostic failure analyses of actual plant components in about twenty pilot plants. About 500 alloys, including commercially available and developmental compositions and weld metals, were tested. The list of refractory materials tested contains over 200 commercially available and developmental refractories. To collect and disseminate the data generated by the DoE-sponsored materials testing and research projects, the NBS/DoE Fossil Energy Materials and Components Performance and Properties Data System was established.

Construction Materials for Coal Conversion--Performance and Properties Data, NBS Special Publication 642, a reference book for the fossil fuel industry, is a result of the combined effort of the two data centers which constituted 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 was 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 was the Materials Properties Data Center, established to collect, abstract, and disseminate construction materials properties and testing performance data. Emphasis was placed on the results of work by the materials research contractors to the Department of Energy.

Data compiled by the two data centers have been tabulated and summarized for inclusion in this book. At first, the book focused on coal gasification, that form of coal conversion for which there was the largest amount of available information in the library of the data centers. With this supplement, material in areas of interest such as coal liquefaction, and direct combustion have been added.

The looseleaf format is designed to permit data to be added and revised easily. The present cutoff date for each project reviewed since the 1982 publication is the contractors' reporting period ending December 31, 1982. 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. Although portions of this book are incomplete, it was felt that the data contained would be of sufficient interest and use to the fossil energy community to warrant publication.

Organization of the Book

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

A. Materials Considerations and Performance Data
B. Materials Testing and Research Results
C. References
D. Index

Part B contains summaries of performance and properties data generated by the DoE-sponsored research projects. Data are presented in graphical and/or tabular format with details of test conditions and procedures given in footnotes. Part A consists of discussions of the Part B data in the context of application to specific component areas of coal conversion plants. Part A also contains data and discussion on the performance of materials and components in actual pilot plant use.

Part A deals with materials needs and materials data for coal conversion 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 gasifiers, "dissolvers", devolatilizers, lockhoppers, etc.)
   - Pressure-Containing Shell
   - Refractory Linings and Components--Dry-Bottom Vessels
   - Refractory Linings and Components--Slagging Vessels
   - Metal Internal Components

3. Product 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

10. Direct Combustion Systems

Each component area title above is a heading for the following 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 are tables of data taken from the files of the Materials and Components Plant Performance Data Center, and from some contractors' reports, 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 Center files.

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.

The numerical data should be viewed with caution. In many tests the number of samples per material per test is few, often only one, so no statistical significance is attached 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 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 the sponsors of this compilation project.

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, 5 percent CH_4, 1 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.

Part B, "Materials Testing and Research Results", contains data from the Materials Properties Data Center files. 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. See Section B.0 for more information about the data in Part B.

Part C 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 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.

Part D is a materials index which permits the user to locate sections dealing with specific alloys or refractories.

ACKNOWLEDGMENT

The authors thank Larry P. Jackson and James Weber, presently of the University of Wyoming Research Corporation, formerly the Laramie Energy Technology Center of the Department of Energy, Laramie, Wyoming, for their support of this Supplement to Special Publication 642. Stanley J. Dapkunas, the Department of Energy/Office of Fossil Energy project monitor, and Wate T. Bakker, his predecessor, initiated the project and supported it through the completion of the first book, SP 642.

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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. A limited number of binders for this publication are available from Dr. H. M. Ondik, Materials Building, Room A229, National Bureau of Standards, Washington, DC 20234; telephone (301) 921-2900.

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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 and impact 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 wear of 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 and 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 the 300 series. Fortunately, operating temperatures in most coal handling situations do not usually exceed 250 °F, and most alloys are metallurgically stable below that temperature.

WEAR RESISTANCE of some steels can be estimated from measurements of hardness and impact strength from Charpy data. An approximate rule of thumb for estimating usefulness in this application is that if hardness is between 50-60 HRC 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, .63, and .113. 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 wear tests. 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, B.2.1.43, B.2.1.60 and B.2.1.61. The test methods used were pin-on-disc, and two- and three-body wear. For martensitic, bainitic, and matrix steels, modified ultra- high-strength steels, some experimental Cr-Si-Mo 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 tempering temperatures between 200-650 °C, wear resistance was found to be generally better at the higher tempering temperatures. Three-body wear ratios showed a 20% variation in the two experimental low-alloy steels listed in Section B.2.1.60. Precipitated carbides in an experimental low-alloy steel reduced the wear ratios in two- and three-body wear tests

(Section B.2.1.61). 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, at tempering temperatures 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.2.1.42). 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 (α+Fe_3C), 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 more to aspects of the test method 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 cobaltbase 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.1.5.1 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, 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 of gasification or liquefaction, may include slurrying, pressurizing of coal/slurry feeds, preheating of feed stock, etc. Major problem areas in gasification plants 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). The slurry feed streams (solvent, coal, and hydrogen-rich gas) of liquefaction plants are passed through preheaters which must resist not only erosion and corrosion of the tube walls but maintain a small temperature differential between the tube wall and the slurry bulk to reduce coking of the coal to a minimum. Many of these items are considered in separate sections of this book.

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A.2.1.1 OPERATING REQUIREMENTS

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

GASIFICATION

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. Feed lockhoppers will have to withstand the maximum pressures and pressure fluctuations, but temperatures in them should not exceed 800 °F (700 K) 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 materials problems associated with, or due to, chemical attack include reactions with chlorides, acidic condensates, hydrogen, and sulfur compounds which might penetrate 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.

LIQUEFACTION

Liquefaction reactors are normally made of welded alloy steels which will be exposed to reaction conditions. Maximum temperatures of 900 °F (755 K) and maximum pressures of 4000 psi can be expected in some processes. Potential problem areas are numerous. Hydrogen sulfide at partial pressures near 10^{-8} torr and oxygen at partial pressures of 10^{-15} torr can cause corrosion losses due to scaling of metal surfaces. Erosion-corrosion due to particulates of charcoal, char, and ash can accentuate the corrosion losses from exposed metal surfaces. Hydrogen in the reaction atmosphere can cause hydrogen-assisted cracking. Stress rupture and stress corrosion are possible problems. Temper embrittlement may occur. Thermal stresses may develop during start-up and shut-down. Localized creep may occur at hot spots. The extent and likelihood of occurrence of these potential problem areas has yet to be established.

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, 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. Steelmaking 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 in service 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. Eight pressure vessel steels were studied and are listed in Table A.2.1.2.2a. A number of developmental alloy steels, modifications of commercial steels, were also evaluated, Table A.2.1.2.2b. Results of the mechanical properties studied appear in Sections B.3.1.11, B.3.1.12, B.3.1.41-.50, B.3.1.64-.77, B.3.1.88, B.3.1.90-.93, B.3.1.98-.110, B.3.1.115-.161, B.3.1.171, and B.3.1.174-.186. Analysis of data in the literature on hydrogen attack of candidate pressure vessel steels appears in Reference [71]. Furthermore, the weldability and clad-ability of several candidate pressure vessel steels by various welding processes are discussed in References [72], [73], and [82].

The focus of these studies was principally on tensile properties, toughness, creep and stress rupture. Limited hardness, relaxation, crack growth, fatigue and environmental-fatigue data were reported. Some strength and toughness data on the properties of welds in some steels were reported. No data were obtained

PRESSURE VESSEL STEELS INVESTIGATED FOR GASIFIER AND REACTION PRESSURE VESSELS FOR COAL CONVERSION SYSTEMS

Steel [85]	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 A387-79b Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum (A387 Modified, also)	Grade 22-"2 1/4Cr-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.3.1.11, .12 [29] B.3.1.41, .43, .44, .46, .47, .50 [35] B.3.1.64, .71 [40] B.3.1.88, .89 [47] B.3.1.90-.93 [47, 50] B.3.1.98-.110 [55-58] B.3.1.115-.161 [35, 59-63, 74-79] B.3.1.171 [82, 83] B.3.1.180, .181, .184-.186 [81] B.1.1.147-.153 [55] B.1.1.177-.186 [61, 62]
		Class 2 Normalized & Tempered or Accelerated Cooled & Tempered	75 to 100	515 to 690	45 minimum	310 minimum	
ASTM A508-80a Quenched and Tempered Vacuum-Treated Carbon & Alloy Steel Forgings for Pressure Vessels	5 Strength Classes Specified 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 A533-80 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 A542-79 Pressure Vessel Plates, Alloy Steel, Quenched & Tempered, Chromium-Molybdenum	4 Strength Classes Specified 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.				

(Table Continued)

ASTM A543-79a Pressure Vessel Plates, Alloy Steel, Quenched & Tempered, Nickel-Chromium-Molybdenum	3 Strength Classes Specified 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, .127, .128 [35] B.3.1.68, .75 [40]
			*Strength range over all classes is tabulated.				
ASTM A204-79a Pressure Vessel Plates, Alloy Steel, Molybdenum	3 Strength Classes Specified C 0.28 max, Mn 0.98 max, P 0.035 max, S 0.040 max, Si 0.45 max, Mo 0.64 max	Plates 1.5 inches & under in thickness supplied in as-rolled condition Plates over 1.5 inches thick normalized	60 to 85	450 to 585	37 minimum	255 minimum	B.3.1.130, .132, .133 [35, 74]
ASTM A516-79b Pressure Vessel Plates, Carbon Steel, For Moderate and Lower-Temperature Service	Grade 70 C 0.31 max, Mn 1.30 max, P 0.035 max, S 0.040 max, Si 0.45 max	Plates 1.5 inches & under in thickness supplied in as-rolled condition (normalized when notch toughness tests required) Plates over 1.5 inches thick normalized	55 to 90	380 to 620	30 to 38 minimum	205 to 260 minimum	B.3.1.131, .134, .135 [35, 74]
ASTM A387-79b Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum	Grade 9-"9 Cr-1 Mo, Modified" C 0.15 max, Mn 0.66 max, P 0.030 max, S 0.030 max, Si 1.05 max, Cr 8 to 10.10, Mo 0.85 to 1.15, V 0.25, Ti 0.02, B 0.002	Class 1 Annealed	60 to 85	415 to 585	30 minimum	228 minimum	B.3.1.101-.110, .115-.118 [56, 57, 58]
		Class 2 Normalized & Tempered or Accelerated Cooled & Tempered	75 to 100	515 to 690	45 minimum	310 minimum	B.3.1.74 [40] B.3.1.180, .184, .185 [81] B.1.1.154-.156 [57]

Table A.2.1.2.2a

on performance of pressure vessel steels exposed to typical coal gasification atmospheres. Almost no thermal fatigue or creep fatigue data were reported. The amount of fracture mechanics data is very limited, and there is clearly a need to obtain more fracture mechanics data for toughness and fatigue. Very few data have been reported on the susceptibility of pressure vessel steels in coal conversion use to temper embrittlement or hydrogen embrittlement. Temper embrittlement is a diffusion problem that can occur at operating temperatures, whereas hydrogen embrittlement is a problem that is more likely to occur during cooldowns as a result of supersaturation. Some interesting preliminary results on methane bubble formation in 2 1/4 Cr-1 Mo steel exposed to hydrogen have been reported (Sections B.1.1.177-.186).

DEVELOPMENTAL PRESSURE VESSEL STEELS INVESTIGATED FOR GASIFIER AND REACTION PRESSURE VESSELS FOR COAL CONVERSION SYSTEMS

Base Steel [85]	Chemistry Highlights (Heat Analysis, wt %)	Heat Treatment	Section B Number and Reference
ASTM A533B	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] B.3.1.181, .183, [81] B.1.1.192 [40]
ASTM A542	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] B.1.1.192 [40]
ASTM A543	A543 base, plus: 0.005 B, 0.015 N individually	Quenched and Tempered (Some Embrittling Heat Treatments)	B.3.1.75 [40] B.3.1.179 [81]
Carbon steel	Carbon steel base (0.1 to 0.2% C, 0.5 Mn) plus: Cr, Mo, Mn, Ni, V, Al, W (in concentrations up to 3%) individually, or in various combinations	Quenched and Tempered	B.3.1.67, .76 [40] B.3.1.181 [81] B.3.1.174-.176, .182 [80] B.1.1.192 [40]
ASTM A387	Grade 21--"3Cr-1Mo" base plus 1Mn-1Ni	Quenched and Tempered	B.3.1.177 [81]

Table A.2.1.2.2b

LABORATORY STUDIES OF COMMERCIAL PRESSURE VESSEL STEELS were made on the following ASTM designations: A387-Grades 22 and 9, A508, A533-Type B, A542, A543, A204 and A516 (See Table A.2.1.2.2a). These 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 steels is described below.

A387-Grade 22: "2 1/4 Cr-1 Mo" and "Modified 2 1/4 Cr-1 Mo"--The mechanical properties of this steel have been studied extensively. Results were obtained on standard 2 1/4 Cr-1 Mo steel, and on a Ti-V-B modification, as well as other modifications with Mn, Ni, and Cr. Results were obtained on weldments as well as on base metal. Data are summarized in the B-sections listed in Table A.2.1.2.2a. Data in Sections B.3.1.74, B.3.1.147-.155, B.3.1.180, B.3.1.184, and B.3.1.185, refer to the modified version of A387-Grade 22.

STANDARD 2 1/4 Cr-1 Mo

Results of toughness tests appear in Sections B.3.1.44, .46, .50, .91, .98-.100, .140, .141, .159-.161, and B.3.1.171. Fatigue test results appear in Sections B.3.1.11, .12, .93, .119, .120 and .137-.139. Results of tensile tests appear in Sections B.3.1.41, .43, .47, .88, .90, .136, .142 and .143. Creep, stress relaxation and stress rupture test results appear in Sections B.3.1.92, .123, .124, .126, .137 and .138. Results of hardness measurements appear in Sections B.3.1.122, and .156-.158. A comparison of tensile and fatigue test results on parent metal and weldments appears in Section B.3.1.144. Results of some interesting experiments on methane bubble nucleation during exposure to hydrogen gas at elevated temperatures appear in Sections B.1.1.177-.186. Results of some crack growth experiments appear in Sections B.3.1.160-.161. Some aspects of weldability using the electroslag process are reported in Sections B.1.1.147-.153.

TOUGHNESS--Results of measurements on base metal appear in Section B.3.1.91. For normalized and tempered longitudinal test specimens in Charpy V-notch tests, the transition temperature* was about -40 °F and the upper shelf energy about 120 foot-pounds. Transverse specimens showed a higher transition temperature. Some further results of base metal measurements appear in Sections B.3.1.44, .46 and .50. Some of these results were obtained on base metal which was heat treated using special equipment which was designed to simulate the cooling rates which occur in commercial heat treating and in welding. 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 at 704 °C 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

*Unless otherwise specified in Part B sections, transition temperatures reported herein are estimated as the temperature corresponding to the midpoint between the upper and lower shelf energies appearing in the absorbed Charpy energy versus temperature relationships determined on standard size test specimens.

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$\sqrt{in}$, 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 the toughness of surface specimens was better than toughness of quarter-thickness specimens.

Results of measurements on actual weldments or on base metal given heat treatments to simulate welding heating cycles appear in Sections B.3.1.98-.100, .140, .141, .159, and .171. Effects of post weld heat treatment on Charpy V-notch toughness of electroslag weldments appear in Section B.3.1.98. Post weld heat treatments at 690 °C lowered the transition temperature and raised the upper shelf energy (Sections B.3.1.40-.41 and B.3.1.98-.99). The transition temperature was sensitive to flux chemistry and the upper shelf energy decreased significantly with increasing heat input (Section B.3.1.100). For both weak and strong directions, a simulated post weld heat treatment of 28 hours at 690 °C improved the Charpy impact energy (Section B.3.1.171). In a comparison of Charpy impact data (Section B.3.1.159), it was found that the base metal showed better toughness properties than did metal in the heat affected zone for both submerged arc and shielded metal arc processes. Results of some preliminary studies of crack growth during 28 to 50 hour exposures of five 2T compact specimens to H_2S resulted in three catastrophic failures and two relatively stable tests in which crack growth rates were in the neighborhood of 0.2-6 x 10^{-8} meters per second (Sections B.3.1.160-.161).

Electroslag weldments were evaluated for susceptibility to temper embrittlement, Section B.1.1.152. Good resistance to temper embrittlement resulted when Cr_2O_3 flux additions were 1% or greater and when MnO flux additions were 5% or less. Weld metal grain size tended to increase with increasing heat input.

FATIGUE--Results of measurements on base metal appear in Sections B.3.1.11, .12, .93, .119, .120, .138, .139, and .186. 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} meters per cycle for $20<\Delta K<70$ MPa-m$^{\frac{1}{2}}$. 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 $\Delta K \geq 50$ MPa-m$^{\frac{1}{2}}$. An increase in carbon monoxide pressure at fixed H_2S pressure caused a noteworthy decrease in crack growth rate for stress intensity factors in the range 20 to 70 MPa-m$^{\frac{1}{2}}$. Additional measurements on base metal appear in Section B.3.1.93, where da/dN ranged between 10^{-9} and 10^{-4}

inches per cycle for ΔK between 8 and 40 ksi$\sqrt{in}$ in hydrogen at ambient temperature. Increasing hydrogen pressure to 4000 psig resulted in significant increases in da/dN over the entire ΔK range (Section B.3.1.93). Exposure of a bainitic 2 1/4 Cr-1 Mo steel to 2000 psi hydrogen at 550 °C for 1000 hours did not have a strong effect on the da/dN vs. ΔK curve (Section B.3.1.186). Some S-N curves measured at 482 and 565 °C appear in Sections B.3.1.119-.120. For values of $\Delta\sigma$ between 400 and 875 MPa (55,000 and 124,000 psi), the cycles to failure generally ranged from 200 to 1000, depending on the nature of the fatigue loading. In some fatigue tests reporting $\Delta\varepsilon$ vs cycles to failure (Sections B.3.1.138-.139), the number of cycles to failure generally ranged from 10^3 to 10^5 for $\Delta\varepsilon$ ranging from 0.4 to 1.

TENSILE PROPERTIES--Results of tensile tests appear in Sections B.3.1.41, .43, .47, .88, .90, .136, .142 and .143. Data on response to heat treatment were obtained using specially designed equipment which simulated the cooling rates which occur in commercial heat treating and in welding. The temperature dependence of the tensile properties for normalized and tempered material appears in Section B.3.1.88. Between 100 and 1000 °F, the yield strength decreased from about 79 to 67 ksi, and the tensile strength decreased from about 95 to 88 ksi. In Section B.3.1.90, it is shown that the room temperature notched tensile strength for various environments is generally between 145 and 153 ksi and that the room temperature ductility is in the neighborhood of 18-24% reduction in area, in contrast to values of about 95 ksi and 75% from unnotched test specimens. The effects of various heat treatments on tensile properties are reported in Sections B.3.1.41, .43, .47, .136, .142 and .143. Increasing the austenitizing temperature from 1700 to 1900 °F has the favorable effect of improving yield and tensile strengths. Ductility seems unaffected by an increase in austenitizing temperature from 1700 to 1900 °F (Sections B.3.1.41, .43 and .47). The austenitizing temperature seems to have a stronger effect on tensile properties than do any post-quench heat treatments reported in Sections B.3.1.136, .142 and .143.

CREEP, STRESS RUPTURE, AND STRESS RELAXATION--Studies of deformation at elevated temperatures appear in Sections B.3.1.92, .121, .123, .124, .126, .137 and .138. A creep strain to failure of about 27% in a test lasting about 280 hours is reported in Section B.3.1.121 at a stress of 35.8 ksi (246.6 MPa) and a temperature of 1050 °F (565 °C). The effect on creep of exposure to hydrogen for up to 50 days (2000 psi/600 °C) is reported in Section B.3.1.124. Exposure to hydrogen tended to accelerate the accumulation of creep strain. For example, 4% creep strain resulted after 288 hours at 16 ksi and 600 °C for an unexposed specimen, whereas an exposed specimen tested under the same conditions accumulated 20% creep strain in about 48 hours. A creep strain of 20% was reported for a 600 hour exposure at 40 ksi and 482 °C for stress relieved material (Section B.3.1.138-Figure E). This same figure shows that stress reversals at intervals of 0.1 hours significantly accelerated the accumulation of creep strain. Creep fatigue results also appear in Section B.3.1.137. For a strain range of 0.35, the number of cycles to failure was slightly over 500,000, whereas for $\Delta\varepsilon = 2$, the number of cycles to failure ranged between 324 and 645. In Section B.3.1.123, it is shown that an oxidized surface can significantly accelerate the accumulation of creep strain at 538 °C and 35 ksi. Stress relaxation reported in Section B.3.1.92 caused a 12 to 28% decrease in stress during tests at 900 to 1000 °F for up to 340 hours. Some load relaxation data obtained at 550 °C appear in Section B.3.1.126. A stress rupture curve in

Section B.3.1.138-Figure B estimates a lifetime of 10^5 hours at 20 ksi and 482 °C. Other stress rupture data in Section B.3.1.124-Figure D show a lifetime of 5000 hours at 1100 °F and 30 ksi. These results also show a noticeable decrease in lifetime due to exposure to hydrogen at 1112 °F.

HARDNESS--Some hardness measurements of base metal and weldments are reported in Sections B.3.1.122 and B.3.1.156-.158. Results of hardness vs. tempering temperature in the range, 1000-1300 °F, showed that hardness decreased from an untempered maximum of HRC 25 to HRC 5 (estimated from Rockwell B-scale measurements) after tempering for 4 hours at 1275 °F (Section B.3.1.157-.158). Some preliminary results on submerged arc and shielded metal arc welds showed that heat affected zone hardness generally was greater than base metal hardness, e.g., 250 vs. 177 Knoop hardness numbers in the heat affected zone and base metal, respectively (Section B.3.1.156). Results of hardness measurements of 309 stainless steel cladding on 2 1/4 Cr-1 Mo base metal in Section B.3.1.122 show that the hardness of the welded zone is higher than that of the heat affected zone and the base metal. Heating the clad 2 1/4 Cr-1 Mo to 1000 °C led to a significant decrease in the hardness of all three regions.

ELECTROSLAG WELDMENTS were evaluated for chemical element distribution as affected by flux additions of Cr_2O_3 and MnO_2, separately or in combination (Sections B.1.1.147, B.1.1.149-.151). Effects of a fluoride flux were also reported (Section B.1.1.153). The concentrations of such elements as chromium, manganese, silicon, oxygen and nitrogen were reported as a function of distance from the starting tab over the first 300 mm. No evaluations of how chemical composition variations affected mechanical properties were reported.

Cr_2O_3 additions tended to depress the manganese and silicon concentrations, but to elevate the oxygen and chromium concentrations. MnO additions in combination with Cr_2O_3 did not have much effect on nitrogen content. MnO additions tended to raise manganese concentration, but to depress silicon concentrations. Continuous additions of Cr_2O_3 and of aluminum did not change chemical element distributions significantly. Fluoride fluxes tended to depress silicon concentrations more than oxide fluxes.

HYDROGEN ATTACK OF 2 1/4 Cr-1 Mo was evaluated (Sections B.1.1.145, .146, .155 and B.1.1.177-.186). Specimens were exposed to hydrogen at 750 to 4000 psi for 168 to 1000 hours at temperatures between 900-1100 °F. Some specimens were strained prior to exposure and others were under stress during exposure (Section B.1.1.145). The detection of bubbles in the scanning electron microscope was regarded as evidence of attack. Attack tended to occur with increasing exposure time and increasing hydrogen pressure, regardless of temperature and state of prestrain or stress. A Nelson diagram summarizing results for 350-hour exposures appears in Section B.1.1.146. In an evaluation of susceptibility to hydrogen attack after a standard gas tungsten arc welding procedure with five percent hydrogen in the shielding gas, it was found that a preheat temperature of about 400 °F tended to prevent cracking (Section B.1.1.155).

Grain boundary cavity formation resulting from hydrogen exposure is described in Sections B.1.1.177-.186. Increasing temperature between 550 and 600 °C and increasing applied stress tended to increase grain boundary cavity density at a hydrogen pressure of 2000 psi (Sections B.1.1.178, .179 and .181). An incubation time to initiate cavity formation of five to ten days was reported. Cavity growth rates tended to increase with applied stress, Section B.1.1.182.

Normalized and tempered materials showed a higher nucleation and cavity growth rate in the presence of an applied stress than did quenched and tempered material, Sections B.1.1.182-.184. In some cases, quenched and tempered material showed higher cavity densities than did normalized and tempered material, Section B.1.1.180. Cold work tended to increase the grain boundary cavity density, Section B.1.1.185. A modification of 2 1/4 Cr-1 Mo containing 0.21 vanadium and 0.0022 titanium developed fewer grain boundary cavities than did standard 2 1/4 Cr-1 Mo during exposure at 600 °C and 2000 psi hydrogen pressure, Section B.1.1.186. Analysis of carbides before and after exposure indicated that Fe_3C carbides were consumed by reaction with hydrogen, whereas five other types of carbide were unaffected, Section B.1.1.177. The types of carbides which form in chromium-molybdenum pressure vessel steels are discussed in Section B.1.1.187. The effect of cavities on elevated temperature mechanical properties of 2 1/4 Cr-1 Mo is discussed earlier in the section on creep, relaxation and stress rupture.

MODIFIED 2 1/4 Cr--1 Mo

Results of toughness tests appear in Sections B.3.1.74, B.3.1.147-.149 and B.3.1.184. Only a small amount of fatigue data (B.3.1.120 and B.3.1.155) have been reported. Tensile properties appear in Sections B.3.1.145, .146 and .150. Results of measurements of time-dependent deformation appear in Sections B.3.1.151, .154, .180, and .185. A "metallurgical damage factor" is discussed in Sections B.3.1.152 and .153. The damage factor, D, includes such features as strain accelerated softening of the metallurgical structure, microvoid formation, and particle coarsening. D values were calculated in References [76] and [77] from creep data using the instantaneous values of creep rate, creep strain, minimum creep rate, and the stress sensitivity of the creep rate. All data reported for 2 1/4 Cr-1 Mo are for base metal.

TOUGHNESS--Effects of heat treatment on Charpy V-notch properties appear in Sections B.3.1.147 and .148. A "quality" heat treatment described in Section B.3.1.147 more than doubled the upper shelf energy and lowered the transition temperature by more than 150 degrees. The effect of forging to different thickness reductions is reported in Section B.3.1.149. Forging to greater thickness reductions has a stronger effect on reducing the transition temperature than on the upper shelf energy. Exposure to hydrogen of five modifications of 2 1/4 Cr-1 Mo steel usually led to a notable increase in transition temperatures (Section B.3.1.184). After hydrogen exposure, a 0.5 Mn + 1 Ni modification showed a large drop in upper shelf energy, but the other modifications did not show very large decreases. Some alloy modifications of 2 1/4 Cr-1 Mo showed good resistance to temper embrittlement in some experiments intended to promote temper embrittlement.

FATIGUE--No fatigue data were reported. However, some creep-fatigue data appear in Section B.3.1.155. $\Delta\varepsilon$ vs. N behavior at 482 °C of modified and standard 2 1/4 Cr-1 Mo is comparable, although the data points for the modified steel fall below those for bainitic standard steel, Figure A. The S-N curve at 482 °C for the modified steel falls between S-N curves for standard 2 1/4 Cr-1 Mo steel in the normalized and tempered and quenched and tempered conditions, Figure B.

TENSILE PROPERTIES--Effects of heat treatment on tensile properties appear in Sections B.3.1.145, and .146. Post-quench heat treatments reduced yield and tensile strengths and increased total elongation. As-quenched yield and tensile strengths were in the neighborhood of 120 and 160 ksi (828 and 1100 MPa). Subsequent to heat treatment, these values dropped to the neighborhood of 70 and 85 ksi (479 and 590 MPa). Total elongation tended to increase from 11-12% in the as-quenched condition to 17-20% after heat treatment. The temperature dependence of yield and tensile strength, and ductility for heat treated materials appears in Section B.3.1.150. Yield strength decreased from to 76.8 to 42.2 ksi (529 to 291 MPa) between 0 and 649 °F. In the same temperature range, the ultimate tensile strength decreased from 91.6 to 44.1 ksi (631 to 304 MPa). Total elongation decreased slightly, then increased noticeably with increasing temperature. Alloy modifications which were not exposed to hydrogen showed tensile properties comparable to the 2 1/4 Cr-1 Mo base metal (Section B.3.1.181). After exposures to 1500 psi hydrogen at 550 °C for up to 1000 hours, the alloy modifications showed strengths higher than the base. However, ductility of the alloy modifications after hydrogen exposure was somewhat less than the base.

CREEP, STRESS RELAXATION, AND STRESS RUPTURE--Creep curves appear in Section B.3.1.151. Creep strains of 3.5% occurred at 482 °C in about 800 hours at an applied stress of 50 ksi and in about 20 hours at 60 ksi, Figure A. Plots of creep rate vs. creep strain showed minima at strains of about 0.4 to 0.8% for stresses in the range 35 to 60 ksi, Figure B. Stress vs. the Larson-Miller parameter appears in Figure E. Creep rate vs. stress at three temperatures appears in Figure F. The stress relaxation data reported in Section B.3.1.154 indicate that the rate of relaxation increases with increasing temperature between 482 and 690 °C. Metallurgical damage factors representing changes in microstructure during time-dependent deformation at elevated temperatures appear in Sections B.3.1.152 and .153. The damage factor, D, ranges from 0.03 to 0.50 for creep strains increasing from 0.003 to 0.05 in tests conducted at 482 °C. An increase in temperature or stress during creep tended to increase the damage factor, Section B.3.1.153. Creep rupture tests at 500 and 600 °C (Section B.3.1.180) showed lifetimes ranging from about 30 to 2000 hours depending on stress and temperature. At a given stress, lifetime dropped significantly as temperature increased from 500 to 600 °C. Exposure to hydrogen tended to reduce stress rupture life, Section B.3.1.185. Alloying 2 1/4 Cr-1 Mo steel with 0.5 Mn + 0.5 Ni + 0.02 V generally led to better stress rupture properties than did alloying with 0.5 Mn + 1.0 Ni + 0.75 Cr (Section B.3.1.185).

A387 Grade 9: "9 Cr--1 Mo-Modified"--Several mechanical properties of this steel were measured. Data are summarized in the numerous B-sections listed in Table A.2.1.2.2a. Most data are on base metal, but a few results were obtained on weldments. Results of toughness tests appear in Section B.3.1.101, .102, and .118. Fatigue data have not been reported. Results of tensile tests appear in Sections B.3.1.103, .104, .106, .109, and .110. Creep, stress relaxation and stress rupture test results appear in Sections B.3.1.105, .107, .108, and .115. Hardness test results appear in Sections B.3.1.116 and .117. Section B.3.1.115 tabulates an evaluation of stress relief cracking in welded materials.

TOUGHNESS--Results of Charpy measurements on base metal appear in Sections B.3.1.101 and .102. The upper shelf energy for transverse specimens was higher than for longitudinal specimens for all four heats which were evaluated. Transverse upper shelf energies ranged from 148 to greater than 240 foot pounds. Transition temperatures evaluated by various means for transverse specimens ranged from -51 to +49 °C. Additions of 0.5% silicon and use of electroslag remelt processes almost doubled the upper shelf energy, and significantly lowered the transition temperature, Section B.3.1.102. Results on weldments appearing in Section B.3.1.118 indicate that the welding process has a significant effect on the upper shelf energy. Submerged arc weld and gas tungsten arc welds gave the highest energy (160 foot pounds) and shielded metal arc welds gave the lowest (85 foot-pounds). The fracture appearance transition temperature of submerged arc welds showed a tendency to increase as niobium additions increased to 0.16%.

FATIGUE--No fatigue data were reported.

TENSILE PROPERTIES--Results of measurements of tensile properties on base metal appear in Section B.3.1.103, B.3.1.106, B.3.1.109, and B.3.1.110. Some data on a weldment appear in Sections B.3.1.104 and B.3.1.106. The temperature dependence of tensile properties is reported in Sections B.3.1.103, .104 and .106. Yield strength of transverse specimens decreased from 82.5 to 16.8 ksi (539 to 116 MPa) between room temperature and 1300 °F. In the same temperature range, ultimate tensile strength decreased from 96.7 to 21.5 ksi (666 to 148 MPa). Uniform elongation decreased with increasing temperature, but total elongation increased. There were fewer data for the weldment than the base metal, but weldment data showed the same trends as the base metal with changing temperature. Tensile properties from six heats of hot extruded tubes appear in Section B.3.1.109. Yield and tensile strength of all heats decreased with increasing temperature in the range room temperature to 1200 °F. Room temperature tensile and yield strengths were in the neighborhood of 96.5 and 75.5 ksi (665 and 520 MPa), respectively. Uniform elongation decreased with increasing temperature, whereas total elongation increased. Uniform elongation at room temperature was in the range 7 to 9%. Tensile data in Section B.3.1.110 are for the front end and tail end of hot extended tubes made by the argon-oxygen-decarburization and the electroslag-remelt/argon-oxygen-decarburization processes.

CREEP AND STRESS RUPTURE--Results on base metal appear in Sections B.3.1.105, .107, and .108. Section B.3.1.115 reports some data on a weldment. Creep data appear in Sections B.3.107 and .108. Tests were conducted at 538, 639 and 704 °C and in the stress range 12 to 46 ksi (83 to 317 MPa) for up to 1300 hours. Strain to rupture was in the neighborhood of 27 to 35%. Stress rupture data appear in Sections B.3.1.105 and .108. The time to rupture at 538 and 649 °C was about 10^3 to 10^4 hours for stresses in the range 29 to 58 ksi (200 to 400 MPa). An evaluation of stress relief cracking in standard and modified 9 Cr-1 Mo steels appears in Section B.3.1.115. In general, the modified steel showed longer times to rupture for higher stresses than were applied to the standard steel.

HARDNESS--Results of hardness tests on a base metal and welds appear in Sections B.3.1.116. Hardness in the heat affected zone was higher than in either the fusion zone or the base metal. Base metal hardness was less than fusion zone hardness.

<u>WELDABILITY OF STANDARD AND MODIFIED 9 Cr-1 Mo</u> in the presence of hydrogen is reported in Section B.1.1.154 and .155. A standard gas tungsten arc welding procedure with hydrogen was used to evaluate susceptibility to hydrogen attack. Specimens were strained by bending along the welding direction after the test.

Preheating at temperatures up to 572 °F helped to minimize cracking (Section B.1.1.154). The preheat temperature required to prevent cracking increased from 100 to 300 °C with increasing strain from 1 to 4% (Section B.1.1.155).

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.

A508: "Carbon and Alloy Steel"--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 energy 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).

A533-Type B: "Quenched and Tempered Alloy Steel, Mn-Mo-Ni"-- 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, B.3.1.49, and B.3.1.127) 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, B.3.1.75, and B.3.1.128. 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 250 ksi$\sqrt{in}$.

A204: "Alloy Steel-Molybdenum"--Results of Charpy impact tests and tensile tests were obtained on A204 steel. Impact data in Section B.3.1.130 show that a post weld heat treatment of 3 1/2 hours at 607 °C improves toughness of the weld metal as compared to the base metal. For example, W-R oriented (specimen axis transverse to major rolling direction) base metal shows an upper shelf energy of about 70 foot-pounds, and a transition temperature in the neighborhood of 100 °C. After postweld heat treatment, W-L oriented (specimen axis perpendicular to welding direction) weld metal shows an upper shelf energy of 90 foot-pounds and a transition temperature around 0 °C. However, toughness properties of W-R oriented base metal did not change significantly with post weld heat treatment.

Tensile data in Sections B.3.1.132 and B.3.1.133 show a 30% decrease in yield strength of base metal as temperature increases from -100 to 650 °F. Ultimate tensile strength of base metal dropped about 5% over the same temperature range, and elongation of the base metal showed a 19% decrease with increasing temperature. Weld metal showed higher yield and tensile strengths than base metal, but elongation was comparable. The temperature dependence of the tensile properties of base and weld metals was also comparable.

A516-Grade 70: "Carbon Steel"--Charpy impact tests and tensile tests were conducted on A516 steel. Impact data in Section B.3.1.131 show that a post weld heat treatment of 3 hours at 607 °C improves toughness of weld metal as compared to base metal. For example, W-R oriented base metal shows an upper-shelf energy of about 70 foot-pounds, and a transition temperature in the neighborhood of 10 °C. After post weld heat treatment, W-L oriented weld metal shows an upper shelf energy of 90 foot-pounds and a transition temperature around 0 °C. However, toughness properties of W-R oriented base metal did not change significantly with post weld heat treatment.

Tensile properties in Sections B.3.1.134 and .135 show a 50% decrease in yield strength of base metal as temperature increases from -100 to 650 °F. Ultimate tensile strength of base metal dropped about 16% over the same temperature range, and elongation of the base metal showed a slight tendency toward an increase. Weld metal showed higher yield and tensile strengths than base metal, and elongation tended to be somewhat lower. The temperature dependence of the tensile properties of base and weld metals was comparable.

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 (Sections B.3.1.65 and B.3.1.181) and Charpy data (Sections B.3.1.71 and B.3.1.72) have been obtained on A533B alloyed with silicon, chromium, or manganese. Alloy modifications generally increased yield and tensile strengths, but did not have a strong effect on ductility (Section B.3.1.65). Exposures to hydrogen (Section B.3.1.181) at 1500 psi and 550 °C for up to 1000 hours tended to decrease yield and tensile strengths of the base steel as well as the modifications. Modification helped to maintain ductility after hydrogen exposures. Results in Sections B.3.1.71 and .72 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.

A study of the effect of hydrogen on the Charpy impact properties of a modified Mn-Mo-Ni base steel was conducted (Section B.3.1.183). Hydrogen exposure was carried out at 550 °C for 1000 hours at either 1500 or 2000 psi. Four compositional variations involving Si, Cr, and Mn additions were studied. For all compositions, hydrogen exposure tended to lower the upper shelf energy and raise the transition temperature. In some cases, tempered specimens from a simulated cooling equivalent to the quarter-thickness position of a 12-inch thick plate showed better impact properties than quenched and tempered material presumably representing surface specimens. Upper shelf energies of the unexposed alloys ranged between 100 and 200 foot-pounds. For some compositions hydrogen exposures at 1500 psi did not reduce the upper shelf energy as much as exposures at 2000 psi. Developmental steels based on A533B which were exposed to hydrogen at 1500 psi and 550 °C for 1000 hours showed blistering and cracking (Section B.1.1.192).

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 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. Developmental steels based on A542 which were exposed to hydrogen at 1500 psi and 550 °C for 1000 hours showed no signs of attack (Section B.1.1.192).

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 (Sections B.3.1.75 and .179) did not improve the response to the embrittlement treatment, but in one case did significantly improve the Charpy properties of the unembrittled remelted material. Remelted A543 alloys containing 0.005 percent boron or 0.015 percent nitrogen (Section B.3.1.75) 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. Rare earth additions of 0.03 percent La and 0.17 percent Ce to a modified A543 steel did not lead to improvements in Charpy properties but resulted in lower impact energies (B.3.1.179).

COMPOSITIONAL VARIATIONS OF CARBON STEEL--Hardness data (Sections B.3.1.67 and .176) were obtained on carbon steel alloyed with chromium, molybdenum, vanadium, aluminum, and/or tungsten. The molybdenum steel showed a peak in the hardness vs. tempering temperature curve, suggesting a tendency toward embrittlement at around 650 °C (Section B.3.1.67). Hardness tended to increase from 350 to 400 Hv with increased cooling rates between 10 and 600 degrees per minute (Section B.3.1.176). Peaks occurred in the hardness vs. cooling rate curves for 0.2 C-1 V-0.5 Mn-3 Ni-1 Si and 0.2 C-1 V-0.5 Mn-3 Ni-1.5 Mo steels at cooling rates of 100 and 300 degrees per minute, respectively, suggesting potential embrittling reactions. 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. The influence of austenitizing temperature and cooling rate on tensile properties of several modified carbon steels is reported in Section B.3.1.174. Yield and tensile strengths ranged from 60 to 136 ksi and 74 to 153 ksi, respectively, and depended upon austenitizing temperature, cooling rate and composition. Higher austenitizing temperatures usually led to higher strengths, but lower ductilities: Alloy modifications helped to maintain strength and ductility after exposures to hydrogen at 1500 psi and 550 °C for up to 1000 hours (Section B.3.1.181).

The influence of austenitizing temperature and cooling rate on Charpy properties of several modified carbon steels is reported in Section B.3.1.175. Upper shelf-energies ranged from 25 to 245 foot-pounds. Increasing the austenitizing temperature from 900 to 1000 °C tended to decrease the upper shelf energy generally, although this did not occur for the 0.2 C-1 V-1.5 Ni-0.5 Mn steel. Exposure to 2000 psi hydrogen at 550 °C for 1000 hours generally decreased the upper shelf energy. However, the upper shelf energy of the 0.2 C-1 V-1.5 Ni-0.5 Mn steel was unaffected by hydrogen exposure.

<u>COMPOSITIONAL VARIATIONS OF A387-GRADE 21 ("3 Cr-1 Mo")</u>--Tensile data were obtained on quenched and tempered 3 Cr-1 Mo with 1 manganese and 1 nickel additions (Section B.3.1.177). Yield and tensile strengths ranged between 1105 and 432 MPa (160.2 and 62.6 ksi) and 1287 and 582 MPa (186.7 and 84.4 ksi), respectively, depending upon tempering temperature. Elongation increased from about 17% in the as-quenched condition to 33% following tempering.

A.2.4.1 OPERATING REQUIREMENTS

Metal internal components for gasification and liquefaction vessels include pressure and temperature probes, transfer line nozzles, distributor plates and tubes, dip legs, cyclones, valves and their support structures, and, in some cases, refractory anchors. Generally, internal components will encounter the most extreme conditions of a specific process. Internal components may be exposed to temperatures of 1000-3000 °F. Pressures may reach 4000 psi in liquefaction reactors and 1000 psi in gasification vessels. Sulfur gas at partial pressures near 10^{-8} torr and oxygen at partial pressures of 10^{-15} torr can cause corrosion losses due to surface scaling. Erosion-corrosion due to charcoal, char, and coal particulates can accentuate the corrosion losses. Hydrogen in the atmosphere can cause hydrogen-assisted cracking. Stress-rupture is a possible problem. Temper embrittlement of alloy steels may occur. During shut downs, all metal internal components may be exposed to condensation, stress, and crevice corrosion as well as other forms of corrosion which occur at the lower temperatures.

A.2.4.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 13 different THERMOWELLS (A.2.4.2.1.1). Nine 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, one ferritic stainless steel - 446, and molybdenum/Ni-Al-Cr/Cr_2O_3. 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, the molybdenum/Ni-Al-Cr/Cr_2O_3, and one of the 310 stainless steel thermowells failed because of reaction with sulfur. Three failures - one 310, one 316 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 molybdenum/Ni-Al-Cr/Cr_2O_3 thermowell exposed to a molten slag environment in the temperature range of 1400-2300 °F had the shortest reported service life (14-30 hours).

PLANT EXPERIENCE for six 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, 316 stainless steel, and Hastelloy X. Operating temperatures ranged from 550 to 1800 °F.

Erosion appeared to be the predominant cause of failure. Such was the case for the cyclones made of Incoloy 800, unlined 310, and 316 stainless steels. The Incoloy 800, the unlined 310 stainless steel and the Hastelloy X 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 Hastelloy X subjected to a bituminous coal/anthracite coal/producer gas environment at a temperature of 1200 °F failed in the shortest time - 20 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.

PLANT EXPERIENCE has been reported for two FRACTIONATOR INTERNALS for liquefaction processes. There are insufficient data to draw any conclusions. Information regarding coupon testing of fractionator internals may be found in Section A.2.4.2.2.5.

THERMOWELL IN-SERVICE PERFORMANCE[5,70]

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
Molybdenum/ Ni-Al-Cr/ Cr_2O_3	Gasifier	Grand Forks ETC	14-30 hr	Molten slag	1400-2300	N.A.	Formation of Ni-Ni_3S_2 eutectic by penetration of sulfur through flame sprayed Cr_2O_3 coating to intermediate Ni-Al-Cr layer leading to liquid layer resulting in loss of protective coating

CYCLONE IN-SERVICE PERFORMANCE[5,70]

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
Hastelloy X	External cyclone	Morgan-town ETC	20 hr	Bituminous coal/anthracite coal/producer gas	1200	128	Perforation of wall due to solid particle impingement

FRACTIONATOR INTERNALS IN-SERVICE PERFORMANCE[70]

Material	Location	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
304 S.S.	Fractionation column T105 liner	Wilsonville Solvent Refined Coal	N.A	Wash solvent/ process solvent	320-570	N.A.	General corrosion and intergranular cracking due to chloride attack
316 S.S.	Fractionation column T105 trays	Wilsonville Solvent Refined Coal	N.A.	Wash solvent/ process solvent	320-570	N.A.	Corrosion due to chloride attack

A.2.4.2.2.1 CORROSION--GASIFICATION

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; streams of erosive particles in turbulent flow. 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, carburization, or hydrogen-assisted corrosion processes. Deterioration due to corrosion includes weight loss, scale formation, internal sulfidation and oxidation, depletion of elements such as chromium and associated loss of protective films, and development of pitting, porosity, and cracking. Such deterioration leads to loss of load-bearing capacity. Corrosion is usually a gradual process initially, but after a few thousand hours exposure may become catastrophic in certain cases known as "breakaway corrosion" (Section B.1.1.128). Breakaway corrosion usually occurs due to local depletion of critical elements which form protective films.

Sulfide reactions seem to be the most frequent and the most harmful. Sulfur partial pressures range from 10^{-5} to 10^{-7} atm. (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. Chromium-containing steels are particularly 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, B.1.1.91-99 and B.1.1.119 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.

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 gasification 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. Methane bubble formation is especially of concern in pressure vessel steels in coal liquefaction systems (see Sections B.1.1.177-.186).

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 and thereby set the stage for corrosion that might not otherwise not have occurred.

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. A summary of some hot-gas corrosion studies of candidate structural materials for coal conversion plants appears in Reference [86].

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 breakaway corrosion does not occur. 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 stages of testing, but decreases as the test proceeds. Moreover, Figure A.2.4.2.2.1b shows that there is a critical time which roughly divides the high rate region (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.

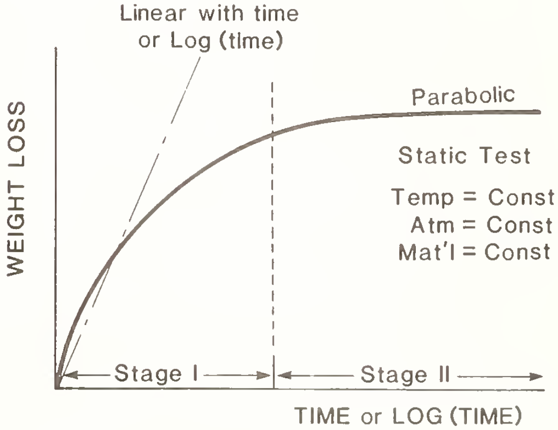


Figure A.2.4.2.2.1a

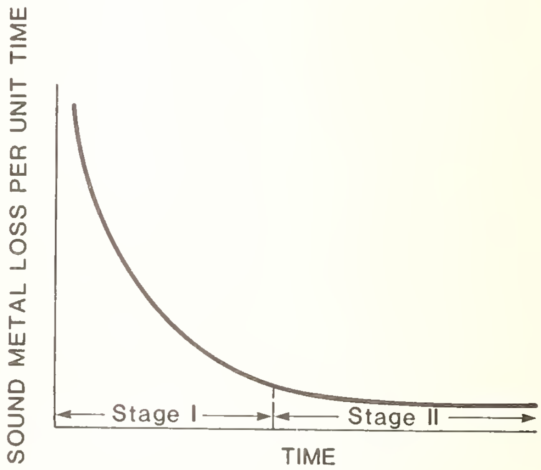


Figure A.2.4.2.2.1b

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, in the absence of breakaway corrosion, long term static corrosion behavior can 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 for 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

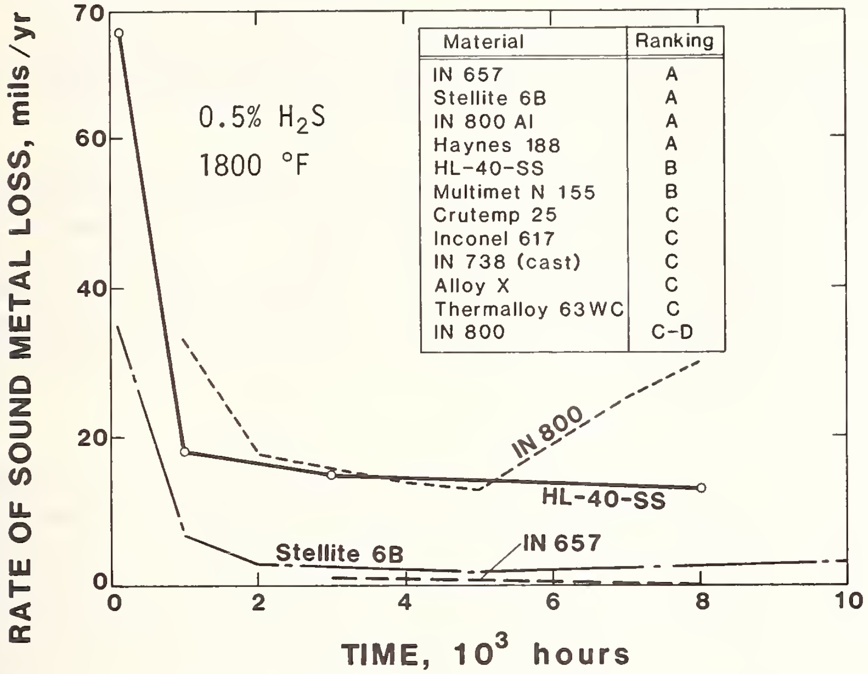


Figure A.2.4.2.2.1c

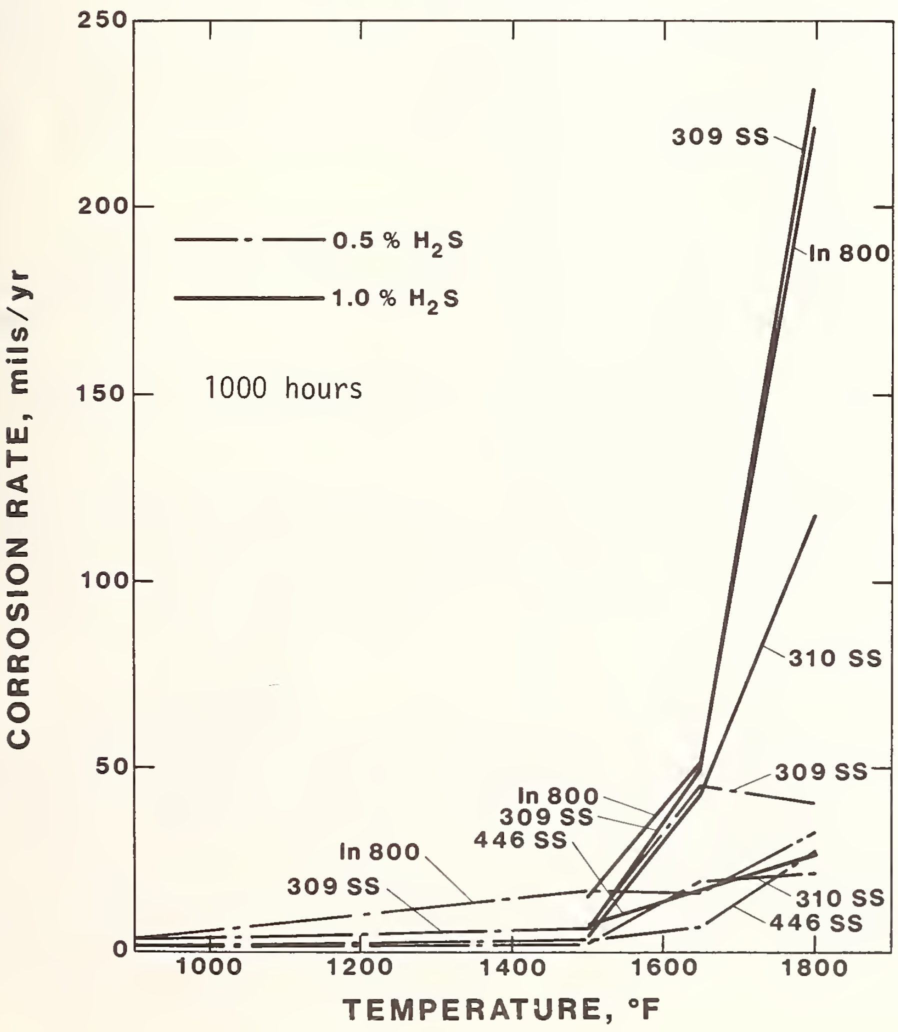


Figure A.2.4.2.2.1d

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 rate of sound metal loss for most alloys seems relatively independent of hydrogen sulfide concentrations at 1500 °F, Figure A.2.4.2.2.1d. 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 H_2S concentration increases from 0.5 to 1.0 percent.

LABORATORY TESTS

PERFORMANCE DATA were obtained in laboratory tests on about 71 structural alloys (see Sections B.1.1.17 and B.1.1.18). In addition to numerous commercial alloys, a few experimental alloys and a few weld metals were tested. Corrosion test specimens were exposed for times between 100 and 10,000 hours, usually in a standard coal gasification atmosphere, at temperatures between 900 and 1800 °F. 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 some cases, corrosion scale was analyzed following exposure.

In almost all cases, the laboratory test results reported in various paragraphs 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.

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.

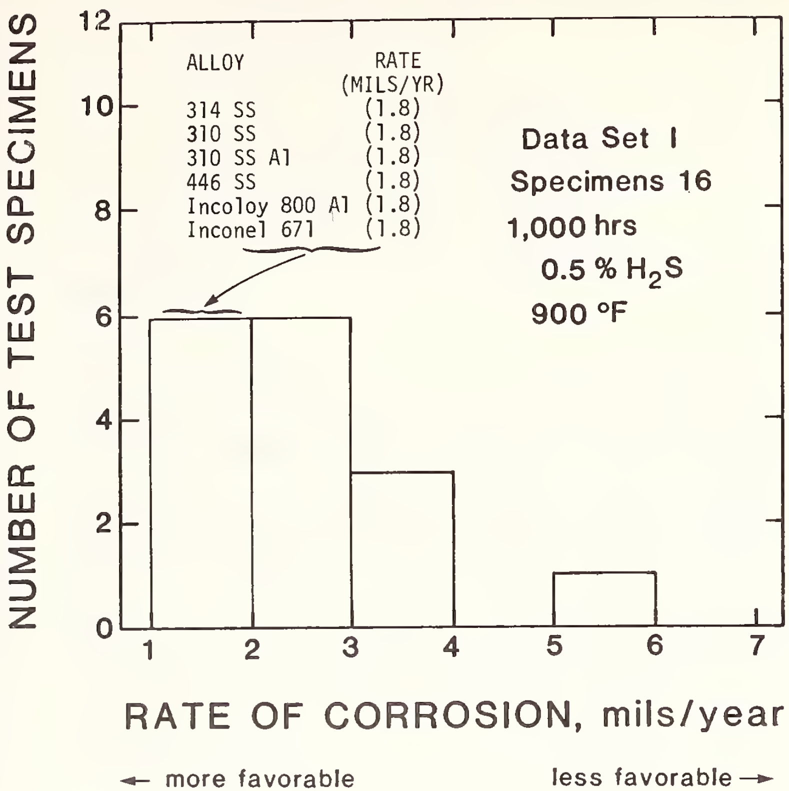
RANKING OF CORROSION RATES of about seventy-one alloys in a simulated coal gasification atmosphere (Section B.1.1.17) appears in the histograms which follow. The histogram form of presentation allows for rapid identification of those alloys which show the most favorable corrosion rates. For example, 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 follows.

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	15
VIIb	1000	1650	0.5	7
VIIIa	10000	1650	1.0	6
VIIIb	6000	1650	1.0	8
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	11
XIIb	3000	1800	1.0	7
XIIc	1000	1800	1.0	31

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

TEMPERATURE AND PRESSURE DEPENDENCE of hot-gas corrosion rates appears in the results of several series of tests. Results on temperature dependence 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. Increasing temperature from 1650 to 1800 °F generally decreased the corrosion resistance of seventeen of twenty-two alloys tested, Section B.1.1.127. However, Multimet N155 and aluminum-coated stainless steel showed no effect with increased temperature. Similar behavior is shown in Section B.1.1.6 for four other alloys, including Type 310 stainless steel. Data in Section B.1.1.6 show a tendency toward a decrease in corrosion rate with increasing pressure. Corrosion rates of twenty-seven alloys tested at 500 and 1000 psi are reported in Sections B.1.1.123 and .124. For exposure times of 5,000 and 10,000 hours at temperatures of 1650 and 1800 °F, some alloys showed a tendency toward an increased corrosion rate at the higher pressure.

Effects of temperature and pressure on the corrosion loss of seven alloys were measured in simulated coal gasification atmospheres containing upwards of 1 percent hydrogen sulfide and 2 percent water vapor (see B.1.1.1 and B.1.1.6). The temperatures were 1382, 1600, and 1800 °F. Pressures were 34, 68, and 102 atmospheres. Exposure time was usually 1000 hours. Corrosion effect was measured as depth of penetration, determined by optical microscopy. These results show that in general the influence of increased temperature at fixed pressure is to increase the corrosion loss. (This point was also illustrated in



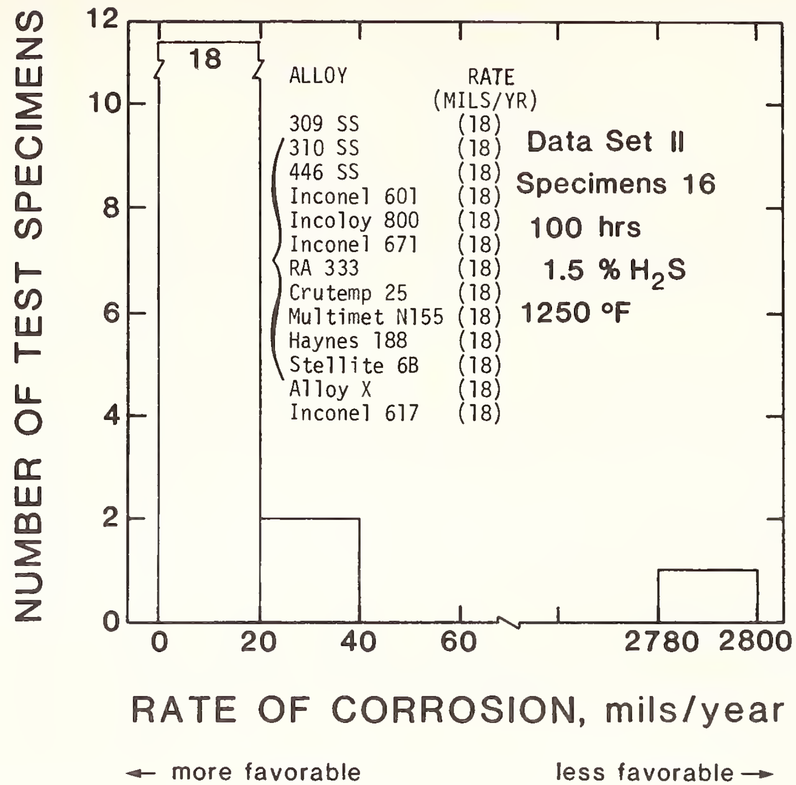
Comments:

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



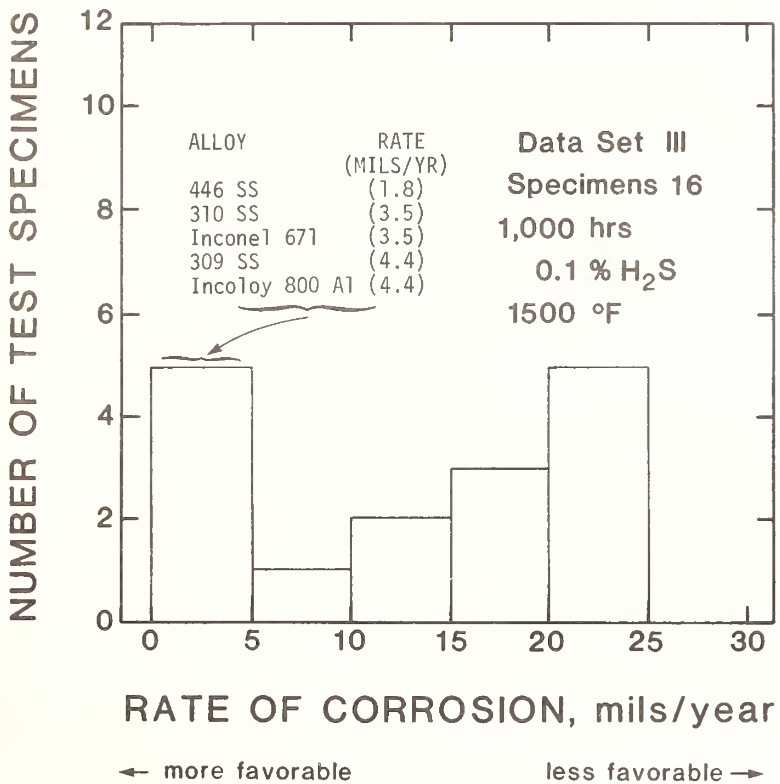
Comments:

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



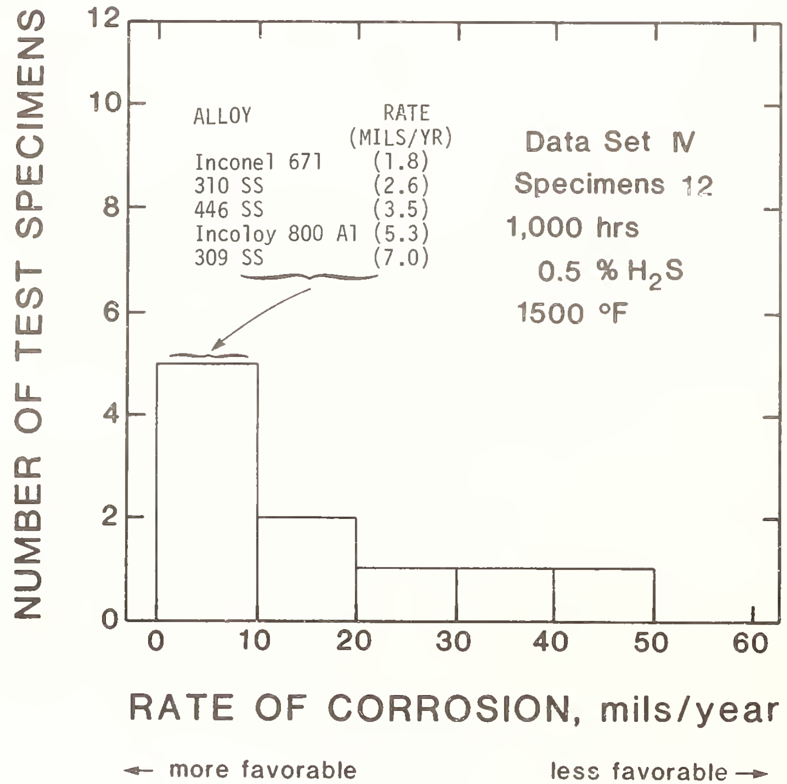
Comments:

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



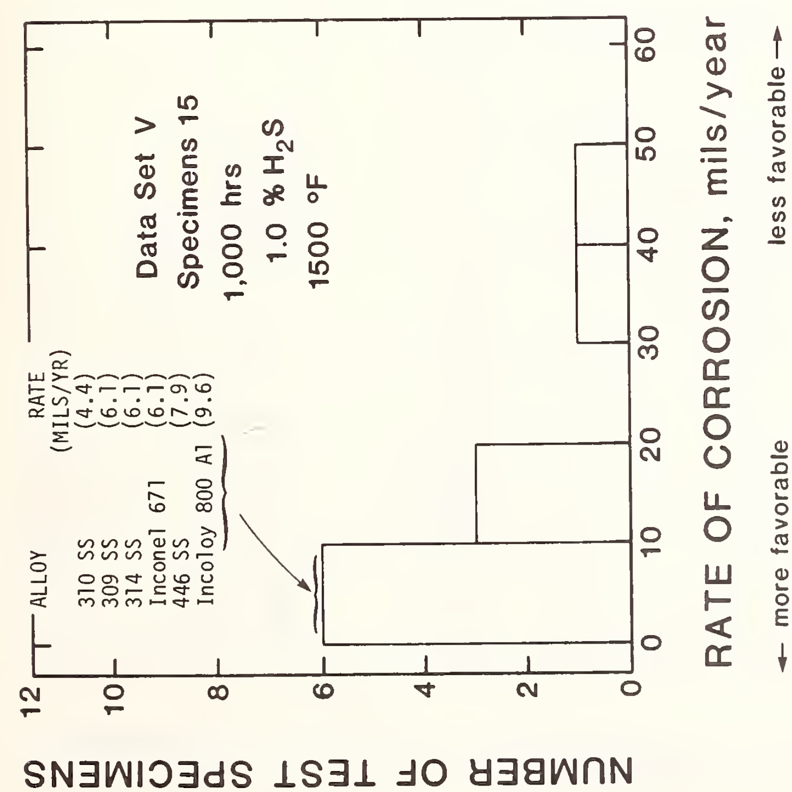
Comments:

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



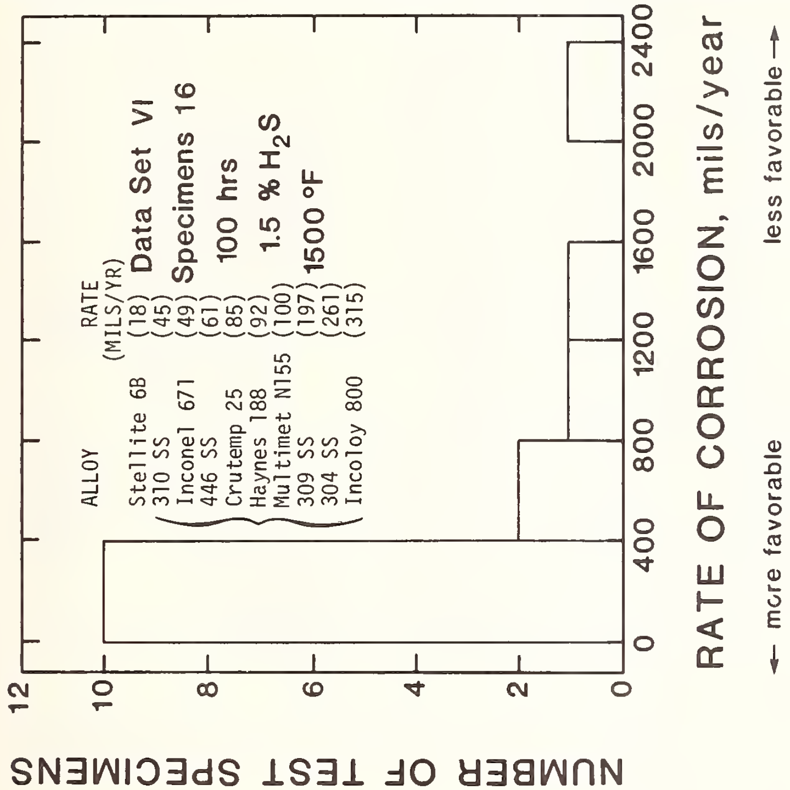
Comments:

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



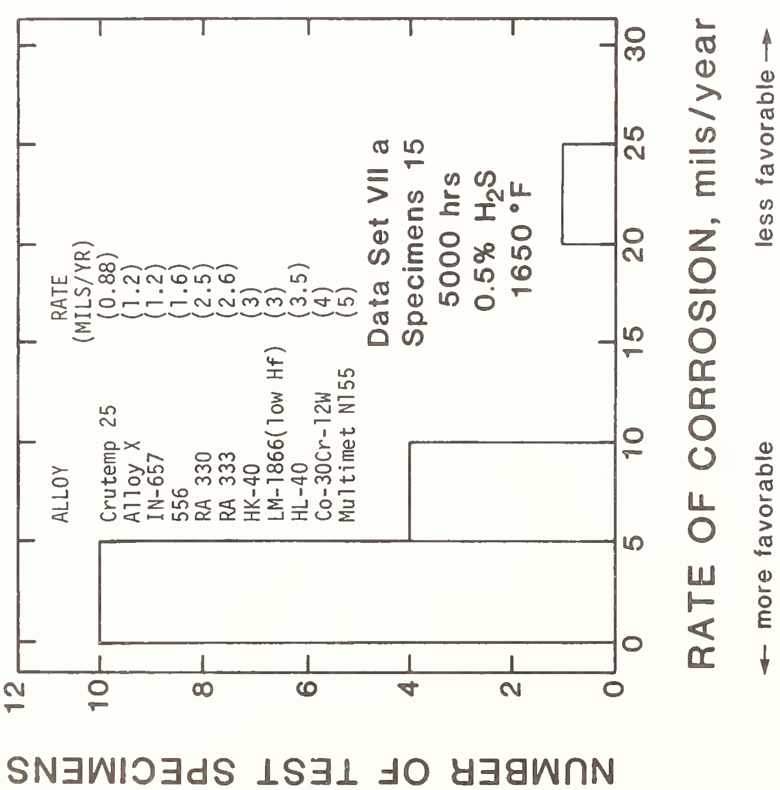
Comments:

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



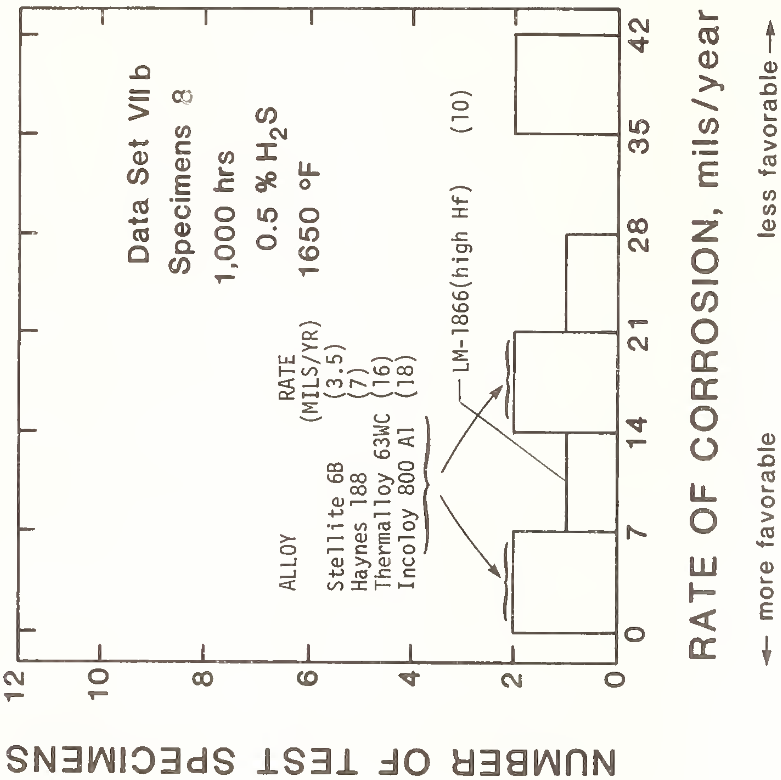
Comments:

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



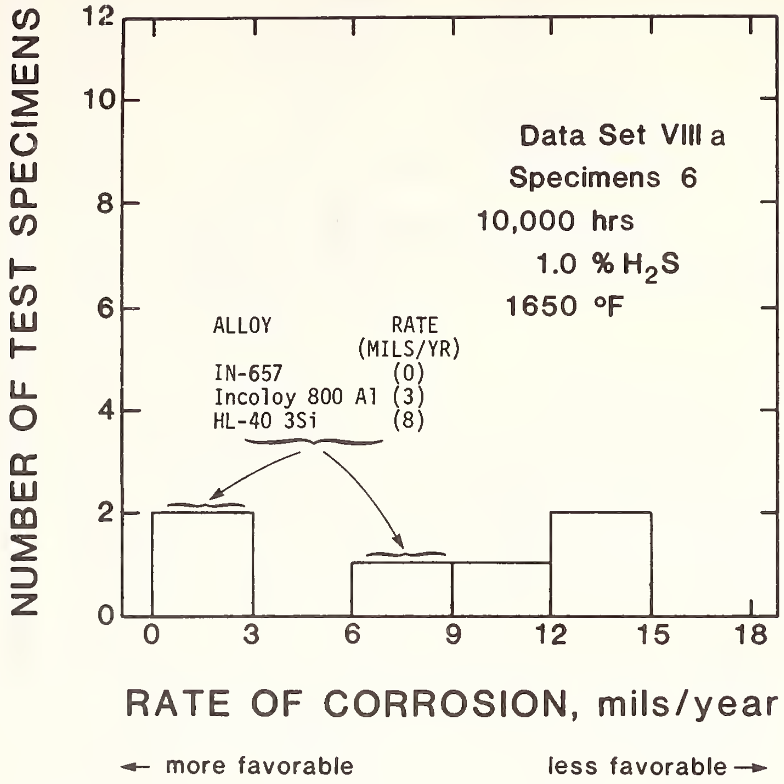
Comments:

Highest corrosion rate : 216 mils/yr

Lowest corrosion rate : 3.5 mils/yr

Least favorable corrosion rate :

Alloy	Rate, mils/yr
253 MA	216
310 SS Al	40
Inconel 617	36
Sanicro 32X	22



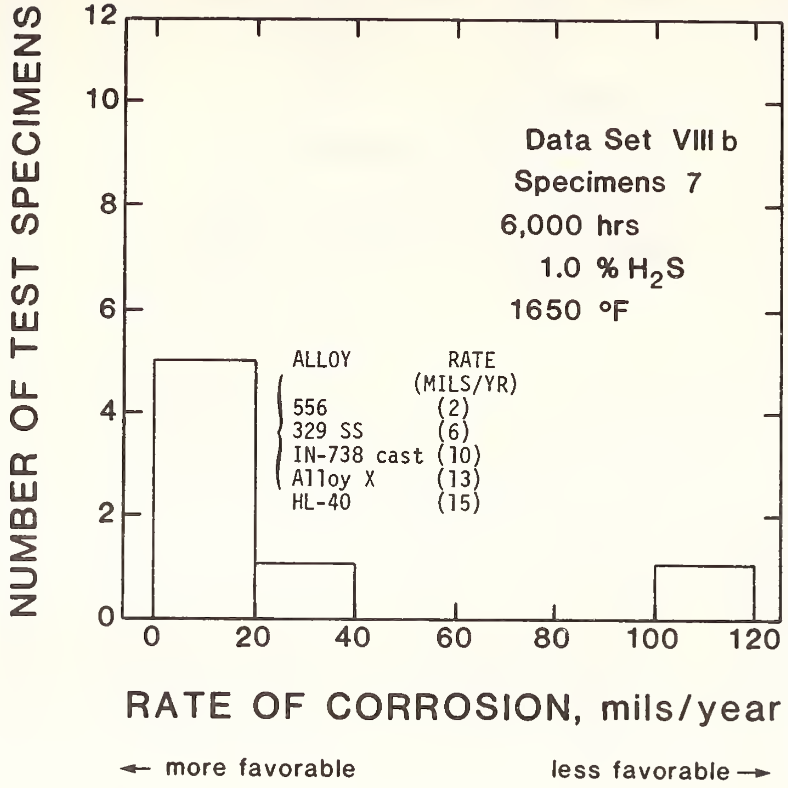
Comments:

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



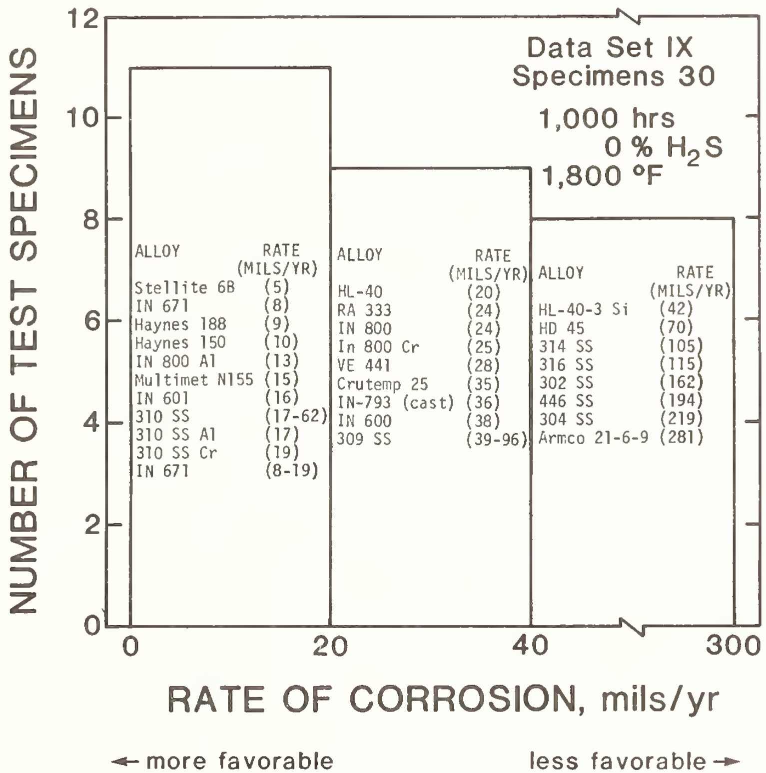
Comments:

Highest corrosion rate:

Lowest corrosion rate:

Least favorable corrosion rate:

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



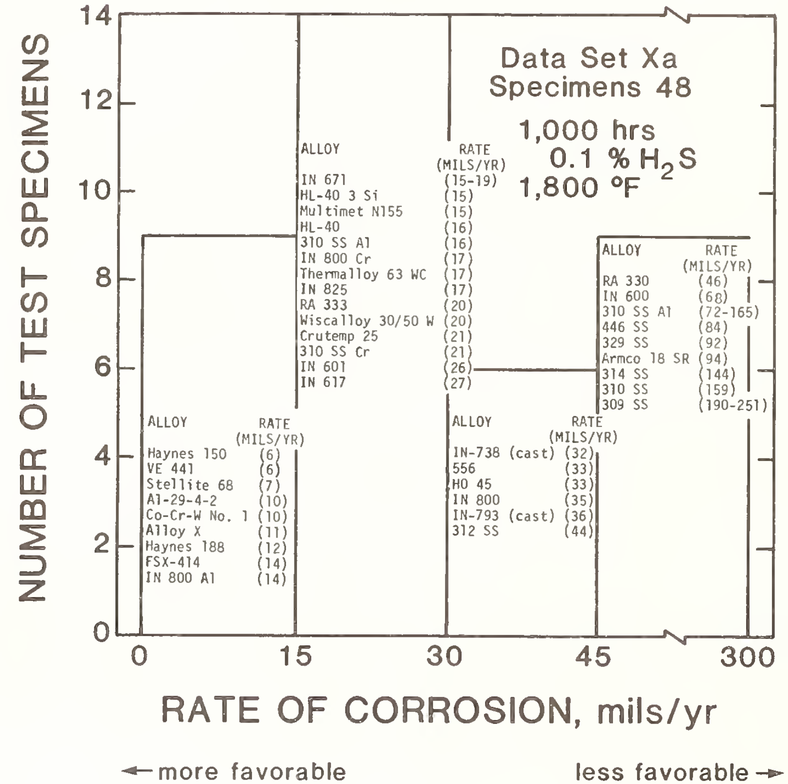
Comments:

Highest corrosion rate : Complete corrosion

Lowest corrosion rate: 5 mils/yr

Least favorable corrosion rate :

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



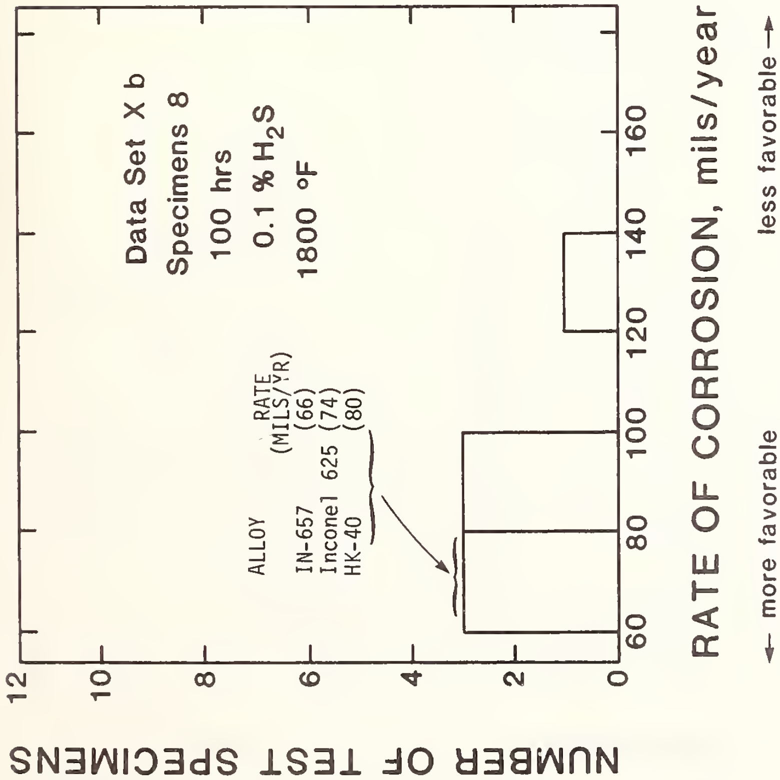
Comments :

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

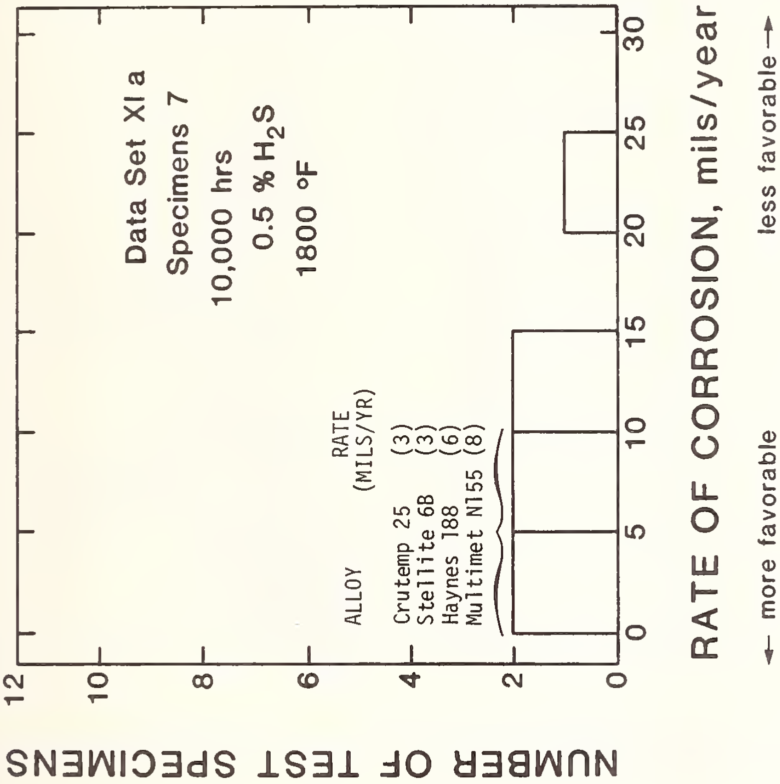


Comments:

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

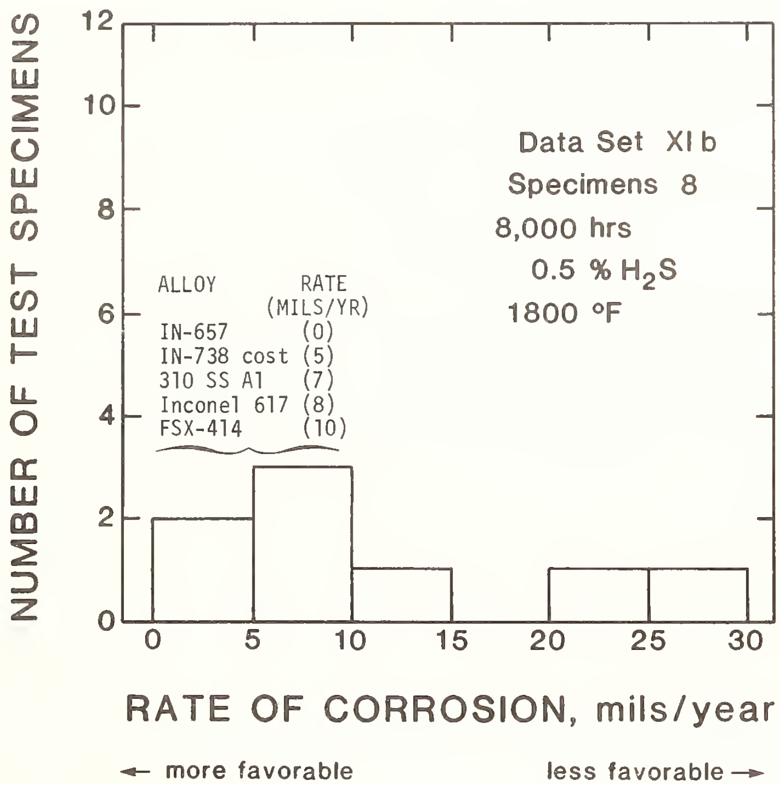


Comments:

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



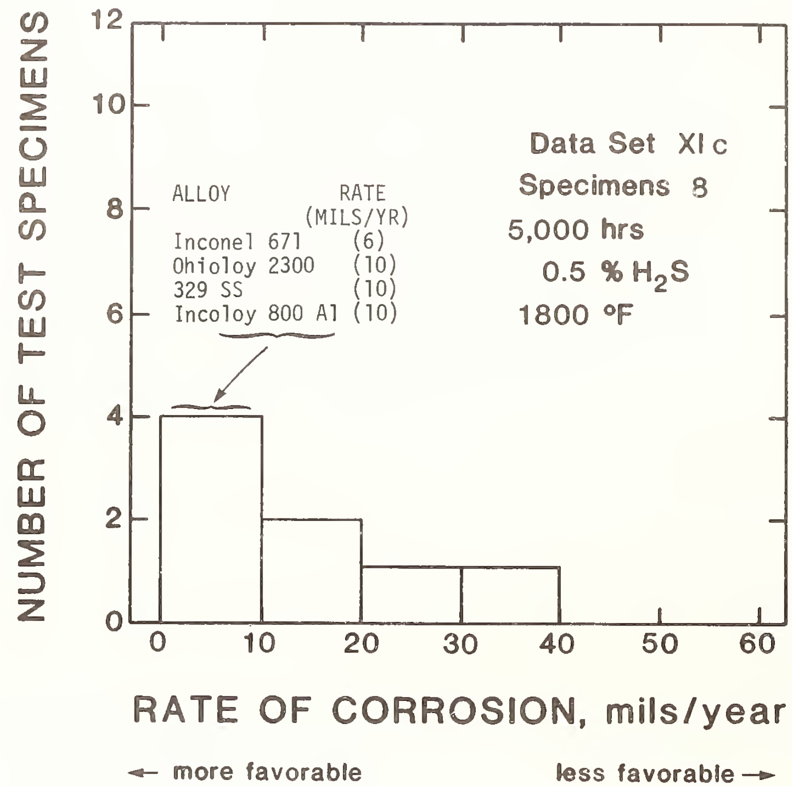
Comments:

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



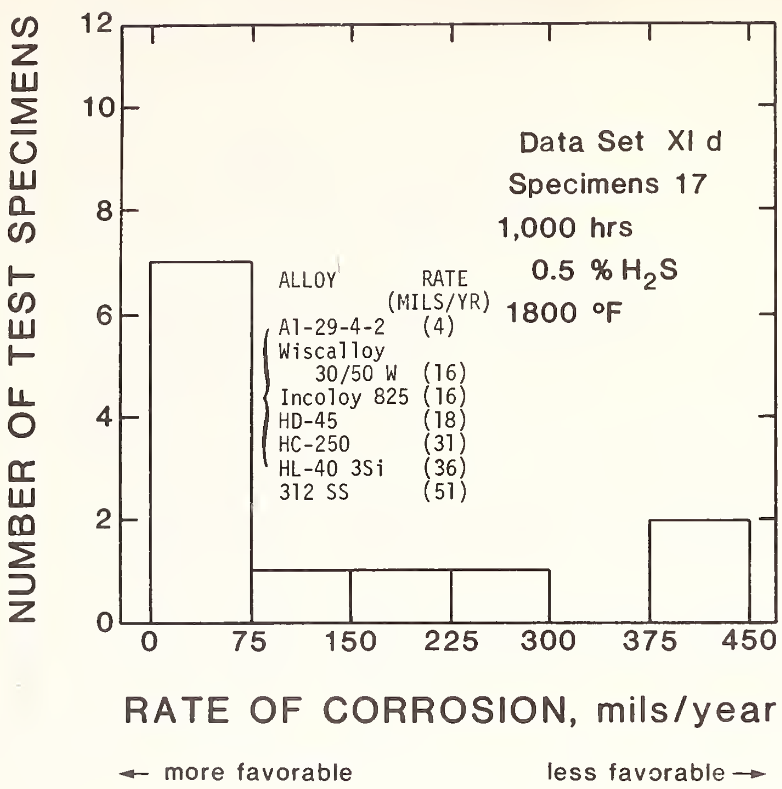
Comments:

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



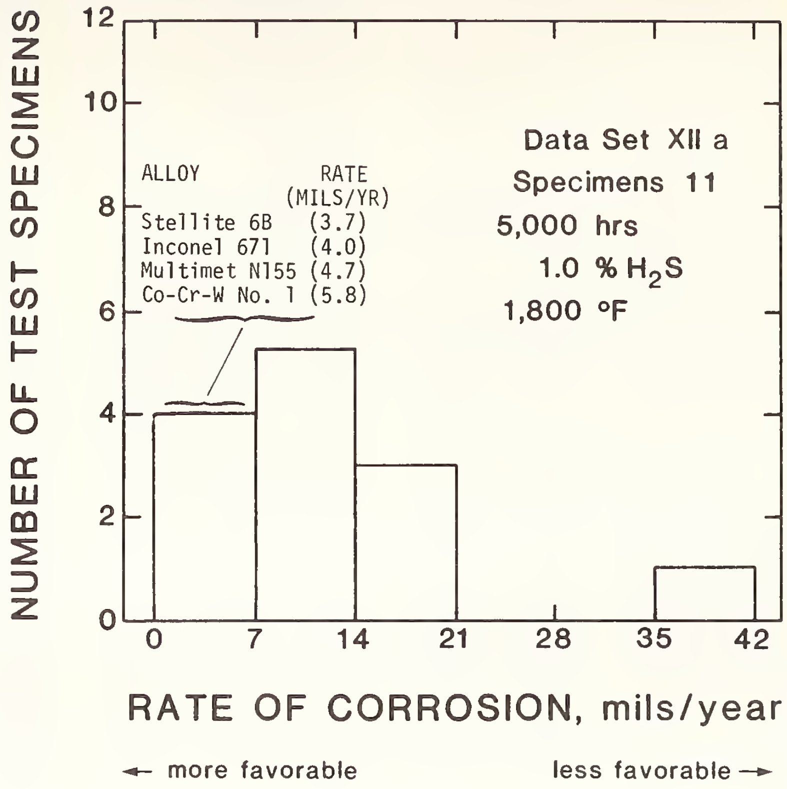
Comments:

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	Corroded completely
Al-16-5-Y	Corroded completely
LM-1866 (low Hf)	Corroded completely
253 MA	Corroded completely



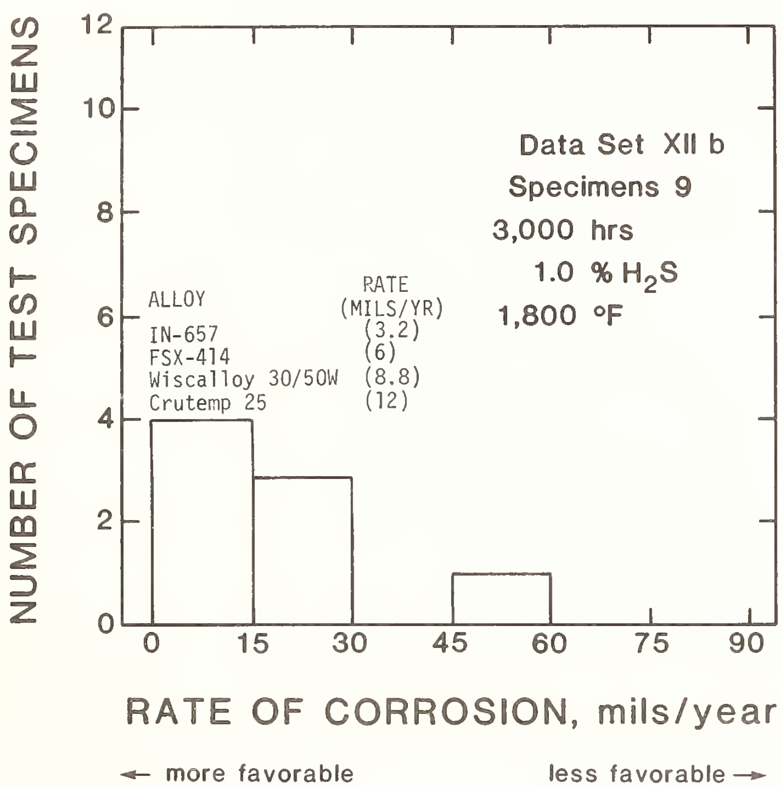
Comments:

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



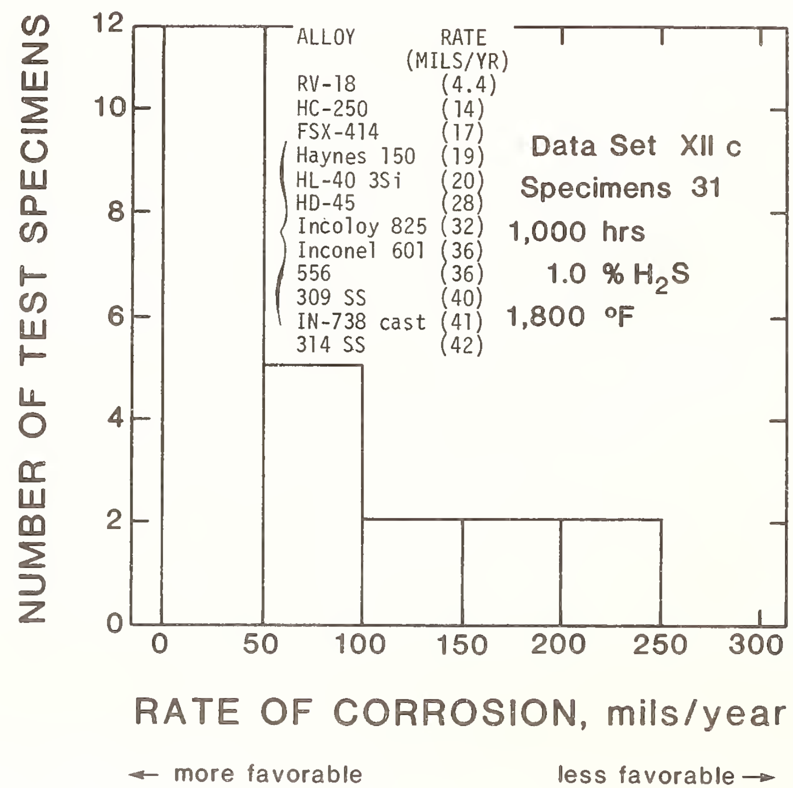
Comments:

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	Corroded completely
316 SS	Corroded completely
Inconel 600	Corroded completely
IN-793 cast	Corroded completely
VE 441	Corroded completely
AL EX-20	Corroded completely
Armco 18 SR	Corroded completely
RA 330	976
309 SS	583
Incoloy 800 Cr	389

Figure A.2.4.2.2.1d.) The results do not show any clear trend for the influence of pressure on corrosion loss at fixed temperature. In some tests, increased pressure resulted in increased corrosion loss, and in others, increased pressure resulted in decreased corrosion loss. In only two cases were conditions such that there was total loss of a test specimen.

The kinetics of penetration, as shown in depth vs. time curves for the seven alloys tested appear in Section B.1.1.2. During 1000 hours exposure, alloys GE 1541, GE 1541 (preoxidized), and Incoloy 800 showed the least depth of penetration, whereas Type 310 and 18-18-2 stainless steels showed the greatest depth of penetration. The kinetics of penetration for 18-18-2 were peculiar, in that depth of penetration at 1382 °F was often greater than at higher temperatures.

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

CORROSION RATES FOR SAMPLES IN CONTACT WITH SOLIDS were measured on nine alloys to determine their corrosion rates during simultaneous exposure to a gas atmosphere and a solid which is a possible slag former for 100 hours. Tests were run at 1800 °F and 1000 psi. In most cases, test results were obtained 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: Western 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 were drilled in each specimen. One hole was hand-packed with one of the solid materials, and the other hole was left empty to serve as an experimental blank. After exposure, the specimens were wire-brushed and the extent of corrosion was determined metallographically. Test data appear in Section B.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.

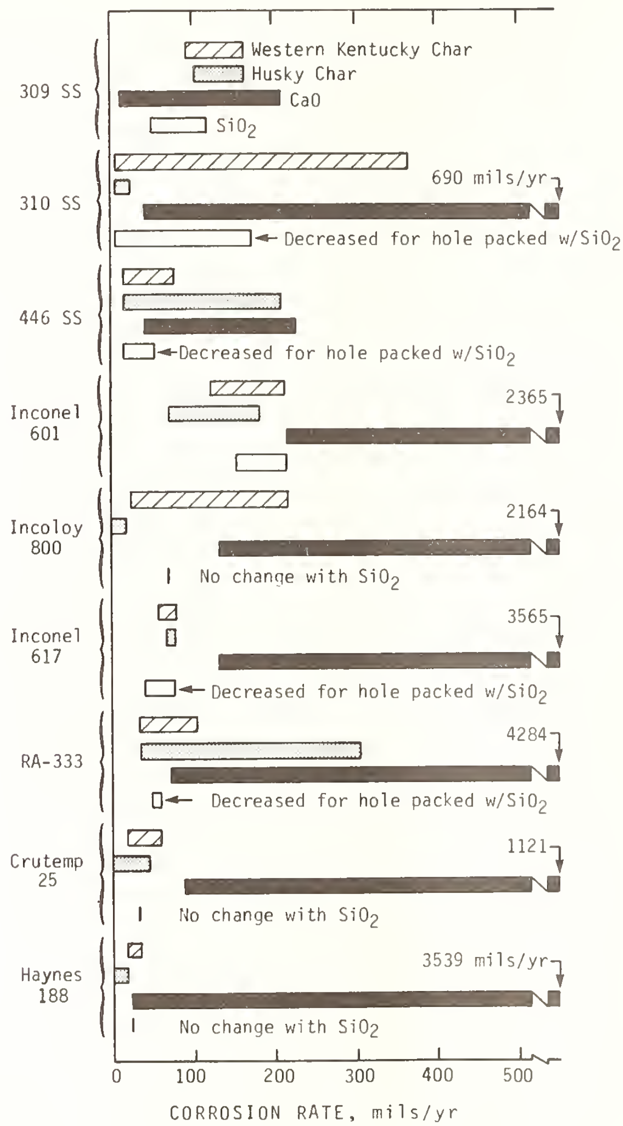


Figure A.2.4.2.2.1e

<u>CHAR CORROSION REACTIONS</u> 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, 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 reactions for GE 1541 and Incoloy MA 956 (see B.1.1.65). Pre-oxidation did not seem to be beneficial for Hastelloy X, Inconel 671, Incoloy 800 or 310 stainless steel (compare B.1.1.54 and B.1.1.64). For some alloys, particularly GE 1541 and Inconel 671, increased pre-oxidation time reduced the char corrosion weight gain.

EFFECTS OF VARIABLE WATER VAPOR CONTENT on hot gas corrosion rates were determined on sixteen alloys. Tests were run at 1800 °F and 1000 psi. In most cases, test results were obtained on a single test specimen of each alloy. Exposures were for 100 hours at two water vapor contents: 20 percent and 40 percent. The analysis of 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

Test data appear in Section B.1.1.20.

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.

Figure A.2.4.2.2.1f

<u>CORROSION RATES IN A LOW-BTU ATMOSPHERE</u> 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.

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.

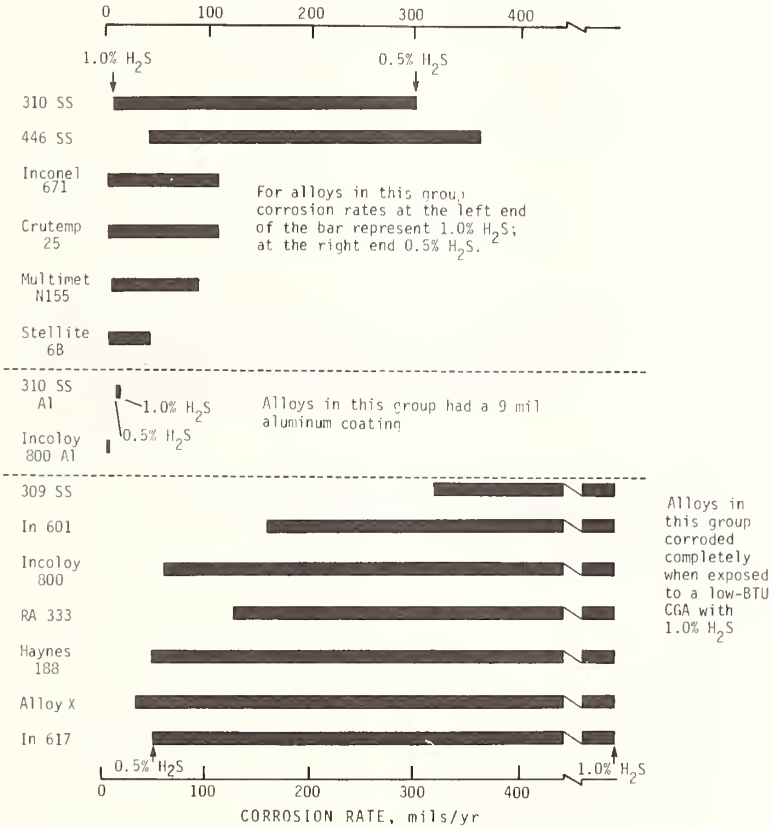


Figure A.2.4.2.2.1g

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.

<u>CORROSION RATES IN A DOLOMITE REGENERATOR ATMOSPHERE</u> 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.

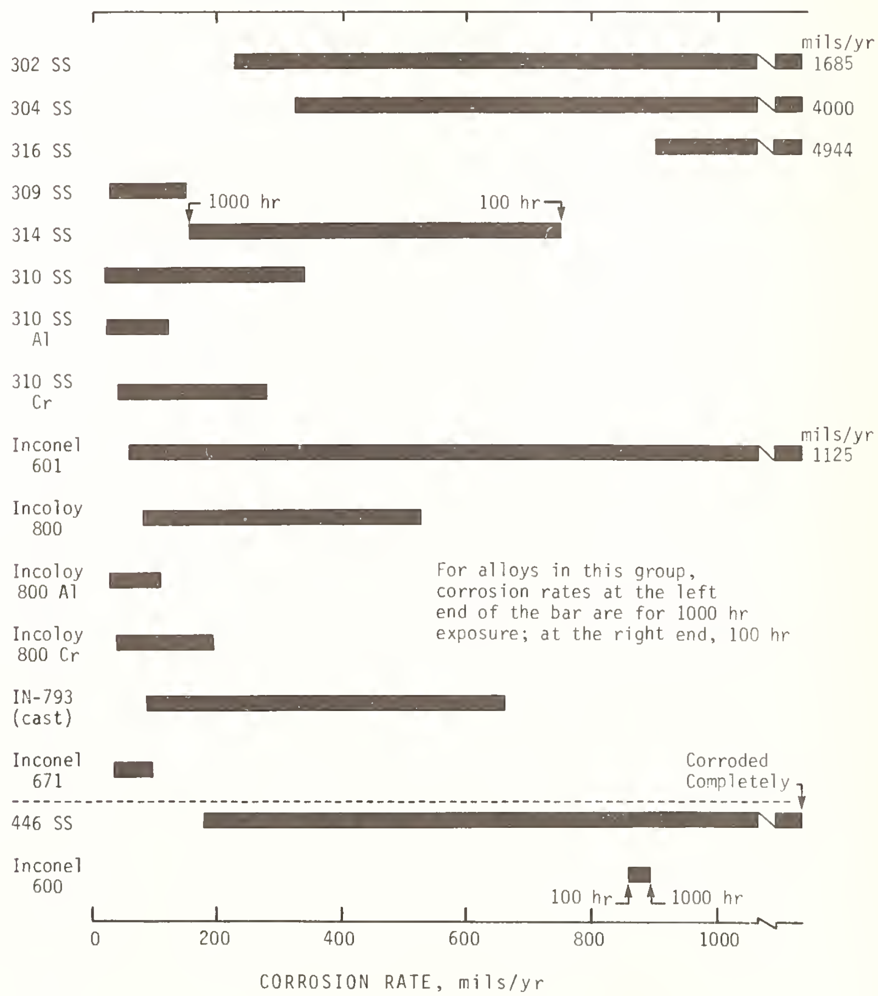


Figure A.2.4.2.2.1h

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.

CORROSION RATES IN METHANATION GASES are reported in Section B.1.1.129. Thirty-six alloys were exposed for up to 1000 hours at 1800 °F in the feed gas and at 1200 °F in the effluent. Rates in the effluent were generally lower than rates in the feed gas. Inconel 671, Incoloy 800 (Al coated), E-Brite 26-1, RA 333 and Stellite 6B showed good corrosion resistance in the feed gas.

HYDROGEN SULFIDE effects on hot gas corrosion rates of twenty-one alloys have been measured at H_2S concentrations up to 1.0 percent in typical coal conversion atmospheres. Typical tests were run at 1000 psi at temperatures of 1500 °F and 1800 °F. In most cases, test results were obtained on a single test specimen of each alloy. Exposure time was usually 1000 hours. The equilibrium gas 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

Tabulated test data appear in Sections B.1.1.17, B.1.1.18, and B.1.1.126.

Results at 1500 and 1800 °F appear in Figures A.2.4.2.2.1i and j, respectively. The influence of temperature on corrosion rate is significant. For example, the corrosion rate of Type 309 stainless steel increased dramatically as temperature increased from 1500 to 1800 °F. In general, corrosion rates increased by a factor of 3 to 5 as temperature increased from 1500 (Figure i) to 1800 °F (Figure j). Most of the alloys tested show a rather weak dependence of corrosion rate on hydrogen sulfide concentration, Section B.1.1.126. Types 309 and 316 stainless steels showed strong increases in corrosion rate as hydrogen sulfide concentration increased to 1.0 percent. A few alloys showed a decrease in corrosion rate with increasing hydrogen sulfide concentration, such as IN 800 at 1500 °F and HD 45 stainless steel at 1800 °F. The best performance at 1800 °F was shown by alloy X, Co-Cr-W No. 1, IN 671 and Crutemp 25 for the range of hydrogen sulfide between 0 and 1.0 percent. Types 309, 310, and 446 stainless steels and IN 671 showed the best performance at 1500 °F over the range of hydrogen sulfide concentrations.

THE PERFORMANCE OF WELDED JOINTS in the hot gas environment of a coal conversion plant is of major interest. Some laboratory tests were run to

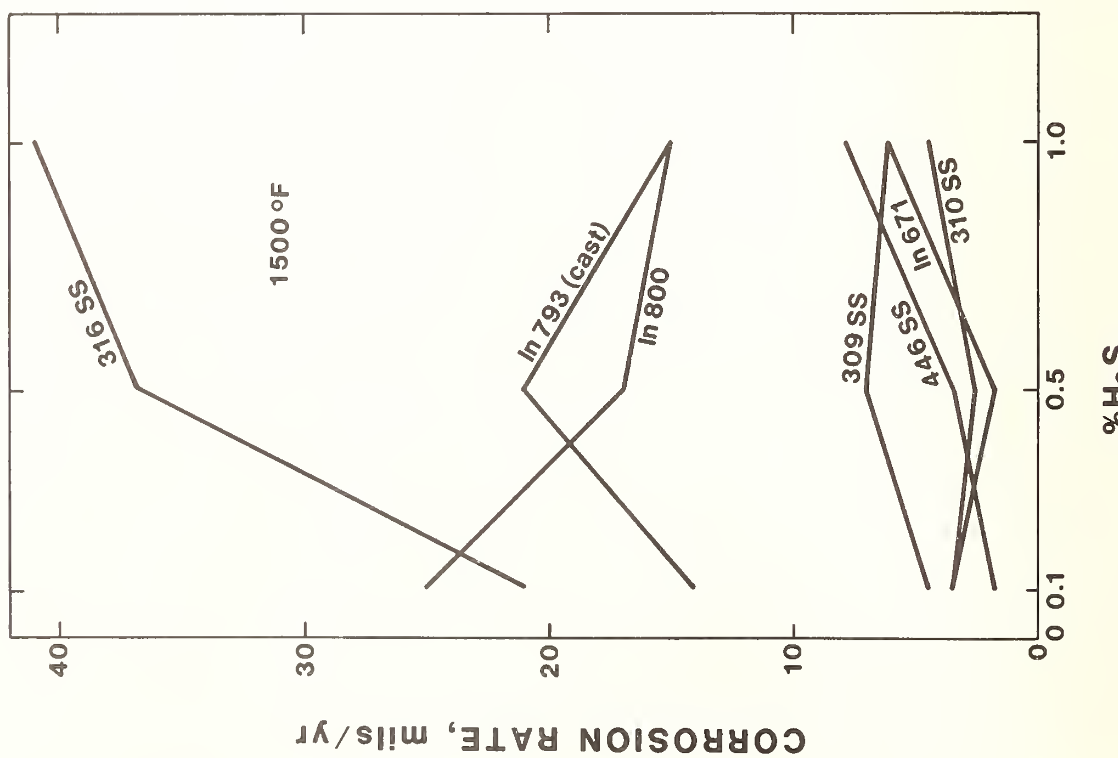


Figure A.2.4.2.2.1i

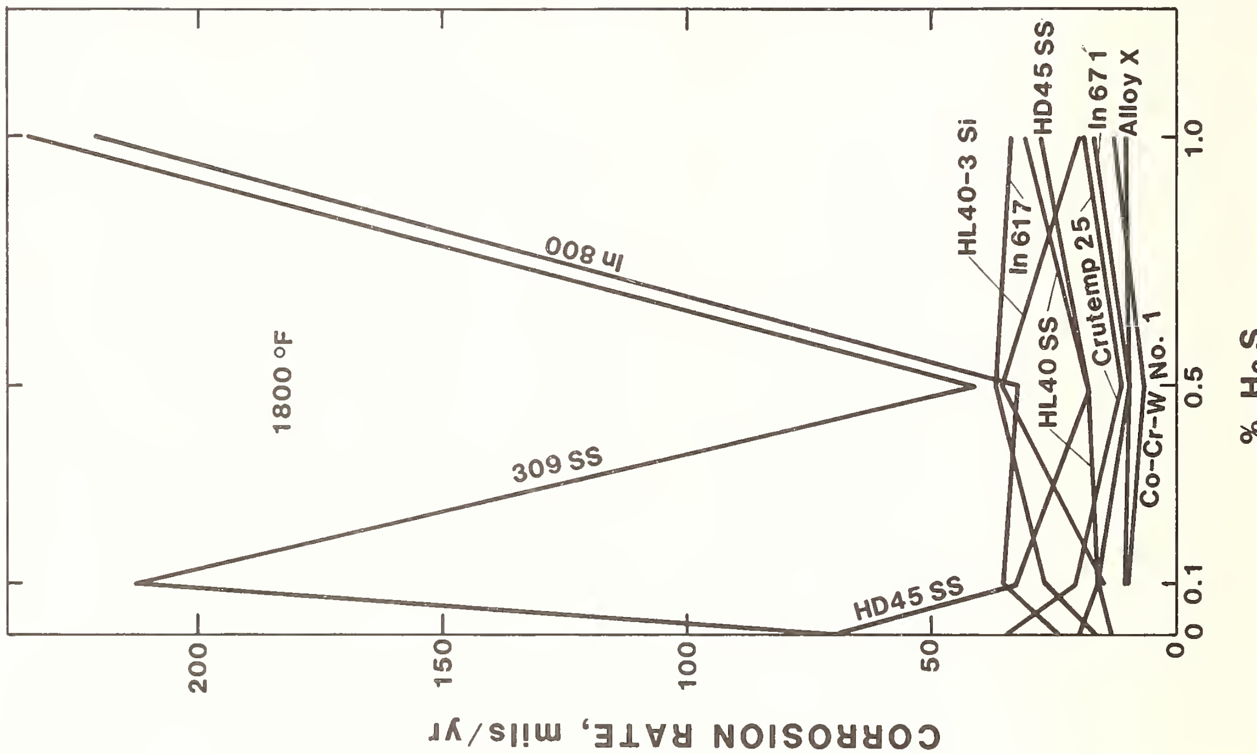


Figure A.2.4.2.2.1j

evaluate performance. Tests were run at 1800 °F and 1000 psi. In most cases, test results were obtained on a single test specimen of each 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 different weld metals were used for the root and cover passes of a single weld to expedite the hot gas corrosion tests. Test data appear in Section B.1.1.24.

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

Some tests were conducted to determine the effects of exposure to a coal gasification atmosphere on weldments made with Types 304 and 310 stainless steel and Incoloy 800H base metal welded with AWS-ER 309, Inconel 72 and R 139 filler metals (Sections B.1.1.112-.117 and .130). Three welding processes were used: submerged arc, gas-metal arc, and gas-tungsten arc with a hot wire addition. Exposures were for 1000 hours at 1800 °F. Effects included scale formation, internal oxidation and sulfidation, and a modest redistribution of elements near the overlay/substrate interface. Elemental distribution near the scale/substrate interface is shown for the substrates in Section B.1.1.115 and for the welding process in B.1.1.116. Elemental distributions before and after

Specimen Number	HAZ Cover Area IN 800H	WELD-COVER (Gas-Tungsten Arc Weld) RA-330-04-15	RA-333-80-16	Metrode 50Cr-50Ni	IN 617	Ranking	HAZ Root Area IN 800H	WELD-ROOT (Shielded Metal Arc Weld) RA-330-04	RA-333	IN 72	IN 617	Ranking
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 IN 800H	WELD-COVER (Gas-Tungsten Arc Weld) RA-330-04-15	RA-333-80-16	Metrode 50CR-50Ni	IN 617	Ranking	BASE METAL Root Area IN 800H	WELD-ROOT (Shielded Metal Arc Weld) RA-330-04	RA-333	IN 72	IN 617	Ranking
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

exposure appear in Section B.1.1.117. These results show a modest redistribution of elements such as aluminum, nickel, chromium, manganese, and iron near the interface. It is not clear if this redistribution has a significant effect on the rate of corrosion. Elements detected in the scales on the weldments included chromium, iron, oxygen, nickel, aluminum and titanium.

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

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

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

Two alloys were given surface conditioning treatments to evaluate effects of surface condition on corrosion resistance. One alloy was 18Cr-5Al-2Mo-1Hf-balance Fe, and the other was 17Cr-3Si-2Mo-balance Fe. Surface conditioning generally improved the corrosion resistance of the first alloy (see B.1.1.71). A pre-oxidized surface showed the least corrosion. In the case of the second alloy, the surface conditioning did not seem beneficial (see B.1.1.73).

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

Type 304 stainless steel showed a large and consistently increasing weight loss with each cycle, indicating a loss of scale due to spalling. Most other alloys showed a weight gain of 0.1 to 2 mg/cm^2 in the first 3 or 4 cycles, indicating an adherent scale. About seven alloys showed an initial weight gain, followed by a loss. The remaining alloys showed a consistent weight 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 stainless steel, 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. Scale may be adherent or loose, continuous or discontinuous. When adherent scale forms 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. Sulfur partial pressures in a coal gasification atmosphere may range from 10^{5} to 10^{7} atmospheres, whereas the range of oxygen partial pressures is usually much lower, 10^{15} to 10^{20} atmospheres.

Both sulfidation and oxidation reactions can occur internally 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.

Scale formation was studied on sixteen structural alloys to determine the characteristics and types of scales and the elements in the scales, Sections B.1.1.118 and .125. Chromium oxide, silicon oxides and various sulfides were detected. Occasionally, scales were adherent, but in many cases the scales spalled. Elements found in the scales included iron, aluminum, chromium, manganese, sulfur, nickel, cobalt and tungsten.

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. The kinetics of scale formation on Type 310 stainless steel and Incoloy 800 in a mixed gas environment at 1382 to 1832 °F is reported in Sections B.1.1.119-.121. Scale thickness and weight gain increased with increasing exposure times, Sections B.1.1.120, .121. At fixed sulfur pressure, scale thickness and penetration of Incoloy 800 tended to decrease with increased oxygen partial pressure. The kinetics of weight gain for five alloys exposed to a mixed gas atmosphere for up to 160 hours at 1600 °F is reported in Section B.1.1.122. MA-956 showed rather high weight gains in short times, whereas Haynes 188 and C-276 showed the smallest weight gains after 160 hours.

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:

Sulfidation-Oxidation Behavior of Experimental and Commercial Alloys

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
- - - 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: Adherent Oxide	Adherent Sulfide	Spalling Oxide	Internal Sulfide	Sulfide Slag	De-stroyed	Comments
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	Results: Adherent Sulfide	Results: Spalling Oxide	Results: Internal Sulfide	Results: Sulfide Slag	Results: 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 pre-oxidized.
-9Al-30Mn	1800		X	24						X	
-9Al-30Mn	1800		X	24				X	X		Nominally reactive gas; samples pre-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 pre-oxidized.
-10Al-20,30Mn	1800		X	24			X	X			Nominally reactive gas; samples pre-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 pre-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 exposure.
-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

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
Commercial alloys											
309 SS	1800	X	X	24	X						
309 SS	1800	X		96	X						
446 SS	1800	X	X	24	X						
446 SS	1800	X		96	X						
Armco 18SR	1800	X	X	24	X						
Armco 18SR	1800	X		96	X						
310 SS	1800	X	X	24			X				Sulfide slag in a 2nd unequil. test.
310 SS	1800	X		96	X						
310 SS	1550		X	50					X		
310 SS	1800		X	1000	X						Steady state exposure.
310 SS	1800		X	1000			X	X			Cyclical exposure.
Ni-46Cr	1800		X	1000	X						Steady state exposure.
Ni-46Cr	1800		X	1000	X			X			Cyclical test; also internal oxide.
Incoloy 800	1800		X	24	X						
Incoloy 800	1800	X		24 & 96			X				
Inconel 600	1800	X	X	24	X				X		
Inconel 600	1800	X		96	X						
Inconel 657	1800	X	X	24	X				X		
Inconel 657	1800	X		96	X						
Inconel 671	1800	X	X	24	X				X		Spalling oxide in a 2nd unequil. test.
Inconel 671	1550		X	50	X						
Haynes 188	1800	X	X	24			X				
Haynes 188	1800	X		96	X				X		
304 SS	1800	X	X	24					X		
314 SS	1800	X	X	24			X				
RA 333	1800	X	X	24					X		

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

Alloy Groups	Test Temp. °F	No. of Cycles	Results, as above: Adherent Oxide	Adherent Sulfide	Spalling Oxide	Internal Sulfide	Sulfide Slag	De- stroyed	Comments
Fe-Al alloys									
-5,8,10,12,15Al	1800	120			X				
Fe-Al-Cr alloys									
-8Al-10Cr	1800	120	X						
Fe-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						
Fe-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						
Fe-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				
Fe-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

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 was evaluated in terms of the type of deterioration which was observed and was specified as adherent oxide, spalled oxide, sulfide slag, etc. Formation of an adherent oxide is regarded as the best performance, since sulfide penetration can lead to disintegration and eventually to total destruction. Exposures were at 1800 °F for most of the tests for times usually between 24 and 100 hours, although a few 500 and 1000 hour exposures were made. Some exposures involved thermal cycling between 1800 °F and ambient temperatures once each hour to provide a severe test of the adherence of scale. Most of these cycling tests were in air although a few were conducted with a reactive gas. A comparison of the performance of each alloy can be made simply by reference to appropriate columns in Table A.2.4.2.2.1b.

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

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

PILOT PLANT TESTING

<u>EXPOSURE IN GAS PHASE LOCATIONS IN PILOT PLANTS</u> produced performance data on commercial and experimental alloys in actual pilot plant locations. Forty-three alloys were exposed in nineteen different gas phase locations at the following pilot plants: HYGAS, Synthane, CO_2 Acceptor, BI-GAS, BATTELLE, U-GAS, PEATGAS (modified HYGAS plant) and Westinghouse. Temperatures ranged from 580 to 2000 °F. Exposure times were between 50 and 3325 hours. These times are for the hours the plant was operating under coal gasification conditions; standby time is not included, nor are the standby conditions specified which affect the alloy performance. Depth of penetration and total sound metal loss, as determined from metallographic and gravimetric analysis, respectively, were used to describe the extent of corrosion. Full exposure conditions, i.e., concentrations of chemical constituents, and fluctuations of temperature and pressure, are not

known. Consequently, the corrosion rates reported here must be interpreted cautiously. Test results appear in Section B.1.1.27.

Table A.2.4.2.2.1c shows a ranking of the results. The performance of each alloy in each plant location can be determined from the appropriate row and column in the table. The performance of the alloys is expressed as a letter code based on arbitrarily chosen limits for the total sound metal loss:

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

The locations in the pilot plants where the specimens were exposed are given by the following code used in Table A.2.4.2.2.1c:

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

BA-1, gasifier off-gas
BA-2, combustor off gas

U-1, gasifier off gas, reducing gas

P-1, steam-oxygen gasifer-freeboard section
P-2, hydro gasifier-freeboard section
P-3, gasifier slurry drier-freeboard section

W-1, gasifier-freeboard section
W-2, hot gas cyclone.

Results in Table A.2.4.2.2.1c show that the performance of a given alloy varies with location and exposure conditions.

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

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		BIGAS
Alloys	H-1	H-2	H-3	H-4	H-5	S-1	S-2	C-1	C-2	B-1
304 SS	s	s		s-e	e	u-e	u-s	s-e	u	
309 SS	e-s	s-e	e-s			u-e	u-s	s-e	u	u
310 SS	e-s	e	e					s-e	u	s
310 SS (Al)	e-s	s	s-u					u-s	u	u
310 SS (Cr)								e-s	s-u	
314 SS									u	s
316 SS	s	s		e-s	e	u-s	u-s			
321 SS	s	e-s				u-s	u-s			
410 SS				s	e-s					
430 SS	s	e-s		e-s		s	u-s			
446 SS	s	e	e						s-u	s
HK-40									u	
HL-40									u	
HC-250									u	
Armco 21-6-9	s	e-u				u-s	u-s	s	u	
Armco 22-13-5	e	e-s				u-s	u-s	s-e	u	s
IN-793	s	e	e-s					s	u	u
Carbon Steel (A515)				e-u	s					
Carbon Steel (Al)				s	e-s					
Crutemp 25									u	
Monel 400				u						
Inconel 600	u	u		s-u		u	u			
Inconel 601	s	u-e	e-s			u-s	u-s			
Inconel 617										s
Inconel 671	e-s	e	e-s					e	u	u
Incoloy 800	e-s	s-e	e-s	e-s		u-e	u-s	s-e	u	u
Incoloy 800 (Al)	s	s	s-u					s	u	u
Incoloy 800 (Cr)								s	u	
Incoloy 825	s	e				s-e	u-e	e-s	u	
RA 330									u	u
RA 333	e-s		e-s			e-u	u-e		u	s
Alloy X	e	s-e				s-e	u-s	s	u	
Haynes 150									u	
Haynes 188									u	s
Titanium				e						
Multimet N155										e
1/2 Mo Steel				s						
5Cr-1/2Mo Steel				s-u						
Stellite 6B										s
556										s
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 Continued)

Table A.2.4.2.2.1c (see text for key)

RANKING OF CORROSION PERFORMANCE OF ALLOYS EXPOSED TO GAS PHASE LOCATIONS IN COAL GASIFICATION PILOT PLANTS (Continued)

	Gasification Plant and Test Location							
	BATTELLE		U-GAS	PEAT GAS			WESTINGHOUSE	
Alloys	BA-1	BA-2	U-1	P-1	P-2	P-3	W-1	W-2
304 SS				s	s	e		
309 SS	u	u		s	e			
310 SS	u	u	s-u	s	s		s	s
310 SS (A1)	u	u	u	e	e		s	u
316 SS					e	e		
321 SS					e			
329 SS							s	
410 SS						e		
430 SS					e	e		
446 SS				s	e			
HK-40			u			e		
HL-40			s					
HC-250	u	u						
Armco 18SR							s	
Armco 21-6-9					e			
Armco 22-13-5					e			
IN-793	u	u		s				
Carbon Steel (A515)						s		
Carbon Steel (A1)						e		
Inconel 617							u	
Inconel 671	u	u	s	s			s	s
Incoloy 800	u	u	s	e	e	e	s	
Incoloy 800 (A1)	u	u		e			u	
Incoloy 825							s	
RA 333	u	u	s-u	e				
Alloy X	u	u	s-u		s	e	u	
Haynes 188			s-u				u	
Titanium 50A						e		
Supertherm 63WC			s-u					
Stellite 6B			s			s		
Multimet N155			s				s	
E-Brite 26-1							s	u
1/2Mo Steel						e		
5Cr-1/2Mo Steel						e		

Table A.2.4.2.2.1c (see text for key)

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
$MgO \cdot ZrO_2$ 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--GASIFICATION

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.2.1.1-.14, B.2.1.21-.22, and B.2.1.46-.51. 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° (see Section B.2.1.47). 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. Most erosion test results reported in Sections B.2.1.1-.14, B.2.1.21-.22, and B.2.1.46-.51 were obtained with Al_2O_3 as the erodent. Sometimes SiC, SiO_2 or pumice was used as an erodent. Erosion due to char, ash, and coal particles is yet to be thoroughly evaluated.

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, and B.2.1.49 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 <u>increased</u> 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

<u>EROSION TESTING</u> 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 indicate a more erosion resistant material than Stellite 6B, values greater than one indicate 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 temperatures may be rather different. Further data are required for definitive choices to 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 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, B.2.1.21-.22, and B.2.1.46-.51. 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. The effect of impingement angle between 15 and 90° on the erosion rate of six alloys appears in Section B.2.1.47; in general, 1015 carbon steel shows the lowest erosion rate, whereas Type 310 stainless steel shows the highest erosion rate. 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 HRC 37 to HRC 52. Chromium metal showed slightly better than average resistance to erosion, whereas chromium plate on steel consistently showed much better than average erosion resistance. For a variety of test conditions, Inconel 671 showed better erosion resistance than any of the other ten materials tested.

Nickel-base alloys for coating and cladding use have been erosion tested at 25 °C with SiC at 90° impingement angle. The coatings were applied to a low carbon steel substrate by three different methods. The data are reported in Section B.2.3.4.

A.2.4.2.2.3 EROSION/CORROSION--GASIFICATION

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 oxygen or sulfur which may produce spalling oxides or sulfide scales. These reactions are 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. Results of laboratory tests have been reviewed. The effects of different combinations of the variables cited above are analyzed in separate sections below. The evaluation in each section focuses on the effect of one variable on erosion/corrosion, e.g., temperature, type of erodent, coatings, etc. For some alloys, preoxidation and coatings improved erosion/corrosion resistance. Among six coatings, magnesium zirconate showed the best performance.

LABORATORY TESTS

EROSION/CORROSION EFFECTS on as many as nineteen alloys have been measured under coal gasification conditions (see B.2.1.23-.26, B.2.1.44-.45 and B.2.1.52). Test samples were exposed to a stream of erodents at an impingement angle of 45° in a coal gasification atmosphere. Three tests were also run in a nitrogen atmosphere to evaluate the erosion effects of the gas alone. Test variables were temperature, pressure, H_2S concentration, particle velocity and size, and type of erodent. The particle size ranged from -20 + 40 mesh (800 to 420 μm) and -30 + 50 mesh (600 to 300 μm) to -100 + 140 mesh (149 to 105 μm). Most tests were given with a particle size of -20 + 40 mesh.

Samples 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 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. One factor to keep in mind in examining the data is that the tests were all of rather short duration, 250 hours or less

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 loss in various tests for which the conditions were the same for any given test set. There are not multiplicate data for all the alloys tested.

Alloy	Max E/C Loss, mils						
Test Set	1	2	3	4	5	6	7
Incoloy 800	130.1 118.2 1.0 165.5	39.7 1.2 0.7	50.9 201.3	27.4 68.8 44.4 4.4		74.1 31.2	12.8 1.5 7.6
Inconel 601	1.0 31.6	33.9 4.1		15.8 26.3			
310 SS	1.7 9.1 14.5	15.6 0.6		12.1 12.2 13.0			
Inconel 671	0.9 0.9 0.9 1.1	0.9 0.8 0.8	7.6 1.1	3.9 0.8 1.5 8.2	1.2 1.3	0.9 1.7	1.2 1.1 1.2
446 SS	5.6 11.9 1.2			18.6 10.4 15.9			
Haynes 188	0.5 0.7 0.2	17.1 1.1		2.5 1.5 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 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 loss 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 Loss, 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 Loss, mils		Max E/C Loss, 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

Alloy	Test Conditions: atm pressure, particle velocity 100 ft/s, 100 hours, 1.0 percent H_2S, coarse Husky char — Max E/C Loss, mils		Test Conditions: 1000 psi, particle velocity 100 ft/s, 50 hours, 1.0 percent H_2S, coarse Husky char — Max E/C Loss, 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 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.

Alloy	Test Conditions: 1800 °F, gas velocity 100 ft/s, 100 hours, 1.0 percent H_2S, no erodent used — Max E/C Loss, mils		Test Conditions: 1800 °F, particle velocity 50 ft/s, 50 hours, 1.0 percent H_2S, coarse Husky char — Max E/C Loss, 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 loss 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 Loss, mils		Max E/C Loss, 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 Loss, mils		Max E/C Loss, 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. This appears to be due to 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 show a marked decrease in material loss at the higher H_2S concentration.

INCREASING PARTICLE VELOCITY generally results in an 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 Loss, 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

	Test Conditions: 1800 °F, 1 atmosphere, 100 hours, 1.0 percent H_2S, coarse FMC char		Test Conditions: 1800 °F, 1000 psi, 50 hours, 1.0 percent H_2S, coarse FMC char	
Alloy	Max E/C Loss, mils		Max E/C Loss, mils	
	50 ft/s	100 ft/s	50 ft/s	100 ft/s
Incoloy 800	2.3	27.4, 68.8, 44.4, 4.4	33.6	50.9, 201.3
Incoloy 800 (Al)	5.6	3.6	1.9	1.1
Inconel 601	12.1	15.8, 26.3	135.1	36.2
310 SS	6.8	12.1, 12.2, 13.0	5.0	25.3
310 SS (Al)	2.6	1.5	1.3	2.9
RA 333	19.4	5.7	90.4	14.9
LM-1866	2.7	14.4	16.9	9.1
446 SS	3.9	18.6, 10.4, 15.9	7.3	20.6
Inconel 671	0.5	3.9, 0.8, 1.5, 8.2	2.5	7.6, 1.1
Crutemp 25	2.3	10.9	1.7	23.9
Haynes 188	7.9	2.5, 1.5, 0.7	106.0	75.7

Alloy	Test Conditions: 1650 °F, 1000 psi, 100 hours, 1.0 percent H_2S, no solid erodent — Max E/C Loss, mils		Test Conditions: 1800 °F, 1000 psi, 100 hours, 1.0 percent H_2S, no solid erodent — Max E/C Loss, 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

Alloy	Test Conditions: 1800 °F, 1 atmosphere, 50 hours, 1.0 percent H_2S, coarse Husky char — Max E/C Loss, mils		Test Conditions: 1800 °F, 1000 psi, 50 hours, 1.0 percent H_2S, coarse Husky char — Max E/C Loss, 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 Loss, 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 definite effect of particle size.

THE ERODENT MATERIAL might be expected to affect the erosion/corrosion metal loss. Various materials, Husky char, FMC char, spent char, coke, alumina, and dolomite were used as solid erodents. Some testing was done without adding solid erodent to evaluate the effect of the impinging gas stream by itself.

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

Alloy	Max E/C Loss, mils			
	No Erodent	Husky Char	FMC Char	Spent Char
Incoloy 800	0.5	0.8, 48.3	27.4, 68.8, 44.4, 4.4	6.7, 13.9
Incoloy 800 (Al)	1.2	3.5	3.6	2.3
Inconel 601	0.7	6.7	15.8, 26.3	0.9
310 SS	0.6	0.7	12.1, 12.2, 13.0	1.5
310 SS (Al)	0.5	2.4	1.5	2.3
RA 333	0.4	2.3	5.7	0.8
LM-1866	0.5	3.3	14.4	2.5
446 SS	0.5	1.1	18.6, 10.4, 15.9	2.4
Inconel 671	0.7	1.2, 1.3	3.9, 0.8, 1.5, 8.2	1.3, 1.7
Crutemp 25	0.7	0.7	10.9	2.1
Haynes 188	0.7	0.8	2.5, 1.5, 0.7	1.4

	Test Conditions: 1800 °F, 1 atmosphere, particle velocity 100 ft/s, 50 hours, 1.0 percent H_2S				Test Conditions: 1800 °F, 1 atmosphere, particle velocity 50 ft/50 hours, 1.0 percent H_2S	
Alloy	Max E/C Loss, mils				Max E/C Loss, mils	
	Alumina	Dolomite	Husky Char	Coke	Alumina	Husky Char
Incoloy 800	1.7	0.6	0.6	5.1	5.8	0.3
Incoloy 800 (Al)	5.4	0.6	3.5	0.9	8.9	0.6
Inconel 601	2.2	0.5	0.6	5.7	0.7	0.7
310 SS	0.8	0.5	0.5	5.6	2.5	0.7
310 SS (Al)	1.9	1.0	0.9	1.2	1.3	3.0
RA 333	1.2	0.5	0.4	1.9	7.6	0.7
LM-1866	2.9	0.7	1.7	5.7	1.3	0.4
446 SS	2.2	0.6	0.8	5.5	1.5	0.9
Inconel 671	1.6	0.8	1.3	3.7	0.5	1.0
Crutemp 25	1.9	0.6	1.2	8.9	14.0	0.5
Haynes 188	1.0	0.6	0.6	5.8	1.2	0.7

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

Alloy	Max E/C Loss, mils	
	Husky char	FMC char
Incoloy 800	155.6	33.6
Incoloy 800 (Al)	1.6	1.9
Inconel 601	0.7	135.1
310 SS	10.5	5.0
310 SS (Al)	4.0	1.3
RA 333	5.1	90.4
LM-1866	3.5	16.9
446 SS	10.9	7.3
Inconel 671	7.8	2.5
Crutemp 25	9.7	1.7
Haynes 188	1.0	106.0

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

Alloy	Max E/C Loss, mils			
	Husky char	FMC char	Spent char	Coke
Incology 800	31.9	50.9,201.3	35.9	98.5
Incology 800 (Al)	1.5	1.1	0.8	5.2
Inconel 601	37.9	36.2	85.4	212.3
310 SS	10.7	25.3	1.7	72.8
310 SS (Al)	3.1	2.9	1.4	3.1
RA 333	46.6	14.9	20.4	86.4
LM-1866	13.9	9.1	1.2	0.9
446 SS	17.8	20.6	3.8	10.8
Inconel 671	72.4	7.6, 1.1	3.2	1.2
Crutemp 25	27.1	23.9	0.8	64.0
Haynes	9.8	75.7	37.4	23.7

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

Alloy	Max E/C Loss, mils		
	Husky char	FMC char	Spent char
Incoloy 800	74.1, 31.2	130.1, 118.2, 1.0, 165.5	0.6, 1.1
Incoloy 800 (Al)	0.5	0.9	2.2
Inconel 601	2.4	1.0, 31.6	0.7
310 SS	1.8	1.7, 9.1, 14.5	1.4
310 SS (Al)	1.1	1.2	1.6
RA 333	0.8	0.5	1.2
LM-1866	0.2	7.0	0.3
446 SS	1.3	5.6, 11.9, 1.2	1.2
Inconel 671	0.9, 1.7	0.9, 0.9, 0.9, 1.1	1.1, 1.7
Crutemp 25	1.2	0.6	1.2
Haynes 188	0.9	0.5, 0.7, 0.2	0.3
Stellite 6B	0.8	0.6	0.8
Wiscalloy 30/50W	0.7	3.0	13.6
HK-40 SS	0.8	6.2	7.6
Alloy X	5.8	22.6	14.4
Sanicro 32X	4.0	113.8	0.7
Multimet N155	21.3	3.2	0.9
Haynes 150	3.0	0.7	0.7
Supertherm T63WC	0.8	4.7	0.7
HL-40 SS	2.5	4.0	0.7
329 SS	2.0	1.6	0.8

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

Alloy	Max E/C Loss, mils		
	Husky char	FMC char	Spent char
Incoloy 800	12.8, 1.5, 7.6	10.8	26.8
Incoloy 800 (Al)	3.1	5.4	1.0
Inconel 601	137.6	53.3	38.8
310 SS	2.4	2.0	3.8
310 SS (Al)	1.5	0.7	0.8
RA 333	63.5	11.0	48.2
LM-1866	1.1	2.6	1.7
446 SS	2.0	1.9	2.2
Inconel 671	1.2, 1.1, 1.2	3.8	12.5
Crutemp 25	3.8	5.5	2.9
Haynes 188	13.4	49.8	44.7

Some trends may be seen in the above data. An obvious, and expected, result is that the least erosion/corrosion occurs when the impinging gas carries no solid erodent as compared with tests in which char is present. Also to be expected is that the larger metal loss occurs when alumina is used as an erodent as compared with either dolomite or char, since alumina, commonly used as abrasive, is much harder than the other two materials. In comparing the results for the two different chars, the situation is not clear cut. In some tests the FMC char appears to cause greater metal loss but examination of all the tests does not yield a definitive result. Compare Section B.1.1.58, in which data appear for some of these same alloys in tests conducted in coal gasification atmospheres in which the alloys were in static contact with the same two chars used in these erosion/corrosion tests. The FMC char, with a higher sulfur content, had a much greater corrosive effect than did the Husky. Coke causes a substantial erosion/corrosion loss which is greater than the loss from Husky or FMC char for a number of alloys. Spent char can cause losses for many alloys which are comparable to or greater than the losses for fresh Husky or FMC char.

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

Alloy	Max E/C Loss, mils		Average Corrosion, mils	
	Unoxidized	Preoxidized	Unoxidized	Preoxidized
Incoloy 800	45.6	5.8	17.6	0.8
Inconel 601	27.6	24.7	8.7	1.7
310 SS	8.0	1.7	0.5	0.7
RA 333	56.6	26.7	29.6	3.7
LM-1866	23.0	1.4	1.1	0.4
446 SS	18.8	5.3	1.3	0.3
Crutemp 25	6.1	3.7	1.1	0.7
Haynes 188	27.5	9.7	1.0	2.7

The corrosion losses tabulated above indicate that pre-oxidation in an atmosphere containing water vapor is generally beneficial in reducing the amount of corrosion loss for hot-gas corrosion as well as for erosion/corrosion. The formation of a continuous adherent protective oxide 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 fact 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 Loss, 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 shows performance of 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 Loss 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.

Alloy	Number of Test Values in Max E/C Range		Total Number of Test Values
	0-5.9 mils	> 6.0 mils	
Inconel 671	66	14	80
Incoloy 800 (Al)	57	7	64
310 SS (Al)	55	6	61
LM-1866	47	17	64
446 SS	76	27	103
Haynes 188	47	23	70
Crutemp	33	29	62
310 SS	47	33	80
RA 333	28	37	65
Inconel 601	32	32	64
Incoloy 800	60	45	105

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

Alloy	Number of Test Values in Max E/C Range		Total Number of Test Values
	0-5.9 mils	> 6.0 mils	
CoCrW No. 1	35	4	39
Stellite 6B	40	0	40
Haynes 150	9	1	10
Supertherm T63WC	8	2	10
HL-40	7	0	7
329 SS	7	0	7
HK-40	5	4	9
Wiscalloy 30/50W	5	4	9
Multimet N155	7	3	10
Sanicro 32X	5	5	10
Alloy X	6	4	10

COATINGS FOR EROSION/CORROSION PROTECTION are being investigated. Refractory coatings on several substrates have been tested to determine their effectiveness in providing erosion/corrosion protection to alloys under 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--GASIFICATION

OVERVIEW

Some metal internal components must support loads under conditions of gaseous corrosion, particularly from sulfur at elevated temperatures in the range, 1200 to 1800 °F. The mechanical properties of structural materials which are of interest for metal internal components include stress rupture and creep, high-temperature tensile properties, fatigue and creep fatigue, hardness, and toughness. 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. The data which have been generated on the mechanical properties of metals exposed to coal gasification environments are limited principally to stress rupture and tensile data. The few preliminary results which are available indicate that exposures to a coal gasification atmosphere can reduce stress rupture life and tensile ductility. Furthermore, test results indicate that prolonged exposure at elevated temperatures can lead to a reduction in 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 STRESS RUPTURE TESTS were carried out on ten alloys to determine the effect of exposure to a coal gasification atmosphere on stress rupture life. Test results were reported on base metal (Sections B.3.1.14, .164, .167 and .169), and on weldments (Sections B.3.1.13, .165, .168 and .169). Tests were conducted at 1200, 1500 and 1800 °F in air and in a standardized coal gasification atmosphere. Lifetime to rupture ranged from 2 to 10,000 hours depending upon the temperature and the alloy. Stress rupture plots of applied stress and effective stress vs. temperature for Haynes 188 and RA 333 (Section B.3.1.166) showed the same trends. Although there is considerable scatter in the data, the data generally show a tendency toward shorter rupture lifetimes for exposures in coal gasification atmospheres as compared to exposures in air. This is evident for both base metal and weldments, as indicated in the graphs plotted in Sections B.3.1.167-.169. Rankings of alloy performance appear in Section B.3.1.15. The rankings show that Stellite 6B supported the highest stress for a 1000-hour stress rupture life test. The next most favorable materials for 1000-hour stress rupture lives were Haynes 188 and HK-40.

Some results of stress rupture performance of weld overlays tested in air appear in Sections B.3.1.78, .79, and .82. The three weld metals used were AWS-ER 309, Inconel Filler Metal 72, and R139. Substrate alloys were Types 304L and 310 stainless steels and Incoloy 800H. Three welding processes were used, as noted in Section B.3.1.82. Stress rupture tests were conducted at 982 °C. The 1000 hour rupture stress was reported. Welds made with R139 generally showed the highest 1000 hour rupture stress.

BIAXIAL STRESS RUPTURE TESTS were carried out on four alloys (Sections B.3.1.25, .26, .95-.97) in air and in simulated coal gasification atmospheres. The tubular specimens were exposed at temperatures between 1200 and 1800 °F. Each alloy showed a substantially shorter stress rupture lifetime for exposures in coal gasification atmospheres as compared to exposures in air (Sections B.3.1.25, .26, .95 and .97). The analysis of performance in Section B.3.1.26 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 Alonized 800H. The effect of exposure to a coal gasification atmosphere was to reduce the biaxial stress rupture life for the four alloys investigated. Axial cyclic loading of Incoloy 800H did not have a notable effect on lifetime.

UNIAXIAL TENSILE PROPERTIES/EXPOSURES TO COAL GASIFICATION ATMOSPHERE - Uniaxial tensile properties of several alloys were measured after exposure to a coal gasification atmosphere. Data on unwelded alloys appear in Sections B.3.1.9-12, B.3.1.22-.24, B.3.1.27, B.3.1.31, B.3.1.80, B.3.1.84, and B.3.1.86. Data on welded alloys appear in Section B.3.1.13, and data on weld overlays appear in Section 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.

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

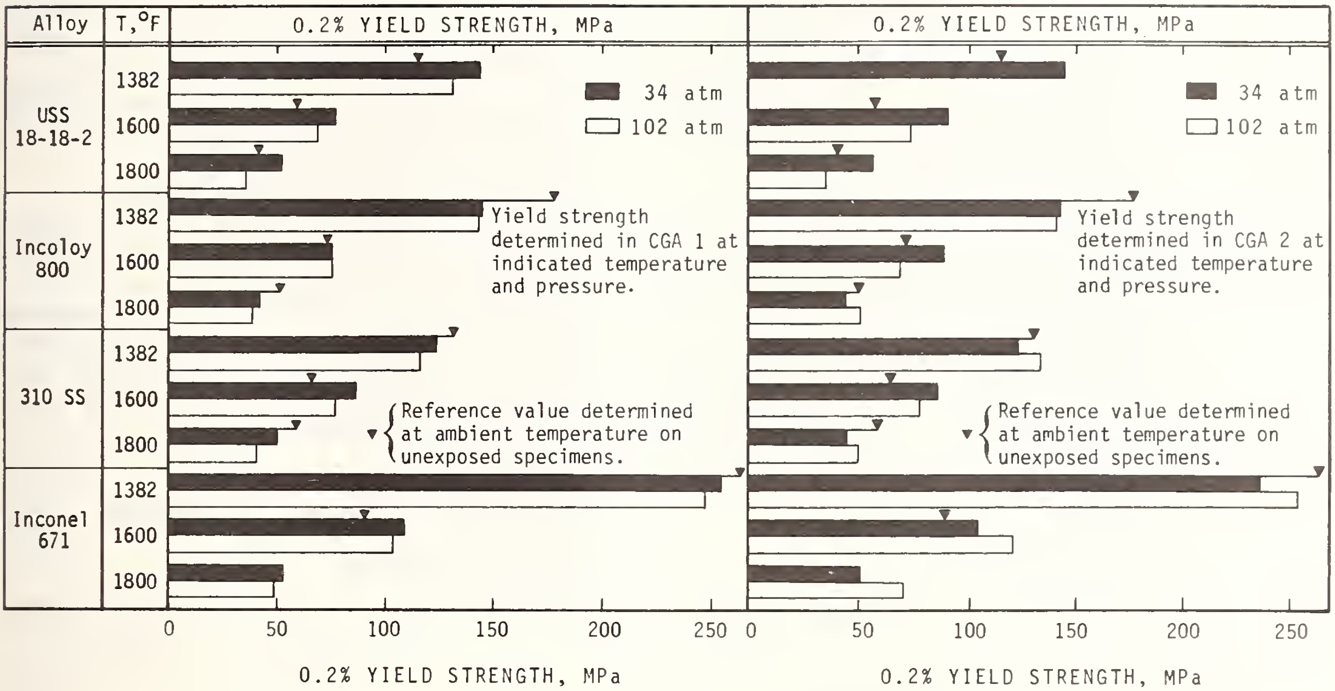


Figure A.2.4.2.2.4a

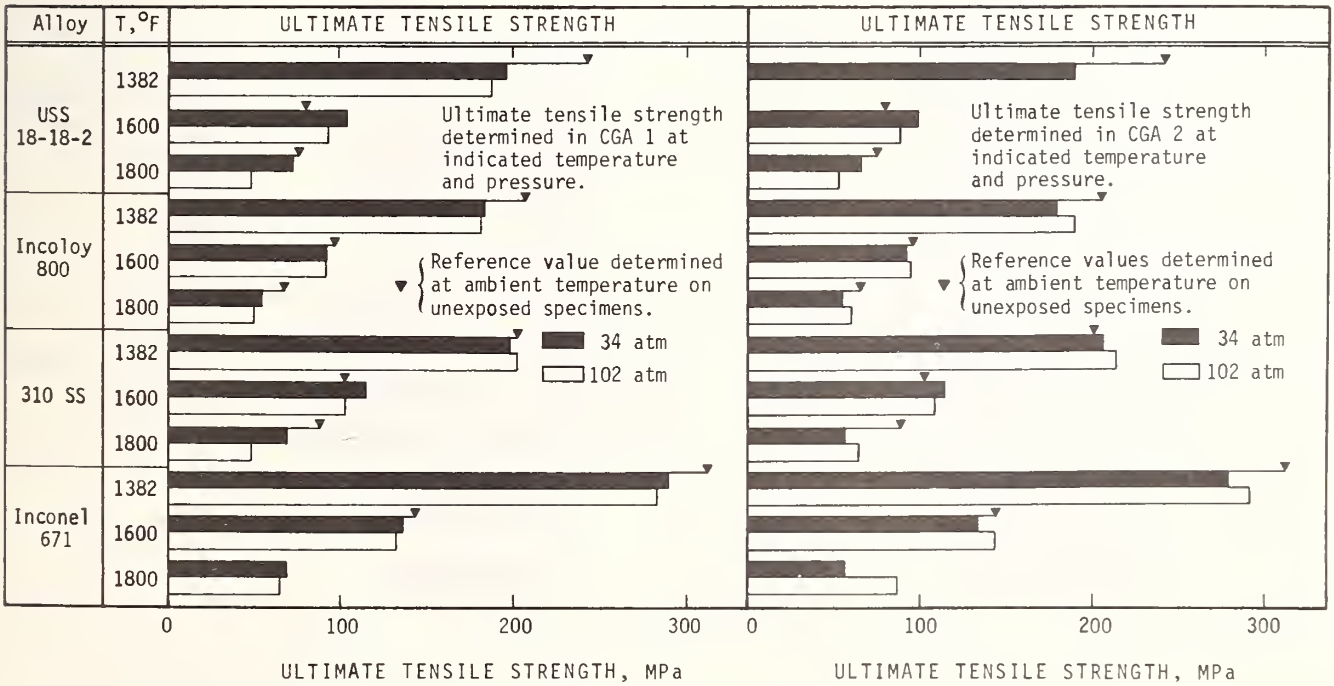


Figure A.2.4.2.2.4b

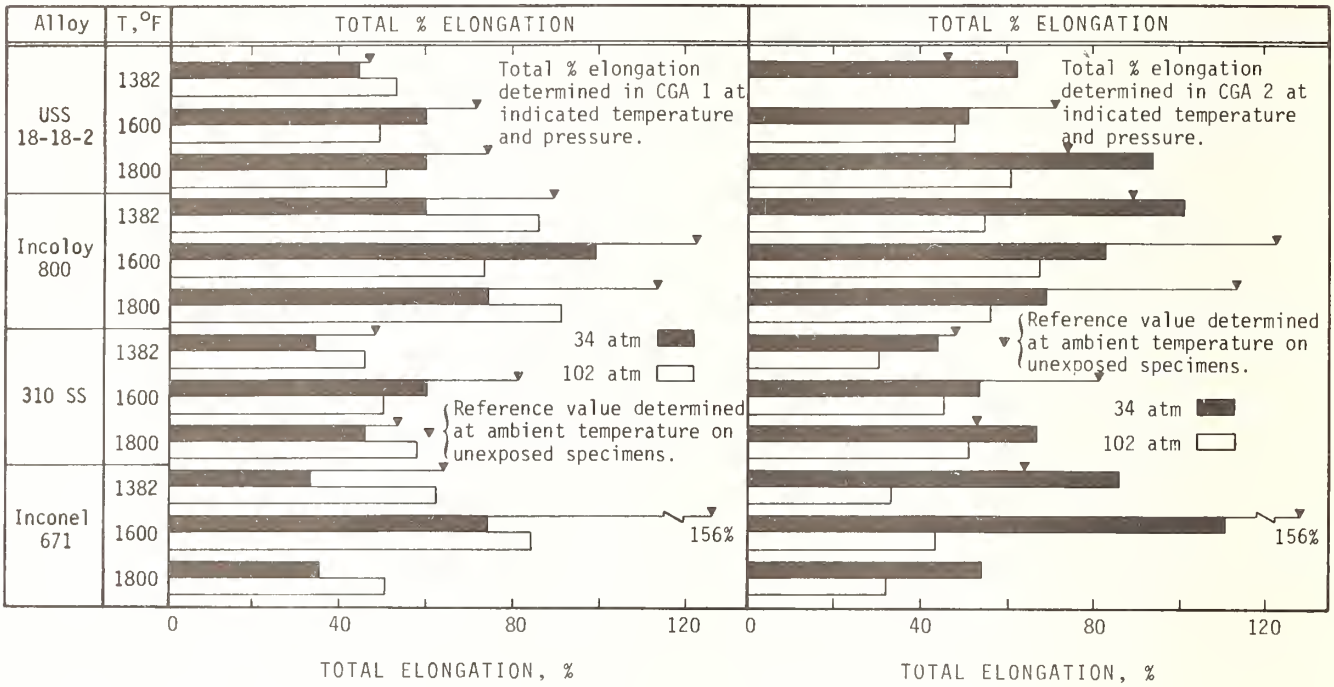


Figure A.2.4.2.2.4c

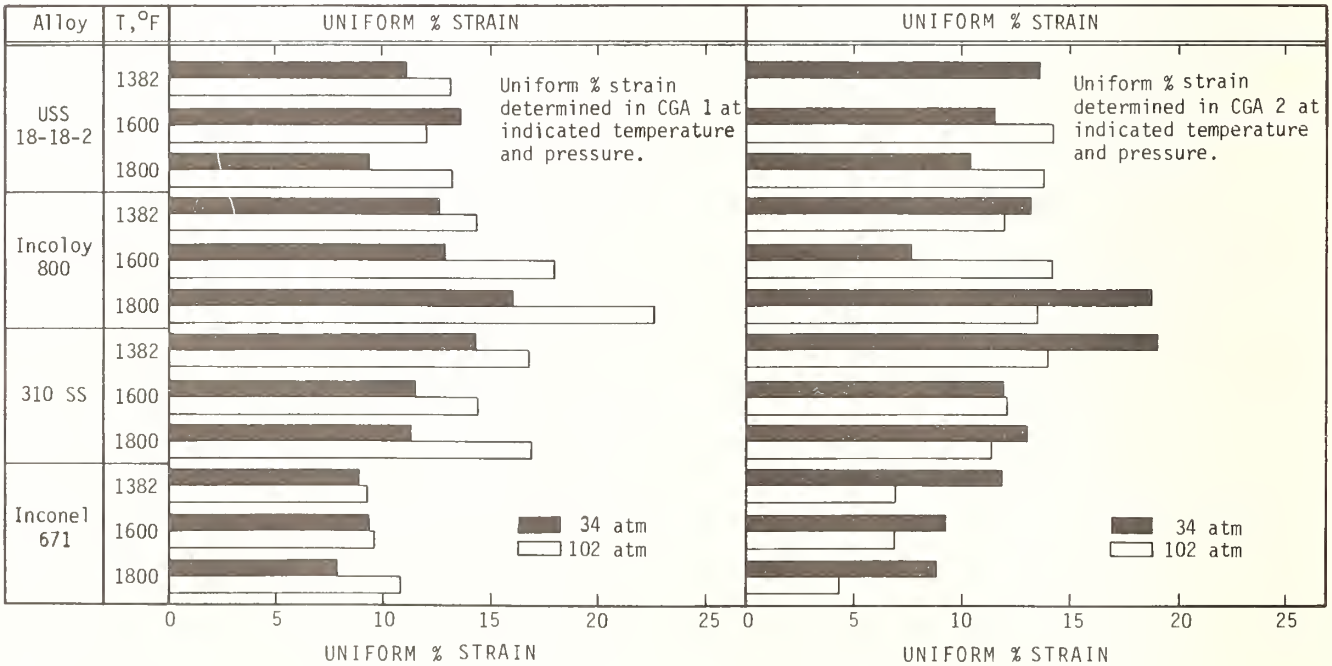


Figure A.2.4.2.2.4d

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 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 for ultimate tensile strength and ductility are compared 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.

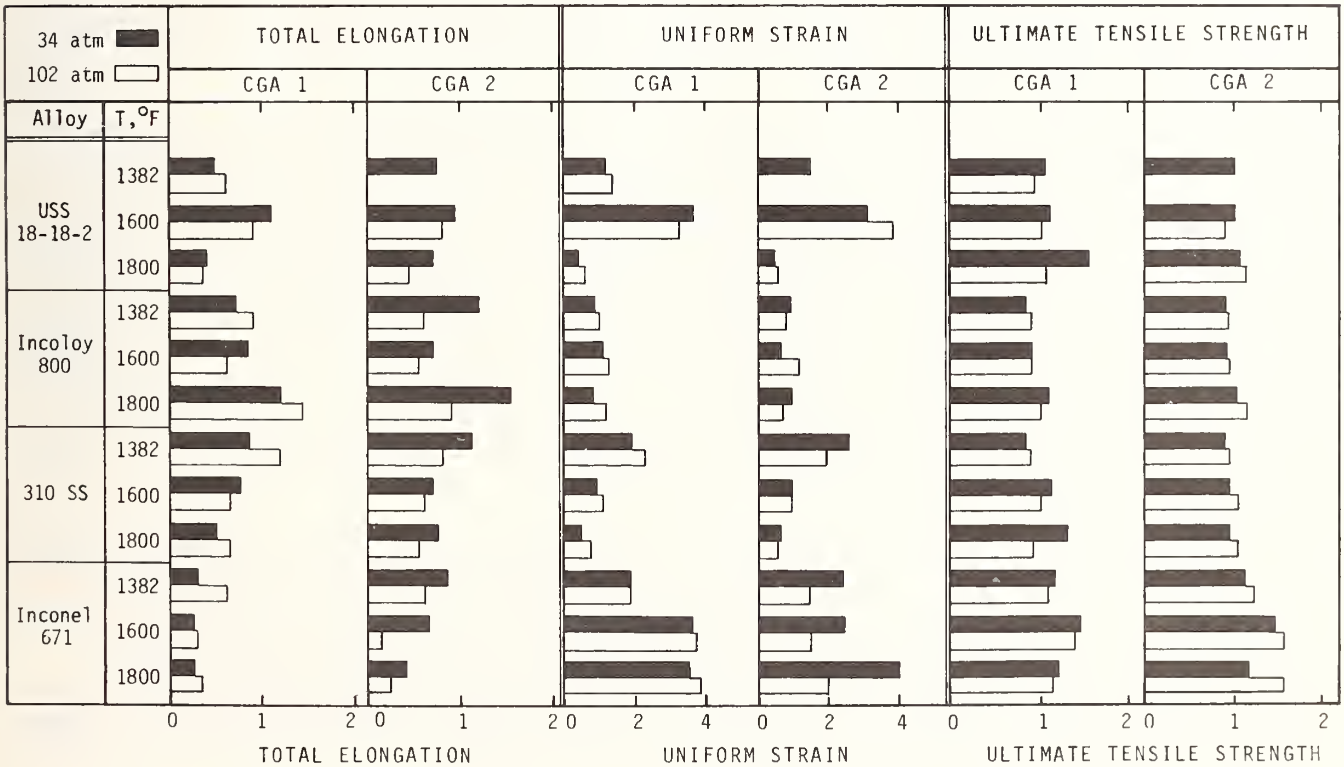


Figure A.2.4.2.2.4e

Some elevated temperature tensile curves for 18-18-2 stainless steel, Incoloy 800, Type 310 stainless steel, and Inconel 671 obtained after exposures to a coal gasification atmosphere for 1000 hours at temperatures between 750 and 982 °C are reported in Sections B.3.1.84 and .86. In general, these plots of engineering stress vs. engineering strain, and true stress vs. true strain, show that the entire tensile curve dropped noticeably as a result of exposure to a coal gasification atmosphere. Furthermore, tensile ductility, as measured by engineering strain or true strain to fracture, dropped precipitously in most tests after exposure to a coal gasification atmosphere. The effect of temperature and pressure on the ultimate tensile strength of these four alloys is reported in Section B.3.1.80.

WELDED ALLOYS 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.

WELD OVERLAYS 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.

The change in tensile properties of some weld overlays due to a 1000 hour exposure in a coal gasification atmosphere at 982 °C is reported in Section B.3.1.83. The three weld metals used were AWS-ER 309, Inconel Filler Metal 72, and R139. Substrate alloys were Types 304L and 310 stainless steels, and Incoloy 800H. Three welding processes were used, as noted in Section B.3.1.83. In general, tensile properties decreased significantly following exposure. The yield strength showed decreases as high as 40 to 50% for various combinations of weld metal, substrate and welding process.

TENSILE DATA ON ALLOYS NOT EXPOSED TO A COAL GASIFICATION ATMOSPHERE are summarized in Section B.3.1.32-.34, .39, .85, and .94. 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.

Increasing temperature from 750 to 982 °C caused the true stress-true strain curves of 18-18-2, Incoloy 800, Type 310 stainless steel and Inconel 671 to drop noticeably (Section B.3.1.85). True strain to fracture increased significantly for Type 310 stainless steel and Inconel 671, decreased slightly for Incoloy 800 and did not change noticeably for 18-18-2.

The temperature variation of yield strength from room temperature to 900 °C appears in Section B.3.1.94 for Types 316 stainless steel, Hastelloy X and Ni_3Al with some minor alloying additives.

LOW-CYCLE FATIGUE DATA were measured on four alloys at 1500 and 1800 °F (Sections B.3.1.16, and .162). The alloys studies were 310 stainless steel, Incoloy 800H, INCO 657, and RA 330. These alloys were not exposed to a coal gasification atmosphere. Results in Sections B.3.1.16 and .162 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. Typical hysteresis loops for unexposed RA 330 and Type 310 stainless steel exposed to a coal gasification atmosphere appear in Section B.3.1.163.

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.

The change in hardness of weldments which were exposed for 1000 hours at 982 °C in a coal gasification atmosphere is reported in Section B.3.1.81. Two filler metals--R139 and Inconel Filler Metal 72--were placed on three substrates--304L stainless steel, 310 stainless steel and Incoloy 800H. Three welding processes were used--submerged arc, gas metal arc, and gas tungsten arc with a hot wire addition. The R139 welds generally showed a higher change in hardness than did the Inconel Filler Metal 72.

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.

CHARPY IMPACT ENERGIES were measured on six alloys to determine the effect of a 1000 hour exposure in a coal gasification atmosphere 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. Other toughness data for various steels which were not exposed to a coal gasification atmosphere are discussed in Section A.2.1.2.2. Some of the discussion is about evaluations of susceptibility to temper embrittlement.

A.2.4.2.2.5 CORROSION--LIQUEFACTION

OVERVIEW

Liquids formed during the conversion of coals to liquid fuels contain chemical constituents which can cause undesired corrosion of structural materials in coal liquefaction plants. Chemical constituents of coal liquids include nitrogen, chlorine, oxygen, and sulfur compounds. Liquids temperatures may be as high as 650 °F. Structural materials in distillation towers and other plant components which experience corrosive attack from coal liquids include various grades of stainless and carbon steels. Erosion and erosion-corrosion sometimes occur due to coal particulates in the coal liquids.

LABORATORY TESTS

THE CORROSION RESISTANCE of 6 commercial alloys was evaluated in 36 coal liquids taken from various locations within 5 coal liquefaction pilot plants (Section B.1.1.136). CHEMICAL CONSTITUENTS in the coal liquids are listed in Section B.1.1.137. The coal liquids were classified by boiling point range as follows: low-below 425 °F; medium-425 to 575 °F; high-above 575 °F. Corrosion resistance was measured at temperatures from 350 to 650 °F. Experiments determined that there were no detectable changes in chemical composition of the coal liquids as a result of thermal exposure in the temperature range, 600-650 °F. Test results were obtained from one or two test coupons given 100 hour exposures. In general no effort was made to monitor the kinetics of the corrosion process for all of the materials. Some preliminary monitoring of the kinetics of the corrosion of carbon steel was undertaken, however (see Section B.1.1.139).

The six commercial alloys tested were: carbon steel (ASTM A515), chrome-moly steel (ASTM A387), Types 316 and 410 stainless steels, Incoloy 825 and Hastelloy C-276. The latter two alloys showed excellent corrosion resistance, with the maximum rate usually much less than 1.1 mils per year. In general, the two stainless steels showed good corrosion resistance in all the coal liquids at all temperatures up to 650 °F. The chrome-moly steel (ASTM A387) usually showed somewhat poorer corrosion resistance than the stainless steels. Carbon steel showed the highest corrosion rate most often and, in extreme cases, exhibited rates of 68 and 128.2 mils per year.

Figure A.2.4.2.2.5a shows the corrosion rates of the two stainless steels, the chrome-moly steel, and the carbon steel in 30 different coal liquids classified according to boiling point range. These results demonstrate that there is no general trend toward increasing corrosion rate with increasing boiling point range. Rather, it appears that corrosion rate is determined principally by the coal liquid itself. Probably the chemical composition and physical properties of the coal liquid act together to determine the corrosion rate. Results in Figure A.2.4.2.2.5a indicate that the corrosion rates of the two stainless steels were substantially lower than those of the carbon and chrome-moly steels. Furthermore, the figure shows that the Type 316 stainless steel had the best overall corrosion resistance to the majority of the coal liquids. Results in Table B.1.1.138 suggest that the presence of a high concentration of chromium contributes to the high corrosion resistance of Type 316 stainless steel.

The average weight loss of carbon steel (A515) due to corrosion in three coal liquids was monitored during exposures up to 50 hours at temperatures of either 500 or 575 °F (see Section B.1.1.139). The test procedures were designed

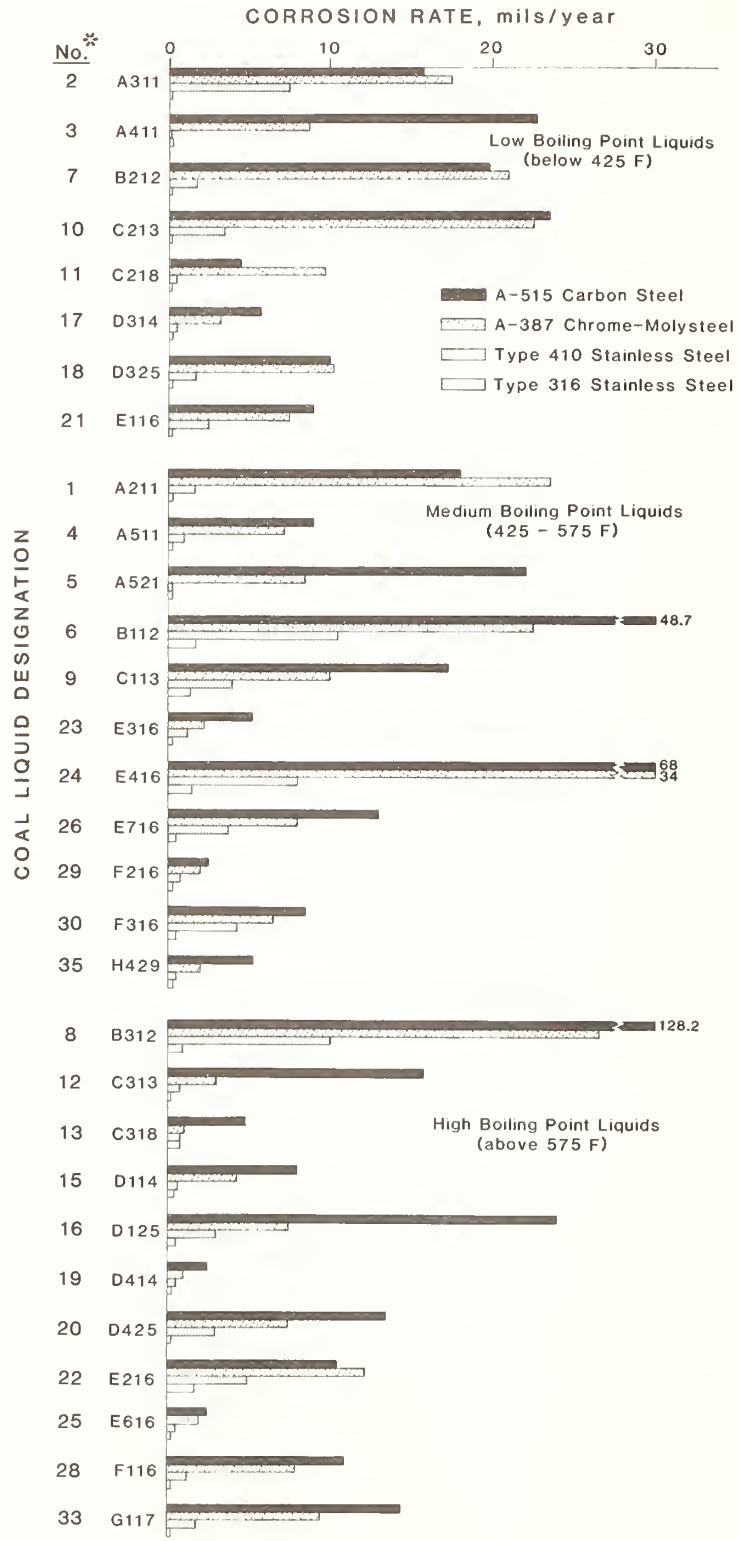


Figure A.2.4.2.2.5a

Corrosion rates in various coal liquids for carbon steel, A-387 steel, and Types 410 and 316 stainless steels. This figure represents data appearing originally in Tables 32-35 of the 1981 annual report cited in Reference [45] and also in Sections B.1.1.136 and B.1.1.137.

* Numbers correspond to the numbers of the coal liquids in Sections B.1.1.136 and B.1.1.137. The second set of letter-number combinations are the coal liquid designations used in the original reports.

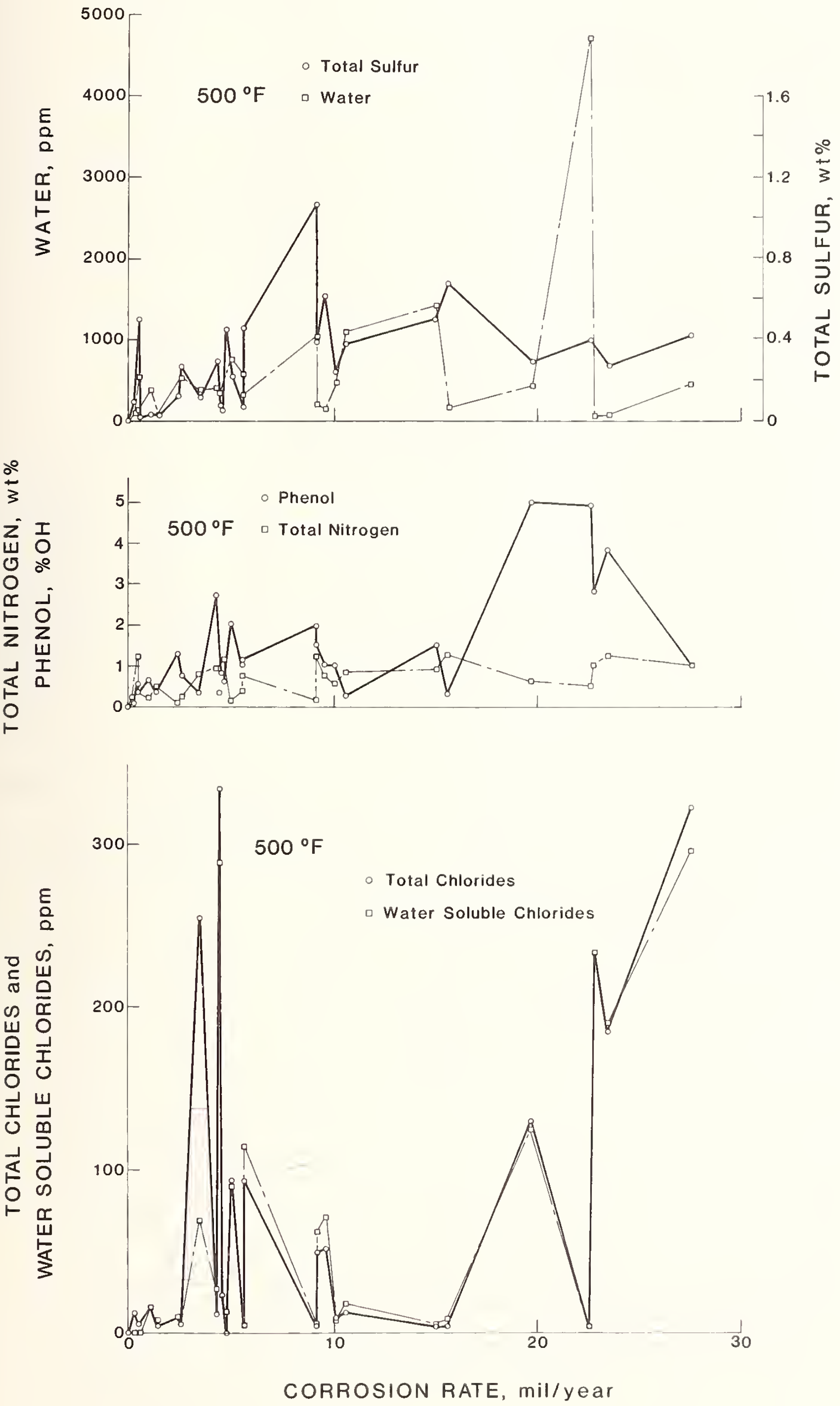


Figure A.2.4.2.2.5b

Carbon Steel

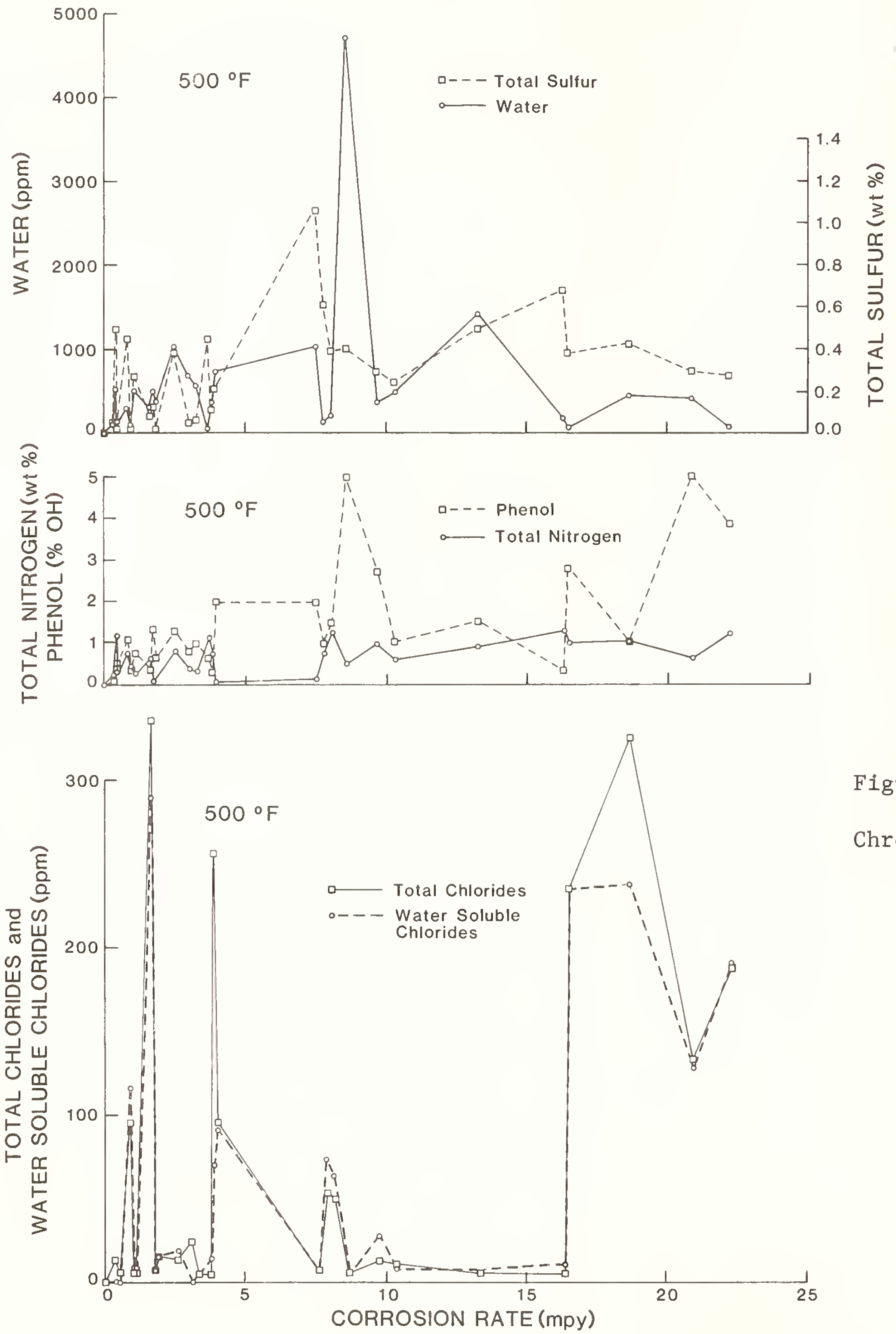


Figure A.2.4.2.2.5c

Chrome-Moly Steel

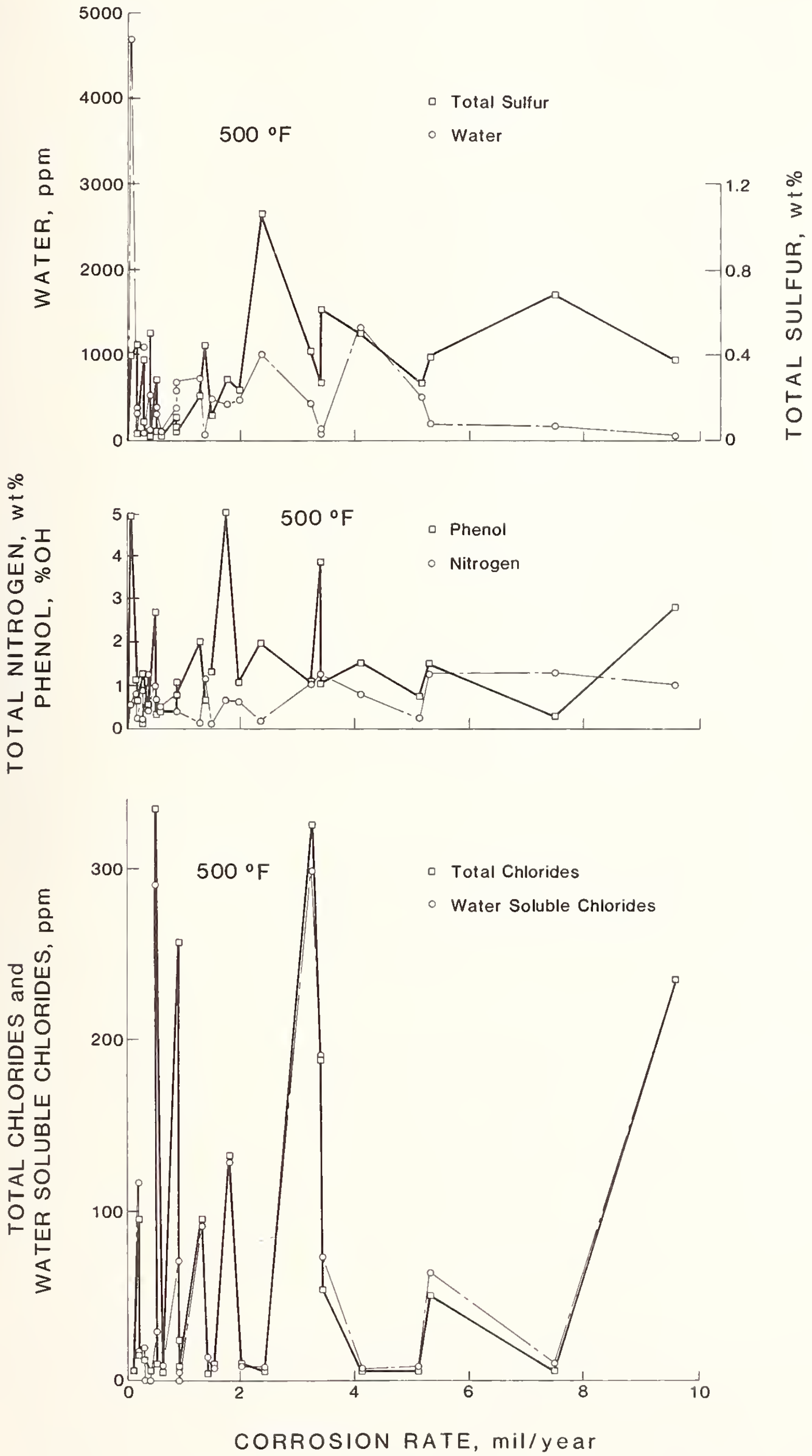


Figure A.2.4.2.2.5d

410 Stainless Steel

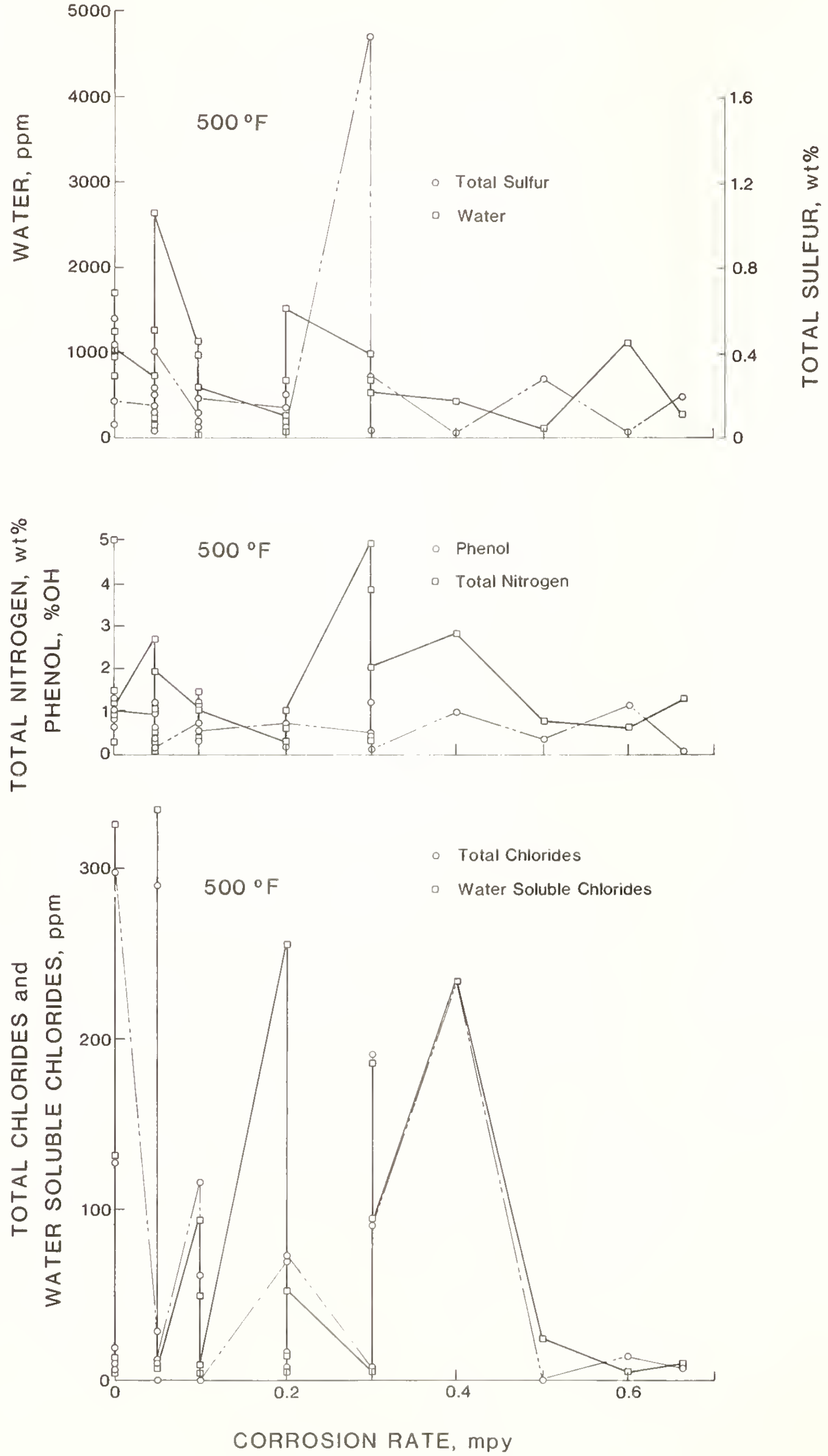


Figure A.2.4.2.2.5e

316 Stainless Steel

to evaluate the general change of the coal liquid during exposure on the rate of corrosion. Graphs of weight loss versus time for three procedures and three coal liquids indicate that: 1) the rate decreases as corrosion proceeds, and 2) the rate will increase if fresh coal liquid is added to the test system.

Corrosion rates of the carbon steel (A515), the chrome-moly steel (A387), and the two stainless steels were plotted versus the concentrations of some of the chemical constituents in the coal liquids listed in Section B.1.1.137. The chemical constituents considered were: total chlorides, water soluble chlorides, phenol, total nitrogen, total sulfur and water. The objective was to search for a correlation between corrosion rate and pre-test concentration of a particular chemical constituent. Results appear in Figures A.2.4.2.2.5b, c, d, and e.

No unambiguous correlations were found between corrosion rate and chemical constituents for any of the four materials. In fact, it appeared that at the fixed test temperature of 500 °F, the coal liquid itself seems to be the major factor that determines the corrosion rate. For example, results on the carbon steel showed that chloride concentrations of less than 10 ppm in 9 different coal liquids correspond to corrosion rates ranging from 1 to 15 mils per year (see Figure A.2.4.2.2.5b) depending upon the coal liquid. This point is reinforced by recognizing in Figure A.2.4.2.2.5b that phenol or total nitrogen concentrations around 1% may correspond to corrosion rates between 1 and 28 mils per year. These results suggest that the graph in Table B.1.1.141 may be misleading. Furthermore, these results suggest that other factors than just the concentration of a single chemical constituent in the coal liquid determines the corrosion rate. Factors to consider include physical properties of the coal liquid, e.g., viscosity, surface tension and thermal conductivity, and the influence of various chemical constituents on the chemical activity of any single constituent.

STRESS CORROSION AND CORROSION RESISTANCE IN COAL LIQUIDS of over forty-three structural alloys were evaluated in laboratory tests (Sections B.1.1.157-.159 and B.1.1.173-.176). Tests were carried out in synthesized corrosive environments and in coal liquids taken from operating pilot plants. Chemical compositions of the coal liquids were not reported. These tests are summarized in the following paragraphs.

IN A SIMULATION OF THE CONOCO ZINC CHLORIDE HYDROCRACKING PROCESS, about 25 alloys were exposed to simulated $ZnCl_2$ recovery conditions (hot leg and cold leg) for 75-500 hours. Temperatures ranged from 500 to 800 °F. Performance of each alloy is ranked in Section B.1.1.157. Corrosion rates ranged from 0.2 to 30.3 mm/year. Alloys with nickel plus molybdenum contents approaching 70% showed good conversion resistance. So did alloys with cobalt plus chromium contents in the range 40 to 85%. Titanium showed extremely poor resistance during 75 hour exposures. Udimet 720 showed extremely good resistance during 500 hour exposures.

EXPOSURES IN SOLVENT REFINED COAL (SRC) LIQUIDS of carbon steel, Type 304 stainless steel and Admiralty brass are reported in Sections B.1.1.173-.176. Test temperatures ranged between 60 and 338 °C, test times ranged from a few hours up to 97 hours. Corrosion rates for carbon steel ranged from 0.003 to 11.3 mm per year, depending upon temperature and type of coal liquid (Section B.1.1.173 and .175). Type 304 stainless steel showed rates as high as 6.79 mm per year in distillate from the Fort Lewis SRC pilot plant, and no corrosion at all in water-washed distillate (Section B.1.1.174). Admiralty brass showed extremely low corrosion rates of 0.01 to 0.62 mm per year during exposures to coal liquids from the Fort Lewis SRC I and II processes (Section B.1.1.176).

EFFECTS OF AGING ON SUSCEPTIBILITY TO STRESS CORROSION CRACKING of nine stainless steels and eight other alloys is reported in Section B.1.1.159. The alloys were aged at 400, 500 and 600 °C for 10, 100, 1000 and 5000 hours. Aged specimens were exposed to a boiling 50% sulfuric acid/ferric sulfate solution for 120 hours and penetration rate was measured to estimate the degree of attack. Penetration rates ranged from 0.11 to 73.4 mm per year. For many alloys, the penetration rate increased with increasing aging temperature. Ferralium and Hastelloy C-276 showed a high susceptibility to penetration for all aging conditions. Hastelloy G-3 and Type 310 stainless steel exhibited good resistance to penetration.

PILOT PLANT TESTING

STRESS CORROSION AND CORROSION IN COAL LIQUIDS of over fifty structural alloys and ten weld filler metals were evaluated in pilot plant exposures in over fifty locations in four pilot plants: Baytown, Fort Lewis, Wilsonville, and Catlettsburg (Sections B.1.1.160-.172). Test procedures are described in each section. Exposure times ranged from 736 hours to 13 months. Stress corrosion susceptibility was evaluated using U-bend specimens. The corrosion rate and, in some cases, the type of attack, were reported in the stress corrosion tests (Sections B.1.1.160-.163). The corrosion rate of unstressed test coupons is reported in Sections B.1.1.165-.172. Test procedures are described in each section. Chemical compositions of the coal liquids/vapors in the various pilot plant locations were not reported.

HIGHLIGHTS OF THE U-BEND STRESS CORROSION TESTS appear in Table A.2.4.2.2.5a. Arbitrarily selected alloys from Sections B.1.1.160-.163 have been included in the arbitrarily defined classifications of corrosion rates in the table to illustrate alloy performance in the matter of corrosion rates and type of attack. The format of Table A.2.4.2.2.5a facilitates preliminary ranking of alloy performance. If more than one exposure time was reported, rates for the longest exposure time were selected for this tabulation. Temperatures and other exposure conditions vary widely with pilot plant location and are listed at the appropriate location in Sections B.1.1.160-.163.

Eight structural alloys and some welds were evaluated at seven locations in the BAYTOWN pilot plant. Chromium-molybdenum alloys often showed the lowest corrosion resistance. The highest corrosion rate was 19.7 mils per year, but most corrosion rates were less than 2 mils per year.

About 19 alloys and 12 weld filler metals were evaluated at five locations in the FORT LEWIS pilot plant. The highest corrosion rate was over 90 mils per year, and at least three specimens corroded completely. However, most rates did not exceed ten mils per year.

About 15 alloys and 11 weld filler metals were evaluated at five locations in the WILSONVILLE pilot plant. One location involved exposure to vapor as well as liquid. The highest corrosion rate was greater than 39 mils per year and one specimen corroded completely. However, the majority of the rates did not exceed ten mils per year.

HIGHLIGHTS OF MATERIALS PERFORMANCE IN U-BEND STRESS-CORROSION TESTS AT VARIOUS LOCATIONS IN COAL LIQUEFACTION PLANTS

		Alloy Performance (Type of Attack)*		
Pilot Plant	Location in Plant	<2 mils/yr (<0.0508 mm/yr)	2 to 5 mils/yr (0.0508 to 0.127 mm/yr)	>5 mils/yr (>0.127 mm/yr)
Baytown (Exxon Donor Solvent Process) See Section B.1.1.160.	Piping from Separator Recycle	Carbon steel 2-1/4 Cr-1 Mo steel 304 SS (sensitized)	(No alloys in this range)	(No alloys in this range)
	Liquefaction Overhead Piping into Separator Condenser	304 SS welded 347 SS welded Ferralium	304 SS (sensitized)	2-1/4 Cr-1 Mo steel 5 Cr-1 Mo steel
	Hydrogenation Overhead Piping into Hot Separator Vapor Condenser	Carbon steel 2-1/4 Cr-1 Mo steel 304 SS (sensitized)	Carbon steel	(No alloys in this range)
	Hydrogenation Overhead Piping from Sour Water Scrubber	Carbon steel 304 SS (sensitized) Incoloy 825	Carbon steel	(No alloys in this range)
	Solvent Fractionator Overhead Piping into Reflux Drum	Carbon steel 304 SS (sensitized) 2-1/4 Cr-1 Mo steel	Carbon steel	5 Cr-1 Mo steel
	Solvent Fractionator Overhead Piping from Condenser	Carbon steel 304 SS (sensitized)	(No alloys in this range)	(No alloys in this range)
	Solvent Fractionator Piping into Distillate Condenser	Carbon steel 2-1/4 Cr-1 Mo steel 304 SS welded	(No alloys in this range)	(No alloys in this range)
Fort Lewis (Solvent Refined Coal Process II) See Section B.1.1.161.	High-Pressure Separator (Flash Drum)	18 Cr-2 Mo steel welded with 26 Cr-1 Mo (N)* E-Brite 26-1 welded with 26 Cr-1 Mo (IC) 332 SS (P)	Incoloy 800H (N)*	410 SS welded with 410 (TC)* 304L SS welded with 308L (IP) 316 SS welded with 316 (N) Inconel 600 welded with Inconel 82 (S, GS) 5 Cr-1 Mo(0.13Nb) steel
	Intermediate-Pressure Separator (Flash Drum)	18 Cr-2 Mo steel (N) E-Brite 26-1 welded with 26 Cr-1 Mo 321 SS welded with 347	410 SS (GS) 9 Cr-1 Mo (modified)	410 SS welded with 410 Inconel 600 welded with Inconel 82 (S, GS) 5 Cr-1 Mo steel
	Recycle Condensate Separator	410 SS (N) 316 SS (N) 5 Cr-1 Mo(0.13Nb) steel 9 Cr-1 Mo steel(modified)	(No alloys in this range)	(No alloys in this range)
	Dissolver Vessel	304 SS welded with 308 (N) 316 SS (N) 347 SS (N)	321 SS welded with 347 (N) 321 SS (N) 20Cb-3 welded with 320 (N) 317L SS welded with 317L (N)	Incoloy 800H welded with Inconel 82 (TC, S) 332 SS welded with Inconel 82
	Wash Solvent Column	(No alloys in this range)	(No alloys in this range)	E-Brite 26-1 welded with 26 Cr-1 Mo (GS) 321 SS welded with 347 (GS) 20Cb-3 welded with 320 (GS)

(Table Continued)

Table A.2.4.2.2.5a

HIGHLIGHTS OF MATERIALS PERFORMANCE IN U-BEND STRESS-CORROSION TESTS AT VARIOUS LOCATIONS IN COAL LIQUEFACTION PLANTS

Continued

Pilot Plant	Location in Plant		Alloy Performance (Type of Attack)* <2 mils/yr (<0.0508 mm/yr)	2 to 5 mils/yr (0.0508 to 0.127 mm/yr)	>5 mils/yr (>0.127 mm/yr)
Wilsonville (Solvent Refined Coal Process)	Fractionation Column		E-Brite 26-1 (N) 304L SS (N) 317L SS (N) 347 SS (N) Inconel 600 (N)	(No alloys in this range)	316 SS (GS) 317L SS (GS) Incoloy 800H (TC, S) 304L SS (TC, P) 310 SS (TC)
See Section B.1.1.162	Dissolver Vessel (near top)	Vapor	Hastelloy C-276 welded with C-276 (S) 316 SS welded with 316 (MM) Incoloy 800H welded with Inconel 82 (IC)	(No alloys in this range)	410 SS welded with 410 (TC)
		Vapor-Liquid Interface	Hastelloy C-276 (N) Inconel 625 (IC) 310 SS welded with 310 (TC) 321 SS welded with 347 (TC) 332 SS (TC) 347 SS (TC)	(No alloys in this range)	(No alloys in this range)
		Liquid	304L SS (TC) 316 SS (TC) Incoloy 800H (MM) 347 SS (MM)	(No alloys in this range)	410 SS (GS)
	Dissolver Vessel Bottom (9958-hour exposure)		316L SS 332 SS 316L welded with 316ELC	321 SS 321 SS welded with 347 304 SS welded with 308 332 SS welded with Inconel 82	7 Cr-1 Mo steel 9 Cr-1 Mo steel Sandvik HT9 Sanicro 41X 410 SS
	High-Pressure Separator		321 SS welded with 347 Incoloy 800H welded with Inconel 82 347 SS welded with 347 304 SS welded with 308	(No alloys in this range)	5 Cr-1 Mo steel 7 Cr-1 Mo steel 9 Cr-1 Mo steel 9 Cr-1 Mo steel(modified)
	High-Pressure Letdown Vessel (Flash Drum)		317L SS 316 SS 304 SS 310 SS Ferralium	347 SS	Carbon steel 5 Cr-1 Mo steel 7 Cr-1 Mo steel 9 Cr-1 Mo steel(modified)
Catlettsburg (H-Coal Process)	Reactor (13-month exposure)	Vapor	316 SS	347 SS welded with 347 310 SS welded with 310 410 SS welded with 410 304 SS	316 SS welded with 316 20Cb-3 welded with 320 Incoloy 800H welded with Inconel 82
See Section B.1.1.163		Liquid	310 SS welded with 310	347 SS welded with 347 304 SS welded with 308	HT9 Incoloy 800H welded with Inconel 82 20Cb-3 welded with 320 410 SS welded with 410 316 SS
	Fractionator (13-month exposure)		All alloys tested showed rates less than or equal to 0.4 mils/yr (0.01 mm/yr)		

(Table Continued)

Table A.2.4.2.2.5a

HIGHLIGHTS OF MATERIALS PERFORMANCE IN U-BEND STRESS-CORROSION TESTS AT VARIOUS LOCATIONS IN COAL LIQUEFACTION PLANTS

Continued

Pilot Plant	Location in Plant		Alloy Performance (Type of Attack)*: <2 mils/yr (<0.0508 mm/yr)	2 to 5 mils/yr (0.0508 to 0.127 mm/yr)	>5 mils/yr (>0.127 mm/yr)
Catlettsburg (H-Coal Process), continued	High-Pressure Flash Drum (13-month exposure)	Vapor	310 SS welded with 310 304 SS welded with 308 410 SS welded with 410	20Cb-3 welded with 320 Incoloy 800H welded with Inconel 82 347 SS welded with 347 304 SS	316 SS 316 SS welded with 316 HT9
		Liquid	347 SS welded with 347 310 SS welded with 310 20Cb-3 welded with 320 Incoloy 800H welded with Inconel 82	HT9 316 SS welded with 316	(No alloys in this range)
	Low-Pressure Flash Drum (13-month exposure)	Vapor	304 SS 316 SS 316 SS welded with 316 347 SS welded with 347 Incoloy 800H welded with Inconel 82 410 SS	9 Cr-1 Mo steel(modi-fied	Carbon steel
		Liquid	HT9 316 SS welded with 316 347 SS welded with 347 9 Cr-1 Mo steel(modified) 410 SS welded with 410	(No alloys in this range)	Carbon steel
	Reactor Efflu-ent Vapor Separator (13-month exposure)	Vapor	(No alloys in this range)	(No alloys in this range)	410 SS welded with 410 304 SS welded with 308 347 SS welded with 347 Incoloy 800H welded with Inconel 82
		Liquid	410 SS welded with 410 304 SS welded with 308 347 SS welded with 347 304 SS 316 SS	(No alloys in this range)	316 SS welded with 316 Carbon steel HT9 9 Cr-1 Mo steel(modified)
	Reactor Efflu-ent Separator (13-month exposure)	Vapor	310 SS welded with 310	347 SS welded with 347 304 SS welded with 308	HT9 304 SS 316 SS 20Cb-3 welded with 320 410 SS welded with 410 316 SS welded with 316 Incoloy 800H welded with Inconel 82
		Liquid	(No alloys in this range)	304 SS welded with 308 347 SS welded with 347	HT9 304 SS 410 SS welded with 410 316 SS welded with 316 Incoloy 800H welded with Inconel 82

*Type of Attack: GS = general surface attack, IC = intergranularly cracked, IP = intergranular penetration, N = no attack, P = pitted slightly, S = sulfidized, TC = transgranularly cracked, MM = mixed mode.

Table A.2.4.2.2.5a

About 19 alloys and 11 weld filler metals were evaluated at five locations at the CATLETTSBURG pilot plant. Each location involved vapor and liquid phase exposures. The highest corrosion rate for a second exposure for 13 months was about 20 mils per year. At least eight specimens were totally lost during exposure in the reactor effluent vapor separator. Many corrosion rates were below five mils per year.

HIGHLIGHTS OF CORROSION TESTS ON UNSTRESSED TEST COUPONS appear in Table A.2.4.2.2.5b. Arbitrarily selected alloys from Sections B.1.1.164-.167, .169 and .170 have been included in the arbitrarily defined classifications of corrosion rates in this table to illustrate alloy performance in the matter of corrosion rates. The format of this table facilitates preliminary ranking of alloy performance. In some cases, times are repeated; otherwise, rates for the longest exposure times were selected for tabulation.

About twenty-one structural materials were evaluated at five tray positions in the atmospheric fractionator of the BAYTOWN pilot plant. Carbon steel generally showed the lowest corrosion resistance. The highest corrosion rate was greater than 166 mils per year (carbon steel), but most rates were less than 2 mils per year. Corrosion rate of Type 410 stainless steel did not vary monotonically with tray number in the fractionator, Section B.1.1.165.

About twenty-five structural materials were evaluated at five tray positions in the atmospheric fractionator of the CATLETTSBURG pilot plant. Carbon steel and Monel 400 generally showed the poorest corrosion resistance. The highest corrosion rate was 620 mils per year (carbon steel), but most rates were less than five mils per year.

About twenty-five structural materials were evaluated at ten locations in the WILSONVILLE pilot plant. Data are reported for several exposure times (1128, 2350, 3552, 4015 and 5730 hours) in Sections B.1.1.167 and B.1.1.169. Only the data representing the 5730 hour exposure are included in Table A.2.4.2.2.5b. The highest corrosion rate was 32.6 mils per year (carbon steel), but most rates were less than one mil per year. Data obtained from exposures at three manways in the fractionation column are reported in Section B.1.1.167. Rather high rates were reported for most alloys tested at the middle manway, but much lower rates were reported for the alloys tested at the top and bottom manways. Extremely low rates, less than one mil per year, were measured for most alloys exposed in the vacuum column, the high-pressure separator, the solvent decanter vessel, the hydrotreater melt tank, and the hydrotreater product recycle tank (Section B.1.1.169). Scale characteristics, including chemical analysis for fifteen constituents, of coupons of several alloys exposed in thirteen locations of the WILSONVILLE pilot plant are reported in Sections B.1.1.168 and B.1.1.172. The variation in scale characteristics is extremely broad, ranging from little penetration to formation of multilayer/multiphase scales to subsurface corrosion and cracking, depending upon exposure location in the pilot plant. Sulfur, carbon and iron were abundant elements in the corrosion scale.

About thirty structural materials were evaluated at five locations in the FORT LEWIS pilot plant. Type 410 stainless steel and aluminum generally showed poor corrosion resistance. The highest corrosion rate was 124 mils per year but most rates were less than five mils per year. Exposure times ranged from 1334 hours to six months. Exposure times have been included in Table A.2.4.2.2.5b

HIGHLIGHTS OF MATERIALS PERFORMANCE IN CORROSION TESTS AT VARIOUS LOCATIONS IN COAL LIQUEFACTION PLANTS

Pilot Plant	Location in Plant		Corrosion Rate		
			<2 mils/yr (<0.0508 mm/yr)	2 to 5 mils/yr (0.0508 to 0.127 mm/yr)	>5 mils/yr (>0.127 mm/yr)
Baytown (Exxon Donor Solvent Process) See Sections B.1.1.164- B.1.1.165.	Atmospheric Fractionator (4920-hour exposure)	Tray 20	304 SS 321 SS Ferralium Haynes 20 Mod Incoloy 825 Inconel 600 Titanium Zirconium	(No alloys in this range)	Carbon steel 410 SS
		Tray 21	Haynes 20 Mod Incoloy 825 Inconel 600 Titanium Zirconium	317LM SS Ferralium	Carbon steel 410 SS 304 SS 321 SS 316 SS 316L SS
		Tray 23	Ferralium Haynes 20 Mod Incoloy 825 Inconel 600 Titanium Zirconium	316L SS 317LM SS	Carbon steel 410 SS 304 SS 321 SS 316 SS
		Tray 25	410 SS 304 SS 321 SS 316 SS 316L SS 316LM SS Titanium Zirconium	(No alloys in this range)	Carbon steel
		Tray 26	410 SS 304 SS 321 SS 316 SS 316L SS 316LM SS Titanium Zirconium	(No alloys in this range)	Carbon steel
Catlettsburg (H-Coal Process) See Section B.1.1.166.	Atmospheric Fractionator (2160-hour exposure)	Tray 9	317 SS 316L SS Sandvik 2RE69 RA 333 20Cb-3 Incoloy 825	(No alloys in this range)	Carbon steel 410 SS Monel 400 304 SS 347 SS 321 SS
		Tray 10	RA 333 20Cb-3 Incoloy 825 Haynes 20 Mod Titanium	317 SS 316L SS Sandvik 2RE69	Carbon steel 410 SS Monel 400 304 SS 347 SS 321 SS
		Tray 11	Sandvik 2RE69 RA 333 20Cb-3 Incoloy 825 Haynes 20 Mod Titanium	321 SS 317 SS 316L SS	Carbon steel 410 SS Monel 400 304 SS 347 SS

(Table Continued)

Table A.2.4.2.2.5b

HIGHLIGHTS OF MATERIALS PERFORMANCE IN CORROSION TESTS AT VARIOUS LOCATIONS IN COAL LIQUEFACTION PLANTS, Continued

Pilot Plant	Location in Plant		Corrosion Rate <2 mils/yr (<0.0508 mm/yr)	Corrosion Rate 2 to 5 mils/yr (0.0508 to 0.127 mm/yr)	Corrosion Rate >5 mils/yr (>0.127 mm/yr)
Catlettsburg (H-Coal Process), continued	Atmospheric Fractionator, continued	Tray 12	304 SS 347 SS Sandvik 2RE69 RA 333 20Cb-3 Incoloy 825 Haynes 20 Mod Titanium	410 SS 321 SS	Carbon steel Monel 400
		Tray 13	410 SS 304 SS 347 SS Sandvik 2RE69 RA 333 20Cb-3 Incoloy 825 Haynes 20 Mod Titanium	(No alloys in this range)	Carbon steel Monel 400
Wilsonville (Solvent Refined Coal Process)	Dissolver--Vapor Phase		316 SS 410 SS 20Cb-3 RA 330	26 Cr-1 Mo steel	(No alloys in this range)
See Sections B.1.1.167, B.1.1.169.	High-Pressure Separator--Vapor Phase		26 Cr-1 Mo steel 410 SS 304L SS 22Cr-13Ni-5Mn alloy	(No alloys in this range)	(No alloys in this range)
(5730-hour exposure)	Solvent Decanter--Liquid-Vapor Interface		No corrosion detected for the three alloys tested: carbon steel, 304L SS, and 410 SS.		
	Reclaim Tank--Liquid Phase		Carbon steel 410 SS	(No alloys in this range)	(No alloys in this range)
	Vacuum Column--Top Manway/Vapor Phase		Carbon steel 304L SS 410 SS	(No alloys in this range)	(No alloys in this range)
	Vacuum Column--Bottom Manway/Vapor Phase		410 SS	(No alloys in this range)	Carbon steel
	Fractionation Column--Top Manway/Liquid Phase		Carbon steel No corrosion detected for seven other alloys tested.		
	Fractionation Column--Middle Manway/Liquid Phase		Incoloy 800 321 SS 304L SS	Carbon steel 410 SS	316 SS
	Fractionation Column--Bottom Manway/Liquid Phase		410 SS Incoloy 800	(No alloys in this range)	Carbon steel
	Light Solvent Surge Tank--Liquid Phase		No corrosion was detected for five other alloys tested.	Carbon steel	
Fort Lewis (Solvent Refined Coal Process) See Section B.1.1.170.	Light Ends Column		Crutemp 25 317LM SS 316 SS 304 SS Hastelloy C-276 Inconel 600	(No alloys in this range)	Aluminum Incoloy 800 410 SS Monel 400

(Table Continued)

Table A.2.4.2.2.5b

HIGHLIGHTS OF MATERIALS PERFORMANCE IN CORROSION TESTS AT VARIOUS LOCATIONS IN COAL LIQUEFACTION PLANTS, Continued

		Corrosion Rate		
Pilot Plant	Location in Plant	<2 mils/yr (<0.0508 mm/yr)	2 to 5 mils/yr (0.0508 to 0.127 mm/yr)	>5 mils/yr (>0.127 mm/yr)
Fort Lewis (Solvent Refined Coal Process), continued	Reboiler Shell (3163-hour exposure)	Hastelloy C-276 321 SS Haynes 263 304 SS (Alonized)	Inconel X-750 Udimet 720 Incoloy 801 Inconel 600	Carbon steel 410 SS Incoloy 800 Nickel Inconel 601
	Wash Solvent Column	The other thirteen specimens tested gained weight during exposure.		410 SS Aluminum
	Middle of Wash Solvent Column (6-month exposure)	Hastelloy G Hastelloy N Inconel 600	20Cb-3 Haynes 20 Mod	304 SS 316 SS 410 SS 317LM SS Inconel 625 Inconel 671
	Top of Wash Solvent Column (6-month exposure)	405 SS 304 SS 20Cb-3 Hastelloy G Hastelloy C-276 317 SS 317LM SS	Carbon steel	(No alloys in this range)

Table A.2.4.2.2.5b

where appropriate. Some results were obtained on the effects of chemical constituents on corrosion rates of alloys exposed in the wash solvent column, Section B.1.1.171. In general, corrosion rates tended to be lower at high concentrations (10 to 75%) of chromium, nickel and molybdenum. Analysis of corrosion scale on Type 317 stainless steel exposed above the middle manway of the wash solvent column are reported in Section B.1.1.172. Sulfur, nickel, carbon, chromium, molybdenum and iron were abundant elements in the corrosion scale.

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* Sections included in SP-642 and Supplement 1 combined.

A.3.1.1 OPERATING REQUIREMENTS

In gasification processes, product gases leave the gasifier at high temperatures and pressures, up to 1,800 °F (1,255 K) and 1,500 psi depending on the process. They will contain some or all of the potentially corrosive and erosive constituents enumerated in Section A.2.2.1. Removal of solid materials is necessary to minimize erosion in downstream components and to comply with air pollution standards.

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

Hot gas clean-up generally utilizes cyclones for solids separation at or near the product gas temperature and pressure. Present technology has not been established for such conditions. Possible problem areas include erosion, deposition and high temperature corrosion (carburization, sulfidation, hydrogen reaction, or temper embrittlement) for metal components in the gasifier overhead lines and cyclones. Refractory linings may reduce these problems if excessive cracking and spalling due to thermal stresses can be avoided.

In liquefaction processes, the liquid product stream from the reactor cooler contains solids, liquids, and gases. Temperatures range between 450 and 700 °F (505 and 644 K) and pressures between 150-200 psi. Solids are removed mechanically by such devices as filters, centrifuges or hydroclones. Solvent de-ashing and vacuum distillation are other techniques used to remove solids. Hydrocarbon precipitation, as temperatures decrease in heat exchangers, can be a source of equipment plugging. Erosion is another problem-area for equipment. To date, filtration via horizontal drum filters is a solid/liquid separation method which has been successful at the pilot-plant level of process development.

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.

A.3.2.1 OPERATING REQUIREMENTS

Removal of the erosive particles and corrosive chemical impurities from the product gas is necessary to prolong the lifetime of downstream components and to meet air pollution standards. Cold gas clean-up generally involves heat 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) would enter the heat exchanger at temperatures and pressures approximating the gasifier exit conditions and leave at temperatures in the 600-800 °F range (589-699 K). The major problems will be erosion and hot gas corrosion as denoted in Section A.3.1.1. Liquid water corrosion should not be a problem except during shutdown periods. High alloy steels or cladding will probably be necessary for the heat exchanger tubes, but the lifetimes of materials under gasification or liquefaction conditions has not been established by industrial experience.

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

In liquefaction processes, components such as reactor effluent coolers, recycled gas coolers and reactor effluent vapor condensors operate at tube-side temperatures between 120 and 950 °F (322 and 783 K). Pressures may be as high as 4000 psi. Possible problems which may have to be addressed in these components include foaming and plugging, thermal stresses and erosion-corrosion.

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

A.3.2.2.1.2 MATERIALS EVALUATION

OVERVIEW

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

LABORATORY TESTS

Alloy coupons were subjected to testing in complex aqueous solutions in autoclaves in order to simulate the quench steps of a variety of coal gasification pilot plants. A volume of liquid was added to the vessel to approximately half the vessel capacity and, for a given test, specified impurities were added to the liquid in amounts based on the total weight of the liquid. Test coupons were inserted, the autoclave purged with nitrogen, the temperature and pressure raised to the test values, and after equilibrium was reached, gases were introduced and circulated. A constant flow of new gas was maintained and condensate was automatically fed back to the vessel. This test procedure was followed for all of the tests described below except for those labeled "dynamic". The dynamic test procedure included provision for a continuous liquid input and periodic discharge to obtain a flow through the test vessel. Corrosion rates were determined from coupon weight loss. Since the data are based on few samples (only one specimen in tests reported in B.1.1.100, and .107, two specimens in B.1.1.105, .108, .109, and three specimens in B.1.1.102, .103, .104) the corrosion rates reported must be viewed with caution.

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

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

Environment	Temperature Range(°F)	Pressure Range (psig)
Aqueous	120 - 462	95 - 1210
Gaseous	200 - 950	100 - 1215

The pH of the twelve environments ranged from 2.9 to 9.7. These environments contained varying concentrations of coal-conversion-atmosphere components as follows:

Component	Concentration Range
H_2S	0.02 - 1.1 mole percent
CO_2	5 - 21 mole percent
NH_3	0.002 - 0.6 mole percent
H_2	9 - 27 mole percent
CO	5 - 15 mole percent
CH_4	0.1 - 0.5 mole percent
N_2	14 - 42 volume percent
Toluene	NIL - 23 volume percent
HCN	NIL - 500 parts per million
Phenol	NIL - 600 parts per million
Chloride	100 -3000 parts per million

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

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

The highest corrosion rates were between 100 and 500 mils per year, whereas the lowest were less than 1 mil per year. In general, if an alloy showed good resistance to an aqueous environment, it also showed good resistance to a gaseous environment, and vice-versa. 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., 15-30 percent, usually showed good corrosion resistance. Austenitic stainless steels (304, 316) showed better corrosion resistance than the Type 400 stainless steels (410, 430). Aluminum 1100 and Aluminum 6061 showed pronounced susceptibility to pitting in aqueous environments.

Within the twelve sets of environmental conditions and compositions appearing in Table A.3.2.2.1.2a, it was found that the highest corrosion rates were associated with Sets 4A, 4B, 5A, and 5B. Sets 4A and 4B had the most acid pH and the highest liquid temperatures, whereas Sets 5A and 5B had the highest H_2S concentrations. Sets 5A and 5B also had the highest gas temperature. These

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

						Chemical Composition (mole percent unless otherwise specified)								Temperature and Pressure			
														LIQUID		GAS	
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. %)	(psig)	(°F)	(psig)	(°F)
1A 1B	7.6 - 9.7 9.2 - 10.6	23 same	1000 0	500 100	3000 same	0.2	15	0.3	17	10	7	-	27	1000	200	1000	600
2A 2B	3.9 - 9.4 7.5 - 8.5	3 NIL	700 same	200 same	3000 100	0.8	18	0.45	22	19	15	-	20	1210	400	1210	400
3A 3B	6.5 - 9.2 7.5 - 8.5	NIL NIL	100 NIL	100 NIL	3000 100	0.02	3.2	0.52	56	15	10	0.18	15	126	120	131	200
4A 4B	3.8 - 3.9 2.9 - 4.2	NIL NIL	NIL NIL	200 NIL	3000 100	0.34	7	NIL	15	26	10	0.5	42	1200	462	1215	597
5A 5B	7.2 - 9.0 7.9 - 9.0	0.04 same	6000 1000	10 NIL	3000 100	1.1	21	0.6	19	9	13	0.1	36	1200	462	1210	950
6A 6B	4.7 - 7.0 4.3 - 7.0	NIL NIL	100 NIL	100 NIL	3000 100	0.35	5	0.002	48	27	5	0.5	14	95	230	100	500

Table A.3.2.2.1.2a

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 comparable 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 simulated 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 resistance 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, 18-2, 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.

FOUR ALLOYS WERE SUBJECTED TO DYNAMIC (INCLUDES GAS AND LIQUID FLOWTHROUGH) LABORATORY TESTS IN AQUEOUS AND GASEOUS ENVIRONMENTS 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.

STATIC (GAS FLOW ONLY, NO LIQUID FLOW) AND DYNAMIC (BOTH GAS AND LIQUID FLOW) LABORATORY TESTS IN AQUEOUS AND GASEOUS ENVIRONMENTS 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.

In some separate corrosion tests on Type 304 stainless steel and carbon steel, the quench environment in a low pressure (500 psig) HYGAS plant location was simulated in the laboratory (Sections B.1.1.131 and B.1.1.132). Tests were carried out in 29 environments. H_2S, HCN and NH_3 varied with environment. Test temperatures ranged from 130 to 300 °F. Exposure times were primarily 150 hours, but some tests were run for 500, 1000 and 1350 hours. Tests were conducted in aqueous and gaseous phases. Corrosion rates tended to be higher in the aqueous phases. The type 304 stainless steel showed the lower corrosion rates for all tests, 0.1 to 2.2 mils per year, the highest rate was associated with a chloride concentration of 1300 ppm. These rates are slightly higher than those reported for type 304 stainless steel in Table B.1.1.109. The carbon steel showed rather high rates, 5.8 to 115 mils per year; the highest rate occurred at 1300 ppm chloride. The surface scales on the carbon steel were primarily FeS. In general these carbon steel corrosion rates are higher than those reported in Section B.1.1.109.

LABORATORY SIMULATIONS OF SOME QUENCH ENVIRONMENTS IN THE LURGI SLAGGING AND DRY ASH PROCESSES were conducted (Section B.1.1.133). Aqueous and gaseous phase corrosion rates of Type 304 stainless steel and carbon steel were measured in 32 test environments. Phenol and ammonia concentrations, as well as slagging and dry ash conditions, varied with environment. Test times were usually 150 hours, but some tests ran for 500 and 2000 hours. Temperatures ranged between 150 and 325 °F. The stainless steel showed the lower corrosion rates in all tests, with a range from 0.1 to 1.3 mils per year. Rates for carbon steel varied between 2.6 and 194 mils per year.

LABORATORY SIMULATIONS OF QUENCH ENVIRONMENTS IN THE WESTINGHOUSE PROCESS were conducted (Sections B.1.1.134 and B.1.1.135). Aqueous and gaseous phase corrosion rates of Type 304 stainless steel and carbon steel were measured in 24 GASIFICATION and 4 DIRECT METHANATION environments. H_2S, HCN and NH_3 varied with environment. Test times were usually 150 hours, although some tests ran for 500 and 1000 hours. Temperatures ranged between 180 and 370 °F. In general, the carbon steel showed much higher corrosion rates (3.2 to 52.1 mils per year) than the stainless steel (<0.1 to 4.3 mils per year). The surface scales on the carbon steel were primarily FeS.

PILOT PLANT TESTING

EXPOSURE IN LIQUID PHASE LOCATIONS IN PILOT PLANTS produced performance data on commercial and experimental alloys in actual pilot plant locations. Twenty-one alloys were exposed in about thirty different liquid phase locations at the following pilot plants: HYGAS, Synthane, CO_2 Acceptor, BI-GAS, U-GAS, PEATGAS (modified HYGAS plant) and Westinghouse.

Temperatures ranged from 60 to 900 °F. Exposure times were between 288 and 5905 hours. These times are for the hours the plant was operating under coal gasification conditions; standby time is not included, nor are the standby conditions specified which affect the alloy performance. Depth of penetration and total sound metal loss, as determined from metallographic and gravimetric analysis, respectively, were used to describe the extent of corrosion. Full exposure conditions, i.e., concentrations of chemical constituents, and fluctuations of temperature and pressure, are not known. Consequently, the corrosion rates reported here must be interpreted cautiously. Test results appear in Section B.1.1.28.

Table A.3.2.2.1.2b shows a ranking of the results. The performance of each alloy in each plant location can be determined from the appropriate row and column in the table. The performance of the alloys is expressed as a letter code based on arbitrarily chosen limits for the total sound metal loss:

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

The locations in the pilot plants where the specimens were exposed are given by the following code used in Table A.3.2.2.1.2b:

H-1	coal pretreater water quench
H-2	product gas prequench tower
H-3	feed slurry mix vessel
H-4	coal pretreater quench tower off-gas
H-5a	quench separator tower/oil phase
H-5b	quench separator tower/gas phase
H-6	quench tower off-gas
H-7	char/slurry mix tank
S-1a	scrubber surge tank/venturi side
S-1b	scrubber surge tank/liquid phase
S-2a	decanter/splash zone
S-2b	decanter/solid-liquid zone
S-3	gasifier char cooler
C-1	gasifier quench tower
C-2	dolomite regenerator quench tower
B-1a	gasifier slag quench/water-saturated vapor
B-1b	gasifier slag quench/liquid phase
B-2	gas washer
B-3	vent gas washer
B-4	recycle gas washer

B-5	cyclone overflow tank
U-1a	product gas scrubber/off gas
U-1b	product gas scrubber/sludge tank
U-2	verturi scrubber collection tank
W-1a	quench/scrubber/vapor phase
W-1b	quench/scrubber/off-gas aqueous phase
P-1a	prequench tower
P-1b	quench separator
P-1c	product gas quench tower off-gas
P-1d	char slurry mix tank

RANKING OF CORROSION PERFORMANCE OF ALLOYS EXPOSED TO LIQUID PHASE LOCATIONS IN COAL GASIFICATION PILOT PLANTS

	Gasification Plant and Test Location														
	HYGAS								SYNTHANE					CO_2 ACCEPTOR	
Alloys	H-1	H-2	H-3	H-4	H-5a	H-5b	H-6	H-7	S-1a	S-1b	S-2a	S-2b	S-3	C-1	C-2
304 SS	s-u	e	e	e	e	e	e	e	e	e	e	e	e	e	e
316 SS				e					e	e				e	e
410 SS		e-s	e-s	e	e-s	u	e-s	e-s	e-s	e	e	e	e-s	s	
430 SS					e-s	e-s			e	e	e	e			
Carbon Steel (A515)	s-u	s-u	u	u	u	u	u	s	s	u	u	s			
Carbon Steel (A1)									e-s	e					
Monel 400									u	u					
Inconel 600									e	e					
Incoloy 800									e	e					
Incoloy 825														e	e
Titanium	e	e							e	e				e	e
Cast Iron A-278	e-s	s-u													s-u
Ni-Resist A-439 D2B	e-s	s													s
Ni-Resist(Cu) A-436 1B	e-s	s-u													s-u
Si-Iron A-518	e-s														
18-18-2	e	e													e
Al Bronze CDA 954	e-s	e-s													s
E-Brite 26-1		e													
20 Cb-3														e	e
Armco 22-13-5														e	e
Welded U-Bends															
Carbon Steel	s		s	s	s	s	s	s			s	s	s		s
304 SS	s	s	s	s	s	s	s	s	s	s	s	s	s		s
316 SS			s												
329 SS	s	s													
18-18-2	s	s													
E-Brite 26-1		s													
Incoloy 800									s	s					

(Table Continued)

Table A.3.2.2.1.2b (See text for key to plant locations and meaning of performance symbols.)

RANKING OF CORROSION PERFORMANCE OF ALLOYS EXPOSED TO LIQUID PHASE LOCATIONS IN COAL GASIFICATION PILOT PLANTS (Continued)

	Gasification Plant and Test Location														
	BI-GAS						U-GAS			Westinghouse		PEAT GAS			
Alloys	B-1a	B-1b	B-2	B-3	B-4	B-5	U-1a	U-1b	U-2	W-1a	W-1b	P-1a	P-1b	P-1c	P-1d
304 SS	e-s	e	e	e	e	e	s-u	e	e	e	e	e	e	e	e
316 SS	e	e	e		e	e	s	e	e	e	e				
329 SS	e	e					s	e							
405 SS	e-s	e	e	e											
410 SS							u	s	s	s	e	e	s	e	e
430 SS							u	s				e	e	e	e
446 SS												e			
Carbon Steel (A515)	s	u		u	s	u	u	u	u	u	s	e	u	u	s
Carbon Steel (TEF)										u	s				
Monel 400			s		s	e									
Inconel 600							s	e							
Incoloy 800							s	e							
Incoloy 825			e												
Titanium							e	e							
Cast Iron A-278												s			
Ni-Resist A-439 D2B												s			
Ni-Resist(Cu) A-436 1B												s			
Al Bronze CDA 954												s			
E-Brite 26-1	e	e							e	e	e				
20 Cb-3			e		e	e									
2¼Cr-1Mo	s-u	u			s-u										
HC-250							u	s							
CN-7M								s	e						
Welded U-Bends															
Carbon Steel				s			s-u	s	s	s	s			s	
304 SS	s	s	s	s	s	s	s-u	s	s	s	s	s	s	s	
316 SS			s	s	s	s	s-u	s	s	s	s				
329 SS	s	s					s-u	s							
405 SS			s	s											
18-18-2												s			
E-Brite 26-1	s	s							s			s			
Incoloy 800							s-u	s							
Inconel 600							s	s							

Table A.3.2.2.1.2b (See text for key to plant locations and meaning of performance symbols.)

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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* Sections included in SP-642 and Supplement 1 combined.

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 65 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, 321 and 347, martensitic stainless steels 410 and 416, and ferritic stainless steel 446. Reported operating temperatures ranged from ambient to 2500 °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 seven of the 18 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. One other Incoloy 800 failure was due to pitting. The longest service life reported for these seven 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 twelve reported 316 stainless steel components, four failed due to stress corrosion cracking, one failed due to sulfidation corrosion, and one failed due to grain boundary embrittlement by chromium sulfides. One of the 347 stainless steel failures was due to stress corrosion cracking.

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. One failure at a weld was caused by through-wall cracking due to attack by liquid $Ni-Ni_3S_2$ eutectic formed by sulfidation of the Inconel 182 weld metal.

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, 321, and 347 stainless steels 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 11 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 three reported failures of bellows made of 321 stainless steel. One failure was from the burnout of an oxygen line in the burner, the second was from pitting corrosion caused by improper drainage, and the third was from perforation due to chloride induced pitting.

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 127 hours for 321 stainless steel at 500 °F in a product gas/coal char/ash environment.

GAS PIPING IN-SERVICE PERFORMANCE[5,70]

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
C-Mo steel (A335 Gr. P1)	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/fluid-ized 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/fluid-ized 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	Westing-house	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

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE[5,70] (Continued)

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
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
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 devolatilizier	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 B-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

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE[5,70] (Continued)

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
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	Westing-house	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.	Westing-house	200 hrs	Product gas	1700-1900	220	360° circumferential crack in central pipe weld of union caused by stress corrosion cracking
Incoloy 800	Gasifier purge pipe		Synthane	N.A.	Steam	1200-1500	N.A.	Pitting
Inconel 600	Purge pipe BB-1 located inside gasifier	7/8 in 1/4 in wall thick-ness	Synthane	114-350 hrs	Steam (In-terior)	800-1500	600	Pits were discovered on OD with depths up to 50% of wall thickness. Caused by sulfidation
Inconel 601	Pipe from sec-ondary air preheater line	N.A.	Pittsburgh Energy Technology Center	~32 hrs	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 fit-ting on line CX-9106	1 1/2 x 3/4 in Schedule 80	BCR BI-GAS	1 yr	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 yrs	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 yrs	Steam	460	500	Five sections of pipe developed leaking cracks near welds caused by stress corrosion cracking

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE[5,70] (Continued)

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
304 S.S.	Pipe from heat-up line LI 2103 E2K	4 in Schedule 40	Synthane	2 yrs	Puel oil/ LP gas/steam/ CO_2/coal gases/O_2/air	800	600	2 in 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 in 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 mos	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 mos	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 hrs	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 hrs	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 hrs	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 S.S. Body 410 S.S. Gland nut 416 S.S. 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 S.S. Flange Incoloy 800 Piping	Clean Coke	3600 hrs	Recycle gas	500-1200	165	Crack occurred between the flange and pipe; believed to be caused by differential expansion of dissimilar metals
316 S.S.	Pipe/elbow joint in the interchanger bypass line	2 in Schedule 40	Clean Coke	3600 hrs	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 E3L	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 hrs	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

(Table Continued)

GAS PIPING IN-SERVICE PERFORMANCE[5,70] (Continued)

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
316 S.S.	Pipe in pre-heater 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 trans-granular 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	Triethyl/ 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
316 S.S.	Tubing from steam-iron reactor	N.A.	Hygas	N.A.	Gas	300-400	N.A.	Stress corrosion cracking
316 S.S.	N_2 purge line	N.A.	Hygas	N.A.	Process gas/steam/ oxygen	1400-1600	N.A.	Fracture due to grain boundary embrittlement by chromium sulfides
321 S.S.	Furnace tube from lift gas furnace	1 5/8 in OD 0.109 wall thick-ness	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 over-head line	4 in	CO_2 Acceptor	~8800 hrs	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 thick-ness	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.
347 S.S./ refractory	Steam/oxygen injection tuyeres	N.A.	Grand Forks ETC	N.A.	Steam/oxygen/ molten slag	530-2550	400	Cracking of tuyere tips due to thermal fatigue
347 S.S.	Tuyere tips	N.A.	Grand Forks ETC	300 hrs	Oxygen/steam	86-2500	N.A.	Severe pitting and cracking due to stress corrosion cracking
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 hrs	Inert gas/ air/recycle gas	500-1500	150	Circumferential cracking found in lower section of coil, possibly due to stress corrosion cracking
R.A. 330/ Inconel 182	Hot gas sampler coupling welded to piping with Inconel 182, steam-oxygen gasifier	0.5 to 0.75	Hygas	8470 hrs	Hot gas	N.A.	N.A.	Circumferential through-wall cracking due to attack by liquid $Ni-Ni_3S_2$ eutectic formed by sulfidation of Inconel 182 weld metal

BELLOWS IN-SERVICE PERFORMANCE[5,70]

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
321 S.S.	IGT-Ugas	127 hr	Product gas/ coal char/ash	500	6-11.5	Perforation due to chloride induced pitting

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.

A.7.2.1 OPERATING REQUIREMENTS

Solids transfer lines moving mixtures of coal, char, ash, and sometimes dolomite connect various stages of the gasifier. Environments vary greatly but 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). Environmental corrosion effects will be aggravated by erosive wear from bulk solids movement. Material problems will be similar to those anticipated for the gasifier internals (Section A.2.4.1) and product gas lines (Section A.7.1.1). Refractory-lined pipes will probably be required for the most severe conditions.

A.7.2.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 21 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), 304, 310, 316 and 446 stainless steels and RA 330. Operating temperatures ranged from 400 to 1800 °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 eight 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 and another failed due to thermal stresses. 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 one of the 316 stainless steel failures were also due to erosion.

Failure of the one reported 310 stainless steel pipe was caused by sulfur corrosion and thermal cycling. One 316 stainless steel failure was due to sulfidation assisted fatigue cracking and one was due to cracking caused by thermal stresses. Stress corrosion cracking was the cause of failure of the one reported 446 stainless steel pipe.

There were two RA 330 failures, both due to cracks induced by thermal stresses. In one case, sulfidation was also involved.

Based on the reported data, erosion was clearly the most frequent cause of failure in the solids piping systems, although thermal stressing was a factor in several cases.

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[5,70]

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	1 in 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	Pipe in gasifier	N.A.	Hygas	N.A.	Char/ash	800-1000	550-1000	Cracking due to thermal stresses
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 cor-rosion and thermal cycling

(Table Continued)

SOLIDS PIPING IN-SERVICE PERFORMANCE[5,70] (Continued)

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press., PSIG	Failure Mode
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
316 S.S.	Hub in char transfer line in gasifier	N.A.	Hygas	N.A.	Hot char	1500-1800	1000	Through-wall fatigue crack assisted by sulfidation at region of high stress concentration
316 S.S.	Pipe in gasifier	N.A.	Hygas	N.A.	Hot char	1500-1800	1000	Through-wall crack due to thermal stresses
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
RA 330	Pipe in gasifier	3 in Schedule 80	Hygas	N.A.	Char/ash	800-1000	550-1000	Cracking due to thermal stresses
RA 330	Spent char transfer line	3 in Schedule 80	Hygas	N.A.	Spent char	1500-1800	1000	Cracking due to thermal stresses and sulfidation

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 materials suitable for application under these conditions appear in Section A.2.4.2.2.

A.7.3.1 OPERATING REQUIREMENTS

Gasification and liquefaction processes transfer pulverized coal carried in water or a hydrocarbon liquid in slurry feed lines. Hydrocarbon liquids are used almost exclusively in liquefaction processes. Turbulent flow conditions usually prevail in all slurry lines due to the high velocities needed to maintain particles in suspension. Consequently, slurry lines are susceptible to erosion as well as corrosion. Temperatures of slurry lines can range from 200 to 1000 °F (366 to 811 K). Pressures may be as high as 1000 psi. Slurry lines from a slag quench tank or a water scrubber quench tower will have the same corrosion problems as the originating vessels.

Carbon steel is probably adequate for low temperature applications. Higher temperature feed lines and the more acid slurry lines will need, at least, stainless steel lining for corrosion resistance. Hard-face inserts for erosion resistance should be used wherever flow perturbations occur such as joints, 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 [5]

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

SCALE FORMATION IN A HYDROGEN-COAL SLURRY ENVIRONMENT on 2 1/4 Cr-1 Mo steel was studied in laboratory tests (see Sections B.1.1.143 and B.1.1.144). Specimens were exposed to coal slurry in a hydrogen atmosphere at 4000 psig at 800 °F in a static environment. Duplicate samples were immersed in the slurry and also suspended above the slurry in the slurry gases. The coal slurry was 35 volume percent of -100 mesh Kentucky bituminous and 65 volume percent centrifuged Synthoil product. Tests lasted for up to 1000 hours.

The scale built up to thicknesses of 0.01 to 0.02 inches during exposures of 900-1000 hours. Samples immersed in the slurry built up scale somewhat more slowly than samples suspended in the slurry gas (Section B.1.1.144). Electron microprobe analysis found indications of S, Fe, O, Mo, Cr and C in the scale (Section B.1.1.143). The microprobe scans covered a distance of up to 0.001 inches from the base metal/scale interface. Iron was the most abundant element in the scale. Noteworthy concentrations of sulfur, chromium and molybdenum were also detected.

SLURRY EROSION was measured on mild steel and ten other structural materials (Sections B.2.1.62-B.2.1.77). The slurries consisted of one type of abrasive particle in a carrier fluid. Abrasive particles used were -30 and -200 mesh Illinois #6 coal, SiC, Al_2O_3, and -325 mesh SiO_2. Slurry fluids included Wilsonville SRC process solvent, deaerated water, creosote oil, kerosene, hexadecane and hexadecane with 1/2% hexadecanoic acid. Variables of the erosion process which were evaluated included: velocity, viscosity, temperature, impingement angle, type of abrasive particle, coal concentration and coal particle size. The materials evaluated were: 1018 and 1020 carbon steels; 4340, 5 Cr-1/2 Mo, and 9 Cr-1 Mo alloy steels; Incoloy 825; Types 304, 309, 316, 321 and 410 stainless steels; and 6061 aluminum alloy. An experimental loop in which some tests were conducted appears in Section B.2.1.65. Other tests were conducted in a 2-liter slurry pot with circulating cylindrical specimens, as described in Sections B.2.1.62, .63, .66, .69-.72. Still other tests used a jet impingement device with a 3mm spray nozzle to direct an unrecirculated jet of slurry onto a fixed flat specimen surface, Sections B.2.1.64, .67, 0.73-0.77. Exposures in most tests were rather short, ranging from 11 minutes to 30 hours. Results from longer exposures would probably give more meaningful data for predicting performance in an actual coal liquefaction plant environment.

EFFECTS OF VELOCITY ON SLURRY EROSION are reported in Sections B.2.1.63, .64, .67, .70, .71 and .76. Erosion generally increased with increasing velocity, regardless of the type of erodent (Sections B.2.1.63, .71 and .76). For some materials, increasing slurry velocity from 20 to 40 feet per second increased erosion by a factor of five or more after five hours exposure (Section B.1.1.71). Mild steel eroded faster than 6061 aluminum alloy over a range of slurry velocities (Section B.2.1.67). In some constant velocity tests, A53 steel eroded faster than five other materials, whereas Types 316 and 410 stainless steels generally eroded slowest of six materials tested (Section B.2.1.71).

EFFECTS OF ANGLE OF IMPINGEMENT ON SLURRY EROSION are reported in Sections B.2.1.64, .67, and .75-.77 for impingement angles between 15 and 90°. Erosion generally decreased with increasing angle of impingement between 15 and 90° for 6061 aluminum alloy, spheroidized 4340, Incoloy 825 and Types 304, 309, 316 and 321 stainless steels, regardless of the type of erodent. Erosion of mild steel increased over a range of low impingement angles, but decreased over a range of high impingement angles (Sections B.2.1.64, .75). Erosion of 6061 aluminum alloy due to a stream of gas and particles impinging on the test specimen generally decreased with increasing impingement angle between 15 and 90°.

EFFECTS OF SLURRY CHARACTERISTICS, SUCH AS VISCOSITY, TYPE OF FLUID, ERODENT CONCENTRATION AND PARTICLE SIZE, ON EROSION are reported in Sections B.2.1.62, .67, .69, .70, .72, .74. Increasing slurry viscosity reduces erosion of mild steel. For example, Figure D in Section B.2.1.62 shows that after 15 hours exposure, mild steel eroded ten times more in a SiC/water slurry of viscosity 0.89 centipoise than in a SiC/SRC process solvent slurry of viscosity 53 centipoise. This same point is illustrated in Section B.2.1.74 for exposures of mild steel to a low-viscosity SiO_2/water slurry and a high-viscosity coal/kerosene slurry. Erosion of several materials was faster in coal/kerosene slurries than in coal/creosote slurries, Section B.2.1.72. Faster erosion occurred in hexadecane slurries than in kerosene slurries, Section B.2.1.69. Additions of 1/2% hexadecanoic acid to hexadecane slurries served as an inhibitor and reduced erosion by about 1/2 after 15 minutes exposure, Section B.2.1.69. The erosion of 6061 aluminum alloy tended to increase with increasing coal content, between 10 and 30% in kerosene, Section B.2.1.67. Changes in coal concentration between 20 and 50% in kerosene did not result in appreciable differences in the erosion of A53 and Type 304 stainless steels, Section B.2.1.70. Erosion increased as coal particle size changed from -200 to -30 mesh in a coal/kerosene slurry at a velocity of 40 feet per second, Section B.2.1.70. Al_2O_3 particles caused more erosion than did -200 mesh Illinois #6 coal particles for a given set of test conditions reported in Section B.2.1.67.

EFFECTS OF TEMPERATURE ON EROSION are reported in Sections B.2.1.71 and .72. Erosion of several alloys exposed for 2 hours in a coal/kerosene slurry decreased between 75 and 200 °F, then increased for temperatures up to 350 °F.

THE EFFECT OF HEAT TREATMENT ON THE SLURRY EROSION OF A 4340 STEEL is reported in Section B.2.1.77. For the hardest condition (as-quenched), erosion was three to four times greater than for a softer condition (quenched and tempered at 200 °C) for angles of impingement ranging between 20 and 90°.

A.7.4.1 OPERATING REQUIREMENTS

Pure liquids lines other than cooling water lines are rare in gasification or liquefaction processes. Those lines which do carry process liquids must have resistance to corrosion by these various liquids. Corrosion problems in liquids lines will be dependent upon location, and generally will be the same as for the components which the lines serve, e.g., sour water piping will need the same materials as the scrubber quench tank. Liquids lines in coal liquefaction processes may carry quench waters or coal liquids. Temperatures may reach 600-800 °F. In gasification processes, lines carrying quench water from the gasifier or from the product gas quench may carry a significant particulate burden of ash or slag. Such lines are more appropriately considered as slurry lines (Section A.7.3).

A.7.4.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for 24 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 °F.

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 formation of deposits on the inside of the piping in a heat exchanger which reduced heat transfer allowing the pipe to overheat.

Two of the eight carbon steel pipes failed due to corrosion and two failed due to a combination of corrosion and fatigue. Two carbon steel failures were 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, the two Incoloy 800 failures, and one of the 310 stainless steel failures were all due to stress corrosion cracking. Two of the three 304 stainless steel failures were due to stress corrosion cracking, 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.

One of the two 310 stainless steel failures 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 from 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[5,70]

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 mos	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 yrs	Glycol	130	100	Fatigue failure
Carbon Steel	Condenser tubing from raw gas quench cooler	3/4 in x 0.095 wall thickness	Hygas	1 yr	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 yrs	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 yrs	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 mos	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 fatigue
Carbon Steel (AISI 4140)	Water pump shaft	1.25 in	Synthane	500-800 hrs	Water	N.A.	N.A.	Fatigue crack initiating at keyway fillet radius
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

(Table Continued)

LIQUID PIPING IN-SERVICE PERFORMANCE[5,70] (Continued)

Material	Location	Description (Plant ID)	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Incoloy 800	Forged reducer butt welded 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
Incoloy 800	Piping in separator float enclosure	2 in	Hygas	1 yr	Toluene/water	400	1000	Intergranular stress corrosion cracking due to sensitization and residual stresses from welding; noxious elements in toluene/water mixture
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 caused 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 caused by chloride stress corrosion cracking
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
310 S.S.	Gasifier water jacket	N.A.	Grand Forks Energy Technology Center	N.A.	Coolant water	N.A.	N.A.	Stress corrosion cracking in region sensitized by welding
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

A.7.4.2.2 MATERIALS EVALUATION

The operating conditions for liquids lines involve exposure to corrosive aqueous fluids over a range of temperatures. 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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* Sections included in SP-642 and Supplement 1 combined.

A.8.1.1 OPERATING REQUIREMENTS

Slurry pumps face the same corrosive and erosive conditions and problems as slurry lines (Section A.7.3.1). Temperatures may reach 1000 °F (881 K). The discharge pressure of slurry pumps used in coal feeding for liquefaction processes may vary between 400 and 4000 psi. It is questionable whether presently available slurry pumps are adequate for reliable service in a commercial-sized gasification or liquefaction plant. Considerable development in both design and materials for this component is still needed. Erosion-resistant materials such as cemented tungsten carbides in the form 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 including 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.

A.8.2.1 OPERATING REQUIREMENTS

Pumps for liquid streams will face the same corrosive problems as the piping lines (Section A.7.4) and their environment will be dependent on their function. In coal gasification processes, the most severe environment will occur in quench water lines from the gasifier and the product gas quench both of which carry a significant particulate burden. For such applications the pumps should be considered in the same context as slurry pumps (Section A.8.1). Coal liquids, particularly those with accumulations of chlorides, represent one of the more corrosive environments in coal liquefaction processes.

A.8.2.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for twelve 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 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, another failed due to a combination of erosion and corrosion of the casing and head (service life not stated), and a third failed due to fatigue cracks initiated at surface defects.

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.

LIQUID PUMP IN-SERVICE PERFORMANCE[5,70]

Material	Description/ Component	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIC	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 hrs	Water	Ambient	N.A.	Pipe seal worn which led to water leak
Carbon Steel	Scrubber recycle water pump (casing)	Synthane	125 hrs	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 hrs	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 recirculating pump (shaft)	Hygas	<4 days	Water/5% solids	150	N.A.	Pump shaft cracked near one end apparently due to overload and vibration
Carbon Steel (AISI 4037)	Water pump cap screw	Synthane	500-800 hrs	Water	N.A.	N.A.	Fatigue crack initiating at surface defects
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 hrs	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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* Sections included in SP-642 and Supplement 1 combined.

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. In general, liquids will be water, hydrocarbons and/or coal liquids. Materials technology transfer from chemical and petroleum industries should be adequate for this application. (If the liquid carries a significant particulate burden, the erosive problem could be quite serious, and these valves should be considered in the context of Slurry and Solids Valves--Section A.9.3).

A.9.2.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE for a LIQUIDS VALVE in one liquefaction plant has been reported. There are insufficient data for any conclusion to be drawn.

LIQUIDS VALVES IN-SERVICE PERFORMANCE[70]

Material	Location	Plant/ Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
17-4PH S.S.	Level control valve seat	Fort Lewis Solvent Refined Coal	N.A.	Recycle condensate	N.A	N.A.	Stress corrosion cracking due to a combination of environmental and residual stresses in material aged to too high a strength level

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 slurry and solids valves vary among the several coal gasification and liquefaction processes, and also depend upon the location of the valve within the process. Water and/or coal liquids are usually the carrier fluids; the particulates include unreacted charcoal, char and ash. Typical service conditions are high temperatures and pressures (maximums are 3000 °F (1922 K) and 1600 psi for gasification and 900 °F (755 K) and 4000 psi for liquefaction) under cyclic loading and exposure to erosive and abrasive particulates. Depending primarily upon temperature of service, slurry and solids valves may be classified into four types. 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 above temperature requirements, valves must also be able to operate at pressures from atmospheric to the process maximum, and to have expected lifetimes of 30,000 cycles while exposed to highly erosive streams containing corrosive gases, water and/or coal liquids. Construction materials and design considerations must fulfill these requirements. 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 protective 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 2000 °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 the 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.

One RA 330 hinge pin was bent and galled due to excessive loading.

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[5,70]

rim Material	Valve Type (Plant ID)	Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
16 S.S. hite Iron	6 in full port ball (0612)	METC	297 cycles	Ash	900	125	Wear: scoring on ball, wear on seat
16 S.S. tellite 6	10 in full bore ball (1005)	METC	257 cycles	Coal	250	300 (max)	Quality control: cracks in ball from a manufacturing defect
16 S.S.	(HV-719)	Westinghouse	200 hrs	Coke breeze/ recycle gas	500	200	Design: valve body distorted by impingement of fine particles
16 S.S.	(HV-718)	Westinghouse	200 hrs	Coke breeze/ recycle gas	500	200	Design: valve body distorted by impingement of fine particles
16 S.S.	(HV-1106)	Westinghouse	200 hrs	Coke breeze/ recycle gas	500	200	Design: valve body distorted by impingement of fine particles
S sleeve eramic seat	Letdown (LCV-405)	Synthane	2 mos	Coal char	N.A.	1000	Erosion
40C S.S.	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 S.S.	Level control (LCV-201)	Synthane	1 mo	Coal char fines in water	180-300	600	Erosion
.A. 330	Hinge pin from solids transfer valve (LV 33C) in fluidized bed of gasifier	Hygas	N.A.	Steam/oxygen	1850-2000	1000	Pin was bent and galled due to excessive loading
.A. 330 aynes 25	High-temperature butterfly (LCV-2002)	CO_2 Acceptor	1200 hrs	Char/inert gas	1450	N.A.	Fabrication: poor weld, butterfly came off shaft
ncoloy 800	High-temperature gate (XCV-2010)	CO_2 Acceptor	∿9 mos	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 hrs	Coal/ash/gas/ air/steam	200-700	N.A.	Wear: gouging and abrasion of seats
arbon Steel	1 in, 800 lb globe	Cresap	2400 hrs	Carbonizer tar slurry, 3-28% solids	300	N.A.	Erosion: hole in bonnet/ body and internals eroded
arbon Steel	Plug (XV-271)	Synthane	1 yr	Water/coal dust/coal char	300	600	Erosion: plug surface
arbon Steel	Gate (in venturi scrubber bypass)	Synthane	6 mos	Char/water/ steam/CO_2/ coal gas	N.A.	N.A.	Erosion: severe, body and gate
ennametal 701 (WC with o-Cr binder)	Pressure letdown (on product oil line)	Synthoil	915 hrs	Product oil with 5-6% solids	257	4000	Erosion: plug tip. stem seat eroded/braze joint cracked
oors 999 eramic	Coors Willis choke (LCV-405A)	Synthane	4 days	Char/water/ dissolved gases	N.A.	N.A.	Erosion: holes in trim and downstream sleeve

(Table Continued)

SOLIDS VALVES IN-SERVICE PERFORMANCE[5,70] (Continued)

Trim Material	Valve Type (Plant ID)	Process	Service Life	Environment	Temp. °F	Press. PSIG	Failure Mode
Stellite 6	Letdown to flare (PCV-2205)	Synthane	1.5 yrs	Char/water/gas	300	600	Erosion: 100% erosion of trim/body unusable
S.S. Carbon Steel	Letdown (PCV-266)	Synthane	37 hrs	Char/water/gas	800	600	Erosion: 50% erosion of trim/groove in downstream pipe
Rubber	3 in pinch (Series B3)	BIGAS	6 mos	Coal slurry	Ambient	N.A.	Misuse, overstressing: tear in rubber sleeve from over-tightening hand wheel

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* Sections included in SP-642 and Supplement 1 combined.

A.10.1 OPERATING REQUIREMENTS

The primary objective of modern direct coal combustion is to use high-sulfur and high-ash coals efficiently and economically in an environmentally acceptable way. Research efforts have been concentrated on atmospheric and pressurized fluidized bed combustion (AFBC and PFBC) with major emphasis on the atmospheric type.

Direct combustion systems can be considered as consisting of three major areas: 1) solids handling system, 2) combustor (including containment shells, heat transfer tubes, baffles and air distributor plates), and 3) peripheral items (including cyclones, carbon burn-up cell, and various heat exchangers. Most potential problem areas have already been discussed in other sections of this book.

Major differences from, for instance, gasification processes, will occur in the composition of the gaseous environment, e.g., flue gases would be higher in CO and CO_2 and lower in H_2 and H_2O than in a typical gasification process. Also, erosion/corrosion reactions of in-bed tubes in a fluidized bed combustor would have no direct parallel in a gasification process. Temperatures in a fluidized bed combustor are limited to 1600-1700 °F (1144-1200 K) and pressures range from atmospheric in AFBCs to 10 atmospheres in PFBCs. Temperatures may go to 2000 °F (1366 K) in carbon burn-up cells, but these units normally do not have in-bed tubes.

In summary, materials used in fluidized bed combustors will be subjected to most of the potential thermal, mechanical and chemical stresses outlined for metal internal gasification needs (Section A.2.4.1) albeit at somewhat lower temperature and pressure limits. In-bed erosion/corrosion problems provide an additional potential complication.

A.10.2.1 PLANT EXPERIENCE

PLANT EXPERIENCE has been reported for two HEAT EXCHANGER TUBE failures. In both cases, the material of construction was 316 stainless steel. Both tube failures occurred after 100 hours of operation and were due to sulfidation ("hot corrosion"). Operating temperatures were 1650 °F and 2000 °F. No definitive conclusion can be drawn from these limited data.

HEAT EXCHANGER TUBES IN-SERVICE PERFORMANCE[70]

Material	Location	Plant/ Process	Service Life	Environment	Temp.	Press.	Failure Mode
316 SS	In-bed heat exchanger tubes, 1/2 in. NPS, schedule 160	Morgantown Energy Technology Center, Atmospheric Fluidized Bed Combustor	100 h	Fluidized Bed	2000 °F	N.A.	"Hot corrosion"-sulfidation, caused by excessive SO_2 and low oxygen pressures
316 SS	U-bend heat exchanger tubes, 1/2 in. schedule 160	Morgantown Energy Technology Center, Atmospheric Fluidized Bed Combustor	100 h	Coal/Flue Gas (1350 ppm SO_2)	1650 °F	N.A.	Sulfidation ("hot corrosion") resulting in tube melting

A.10.2.2 MATERIALS EVALUATION

OVERVIEW

Corrosion of structural metals for heat exchanger tubes was determined following exposures in flue gases from coal-fixed steam generators and in atmospheric fluidized-bed combustion facilities. Corrosion and erosion-corrosion rates were measured and are reported in Sections B.1.1.8-.11, .13, .84, .85, .87, .88, .188-.191, and B.2.1.35. Results of metallographic examination and scale analysis appear in Sections B.1.1.7, .14, .15, .86, .89, .90, .91, .97, and B.2.1.36-.39. Some hardness measurements were reported on test specimens after exposures in flue gases (B.3.1.28-.30) and in a fluidized bed coal combustor (Section B.3.1.51). For the same alloys and similar exposure times, corrosion rates were considerably lower than rates reported for exposures to a standard coal gasification atmosphere in Section A.2.4.2.2.1. Similar corrosion products formed, regardless of the exposure medium.

FLUE GAS EXPOSURE of seven alloys in a coal fired steam generator resulted in the corrosion losses reported in Sections B.1.1.11 and .13. The graphs in Section B.1.1.11 show that the type of coal feedstock influences the weight loss. For example, all seven alloys showed rather substantial losses in Lignite A coal, but not in HV bituminous A coal. Inconel 617 showed the least loss in all four of the coals used in the tests. On the other hand, Alloy 12R72 tended to show rather high losses in all four coals. Some welds involving combinations of Type 316 stainless steel, Incoloy 800, and Haynes 188 joined with Inconel 82 and Inconel 617 filler metal were studied after exposure to flue gas (Section B.1.1.7). Exposures were at 800-1280 °F for 3552 to 8081 hours. Although the welds showed lack of penetration, porosity and cold shuts, very little corrosive attack occurred during exposure. Hardness tended to show a slight decrease with exposure (Section B.3.1.30). Microstructure changes of six alloys and two coated alloys exposed to flue gases from four coal feed stocks are reported in Section B.1.1.15. Exposure times and temperatures ranged from 300-7368 hours and 700-1710 °F, respectively. Observations generally included carbide precipitation (inter- and intra-granular), oxidation, and chromium depletion.

CORROSION RATES AND EROSION/CORROSION DATA IN AN ATMOSPHERIC FLUIDIZED BED COAL COMBUSTOR are reported for fourteen alloys in Sections B.1.1.8-.10, .84, .85, .87, .88, .188-.191 and B.2.1.35, .36, .38 and .39. Graphs of metal loss (wastage) vs. temperature for ten alloys (Sections B.1.1.85 and B.1.1.87) show that the metal loss generally increases with increasing temperature for exposures of 1500 hours. The time dependence of the average corrosion rate for exposures of up to 1500 hours at temperatures between 1200 and 1500 °C are tabulated in Section B.2.1.35 and graphed in Sections B.1.1.84 and B.1.1.88. Average rates for Types 304 and 310 stainless steel, and for P9, IN 671 and FSX 414 were comparable, and did not exceed 0.05 mils per year. Rates for exposures in the beds were higher than for exposures in the freeboard position. The influence of salt additions on penetration and scale formation for fourteen alloys is reported in Sections B.1.1.188-.191. Exposures were for 100 hours at temperatures near 1571 °F. Salt additions generally increased the depth of penetration and scale thickness (Sections B.1.1.188 and .190). Air cooling the test specimens tended to decrease the depth of penetration (compare results in Sections B.1.1.189 and .191). Tubular specimens of six alloys exposed during 144 hour exposures at 400 to 890 °F showed notable weight losses (Section B.2.1.36). Test specimens of four alloys showed significant metal loss during a 1080 hour exposure at 1620 °F. Losses were much higher in the lower bed than in the upper bed (Section B.2.1.38). A comparison of scale thickness formed on three alloys exposed in air and in a fluidized bed coal combustor at temperatures between 610 and 1068 °F for 144 hours showed that much higher scale thicknesses resulted from exposure in the fluidized bed than in air (Section B.2.1.39).

Fireside corrosion measurements (Section B.1.1.8) showed comparable maximum oxide scale thicknesses on Types 304, 310 and 316 stainless steels and Incoloy 800H. The maximum penetration of intergranular corrosion was also comparable. A comparison of fireside and airside corrosion generally showed higher oxide scale thicknesses for airside exposures (Section B.1.1.9). Type 304 stainless steel generally showed better oxidation resistance and resistance to intergranular penetration than did 2 1/4 Cr-1 Mo steel (Section B.3.1.10).

SCALE FORMATION AND MICROSTRUCTURE CHANGES following exposure in an atmospheric fluidized bed coal combustor are reported in Sections B.1.1.14, .86, .89, .90 and B.2.1.37. Surface appearance and phase identification after air exposures at elevated temperatures are reported in Sections B.1.1.91 and .97 to facilitate comparisons with scale formation after exposure in a fluidized bed. The principal phases detected on Alloy P9, E-Brite (26-1) and Type 316 stainless steel after air exposures for 144 hours at 1600 °F were Fe_2O_3, $(Cr,Fe)_2O_3$ and Cr_2O_3 (Section B.1.1.91). Fe_2O_3 was also detected after exposure in a fluidized bed (Section B.2.1.37). Corrosion products formed after air exposures at temperatures between 215 and 925 °F for up to 144 hours included gold and yellow powder, red-rust scale and heavy black scale, depending upon the alloy (Section B.1.1.97). Intensity profiles for Fe, Cr, Ni and Ca in the scale formed on Type 316 stainless steel, E-Brite, and P9 exposed for 144 hours at 685-910 °F generally show lower intensities in the scales than in the base metal, which indicates depletion (Section B.1.1.86). Phases identified in the scales included Fe_2O_3, Fe_3O_4, $CaSO_4$, $K_3Fe(SO_4)_3$, and $CaFe_2Si_3O_{12}$ (Section B.2.1.37). Microstructural observations made on 12 alloys and two coated alloys exposed in various locations at temperatures between 1440 and 1620 °F for up to 1500 hours are reported in Sections B.1.1.14, .89 and .90. Results show indications of carbon pick-up, intergranular oxide penetration, and carbide precipitation. Insufficient information is presented for making a meaningful assessment of the role of coatings in the corrosion process.

HARDNESS MEASUREMENTS were made on seven alloys exposed to flue gases from four coals (Section B.3.1.28-.30) and in a fluidized bed coal combustor (Section B.3.1.51). Exposure conditions ranged between temperatures of 1100 and 1700 °F for up to 1500 hours. Hardness tended to show a slight decrease in some cases (Sections B.3.1.28, .30, and .51), no trend in other cases (Section B.3.1.29), and an increase in some cases (Section B.3.1.51).

INTRODUCTION

The purpose of Part B is twofold. The first is to present the data on which the "Materials Evaluation" portions of Part A of this book are based. The second is to make available, in one place, the information generated by the wide variety of projects which are sponsored by the Department of Energy in the field of materials for fossil energy applications. The contents of this section, therefore, are data summaries abstracted from the reports of materials research contractors to the Department of Energy. Some tables and graphs have been generated by the compilers using the data given in the reports, others are reproduced from the reports with little or no modification. The units appearing in the tables or graphs are those used by the authors of the various reports, the compilers not having converted all data to a common system of units. Although this practice results in a wide variation in the reporting of the data, and requires the user to exercise great care in comparing data from table to table, conversion to a common system of units for all the data in Part B would have been a very costly effort.

The original sources of the data are identified by the number in square brackets following the title of each table or other data summary. References to the source documents may be found by looking for that number in Part E, References. In order to condense the information and to bring related data together, data from more than one individual report may appear in a given summary. The same data may appear in more than one of the source reports. The references, therefore, are to the series of reports for a given project and, in some cases, to related publications by the same authors. It was considered unnecessary, and possibly confusing, to attempt to identify the specific report(s) of a series from which a given data value was taken. Those readers who wish to check the original reports would do well to examine the entire series in any event. For alloy data, the project reports are covered through the reporting periods ending December 31, 1982. For refractories data the coverage of the projects varies, depending on the reports on hand at the time those data were abstracted for the first issue of the book. The second supplement of this book will contain more data from the refractories projects.

The great majority of the programs generating the data presented in Part B have one or more of the following purposes:

1. 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.

2. To develop materials with specific resistance to the effects of coal conversion conditions.

3. 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 the footnotes to tables and graphs in Part B. Conditions for the exposures are given much the same as they are in the source documents, with 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 therefore 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, 5 percent CH_4, 1 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 is attached to these 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 (mole %)[d]												
RUN PRESSURE 34 ATM. (500 PSIG)												
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. (1500 PSIG)												
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 (mole %)[e]												
RUN PRESSURE 34 ATM. (500 PSIG)												
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. (1500 PSIG)												
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., 77 °F: CO 0.201, CO_2 0.115, H_2 0.201, H_2O 0.172, H_2S 0.010, CH_4 0.300 (mole fraction)[f]												
RUN PRESSURE 68 ATM. (1000 PSIG)												
USS 18-18-2	306	201	370	571	58[g]	60[g]	77[g]	137[g]	--	--	--	--
Incoloy 800	32	49	120	169	40[g]	62[g]	178[g]	240[g]	26	16	286	302
AISI 310	74	42	95	137	84[g]	41[g]	226[g]	267[g]	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[g]	17[g]	8[g]	25[g]	6	14	43	57
GE 1541 (ox)[h]	16	20	16	36	20[g]	14[g]	147[g]	160[g]	11	15	14	29
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 (mole %)[i]												
RUN PRESSURE 34 ATM. (500 PSIG)												
USS 18-18-2	56	47	66	113	completely corroded after 390 h				completely corroded after 245 h			
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)[j]	343	370(665)[j]
Inconel 671	9	6	18	24	29	35	133	162	70	61	465	526
Input gas, 1 atm., 77 °F: CO 26.0, CO_2 14.9, H_2 26.0, H_2O 22.2, H_2S 1.0, CH_4 10.0 (mole %)[k]												
RUN PRESSURE 34 ATM. (500 PSIG)												
USS 18-18-2	16	15	16	31	19	11	19	30	37	121	52	173
Incoloy 800	9	15	17	32	13	27	37	64	29	23	73	96
AISI 310	10	15	23	38	20	25	24	49	29	24	65	89
Inconel 671	16	19	16	35	9	27	23	50	16	40	73	113

[a]Corrosion effect measured on micrographs of specimens 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 at the indicated pressures. Actual temperatures experienced by individual samples varied somewhat depending on sample location.

(Continued)

CORROSION LOSS[a] OF SOME ALLOYS UPON EXPOSURE TO SIMULATED COAL GASIFICATION ATMOSPHERES[b][7]
(Continued)

[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 (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), 11.0 Ni, 20.90 Cr, 1.93 Si, 0.090 C, 0.46 Mn, 0.335 others, balance Fe; GE 1541 (General Electric), 15.2 Cr, 4.95 Al, 0.7 Y, 0.012 C, 0.07 Si, 0.005 others, 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 (solid)	22.6	12.0	1.4	25.4	18.0	8.3
log $P(O_2)$	-19.19	-17.31	-16.10	-18.67	-16.68	-15.34
log $P(S_2)$	-6.05	-5.55	-5.07	-5.61	-5.15	-4.75
log a_c	1.00	1.00	1.00	1.00	1.00	1.00

[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 (solid)	24.0	13.7	3.5	26.7	19.5	10.1
log P (O_2)	-19.21	-17.32	-16.11	-18.68	-16.70	-15.35
log P (S_2)	-6.32	-5.83	-5.35	-5.93	-5.42	-5.08
log a_c	1.00	1.00	1.00	1.00	1.00	1.00

[f]Equilibrium compositions:

	1382 °F	1600 °F	1800 °F
CO	0.061	0.157	0.266
CO_2	0.111	0.082	0.046
H_2	0.186	0.297	0.403
H_2O	0.256	0.181	0.110
H_2S	0.009	0.008	0.008
CH_4	0.214	0.166	0.122
C (solid)	0.164	0.108	0.04
log P (O_2)	-19.16	-17.21	-15.91
log P (S_2)	-6.69	-6.22	-5.76
log a_c	1.00	1.00	1.00

[g]These values are for 642 hours exposure.

[h]These samples were pre-oxidized for 30 hours at 2100 °F, 100 torr O_2.

[i]Equilibrium compositions:

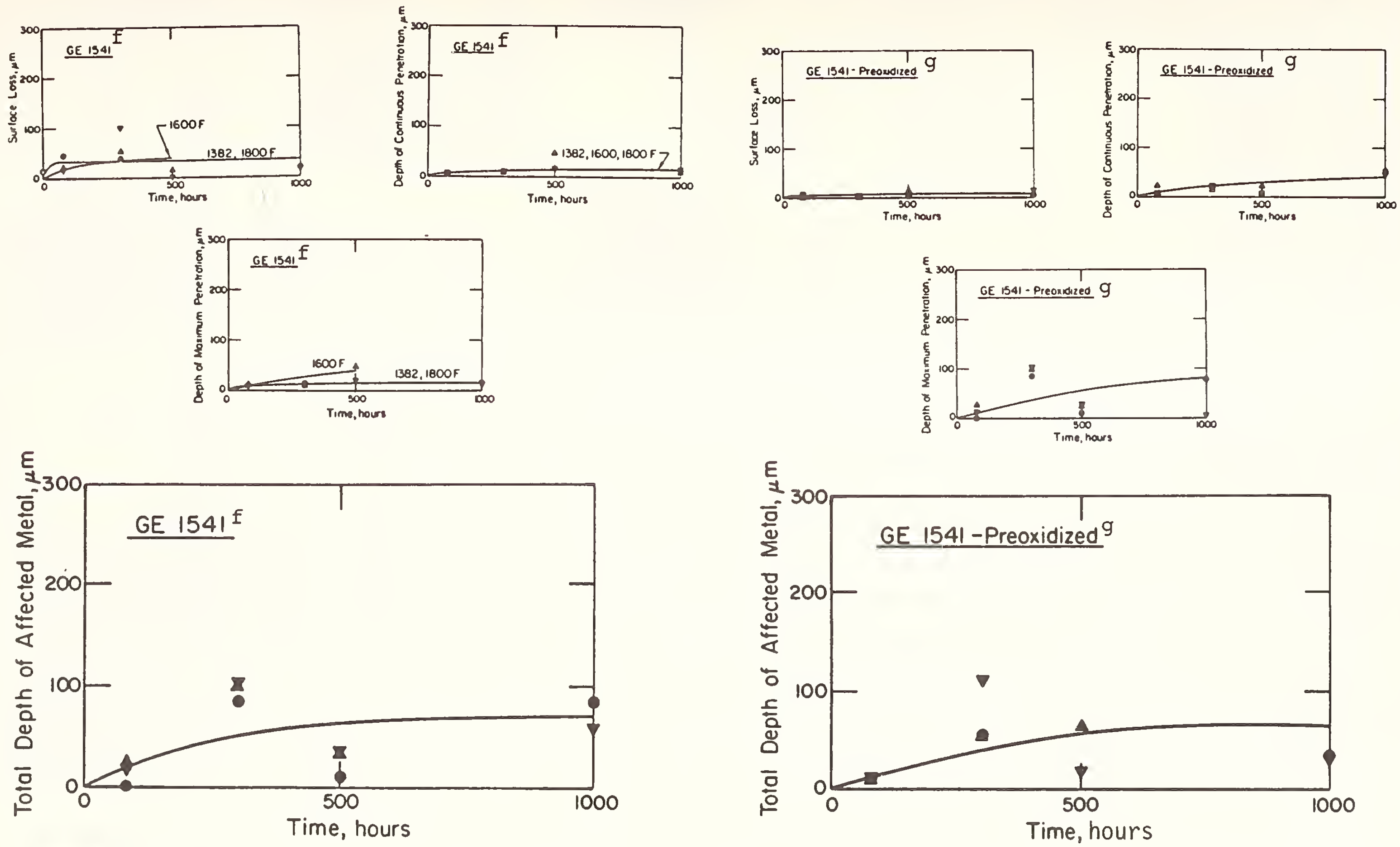
	1382 °F	1600 °F	1800 °F
CO	8.796	15.542	19.068
CO_2	19.360	14.568	11.723
H_2	23.801	32.055	33.653
H_2O	39.806	34.816	34.319
H_2S	0.944	0.857	0.841
CH_4	7.282	2.149	0.396
COS	0.011	0.011	---
log P (O_2)	-18.992	-16.705	-14.770
log P (S_2)	-6.86	-6.23	-5.575
log a_c	-0.26	-0.57	-0.99

[j]Data for both samples are given.

[k]Equilibrium compositions:

	1382 °F	1600 °F	1800 °F
CO	12.5	27.4	33.0
CO_2	20.8	13.9	9.0
H_2	20.6	32.0	38.6
H_2O	26.1	18.8	16.5
H_2S	1.0	0.9	0.8
CH_4	11.8	7.0	2.0
C (solid)	7.2	---	---
COS	0.02	0.03	0.03
log P (O_2)	-19.23	-17.24	-15.52
log P (S_2)	-6.67	-6.16	-5.67
log a_c	+0.009	-0.054	-0.39

CORROSION KINETICS FOR SEVERAL ALLOYS EXPOSED TO A SIMULATED COAL GASIFICATION ATMOSPHERE[a][7], Continued



[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]

Atmosphere No. 1[c]	Atmosphere No. 2[d]		Atmosphere No. 3[e]		Atmosphere No. 4[f]	Atmosphere No. 5[g]
68 atm	34 atm	102 atm	34 atm	102 atm	34 atm	34 atm
GENERAL RESULTS FOR ALLOYS TESTED						
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 deposited C; thin adherent corrosion 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. At 1600 °F outer scales (except 671) were Cr_2O_3 with small islands of Cr, Fe, & Ni non-uniformly dispersed; penetration solely by Cr sulfides along grain boundaries. At 1800 °F internal penetration greater; some sulfide inclusion in Cr_2O_3 outer scales; some Ni-Fe sulfides at outer edge of scale.		Corrosive attack similar to that in Atmosphere 2, but sulfide/oxide attack less severe than in Atm. 2 at 1600 & 1800; less subscale formation, continuous penetration, & internal sulfide precipitation. (Sandvik 253 MA tested; at 1800 °F had less surface attack than 18-18-2 & less discontinuous penetration than the other three alloys.)		Cr_2O_3- rich protective scale formed; oxide subsurface precipitation, with small amounts of sulfide.	
18-18-2[h]						
Exposure at 1382 °F						
Corroded fastest at 1382; rapid surface loss & corrosion penetration.	See general results.	Thick mottled gray deposit, essentially C; surface attacked through scale formation & sulfide penetration.	See general results.	Thin oxide/sulfide protective scales formed; few small discrete Cr-rich sulfide precipitates in alloy surface; some oxide penetration along grain boundaries intersecting metal/oxide surface.	See general results.	Continuous protective external scales with ragged metal/oxide interface due to oxide penetration of grain boundary.
Exposure at 1600 °F						
Removed early; irregular corrosion pattern, metal-dusting type attack; slower corrosion than at 1382, rate similar to IN 800.	See general results.	Same as at 1382.	See general results.	Same as at 1382.	Complete conversion to sulfide scale; sample removed at 390 hours.	
Exposure at 1800 °F						
Same as at 1600.	See general results; Cr sulfide precipitates at grain boundaries destroyed surface integrity.	Same as at 1382 with more extensive sulfide penetra tion.	See general results.	Same as at 1382.	Same as at 1600, sample removed at 245 hours; scales apparently Cr_2O_3-rich, protective in nature.	Subscale formation more extensive; rapid sulfidation/oxidation attack produced non-protective layered scale in some areas.
INCOLOY 800[h]						
Exposure at 1382 °F						
Fe-Cr-Ni outer scale, remainder Cr-rich; Cr-rich subscale penetration to ~90 μm; 11.4% Cr in alloy beneath scale; Cr-rich carbide precipitates below Cr-depleted area.	Below tree-like C growths protective sulfide scale; local scale degradation forming Fe, S, and Ni-containing nodules; Cr-rich carbides extend to 120 μm; Cr sulfides precipitated to ~60 μm; Cr depletion to 200 μm, Cr level at alloy-scale interface ~10%.	Almost continuous Cr-rich scale; scale penetrated by sulfide precipitates; thick gray carbon deposits.	See general results.	Thin uniform oxide/sulfide scales; extensive grain boundary penetration by oxides; band of sulfides found deeper in alloy ahead of oxides, precipitates increasing in size and number with increasing temperature.	See general results.	Similar to 18-18-2 at all temperatures with subscale sulfide (not oxide) penetration increasing with temperature.

(Continued)

METALLOGRAPHIC CHARACTERIZATION[a] OF VARIOUS ALLOYS EXPOSED TO COAL GASIFICATION ATMOSPHERES[b] AT SEVERAL TEMPERATURES[7], Continued

	Atmosphere No. 1[c]	Atmosphere No. 2[d]		Atmosphere No. 3[e]		Atmosphere No. 4[f]	Atmosphere No. 5[g]
	68 atm	34 atm	102 atm	34 atm	102 atm	34 atm	34 atm
INCOLOY 800[h], continued							
Exposure at 1600 °F	Removed after 500 hours; irregular corrosion pattern, Cr-rich sulfides precipitated; 6.9% Cr in alloy; Cr depletion to ∿130 μm; Cr-rich sulfide subscale extended along grain boundaries to ∿120 μm; metal-dusting type attack, Cr carbides precipitated deeper than sulfides.	Same as at 1382 but Cr depletion extended to ∿130 μm; Cr level at alloy-scale interface ∿12%.	Same as at 1382 but with localized breakdown & penetration of Cr-rich scale by massive Fe- and Ni-rich sulfides.	Uniform and adherent external scales over most of the surface.	Same as at 1382.	Sulfide scales were flaking off samples at 390 hours.	Same as at 1382.
Exposure at 1800 °F	Cr-rich oxide scale layer Si-rich at base; Cr level in alloy beneath scale 12.2%; Cr depletion & Cr-rich sulfide subscale extended ∿250 μm; no Cr-rich precipitates found.	Same as at 1382 but Cr depletion extended to 230 μm; Cr level at alloy-scale interface ∿9%; Cr sulfides penetrated and partially destroyed surface integrity.	Same as at 1600.	Same as at 1600.	Same as at 1382.		Same as at 1382.
310 SS[h]							
Exposure at 1382 °F	See general results.	See general results; penetration occurred along Cr carbide precipitates in grain boundaries.	Results similar to those for IN 800.	See general results.	Surface extremely ragged, shallow penetrations of oxide/sulfide scale; band of Cr-rich sulfides formed in subjent alloy at grain boundaries.	See general results.	Similar to 18-18-2 at all temperatures with subscale sulfide (not oxide) penetration increasing with temperature.
Exposure at 1600 °F	Removed early; irregular corrosion pattern; metal-dusting type attack, apparently Cr carbides precipitated deeper than sulfides.	See general results.	Results similar to those for IN 800.	See general results.	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 were Cr-rich sulfides in boundaries.	Scales flaked off.	Same as at 1382.
Exposure at 1800 °F	See general results.	See results for 18-18-2; Cr sulfides penetrated and partially destroyed surface integrity.	Results similar to those for IN 800.	See general results.	Scale appeared protective but metal/oxide interface was ragged and undercut by scale in places; fewer & smaller precipitates than at 1600.	Single sheet of thick sulfide scale spalled off at 245 hours; scales flaked off.	Same as at 1382.
INCONEL 671[h]							
Exposure at 1382 °F	Best corrosion resistance of all alloys.	See general results.	Little surface attack; only moderate sulfide penetration; some carbon deposition.	See general results	Heavily attacked; surface layers heavily sulfidized; some sulfide networks oxidized driving S into alloy to form deep precipitates.	See general results.	Continuous protective scale at all temperatures; subscale of discrete oxide precipitates increased with temperature.
Exposure at 1600 °F	Best corrosion resistance of all alloys.	See general results.	Same as at 1382.	See general results.	Heaviest attack at this temperature, results as at 1382.	See general results.	
Exposure at 1800 °F	Best corrosion resistance of all alloys.	See general results.	Sharp increase in both forms of attack; voluminous Ni-rich sulfides outside thin "protective" Cr-rich scale; deep penetration of Cr-rich sulfides.	See general results.	Same as at 1382 but complete layers of sulfide appeared protective, further penetration occurred only beneath breaks in layers.	See general results.	

(Continued)

METALLOGRAPHIC CHARACTERIZATION[a] OF VARIOUS ALLOYS EXPOSED TO COAL GASIFICATION ATMOSPHERES[b] AT SEVERAL TEMPERATURES[7], Continued

Footnotes

[a]Full section photomicrographs of polished and etched samples were taken of specimens 0.5 x 0.74 x 0.1 in.; some x-ray fluorescence and electron microprobe line scans were also performed.

[b]Specimens in as-machined condition were exposed to the various atmospheres for 1000 hours at the pressures and temperatures indicated.

[c]Composition of atmosphere no. 1:

	Input gas, 1 atm, 77 °F	Equilibrium at 68 atm		
	mole fraction	1382 °F	1600 °F	1800 °F
CO	0.201	0.061	0.157	0.266
CO_2	0.115	0.111	0.082	0.046
H_2	0.201	0.186	0.297	0.403
H_2O	0.172	0.256	0.181	0.110
H_2S	0.010	0.009	0.008	0.008
CH_4	0.300	0.214	0.166	0.122
C(solid)		0.164	0.108	0.04
log $P(O_2)$(P in atm)		-19.16	-17.21	-15.91
log $P(S_2)$		-6.69	-6.22	-5.76
log a_c		1.00	1.00	1.00

[d]Composition of atmosphere no. 2:

	Input gas, 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(solid)		22.6	12.0	1.4	25.4	18.0	8.3
log $P(O_2)$(P in atm)		-19.19	-17.31	-16.10	-18.67	-16.68	-15.34
log $P(S_2)$		-6.05	-5.55	-5.07	-5.61	-5.15	-4.75
log a_c		1.00	1.00	1.00	1.00	1.00	1.00

[e]Composition of atmosphere no. 3:

	Input gas, 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(solid)		24.0	13.7	3.5	26.7	19.5	10.1
log $P(O_2)$(P in atm)		-19.21	-17.32	-16.11	-18.68	-16.70	-15.35
log $P(S_2)$		-6.32	-5.83	-5.35	-5.93	-5.42	-5.08
log a_c		1.00	1.00	1.00	1.00	1.00	1.00

[f]Composition of atmosphere no. 4:

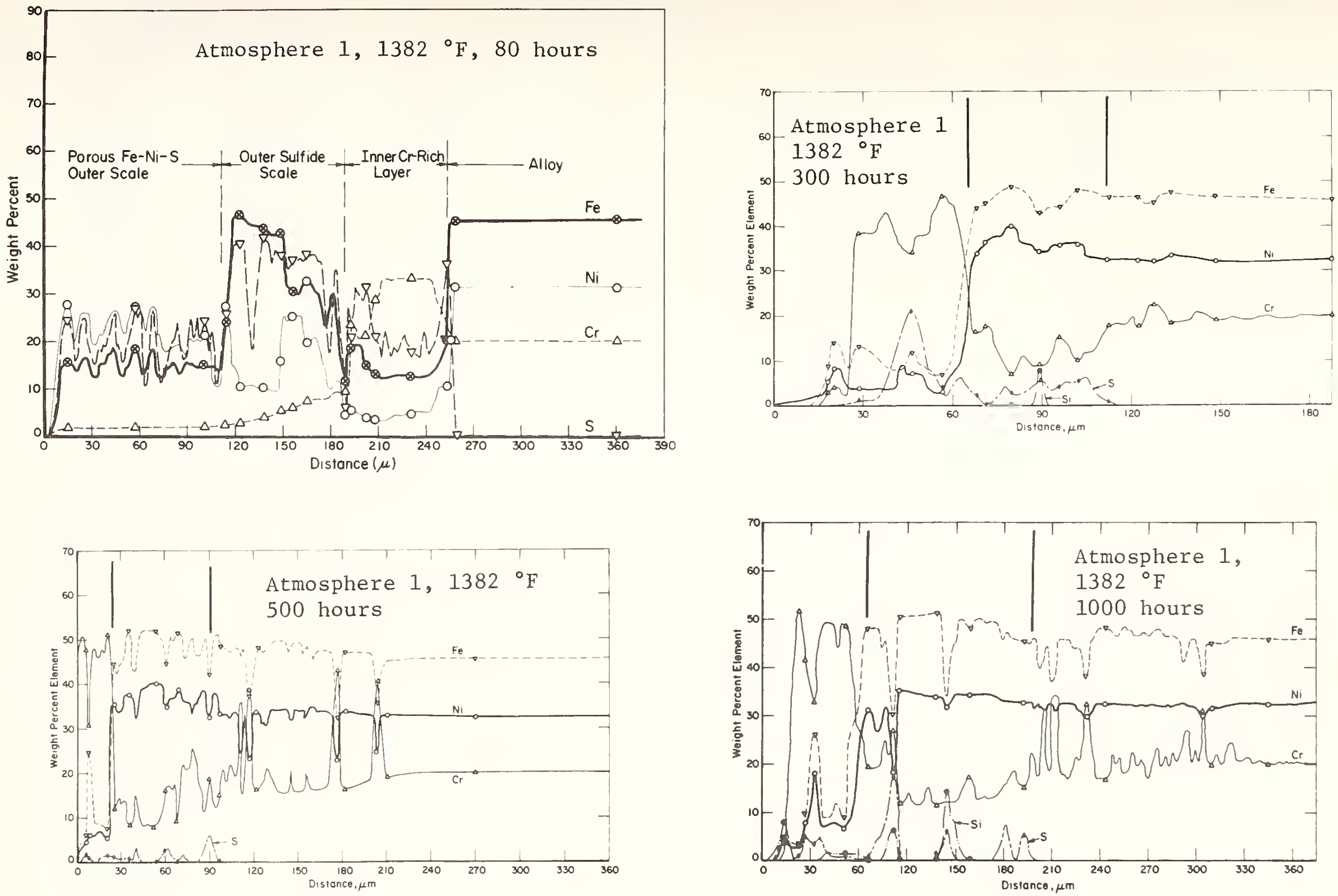
	Input gas, 1 atm, 77 °F	Equilibrium at 34 atm		
	mole %	1382 °F	1600 °F	1800 °F
CO	11.7	8.796	15.542	19.068
CO_2	15.4	19.360	14.568	11.723
H_2	12.9	23.801	32.055	33.653
H_2O	48.9	39.806	34.816	34.319
H_2S	1.0	0.944	0.857	0.841
CH_4	10.0	7.282	2.149	0.396
COS		0.011	0.011	---
log $P(O_2)$(P in atm)		-18.992	-16.705	-14.770
log $P(S_2)$		-6.86	-6.23	-5.575
log a_c		-0.26	-0.57	-0.99

[g]Composition of atmosphere no. 5:

	Input gas, 1 atm, 77 °F	Equilibrium at 34 atm		
	mole %	1382 °F	1600 °F	1800 °F
CO	26.0	12.5	27.4	33.0
CO_2	14.9	20.8	13.9	9.0
H_2	26.0	20.6	32.0	38.6
H_2O	22.2	26.1	18.8	16.5
H_2S	1.0	1.0	0.9	0.8
CH_4	10.0	11.8	7.0	2.0
C(solid)		7.2	--	--
COS		0.02	0.03	0.03
log $P(O_2)$(P in atm)		-19.23	-17.24	-15.52
log $P(S_2)$		-6.67	-6.16	-5.67
log a_c		+0.009	-0.054	-0.39

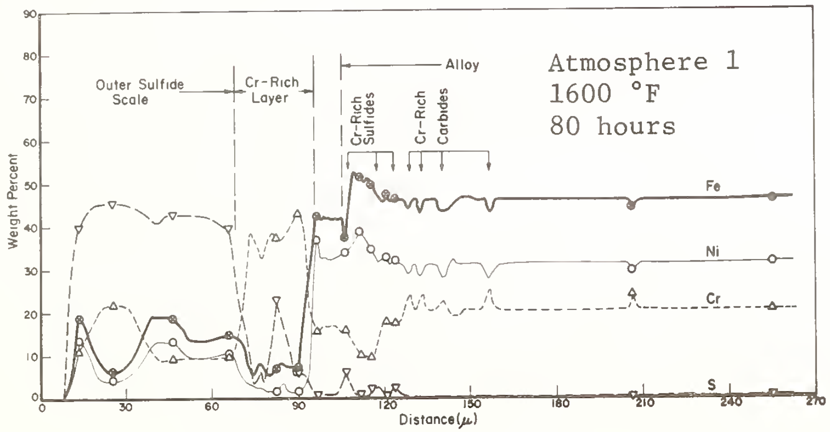
[h]Alloy compositions in weight percent: United States Steel 18-18-2, 18.5 Cr, 17.9 Ni, 2.05 Si, 1.25 Mn, 0.06 C, 0.296 others, balance Fe; Incoloy 800 (A.M. Castle), 20.19 Cr, 31.16 Ni, 45.89 Fe, 0.35 Si, 1.11 Mn, 0.04 C, 1.37 others; 310 SS (Rolled Alloys), 24.71 Cr, 19.02 Ni, 0.72 Si, 1.76 Mn, 0.06 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.

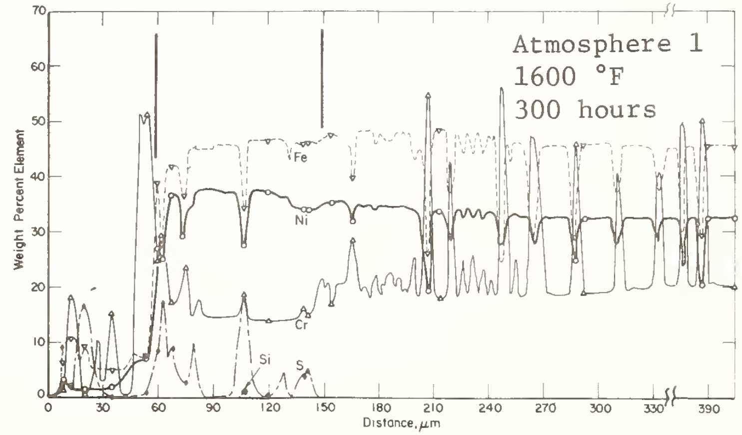
ANALYSIS[a] OF CORROSION SCALE FORMED ON INCOLOY 800[b] SUBJECTED TO COAL GASIFICATION ATMOSPHERES[c] AT SEVERAL TEMPERATURES[d][7]

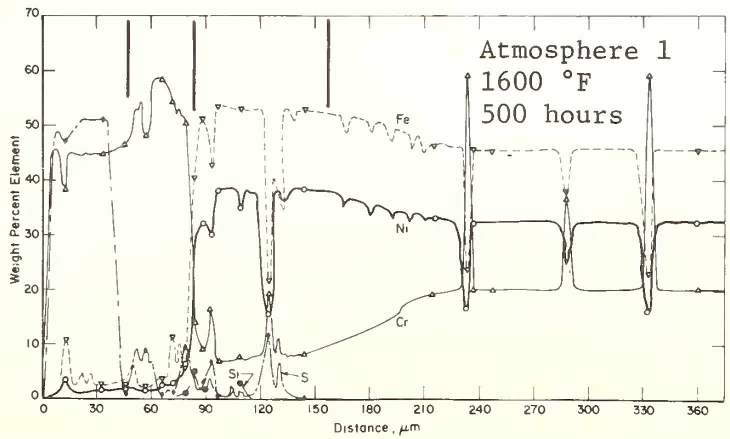


(Continued)

ANALYSIS[a] OF CORROSION SCALE FORMED ON INCOLOY 800[b] SUBJECTED TO COAL GASIFICATION ATMOSPHERES[c] AT SEVERAL TEMPERATURES[d][7], Continued



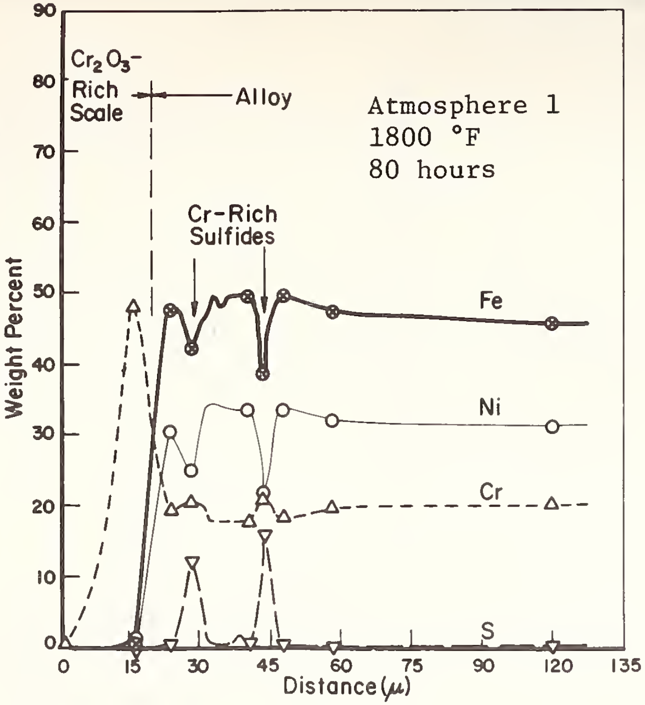




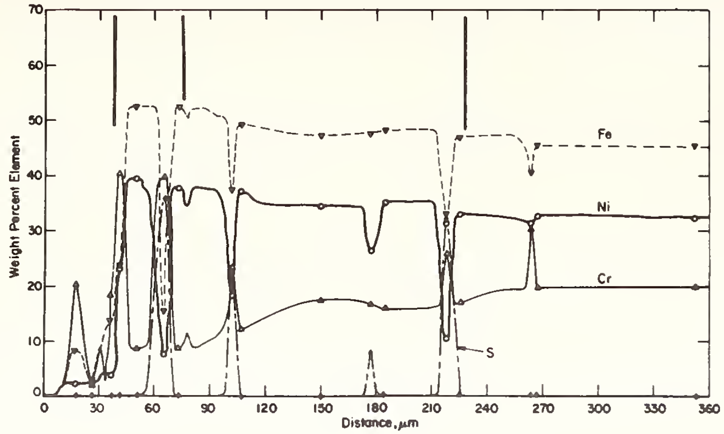
No 1000 hour data available--
specimen removed after 500 hours
because corrosion was excessive.

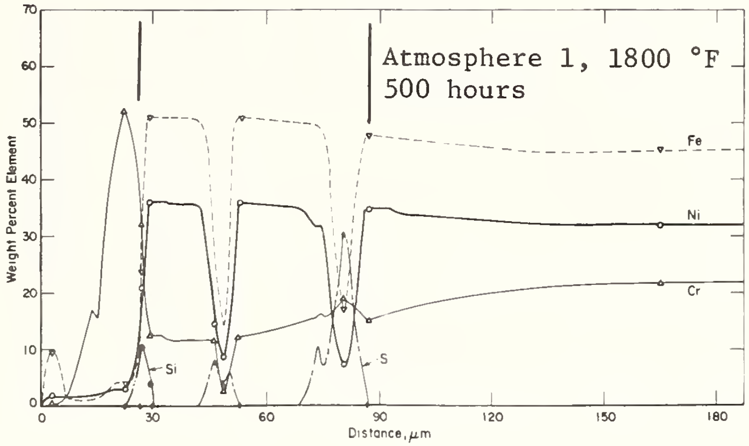
(Continued)

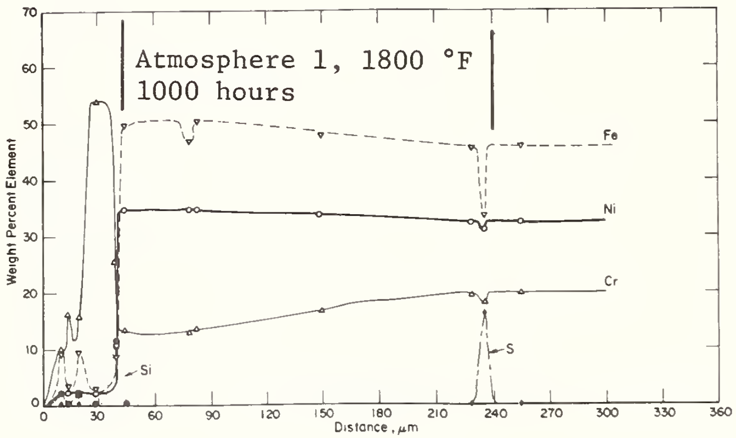
ANALYSIS[a] OF CORROSION SCALE FORMED ON INCOLOY 800[b] SUBJECTED TO COAL GASIFICATION ATMOSPHERES[c] AT SEVERAL TEMPERATURES[d][7], Continued



Atmosphere 1, 1800 °F, 300 hours

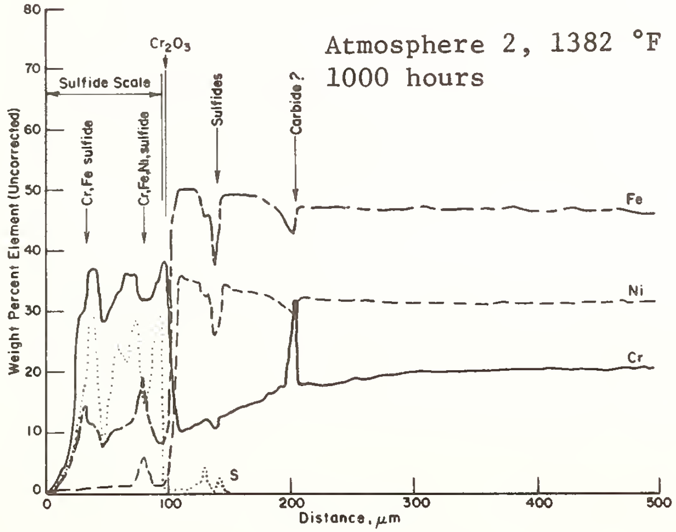


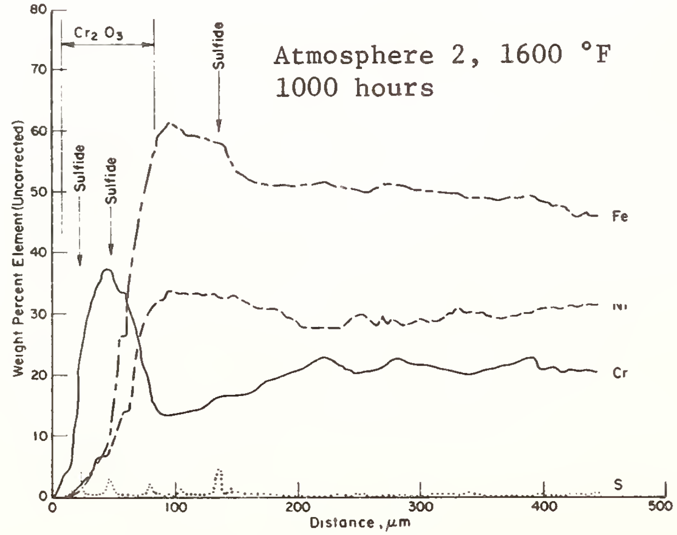


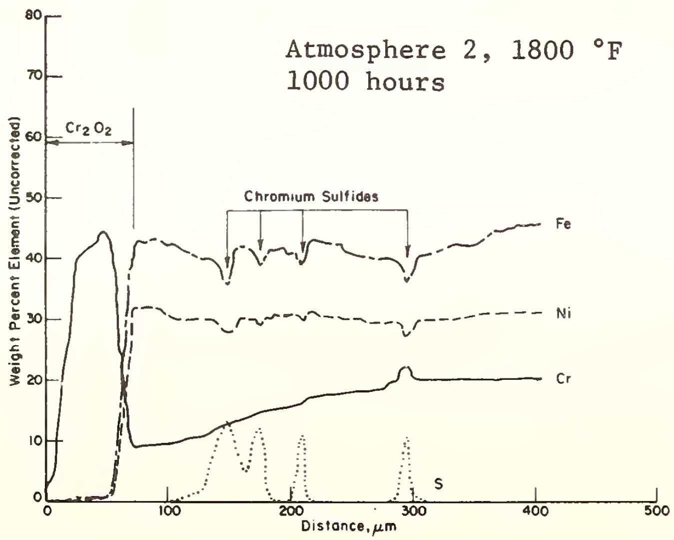


(Continued)

ANALYSIS[a] OF CORROSION SCALE FORMED ON INCOLOY 800[b] SUBJECTED TO COAL GASIFICATION ATMOSPHERES[c] AT SEVERAL TEMPERATURES[d][7], Continued







(Continued)

ANALYSIS[a] OF CORROSION SCALE FORMED ON INCOLOY 800[b] SUBJECTED TO COAL GASIFICATION ATMOSPHERES[c] AT SEVERAL TEMPERATURES[d] [7], Continued

[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]Compositions of coal gasification atmospheres used:

Atmosphere 1 (exposure at 68 atm or 1000 psi)

	Input gas, 1 atm, 77 °F	Equilibrium at 68 atm		
	mole fraction	1382 °F	1600 °F	1800 °F
CO	0.201	0.061	0.157	0.266
CO_2	0.115	0.111	0.082	0.046
H_2	0.201	0.186	0.297	0.403
H_2O	0.172	0.256	0.181	0.110
H_2S	0.010	0.009	0.008	0.008
CH_4	0.300	0.214	0.166	0.122
C(solid)		0.164	0.108	0.04
log $P(O_2)$(P in atm)		-19.16	-17.21	-15.61
log $P(S_2)$(P in atm)		-6.69	-6.22	-5.76
log a_c		1.00	1.00	1.00

Atmosphere 2 (exposure at 34 atm or 500 psi)

	Input gas, 1 atm, 77 °F	Equilibrium at 34 atm		
	mole %	1382 °F	1600 °F	1800 °F
CO	22.75	10.9	27.5	44.6
CO_2	30.20	18.9	12.9	6.3
H_2	25.47	16.0	25.8	34.3
H_2O		21.2	14.0	7.6
H_2S	1.96	1.6	1.5	1.5
CH_4	19.61	8.6	6.3	4.3
C(solid)		22.6	12.0	1.4
log $P(O_2)$(P in atm)		-19.19	-17.31	-16.10
log $P(S_2)$(P in atm)		-6.05	-5.55	-5.07
log a_c				

[d]Temperatures of exposures as well as the length of time are indicated on each analysis.

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.
		3552	932	Precipitates in grain boundaries; similar to 6478 hr exposure.
		3552	994	Similar to 6478 hr exposure.
		3552	933	Similar to 6478 hr exposure.
		6478	956	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.
		2950	1261	Fine precipitates in grains; large precipitates in grain boundaries.
		3672	1211	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.
		7368	700	Precipitates small and almost continuous along grain boundaries; fine precipitates within grains.
		7368	1138	Large precipitates within grains. Fine precipitates near surface; large precipitates in boundaries.
		7368	1188	Fine precipitates at surface; precipitates in grain boundaries, and fine precipitates within grains to depth of 25 mils from surface.
		7368	1280	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.
		600	953	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)

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 Activity[b]	Exposure Time, h	Weight Gain per unit area mg/cm^2	Carbon Gain per unit area mg/cm^2
Inconel 600	0.151	100	c	-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

[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] mils/yr	mm/yr	Exposure Time, hr[d]
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

(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 1.5% H S, 1250 °F (continued) - - - - - -				
Alloy X	20Fe-45Ni-22Cr-9Mo	18	0.45	100
Inconel 617	54Ni-22Cr-13Co-9Mo	18	0.45	100
- - - - - - - - - - - - Test Condition: CGA[a] with 0.1% H_2S, 1500 °F - - - - - - - - - - -				
302SS	Fe-9Ni-18Cr	18	0.45	1000
304SS	Fe-9Ni-19Cr	16	0.40	1000
316SS	Fe-14Ni-17Cr	21	0.53	1000
309SS	Fe-15Ni-23Cr	4.4	0.11	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	5.3	0.13	1000
310SS	Fe-20Ni-25Cr-2Mn	3.5	0.09	1000
310SS Al[e]		13	0.33	1000
310SS Cr[f]		25	0.65	1000
446SS	Fe-24Cr	1.8	0.04	1000
Inconel 600	7Fe-77Ni-16Cr	19	0.49	1000
Inconel 601	16Fe-60Ni-23Cr	25	0.65	1000
Incoloy 800	47Fe-31Ni-21Cr	25	0.65	1000
Incoloy 800 Al[e]		4.4	0.11	1000
Incoloy 800 Cr[f]		25	0.65	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	14	0.36	1000
Inconel 671	48Ni-50Cr	3.5	0.09	1000
- - - - - - - - - - - - Test Condition: CGA[a] with 0.5% H_2S, 1500 °F - - - - - - - - - -				
304SS	Fe-9Ni-19Cr	46	1.2	1000
316SS	Fe-14Ni-17Cr	37	0.93	1000
309SS	Fe-15Ni-23Cr	7.0	0.18	1000
310SS	Fe-20Ni-25Cr-2Mn	2.6	0.07	1000
310SS Al[e]		11	0.27	1000
446SS	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]
(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 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)

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, 1650 °F	- - - - -	- - - - -
304SS	Fe-9Ni-19Cr	53	1.36	2000
309SS	Fe-15Ni-23Cr	83	2.1	3000
310SS	Fe-20Ni-25Cr-2Mn	15	0.39	10,000
310SS Al[e]		6	0.16	9000
446SS	Fe-24Cr	4	0.11	10,000
Inconel 601	16Fe-60Ni-23Cr	24	0.61	2000
Incoloy 800	47Fe-31Ni-21Cr	5	0.13	10,000
Incoloy 800 Al[e]		3	0.07	8000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	5	0.12	10,000
Inconel 671	48Ni-50Cr	2	0.04	4000
HL-40	47Fe-19Ni-31Cr	2	0.06	10,000
RA 333	16Fe-45Ni-26Cr-4Mo	14[h]	0.35	10,000
Crutemp 25	47Fe-25Ni-25Cr	1	0.03	10,000
Multimet N155	29Fe-20Ni-21Cr-20Co	5	0.14	5000
Haynes 188	Co-23Ni-22Cr	1	0.04	9000
Stellite 6B	3Ni-28Cr-57Co-5W	1	0.02	8000
Co-Cr-W No. 1	Co-30Cr-12W	4	0.10	5000
Thermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	2	0.05	9000
Alloy X	20Fe-45Ni-22Cr-9Mo	1	0.01	10,000
Sanicro 32X	Fe-32Ni-22Cr-3W	5	0.12	9000
HK-40	Fe-20Ni-28Cr	3	0.09	5000
RA 330	Fe-36Ni-19Cr	2	0.05	10,000
IN-657	50Ni-48Cr	1	0.02	10,000
556	Fe-20Ni-22Cr-20Co-3Mo	1	0.03	10,000
Inconel 617	54Ni-22Cr-13Co-9Mo	5	0.12	7000
LM-1866 (low Hf)	Fe-18Cr-5Al-1Mo-1Hf	3	0.09	5000
LM-1866 (high Hf)		10	0.26	1000
253 MA	Fe-11Ni-21Cr	216	5.49	1000
RV-18	Fe-32Ni-35Cr-32Co	4	0.09	4000
RV-19	Fe-26Ni-30Cr-26Co	1	0.03	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	mm/yr	Exposure Time, hr[d]
Test Condition: CGA[a] with 1.0% H_2S, 1650 °F				
309SS	Fe-15Ni-23Cr	50[i]	1.28[i]	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
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

(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% H_2S, 1800 °F (continued)				
316SS	Fe-14Ni-17Cr	115	2.9	1000
309SS	Fe-15Ni-23Cr	39 96	1.0 }j 2.4	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	105	2.7	1000
310SS	Fe-20Ni-25Cr-2Mn	17 62	0.44 }j 1.58	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 }j 0.20	1000
HC-250	68Fe-28Cr-3C	completely corroded		1000
HD-45	62Fe-5Ni-30Cr	70	1.8	1000
HL-40	47Fe-19Ni-31Cr	20	0.50	1000
HL-40 3Si	46Fe-19Ni-31Cr-3Si	42	1.1	1000
RA 333	16Fe-45Ni-26Cr-4Mo	24	0.60	1000
Crutemp 25	47Fe-25Ni-25Cr	35	0.90	1000
Multimet N155	29Fe-20Ni-21Cr-20Co	15	0.38	1000
Haynes 150	Co-18Fe-28Cr	10	0.25	1000
Haynes 188	Co-23Ni-22Cr	9	0.24	1000
Stellite 6B	3Ni-28Cr-57Co-5W	5	0.13	1000
VE 441	82Fe-15Al-3Mo	28	0.70	1000
Armco 21-6-9	63Fe-9Ni-21Cr-8Mn	281	7.13	1000
Test Condition: CGA[a] with 0.1% H_2S, 1800 °F				
302SS	Fe-9Ni-18Cr	380	9.7	1000
304SS	Fe-9Ni-19Cr	549	14	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 0.1% H_2S, 1800 °F (continued)				
316SS	Fe-14Ni-17Cr	480	12	1000
309SS	Fe-15Ni-23Cr	197	5.0 } j	1000
		k { 251	6.4 } j	1000
		k { 190	4.8	1000
314SS	Fe-20Ni-24Cr-2Mn-2Si	144	3.7	1000
310SS	Fe-20Ni-25Cr-2Mn	159	4.0	1000
310SS Al[e]		165	4.2 } j	1000
		16	0.41 } j	
		k { 100	2.5 } j	
		k { 72	1.8	
310SS Cr[f]		21	0.53	1000
446SS	Fe-24Cr	84	2.1	1000
Inconel 600	7Fe-77Ni-16Cr	68	1.7	1000
Inconel 601	16Fe-60Ni-23Cr	26	0.66	1000
Incoloy 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
Inconel 671	48Ni-50Cr	15	0.38 } j	1000
		16	0.42 } j	
		k { 17	0.44 } j	
		k { 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

(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)				
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-3Si	405	10	100
Thermalloy 63	Fe-36Ni-28Cr	99	2.5	100
Thermalloy 63W	Fe-36Ni-28Cr-5W	130	3.3	100
RA 330	Fe-36Ni-19Cr	46	1.2	1000
IN-657	50Ni-48Cr	66	1.7	100
IN-738 (cast)	Ni-16Cr-8Co-3Al-3Ti	32	0.81	1000
556	Fe-20Ni-22Cr-20Co-3Mo	33	0.85	1000
Inconel 617	54Ni-22Cr-13Co-9Mo	27	0.68	1000
Test Condition: CGA[a] with 0.5% H_2S, 1800 °F				
309SS	Fe-15Ni-23Cr	109	2.8	5000
314SS	Fe-20Ni-24Cr-2Mn-2Si	24	0.62	4000
310SS	Fe-20Ni-25Cr-2Mn	162 17	4.1 0.43 }[j]	5000
310SS Al[e]		7	0.18	8000
446SS	Fe-24Cr	17	0.42	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	mm/yr	Exposure Time, hr[d]
Test Condition: CGA[a] with 0.5% H_2S, 1800 °F (continued)				
Incoloy 800	47Fe-31Ni-21Cr	30	0.75	8000
Incoloy 800 Al[e]		10	0.26	5000
Inconel 671	48Ni-50Cr	12 6	0.32 0.15 }j	5000
HC-250	68Fe-28Cr-3C	31	0.78	1000
HD-45	62Fe-5Ni-30Cr	18	0.46	1000
HL-40	47Fe-19Ni-31Cr	13	0.32	8000
HL-40 3Si	46Fe-19Ni-31Cr-3Si	36	0.92	1000
RA 333	16Fe-45Ni-26Cr-4Mo	30	0.70	7000
Crutemp 25	47Fe-25Ni-25Cr	3	0.08	10,000
Multimet N155	29Fe-20Ni-21Cr-20Co	8	0.21	10,000
Haynes 150	Co-18Fe-28Cr	2	0.06	6000
Haynes 188	Co-23Ni-22Cr	6	0.16	10,000
Stellite 6B	3Ni-28Cr-57Co-5W	3	0.07	10,000
VE 441	82Fe-15Al-3Mo	completely corroded		1000
Crucible Ni	90Ni-3Cr-4Al	completely corroded		100
Armco 21-6-9	63Fe-9Ni-21Cr-8Mn	174	4.4	1000
312SS	Fe-9Ni-31Cr	51	1.3	1000
329SS	Fe-4Ni-27Cr	10	0.3	5000
AL 29-4-2	Fe-2Ni-30Cr-4Mo	4	0.10	1000
AL EX-20	Fe-3Ni-5Cr-10Al-20Mn	completely corroded		1000
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

(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)				
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	15	1000
		k{ 40	1.0 }j	
		79	2.0	
314SS	Fe-20Ni-24Cr-2Mn-2Si	42	1.1	1000
310SS	Fe-20Ni-25Cr-2Mn	164	4.2	1000
		k{ 134	3.4 }j	
		55	1.4	
310SS Al[e]		20	0.50	10,000
310SS Cr[f]		223	5.7	1000
446SS	Fe-24Cr	18	0.47	2000
Inconel 600	7Fe-77Ni-16Cr	completely corroded		1000
Inconel 601	16Fe-60Ni-23Cr	36	0.91	1000
Incoloy 800	47Fe-31Ni-21Cr	221	5.6	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 1.0% H_2S, 1800 °F (continued)				
Incoloy 800 Al[e]		14[l]	0.35[l]	10,000
Incoloy 800 Cr[f]		389	9.9	1000
IN-793 (cast)	43Fe-32Ni-21Cr-2Al	completely corroded		1000
Inconel 671	48Ni-50Cr	1	0.04	10,000
HC-250	68Fe-28Cr-3C	14	0.34	1000
HD-45	62Fe-5Ni-30Cr	28	0.72	1000
HL-40	47Fe-19Ni-31Cr	10	0.26	10,000
HL-40 3Si	46Fe-19Ni-31Cr-3Si	20	0.51	1000
RA 333	16Fe-45Ni-26Cr-4Mo	222	5.6	2000
Crutemp 25	47Fe-25Ni-25Cr	12	0.30	8000
Multimet N155	29Fe-20Ni-21Cr-20Co	4	0.11	10,000
Haynes 150	Co-18Fe-28Cr	3	0.07	7000
Haynes 188	Co-23Ni-22Cr	92[j]	2.3[j]	2000
Stellite 6B	3Ni-28Cr-57Co-5W	2	0.06	10,000
VE 441	82Fe-15Al-3Mo	completely corroded		1000
Crucible Ni	90Ni-3Cr-4Al	completely corroded		100
Armco 21-6-9	63Fe-9Ni-21Cr-8Mn	162	4.1	1000
312SS	Fe-9Ni-31Cr	72	1.8	1000
329SS	Fe-4Ni-27Cr	100	2.6	100
AL 29-4-2	Fe-2Ni-30Cr-4Mo	54	1.4	1000
AL EX-20	Fe-3Ni-5Cr-10Al-20Mn	completely corroded		1000
Co-Cr-W No. 1	Co-30Cr-12W	3	0.08	10,000
Thermalloy 63WC	Fe-36Ni-28Cr-15Co-5W	13[l]	0.33[l]	10,000
Wiscalloy 30/50W	Fe-49Ni-28Cr-4W	3	0.08	10,000
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[m]	2.3[m]	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	6	0.16	3000

(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, 1800 °F (continued) - - -				
HK-40	Fe-20Ni-28Cr	30	0.77	7000
HK-40 3Si	Fe-22Ni-26Cr-3Si	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	1	0.04	8000
IN-738 (cast)	Ni-16Cr-8Co-3Al-3Ti	25	0.64	3000
556	Fe-20Ni-22Cr-20Co-3Mo	36	0.92	1000
Inconel 617	54Ni-22Cr-13Co-9Mo	k{ 16 154[n]	0.41 3.91[n]	6000
RV-18	Fe-32Ni-35Cr-32Co	1	0.03	6000
RV-19	Fe-26Ni-30Cr-26Co	9	0.22	5000
36Cr-36Ni	Fe-36Ni-36Cr	7	0.18	5000
31Cr-28Ni	Fe-28Ni-31Cr	9	0.22	4000
31Cr-36Ni	Fe-36Ni-31Cr	8	0.19	5000
31Cr-44Ni	Fe-44Ni-31Cr	5	0.13	4000

[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

[b]Approximate compositions only.

[c]Values are for one test specimen (1 in x 1 in x 1/4 in) exposed to the indicated conditions. Although duplicate specimens were exposed, as a rule only one was 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. See B.1.1.18 for a measure of the agreement of rates extrapolated from data for various exposure times and B.1.1.19 for a measure of the reproducibility of the data.

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE[a] [13]
(continued)

[d]The exposure time given is the maximum test time for which the alloy was subjected to the stated conditions.

[e]Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusior process (Alonized).

[f]Chromium coating (∿0.6 mils) applied by Alloy Surfaces, Inc.

[g]Extensive metal-oxide scale with possible melting.

[h]Localized corrosion elsewhere, total corrosion 3.4 mils.

[i]A second specimen corroded completely.

[j]Values for specimens from two different runs.

[k]Two specimens were examined in this run.

[l]Localized corrosion.

[m]Two specimens completely corroded.

[n]Edge corrosion.

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a][13]

Alloy	Rate of Total Sound Metal Loss[b], mils/yr (mm/yr)										
Test Time, hr	100	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Test Condition: CGA[a] with 0.5% H_2S, 1650 °F											
304SS		64(1.62)	53(1.36)								
309SS		46(1.2)		83(2.1)							
310SS		20(0.50)				23(0.58)					15(0.39)
310SS Al[c]		39(1.00)				11(0.29)				6(0.16)	
446SS		7.9(0.20)				6.5(0.16)					4(0.11)
Inconel 601		44(1.12)	24(0.61)								
Incoloy 800		12(0.31)				6.7(0.17)					5(0.13)
Incoloy 800 Al[c]		18(0.46)				6(0.15)			3(0.07)		
IN-793 (cast)		33(0.85)				10(0.25)					5(0.12)
Inconel 671		14(0.36)		2(0.05)	2(0.04)						
HL-40		15(0.38)				3.5(0.09)					2(0.06)
RA 333		9.6(0.24)				2.6(0.07)					14(0.35)[d]
Crutemp 25		7.0(0.18)				0.88(0.02)					1(0.03)
Multimet N155		25(0.64)			7(0.18)	5(0.14)					
Haynes 188		7(0.18)				6(0.15) 24(0.62)[e]				1(0.04)	
Stellite 6B		4(0.09)				2(0.04)			1(0.02)		
Co-Cr-W No. 1		11(0.27)			3(0.09)	4(0.10)					
Thermalloy 63WC		16(0.40)				4(0.10)				2(0.05)	
Alloy X		3.5(0.09)				1.2(0.03)					1.(0.01)
Sanicro 32X		22(0.55)				8(0.21) 23(0.59)[f]				5(0.12)	
HK-40		32(0.82)			3(0.09)	3(0.09)					
RA 330		8.8(0.22)				2.5(0.06)					2(0.05)
IN-657		3.5(0.09)				1.2(0.03)					1(0.02)
556		4.4(0.11)				1.6(0.04)					1(0.03)
Inconel 617		36(0.90)				10(0.26)[g]		5(0.12)			
LM-1866		153(3.89)[h]				3(0.09)					
RV-18		5(0.12)		2(0.06)	4(0.09)						
RV-19		4(0.11)		1(0.03)	1(0.03)						
Test Condition: CGA[a] with 1.0% H_2S, 1650 °F											
310SS		43(1.1)	6(0.15)		7(0.19)						13(0.33)
310SS 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(0.30)	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)						
329SS			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											
309SS	394(10)	197(5.0) 251(6.4) 190(4.8)									

(Table Continued)

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a][13]

(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	9000	10000
Test Condition: CGA[a] with 0.1% H_2S, 1800 °F (continued)											
310SS	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)									
312SS	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 63WC	66(1.7)	17(0.42)									
Wiscalloy 30/50W	109(2.8)	20(0.51)									
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											
309SS	52(1.32)	50(1.3) 55(1.4) 19(0.48)	10(0.26), 257(6.5)[i]	181(4.6)	163(4.1)	109(2.8)					
314SS		98(2.5)	77(2.0) 251(6.4)		24(0.62)						
310SS		27(0.69) 17(0.43)	393(10) 167(4.3)			162(4.1)					
310SS Al[c]				12(0.31)					7(0.18)		
446SS		28(0.72)	28(0.71) 53(1.4)	30(.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									

(Table Continued)

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a][13]

(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	9000	10000
Test Condition: CGA[a] with 0.5% H_2S, 1800 °F (continued)											
Armco 21-6-9	199(5.1)	174(4.4)									
329SS		30(0.7)		10(0.4)		10(0.3)					
Co-Cr-W No. 1		7(0.17)		1(0.03)				2(0.04)			
Thermalloy 63WC		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 32X				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)
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-36Ni		481(12)	10(0.2)								
Fe-31Cr-36Ni		20(0.6)		60(1.6)		40(1.0)					
Fe-31Cr-28Ni		20(0.6)		30(0.7)		20(0.5)					
Fe-31Cr-44Ni		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											
302SS	3872(98) 1174(30)	Completely corroded									
304SS	4030(102) 596(15)	Completely corroded									
316SS	1104(28) 1647(42)	Completely corroded									
309SS	61(1.6) 272(6.9) 314(8.0) 261(6.6)	583(15) 40(1.0) 79(2.0)									
314SS	70(1.8) 245(6.2)	42(1.1)									
310SS	44(1.1) 237(6.0) 307(7.8) 211(5.4)	164(4.2) 134(3.4) 55(1.4)									
310SS Al[c]	131(3.3) 131(3.3)	20(0.51)	79(2.0)[j]	52(1.3)		7(0.19)					20(0.50)
446SS	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)[j]	17(0.43)		6(0.14)					14(0.35)[k]
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)					1(0.04)
HC-250	43(1.1)	14(0.34)									
HD-45	61(1.5)	28(0.72)									

(Table Continued)

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a][13]
(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	9000	10000
Test Condition: CGA[a] with 1.0% H_2S, 1800 °F (continued)											
HL-40	70(1.8)	31(0.79)		21(0.53)		15(0.39)					10(0.26)
HL-40 3Si	74(1.9)	20(0.51)									
RA 333	52(1.3)	37(0.95)	222(5.6)								
Crutemp 25	69(1.8)	19(0.49)		12(0.30)		9(0.23)			12(0.30)		
Multimet N155	43(1.1)	11(0.28)		19(0.47)		4.7(0.12)					4(0.11)
Haynes 150	35(0.88)	19(0.47)		3(0.07)		2(0.04)		3(0.07)			
Haynes 188	43(1.1)	7(0.18)	92(2.3)[l]								
Stellite 6B	39(0.99)	19(0.49)		4.4(0.11)		3.7(0.09)					2(0.06)
VE 441	18(0.45)	Completely corroded									
Armco 21-6-9	348(8.8)	162(4.1)									
312SS	171(4.4)	72(1.8)									
AL 29-4-2	53(1.4)	54(1.4)									
AL EX-20	245(6.2)	Completely corroded									
Co-Cr-W No. 1	40(1.0)	13(0.34)		1.5(0.04)		5.8(0.15)					3(0.08)
Thermalloy 63WC	71(1.8)	34(0.86) 24(0.62)		23(0.59)		36(0.91)					13(0.33)[k]
Wiscalloy 30/50W	99(2.5)	20(0.50)	11(0.29)[j]	8.8(0.22)		10(0.26)					3(0.08)
Armco 18SR	88(2.2)	Completely corroded									
Armco 22-13-5	253(6.4)	126(3.2)									
Alloy X	66(1.7)	11(0.27)	90(2.3)[m]								
HK-40				7(0.17)		6(0.16)		30(0.77)			
Incoloy 825	92(2.3)	32(0.82)									
FSX-414	78(2.0)	17(0.43)	6(0.14)	6(0.16)							
RA 330	285(7.2)	976(25)									
IN-657	26(0.67)			3.2(0.08)		2(0.04)			1(0.04)		
IN-738 (cast)	194(4.9)	41(1.1) 51(1.3)	20(0.52)	25(0.64)							
556	177(4.5)	36(0.92)									
Inconel 617	125(3.2)	34(0.87)		16(0.39)[n] 110(2.8)[o]		9(0.23) 37(0.93)[o]	16(0.41) 154(3.91)[o]				
RV-18		4(0.11)		2(0.06)			1(0.03)				
RV-19		7(0.18)		1(0.02)		9(0.22)					
Fe-36Cr-36Ni		10(0.25)		5(0.13)		7(0.18)					
Fe-31Cr-28Ni		4(0.09)		6(0.16)	9(0.22)						
Fe-31Cr-36Ni		14(0.35)		4(0.10)		8(0.19)					
Fe-31Cr-44Ni		14(0.35)		10(0.25)	5(0.13)						

[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	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

[b]Values are for one test specimen (1 in x 1 in x 1/4 in) exposed to the indicated conditions. Although duplicate specimens were exposed, as a rule only one was 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 time.

[c]Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

(Table Continued)

COMPARISON OF THE CORROSION DATA OF SOME ALLOYS BASED ON VARIOUS TIMES OF EXPOSURE TO A COAL GASIFICATION ATMOSPHERE[a] [13]
(Continued)

[d]Localized corrosion; elsewhere, total corrosion 4.3 mils.

[e]Area of edge corrosion; elsewhere, total corrosion 3.4 mils.

[f]Localized corrosion; elsewhere, total corrosion 4.6 mils.

[g]Localized corrosion; elsewhere, total corrosion 4.3 mils.

[h]Adjacent to edge corrosion.

[i]Specimen reacted with an adjacent 446 SS specimen.

[j]Specimen possibly contaminated.

[k]Localized corrosion.

[l]One specimen completely corroded.

[m]Two specimens completely corroded.

[n]Overall corrosion.

[o]Edge 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.

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.

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.

Cast irons produced at the Climax Molybdenum Research Laboratories.

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44]

	Steam-oxygen gasifier fluidized bed (HYGAS); H_2O, CO_2, CO, H_2, H_2S, ash, char											
	1339°F, 980 psig, 1718 h			1340°F, 925 psig, 1329 h			1382°F, 619 psig, 2393 h			1660°F, 605 psig, 671 h		
Alloy[c]	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr
430 SS	3.4	0.018	0.47									
304 SS	0.7	0.005	0.12									
321 SS	1.2	0.007	0.18									
316 SS	3.5	0.019	0.49									
309 SS	0.4	0.003	0.08	0.7	0.006	0.15	1.0	0.004	0.11	0.8	0.013	0.33
Armco 21-6-9	0.9	0.006	0.14									
Armco 22-13-5	0.2	0.002	0.05									
Incoloy 800	0.6	0.004	0.10	0.8	0.007	0.17	1.5	0.006	0.16	1.0	0.016	0.40
Incoloy 800 Al[d]				5.1	0.035	0.89	5.4	0.026	0.67	3.4	0.055	1.39
Incoloy 825	1.0	0.006	0.16									
RA 333	0.6	0.004	0.10	0.7	0.006	0.15	0.6	0.003	0.07	6.1[e]	0.082[e]	2.09[e]
Alloy X	0.6	0.004	0.10									
Inconel 601	2.2	0.012	0.31									
Inconel 600	Essentially completely corroded.											
IN-793				2.3	0.016	0.42	1.9	0.008	0.20	3.3	0.044	1.13
446 SS				0.5	0.009	0.22	0.2	0.008	0.21	0.1	0.012	0.30
310 SS				0.5	0.005	0.12	0.6	0.003	0.07	0.2	0.005	0.13
310 SS Al[d]				2.4	0.031	0.79	5.8	0.002	0.06	4.5[f]	0.099[f]	2.52[f]
Inconel 671				0.4	0.007	0.17	0.2	0.003	0.07	0.2	0.010	0.26
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.								

	Low-temperature first-stage reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char											
	1013°F, 921 psig, 1355 h			977°F, 980 psig, 1554 h			984°F, 619 psig, 2292 h			1053°F, 601 psig, 924 h		
Alloy[c]	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	Total Sound Metal Loss[a] mm/yr
430 SS	0.3	0.003	0.08				1.4	0.006	0.15	1.4	0.015	0.39
304 SS	0.9	0.007	0.18				1.9	0.008	0.20	1.2	0.013	0.34
321 SS	1.8	0.013	0.33				0.7	0.003	0.09	2.0	0.021	0.53
316 SS	0.9	0.007	0.18				1.4	0.006	0.15	1.2	0.013	0.34
309 SS	0.7	0.006	0.15	0.2	0.002	0.06	0.3	0.002	0.05	1.2	0.013	0.34
Armco 21-6-9	1.8	0.013	0.33				0.6	0.003	0.08	7.3	0.071	1.81
Armco 22-13-5	0.3	0.003	0.08				0.3	0.002	0.05	1.6	0.017	0.43
Incoloy 800	0.6	0.005	0.13	0.2	0.002	0.06	0.9	0.004	0.11	0.2	0.004	0.10
Incoloy 800 Al[d]				1.1	0.007	0.18						
Incoloy 825							0.6	0.003	0.08	0.2	0.004	0.10
Alloy X							0.2	0.002	0.04	1.4	0.015	0.39
Inconel 601	Essentially completely corroded.			0.3	0.003	0.07	0.3	0.002	0.05	1.4	0.015	0.39
Inconel 600	2.7	0.68	1.72				Essentially completely corroded.			6.7	1.185	30.1
IN-793				0.3	0.003	0.08						
446 SS				0.3	0.003	0.07						
310 SS	0.2	0.002	0.06									
310 SS Al[d]	1.0	0.007	0.17									
Inconel 671				0.2	0.002	0.06						

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

High-temperature second-stage reactor (HYGAS); H_2O, CO, CO_2, H_2, H_2S, CH_4, char

Alloy[c]	1306°F, 980 psig, 1554 h			1271°F, 923 psig, 1355 h			1360°F, 621 psig, 2292 h			1525°F, 603 psig, 924 h		
	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr
Incoloy 800	0.2	0.002	0.06	0.8	0.006	0.16	0.9	0.004	0.11	1.7	0.018	0.46
Incoloy 800 Al[d]	2.7	0.016	0.40	5.2	0.036	0.90	6.4	0.033	0.84	5.3	0.056	1.42
310 SS	0.2	0.002	0.06	0.4	0.004	0.10	0	0.001	0.02	0.2	0.004	0.10
310 SS Al[d]	2.5	0.015	0.38	3.4	0.034	0.87	8.7	0.054	1.38	4.9	0.106	2.70
309 SS	0.2	0.002	0.06	0.5	0.005	0.11	0.2	0.002	0.04	0.2	0.004	0.10
446 SS	0.3	0.003	0.08	0.3	0.003	0.08	0.7	0.004	0.10	0.2	0.004	0.10
Inconel 601	0.2	0.002	0.06	1.7	0.012	0.31						
IN-793	0.2	0.002	0.06	0.4	0.004	0.10	2.5	0.010	0.26	1.8	0.019	0.48
Inconel 671	0.1	0.002	0.05	0.5	0.005	0.13	0.3	0.003	0.08	0.2	0.004	0.10
RA 333							1.7	0.007	0.19	0.2	0.004	0.10

Hydrogasifier upper reactor (HYGAS) off-gas (slurry dryer); H_2O, CO, H_2, CH_4, CO_2, toluene, coal fines

Alloy[c]	591°F, 949 psig, 2909 h			580°F, 985 psi, 1150 h			833°F, 617 psig, 2292 h			541°F, 599 psig, 924 h		
	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr
Carbon steel A515	0	0.011	0.28	--	0.001	0.02	1.1	0.029	0.74	7.9	0.077	1.95
Carbon steel Al[g]	11.5	0.035	0.89	--[h]	--[h]		2.3	0.013	0.34	2.8	0.045	1.13
Carbon steel (1/2 Mo)							2.5	0.010	0.26	4.9	0.048	1.23
Carbon steel (5 Cr-1/2 Mo)							2.4	0.016	0.42	5.1	0.052	1.32
Monel 400	0	0.266	6.75	--[h]	{0.095 (0.125	2.41 3.16)}[i]	0	0.215	5.47	0.8	0.339	8.60
304 SS	1.7	0.006	0.15	1.6	--[h]		0	0.001	0.03	0	0.002	0.05
316 SS	1.5	0.009	0.22	--[h]	--[h]		0	0.002	0.04	0	0.002	0.05
410 SS	4.0	0.013	0.32	1.0	--[h]		0.9	0.007	0.17	1.2	0.013	0.34
430 SS	0.6	0.002	0.06	{2.2 1.0}	--[h]		1.9	0.008	0.20	2.6	0.027	0.68
Inconel 600	0.4	0.164	4.17	--[h]	{0.033 (0.043	0.82 1.08)}[i]	0	0.106	2.68	1.8	0.161	4.09
Incoloy 800	0.4	0.002	0.05	--[h]	0.000	0.005	0.4	0.005	0.13	0	0.002	0.05
Titanium 50A	0.3	0.002	0.04	--[h]	--[h]		0	0.001	0.03	0	0.002	0.05
Welded U-Bends												
304 SS	No stress-corrosion cracks.			No stress-corrosion cracks.								
Incoloy 800	No stress-corrosion cracks.			No stress-corrosion cracks.								

Coal pretreater off-gas (HYGAS); neutral gas, H_2O, O_2, CH_4, N_2, coal fines and tar, some SO_2

Alloy[c]	797°F, 2.4 psig, 1719 h			730°F, 2.7 psig, 1790 h			737°F, 2.7 psig, 3325 h			775.7°F, 3.1 psig, 1803h		
	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr
Carbon steel A515	{-- -- 2.0	0.008 0.002 (0.014	0.20 0.05 0.36)}[i]	4.5	0.024	0.61	0.7	0.006	0.15	3.5	0.018	0.46
Carbon steel Al[g]	--	0.000	0.002	5.9	0.032	0.81	3.7	0.012	0.31	7.1	0.052	1.31
304 SS	0.2	0.000	0.002	0.2	0.002	0.05	0.6	0.002	0.05	0.2	0.002	0.05
316 SS	--	0.000	0.002	0.2	0.002	0.05	0.4	0.002	0.04	0.2	0.002	0.05
410 SS	0.3	0.001	0.02	3.6	0.022	0.56	2.0	0.008	0.21	2.2	0.012	0.30
Welded U-Bends												
304 SS	No visible cracks.			No stress-corrosion cracks.			No stress-corrosion cracks.			No stress-corrosion cracks.		
316 SS	No visible cracks.			No stress-corrosion cracks.			No stress-corrosion cracks.			No stress-corrosion cracks.		

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], 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 h			1434°F, 600 psi, 781.4 h			1290°F, 600 psi, 181 h			1284°F, 600 psi, 781.8 h		
	Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]	
Alloy[c]	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr
304 SS	1.7	0.102	2.58	0.2	0.005	0.13	2.7	0.140	3.56	0.8	0.011	0.29
309 SS	0.9	0.082	2.09	0.2	0.004	0.11	1.4	0.096	2.44	0.6	0.009	0.23
Incoloy 800	5.6	0.300	7.62	0.2	0.004	0.11	1.4	0.096	2.44	0.5	0.007	0.19
Incoloy 825	0.3	0.024	0.61	0.2	0.004	0.11	0.9	0.053	1.35	0.2	0.004	0.11
Alloy X	0.3	0.044	1.11	0.3	0.005	0.13	1.3	0.073	1.85	0.3	0.006	0.14
RA 333	0.5	0.034	0.86	0.2	0.004	0.10	1.0	0.058	1.47	0.6	0.002	0.04
316 SS	2.0	0.107	2.71	2.0	0.025	0.63	4.8	0.256	6.50	1.5	0.020	0.50
321 SS	3.4	0.208	5.29	1.3	0.017	0.43	2.0	0.121	3.07	1.3	0.018	0.46
Armco 21-6-9	3.3	0.179	4.55	0.5	0.007	0.19	4.5	0.247	6.27	0.4	0.007	0.17
Armco 22-13-5	1.4	0.097	2.46	0.3	0.006	0.14	3.5	0.179	4.55	0.4	0.007	0.17
430 SS	0.2	0.024	0.61	0.7	0.010	0.24	1.4	0.101	2.56	0.4	0.006	0.16
Inconel 600	0.6	2.425	61.59	34.4	0.878	22.30	1.9	1.350	34.29	15.1	0.582	14.77
Inconel 601	2.0	0.116	2.95	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, 1000h			1400-1600°F, 150 psi, 2390h			1400-1600°F, 150 psi, 1455h		
	Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a,j]		Depth of Penetration	Total Sound Metal Loss[a]	
Alloy[c]	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[d]	0	0.046	1.17	2.9	0.031	0.79	1.8	0.032	0.80
Incoloy 800 Cr[k]	0.59	0.011	0.27	2.4	0.010	0.24	0.7	0.007	0.17
310 SS	1.97[l]	0.019	0.48	0.4	0.002	0.06	0.4	0.004	0.09
310 SS Al[d]	5.41	0.054	1.38	7.1	0.030	0.75	7.1	0.050	1.26
310 SS Cr[k]	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[l]	0.023	0.59	0.4	0.003	0.09
304 SS	3.05	0.029	0.73	3.8[l]	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	1.9	0.008	0.20	1.1	0.008	0.20
Incoloy 825	0.39	0.005	0.13	6.2[l]	0.030	0.76	0.3	0.003	0.08

	Dolomite regenerator off-gas (CONOCO CO_2 ACCEPTOR); 3CO, $27CO_2$, $70N_2$, trace H_2S								
	1850°F, 150 psi, 800 h			1850°F, 150 psi, 1600 h			1800-1900°F, 150 psi, 740h		
	Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]	
Alloy[c]	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr
Incoloy 800	15.26	0.218	5.52	Completely corroded.					
Incoloy 800 Al[d]	4.72	0.065	1.64	12.97[m]	0.079[m]	2.01	18.3	0.252	6.40
Incoloy 800 Cr[k]	12.01	0.242	6.15	Completely corroded.					
310 SS	5.02	0.064	1.61	17.09	0.412	10.46	8.3	0.916[n]	23.27[n]
310 SS Al[d]	4.92	0.065	1.64	11.77[m]	0.080[m]	2.03	14.4	0.215	5.46
310 SS Cr[k]	4.92	0.066	1.67	Essentially completely corroded.					
309 SS	6.40	0.111	2.81	Essentially completely corroded.			8.9	0.406[n]	10.31[n]
304 SS	16.73	0.645	16.38	Completely corroded.					
446 SS	1.97	0.031	0.78				2.9	0.354[n]	8.99[n]
IN-793	12.80	0.149	3.78	28.09	0.317	8.05	30.1	0.848	21.54
Inconel 671	0.00	1.369	34.8	Essentially completely corroded.			Both specimens completely corroded.		
Armco 21-6-9	6.50	0.078	1.98	24.33	0.199	5.05	5.8	0.688[n]	17.48[n]

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

Dolomite regenerator off-gas (CONOCO CO_2 ACCEPTOR), Continued

Alloy							
Armco 22-13-5	5.61	0.085	2.17	Essentially completely corroded.	5.2	0.899[n]	22.83[n]
Alloy X	10.33	0.438	11.1	Essentially completely corroded.			
Incoloy 825	25.14	0.753	19.1	Completely corroded.			
314 SS					7.4	0.404	10.26
Haynes 150					35.1	0.569	14.45
Crutemp 25					9.0	0.496[n]	12.60[n]
HC-250					5.3	0.118	4.78
HL-40					15.4	0.211	5.36
HK-40					21.6	0.310	7.87
RA 330					14.3	1.040[n]	26.42[n]
RA 333					26.7	0.919	23.34
Haynes 188					Both specimens completely corroded.		

	Gasifier off-gas (BI-GAS); H_2O, CO_2, CO, H_2, N_2, CH_4, H_2S, ash and char entrained						Gasifier off-gas (BATTELLE)[p], 100 psi; 50 h coal feed, max. temp. 1600°F			Combustor off-gas (BATTELLE)[p], 100 psi, 50 h coal feed, max. temp. 2000°F		
	1700°F, 750 psig, 406 h			1525-1750°F, 750 psig, 1784h								
Alloy[c]	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr
Incoloy 800	0.9	0.074	1.88	1.2	0.007	0.18	0.4	0.123	3.11	0.6	0.175	4.45
Incoloy 800 Al[d]	3.0	0.238	6.04	3.7	0.040	1.01	0.4[q]	0.123	3.11	0.5[q]	0.175	4.45
310 SS	0.4	0.014	0.34	1.4	0.008	0.20	0.4	0.105	2.67	1.1	0.228	5.79
310 SS Al[d]	4.2	0.211	5.36	4.7	0.127	3.21	0.5[q]	0.158	4.01	0.5[q]	0.210	5.34
309 SS	0.5	0.061	1.55				0.5	0.123	3.11	0.7	0.158	4.01
446 SS	0.2	0.009	0.22									
IN-793	5.0	0.213	5.40				0.9	0.193	4.90	1.1	0.228	5.79
Inconel 671	0.2	0.061	1.55	0.6	0.005	0.13	1.0	0.210	5.34	2.2	0.456	11.57
314 SS	0.8	0.027	0.70									
RA 330	2.2	0.062	1.58									
RA 333	0.8	0.022	0.55	1.0	0.010	0.25	0.5	0.123	3.11	0.9	0.245	6.23
Armco 22-13-5	0.8	0.028	0.72									
HC-250							0.8	0.210	5.34	0.9	0.210	5.34
Alloy X							0.3	0.123	3.11	0.6	0.140	3.56
Multimet N155				0.4	0.003	0.08						
Haynes 188				1.0	0.006	0.15						
556				1.0	0.006	0.15						
Stellite 6B				1.2	0.007	0.18						
Inconel 617				2.6	0.014	0.35						

	Gasifier off-gas (U-GAS); reducing gas, H_2O, CO_2, CO, H_2, CH_4, N_2, H_2S, ash & char (entrained)								
	1850-1900°F, 15 psi, 1076h			1835-1953°F, 10-42psig, 1581h			1816-1900°F, 30 psig, 264 h		
Alloy[c]	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr	Depth of Penetration mils	Total Sound Metal Loss[a] in/yr	mm/yr
310 SS	4.1	0.070	1.78	9.1[r]	0.052[r]	1.31	--	0.006	0.15
310 SS Al[d]	4.1[s]	0.037	0.94	5.7	0.048	1.22	No penetration of diffusion zone.		
Incoloy 800 Al[d]	4.8	0.044	1.12	4.1	0.026	0.66	No penetration of diffusion zone.		
HK-40	5.3	0.076	1.92	5.1	0.034	0.87	1.57	0.062	1.57
HL-40	2.5	0.030	0.76	6.3	0.036	0.91	1.18	0.050	1.26
Supertherm 63WC	5.8	0.068	1.73	5.3	0.031	0.77	0.98	0.034	0.87
Stellite 6B	0.7	0.008	0.20	2.0	0.012	0.31	0.4	0.018	0.45
Multimet N155	3.2	0.032	0.81	1.8	0.022	0.56	--	0.006	0.14
Inconel 671	1.2	0.020	0.51	3.2	0.023	0.59	0.2	0.009	0.22
Haynes 188	10.1	0.085	2.16	1.6	0.010	0.25	--	0.004	0.09
Alloy X	38.0[n]	0.935[n]	23.75	2.2	0.013	0.34	--	0.007	0.17
RA 333	Both samples completely corroded.			5.3	0.031	0.77	1.57[t]	0.053	1.35

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

	PEATGAS plant[u] (modified HYGAS plant); 300-500 psig, 449 h								
	Steam-oxygen gasifier freeboard section 1040-1625 °F			Hydrogasifier freeboard section 900-1165 °F			Gasifier slurry dryer freeboard section 570-1080 °F		
	Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]	
Alloy[c]	mils	in/yr	mm/yr	mils	in/yr	mm/yr	mils	in/yr	mm/yr
309 SS	--	0.010	0.26	--	0.004	0.11			
310 SS	--	0.005	0.12	--	0.005	0.12			
310 SS Al[v]	Diffusion zone not penetrated.			Substrate not attacked.[x]					
304 SS	--	0.012	0.30	0.9[y]	0.019	0.49	--	0.003	0.07
316 SS				--	0.001	0.02	--	0.002	0.04
321 SS				--	0.003	0.07			
410 SS							--	0.001	0.04
430 SS				--	0.001	0.03	--	0.002	0.05
446 SS	--	0.005	0.12	--	0.002	0.05	--	0.002	0.05
Incoloy 800	--	0.002	0.06	--	0.000	0.01	--	0.002	0.05
Incoloy 800 Al[v]	Diffusion zone not penetrated.								
IN-793	0.4[w]	0.010	0.26						
Inconel 671	--	0.009	0.22						
RA 333	--	0.002	0.06						
Armco 21-6-9				--	0.001	0.04			
Armco 22-13-5				--	0.000	0.01			
Alloy X				--	0.006	0.16			
Inconel 600							--	0.003	0.08
Carbon steel A515							--	0.006	0.14
Carbon steel A515 Al[v]							Diffusion zone not penetrated.		
Carbon steel (1/2 Mo)							--	0.002	0.04
Carbon steel (5 Cr-1/2 Mo)							--	0.001	0.04
Titanium 50A							--	0.001	0.02

	Gasifier freeboard section (WESTINGHOUSE) 1525-1810°F, 232psig, 1100h			Hot gas cyclone (WESTINGHOUSE) 1286-1800°F, 232psig, 1100h		
	Depth of Penetration	Total Sound Metal Loss[a]		Depth of Penetration	Total Sound Metal Loss[a]	
Alloy[c]	mils	in/yr	mm/yr	mils	in/yr	mm/yr
310 SS	0.4	0.005	0.12	1.6	0.035	0.89
310 SS Al[g]	3.1[z]	0.037	0.94	16.0*	0.127*	3.23
329 SS	1.0	0.022	0.56			
Incoloy 800	0.4	0.005	0.12			
Incoloy 800 Al[g]	7.6[z]	0.122	3.10			
Incoloy 825	0.6†	0.009†	0.22			
Inconel 617	14.2	0.315	8.00			
Inconel 671	0.4	0.005	0.12	0.8	0.008	0.20
Alloy X	7.7	0.285	7.24			
Multimet N155	0.4	0.005	0.12			
Stellite 6B	1.0	0.009	0.22			
E-Brite 26-1	1.0	0.009	0.22	1.4	0.14	0.34
Armco 18SR	1.0	0.009	0.22			
Haynes 188	--	0.495	12.6			

[a]Both gravimetric and metallographic analyses were used to determine the extent of corrosion. Most values are the average of data for 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. Corrosion rates are for comparison of alloy performance only and apply only for the reported test duration. The rates can not be linearly extrapolated to longer test times.

[b]Data for exposures in a total of 18 locations for eight pilot plants are included. Several exposures in some locations are reported. The conditions are such that all constituents are gas phase except for dispersed solids. Average temperatures or temperature ranges, pressures, and the type of environment are given when known as well as the exposure times which are for full operating conditions; standby periods were omitted.

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN GAS-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

Footnotes continued

[c]Specimens were flat coupons except for some welded U-bend specimens which are so designated in the table. Approximate alloy compositions including only major constituents follow: 430 SS, Fe-17Cr; 304 SS, 70Fe-9Ni-19Cr; 321 SS, Fe-10Ni-18Cr; 316 SS, 65Fe-14Ni-17Cr; 309 SS, 61Fe-15Ni-23Cr; Armco 21-6-9, 63Fe-9Ni-21Cr-8Mn; Armco 22-13-5, Fe-14Ni-21Cr-5Mn; Incoloy 800, 47Fe-31Ni-21Cr; Incoloy 825, 28Fe-42Ni-22Cr; RA 333, 16Fe-45Ni-26Cr-3Co-4Mo-3W; Alloy X, 20Fe-45Ni-22Cr-9Mo; Inconel 601, 16Fe-60Ni-23Cr; Inconel 600, 7Fe-77Ni-16Cr; IN-793, 43Fe-32Ni-21Cr; 446 SS, 75Fe-24Cr; 310 SS, 52Fe-20Ni-25Cr; Inconel 671, 48Ni-50Cr; 314 SS, 52Fe-20Ni-24Cr; RA 330, Fe-36Ni-19Cr; Monel 400, 54Ni-33Cu-2Fe; Haynes 150, Co-18Fe-28Cr; Crutemp 25, 47Fe-25Ni-25Cr; HC-250, 68Fe-28Cr-3C; HL-40, 47Fe-19Ni-31Cr; HK-40, Fe-20Ni-28Cr; Haynes 188, Co-23Ni-22Cr; Multimet N155, 29Fe-20Ni-21Cr-20Co-3Mo-3W; 556, Fe-20Ni-22Cr-20Co-3Mo-3W; Stellite 6B, 57Co-2Fe-3Ni-28Cr-5W; Inconel 617, 54Ni-22Cr-13Co-9Mo; Supertherm 63WC, Fe-36Ni-28Cr-15Co-5W; 410 SS, Fe-12Cr; E-Brite 26-1, Fe-26Cr-1Mo; Armco 18SR, Fe-18Cr-2Al; 329 SS, Fe-4Ni-27Cr. Compositions are in weight percent; if no number appears before a constituent, e.g. Fe, that indicates that the balance of the alloy consists of that element.

[d]Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

[e]Localized attack at sample edge.

[f]Localized attack extending through the diffusion zone.

[g]Pack aluminized.

[h]Metal loss was negligible.

[i]Both gravimetric and metallographic values given, metallographic values in parentheses.

[j]Note: In the MPC topical report (see reference [12]) "Corrosion and Degradation of Materials in the Conoco Coal CO_2-Acceptor Coal Gasification Plant", Table 7, page 28, is in error. The fifth column of the table containing these data was typed incorrectly, displacing the correct values one down.

[k]Chromized.

[l]Localized corroded areas.

[m]Samples used in this test were aluminized at IITRI.

[n]Second specimen essentially completely corroded.

[o]Both specimens completely corroded.

[p]Total time of operation 264 hours. Temperature range in the gasifier 300-1000 °F, atmosphere that of the combustion products of natural gas. Temperature range in the combustor 500-1000 °F, atmosphere also that of natural gas combustion products. Results of this test are tentative, only representative of start-up conditions.

[q]Some additional internal corrosion along cracks in the outer coating layer.

[r]Localized grain boundary attack in one isolated area.

[s]Internal corrosion mainly along cracks in outer coating.

[t]Localized internal penetration.

[u]The PEATGAS pilot plant is physically the HYGAS pilot plant with modification to the steam-oxygen gasifier (elimination of the second-stage hydrogasifier) to gasify peat. Locations for coupons are the same as in the HYGAS plant.

[v]Pack-aluminized at 1800 °F.

[w]Subsurface oxidation of aluminum (alloying constituent of IN-793).

[x]Complete removal of coating and diffusion zone in many areas.

[y]Localized area of intergranular corrosion.

[z]Diffusion zone was penetrated in one isolated area only. The value quoted corresponds to the thickness of the diffusion zone.

[*]Ash deposition of sample surface.

[†]Corrosion data not representative of entire sample. Extensive corrosion around mounting holes.

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44]

	Coal pretreater water quench (HYGAS); H_2O, O_2, CO, CH_4, N_2							
	~70 °F, 2.7 psig, 1575(2845) h[d]				158 °F, 1.0 psig, 1719(3228) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	7.8(26.7)	4.3(14.8)	--	--	54.1(93.3) 51.8	28.8(49.6) 27.6	(8.8)	
Cast iron A-278	4.4	2.5	3.3	2.3	34.9(93.8) 33.2	18.6(49.9) 17.7	(17.6)	
Ni-Resist A-439 D2B	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) A-436 1B	2.8	1.5	1.1	0.9	20.6(84.7) 20.5	11.0(45.0) 10.9	(15.0)	
Si-Iron A-518	0.6	0.3	8.7	6.3	14.5(82.6) 13.2	7.7(43.9) 7.0	(18.1)	
304 SS	0.2	<0.1	2.4	1.5	--[e] --[e]	--[e] --[e]	13.1 15.6	9.3 7.9
18-18-2	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 CDA 954	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 cracks.				No visible cracks.			
329 SS	No stress-corrosion cracks.							
304 SS	No stress-corrosion cracks.				No visible cracks.			
18-18-2	No stress-corrosion cracks.				No visible cracks.			

	Product gas prequench tower (HYGAS); process condensate, water, char fines, ash															
	171 °F, 950 psig, 2909(10,429) h[d]				205 °F, 990 psi, 1150(2010) h[d]				167 °F, 609 psig, 2292(5888) h[d]				198 °F, 588 psig, 823(1848) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	19.9(57.8)	5.5(16.1)	4.9	3.4	8.8(20.0) 9.0	3.1(7.3) 3.3	-- --	-- --	44.7(49)	17.4(19)	--	--	78.2(189.4)	34.9(84.4)	--	--
Cast iron A-278	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	10.3	4.0	--	--	78.1(157.5)	30.3(70.2)	--	--
Ni-Resist A-439 D2B	22.0(30.1)	6.1(8.4)	3.6	2.6	7.0(15.2) 6.6	2.6(5.5) 2.4	-- --	-- --	12.2	4.8	--	--	42.1(103.2)	18.7(46.0)	--	--
Ni-Resist (Cu) A-436 1B	21.7(39.7)	6.0(11.1)	3.4	2.4	6.9(14.5) 6.8	2.5(5.3) 2.5	-- --	-- --	10.3	4.0	--	--	64.4(124.5)	28.7(55.5)	--	--
304 SS	<0.1	--	1.2	0.8	0.07 0.07	0.02 0.02	not measurable		<0.2	<0.1	--	--	<1.1	<0.5	9.0[f]	3.5
18-18-2	0.1	--	1.8	1.4	0.07 0.07	0.02 0.02	10.8 9.1	8.3 7.7	<0.2	<0.1	7.96	2.5	<1.1	<0.5	--	--
Al Bronze CDA 954	3.9(12.3)	1.1(3.4)	7.1	5.0	3.12(7.2) 3.3	1.1(2.6) 1.2	-- --	-- --	14.1(39)	5.8(15)	--	--	13.3(43.6)	5.9(23.0)	--	--
Titanium 50A	<0.1	--	--	--	-- --	-- --	-- --	-- --	<0.2	<0.1	--	--	<1.1	<0.5	--	--

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

	Product gas prequench tower (HYGAS); process condensate, water, char fines, ash, continued															
410 SS	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	3.6	1.4	9.4	6.3	16.5(64.9)	7.4(28.9)	10.6	5.0
329 SS					-- --	-- --	-- --	-- --								
E-Brite 26-1									<0.2	<0.1	--	--	<1.1	<0.5	--	--
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.				No stress-corrosion cracks.				No stress-corrosion cracks.			
18-18-2	No stress-corrosion cracks.				No visible stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			
E-Brite 26-1									No stress-corrosion cracks.				No stress-corrosion cracks.			

	Feed slurry mix vessel (HYGAS); treated coal fines plus toluene											
	180 °F, 1 atm, 288(2118) h[d]		85 °F, 3 psi, 1150(2046) h[d]		85 °F, 1 atm, 5905(9922) h[d]				85 °F, 5 psig, 1004(1576) h[d]			
	Corrosion Rate mils/year		Corrosion Rate mils/year		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	Operational[a]	Total[a]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	17.9 16.7	2.44 2.27	3.28 4.27	1.84 2.40	12.3(20.0)	7.3(11.9)	--	--	41.5(114.3)	25.2(72.8)	--	--
410 SS	0.18 0.30	0.02 0.04[g]	0.04 0.015	0.02 0.01	0.9	0.5	12.0	4.4	20.1	12.8	7.8	3.1
304 SS	0.06 0.03	0.01 0.004	0.022 0.015	0.01 0.01	<0.1	<0.1	--	--	<0.9	<0.6	--	--

	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) h[d]				174 °F, 1 atm, 1790(3296) h[d]				174 °F, 2.7 psig, 3325(4504) h[d]				184 °F, 1.1 psig, 1801(2056) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	36.4(46.4) 37.4	19.1(24.7) 19.9	-- --	-- --	43.0(68.4)	23.4(37.2)	--	--	31.4(42.4)	23.1(31.3)	--	--	68.6(191.6)	60.1(167.9)	--	--
410 SS	1.3 1.2	0.7 0.7	-- --	-- --	1.0	0.5	10.4	5.8	1.1	0.8	9.2	4.7	<0.5	<0.4	3.0	2.1
304 SS	0.1 0.1	0.1 0.1	-- --	-- --	<0.1	<0.1	3.3	1.6	<0.3	<0.2	2.7	1.4	<0.5	<0.4	--	--
316 SS	-- 0.1	-- --	-- --	-- --	<0.1	<0.1	1.2	0.9	<0.3	<0.2	2.8	1.6	<0.5	<0.4	--	--
Welded U-Bends																
Carbon steel	No visible cracks.												No stress-corrosion cracks.			
304 SS	No visible cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			
316 SS	No visible cracks.				No stress-corrosion cracks.				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[12,44], Continued

Quench separator tower (HYGAS); process condensate, water, char fines, ash

	OIL PHASE								GAS PHASE							
	140 °F, 990 psi, 1150 h operation; 120 °F, 650 psi, 2010 h standby				120 °F, 588 psig, 924(2024) h[d]				95 °F, 949 psig, 2909(10,429) h[d]				93 °F, 608 psig, 2292(5888) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	30.0(46.5)	10.9(16.9)	--	--	101.4(291.1)	43.5(132.9)	--	--	145.3(131.7)	40.5(36.7)	5.6	4.3	133.6(157)	52.0(61)	--	--
	16.1(39.6)	5.8(14.4)	--	--												
410 SS	1.7	0.6	7.5	5.3	20.9(88.2)	8.9(40.3)	13.8	4.5	41.8(82.7)	11.7(23.1)	9.1	7.4	22.8(76)	8.8(30)	12.4	5.0
	4.4	1.6	9.4	7.8												
430 SS	0.7	0.2	10.6	7.4	12.8(66.4)	5.5(30.3)	10.4	5.7	4.8(22.6)	1.3(6.3)	11.8	6.5	11.7(69)	4.6(27)	11.4	5.8
	0.8	0.2	14.3	9.0												
304 SS	0.02	0.01	2.9	--	<0.9	<0.4	6.5	4.2	<0.1	--	10.3	5.8	<0.1	<0.1	4.2	1.8
	0.02	0.01	0.8	--												
Welded U-Bends																
Carbon steel	No visible stress-corrosion cracks.				No stress-corrosion cracks.								No stress-corrosion cracks.			
304 SS	No visible stress-corrosion cracks.				No stress-corrosion cracks.				No visible stress-corrosion cracks.				No stress-corrosion cracks.			

Quench tower off-gas (HYGAS); product gas

	97 °F, 909 psig, 1247(3356) h[d]				108 °F, 900-1100 psi, 1596(6018)h[d]				101 °F, 607 psig, 2292(5888) h[d]				100 °F, 588 psig, 924(2160) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	77.2(131.9)	28.7(49.0)	8.6	4.6	(155)	(41.2)			99.0(122)	38.5(47)	--	--	237.5(554.6)	101.7(237.3)	--	--
					(171)	(45.3)										
410 SS	5.6	2.1	9.6	7.6	1.43	0.52	5.9	12.9	17.6(35)	6.8(13)	16.4	5.2	28.5(75.8)	12.2(32.4)	17.4	6.7
					1.04	0.38	8.2	18.[illegible]								
304 SS	<0.1	<0.1	0.9	0.9	0.02	0.01	--	--	<0.2	<0.1	3.7	2.3	<0.9	<0.4	14.2	4.1
					0.02	0.01	--	--								
Welded U-Bends																
Carbon steel	No stress-corrosion cracks, badly corroded.				No stress-corrosion cracks.											
304 SS					No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			

Char/slurry mix tank (HYGAS); char, ash, water

	95 °F, 890 psi, 1350 h operation; 880 °F, 730 psi, 1760 h standby				135 °F, 907 psig, 2909(8041) h[d]				100 °F, 28 psig, 2292(5328) h[d]				100 °F, 588 psig, 924(2024) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	19.1(43.5)	8.3(18.9)	--	--	101.4(149.5)	36.7(54.1)	8.4	5.9	108(116)	47(50)	--	--	80.1(137.5)	36.6(62.8)	--	--
	6.7(13.5)	2.9(5.9)	--	--												
410 SS	1.6	0.7	11.4	8.8	10.5(53.5)	3.8(19.4)	15.8	11.8	1.9(83)	8.2(36)	15.8	6.5	10.0(11.4)	4.6(5.2)	7.4	3.1
	0.2	0.07	3.6	--												
304 SS	0.02	0.01	--	--	<0.1	--	0.7	0.2	1.2	0.5	--	--	<0.9	<0.4	3.8	2.9
	0.07	0.03	--	--												
Welded U-Bends																
Carbon steel													No stress-corrosion cracks.			
304 SS													No stress-corrosion cracks.			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], 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								Liquid phase; water, condensate, ash, char, tar (traces)			
	385 °F, 600 psig, 592(2046) h[d]				445 °F, 600 psi, 618(3687) h[d]				385 °F, 600 psig, 592(2046) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	58.2(124.3)	16.8(36.0)			56.7(143.1)	9.5(24.0)	--	--	55.3(182.0)	16.0(52.7)		
	54.0(136.1)	15.6(39.4)			55.3	9.3	--	--	51.6(229.4)	14.9(66.4)		
Carbon steel Al[h] A515	5.6(69.5)	1.6(20.2)			11.8(18.4)	2.0(3.1)	--	--	5.8(79.9)	1.7(23.1)		
	6.1	1.8			12.0	2.0	--	--	4.9	1.4		
410 SS	4.1	1.2	3.2	1.5	8.5(35.4)	1.4(6.0)	2.8	2.1	4.4	1.3	7.9	2.6
	4.1	1.2	6.9	6.1	22.7	3.8	6.9	3.7	5.5	1.6	4.7	2.1
430 SS	1.5	0.4	3.8	1.4	3.4	0.6	4.4	2.4	2.8	0.8	--	--
	1.5	0.4	2.3	0.9	4.3	0.7	3.0	1.2	2.8	0.8	--	--
304 SS	0.07	0.02	--	--	0.4	0.1	5.3	1.9	0.09	0.03	--	--
	0.07	0.02	--	--	0.3	0.1	1.5	1.1	0.09	0.03	1.5	--
316 SS	0.06	0.02	0.6	--	0.6	0.1	0.6	0.4	0.15	0.04	1.2	--
	0.06	0.02	0.7	0.5	0.3	0.1	0.9	0.6	0.30	0.09	0.9	--
Incoloy 800	0.07	0.02	1.2	0.4	0.3	0.1	0.5	0.3	0.13	0.04	0.6	--
	0.07	0.02	--	--	0.9	0.1	0.7	0.5	0.06	0.02	0.2	--
Inconel 600	0.9	0.3	4.8	1.3	0.9	0.1	0.7	0.6	1.5	0.4	--	--
	0.7	0.2	5.2	1.6	1.0	0.2	0.8	0.5	1.3	0.4	7.0	2.4
Monel 400	189.1(310.7)	54.7(88.9)	--	--	66.6(90.7)	11.2(15.2)	--	--	56.8(119.9)	16.4(34.7)	--	--
	222.6(293.0)	64.4(84.8)	--	--	60.9	10.2	--	--	51.1(131.7)	14.8(38.1)	--	--
Titanium 50A	0.10	0.03	--	--	0.6	0.1	1.0	0.7	0.30	0.09	--	--
	0.30	0.09	--	--	0.3	0.1	0.8	0.5	0.30	0.09	--	--
Welded U-Bends												
304 SS	No visible cracks.				No visible cracks.				No visible cracks.			
Incoloy 800	No visible cracks.				No visible cracks.				No visible cracks.			

	Decanter (SYNTHANE)															
	Splash zone, liquids; water, condensates, ash, char, tar (traces)								Solid-liquid zone; water, condensates, ash, char, tar, solids							
	220 °F, <5 psig, 592(2046) h[d]				190 °F, 5 psi, 618(3687) h[d]				220 °F, <5 psig, 592(2046) h[d]				190 °F, 5 psi, 618(3687) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	40.0(112.5)	11.6(32.5)	--	--	29.8(62.4)	5.0(10.5)	--	--	28.1(78.4)	8.1(31.3)			21.3(52.4)	3.6(8.8)	--	--
	47.4(161.3)	13.7(46.7)	--	--	28.3	4.8	--	--	29.6(69.6)	8.6(20.1)			17.0	2.9	--	--
410 SS	2.5	0.7	12.1	5.4	1.4	0.3	3.0	1.7	0.9	0.3	12.8	3.3	0.9	0.1	1.7	1.0
	0.7	0.2	4.9	1.8	1.4	0.3	2.6	1.4	0.9	0.3	9.2	2.3	0.7	0.1	2.6	1.5
430 SS	0.14	0.04	--	--	0.9	0.1	8.1	3.1	0.6	0.2	4.6	2.5	0.4	0.1	4.4	2.4
	0.14	0.04	--	--	0.9	0.1	13.4	4.9	0.4	0.1	4.2	2.9	0.6	0.1	3.0	1.2
304 SS	--	--	--	--	0.3	0.1	1.9	1.2	--	--	--	--	0.1	0.1	5.3	1.9
	--	--	--	--	0.3	0.1	2.0	1.1	--	--	--	--	0.1	0.1	1.5	1.1
Welded U-Bends																
Carbon steel	No visible stress-corrosion cracks.				No visible cracks.				No visible stress-corrosion cracks.				No visible cracks.			
304 SS	No visible stress-corrosion cracks.				No visible cracks.				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[12,44], Continued

	Gasifier char cooler (SYNTHANE), vapor phase; saturated water, char							
	800 °F, 600 psi, 417(3421) h[d]				600-900 °F, 600 psig, 592(2046) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	(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.			

	Gasifier quench tower (CONOCO CO_2 ACCEPTOR)				Dolomite regenerator quench tower (CONOCO CO_2 ACCEPTOR)											
	120 °F, 145 psig, 1215(3959) h[d]				135 °F, 135 psig, 2990(4101) h[d]				130 °F, 130 psig, 1710(6479) h[d]				130 °F, 135 psig, 2161(3911) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	51.8(101.7)	15.9(31.2)	--	--	26.6(40.7)	11.2(17.2)	--	--	46.1(80.4)	12.2(21.2)	--	--	50.4(55.1)	27.9(30.5)	6.5	1.8
	50.7(101.7)	15.6(31.2)	--	--	26.7	11.2	--	--	42.2(62.5)	11.2(16.5)	--	--	48.4(65.7)	26.7(36.3)	2.2	1.5
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	0.10	0.03	--	--	0.0	0.0	--	--
	0.07	0.02	--	--	0.08	0.03	--	--	0.10	0.03	--	--	0.0	0.0	--	--
316 SS	0.03	0.009	--	--	0.03	0.01	--	--	0.15	0.04	--	--	0.0	0.0	--	--
	0.03	0.009	--	--	0.06	0.02	--	--	0.15	0.04	--	--	0.0	0.0	--	--
Incoloy 825	0.01	0.004	--	--	0.01	--	0.68	0.42	0.10	0.03	--	--	0.0	0.0	--	--
	0.04	0.01	--	--	0.04	0.02	0.76	0.44	0.10	0.03	--	--	0.0	0.0	--	--
20Cb-3	0.04	0.01	--	--	0.07	0.03	--	--	0.10	0.03	1.8	1.2	0.0	0.0	--	--
	0.07	0.02	1.1	--	0.11	0.05	--	--	0.10	0.03	--	--	0.0	0.0	--	--
Armco 22-13-5	0.07	0.02	1.0	--	0.05	0.02	--	--	0.05	0.01	--	--	0.0	0.0	--	--
	0.4	0.1	5.9	3.9	0.04	0.02	--	--	0.05	0.01	0.7	--	0.0	0.0	--	--
Titanium 50A	0.14	0.04	--	--	0.04	0.02	--	--	0.26	0.07	--	--	0.1	0.0	--	--
	0.07	0.02	1.6	0.9	0.05	0.02	--	--	0.15	0.04	--	--	0.1	0.0	--	--
Cast iron A-278					14.6(27.2)	6.2(11.5)	--	--	48.8(107.6)	12.9(28.4)	--	--	53.3(69.3)	29.4(38.3)	--	--
					14.0	5.9	--	--	48.1(117.8)	12.7(31.1)	--	--	53.2	29.4	--	--
Ni-Resist (Cu) A-436 1B					14.1(12.3)	5.9(5.2)	--	--	59.8(86.1)	15.8(22.7)	--	--	32.1(60.0)	17.8(33.1)	2.4	1.7
					10.6	4.5	--	--	59.2(68.7)	15.6(18.1)	--	--	30.9	17.1	2.7	1.4
Ni-Resist A439 D2B					13.8(26.7)	5.8(11.2)	--	--	40.2(41.5)	10.6(11.0)	--	--	31.3(39.3)	17.3(21.7)	--	--
					13.1	5.5	--	--	44.2(56.9)	11.7(15.0)	--	--	31.0	17.1	--	--
18-18-2					0.1	0.4	--	--	0.15	0.04	--	--	0.1	0.0	--	--
					0.1	0.1	--	--	0.20	0.05	--	--	0.1	0.0	--	--
Al Bronze CDA 954					7.3(12.6)	3.1(5.3)	--	--	16.9(60.5)	4.5(16.0)	--	--	17.3(23.2)	9.6(12.8)	--	--
					7.1	3.0	--	--	16.9(47.1)	4.5(12.4)	--	--	19.2	10.6	--	--
Welded U-Bends																
Carbon steel					No visible stress-corrosion cracks.				No visible cracks.				No stress-corrosion cracks (unwelded coupon).			
304 SS					No visible stress-corrosion cracks.				No visible cracks.				No stress-corrosion cracks.			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

Gasifier slag quench (BI-GAS)

	Vapor phase; saturated water								Liquid phase; char, ash, water							
	470 °F, 750 psig, 1043(10,225) h[d]				400-600°F, 750 psig, 1784(5870)h[d]				70 °F, 750 psig, 1043(10,224) h[d]				60-75 °F, 750 psig, 1784(5870)h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	20.1(62.1)	2.05(6.3)	--	--	109.5(104.1)	33.3(31.6)	--	--	79.7(120.8)	8.1(12.3)	--	--	135.6(176.8)	41.2(53.7)	--	--
304 SS	<1	<1	5.5	--	9.8(15.7)	3.0(4.8)	9.4	6.2	<1	<1	--	--	0.1	0.03	--	--
2 1/4 Cr-1 Mo	22.7(79.8)	2.31(8.1)	--	--	84.7(101.2)	25.8(30.7)	--	--	36.2(71.3)	5.7(7.3)	--	--	115.0(117.9)	34.9(35.8)	--	--
316 SS	<1	<1	--	--	4.5	1.4	4.7	2.7					0.1	0.03	--	--
405 SS	<1	<1	4.4	2.6	22.3(35.9)	6.7(10.9)	4.2	2.9	<1	<1	--	--	0.2	0.1	--	--
329 SS	<1	<1	--	--					<1	<1	--	--	0.14	0.04	--	--
E-Brite 26-1	<1	<1	--	--	2.0	0.6	3.6	2.7	<1	<1	0.8	0.4	0.1	0.03	--	--
Welded U-Bends																
304 SS	No stress-corrosion cracks.				No stress-corrosion cracks.[i]				No stress-corrosion cracks.				No stress-corrosion cracks.			
329 SS	No stress-corrosion cracks.				No stress-corrosion cracks.[i]				No stress-corrosion cracks.				No stress-corrosion cracks.			
E-Brite 26-1	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			

	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) h[d]				350-435°F, 750 psig, 1784(5870)h[d]				225 °F, ∿5 psig, 803(8016) h[d]				230-260°F, 10 psig, 1784(5870)h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	18.5(114.9)	1.9(11.7)	--	--	20.1(45.2)	6.2(13.7)	--	--	43.6(94.8)	4.4(9.5)	--	--	98.1(94.3)	29.8(28.7)	--	--
304 SS	<1	<1	--	--	0.2	0.04	--	--	<1	<1	--	--	0.4	0.1	--	--
316 SS	<1	<1	--	--	0.30	0.09	--	--								
405 SS	2.5	<1	--	--	2.0	0.6	5.8	4.4	<1	<1	9.2	4.4	1.0	0.3	10.2	5.9
Monel 400	15.9(18.9)	1.6(1.9)	--	--	29.5(30.4)	8.9(9.3)	2.1	1.1								
Incoloy 825	<1	<1	--	--												
20Cb-3					0.10	0.03	--	--								
Welded U-Bends																
Carbon steel									No stress-corrosion cracks.				No stress-corrosion cracks.			
304 SS	No stress-corrosion cracks.				No stress-corrosion cracks.								No stress-corrosion cracks.			
316 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.							
405 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				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[12,44], Continued

	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) h[d]				300 °F, 740 psig, 1784(5870) h[d]				65-75 °F, 1 atm, 778(8016) h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	25.9(205.8)	2.5(20.0)	--	--	38.1(61.4)	11.6(18.7)	--	--	54.0(181.3)	5.2(17.6)	--	--
304 SS	<1	<1	--	--	0.07	0.02	--	--	<1	--	2.2	1.0
316 SS	<1	<1	1.4	1.3	0.12	0.04	--	--	<1	--	--	--
Monel 400	16.9(25.9)	1.6(2.5)	--	--	25.9(63.3)	7.9(19.3)	2.4	1.3	3.3	<1	--	--
2 1/4 Cr-1 Mo	40.5(67.4)	3.9(6.5)	--	--	55.6(85.0)	16.9(25.8)	--	--				
20Cb-3	<1	<1	--	--	0.04	0.01	--	--	<1	--	--	--
Welded U-Bends												
304 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			
316 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			

	Product gas scrubber (U-GAS)													
	Off-gas							Sludge tank aqueous phase						
	175 °F, 15 psig, 1049 h[j]			170-185°F, 10-42psig, 1581(1941)h[d]				60-70 °F, 1 atm, 680 h[j]			70-85 °F, 1 atm, 1581(1941) h[d]			
	Corrosion Rate mils/year	Pit Depth mils		Corrosion Rate[l] mils/year		Pit Depth mils		Corrosion Rate mils/year	Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a,j]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a,j]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	246.3(374.1)[k]	--	--	63.2(475.4)[k]	51.5(387.2)[k]			154.7(428.6)	m	m	84.8(184.5)[k]	69.1(150.3)[k]		
	221.3	--	--					154.1	m	m				
304 SS	49.3(106.1)[p]	13.8	5.4	16.3	13.1	12.0[n]	6.9[n]	1.4	o	o	<1.1	<0.9		
	66.0	10.9	6.1					1.4	o	o				
316 SS	25.1(56.0)[q]	10.8	8.0	16.3	13.1	18.2[n]	8.3[n]	1.4	o	o	<1.1	<0.9		
	25.1	8.8	6.8					1.4	o	o				
410 SS	126.1(206.3)[r]	--	--	88.5(225.0)[s]	72.2(183.2)[s]	t	t	12.3	6.2	4.3	6.5(34.4)[u]	5.0(28.0)[u]	6.6	4.7
	121.1	--	--					12.3	9.2	4.2				
Inconel 600	31.7(64.3)[k]	--	--	23.0[k]	18.5[k]	t	t	1.4	m	m	<1.1	<0.9		
	35.9	--	--					1.4	m	m				
Incoloy 800				15.1	12.2	9.2[n]	6.0[n]				<1.1	<0.9		
430 SS				95.8(191.2)[s]	78.1(155.7)[s]	t	t				8.0(38.8)[u]	6.3(31.6)[u]	5.0	3.6
Titanium 50A				<1.1	<0.9	o	o				<1.1	<0.9		
HC-250				219.4(238.8)[s]	178.7(194.5)[s]	t	t				8.0(47.1)[k]	6.3(38.4)[k]	7.3	3.4
CN-7M				8.0	6.3	19.5[n]	8.1[n]				<1.1	<0.9		
329 SS				6.0	5.0	18.4[n]	4.1[n]				<1.1	<0.9		
Welded U-Bends														
Carbon steel	No stress-corrosion cracks.			No stress-corrosion cracks. Severe overall corrosion.				No stress-corrosion cracks.			No stress-corrosion cracks.			
304 SS	No stress-corrosion cracks.			No stress-corrosion cracks. Severe pitting, weld and heat affected zones.				No stress-corrosion cracks.			No stress-corrosion cracks.			
316 SS	No stress-corrosion cracks.			No stress-corrosion cracks. Severe overall pitting.				No stress-corrosion cracks.			No stress-corrosion cracks.			
Inconel 600	No stress-corrosion cracks.			No stress-corrosion cracks. Overall corrosion.				No stress-corrosion cracks.			No stress-corrosion cracks.			
329 SS				No stress-corrosion cracks. Severe pitting, weld and heat affected zones.							No stress-corrosion cracks.			
Incoloy 800				No stress-corrosion cracks. Severe overall pitting.							No stress-corrosion cracks.			

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

	Venturi Scrubber Collection Tank (U-GAS) aqueous phase				Quench/scrubber (WESTINGHOUSE) Vapor phase				Quench/scrubber (WESTINGHOUSE) Off-gas, aqueous phase			
	70-85 °F, 0 psig, 264(312) h[d]				275-350 °F, 230 psig, 1100(1320)h[d]				264-337°F, 230psig, 1100(1320)h[d]			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
Carbon steel A515	79.6(169.2)	67.4(143.2)	--	--	85.3(191)	70.0(159)	--	--	36.3(147)	30.5(122)	--	--
Carbon steel (TEF)[v]					80.3(151)	67.0(126)	--	--	25.5(92)	21.2(77)	--	--
304 SS	<3.3	<2.8	--	--	<0.8	<0.7	--	--	<0.8	<0.7	--	--
316 SS	<3.3	<2.8	--	--	<0.8	<0.7	--	--	<0.8	<0.7	--	--
410 SS	10.0	8.4	--	--	30.0(95)	24.6(80)	13.8	5.5	4.8	4.0	19.3	6.0
E-Brite 26-1	<3.3	<2.8	--	--	<0.8	<0.7	1.5	0.6	<0.8	<0.7	--	--
Welded U-Bends												
Carbon steel	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			
304 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			
316 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.			
E-Brite 26-1	No stress-corrosion cracks.											

PEATGAS plant[w] (modified HYGAS plant); 300-500 psig, 449(852) h[d]

	Prequench tower liquid phase				Quench separator liquid phase				Product gas quench tower off-gas				Char slurry mix tank slurry phase			
	85-270 °F				74-110 °F				70-190 °F				110-280 °F			
	Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils		Corrosion Rate mils/year		Pit Depth mils	
Alloy[c]	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg	Operational[a]	Total[a]	max	avg
304 SS	0.19	0.10	--	--	0.25	0.13	--	--	0.16	0.08	--	--	0.09	0.05	--	--
410 SS	0.30	0.16	--	--	7.44	3.92	--	--	4.09	2.16	--	--	0.77	0.41	--	--
430 SS	0.36	0.19	--	--	0.51	0.27	--	--	0.85	0.45	--	--	1.03	0.54	--	--
446 SS	0.46	0.25	--	--												
Carbon steel A515	0.50	0.26	--	--	163.66	86.25	--	--	122.19	64.40	--	--	44.84	23.63	--	--
Ni-Resist A439 D2B	2.39	1.26	--	--												
Ni-Resist (Cu) A436 1B	2.44	1.29	--	--												
Al Bronze CDA 954	2.93	1.54	--	--												
Cast iron A-278	16.32	8.6	--	--												
Welded U-Bends																
Carbon steel									No stress-corrosion cracks.							
304 SS	No stress-corrosion cracks.				No stress-corrosion cracks.				No stress-corrosion cracks.							
18-18-2	No stress-corrosion cracks.															
E-Brite 26-1	No stress-corrosion cracks.															

[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 the rest of the 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. The rate is based on both operational exposure time and time of full exposure which includes standby time. Corrosion rates are for comparison of alloy performance only and apply only for the reported test time. The rates can not be linearly extrapolated to longer test times.

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN LIQUID-PHASE LOCATIONS[b] IN COAL GASIFICATION PILOT PLANTS[12,44], Continued

Footnotes continued

[b]Data for a total of 29 locations in seven 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 when known with exposure times for full operation as well as total exposure time which is the sum of operation plus standby time.

[c]Specimens were flat coupons except for some welded U-bend specimens which are so designated in the table. Approximate alloy compositions including only major constituents follow: Cast iron, Fe-3C-2Si-2Ni; Ni-Resist, Fe-20Ni-3Cr-3Si-3C; Ni-Resist (Cu), Fe-18Ni-4Cr-3Si-7Cu-3C; Si-iron, Fe-15Si; 304 SS, 70Fe-9Ni-19Cr; 18-18-2, Fe-18Ni-18Cr-2Si; Al Bronze, Cu-10Al-3Fe-2Ni; 329 SS, Fe-4Ni-27Cr; 410 SS, Fe-12Cr; E-Brite 26-1, Fe-26Cr-1Mo; 316 SS, 65Fe-14Ni-17Cr; 430 SS, Fe-17Cr; Incoloy 800, 47Fe-31Ni-21Cr; Inconel 600, 7Fe-77Ni-16Cr; Monel 400, 64Ni-33Cu-2Fe; Incoloy 825, 28Fe-42Ni-22Cr-3Mo-2Cu; 20 Cb-3, Fe-33Ni-19Cr-2Mo-3Cu; Armco 22-13-5, Fe-14Ni-21Cr; 2 1/4 Cr-1 Mo, Fe-2.25Cr-1Mo; 405 SS, Fe-13Cr; HC-250, 68Fe-28Cr-3C;CN-7M, 42Fe-29Ni-21Cr-3Cu; 446 SS, 75Fe-24Cr. Compositions are in weight percent; if no number appears before a constituent, e.g., Fe, that indicates that the balance of the alloy consists of that element.

[d]The first time given is that of full operational conditions, the second time in parentheses is the total time the specimens were exposed in the system and includes the standby time.

[e]Metal loss was negligible.

[f]Pitting toward the edges of samples.

[g]Some pitting along one edge.

[h]Aluminized carbon steel.

[i]Both samples melted through in the U-bend area by molten slag.

[j]Operational time only, total exposure time not known.

[k]Overall corrosion.

[l]All specimens covered with process debris.

[m]General overall corrosion; no pitting assessment possible.

[n]Severe edge pitting.

[o]No pitting detected.

[p]Severe edge pitting, 80% overall corrosion.

[q]Severe edge pitting, 40% overall corrosion.

[r]Overall corrosion, sandpaper appearance.

[s]Overall corrosion (highly irregular).

[t]Difficult to assess.

[u]Scattered localized corrosion.

[v]Teflon Gray (FeP), DuPont (Slipmate Co., Melrose Park, IL).

[w]The PEATGAS pilot plant is physically the HYGAS pilot plant with modification to the steam-oxygen gasifier (elimination of the second-stage hydrogasifier) to gasify peat. Locations for coupons are the same as in the HYGAS plant.

CORROSION OF UNWELDED AND WELDED SPECIMENS[a] OF SELECTED ALLOYS IN A SIMULATED CORROSIVE GAS ENVIRONMENT[b][31]

Alloy[a]	Scale (μm)	Internal Oxidation (μm)	Total Affected Depth[c] (μm)	Comments
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

[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.

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF ONE SIMULATED PILOT PLANT QUENCH ENVIRONMENT[b][38]

Alloy[a]	Corrosion Rate[c], Mils/Yr Aqueous	Corrosion Rate[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	Time,hr	Environment[b]
Carbon steel	20.8[e]	8.0[e]	0.4	0.3[e]	0.3	0.2[e]	150	Standard: CO_2 16.3%, CO 14.4%, (CO/CO_2 = 0.9), 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% 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	0.3[e]	0.2	0.1[e]	150	Standard with temperature 300 °F (H_2O 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_2O 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_2O 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	0.1[f]	0.3	0.2[f]	150	Standard with pressure 900 psig (H_2O 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_2H_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_6H_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	0.2[e]	0.3	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	0.4[f]	1.4	0.9[f]	150	Standard with NH_3 0.1%, temperature 150 °F (H_2O 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	0.4[f]	0.8	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	0.5[f]	0.9	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 Aqueous	Corrosion Rate[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	Time,hr	Environment[b]
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	0.9[e]	0.6	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	1.3[f]	1.4	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	0.2[f]	0.3	0.1[f]	150	Standard with H_2S 1.5%, pressure 900 psig (H_2O 21.4%)
304 SS	0.4	0.3	0.3	0.2	<0.1	<0.1		
Carbon steel	32.5[f]	11.4[f]	0.7	0.3[f]	0.8	0.2[f]	150	Standard with H_2S 0.1%, pressure 300 psig (H_2O 62%)
304 SS	0.4	0.2	<0.1	<0.1	<0.1	<0.1		
Carbon steel	28.6[g]	10.7	1.2	0.4	0.7	0.3	150	Standard with H_2S 0.1%, pressure 300 psig (H_2O 62%) (repeat of immediately preceding test)
304 SS	0.2	0.1	<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 62%)
304 SS	0.3	0.1	0.3	0.2	0.2	0.1		
Carbon steel	5.6[e]	4.0[e]	0.6	0.3[e]	0.5	0.3[e]	500	Standard with H_2S 1.5%, NH_3 0.8%, temperature 350 °F
304 SS	<0.1	0.1	<0.1	<0.1	<0.1	<0.1		
Carbon steel	23.1	9.6	1.0	0.3	0.6	0.3	150	Standard with no purging
304 SS	0.5	0.2	<0.1	<0.1	<0.1	<0.1		
Carbon steel	17.0	21.1	<0.1	<0.1	1.0	0.5	150	Standard with 900 ppm O_2
304 SS	0.9	0.4	<0.1	<0.1	<0.1	<0.1		

[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-01-69 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:

$$\text{mils/yr} = \frac{\text{weight loss (mg)} \times \text{constant}}{\text{area (in}^2\text{)} \times \text{time (hr)} \times \text{alloy density (g/cc)}}$$

. Specimens were exposed both in liquid in the autoclave and above the liquid. 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. The max values above are the largest values of all maximum values for all specimens. The ave 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.

[g]In Table 3-3, page 3-15, in the 1980 annual report, FE-1784-72 and Table 30, page 76 of the final report, GRI-80/0167 (see reference [38]), this value is misprinted as 38.6. The average of the values given in Table C-1, page C-2 of the 1980 annual report is 28.6.

PROGRESS OF CORROSION BY SIMULATED COAL GASIFICATION ATMOSPHERE WITH TIME FOR SEVERAL ALLOYS[7]

		Depth of Corrosion Penetration (μm)[a]											
		1382 °F[b]				1600 °F[b]				1800 °F[b]			
Alloy[c]	Exposure Time, hr	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
18-18-2	80	26	42	40	82	30	21	48	69	12	6	30	36
	300	37	109	50	159	74	7	110	117	32	11	75	86
	500	44	307	58	365	52[d]	11[d]	94[d]	105[d]	79	32	155	187
	1000	306	201	370	571	58[d]	60[d]	77[d]	137[d]	--	--	--	--
Incoloy 800	80	12	19	12	31	32	0	64	64	17	0	44	44
	300	33	73	96	169	74	68	110	156	92	14	192	206
	500	52	58	98	156	60[d]	28[d]	142[d]	170[d]	48	12	92	104
	1000	32	49	120	169	40[d]	62[d]	178[d]	240[d]	26	16	286	302
310 SS	80	26	22	26	48	56	29	76	105	7	0	45	45
	300	49	30	66	96	74	53	148	201	26	0	136	141
	500	140	56	160	216	208[d]	56[d]	216[d]	272[d]	80	7	196	203
	1000	74	42	95	137	84[d]	41[d]	226[d]	267[d]	22	13	184	197
Inconel 671	80	5	0	7	7	6	0	6	6	13	0	37	37
	300	22	0	78	78	17	0	50	50	12	0	62	62
	500	12	7	84	91	26	5	54	54	21	7	59	70
	1000	20	26	103	129	12	15	68	83	12	14	69	83
GE 1541	80	2	0	2	2	23	0	27	27	7	7	11	18
	300	8	41	14	55	6	55	11	66	7	101	11	112
	500	7	0	11	11	21	14	21	35	8	7	29	36
	1000	54	6	78	84	7	17	8	25	6	14	43	57
GE 1541 (pre-oxidized)[e]	80	9	13	9	22	7	21	11	32	10	47	10	57
	300	14[d]	0[d]	86[d]	86[d]	15	0	96	96	19	0	102	102
	500	90[d]	11[d]	96[d]	107[d]	48[d]	16[d]	48[d]	64[d]	18	0	20	20
	1000	16	20	16	36	20[d]	14[d]	147[d]	160[d]	11	15	14	29

[a]Corrosion effect measured on micrographs of specimens 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 the stated times at the temperatures given in the heading of the table at 68 atm (1000 psig) pressure. The composition of the gaseous atmosphere was:

	Input Gas 1 atm, 77 °F	Equilibrium Compositions 1382 °F	1600 °F	1800 °F
CO	0.201	0.061	0.157	0.266
CO_2	0.115	0.111	0.082	0.046
H_2	0.201	0.186	0.297	0.403
H_2O	0.172	0.256	0.181	0.110
H_2S	0.010	0.009	0.008	0.008
CH_4	0.300	0.214	0.166	0.122
C(solid)		0.164	0.108	0.04
log $P(O_2)$		-19.16	-17.21	-15.91
log $P(S_2)$		-6.69	-6.22	-5.76
log a_c		1.00	1.00	1.00

Gas compositions in mole fractions.
Partial pressures in atmospheres.

[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; 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 (Ceneral Electric), 15.2 Cr, 4.95 Al, 0.7 Y, 0.012 C, 0.07 Si, 0.005 others, balance Fe.

[d]Data are for 642 hours.

[e]These samples were preoxidized for 30 hours at 2100 °F, 100 torr O_2.

WEIGHT CHANGE AND PENETRATION DUE TO EXPOSURE OF SEVERAL ALLOYS[a] TO A SIMULATED COAL GASIFICATION ENVIRONMENT[b] [8]

Alloy[a]	Surface Loss[c] mm	Surface Loss[c] in.	Maximum Depth of Affected Metal[c] mm	Maximum Depth of Affected Metal[c] in.	Total Affected Metal mm	Total Affected Metal in.	Change in Weight[d], g/cm Undescaled	Change in Weight[d], g/cm Descaled
304L SS	No surface loss or depth measurements possible. All four specimens were totally destroyed by the formation of mixed oxides and sulfides. Only small kernels of alloy remained in the centers of the coupons.						-308	-1346
							-318	-1329
							-472	-1266
							-639	destroyed
310 SS	0.0152	0.0006	0.3200	0.0126	0.3352	0.0132	+ 30.6	- 85.8
	0.0305	0.0012	0.1143	0.0045	0.1448	0.0057	+ 6.2	- 129.1
	0.0203	0.0008	0.1219	0.0048	0.1422	0.0056	+ 9.0	- 55.5
	0.0152	0.0006	0.1168	0.0046	0.1320	0.0052	+ 12.4	- 20.2
average	0.0165	0.0008	0.1682	0.0066	0.1885	0.0074		
Incoloy 800H	0.2870	0.0113	2.675	0.1053	2.962	0.1166	+ 43.0	- 320.4
	0.1041	0.0041	2.670	0.1051	2.774	0.1092	+206.8	- 261.0
	0.1803	0.0071	2.570	0.1012	2.750	0.1083	+ 72.2	- 413.0
	0.1981	0.0078	1.090	0.0429	1.288	0.0507	- 40.5	- 163.0
average	0.1924	0.0076	2.251	0.0886	2.443	0.0962		

[a] These alloys were used as substrates in studies of weld overlays. See Sections B.1.1.112-114 for corrosion data for the weld overlays on these substrates. Four unwelded coupons (25.4 x 19.0 x 9.5 mm) of each alloy were exposed.

[b] The samples were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

[c] Samples were examined by metallographic methods. Original measurements were in micron.

[d] After weighing, one half of each sample was masked and the scale removed by a fine air-driven abrasive spray. The masked portion was used for metallographic and microprobe examination.

EFFECT OF A SIMULATED COAL GASIFICATION EXPOSURE[a] ON THE THICKNESS[b] OF SEVERAL WELD OVERLAYS[c] [8]

Weld Overlay[c]	Weldment Thickness (inches)[b] Single Layer Overlay As Welded	Single Layer Overlay Exposed	Single Layer Overlay Change	Double Layer Overlay As Welded	Double Layer Overlay Exposed	Double Layer Overlay Change
AWS-ER309 Filler on 304L SS--GMAW	1.269	1.306	+0.037	1.489	1.498	+0.009
AWS-ER309 Filler on 304L SS--SAW	1.321	1.339	+0.018	1.570	1.574	+0.004
AWS-ER309 Filler on 304L SS--GTAW-HW	1.285	1.370	+0.085	1.515	1.540	+0.025
Inconel Filler Metal 72 on 304L SS--GMAW	1.270	1.272	+0.002	1.529	1.533	+0.004
Inconel Filler Metal 72 on 304L SS--SAW	1.347	1.346	-0.001	1.673	1.683	+0.010
Inconel Filler Metal 72 on 304L SS--GTAW-HW	1.238	1.237	-0.001	1.448	1.444	-0.004
Inconel Filler Metal 72 on 310 SS--GMAW	1.309	1.319	+0.010	1.562	1.562	0
Inconel Filler Metal 72 on 310 SS--SAW	1.396	1.393	-0.003	1.703	1.705	+0.002
Inconel Filler Metal 72 on 310 SS--GTAW-HW	1.308	1.312	+0.004	1.528	1.527	-0.001
Inconel Filler Metal 72 on Incoloy 800H--GMAW	1.309	1.310	+0.001	1.546	1.548	+0.002
Inconel Filler Metal 72 on Incoloy 800H--SAW	1.402	1.404	+0.002	1.723	1.730	+0.007
Inconel Filler Metal 72 on Incoloy 800H--GTAW-HW	1.326	1.326	0	1.543	1.543	0
R139 Filler Metal on 304L SS--GMAW	1.301	1.305	+0.004	1.536	1.541	+0.005
R139 Filler Metal on 304L SS--SAW	1.359	1.362	+0.003	1.676	1.671	-0.005
R139 Filler Metal on 304L SS--GTAW-HW	1.273	1.283	+0.010	1.524	1.525	+0.001
R139 Filler Metal on 310 SS--GMAW	1.322	1.326	+0.004	1.563	1.560	-0.003
R139 Filler Metal on 310 SS--SAW	1.375	1.374	+0.001	1.656	1.650	-0.006
R139 Filler Metal on 310 SS--GTAW-HW	1.307	1.308	+0.001	1.546	1.550	+0.004
R139 Filler Metal on Incoloy 800H--GMAW	1.335	1.334	-0.001	1.600	1.617	+0.017
R139 Filler Metal on Incoloy 800H--SAW	1.391	1.394	+0.003	1.671	1.681	+0.010
R139 Filler Metal on Incoloy 800H--GTAW-HW	1.317	1.321	+0.004	1.540	1.541	+0.001

[a] Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

[b] Overlays were on both surfaces. Each specimen was measured in 8 locations before and after exposure. Weldments were not descaled before measuring. Specimens were 279 x 168 x 32-44 mm.

[c] Single and double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW). Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

MEASUREMENTS FROM OUTER SCALE OF AFFECTED METAL OF WELD OVERLAYS[a] EXPOSED TO A SIMULATED COAL GASIFICATION ATMOSPHERE[b][8]

Weld Overlay[a]	No. of Layers[a]	Scale Thickness (in)[c]		Internal Oxidation (in)[c]		Internal Sulfidation (in)[c]		Subscale Porosity[c] (in)	Maximum Depth Affected Metal[c] (in)	
		A	B	A	B	A	B		A	B
AWS-ER309 Filler on 304L SS--GMAW	1	0.0062	0.0115	0.0275	-	0.0275	0.0290	-	0.0337	0.0405
	2	0.0008	0.0110	0.0019	-	-	0.0122	-	0.0027	0.0232
AWS-ER309 Filler on 304L SS--SAW	1	0.0013	0.0080	0.0021	-	0.0024	0.0123	-	0.0037	0.0203
	2	0.0007	0.0010	0.0019	-	-	0.0015	-	0.0026	0.0025
AWS-ER309 Filler on 304L SS-GTAW-HW	1	0.0204	0.0180	-	-	-	0.0063	-	0.0204	0.0243
	2	0.0086	0.0045	0.0137	-	0.0137	0.0055	-	0.0223	0.0505
Inconel Filler Metal 72 on 304L SS--GMAW	1	0.0005	0.0015	-	0.0039	-	-	0.0036	0.0005	0.0054
	2	0.0001	0.0010	-	0.0035	-	-	0.0028	0.0001	0.0045
Inconel Filler Metal 72 on 304L SS--SAW	1	0.0003	0.0005	-	0.0060	-	-	0.0029	0.0003	0.0065
	2	0.0002	0.0008	-	0.0002	-	-	0.005	0.0002	0.0010
Inconel Filler Metal 72 on 304L SS--GTAW-HW	1	0.0002	0.0007	-	0.0077	-	-	0.0088	0.0002	0.0084
	2	0.0007	0.0010	-	0.0040	-	-	0.0030	0.0007	0.0050
Inconel Filler Metal 72 on 310 SS--GMAW	1	0.0004	0.0002	-	0.0003	-	-	0.0024	0.0004	0.0005
	2	0.0004	0.0005	-	0.0005	-	-	0.0028	0.0004	0.0010
Inconel Filler Metal 72 on 310 SS--SAW	1	0.0002	0.0005	-	0.0010	-	-	0.0018	0.0002	0.0015
	2	0.0004	0.0005	-	0.0015	-	-	0.0024	0.0004	0.0020
Inconel Filler Metal 72 on 310 SS--GTAW-HW	1	0.0006	0.0007	0.0020	0.0018	-	-	0.0030	0.0026	0.0025
	2	0.0002	0.0010	0.0005	0.0027	-	-	0.0031	0.0007	0.0037
Inconel Filler Metal 72 on Incoloy 800H--GMAW	1	0.0003	0.0008	0.0027	0.0057	-	-	0.0032	0.0030	0.0065
	2	0.0002	0.0005	0.0011	0.0050	0.0020	-	-	0.0025	0.0055
Inconel Filler Metal 72 on Incoloy 800H--SAW	1	0.0003	0.0006	-	-	-	-	0.0025	0.0003	0.0006
	2	0.0001	0.0005	-	0.0013	-	-	-	0.0001	0.0018
Inconel Filler Metal 72 on Incoloy 800H--GTAW-HW	1	0.0003	0.0005	-	0.0065	-	-	0.0005	0.0003	0.0070
	2	0.0001	0.0015	-	0.0030	-	-	0.0028	0.0001	0.0045
R139 Filler Metal on 304L SS--GMAW	1	0.0011	0.0015	0.0027	-	0.0032	0.0054	-	0.0043	0.0069
	2	0.0012	0.0015	0.0022	-	0.0025	0.0060	-	0.0037	0.0075
R139 Filler Metal on 304L SS--SAW	1	0.0012	0.0027	0.0022	-	0.0061	0.0056	-	0.0073	0.0083
	2	0.0007	0.0051	0.0021	-	0.0093	0.0063	-	0.0100	0.0114
R139 Filler Metal on 304L SS--GTAW-HW	1	0.0023	0.0045	0.0039	-	0.0039	0.0059	-	0.0062	0.0104
	2	0.0008	0.0020	0.0023	-	-	0.0080	-	0.0031	0.0100
R139 Filler Metal on 310 SS--GMAW	1	0.0001	0.0010	0.0011	-	-	0.0075	0.0062	0.0012	0.0085
	2	0.0004	0.0010	0.0019	0.0030	-	-	0.0064	0.0023	0.0040
R139 Filler Metal on 310 SS--SAW	1	0.0009	0.0008	0.0022	0.0022	-	-	0.0055	0.0031	0.0030
	2	0.0001	0.0010	0.0010	0.0021	-	-	0.0050	0.0011	0.0031
R139 Filler Metal on 310 SS--GTAW-HW	1	0.0005	0.0006	0.0020	0.0019	-	-	0.0052	0.0025	0.0025
	2	0.0007	0.0010	0.0020	0.0025	-	-	0.0042	0.0027	0.0035
R139 Filler Metal on Incoloy 800H--GMAW	1	0.0007	0.0005	0.0019	0.0025	-	-	0.0076	0.0026	0.0030
	2	0.0007	0.0008	0.0015	0.0027	-	-	-	0.0022	0.0035
R139 Filler Metal on Incoloy 800H--SAW	1	0.0003	0.0008	0.0012	0.0072	-	-	0.0098	0.0015	0.0080
	2	0.0006	0.0006	0.0021	0.0021	-	-	0.0044	0.0027	0.0027
R139 Filler Metal on Incoloy 800H--GTAW-HW	1	0.0008	0.0010	0.0020	0.0025	-	-	0.0060	0.0028	0.0035
	2	0.0008	0.0006	0.0023	0.0027	-	-	0.0075	0.0031	0.0033

[a]Single and double layers of weld filler metals were deposited on both surfaces of substrate specimens using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW). Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.07% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

[b]Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

[c]Measurements were made in microns and converted to inches. Exposed specimens were sectioned and polished but not descaled before measuring. Measurements were made in two ways. Values given in the A columns were obtained by measuring large weldment specimens at a single location corresponding as much as possible to a single referenced point. Due to the undulating weld surface there was some uncertainty about the location of some of the reference points with respect to the plane of polish that was frequently greater than the depth of attack. These values must be considered as approximate. Values given in the B columns are for maximum corrosion on small one-inch specimens. These measurements were made without regard to the original reference point. These values do not include any accounting for subscale Kirkendall porosity but do include all indications of corrosion as affected metal. The B column values are therefore generally greater than the A column values.

ELEMENTS IDENTIFIED[a] IN SCALE FORMED ON WELD OVERLAYS[b] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[c][8]

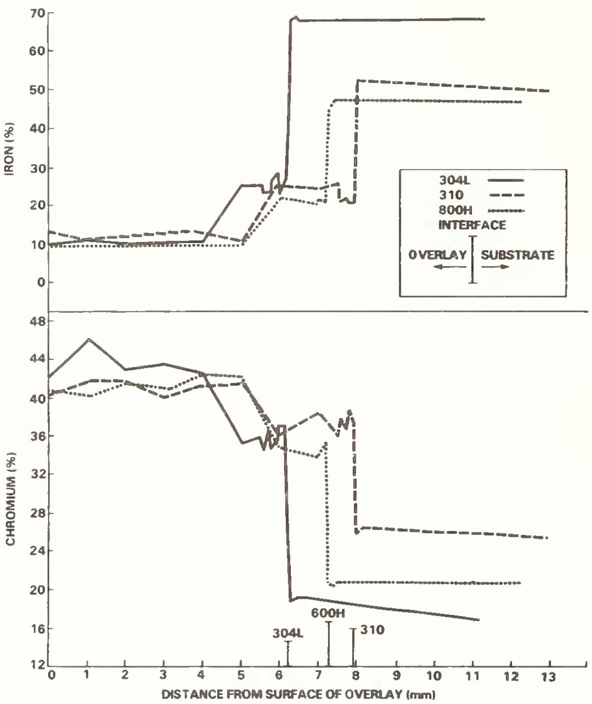
Weld Overlay[b]	Elements in Scale	Probable Scale Specie
AWS-ER309 Filler on 304L SS--GMAW	Cr, Fe, O, less Ni than overlay	Fe-Cr[d] spinel, Cr oxide under spinel
Inconel Filler Metal 72 on 304L SS--GTAW-HW	High Cr, O, some Ti, no Fe or Ni	Cr_2O_3 + Ti
Inconel Filler Metal 72 on 310 SS--SAW	Cr, O, no Fe, Ni, or Ti	Cr_2O_3
Inconel Filler Metal 72 on Incoloy 800H--GMAW	Cr, O, some Ti, no Fe or Ni	Cr_2O_3 + Ti
R139 Filler Metal on 304L SS--GTAW-HW	Al, Cr, O, some Fe and Ti, no Ni; Al in lower part of scale	Cr_2O_3 and Al_2O_3
R139 Filler Metal on 310 SS--SAW	Cr, O, trace of Ti, Al, Si, and Fe	Cr_2O_3
R139 Filler Metal on Incoloy 800H--GMAW	Cr, Al, O, some Fe and Ni	Cr_2O_3, Al_2O_3

[a]Identification by x-ray scanning of scale.

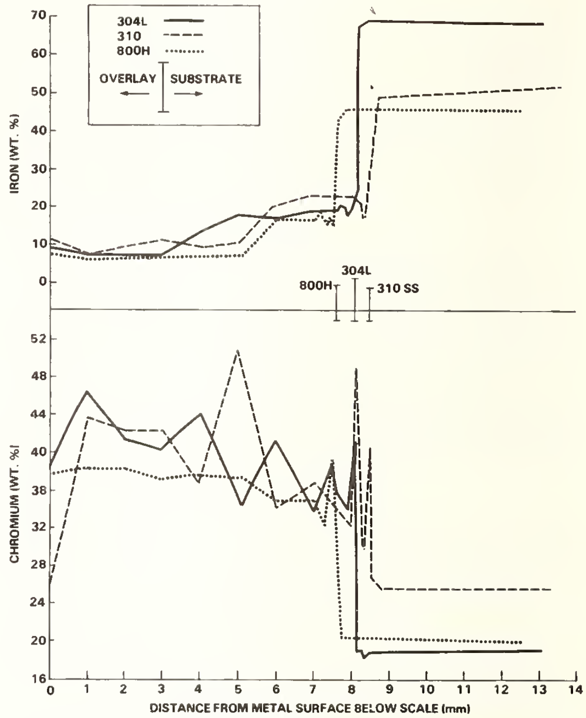
[b]Single and double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW). Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

[c]Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

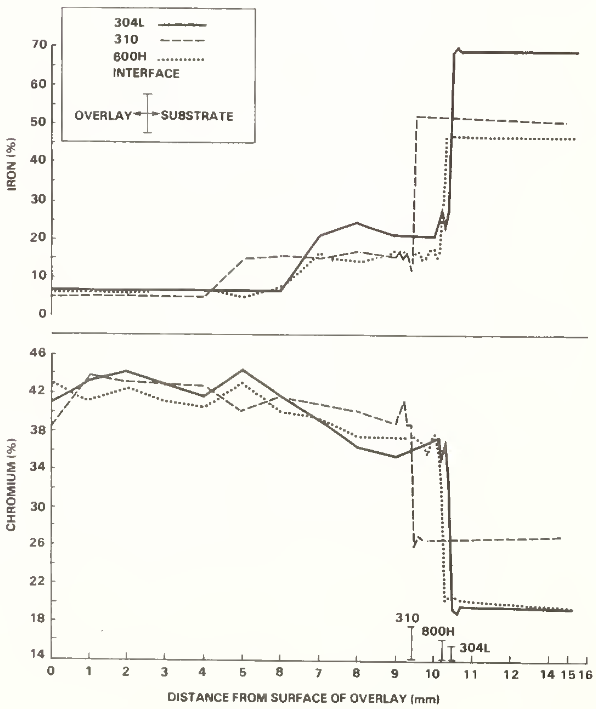
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE SUBSTRATE AFTER EXPOSURE IN COAL GASIFICATION ATMOSPHERE[c][8]



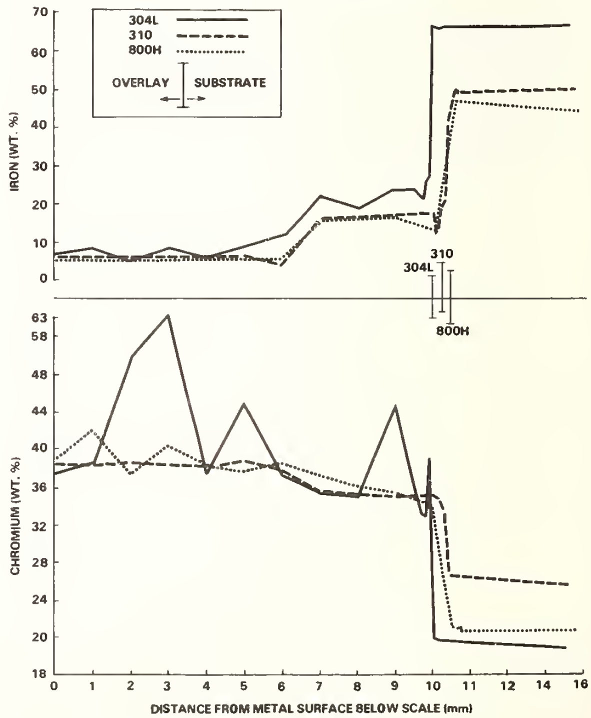
Inconel Filler 72--GMAW, as welded



Inconel Filler 72--GMAW, exposed



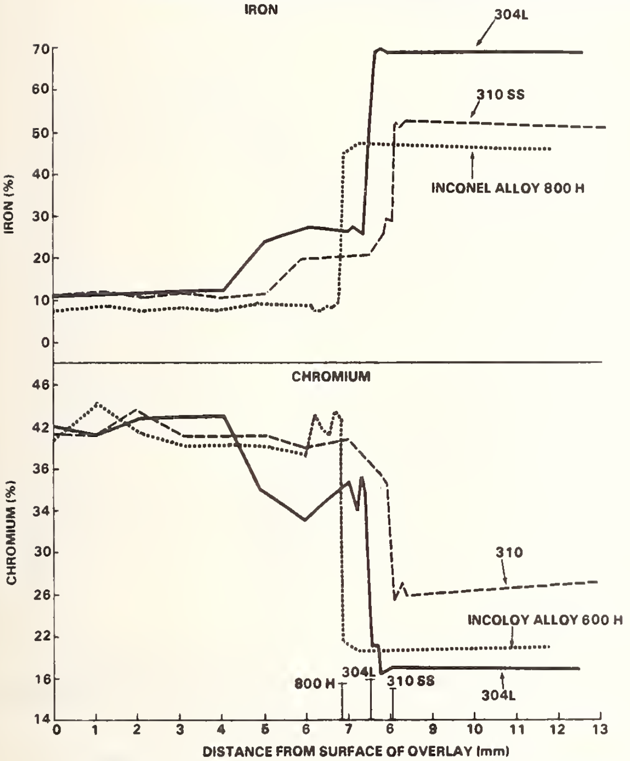
Inconel Filler 72--SAW, as welded



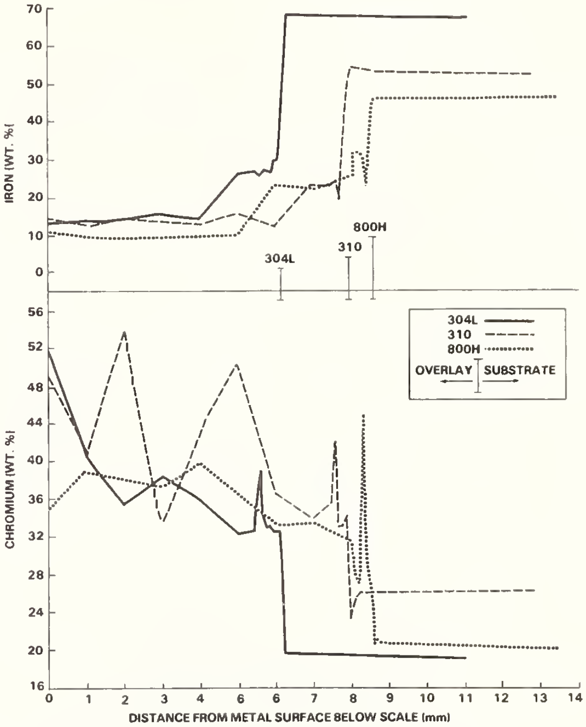
Inconel Filler 72--SAW, exposed

(Continued)

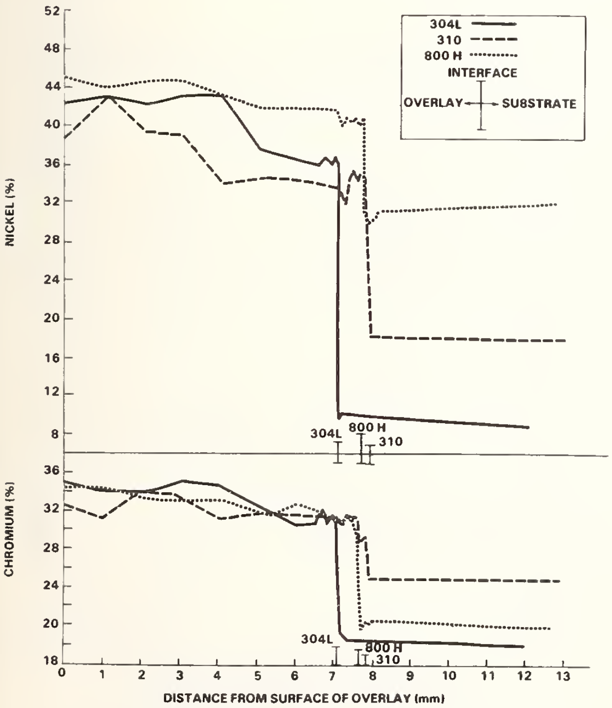
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE SUBSTRATE AFTER EXPOSURE IN COAL GASIFICATION ATMOSPHERE[c][8], Continued



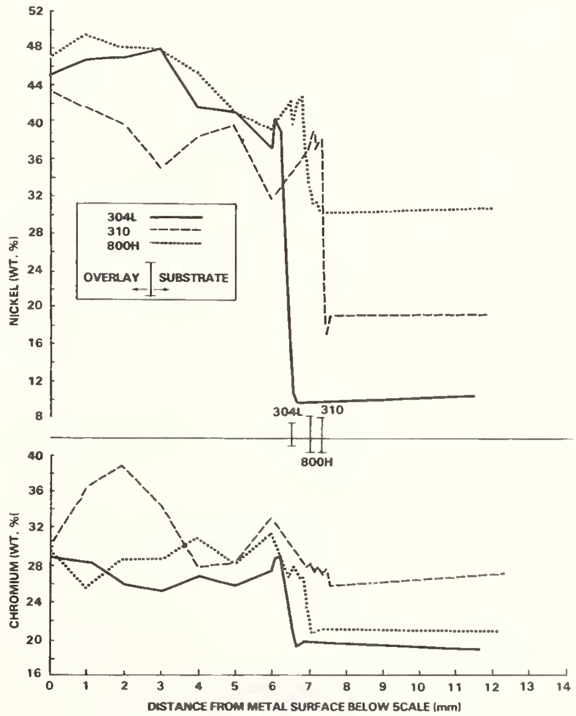
Inconel Filler 72--GTAW-HW, as welded



Inconel Filler 72--GTAW, exposed



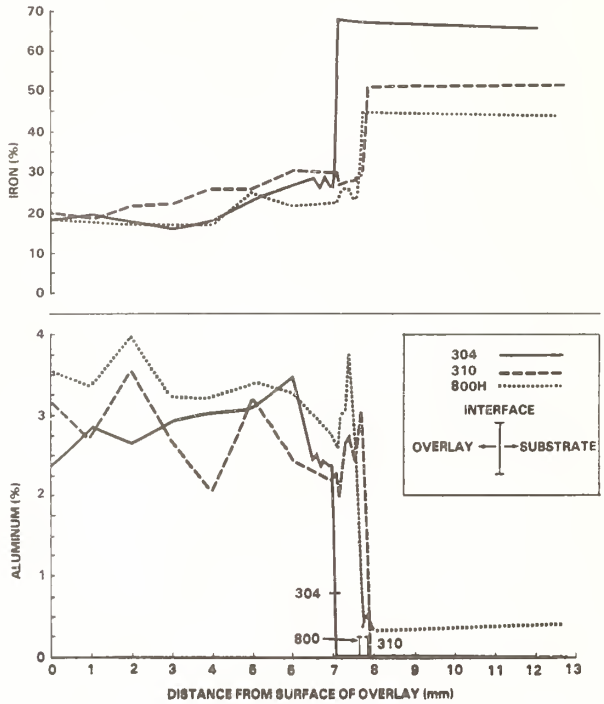
R139 Filler--GMAW, as welded



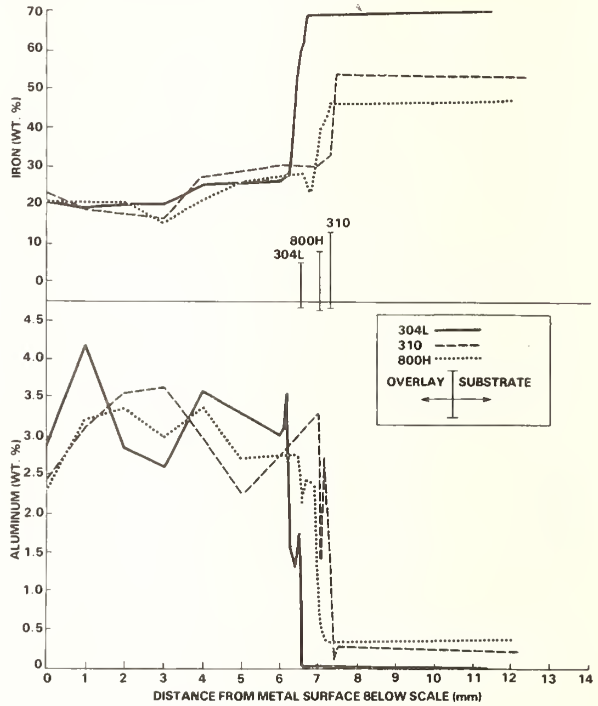
R139 Filler--GMAW, exposed

(Continued)

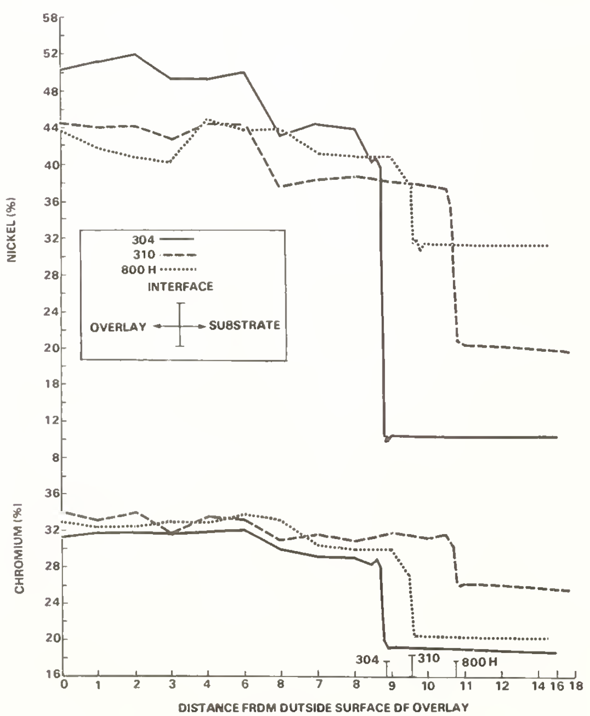
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE SUBSTRATE AFTER EXPOSURE IN COAL GASIFICATION ATMOSPHERE[c][8], Continued



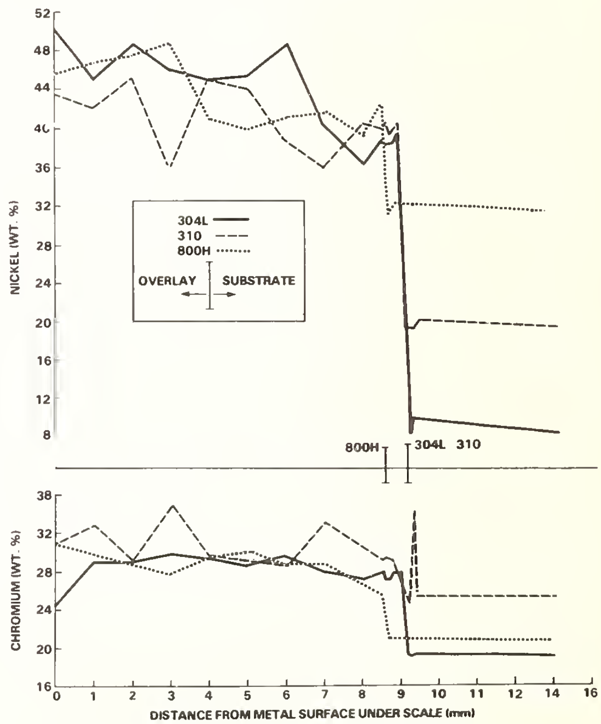
R139 Filler--GMAW, as welded



R139 Filler--GMAW, exposed



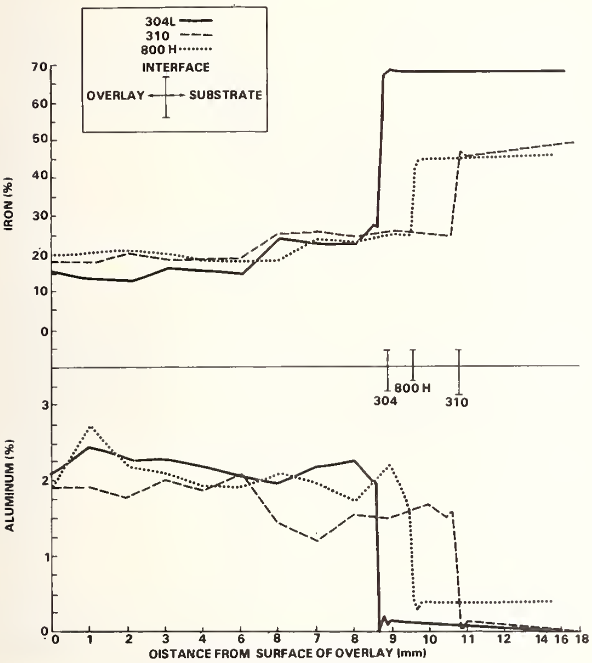
R139 Filler--SAW, as welded



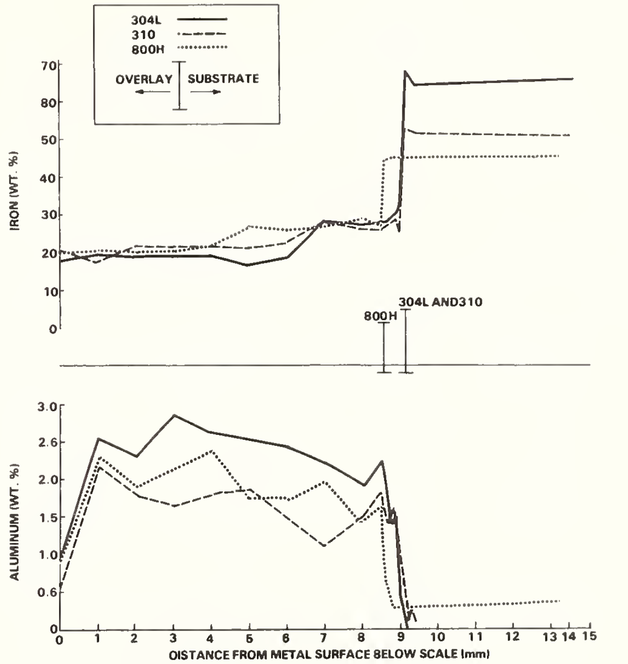
R139 Filler--SAW, exposed

(Continued)

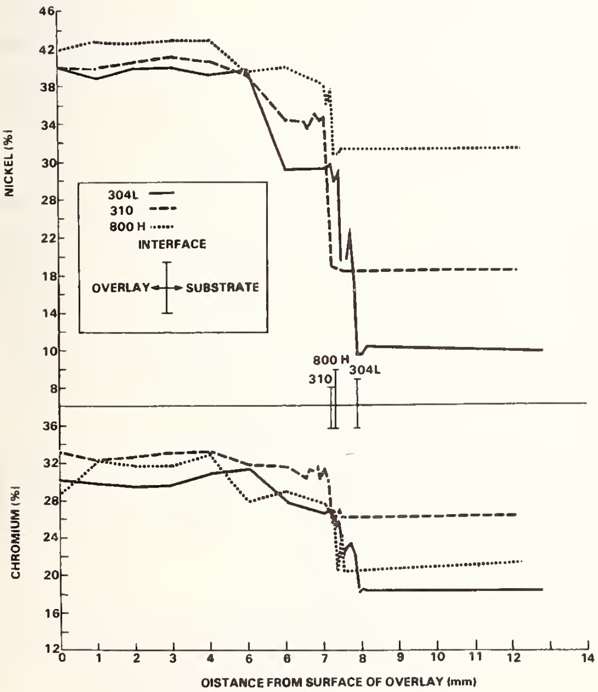
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE SUBSTRATE AFTER EXPOSURE IN COAL GASIFICATION ATMOSPHERE[c][8], Continued



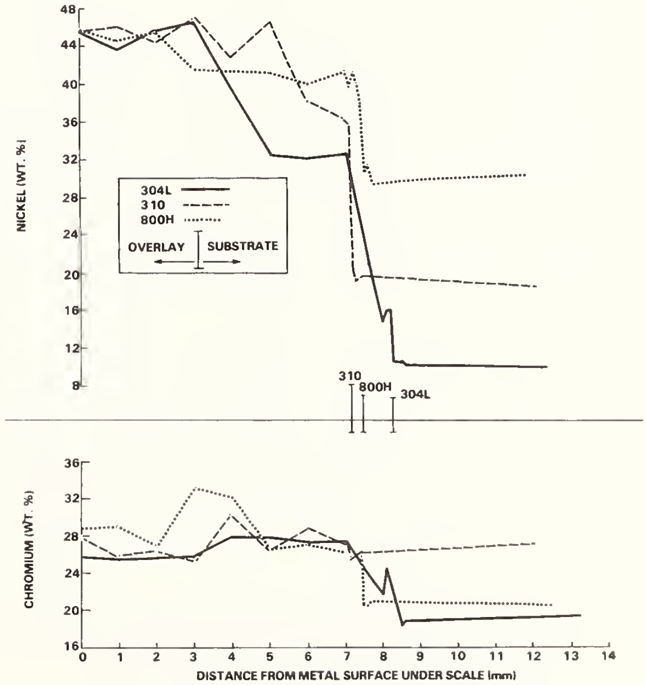
R139 Filler--SAW, as welded



R139 Filler--SAW, exposed



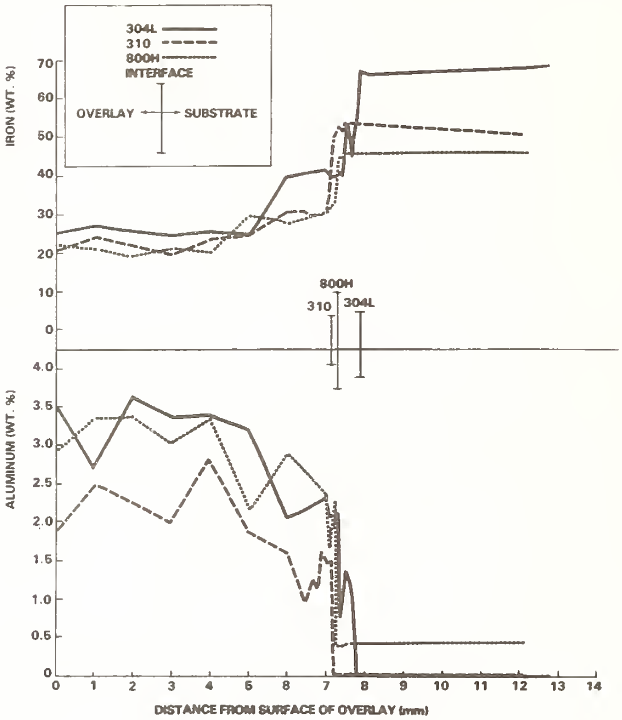
R139 Filler--GTAW-HW, as welded



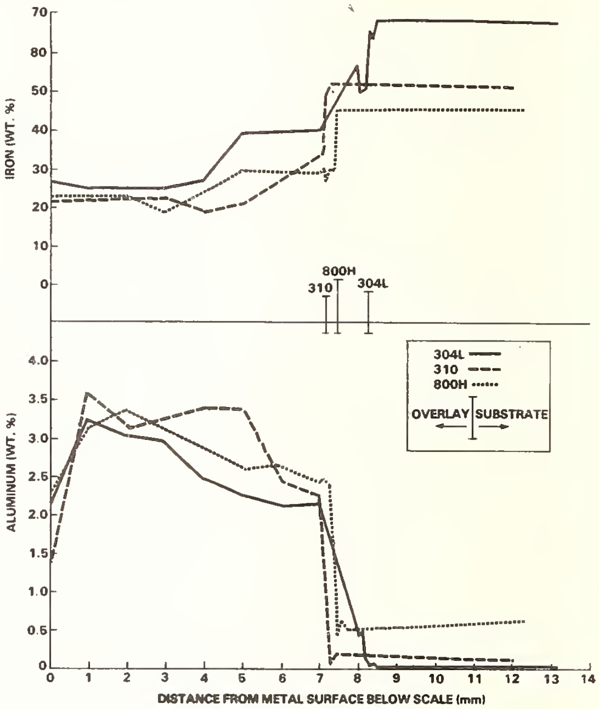
R139 Filler--GTAW-HW, exposed

(Continued)

EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE SUBSTRATE AFTER EXPOSURE IN COAL GASIFICATION ATMOSPHERE[c][8], Continued



R139 Filler--GTAW-HW, as welded



R139 Filler--GTAW-HW, exposed

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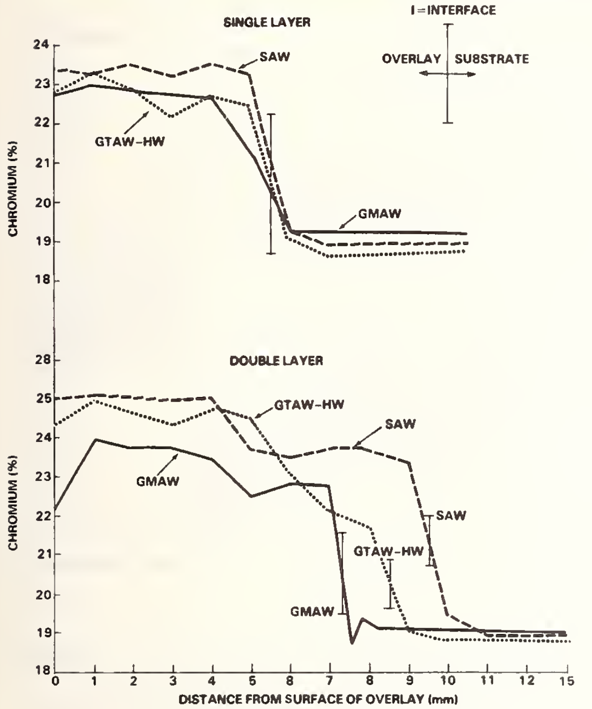
[a]Distribution of selected elements was determined on cross-sections of weldments using an electron probe microanalyzer. Concentrations were measured from about 0.025mm below the surface at 1 mm intervals to a point just before the apparent fusion line, then in 0.1 mm intervals to an arbitrary distance just beyond the fusion line, and finally in the substrate about 5 mm from the fusion line. A point counting technique was used. NOTE: differences in the location of the interface of overlay and substrate before and after exposure should not be attributed to the exposure since measurements were not made on the same specimen. Also, measurements after exposure were made with the scale-metal interface used as the reference point, which could be considerably different from the original "as welded" surface depending on the degree of scaling and metal loss. Comparison of "before" and "after" composition profiles should emphasize major changes only.

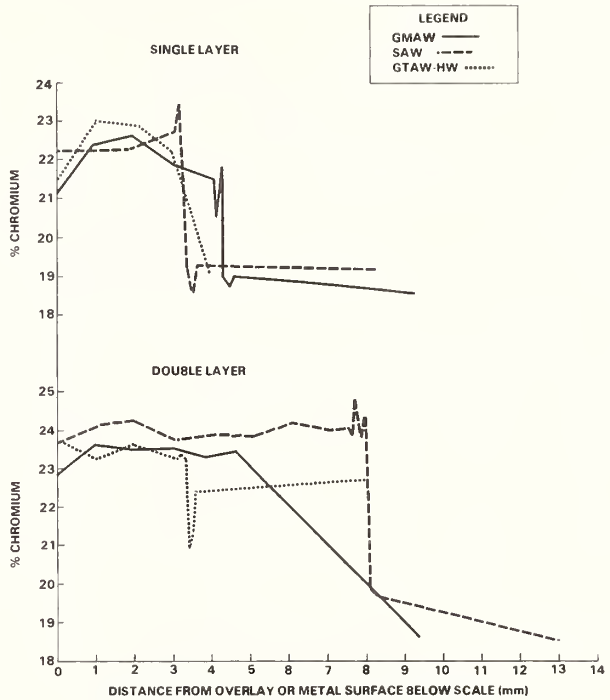
[b]Double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW). Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al. The substrates are 304L SS, 310 SS, and Inconel 800H.

[c]Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

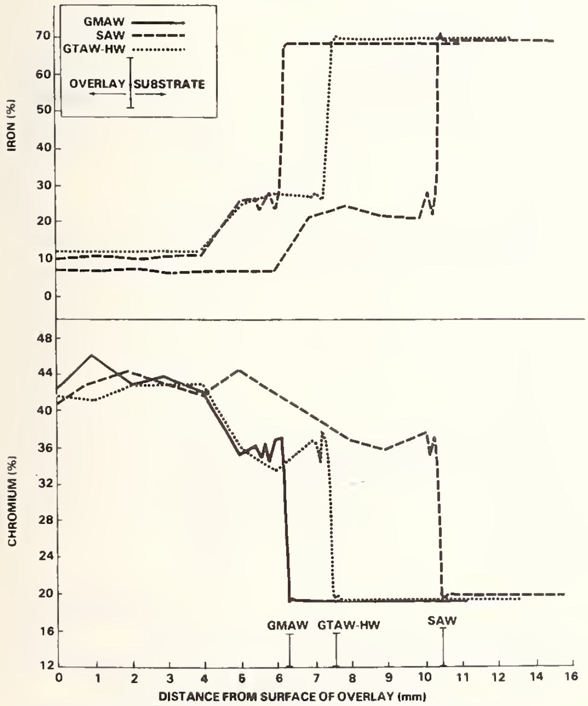
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE WELD PROCESS[c] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[d][8]



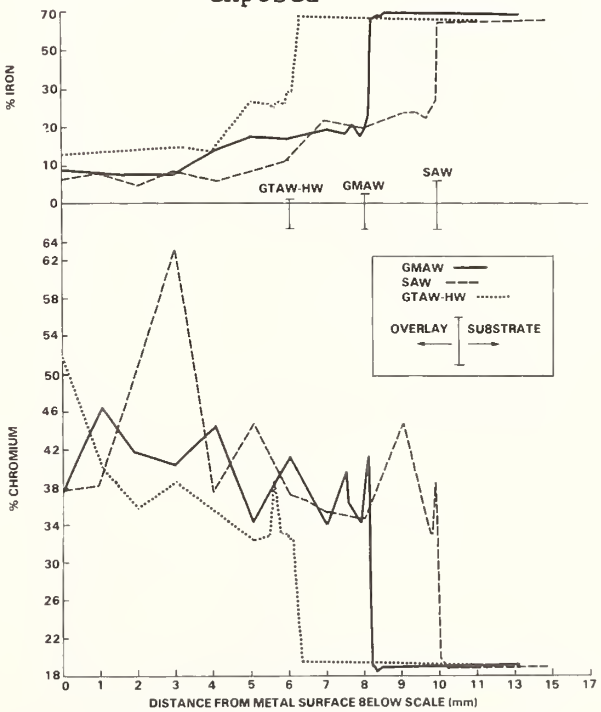
AWS-ER309 Filler on 304L SS, as welded



AWS-ER309 Filler on 304L SS, exposed



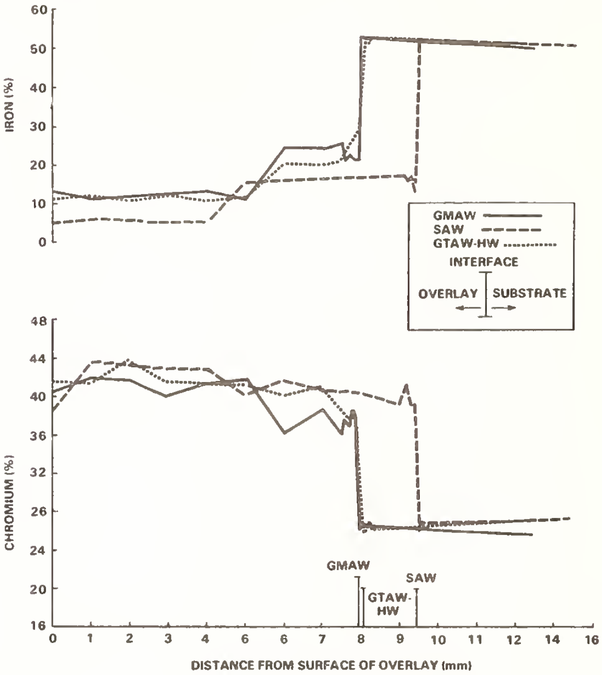
Inconel Filler 72 on 304L SS, as welded



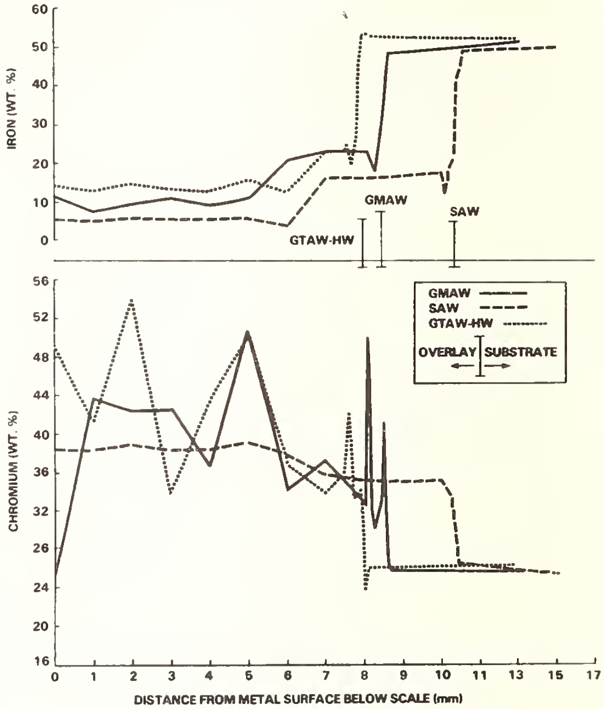
Inconel Filler 72 on 304L SS, exposed

(Continued)

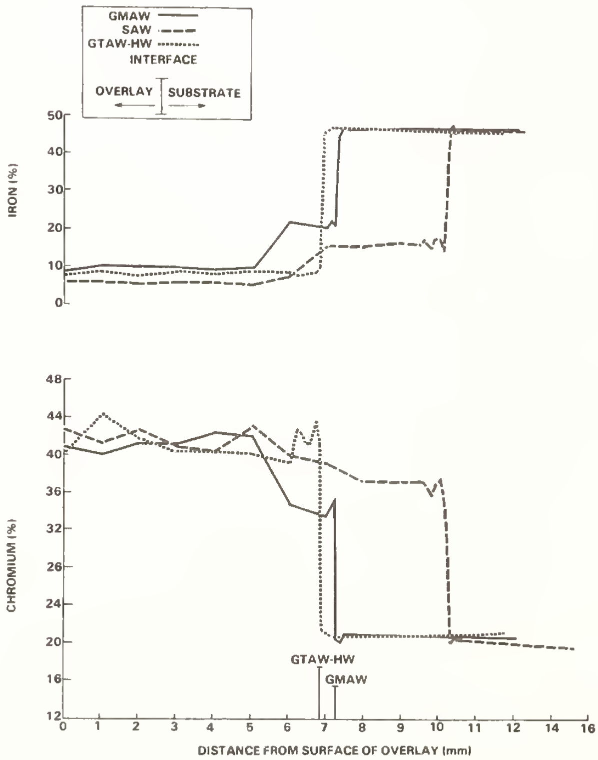
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE WELD PROCESS[c] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[d][8], Continued



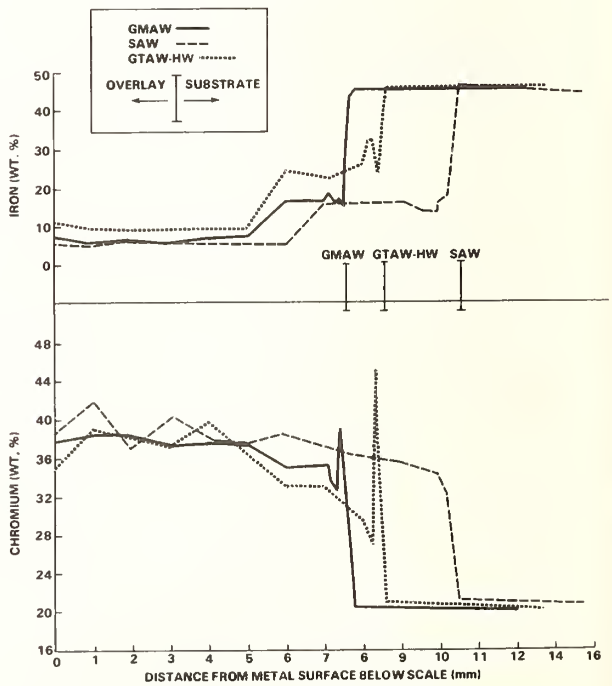
Inconel Filler 72 on 310 SS, as welded



Inconel Filler 72 on 310 SS, exposed



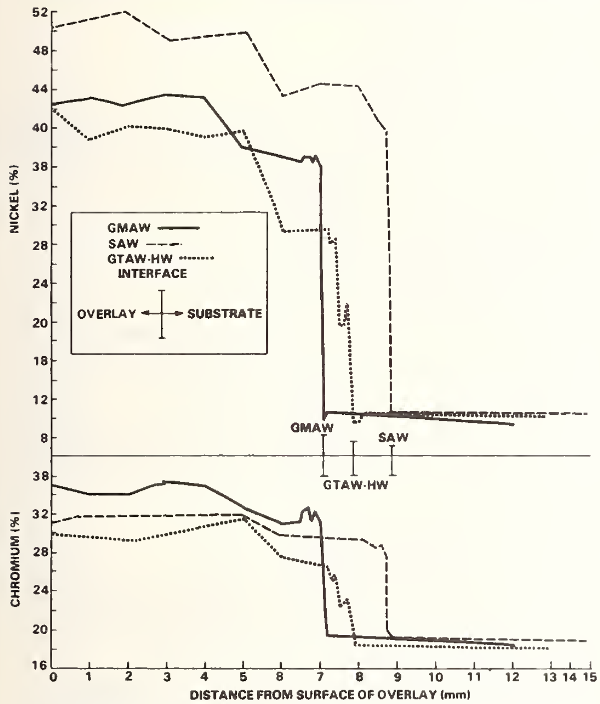
Inconel Filler 72 on Incoloy 800H, as welded



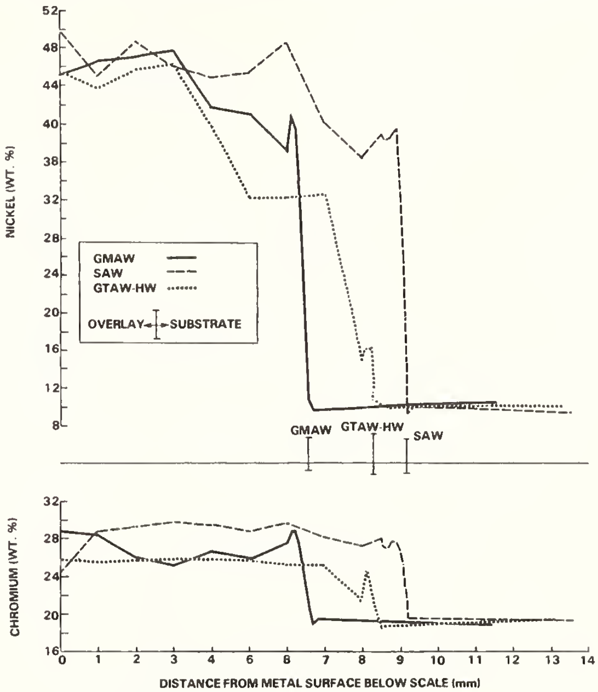
Inconel Filler 72 on Incoloy 800H, exposed

(Continued)

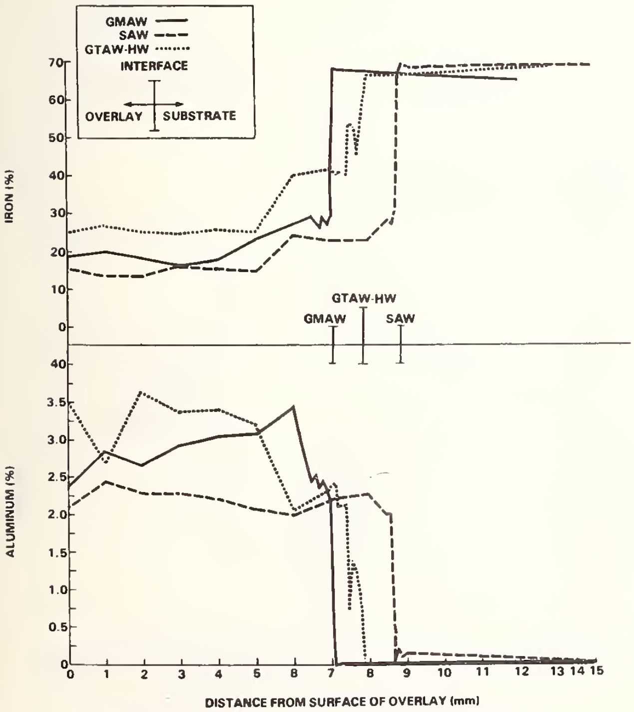
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE WELD PROCESS[c] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[d][8], Continued



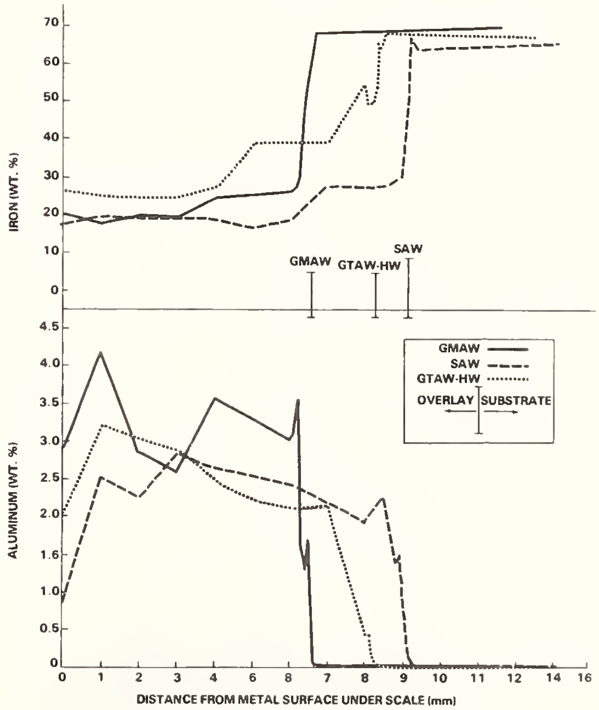
R139 Filler on 304L SS, as welded



R139 Filler on 304L, exposed



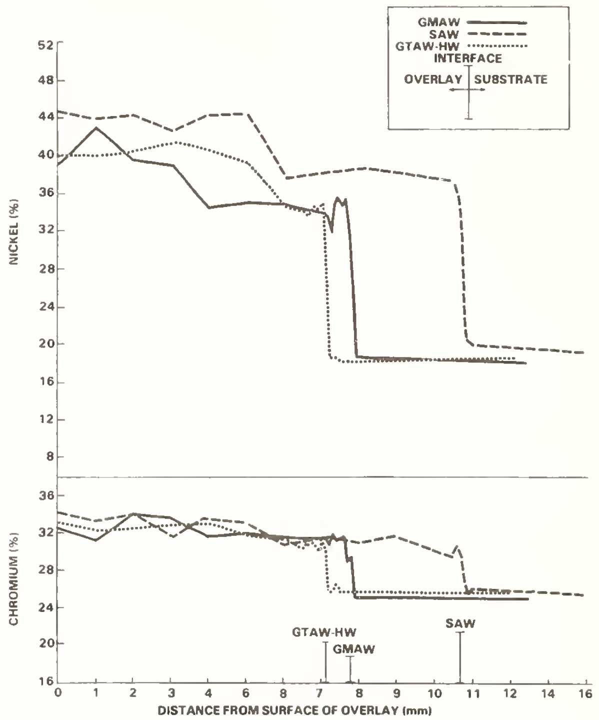
R139 Filler on 304L, as welded



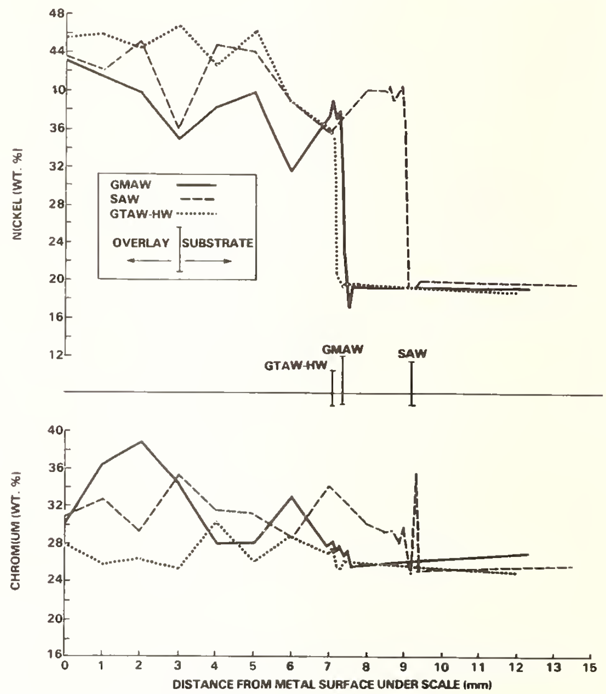
R139 Filler on 304L, exposed

(Continued)

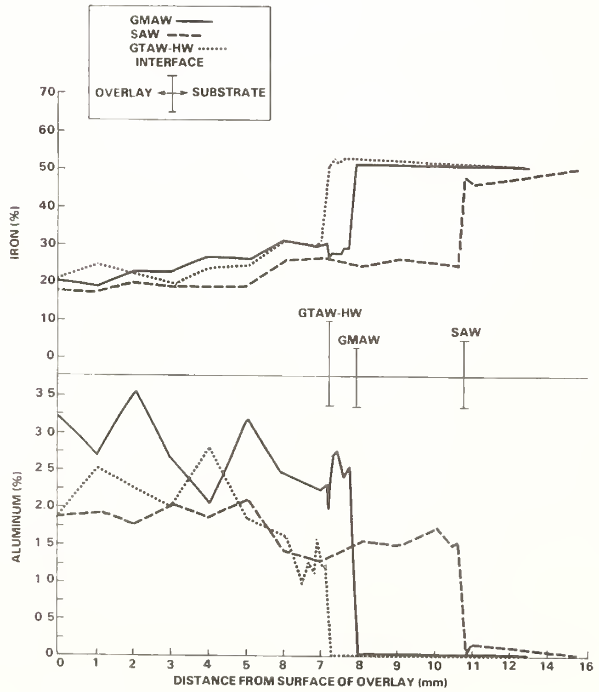
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE WELD PROCESS[c] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[d][8], Continued

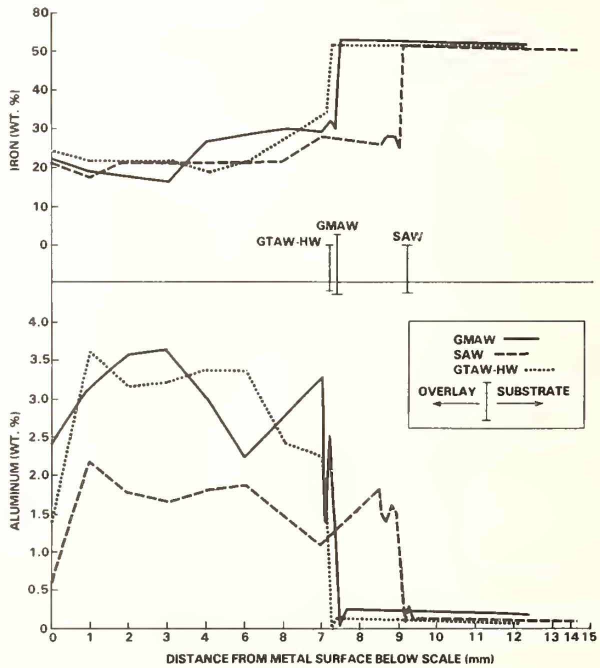


R139 Filler on 310 SS, as welded



R139 Filler on 310 SS, exposed

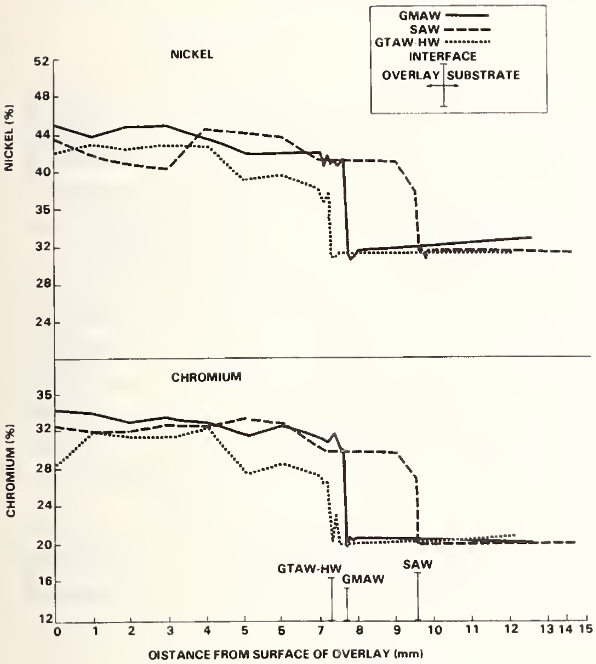




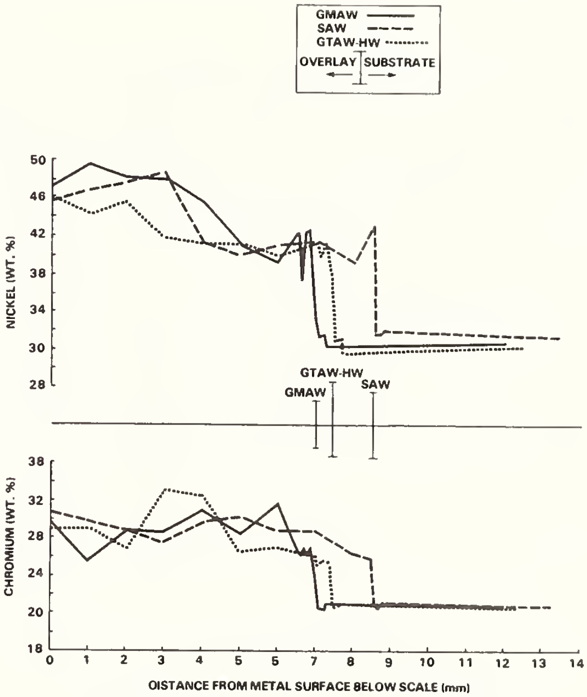
R139 Filler on 310 SS, as welded R139 Filler on 310 SS, exposed

(Continued)

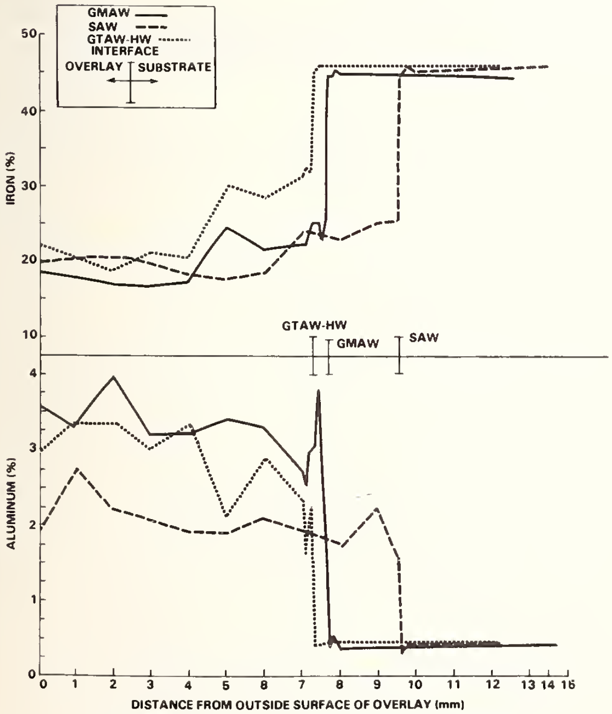
EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE WELD PROCESS[c] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[d][8], Continued



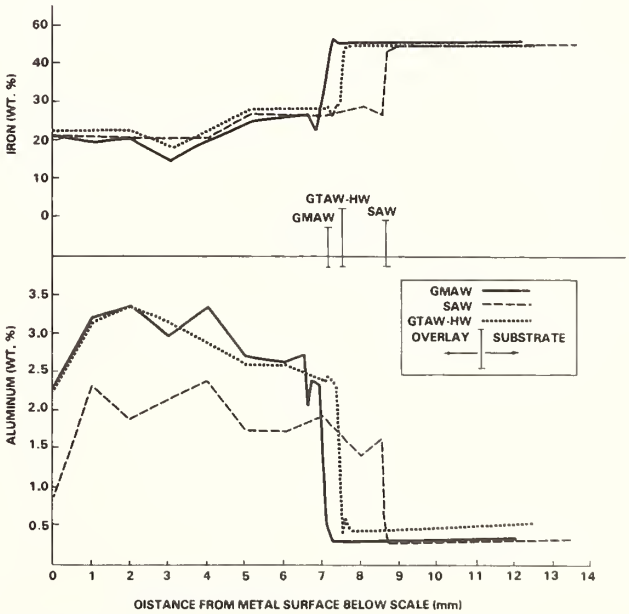
R139 Filler on Incoloy 800H, as welded



R139 Filler on Incoloy 800H, exposed



R139 Filler on Incoloy 800H, as welded



R139 Filler on Incoloy 800H, exposed

(Continued)

EFFECT ON ELEMENTAL DISTRIBUTION[a] IN WELD OVERLAYS[b] OF THE WELD PROCESS[c] AFTER EXPOSURE TO A SIMULATED COAL GASIFICATION ATMOSPHERE[d][8], Continued

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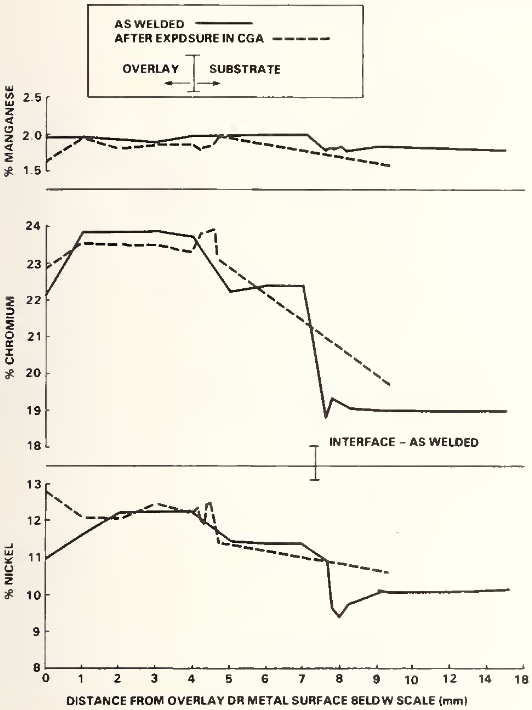
[a]Distribution of selected elements was determined on cross-sections of weldments using an electron probe microanalyzer. Concentrations were measured from about 0.025 mm below the surface at 1 mm intervals to a point just before the apparent fusion line, then in 0.1 mm intervals to an arbitrary distance just beyond the fusion line, and finally in the substrate about 5 mm from the fusion line. A point counting technique was used. NOTE: differences in the location of the interface of overlay and substrate before and after exposure should not be attributed to the exposure since measurements were not made on the same specimen. Also, measurements after exposure were made with the scale-metal interface used as the reference point, which could be considerably different from the original "as welded" surface depending on the degree of scaling and metal loss. Comparison of "before" and "after" composition profiles should emphasize major changes only.

[b]All of the overlays consist of double layers except for AWS-ER309 Filler on 304L SS where results are given for both single and double layers. Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

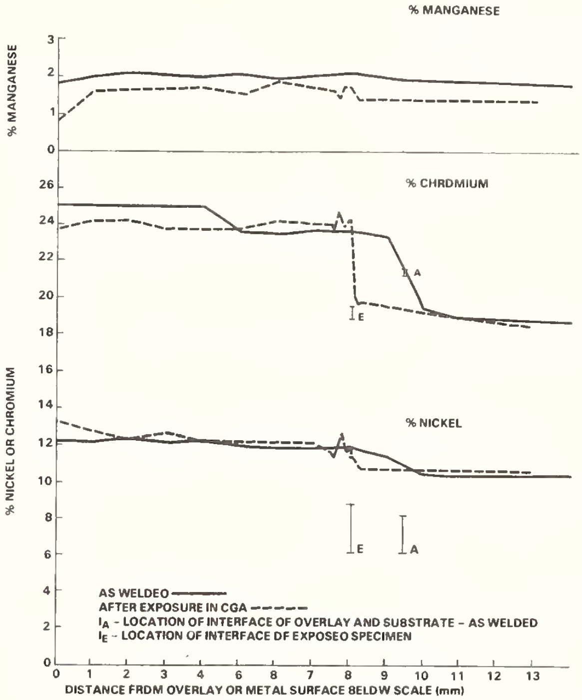
[c]Three weld processes were used: SAW = submerged arc, GMAW = gas metal arc, GTAW-HW = gas tungsten arc with a hot wire addition.

[d]Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

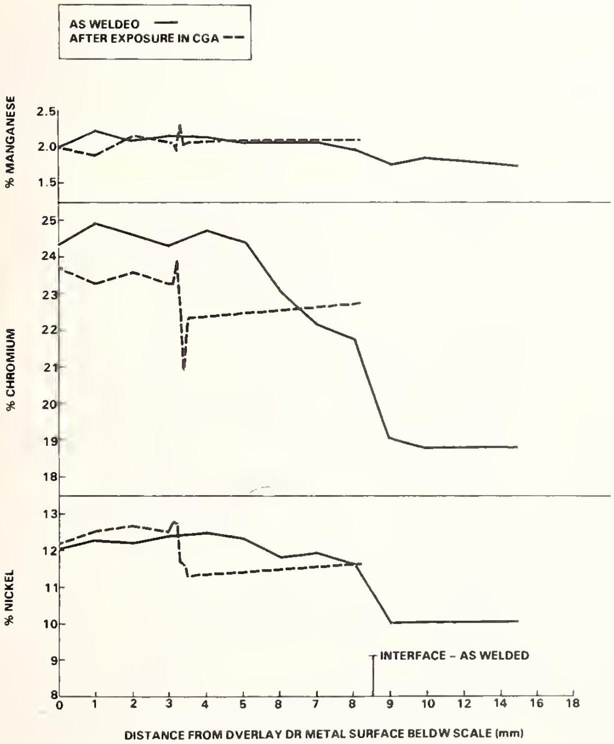
EFFECT OF A COAL GASIFICATION EXPOSURE[a] ON THE DISTRIBUTION[b] OF VARIOUS ELEMENTS IN WELD OVERLAYS[c][8]



AWS-ER309 Filler on 304L SS--GMAW



AWS-ER309 Filler on 304L SS--SAW

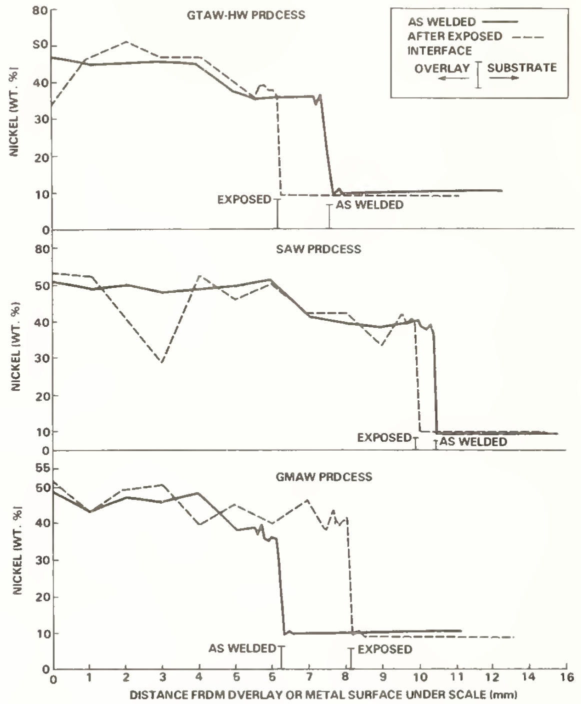


AWS-ER309 Filler

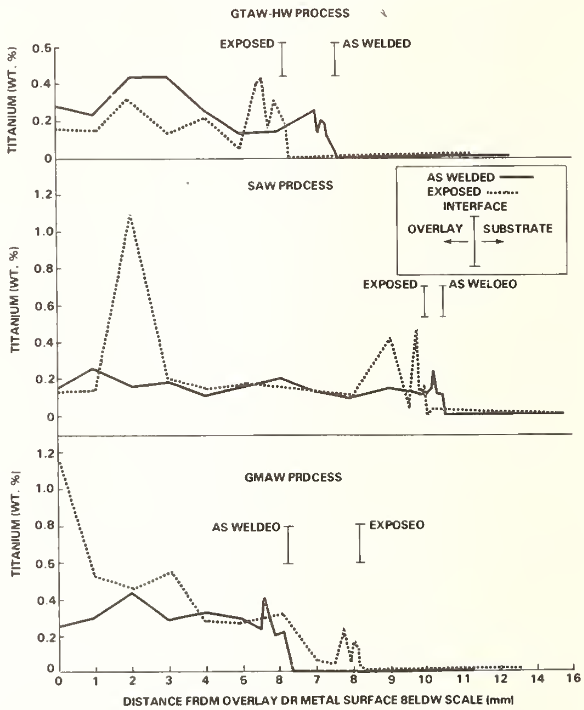
on 304L SS--GTAW-HW

(Continued)

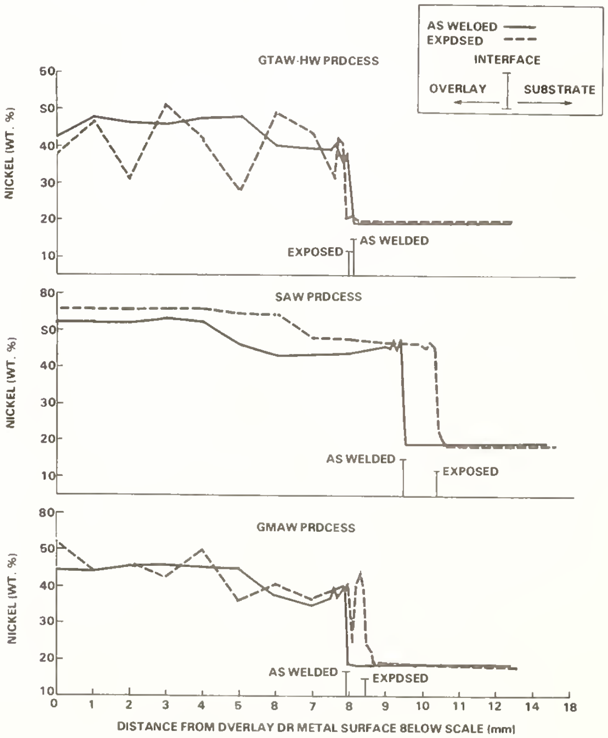
EFFECT OF A COAL GASIFICATION EXPOSURE[a] ON THE DISTRIBUTION[b] OF VARIOUS ELEMENTS IN WELD OVERLAYS[c][8], Continued



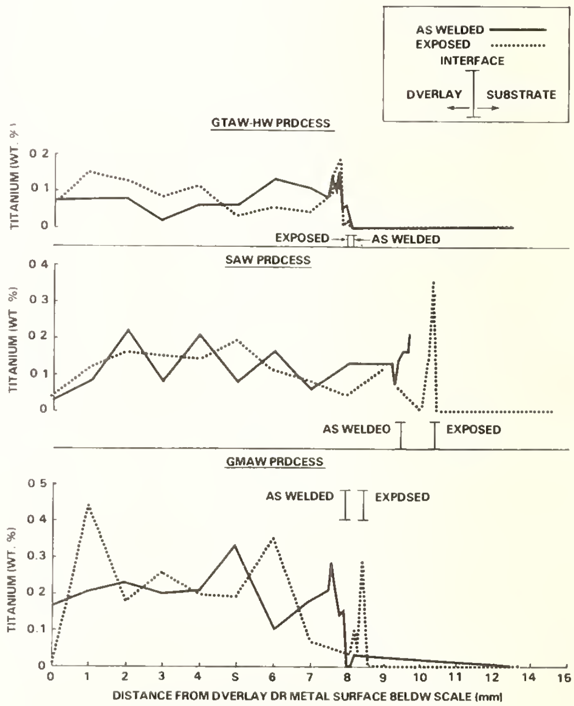
Inconel Filler 72 on 304L SS



Inconel Filler 72 on 304L SS



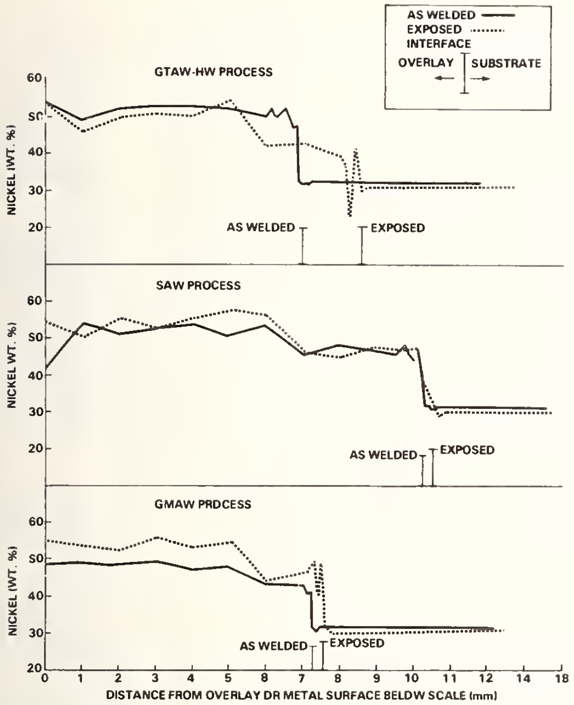
Inconel Filler 72 on 310 SS



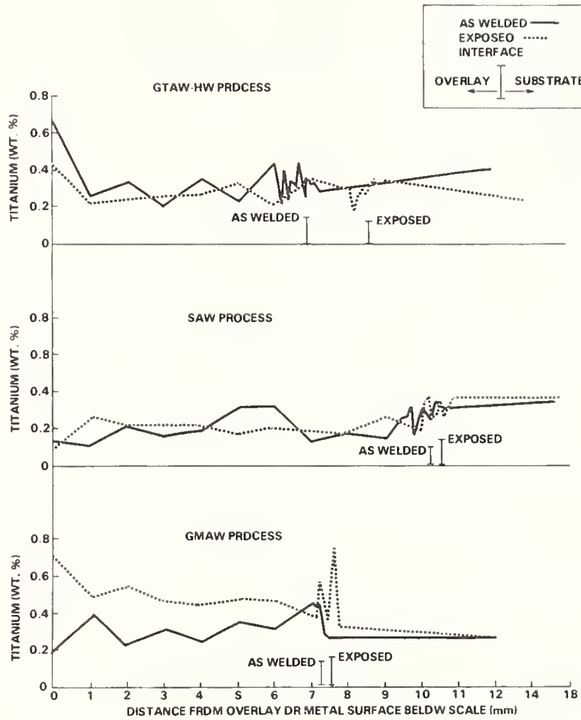
Inconel Filler 72 on 310 SS

(Continued)

EFFECT OF A COAL GASIFICATION EXPOSURE[a] ON THE DISTRIBUTION[b] OF VARIOUS ELEMENTS IN WELD OVERLAYS[c][8], Continued



Inconel Filler 72 on Incoloy 800H



Inconel Filler 72 on Incoloy 800H

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[a] Specimens were exposed to a simulated coal gasification atmosphere (CGA) for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

[b] Distribution of selected elements was determined on cross-sections of weldments using an electron probe microanalyzer. Concentrations were measured from about 0.025 mm below the surface at 1 mm intervals to a point just before the apparent fusion line, then in 0.1 mm intervals to an arbitrary distance just beyond the fusion line, and finally in the substrate about 5 mm from the fusion line. A point counting technique was used. NOTE: differences in the location of the interface of overlay and substrate before and after exposure should not be attributed to the exposure since measurements were not made on the same specimen. Also, measurements after exposure were made with the scale-metal interface used as the reference point, which could be considerably different from the original "as welded" surface depending on the degree of scaling and metal loss. Comparison of "before" and "after" composition profiles should emphasize major changes only.

[c] Double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW). Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

CORROSION-PRODUCT ANALYSIS[a] OF ALLOY SPECIMENS[b] AFTER EXPOSURE[c] TO COAL GASIFICATION ATMOSPHERES[d][30]

	750 °C (1382 °F)			871 °C (1600 °F)			982 °C (1800 °F)		
Alloy[b]	Scale Thickness μm	Depth Of Penetration μm	Type of Scale	Scale Thickness μm	Depth of Penetration μm	Type of Scale	Scale Thickness μm	Depth of Penetration μm	Type of Scale
Atmosphere No. 1 (input gas, vol. %): CO 11.7, CO_2 15.4, CH_4 10.0, H_2 13.0, H_2O 48.9, H_2S 1.0[d]									
USS 18-18-2	63.8	31.9	Cr/Fe sulfide	--	--	Sulfide	12.3	73.8	Cr oxide/Si oxide
INCOLOY 800	6.0	16.0	Cr-rich oxide	--	--	Sulfide	20.0	114.3	Cr oxide/sulfide
310 SS	6.3	5.0	Cr-rich oxide	34.0	68.6	(Cr,Mn) oxide	18.5	98.5	Cr oxide/sulfide
INCONEL 671	3.1	13.8	Cr oxide	22.8	57.1	(Cr,Ni) sulfide	6.2	100.2	Cr oxide
Atmosphere No. 2 (input gas, vol. %): CO 17.3, CO_2 11.5, CH_4 10.0, H_2 23.0, H_2O 37.2, H_2S 1.0[d]									
USS 18-18-2	7.1	20.5	Cr oxide/sulfide				710.2	580.6	Cr oxide, Fe sulfide
INCOLOY 800	15.0	30.8	Cr-rich oxide	694.0	764.0	(Fe,Ni) sulfide	416.7	335.1	Cr/(Cr,Fe) sulfide
310 SS	4.7	23.5	Cr oxide/sulfide				310.9	532.7	Cr sulfide
INCONEL 671	3.5	18.8	Cr oxide	25.6	410.0	Cr sulfide	7.1	113.6	Cr oxide
Atmosphere No. 3 (input gas, vol. %): CO 26.0, CO_2 14.9, CH_4 10.0, H_2 26.0, H_2O 22.1, H_2S 1.0[d]									
USS 18-18-2	43.1	30.8	Fe/(Fe,Ni) sulfide	--	--		20	347	Cr oxide
INCOLOY 800	10.0	26.7	Cr-rich oxide	16.7	50	Cr sulfide	533	367	(Cr,Fe) sulfide/ Cr oxide
310 SS	5.7	20.0	Cr-rich oxide	--	--		21	253	Cr oxide
INCONEL 671	29.5	18.9	Cr sulfide/(Cr,Ni) sulfide	4.5	16	Cr-rich oxide	78	267	Cr oxide
Atmosphere No. 4 (input gas, vol. %): CO 9.1, CO_2 12.0, CH_4 30.0, H_2 10.0, H_2O 37.9, H_2S 1.0[d]									
USS 18-18-2	160.0	91.4	Fe sulfide	--	--	Cr sulfide			
INCOLOY 800	235.3	258.9	(Cr,Fe) sulfide	50	212.5	Fe sulfide			
310 SS	196.9	141.5	(Cr,Ni) sulfide	586	759	(Fe,Cr) sulfide			
INCONEL 671	20.0	42.5	Cr sulfide	--	--				
Atmosphere No. 5 (input gas, vol. %): CO 13.4, CO_2 8.9, CH_4 30.0, H_2 17.8, H_2O 28.9, H_2S 1.0[d]									
USS 18-18-2	180	43	Fe sulfide						
INCOLOY 800	130	140	(Cr,Fe) sulfide						
310 SS	35	147	(Cr,Fe) sulfide						
INCONEL 671	133	71	Cr sulfide						
Atmosphere No. 6 (input gas, vol. %): CO 20.1, CO_2 11.5, CH_4 30.0, H_2 20.1, H_2O 17.3, H_2S 1.0[d]									
USS 18-18-2	125	32	Fe sulfide/Cr oxide	67	133	Cr sulfide			
INCOLOY 800	118	150	(Fe,Cr) sulfide/ Cr oxide	40	107	Cr sulfide			
310 SS	95	158	Cr-Fe-Ni sulfide	133	80	(Cr,Fe) sulfide			
INCONEL 671	116	126	Cr-Ni sulfide	9	11	Cr sulfide			

[a]Cross-sections of exposed specimens were examined by scanning-electron microscopy and energy-dispersive x-ray analysis to determine the type of scale, its thickness, and the depth of penetration.

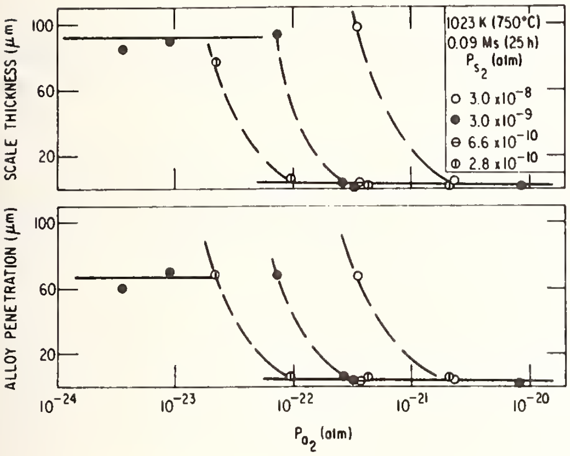
[b]Alloy compositions in weight percent: USS 18-18-2, 18.5 Cr, 17.8 Ni, 0.06 C, 0.011 S, 1.25 Mn, 2.05 Si, balance Fe; Incoloy 800, 21 Cr, 32.5 Ni, 0.05 C, 0.008 S, 0.75 Mn, 0.35 Si, 0.38 Al, 0.38 Ti, 46.0 Fe; 310 SS, 25 Cr, 20 Ni, 0.25 C, 1.5 Mn, 0.4 Si, balance Fe; Inconel 671, 48 Cr, 50 Ni, 0.05 C, 0.35 Ti.

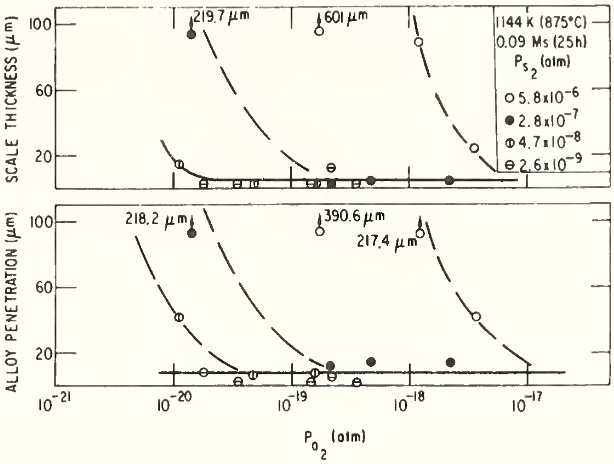
[c]Specimens were exposed to the given atmospheres for 1000 hours at 1 atm pressure at the indicated temperatures.

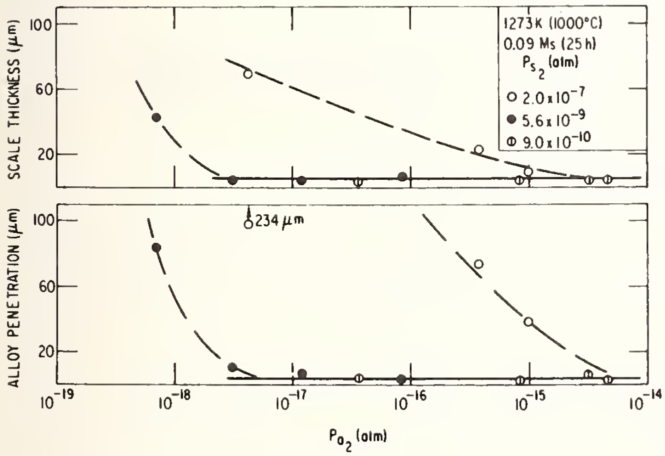
[d]Coal gasification atmospheres:

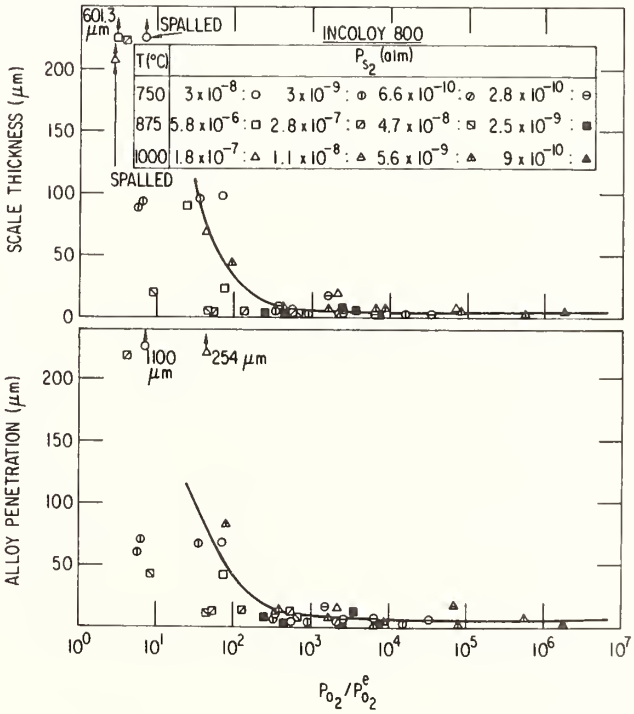
	P_{O_2}, atm			P_{S_2}, atm			a_C		
	750 °C	871 °C	982 °C	750 °C	871 °C	982 °C	750 °C	871 °C	982 °C
Atmosphere No. 1:	$1.7x10^{-20}$	$1.1x10^{-17}$	$1.3x10^{-15}$	$3.8x10^{-8}$	$4.0x10^{-7}$	$2.4x10^{-6}$	0.056	0.010	0.003
Atmosphere No. 2:	$5.9x10^{-21}$	$3.6x10^{-18}$	$4.5x10^{-16}$	$2.7x10^{-8}$	$2.7x10^{-7}$	$1.5x10^{-6}$	0.125	0.023	0.006
Atmosphere No. 3:	$2.2x10^{-21}$	$1.4x10^{-18}$	$1.8x10^{-16}$	$2.9x10^{-8}$	$2.8x10^{-7}$	$1.6x10^{-6}$	0.325	0.056	0.014
Atmosphere No. 4:	$6.7x10^{-22}$	$3.2x10^{-19}$	$3.9x10^{-17}$	$9.9x10^{-9}$	$8.7x10^{-8}$	$4.8x10^{-7}$	0.487	0.096	
Atmosphere No. 5:	$1.9x10^{-22}$	$5.0x10^{-20}$	$5.4x10^{-18}$	$9.7x10^{-9}$	$7.6x10^{-8}$	$4.1x10^{-7}$	1.0		
Atmosphere No. 6:	$1.9x10^{-22}$	$4.9x10^{-21}$	$4.2x10^{-20}$	$1.1x10^{-8}$	$8.6x10^{-8}$	$4.4x10^{-7}$	1.0	1.0	

SCALE THICKNESS AND PENETRATION DEPTH[a] VS OXYGEN PARTIAL PRESSURE[b] FOR INCOLOY 800[c] EXPOSED TO MIXED GAS ENVIRONMENTS[d][30]









(Continued)

SCALE THICKNESS AND PENETRATION DEPTH[a] VS OXYGEN PARTIAL PRESSURE[b] FOR INCOLOY 800[c] EXPOSED TO MIXED GAS ENVIRONMENTS[d][30], Continued

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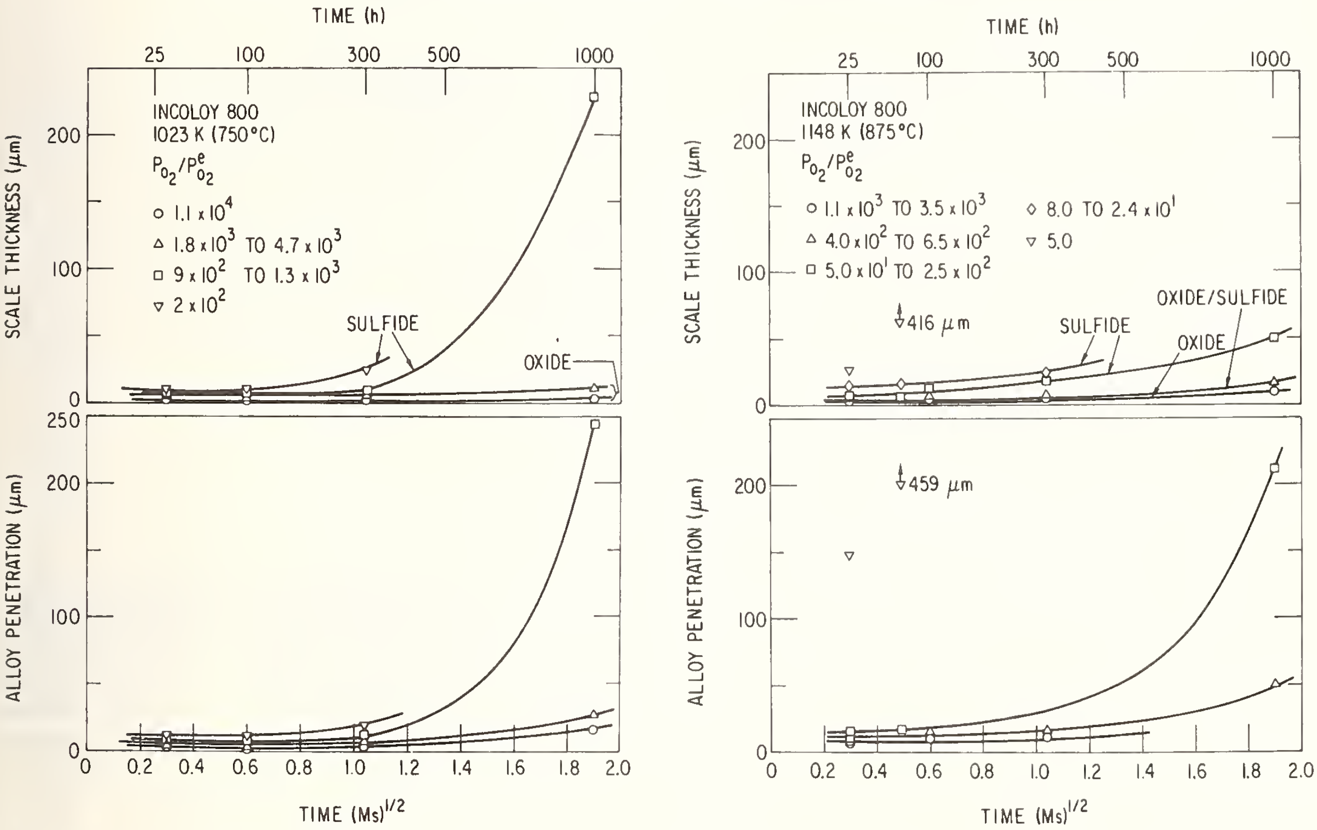
[a]Scale thickness and alloy penetration depth obtained by examining cross-sections of exposed specimens by scanning-electron microscopy and energy dispersive x-ray analysis.

[b]P_{O_2} is partial pressure of oxygen in the experimental gas environment. $P^e_{O_2}$ corresponds to the oxygen partial pressure at the phase boundary of chromium oxide/chromium sulfide equilibrium. The ratio $P_{O_2}/P^e_{O_2}$ is defined as an excess parameter.

[c]Alloy composition in weight percent: 21 Cr, 32.5 Ni, 0.05 C, 0.008 S, 0.75 Mn, 0.35 Si, 0.38 Al, 0.38 Ti, 46.0 Fe.

[d]Specimens were exposed to the mixed gas atmosphere (CO, CO_2, CH_4, H_2, H_2O, H_2S) for 25 hours at 1 atm pressure at the indicated temperatures.

VARIATION OF SCALE THICKNESS AND PENETRATION DEPTH[a] WITH TIME FOR INCOLOY 800[b] EXPOSED TO MIXED GAS ENVIRONMENTS[c][30]



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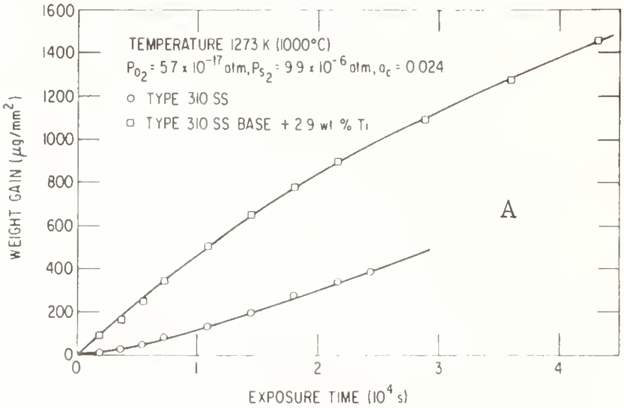
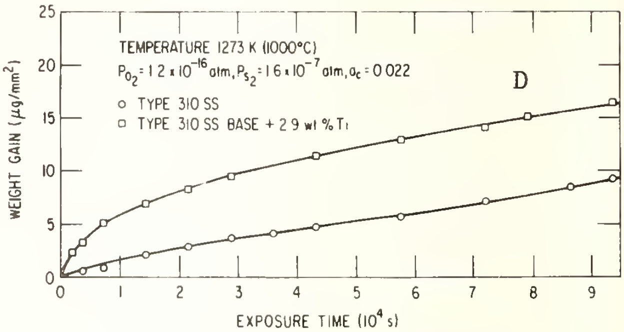
[a]Scale thickness and alloy penetration depth obtained by examining cross-sections of exposed specimens by scanning-electron microscopy and energy dispersive x-ray analysis.

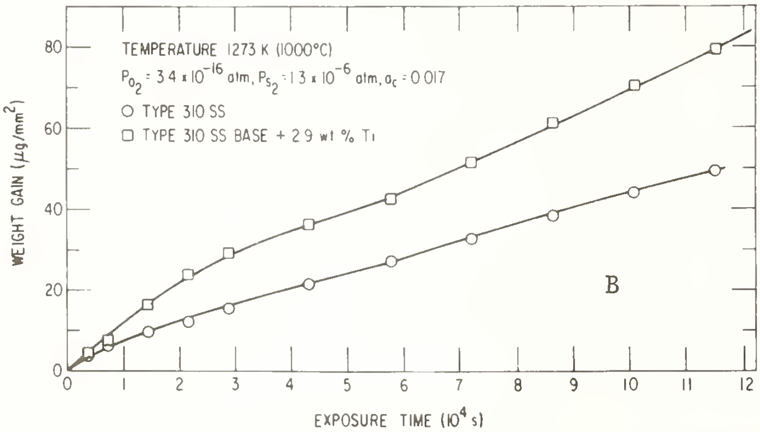
[b]Alloy composition in weight percent: 21 Cr, 32.5 Ni, 0.05 C, 0.008 S, 0.75 Mn, 0.35 Si, 0.38 Al, 0.38 Ti, 46.0 Fe.

[c]Specimens were exposed to the mixed gas environment (CO, CO_2, CH_4, H_2, H_2O, H_2S) for 1000 hours at 1 atm pressure at the indicated temperatures. The gas composition is express as an excess parameter, $P_{O_2}/P^e_{O_2}$. P_{O_2} is the partial pressure of oxygen in the experimental gas environment. $P^e_{O_2}$ corresponds to the oxygen partial pressure at the phase boundary of chromium oxide/chromium sulfide equilibrium.

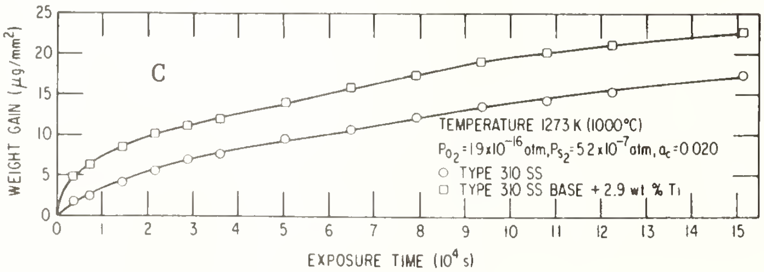
WEIGHT GAIN VS TIME CURVES FOR COMMERCIAL AND Ti-MODIFIED TYPE 310 SS[a] AFTER EXPOSURE TO MIXED GAS ENVIRONMENTS[b][30]







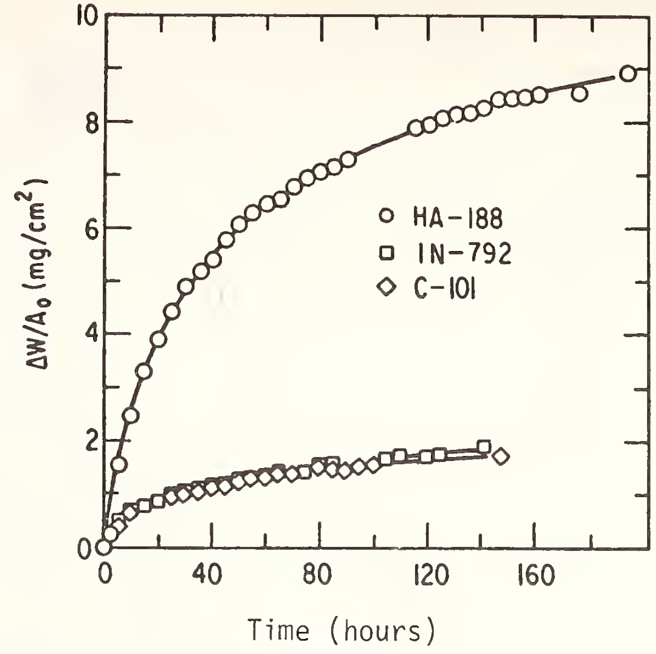
	Type of Scale	
	310 SS	310 SS + Ti
A	Cr-rich sulfide	Cr-rich sulfide
B	Cr-rich oxide	(Cr,Ti) oxide
C	Cr-rich oxide	(Cr,Ti) oxide
D	Cr-rich oxide	(Cr,Ti) oxide

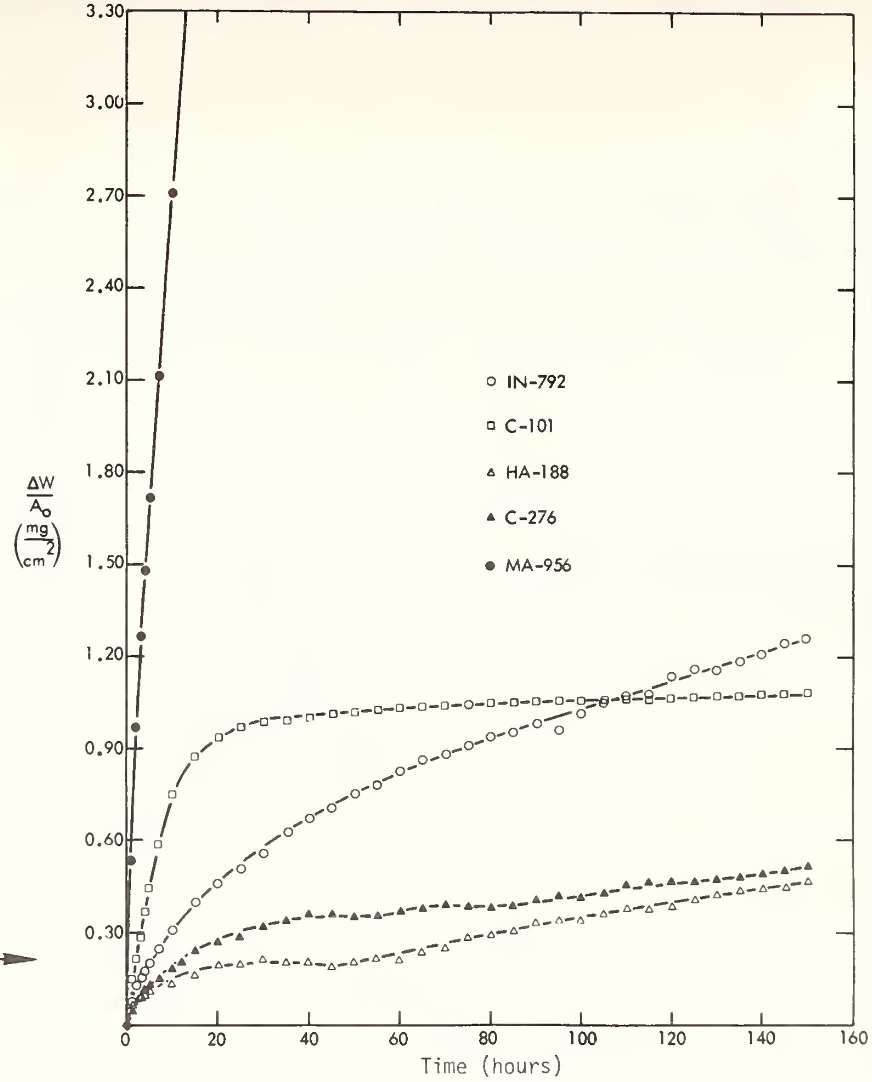


[a] Alloy compositions in weight percent: 310 SS, 24.2 Cr, 19.5 Ni, 1.5 Mn, 0.4 Si balance Fe; 310 SS + 3Ti, 25.0 Cr, 20.0 Ni, 2.9 Ti, balance Fe.

[b] Specimens were exposed to the mixed gas environment (CO, CO_2, CH_4, H_2, H_2O, H_2S) at 1 atm pressure at the indicated temperature. The input gas composition was regulated to provide the partial pressure for oxygen and sulfur and the carbon activity indicated on the graphs.

WEIGHT GAIN PER UNIT SURFACE AREA OF VARIOUS ALLOYS[a] SUBJECTED TO MIXED GAS ATMOSPHERES[b][30]



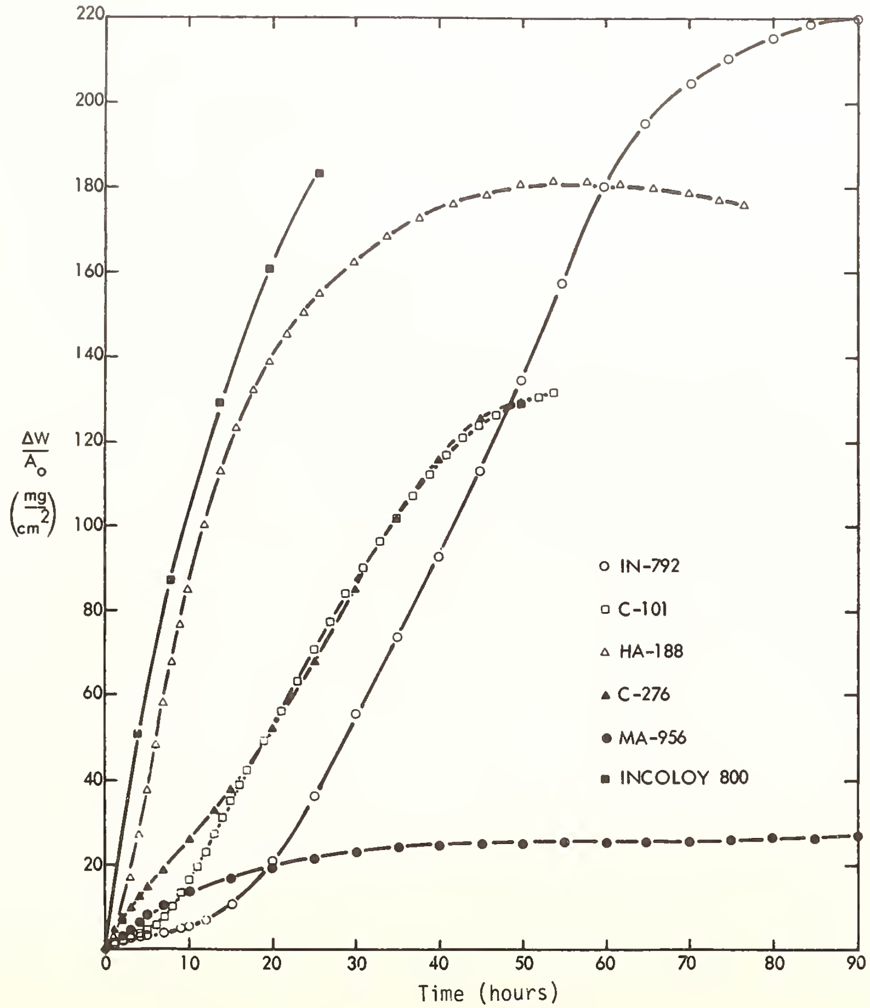


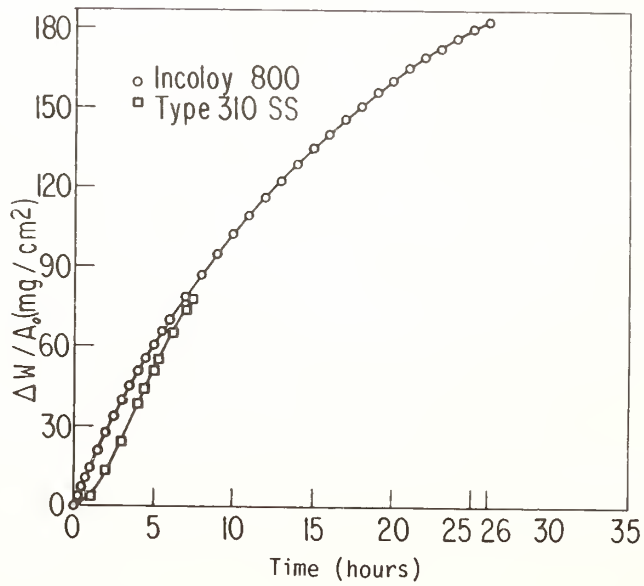
Atmosphere 1:[c]
P_{O_2} << oxide-scale formation threshold P_{O_2}
$P_{S_2} < P_{S_2}$ for base-metal sulfidation

Atmosphere 2:[d]
P_{O_2} > threshold P_{O_2} for oxide-scale formation

(Continued)

WEIGHT GAIN PER UNIT SURFACE AREA OF VARIOUS ALLOYS[a] SUBJECTED TO MIXED GAS ATMOSPHERES[b][30], Continued





Atmosphere 3:[e]

P_{O_2} < oxide-scale formation threshold P_{O_2}

P_{S_2} > P_{S_2} for base-metal sulfidation

(Continued)

WEIGHT GAIN PER UNIT SURFACE AREA OF VARIOUS ALLOYS[a] SUBJECTED TO MIXED GAS ATMOSPHERES[b][30], Continued

[a] All annealed and wrought alloys were polished through 240 grit SiC, rinsed with ethyl alcohol, then exposed to the mixed gas atmospheres. Cast alloys were tested as received. Alloys tested were (composition in weight percent): Incoloy 800 (annealed sheet), 0.05 C, 0.8 Mn, 0.5 Si, 21.0 Cr, 32.5 Ni, 0.4 Al, 0.4 Ti, balance Fe; 310 SS (annealed sheet), 0.25 C, 2.0 Mn, 1.5 Si, 25.0 Cr, 20.0 Ni, balance Fe; Hastelloy C-276 (annealed sheet), 0.02 C, 5.5 Fe, 2.5 Co, 15.5 Cr, 16 Mo, 3.8 W, 1.0 Mn, 0.05 Si, 0.35 V, balance Ni; Haynes 188 (annealed sheet), <0.1 C, 22 Ni, <3 Fe, 22 Cr, 14 W, <1.25 Mn, 0.3 Si, 0.04 La, balance Co; Inconel 792 (as-cast), 0.07 C, 9 Co, 12.7 Cr, 2 Mo, 3.9 W, 3.2 Al, 4.2 Ti, 3.9 Ta, 0.1 Zr, 0.02 B, balance Ni; Inconel C-101 (as-cast), 0.08 C, 9 Co, 12.7 Cr, 2 Mo, 4 W, 3.2 Al, 4.2 Ti, 4 Ta, 0.1 Zr, 0.2 B, 1.1 Hf, balance Ni; oxide-dispersion strengthened MA-956 (wrought P/M sheet), 20 Cr, 4.5 Al, 0.5 Ti, 0.6 Y_2O_3, balance Fe.

[b] Specimens were subjected to the atmospheres at 1144 K at 1 atm pressure. The compositions were adjusted by maintaining the relative flow rates of the input gases.

[c] Atmosphere 1 (in vol % and atm): CO 4.65, CO_2 5.31, CH_4 3.32, H_2 86.4, H_2S 0.30, P_{O_2} 8.5×10^{-21}, P_{S_2} 8.5×10^{-9}, a_C 0.251.

[d] Atmosphere 2 (in vol % and atm): CO 22.86, CO_2 45.70, CH_4 7.62, H_2 23.40, H_2S 0.42, P_{O_2} 4.2×10^{-18}, P_{S_2} 4.1×10^{-8}, a_C 0.043.

[e] Atmosphere 3 (in vol % and atm): CO 22.5, CO_2 45.0, CH_4 7.5, H_2 24.06, H_2S 0.94, P_{O_2} 4.1×10^{-18}, P_{S_2} 9.4×10^{-7}, a_C 0.043.

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE AT LOWERED PRESSURE[a][13]

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c], mils/yr(mm/yr)								
	Test Time, hr	1000	2000	3000	4000	5000	7000	8000	9000	10000
Test Condition: CGA[a], 1650 °F										
Incoloy 800	47Fe-31Ni-21Cr	73(1.86)				25(0.62)				10(0.25)
Incoloy 800 Al[d]		9(0.23)				3(0.07)				3(0.07)
310 SS	Fe-20Ni-25Cr-2Mn	42(1.05)				16(0.40)				5(0.13)
310 SS Al[d]		27(0.67)				6(0.15)				5(0.13)
309 SS	Fe-15Ni-23Cr	59(1.49)				11(0.28)				13(0.33)
Alloy X	20Fe-45Ni-22Cr-9Mo	19(0.49)				3(0.08)				1(0.02)
RA 333	16Fe-45Ni-26Cr-4Mo	9(0.23)				2(0.05)				2(0.04)
Inconel 657	50Ni-48Cr	7(0.18)				2(0.05)				1(0.02)
Crutemp 25	47Fe-25Ni-25Cr	8(0.22)				9(0.22)				1(0.02)
Haynes 188	Co-23Ni-22Cr	25(0.65)				5(0.13)				1(0.02)
Haynes 556	Fe-20Ni-22Cr-20Co-3Mo	17(0.42)				14(0.36)				6(0.14)
329 SS	Fe-4Ni-27Cr	4(0.11)				2(0.05)			2(0.04)	
Multimet N155	29Fe-20Ni-21Cr-20Co	3(0.08)				1(0.02)			1(0.02)	
Stellite 6B	3Ni-28Cr-57Co-5W	3(0.08)				1(0.04)			0(0.01)	
Co-Cr-W No. 1	Co-30Cr-12W	3(0.08)				1(0.02)			1(0.03)	
Incoloy 793	43Fe-32Ni-21Cr-2Al	27(0.69)	18(0.45)			10(0.25)				
Inconel 671	48Ni-50Cr	5(0.13)				1(0.03)				
Wiscalloy 30/50W	Fe-49Ni-28Cr-4W	555(14.1)			2(0.06)					
Thermalloy 63WC	Fe-26Ni-28Cr-15Co-5W	97(2.46)				88(2.23)				
Inconel 617	54Ni-22Cr-13Co-9Mo	185(4.69)								
446 SS	Fe-24Cr	6(0.14)			4(0.09)					
HL-40	47Fe-19Ni-31Cr	13(0.33)			3(0.08)					
HK-40	Fe-20Ni-28Cr	26(0.65)		7(0.17)						
IN-738	Ni-16Cr-8Co-3Al-3Ti	23(0.59)		14(0.35)						
Sanicro 32X	Fe-32Ni-22Cr-3W	8(0.21)		10(0.27)						
LM-1866	Fe-18Cr-5Al-1Mo-1Hf	6(0.16)				2(0.04)				
Test Condition: CGA[a], 1800 °F										
Incoloy 800	47Fe-31Ni-21Cr	49(1.25)				57(1.45)	77(1.95)			
Incoloy 800 Al[d]		8(0.21)	4(0.09)		4(0.10)	14(0.35)				4(0.11)
310 SS	Fe-20Ni-25Cr-2Mn	5(0.12)				10(0.26)	47(1.18)			
310 SS Al[d]		18(0.47)	7(0.18)		7(0.17)	70(1.78)				8(0.21)
309 SS	Fe-15Ni-23Cr	455(11.6)	118(2.98)		117(1.03)					
Alloy X	20Fe-45Ni-22Cr-9Mo	6(0.14)		completely corroded						
RA 333	16Fe-45Ni-26Cr-4Mo	8(0.20)		241(6.12)						
Inconel 657	50Ni-48Cr	11(0.28)				4(0.09)			2(0.05)	
Crutemp 25	47Fe-25Ni-25Cr	7(0.17)				3(0.07)			2(0.05)	
Haynes 188	Co-23Ni-22Cr	7(0.18)				0(0.01)				7(0.18)
Multimet N155	29Fe-20Ni-21Cr-20Co	8(0.21)				15(0.37)				2(0.06)
Stellite 6B	3Ni-28Cr-57Co-5W	5(0.13)				2(0.06)				2(0.04)
Co-Cr-W No. 1	Co-30Cr-12W	5(0.12)				5(0.12)				3(0.07)
Inconel 671	48Ni-50Cr	9(0.23)				1(0.02)				1(0.02)
Wiscalloy 30/50W	Fe-49Ni-28Cr-4W	12(0.31)				97(2.46)				
Thermalloy 63WC	Fe-26Ni-28Cr-15Co-5W	12(0.30)				3(0.08)				completely corroded
Inconel 617	54Ni-22Cr-13Co-9Mo	45(1.15)			13(0.34)					
446 SS	Fe-24Cr	27(0.69)				9(0.22)			19(0.49)	
HL-40	47Fe-19Ni-31Cr	26(0.66)				10(0.24)				1(0.02)
HK-40	Fe-20Ni-28Cr	11(0.28)		4(0.10)		6(0.14)				
IN-738	Ni-16Cr-8Co-3Al-3Ti	98(2.50)				66(1.67)				
LM-1866	Fe-18Cr-5Al-1Mo-1Hf	6(0.15)				3(0.07)				

(Table Continued)

CORROSION BEHAVIOR OF SOME ALLOYS SUBJECTED TO A COAL GASIFICATION ATMOSPHERE AT LOWERED PRESSURE[a][13], Continued

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c], mils/yr(mm/yr)								
	Test Time, hr	1000	2000	3000	4000	5000	7000	8000	9000	10000
Test Condition: CGA[a], 1800 °F, continued										
RV-18	Fe-32Ni-35Cr-32Co	4(0.09)				4(0.10)		1(0.02)		
RV-19	Fe-26Ni-30Cr-26Co	5(0.12)	2(0.05)		1(0.03)					
FSX-414	Co-10Ni-29Cr-7W	8(0.22)		2(0.05)		26(0.65)				
Haynes 150	Co-18Fe-28Cr	3(0.07)				7(0.19)		4(0.10)		
31Cr-28Ni	Fe-28Ni-31Cr	5(0.13)		5(0.12)		3(0.09)				
31Cr-36Ni	Fe-36Ni-31Cr	4(0.11)		4(0.09)		3(0.08)				
36Cr-36Ni	Fe-36Ni-36Cr	6(0.15)		4(0.09)		2(0.06)				
31Cr-44Ni	Fe-44Ni-31Cr	7(0.17)		5(0.13)		40(1.02)				

[a]CGA = coal gasification atmosphere. All tests were run at 500 psi. Compare with Sections B.1.1.17 and B.1.1.18 for corrosion data for these alloys tested in the same atmosphere at 1000 psi. Gas compositions follow:

Component	Gas Composition, volume percent		
	Inlet	Equilibrium (calculated) 1650 °F	Equilibrium (calculated) 1800 °F
H_2	24	27	31
CO	18	14	17
CO_2	12	17	15
CH_4	5	6	3
NH_3	1	1	1
H_2S	1.0	1.0	1.0
H_2O	balance	balance	balance
P_{O_2}, atm		4.1×10^{-17}	1.05×10^{-15}
P_{S_2}, atm		9.2×10^{-7}	2.7×10^{-6}
a_C		0.240	0.119

[b]Compositions are in weight percent. If no number appears before a constituent, e.g., Fe, that indicates that the balance of the alloy consists of that element.

[c]Values are for one test specimen exposed to the indicated conditions. Although more than one specimen was exposed, as a rule only one was 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 time.

[d]Aluminum coating (~9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

COMPARISON OF CORROSION BEHAVIOR[a] OF ALLOYS IN COAL GASIFICATION ATMOSPHERE AT TWO PRESSURES[b][13]

Alloy	Rate of Total Sound Metal Loss[a], mils/year					
	1000 hours		5000 hours		10,000 hours	
	500 psig	1000 psig	500 psig	1000 psig	500 psig	1000 psig
TEST AT 1650 °F						
Incoloy 800	73	53	25	12 (4)[d]	9.7	15
Incoloy 800 Al[c]	9.6	11	2.8	3.9(4)	2.7	3.5
310 SS	41	43	16	7.5(4)	5.1	13
310 SS Al[c]	26	17	5.8	5.7(4)	5.1	11
309 SS	58	51[e]	11	no data	13	no data
Alloy X	19	2.2(2)	2.8	17	0.9	no data
RA 333	8.8	11	1.9	3.3(4)	1.7	9.4(8)
Inconel 657	7.0	8.8	2.1	2.0(4)	0.8	0.4
Crutemp 25	8.8	11	8.8	3.3(4)	0.9	8.4
Haynes 188	25	3.5	5.3	38 (4)	0.7	no data
Haynes 556	17	3.1(2)	14	9.6	5.6	no data
329 SS	4.4	13 (2)	1.9	8.4	1.7(9)	no data
Multimet N155	3.5	13 (2)	0.9	no data	0.7(9)	3.9(8)
Stellite 6B	3.5	7.0	1.4	2.3(3)	0.5(9)	0.6(9)
Co-Cr-W No. 1	3.5	3.5	0.9	18 (3)	1.3(9)	0.7(9)
Incoloy 793	27	18 (2)	10	no data		
Inconel 671	5.3	2.2(2)	1.1	2.0(4)		
Wiscalloy 30/50W	555	311	2.2(4)	21 (2)		
Thermalloy 63WC	96	238 (2)	88	111 (6)		
Inconel 617	185	completely corroded(2)				
HL-40	13	12 (2)	3.3(4)	33		
HK-40	25	49[e]	6.7(3)	28		
IN-738	23	19 (2)	14 (3)	6.9(6)		
Sanicro 32X	7.9	11	11 (3)	6.4(3)		
TEST AT 1800 °F						
Incoloy 800	49	219	57	no data	77 (7)	no data
Incoloy 800 Al[c]	7.9	12	3.9(4)	5.4	4.4	14
310 SS	5.3	164	10	no data	46 (7)	no data

(Table Continued)

COMPARISON OF CORROSION BEHAVIOR[a] OF ALLOYS IN COAL GASIFICATION ATMOSPHERE AT TWO PRESSURES[b][13], Continued

Alloy	Rate of Total Sound Metal Loss[a], mils/year					
	1000 hours		5000 hours		10,000 hours	
	500 psig	1000 psig	500 psig	1000 psig	500 psig	1000 psig
TEST AT 1800 °F, continued						
310 SS Al[c]	18	29	6.8	7.5	8.4	20
309 SS	455	39,79	117 (4)	no data		
Alloy X	5.3	11	completely corroded	90 (2)		
RA 333	7.9	37	241	222 (2)		
Inconel 657	11	no data	3.5	1.8	1.9(9)	1.4(8)
Crutemp 25	7.0	19	2.6	9.1	1.9(9)	12 (8)
Haynes 188	7.0	7.0	2.8	no data	7.2[f]	no data
Multimet N155	8.8	11	15	4.7	2.5	4.5
Stellite 6B	5.3	20	2.1	3.7	1.6	2.5
Co-Cr-W No. 1	4.4	13	4.7	5.8	2.7	3.2
Inconel 671	8.8	15	0.9	4.0	0.6	1.5
Wiscalloy 30/50W	12	19	97	10	no data	3.0
Thermalloy 63WC	11	34	3.2	36	completely corroded	13
Inconel 617	45	34	13[f] (4)	37		
446 SS	26	27	8.6	no data	19 (9)	no data
HL-40	26	32	9.6	15	4.6	10
HK-40	11	no data	5.6	6.1		
IN-738	98	4.2	66	no data		
RV-18	3.5	4.4	3.9	1.4	0.7(8)	0.9(6)
RV-19	2.2(2)	7.0	1.1(4)	8.9		
FSX-414	8.8	18	26	no data		
Haynes 150	2.6	18	7.5	1.8	4.1(8)	2.6(7)
31Cr-28Ni	5.3	3.5	3.3	8.5(4)		
31Cr-36Ni	4.4	14	3.3	7.7		
36Cr-36Ni	6.1	9.6	2.3	7.2		
31Cr-44Ni	6.1	14	40	4.4(4)		

[a] Rate values are for one test specimen exposed to the indicated conditions. Although more than one specimen was exposed, as a rule only one was sectioned,

(Table Continued)

COMPARISON OF CORROSION BEHAVIOR[a] OF ALLOYS IN COAL GASIFICATION ATMOSPHERE AT TWO PRESSURES[b][13], Continued

Footnotes continued

wire-brushed, and the depth of corrosion determined metallographically. Scale thickness, depth of internal corrosion, and the 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 time.

[b]See Sections B.1.1.17, B.1.1.18, and B.1.1.123 for the data for this table and the full exposure conditions. B.1.1.17 and B.1.1.18 contain data for alloys exposed to a simulated coal gasification atmosphere at 1000 psi and B.1.1.123 contains data for the alloys exposed to the same atmosphere at 500 psi. The data are compared for various exposure times at two temperatures, 1650 and 1800 °F and for one H_2S concentration, 1 volume percent. Where data do not exist for the exposure times given in the table headings, values for other exposure times have been included. The substituted value is identified by giving the exposure time in parentheses in thousands of hours following the rate value, e.g., (9) means a 9000-hour exposure. In addition, there are some data for additional exposure times for a few alloys:

Alloy	500 psig	1000 psig
Alloy X	completely corroded (3)	90 (2)
RA 333	241 (3)	222 (2)
HK-40	4.1	6.7
FSX-414	1.8	6.4
31Cr-28Ni	5.0	6.4
31Cr-36Ni	3.5	3.8
36Cr-36Ni	3.5	5.3
31Cr-44Ni	5.3	9.9

[c]Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

[d]The rate value corresponds to an exposure time different from the time given in the table heading. The actual time is given in parentheses in thousands of hours, i.e., (4) means a 4000-hour exposure.

[e]A second specimen corroded completely in 2000 hours.

[f]One end completely corroded.

[g]Contaminated.

ANALYSIS[a] OF SURFACE SCALES FORMED ON ALLOYS EXPOSED TO A COAL GASIFICATION ATMOSPHERE[b][13]

Alloy	Exposure Temp. & % H_2S	Exposure Time, h	Location of Analysis	Elements Identified and Concentration > 10 At. %	2-10 At. %	< 2 At. %
310 SS Al[c]	1650 °F 0.5 %	5000	Thick surface scale area	Al, Mn, Cr, Fe		Ni
			Thin surface scale area	Cr, Fe, Mn	Al	
			Spalled area	Fe, Cr, Al	Ni, Mn, S	
			Particles on spalled area	S, Ni	Fe, Cr	
Incoloy 800 Al[c]		5000	Surface scale	Cr, Fe, Al	S, Ni, Mn	--
			Spalled area	Cr, Fe, Al	Ni, Mn, S	Ti
			Particles on spalled area	S, Ni, Fe	Cr	
Haynes 188		5000	Thick scale	Mn, Cr, Fe	Co	
			Thin scale	Cr, Mn, Fe	--	Co
			Spalled area, dark	Co, Cr, Ni	Fe	Mn, W
			Spalled area, light	Cr	Co, Ni	Fe
Co-Cr-W No. 1		1000	Surface scale	Cr, Fe	--	Co
Thermalloy 63WC		5000	Surface scale	Cr, Fe	Mn	Ni
Sanicro 32X	1650 °F 0.5 %	5000	Surface scale	Cr, Mn, Fe	S	Ni
			Particles on surface area	S, Ni	Cr, Fe, Mn	--
			Spalled area, dark	Cr	Ti, Fe	Ni
			Spalled area, light	Fe, Cr, Ni	Si	--
310 SS Al[c]	1800 °F 1.0 %	5000	Surface scale	Al, Cr, Fe, Mn	Ni	--
			Particles on surface scale	Al	Cr, Fe, Mn	Ni
			Spalled area	Cr, Fe	Mn, Al	Ni
			Particles on spalled area	Ni, S	Cr, Fe	Mn
Incoloy 800 Al[c]		5000	Surface scale	Cr, Fe, Al	Ni, Mn	--
			Spalled area	Al, Fe	Cr, Ni	Mn, Ti
			Particles on spalled area	Al, Cr, Fe, Ni	Mn	Ti
Crutemp 25		3000	Outer surface scale	Cr, Fe, Mn	--	--
			Inner surface scale	Cr, Fe	Mn	--
		5000	Surface scale	Cr, Fe	Mn	Ni
			Spalled area	Cr	Fe	Mn
Stellite 6B		5000	Outer surface scale	Cr, Fe, Mn	--	Ni
			Inner surface area	Cr, Fe	Mn	Ni
Co-Cr-W No. 1		5000	Surface scale	Cr, Fe	Ni	--
			Spalled area, dark	Cr	--	Fe, Co, W
			Spalled area, light	Cr, Co	Fe	W

(Table Continued)

ANALYSIS[a] OF SURFACE SCALES FORMED ON ALLOYS EXPOSED TO A COAL GASIFICATION ATMOSPHERE[b][13], Continued

Alloy	Exposure Temp. & % H_2S	Exposure Time, h	Location of Analysis	Elements Identified and Concentration > 10 At. %	2-10 At. %	< 2 At. %
Thermalloy 63WC	1800 °F 1.0 % contd.	5000	Surface scale, thick	Cr, Fe	Co, Ni, Mn, S	--
			Particles on thick scale	Ni, S	Fe, Co, Cr	--
			Surface scale, thin	Cr, Fe	Mn	Co, Ni
			Spalled area	Cr	Fe	S, Co, Ni, Mn
IN-657	↓	3000	Surface scale	Cr, Fe	--	--
			Spalled area, dark	Cr	Ni	--
			Spalled area, light	Cr, Ni	Nb	--
		5000	Outer surface scale, gray	Cr, Fe	--	--
			Inner surface scale	Cr, Fe	--	--
			Spalled area	Cr	--	--
Inconel 617	↓	5000	Surface scale	Cr, Fe	Mn	Co, Ni
			Spalled area	Cr	Ti	Fe, Ni
			Edge corrosion, flat particles	Cr, Ni, S	Co, Fe	--
			Edge corrosion, spherical particles	S, Ni	Co	Fe, Cr

[a]Surface scales examined by energy dispersive x-ray analysis.

[b]Exposures were for the given times at the indicated temperatures at 1000 psi pressure. The equilibrium gas compositions at the test temperatures are:

Component	Input gas	1650 °F	1800 °F
H_2	24	27	31
CO	18	14	17
CO_2	12	17	15
CH_4	5	6	3
NH_3	1	1	1
H_2S	0.5 or 1.0	0.5 or 1.0	0.5 or 1.0
H_2O	balance	balance	balance

Units are volume percent.

[c]Aluminum coating (~9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

APPARENT EFFECT OF H_2S CONTENT OF A SIMULATED COAL GASIFICATION ATMOSPHERE[a] ON THE CORROSION RESISTANCE[b] OF SOME ALLOYS[13]

Alloy	% Cr	Effect of 0.5 and 1.0 vol % H_2S 1650 °F	1800 °F
Inconel 671	50.2	No effect	Slightly worse at 1%
IN-657	48.0	No effect	No effect
HL-40	30.9	Much worse at 1%	No effect
Co-Cr-W No. 1	30.0	Slightly worse at 0.5%	No effect
Thermalloy 63WC	28.2	Much worse at 1%	No effect
Stellite 6B	28.1	No effect	No effect
HK-40	28.0	Much worse at 1%	No effect
RA 333	26.2	No effect	Much worse at 1%
Crutemp 25	25.4	Slightly worse at 1%	Slightly worse at 1%
310 SS	25.0	No effect	Not tested at 1%, 1800
310 SS Al[c]	25.0	No effect	Worse at 1%
446 SS	24.0	Not tested at 1%, 1650	Inconclusive
309 SS	23.0	Worse at 1%	Not tested at 1%, 1800
Haynes 188	22.0	Inconclusive	Much worse at 1%
556	22.0	No effect	Not tested at 1%, 1800
Inconel 617	22.0	Much worse at 1%	Much worse at 1%
Alloy X	21.9	Much worse at 1%	Much worse at 1%
Sanicro 32X	21.6	Worse at 1%	Not tested at 1%, 1800
Multimet N155	20.9	No effect	Slightly worse at 0.5%
Incoloy 800	20.6	Worse at 1%	Not tested at 1%, 1800
Incoloy 800 Al[c]	20.6	No effect	No effect

[a]See footnote a of B.1.1.18 for gas compositions.

[b]See footnote c of B.1.1.17 and footnote b of B.1.1.18 for measurement of corrosion behavior. See Sections B.1.1.17 and B.1.1.18 for data on which this table is based.

[c]Aluminum coating (∼9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

APPARENT EFFECT OF TEMPERATURE ON THE CORROSION RESISTANCE[a] OF SOME ALLOYS EXPOSED TO A SIMULATED COAL GASIFICATION ATMOSPHERE[b][13]

Alloy	% Cr	Effect of Temperature (1650 and 1800 °F) 0.5 vol % H_2S	1.0 vol % H_2S
Inconel 671	50.2	Slightly worse at 1800	No effect
IN-657	48.0	No effect	No effect
HL-40	30.9	Much worse at 1800	No effect
Co-Cr-W No. 1	30.0	Slightly worse at 1650	Slightly worse at 1800
Thermalloy 63WC	28.2	Worse at 1800	Worse at 1650
Stellite 6B	28.1	Slightly worse at 1800	Slightly worse at 1800
HK-40	28.0	Worse at 1800	No effect
Wiscalloy 30/50W	27.9	Not tested at 0.5%	Much worse at 1650
RA 333	26.2	Worse at 1800	Much worse at 1800
Crutemp 25	25.4	Slightly worse at 1800	Slightly worse at 1800
310 SS	25.0	Much worse at 1800	Not tested at 1800
310 SS Al[c]	25.0	No effect	Slightly worse at 1800
446 SS	24.0	Much worse at 1800	Not tested at 1650, 1%
309 SS	23.0	Worse at 1800	Not tested at 1800, 1%
Haynes 188	22.0	Inconclusive	Much worse at 1800
556	22.0	Much worse at 1800	Not tested at 1800, 1%
Inconel 617	22.0	Worse at 1800	Worse at 1650
Alloy X	21.9	Worse at 1800	Much worse at 1800
Sanicro 32X	21.6	Worse at 1800	Not tested at 1800, 1%
Multimet N155	20.9	No effect	No effect
Incoloy 800	20.6	Much worse at 1800	Not tested at 1800, 1%
Incoloy 800 Al[c]	20.6	Worse at 1800	Worse at 1800

[a] See footnote c of B.1.1.17 and footnote b of B.1.1.18 for measurement of corrosion behavior. See Sections B.1.1.17 and B.1.1.18 for data on which this table is based.

[b] See footnote a of B.1.1.18 for gas compositions.

[c] Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

ESTIMATED TIME[a] TO BREAKAWAY CORROSION OF ALLOYS SUBJECTED TO COAL GASIFICATION ATMOSPHERES[b][13]

		Estimated Time, 1000 hours							
		1650 °F 0.5% H_2S		1650 °F 1.0% H_2S		1800 °F 0.5% H_2S		1800 °F 1.0% H_2S	
Alloy	% Cr	M[a]	G[a]	M[a]	G[a]	M[a]	G[a]	M[a]	G[a]
Inconel 671	50.2	>10	>10	>10	>10	>10	>10	>10	>10
IN-657	48.0	>10	>10	>10	>10	>10	>10	>10	>10
HL-40	30.9	>10	>10	3	2	>10	>10	>10	>10
Co-Cr-W No. 1	30.0	>10	>10	> 9	> 9	>10	>10	>10	>10
Thermalloy 63WC	28.2	>10	>10	2	4	>10	>10	>10	8
Stellite 6B	28.1	>10	>10	>10	>10	>10	>10	>10	>10
HK-40	28.0	>10	>10	2	1	1	1	7	5
Wiscalloy 30/50W	27.9	--	--	1	1	--	--	>10	>10
RA 333	26.2	10	>10	> 8	7	5	4	2	2
Crutemp 25	25.4	>10	>10	>10	3	>10	>10	> 8	6
310 SS	25.0	<10	3	10	10	1	< 1	--	--
310 SS Al[c]	25.0	>10	>10	10	>10	>10	>10	10	>10
446 SS	24.0	>10	>10	--	--	> 4	1	2	d
309 SS	23.0	3	2	< 1	< 1	3	4	--	--
Haynes 188	22.0	5	>10	3	3	10	>10	< 1	1
556	22.0	>10	>10	>10	>10	1	1	--	--
Inconel 617	22.0	10	>10	1	< 1	> 8	> 8	3	4
Alloy X	21.9	>10	>10	>10	>10	10	>10	1	1
Sanicro 32X	21.6	< 5	4	5	6	1	1	--	--
Multimet N155	20.9	>10	>10	>10	>10	>10	>10	>10	9
Incoloy 800	20.6	>10	>10	10	8	7	6	--	--
Incoloy 800 Al[c]	20.6	>10	>10	>10	>10	> 5	> 5	10	>10

[a]Times based on metallographic measurements (M) and gravimetric analyses (G) of the alloy coupons exposed to the coal gasification atmospheres at 1650 and 1800 °F with two levels of H_2S content, 0.5 and 1.0 volume percent.

[b]See B.1.1.18 for the gas compositions.

[c]Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

[d]Inconclusive.

CORROSION BEHAVIOR OF ALLOYS SUBJECTED TO THE FEED AND EFFLUENT GASES OF DIRECT METHANATION[a][13]

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] in/yr	mm/yr	Exposure Time hr[d]
Feed to Direct Methanation,[a] 1.3% H_2S, 1800 °F				
309 SS	Fe-15Ni-23Cr	0.358	9.09	1000
310 SS	Fe-20Ni-25Cr-2Mn	0.010	0.25	1000
310 SS Al[e]		0.047	1.18	1000
Incoloy 800	47Fe-31Ni-21Cr	Catastrophically corroded.		500
Incoloy 800 Al[e]		0.008	0.20	1000
Inconel 617	54Ni-22Cr-13Co-9Mo	0.177	4.51	1000
Inconel 671	48Ni-50Cr	0.008	0.21	1000
RA 333	16Fe-45Ni-26Cr-4Mo	0.931	23.64	500
RA 330TX	Fe-33Ni-19Cr-2Mo-3Cu	0.336	8.53	500
Crutemp 25	47Fe-25Ni-25Cr	0.023	0.57	1000
Multimet N155	29Fe-20Ni-21Cr-20Co	0.015	0.39	1000
Alloy X	20Fe-45Ni-22Cr-9Mo	2.826	71.79	100
Stellite 6B	3Ni-28Cr-57Co-5W	0.008	0.20	1000
Haynes 150	Co-18Fe-28Cr	0.096	2.43	1000
Haynes 188	Co-23Ni-22Cr	0.033	0.83	1000
Haynes 556	Fe-20Ni-22Cr-20Co-3Mo	0.023	0.58	1000
Co-Cr-W No. 1	Co-30Cr-12W	0.008	0.07	1000
E-Brite 26-1	73Fe-26Cr-1Mo	0.004	0.10	1000
Effluent from Direct Methanation,[a] 1.8% H_2S, 1200 °F				
304 SS	Fe-9Ni-19Cr	0.007	0.19	1000
309 SS	Fe-15Ni-23Cr	0.005	0.13	1000
310 SS	Fe-20Ni-25Cr-2Mn	0.008	0.19	1000
312 SS	Fe-9Ni-31Cr	0.011	0.28	1000
316 SS	Fe-14Ni-17Cr	0.007	0.17	1000
329 SS	Fe-4Ni-27Cr	0.009	0.22	1000
410 SS	Fe-12Cr	0.076	1.94	1000
446 SS	Fe-24Cr	0.009	0.23	1000
Incoloy 800	47Fe-31Ni-21Cr	0.010	0.25	1000

(Table Continued)

CORROSION BEHAVIOR OF ALLOYS SUBJECTED TO THE FEED AND EFFLUENT GASES OF DIRECT METHANATION[a][13], Continued

Alloy	Major Alloying Constituents[b]	Rate of Total Sound Metal Loss[c] in/yr	Rate of Total Sound Metal Loss[c] mm/yr	Exposure Time[d] hr
- - - -Effluent from Direct Methanation,[a] 1.8% H_2S, 1200 °F, continued- - -				
Incoloy 825	28Fe-42Ni-22Cr	0.015	0.39	1000
Inconel 600	7Fe-77Ni-16Cr	Completely corroded.		500
Inconel 601	16Fe-60Ni-23Cr	0.147	3.75	1000
Inconel 617	54Ni-22Cr-13Co-9Mo	0.057	1.45	1000
RA 333	16Fe-45Ni-26Cr-4Mo	0.011	0.27	1000
RA 330TX	Fe-33Ni-19Cr-2Mo-3Cu	0.007	0.18	1000
Crutemp 25	47Fe-25Ni-25Cr	0.010	0.25	1000
Multimet N155	29Fe-20Ni-21Cr-20Co	0.007	0.18	1000
Armco 21-6-9	63Fe-9Ni-21Cr-8Mn	0.006	0.16	1000
Armco 22-13-5	Fe-14Ni-21Cr-5Mn	0.006	0.15[f]	1000
AL 29-4-2	Fe-2Ni-30Cr-4Mo	0.014[g]	0.34	1000
20Cb-3	Fe-33Ni-19Cr-2Mo-3Cu	0.012	0.31	1000
E-Brite 26-1	73Fe-26Cr-1Mo	0.019	0.48	1000

[a]The atmospheres used in these tests are the calculated equilibrium compositions of the Westinghouse plant feed and effluent gases from the direct methanation component. The compositions are, in volume percent,

Constituent	Feed Gas Input	Feed Gas Equilibrium	Effluent Gas Input	Effluent Gas Equilibrium
CO	5.7	15.5	40.7	45.3
CO_2	48.9	38.1	12.5	7.2
H_2	3.7	6.0	25.4	32.4
CH_4	35.1	30.0	9.8	4.8
H_2S	2.1	1.8	1.5	1.3
N_2	0.7	1.2	0.5	0.8
NH_3	1.2	0.006	0.8	0.009
H_2O	2.6	7.2	8.8	8.1

System pressure is 600 psi, maximum exposure time was 1000 hours.

[b]Compositions are in weight percent. If no number appears before a constituent, e.g., Fe, that indicates that the balance of the alloy consists of that element.

[c]Values are for one test specimen exposed to the indicated conditions. Although more than one specimen was exposed, as a rule only one was sectioned, wire-brushed, and the depth of corrosion determined metallographically. Scale thickness, depth of internal corrosion, and diffusion zone thickness

(Table Continued)

CORROSION BEHAVIOR OF ALLOYS SUBJECTED TO THE FEED AND EFFLUENT GASES OF DIRECT METHANATION[a][13], Continued

Footnotes continued

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 time.

[d]The exposure time given is the maximum test time for which the alloy was subjected to the stated conditions.

[e]Aluminum coating (∿9 mils) applied by Alon Processing, Inc. by a pack diffusion process (Alonized).

[f]Table A-8, page A-12 of The Metal Properties Council, Inc. annual report, March 15, 1983, gives a value of 1.33 for this quantity. That value is not consistent with the rest of the data for this alloy.

[g]In the same table mentioned in footnote f, the value for the average depth of penetration in mils for this alloy is given as 1.10 but should be 1.20 to be consistent with the rest of the data and with other tables in the report.

CORROSION BEHAVIOR[a] OF WELDMENTS SUBJECTED TO A SIMULATED COAL GASIFICATION ATMOSPHERE[b][13]

Weldment[c]			Type of Loss[d]	Sound Metal Loss,[a] mils			
Base Metal	Filler Metal	Weld Type/Joint Design		Base	HAZ[e]	Weld	Reference Specimen
310 SS	E310-15-16	SMAW/double V	S	0.3	0.3	0.5	0.2
			P	0.7	1.2	0.8	0.4
			T	1.0	1.5	1.3	0.6
Haynes 188	188	GTAW/double V	S	0.2	--	0.2	0.2
			P	0.2		0.5	0.6
			T	0.4		0.7	0.8
Inconel 657	50-50Nb	SMAW/single V	S	0.3	0.5	0.2	0.5
			P	0.6	0.5	0.3	0.2
			T	0.9	1.0	0.5	0.7
RA 333	RA-333-70-16	SMAW/double V	S	0.2	0.2	0.2	0.2
			P	1.6	0.7	1.5	0.8
			T	1.8	0.9	1.7	1.0
				Overlay	Outer Layer	Inner Layer	800H base
Incoloy 800H	FM 72	SAW/double layer overlay	S	0.4	0.3	0.4	0.6
			P	0.3	0.4	0.1	4.8
			T	0.7	0.7	0.5	5.4

[a]One weldment specimen and one reference specimen of the base metal exposed to the indicated conditions were examined for corrosion. 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.

[b]The input composition of the atmosphere to which the weldments were exposed was (in volume percent): 24 H_2, 18 CO, 12 CO_2, 5 CH_4, 1 NH_3, 0.5 H_2S, balance H_2O. The temperature was 1650 °F, the pressure 500 psig, and the exposure time 1000 hours.

[c]For all four weldments the progression was forehand, multipass.

[d]S = scaling loss, P = internal corrosion, T = total sound metal loss. [e]HAZ = heat-affected zone.

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF A SIMULATED PILOT PLANT QUENCH ENVIRONMENT AT LOWERED PRESSURE[b][38]

Alloy[a]	Corrosion Rate,[c] mils/yr				Pit Depth,[d] mils								Time, hr	Environment[b]
	Autoclave		Trap		Autoclave				Trap					
	Aqueous	Gaseous	Aqueous	Gaseous	Aqueous		Gaseous		Aqueous		Gaseous			
					max	ave	max	ave	max	ave	max	ave		
Carbon steel	23.3	4.0	2.9	0.7	0.7	0.3	0.6	0.2	0.3	0.2	0.2	0.1	150	Standard (mole %): CO_2 14.2, CO 11.2, (CO/CO_2 =0.8), H_2S 0.77, NH_3 0.41, CH_4 7.36, C_2H_6 0.21, C_6H_6 3.18, toluene 15.3, H_2 20.5, H_2O 26.8, N_2+ Ar 0.04, HCN 0.04, phenol 0.03, HCl 0.02, COS 0.03; temperature 380 °F, pressure 500 psig. This test at 130 °F.
304 SS	<0.1	<0.1			<0.1	<0.1	<0.1	<0.1						
Carbon steel	7.7	1.5	25.1	10.3	1.2	0.5	1.0	0.5	0.6	0.4	0.6	0.4	500	Standard, temperature at 130 °F
304 SS	<0.1	<0.1			0.3	0.2	0.2	0.1						
Carbon steel	6.5	5.2	4.6	4.1	0.8	0.3	0.9	0.3	0.4	0.2	0.2	0.1	150	Standard, temperature at 250 °F
304 SS	<0.1	<0.1			<0.1	<0.1	<0.1	<0.1						
Carbon steel	7.5	2.2	1.6	1.5	1.0	0.4	1.0	0.4	0.8	0.4	0.4	0.2	500	Standard, temperature at 250 °F
304 SS	<0.1	<0.1			<0.1	<0.1	<0.1	<0.1						
Carbon steel	10.7	6.2			0.8	0.3	0.6	0.2					150	Standard, temperature at 300 °F
304 SS	<0.1	<0.1			<0.1	<0.1	<0.1	<0.1						
Carbon steel	5.8	2.7			0.8	0.3	0.9	0.4					500	Standard, temperature at 300 °F
304 SS	0.1	<0.1			<0.1	<0.1	<0.1	<0.1						
Carbon steel	11.4	9.6			0.7	0.3	0.4	0.2					150	Standard
304 SS	0.5	0.2			<0.1	<0.1	<0.1	<0.1						
Carbon steel	8.3	7.7			<0.1	<0.1	<0.1	<0.1					500	Standard
304 SS	0.3	0.2			<0.1	<0.1	<0.1	<0.1						
Carbon steel	19.8	9.0			0.7	0.3	0.7	0.3					150	Standard, H_2S 1.5%, NH_3 0.1%
304 SS	0.1	0.1			0.1	0.1	0.1	0.1						
Carbon steel	7.9	4.6			0.6	0.4	1.1	0.5					500	Standard, H_2S 1.3%, NH_3 0.1%
304 SS	0.1	<0.1			<0.1	<0.1	<0.1	<0.1						
Carbon steel	13.0	6.2			0.7	0.2	0.5	0.2					150	Standard, H_2S 1.3%, NH_3 0.8%
304 SS	0.2	0.1			0.1	0.1	0.1	0.1						
Carbon steel	24.5	16.1	50.2	9.3	0.7	0.2	0.4	0.2	0.4	0.2	0.3	0.2	150	Standard, 100 ppm HCN
304 SS	0.8	0.6			<0.1	<0.1	<0.1	<0.1						
Carbon steel	12.4	8.7	58.4	57.0	0.5	0.2	0.5	0.2	0.3	0.1	0.2	0.1	500	Standard, 100 ppm HCN
304 SS	0.3	0.3			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	22.5	11.6	14.4	7.5	0.5	0.2	0.4	0.1	0.4	0.2	0.2	0.1	150	Standard, 1000 ppm HCN
304 SS	0.5	0.2			<0.1	<0.1	<0.1	<0.1						
Carbon steel	20.7	16.7	81.2	37.0	0.7	0.3	0.8	0.3	0.5	0.3	0.5	0.3	150	Standard, CO/CO_2 = 0.7
304 SS	0.5	0.5			0.3	0.2	<0.1	<0.1						
Carbon steel	20.9	13.7	15.8	5.0	0.6	0.2	0.7	0.3	0.8	0.5	0.6	0.4	150	Standard, CO/CO_2 = 1.0
304 SS	0.5	0.2			<0.1	<0.1	<0.1	<0.1						
Carbon steel	16.9	17.3	61.0	15.4	0.6	0.2	0.5	0.2	0.8	0.5	0.4	0.2	150	Standard, H_2S 1.5%
304 SS	0.6	0.5			0.4	0.2	0.2	0.1						

(Table Continued)

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF A SIMULATED PILOT PLANT QUENCH ENVIRONMENT AT LOWERED PRESSURE[b][38], Continued

Alloy[a]	Corrosion Rate,[c] mils/yr				Pit Depth,[d] mils								Time, hr	Environment[b]
	Autoclave		Trap		Autoclave				Trap					
	Aqueous	Gaseous	Aqueous	Gaseous	Aqueous		Gaseous		Aqueous		Gaseous			
					max	ave	max	ave	max	ave	max	ave		
Carbon steel	14.0	8.1	28.8	26.1	0.5	0.2	0.4	0.2	1.0	0.8	1.0	0.8	500	Standard, H_2S 1.5%
304 SS	0.4	0.3			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	17.7	9.3	17.2	15.9	0.4	0.2	0.4	0.1	0.4	0.3	0.4	0.2	150	Standard, H_2S 0.1%
304 SS	0.4	0.4			<0.1	<0.1	<0.1	<0.1						
Carbon steel	42.8	25.2	135	85	2.4	0.9	1.0	0.4	0.3	0.2	0.2	0.1	150	Standard, 900 ppm O_2
304 SS	0.9	0.8			<0.1	<0.1	<0.1	<0.1						
Carbon steel	28.1	15.4	40.1	13.0	0.6	0.2	0.6	0.2	<0.1	<0.1	0.2	0.1	150	Standard, 110 ppm Cl^- (as HCl)
304 SS	0.9	0.9			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	115	63.5	23.9	5.4	0.6	0.3	0.8	0.4	<0.1	<0.1	<0.1	<0.1	150	Standard, 1300 ppm Cl^- (as HCl)
304 SS[g1]	2.2	1.1			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	34.2	15.2	42.5	7.8	0.6	0.2	0.4	0.2	<0.1	<0.1	<0.1	<0.1	150	Standard, 110 ppm Cl^- (as HCl), H_2S 1.5%, NH_3 0.1%
304 SS	1.0	1.0			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	105	68.0	143[e]	7.3	0.7	0.3	1.2	0.7	<0.1	<0.1	<0.1	<0.1	150	Standard, 1300 ppm Cl^- (as HCl), NH_3 1.0%
304 SS[g2]	1.3	1.5			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	45.2	14.3	30.2	6.4	0.4	0.2	0.8	0.4	0.2	0.1	<0.1	<0.1	150	Standard, 430 ppm Cl^- (as HCl)
304 SS	1.2	0.9			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	14.0	5.8	43.7	2.0	0.6	0.2	0.3	0.2	0.4	0.2	0.6	0.3	500	Standard, 100 ppm HCN, NH_3 0.1%, CO/CO_2=0.7
304 SS	0.3	0.2			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	11.7	7.2	13.1	5.2	0.5	0.2	0.3	0.1	0.6	0.3	<0.1	<0.1	500	Standard, 1000 ppm HCN, NH_3 0.8%, CO/CO_2=1.0
304 SS	0.4	0.2			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
Carbon steel	8.0	5.8	45.5	14.6	0.6	0.3	0.6	0.3	<0.1	<0.1	<0.1	<0.1	1000	Standard, 110 ppm Cl^- (as HCl)
304 SS[g3]	0.2	0.2			0.2	0.1	0.2	0.1	1.2	0.1				
Carbon steel	f		69.7	9.8					<0.1	<0.1	<0.1	<0.1	1350	Standard, 110 ppm Cl^- (as HCl)
304 SS	f								<0.1	<0.1				

[a]Specimens were machined to 1 in square by 1/4 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-01-69 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 Low-Pressure), compare B.1.1.109 for HYGAS High-Pressure tests. 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/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 Low-Pressure). Some tests included placing coupons in a trap vessel which collected autoclave exit gas containing water vapor. Coupons were placed so that rising condensed water slowly immersed them. Trap temperature was always below 100 °F.

[c]Corrosion rate was calculated from the weight loss by the following equation: $\text{mils/yr} = \dfrac{\text{weight loss(mg)} \times \text{constant}}{\text{area(in}^2) \times \text{time(hr)} \times \text{alloy density(g/cc)}}$. Specimens were exposed in both liquid in the autoclave and above the liquid. Values are averages of 5 or 6 coupon values for carbon steel, of 2 coupons for 304 SS, and the trap value is always for one coupon.

(Table Continued)

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF A SIMULATED PILOT PLANT QUENCH ENVIRONMENT AT LOWERED PRESSURE[b][38], Continued

Footnotes continued

[d]Pitting was evaluated by an in-focus/out-of-focus technique on the top edge and the bottom of pits. Some 10 to 15 pit depths were measured per specimen and the results given in terms of max (maximum pit depth measured, mils) and ave (average of the 10 largest pits measured, mils). Minimum measurable depth was 0.1 mil. Max values above are the largest values of all maximum values for all specimens. See footnote c for averages.

[e]Value is given as 1.43 in Table C-1, page C-4, in the 1980 annual report, FE-1784-72 (see reference [38]).

[f]Autoclave coupons were defective.

[g]Bolted U-bend samples of carbon steel and 304 SS following ASTM G30-79 were used to evaluate stress-corrosion cracking in the environments. 304 SS specimens were either annealed and quenched or sensitized at 1200 °F (649 °C) in argon for one hour. Presence of residual stress condition ascertained by the boiling $MgCl_2$ test, ASTM G36-73. No carbon steel U-bends showed any stress-corrosion cracking in any of the tests, 304 SS showed stress-corrosion cracking in only these tests:

	Environment	Time	Phase	Type of U-bend
1	Standard, 1300 ppm Cl^-	150	Aqueous	Sensitized
			Gaseous	Annealed
2	Standard, 1300 ppm Cl^-, NH_3 1.0%	150	Aqueous	Sensitized
			Gaseous	Sensitized, Annealed
3	Standard, 110 ppm Cl^-	1000	Aqueous	Sensitized
			Gaseous	Sensitized, Annealed

ANALYSIS OF CORROSION SCALE[a] ON CARBON STEEL EXPOSED TO SIMULATED COAL GASIFICATION PLANT QUENCH CONDITIONS[b][38]

Test Environment[b]	Temperature °F	Pressure psig	Time hr	Phase[d]	FeS^c Surface	FeS^c Cross Section[e]	$FeCO_3$[c] Surface	$FeCO_3$[c] Cross Section[e]	Hydrated Fe Oxides, Nitrides[c] Surface	Hydrated Fe Oxides, Nitrides[c] Cross Section[e]
Standard A: CO_2 16.3%, CO 14.4%, (CO/CO_2=0.9), 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%, N_2 0%, HCN 100 ppm, phenol 500 ppm, chloride 3000 ppm. This test H_2S 0.1%.	380	300	150	Gaseous	58.0	--	2.7	--	39.0	--
				Aqueous	91.0	--	0.8	--	8.2	--
Standard A: no purging.	380	1200	150	Gaseous	91.0	92.7	3.3	3.3	5.7	4.1
				Aqueous	95.0	--	3.6	--	1.4	--
Standard A: 900 ppm O_2.	380	1200	150	Gaseous	82.5	85.1	0.29	2.9	17.2	12.0
				Aqueous	74.4	86.4	1.93	1.93	23.7	11.7
Standard B: CO_2 14.2%, CO 11.2%, (CO/CO_2=0.8), H_2S 0.77%, NH_3 0.41%, CH_4 7.36%, C_2H_6 0.21%, C_6H_6 3.18%, toluene 15.3%, H_2 20.5%, H_2O 26.8%, N_2+ Ar 0.04%, HCN 0.04%, phenol 0.03%, HCl 0.02%, COS 0.03%.	130	500	500	Trap, G[d]	72.5	--	0.9	--	26.6	--
				Gaseous	70.5	--	1.3	--	28.3	--
				Aqueous	60.5	53.0	1.6	1.6	37.9	45.5
Standard B	250	500	500	Trap, A[d]	53.7	--	0.9	--	45.4	--
				Gaseous	83.5	--	2.2	--	14.3	--
				Aqueous	92.4	--	0.4	--	7.2	--
Standard B	300	500	150	Gaseous	84.5	94.1	0.97	0.97	14.5	4.9
				Aqueous	63.8	69.7	1.35	1.35	34.8	28.9
Standard B	300	500	500	Gaseous	90.6	--	1.6	--	7.7	--
				Aqueous	81.2	86.9	1.5	1.5	17.4	11.7
Standard B	380	500	150	Gaseous	86.0	--	1.6	--	12.4	--
				Aqueous	94.3	71.4	1.4	1.5	4.3	27.2
Standard B	380	500	500	Gaseous	94.9	72.5	3.6	3.6	1.5	24.0
				Aqueous	78.9	88.4	0.7	0.7	20.4	10.9
Standard B: H_2S 1.5%, NH_3 0.1%	380	500	150	Gaseous	86.0	--	1.0	--	13.0	--
				Aqueous	88.0	74.9	0.6	0.6	11.0	24.2
Standard B: H_2S 1.3%, NH_3 0.1%	380	500	500	Aqueous	86.0	87.8	0.8	0.8	13.2	11.5
Standard B: H_2S 1.3%, NH_3 0.8%	380	500	150	Aqueous	88.8	88.8	1.55	1.55	9.65	9.65
Standard B: 100 ppm HCN	380	500	500	Gaseous	90.5	--	4.7	--	4.8	--
				Aqueous	91.1	84.3	2.9	2.9	6.0	12.8
Standard B: CO/CO_2 = 0.7	380	500	150	Gaseous	89.4	--	0.6	--	10.0	--
				Aqueous	92.3	92.9	0.4	0.4	7.3	6.7
Standard B: CO/CO_2 = 1.0	380	500	150	Gaseous	88.6	--	0.2	--	11.2	--
				Aqueous	80.2	--	0.3	--	19.5	--
Standard B: H_2S 1.5%	380	500	150	Gaseous	62.0	--	0.6	--	37.4	--
				Aqueous	89.7	85.0	0.8	0.8	9.5	14.2
Standard B: H_2S 1.5%	380	500	500	Gaseous	89.8	--	0.9	--	9.3	--
				Aqueous	84.7	84.7	1.0	1.0	14.3	14.3
Standard B: H_2S 0.1%	380	500	150	Gaseous	86.3	90.3	2.6	2.6	11.1	7.1
				Aqueous	75.5	76.2	1.3	1.3	23.2	22.6
Standard B: 900 ppm O_2	380	500	150	Trap, G[d]	65.3	--	1.0	--	33.7	--
				Trap, A[d]	50.4	--	2.8	--	46.8	--
				Gaseous	86.9	--	1.9	--	11.2	--
				Aqueous	90.0	84.4	2.5	2.5	7.5	13.1
Standard B: 110 ppm Cl^- (as HCl)	380	500	150	Trap, A[d]	76.9	--	6.4	--	16.7	--
				Gaseous	80.4	--	2.9	--	16.7	--
				Aqueous	91.6	--	1.9	--	6.5	--

(Table Continued)

ANALYSIS OF CORROSION SCALE[a] ON CARBON STEEL EXPOSED TO SIMULATED COAL GASIFICATION PLANT QUENCH CONDITIONS[b][38], Contd.

Test Environment[b]	Temperature °F	Pressure psig	Time hr	Phase[d]	FeS^c Surface	FeS^c Cross Section[e]	$FeCO_3{}^c$ Surface	$FeCO_3{}^c$ Cross Section[e]	Hydrated Fe Oxides, Nitrides[c] Surface	Hydrated Fe Oxides, Nitrides[c] Cross Section[e]
Standard B: 1300 ppm Cl^- (as HCl)	380	500	150	Trap, A[d]	83.6	--	5.5	--	10.9	--
				Gaseous	90.1	--	1.8	--	8.2	--
				Aqueous	47.6	--	2.0	--	50.4	--
Standard B: 110 ppm Cl^- (as HCl), H_2S 1.5%, NH_3 0.1%	380	500	150	Trap, A[d]	67.7	--	0.9	--	31.5	--
				Gaseous	90.1	--	5.9	--	4.1	--
				Aqueous	90.9	--	3.6	--	5.6	--
Standard B: 1300 ppm Cl^- (as HCl), NH_3 1.0%	380	500	150	Aqueous	80.6	--	2.5	--	16.9	--
Standard B: 430 ppm Cl^- (as HCl)	380	500	150	Gaseous	91.7	--	1.0	--	7.3	--
				Aqueous	87.4	--	3.2	--	9.4	--
Standard B: 100 ppm HCN, NH_3 0.1%, CO/CO_2= 0.7	380	500	500	Gaseous	93.5	--	4.2	--	2.3	--
				Aqueous	79.7	83.6	3.5	3.5	16.8	13.0
Standard B: 1000 ppm HCN, NH_3 0.1%, CO/CO_2=1.0	380	500	500	Gaseous	68.1	--	8.3	--	23.6	--
				Aqueous	92.8	95.1	4.6	4.6	2.6	0.33
Standard B: 110 ppm Cl^- (as HCl)	380	500	1350	Trap, G[d]	81.8	--	1.9	--	16.3	--
				Trap, A[d]	53.7	--	5.4	--	40.3	--
				Trap, A[f]	91.2	--	1.0	--	8.0	--

[a] A scanning electron microscope fitted with energy-dispersive x-ray (EDX) and 4-crystal wavelength-dispersive (WDX) spectrometers was used to examine the scale on the coupons tested and determine the detailed quantitative elemental chemistry. Analyses were obtained from typical areas of scale. See B.1.1.109 and B.1.1.131 for other corrosion data for these coupons for the same tests.

[b] Tests conducted in autoclaves to simulate the quench step of a coal gasification process (HYGAS). 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/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 environments given are based on demonstration plant concepts. Standard A is HYGAS High-Pressure design, and Standard B is HYGAS Low-Pressure design. Some tests included placing coupons in a trap vessel which collected autoclave exit gas that contained water vapor. Coupons were placed so that rising condensed water slowly immersed them.

[c] Estimated amounts of scale products are based on the elemental analysis. EDX results indicated that all S present was tied up as FeS. It was assumed that all C present was in $FeCO_3$ and that the remaining Fe, O, and N were in the form of hydrated iron oxides, $Fe(OH)_2$ and $Fe(OH)_3$, and Fe nitrides. Amounts are weight percent.

[d] The coupons were subjected to the conditions in the autoclave both above and below the liquid line. Some coupons were placed in a trap vessel, see footnote b, and A and G indicate the position of the coupon with respect to the liquid line in the trap.

[e] Average quantitative elemental analysis from a representative cross-section of the corrosion scale.

[f] This last sample is not carbon steel, but 304 SS.

AQUEOUS CORROSION OF ALLOYS[a] SUBJECTED TO VARIATIONS OF A SLAGGING AND A DRY-ASH COAL GASIFICATION QUENCH ENVIRONMENT[b][38]

Alloy[a]	Corrosion Rate,[c] mils/yr				Pit Depth,[d] mils					Time, hr	Environment[b]
	Autoclave		Trap		Autoclave				Trap		
	Aqueous	Gaseous	Aqueous	Gaseous	Aqueous max	Aqueous ave	Gaseous max	Gaseous ave			
Carbon steel 304 SS	3.4 0.1	3.6 0.2	3.8 --	2.6					In 150-hr tests, carbon steel showed no significant pitting; max values for all tests were 0.4 aqueous, 0.3 gaseous. 304 SS in all tests had max value <0.1.	150	Standard Slagging, H_2 29%, CO 55%, CO_2 3.5%, CH_4 7.1%, H_2S 0.5%, C_2H_6 0.6%, N_2 4.4%, NH_3 1500 ppm, CN^- 200 ppm, Cl^- 1200 ppm, phenol 15000 ppm. Standard pressure 355 psig, Standard temperature 325 °F. This test 150 °F.
Carbon steel 304 SS	10.5 <0.1	6.7 <0.1	1.0 0.1	1.0						150	Standard Slagging, 250 °F
Carbon steel 304 SS	15.2 0.1	12.5 0.1	0.5 <0.1	0.6					In longer tests, carbon steel showed some pitting but no pits deeper than 1.0 mil.	150	Standard Slagging
Carbon steel 304 SS	9.5 0.2	6.7 <0.1	1.3 <0.1	2.3	0.8 0.3	0.4 0.2	0.8 <0.1	0.6 <0.1		500	Standard Slagging
Carbon steel 304 SS	29.5 0.8	8.5 1.8	5.2 0.1	1.0	0.3 0.1	0.1 0.1	0.4 0.7	0.2 0.4	304 SS was not pitted at all.	2000	Standard Slagging
Carbon steel 304 SS	15.4 0.2	13.9 0.1	0.2 0.2	0.4						150	Standard Slagging, 375 °F
Carbon steel 304 SS	11.6 <0.1	10.6 <0.1	5.2 <0.1	5.0						150	Standard Slagging, no phenol
Carbon steel 304 SS[e1]	27.6 0.5	32.0 0.5	2.1 0.2	1.9	0.9 1.0	0.6 0.5	1.8 0.7	0.7 0.5		150	Standard Slagging, 5000 ppm phenol
Carbon steel 304 SS	194 0.1	8.6 0.1	6.4 <0.1	1.4	0.6 0.4	0.3 0.2	0.8 0.3	0.5 0.1		150	Standard Slagging, no NH_3
Carbon steel 304 SS[e2]	57.2 0.7	27.0 2.8	12.7 0.3	3.8						150	Standard Slagging, 500 ppm NH_3
Carbon steel 304 SS[e3]	42.2 0.2	21.1 0.7	37.4 <0.1	9.5						500	Standard Slagging, 500 ppm NH_3
Carbon steel 304 SS	19.6 0.7	9.2 0.4	1.8 0.3	1.1						150	Standard Slagging, 3000 ppm NH_3
Carbon steel 304 SS	34.0 0.2	8.5 0.1	9.2 <0.1	1.9						150	Standard Slagging, 2000 ppm Cl^-
Carbon steel 304 SS[e4]	28.7 1.3	13.3 0.3	6.7 0.2	0.9	1.4 0.4	1.0 0.2	0.9 0.3	0.4 0.2		150	Standard Slagging, 3000 ppm Cl^-
Carbon steel 304 SS	13.7 0.3	7.1 0.2	2.9 0.2	2.9						150	Standard Slagging, 1.5% H_2S
Carbon steel 304 SS[e5]	30.5 0.1	20.8 0.1	7.0 <0.1	3.2						150	Standard Slagging, 10 ppm HCN
Carbon steel 304 SS	3.8 0.2	5.6 0.8	10.9 --	5.5						150	Standard Dry-ash, H_2 39%, CO 18%, CO_2 31%, CH_4 8.4%, H_2S 0.7%, C_2H_6 0.6%, N_2 2.4%, NH_3 1500 ppm, CN^- 200 ppm, Cl^- 1200 ppm, phenol 15000 ppm. Standard pressure 355 psig, standard temperature 325 °F. This test 150 °F.

(Table Continued)

AQUEOUS CORROSION OF ALLOYS[a] SUBJECTED TO VARIATIONS OF A SLAGGING AND A DRY-ASH COAL GASIFICATION QUENCH ENVIRONMENT[b][38], Continued

Alloy[a]	Corrosion Rate,[c] mils/yr: Autoclave Aqueous	Autoclave Gaseous	Trap Aqueous	Trap Gaseous	Pit Depth,[d] mils: Autoclave Aqueous max	Autoclave Aqueous ave	Autoclave Gaseous max	Autoclave Gaseous ave	Trap	Time, hr	Environment
Carbon steel	3.9	9.6	2.0	1.6					See preceding page.	150	Standard Dry-ash, 250 °F
304 SS	0.1	0.3	0.2								
Carbon steel	11.3	9.7	3.9	2.2						150	Standard Dry-ash
304 SS	0.1	0.1	0.1								
Carbon steel	11.3	10.2	8.2	13.6	1.0	0.7	0.7	0.4		500	Standard Dry-ash
304 SS	0.3	0.2	<0.1		0.5	0.4	0.4	0.2			
Carbon steel	2.6	2.6	0.9	0.5	0.4	0.2	0.7	0.6		2000	Standard Dry-ash
304 SS	1.3	1.7	<0.1		0.2	0.1	0.5	0.3			
Carbon steel	11.1	9.7	1.3	0.8						150	Standard Dry-ash, 375 °F
304 SS	0.3	0.1	0.2								
Carbon steel	7.3	3.5	3.0	1.0						150	Standard Dry-ash, no phenol
304 SS	0.1	0.2	0.1								
Carbon steel	20.0	15.4	4.8	2.9	0.7	0.4	0.6	0.3		150	Standard Dry-ash, 5000 ppm phenol
304 SS[e6]	0.2	0.6	0.2		<0.1	<0.1	0.4	0.4			
Carbon steel	134	43.6	16.8	11.1	1.0	0.5	0.7	0.4		150	Standard Dry-ash, no NH_3
304 SS	0.2	0.3	<0.1		0.3	0.2	0.2	0.1			
Carbon steel	43.9	14.2	8.1	1.8						150	Standard Dry-ash, 500 ppm NH_3
304 SS[e7]	0.5	0.9	0.3								
Carbon steel	51.5	19.1	4.9	4.8						500	Standard Dry-ash, 500 ppm NH_3
304 SS[e8]	0.3	0.8	<0.1								
Carbon steel	9.9	6.7	4.3	2.3						150	Standard Dry-ash, 3000 ppm NH_3
304 SS	0.3	0.4	0.3								
Carbon steel	13.8	9.7	3.3	1.6						150	Standard Dry-ash, 2000 ppm Cl^-
304 SS	0.2	0.1	<0.1								
Carbon steel	11.2	5.7	1.4	0.9	0.5	0.2	0.5	0.2		150	Standard Dry-ash, 3000 ppm Cl^-
304 SS	0.3	0.2	0.3		0.3	0.1	0.2	0.1			
Carbon steel	5.9	11.5	4.7	1.8						150	Standard Dry-ash, 1.5% H_2S
304 SS	0.4	0.4	0.2								
Carbon steel	28.3	15.9	5.3	4.6						150	Standard Dry-ash, 10 ppm HCN
304 SS	0.1	0.1	<0.1								

[a]Specimens were machined to 1 in square by 1/4 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-01-69 with modified cleaning time of 20 min and reweighed.

[b]Tests conducted in autoclaves to simulate the quench steps of a coal gasification process (LURGI Slagging and Dry-ash 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/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. Some tests included placing coupons in a trap vessel which collected autoclave exit gas containing water vapor. Coupons were placed so that rising condensed water slowly immersed them.

[c]Corrosion rate was calculated from the weight loss by the following equation: mils/yr = $\frac{\text{weight loss(mg)} \times \text{constant}}{\text{area(in}^2) \times \text{time(hr)} \times \text{alloy density(g/cc)}}$. Specimens

(Table Continued)

AQUEOUS CORROSION OF ALLOYS[a] SUBJECTED TO VARIATIONS OF A SLAGGING AND A DRY-ASH COAL GASIFICATION QUENCH ENVIRONMENT[b][38], Continued

Footnotes continued

were exposed in both liquid in the autoclave and above the liquid. Values are averages of 5 coupons for carbon steel, of 2 coupons for 304 SS. The trap value is for one coupon.

[d]Pitting was evaluated by an in-focus/out-of-focus technique on the top edge and the bottom of pits. Some 10 to 15 pit depths were measured per specimen and the results given in terms of max (maximum pit depth measured, mils) and ave (average of the 10 largest pits measured, mils). Minimum measurable depth was 0.1 mil. Max values above are the largest values of all maximum values for all specimens. See footnote c for averages. Where values do not appear above, the pit depths were less than the measurable minimum.

[e]Notes on stress-corrosion cracking tests. Bolted U-bend samples of 304 SS (unwelded) following ASTM G30-79 were used to evaluate stress-corrosion cracking in the above environments. Specimens were either annealed and quenched or sensitized at 1200 °F (649 °C) in argon for one hour. Presence of residual stress condition ascertained by the boiling $MgCl_2$ test, ASTM G36-73. Stress-corrosion cracking was observed in these tests:

	Environment	Time	Phase	Type of U-bend
1	Slagging, 5000 ppm phenol	150	Aqueous	Sensitized
2	Slagging, 500 ppm NH_3	150	Gaseous	Sensitized
3	Slagging, 500 ppm NH_3	500	Gaseous	Sensitized
4	Slagging, 3000 ppm Cl^-	150	Gaseous	Sensitized
5	Slagging, 10 ppm HCN	150	Gaseous	Sensitized
6	Dry-ash, 5000 ppm phenol	150	Gaseous	Annealed
7	Dry-ash, 500 ppm NH_3	150	Gaseous	Sensitized
8	Dry-ash, 500 ppm NH_3	500	Gaseous	Annealed
9	Dry-ash, 500 ppm NH_3	500	Gaseous	Sensitized

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF THREE SIMULATED QUENCH ENVIRONMENTS[b][38]

	Corrosion Rate,[c] mils/yr					
	Autoclave		Trap			
Alloy[a]	Aqueous	Gaseous	Aqueous	Gaseous	Time, hr	Environment[b]
Carbon steel	9.8	11.5	50.0	189	150	Standard A (vol %): H_2O 9.0, H_2 16.5, CO 44.2, CO_2 28.3, CH_4 1.5, H_2S 0.4, NH_3 440 ppm, CN^- 10 ppm, Cl^- 100 ppm, phenol 10 ppm. Standard temperature 300 °F, standard pressure 130 psi.
304 SS	1.0	<0.1	<0.1			
Carbon steel	3.8	7.6	6.9	1.9	1000	Standard A
304 SS	<0.1	<0.1	<0.1			
Carbon steel	10.1	16.4	60.3	52.3	150	Standard A, 230 psi
304 SS	<0.1	1.2	<0.1			
Carbon steel	33.0	22.4	25.0	10.2	150	Standard A, 230 psi, 110 ppm NH_3
304 SS[d1]	<0.1	0.6	<0.1			
Carbon steel	7.9	29.7	78.2	13.1	150	Standard B (vol%): H_2 28.0, CO 50.0, CO_2 15.0, CH_4 6.0, H_2S 0.5, NH_3 440 ppm, CN^- 10 ppm, Cl^- 100 ppm, phenol 10 ppm. Standard temperature 235 °F, standard pressure 230 psi.
304 SS	<0.1	0.4	<0.1			
Carbon steel	19.3	27.9	27.0	5.8	150	Standard B
304 SS	<0.1	0.8	<0.1			
Carbon steel	3.2	2.8	20.8	2.9	500	Standard B
304 SS[d2]	<0.1	0.4	<0.1			
Carbon steel	14.1	23.8	9.2	6.3	150	Standard B, 180 °F
304 SS	<0.1	0.5	<0.1			
Carbon steel	51.8	4.0	1.7	2.0	150	Standard B, 180 °F, H_2S 0.5%, NH_3 110 ppm
304 SS	<0.1	0.1	0.3			
Carbon steel	45.7	6.7	9.8	3.4	150	Standard B, 180 °F, H_2S 1.5%, NH_3 110 ppm
304 SS	0.5	0.2	0.3			
Carbon steel	35.0	11.8	10.2	2.5	150	Standard B, 180 °F, H_2S 1.5%, NH_3 110 ppm
304 SS	<0.1	0.1	<0.1			
Carbon steel	31.4	13.0	18.4	5.4	150	Standard B, 300 °F, H_2S 1.5%, NH_3 110 ppm
304 SS	1.6	0.9	0.2			
Carbon steel	5.4	5.7	2.1	1.4	150	Standard B, 180 °F, H_2S 1.5%
304 SS	0.2	0.2	<0.1			
Carbon steel	22.1	4.3	5.2	2.2	150	Standard B, 180 °F, H_2S 0.5%, HCN 20 ppm, NH_3 110 ppm
304 SS	<0.1	<0.1	<0.1			
Carbon steel	6.3	7.9	1.5	0.7	150	Standard B, 800 ppm NH_3
304 SS[d3]	<0.1	<0.1	<0.1			
Carbon steel	10.2	9.2	23.6	9.5	150	Standard B, H_2S 1.0%
304 SS[d4]	0.1	0.1	0.2			
Carbon steel	9.7	7.1	8.8	4.1	150	Standard B, H_2S 1.0%
304 SS	0.1	0.2	0.2			
Carbon steel	9.6	12.9	81.0	70.3	150	Standard B, 300 °F, H_2S 1.0%
304 SS[d5]	0.2	0.3	0.1			
Carbon steel	7.5	28.3	60.0	3.9	150	Standard B, H_2S 1.5%
304 SS	<0.1	0.2	<0.1			
Carbon steel	11.9	6.2	5.5	3.8	150	Standard B, 0 ppm HCN
304 SS	<0.1	0.1	<0.1			
Carbon steel	10.4	8.1	6.6	4.2	150	Standard B, 20 ppm HCN
304 SS	<0.1	<0.1	<0.1			
Carbon steel	26.2	15.5	1.8	4.0	150	Direct Methanation (vol %): CO 40.7, CO_2 12.5, CH_4 9.8, H_2 25.4, H_2S 1.5, NH_3 0.8,[e] H_2O 8.8. Standard temperature 370 °F, standard pressure 600 psi.
304 SS	2.1	1.1	0.2			

(Table Continued)

AQUEOUS CORROSION OF ALLOYS[a] IN VARIATIONS OF THREE SIMULATED QUENCH ENVIRONMENTS[b][38], Continued

	Corrosion Rate,[c] mils/yr					
	Autoclave		Trap			
Alloy[a]	Aqueous	Gaseous	Aqueous	Gaseous	Time, hr	Environment[b]
Carbon steel	52.1	42.3	10.6	3.8	150	Direct Methanation, 500 °F
304 SS	4.3	5.2	0.2			
Carbon steel	8.8	7.0	4.6	0.6	500	Direct Methanation
304 SS	0.3	0.2	<0.1			
Carbon steel	26.3	9.3	2.9	2.4	500	Direct Methanation, begun at 500 °F for 118 hours, completed at 370 °F
304 SS[d6]	0.8	0.9	0.1			

[a] Specimens were machined to 1 in square by 1/4 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-01-69 with modified cleaning time of 20 min and reweighed.

[b] Tests conducted in autoclaves to simulate the quench steps of a coal gasification process (Westinghouse gasification and direct methanation steps). 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/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. Some tests included placing coupons in a trap vessel which collected autoclave exit gas containing water vapor. Coupons were placed so that rising condensed water slowly immersed them. Trap temperature was always below 100 °F.

[c] Corrosion rate was calculated from 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 in both liquid in the autoclave and above the liquid. Values are averages of 5 coupons for carbon steel, of two coupons for 304 SS, and the trap value is always for one coupon.

Pitting was evaluated by an in-focus/out-of-focus technique on the top edge and the bottom of pits. The minimum measurable depth was 0.1 mil. Pitting for all samples in all locations under all test conditions was less than 0.1 mil.

[d] Note on stress-corrosion cracking tests. Bolted U-bend samples of carbon steel and 304 SS following ASTM G30-79 were used to evaluate stress-corrosion cracking in the environments. 304 SS specimens were either annealed and quenched or sensitized at 1200 °F (649 °C) in argon for one hour. Presence of residual stress conditions ascertained by the boiling $MgCl_2$ test, ASTM G36-73. No carbon steel U-bends showed any stress-corrosion cracking in any of the environments. 304 SS showed stress-corrosion cracking in only these tests:

	Environment	Time	Phase	Type of U-bend
1	Standard A, 110 ppm NH_3, 230 psi	150	Gaseous	Sensitized, Annealed
2	Standard B	500	Gaseous	Sensitized, Annealed
3	Standard B, 880 ppm NH_3	150	Gaseous	Annealed
4	Standard B, H_2S 1.0%	150	Gaseous	Sensitized
5	Standard B, 300 °F, H_2S 1.0%	150	Gaseous	Sensitized
6	Direct Methanation, begun at 500 °F for 118 hours, completed at 370 °F	500	Aqueous	Sensitized

[e] Table 36, page 98, of report GRI-80/0167, see reference [38], states that this test was run at 500 °F, but that is in disagreement with the text of the report.

ANALYSIS OF CORROSION SCALE[a] ON CARBON STEEL EXPOSED TO VARIATIONS OF THREE SIMULATED QUENCH ENVIRONMENTS[b][38]

Test Environment[b]	Temperature °F	Pressure psig	Time hr	Phase	FeS[c] Surface	FeS[c] Cross Section[d]	$FeCO_3$[c] Surface	$FeCO_3$[c] Cross Section[d]	$Fe(OH)_x$ + others[c] Surface	$Fe(OH)_x$ + others[c] Cross Section[d]
Standard A (vol %): H_2O 9.0, H_2 16.5, CO 44.2, CO_2 28.3, CH_4 1.5, H_2S 0.4, NH_3 440 ppm, CN^- 10 ppm, Cl^- 100 ppm, phenol 10 ppm.	300	130	150	Aqueous	70	60	5.0	5.0	25	35
				Gaseous	69		2.5		29	
Standard A	300	130	1000	Aqueous	66	73	2.9	2.9	31	24
				Gaseous	70		3.1		27	
Standard A	300	230	150	Aqueous	84	70	5.9	5.9	10	25
				Gaseous	89		5.0		6.5	
Standard A, 110 ppm NH_3	300	230	150	Aqueous	89	59	3.5	3.5	7.9	38
				Gaseous	89		5.7		5.5	
Standard B (vol %): H_2 28.0, CO 50.0, CO_2 15.0 CH_4 6.0, H_2S 0.5, NH_3 440 ppm, CN^- 10 ppm, Cl^- 100 ppm, phenol 10 ppm.	235	230	150	Aqueous	75	79	4.6	4.6	21	17
				Gaseous	64		4.0		32	
Standard B	235	230	150	Aqueous	84	68	3.5	3.4	12	28
				Gaseous	78		2.9		20	
Standard B	235	230	500	Aqueous	61	--	2.2	--	37	--
				Gaseous	91		6.4		2.8	
Standard B	180	230	150	Aqueous	71	79	2.3	2.3	27	19
				Gaseous	71		3.0		27	
Standard B, H_2S 0.5%, NH_3 110 ppm	180	230	150	Aqueous	91	95	0.3	0.3	9.0	4.5
				Gaseous	85		2.8		17	
Standard B, H_2S 1.5%, NH_3 110 ppm	180	230	150	Aqueous	77	78	1.3	9.1	22	13
				Gaseous	71		9.1		20	
Standard B, H_2S 1.5%, NH_3 110 ppm	180	230	150	Aqueous	87	96	2.6	2.6	11	1.6
				Gaseous	89		1.3		9.8	
Standard B, H_2S 1.5%, NH_3 110 ppm	300	230	150	Aqueous	72	78	0.9	0.9	27	22
				Gaseous	77		2.7		21	
Standard B, H_2S 1.5%	180	230	150	Aqueous	74	--	3.2	--	23	--
				Gaseous	82	78	2.8	3	16	19
Standard B, H_2S 0.5%, HCN 20 ppm, NH_3 110 ppm	180	230	150	Aqueous	88	87	2.8	2.8	9.6	8.6
				Gaseous	91		2.9		5.8	
Standard B, 800 ppm NH_3	235	230	150	Aqueous	58	--	2.9	--	39	--
				Gaseous	67		6.0		27[e]	
Standard B, H_2S 1.0%	235	230	150	Aqueous	80	87	5.3	5.3	14	8.0
				Gaseous	81		5.5		14	
Standard B, H_2S 1.0%	235	230	150	Aqueous	77	86	2.0	2.0	21	12
				Gaseous	93		5.1		2.1	
Standard B, H_2S 1.0%	300	230	150	Aqueous	74	--	5.3	--	20	--
				Gaseous	78		2.1		20	
Standard B, H_2S 1.5%	235	230	150	Aqueous	74	70	4.0	4.0	22	26
				Gaseous	81		3.1		16	
Standard B, 0 ppm HCN	235	230	150	Aqueous	87	92	2.4	2.4	11	6.0
				Gaseous	81		0.1		19	
Standard B, 20 ppm HCN	235	230	150	Aqueous	84	83	2.3	2.3	14	15
				Gaseous	84		1.6		15	
Direct Methanation (vol %): CO 40.7, CO_2 12.5, CH_4 9.8, H_2 25.4, H_2S 1.5, NH_3 0.8, H_2O 8.8.	370	600	150	Aqueous	77	86	2.9	2.9	20	11
				Gaseous	74		2.8		23	

(Table Continued)

ANALYSIS OF CORROSION SCALE[a] ON CARBON STEEL EXPOSED TO VARIATIONS OF THREE SIMULATED QUENCH ENVIRONMENTS[b][38], Contd.

Test Environment[b]	Temperature °F	Pressure psig	Time hr	Phase	FeS[c] Surface	FeS[c] Cross Section[d]	$FeCO_3$[c] Surface	$FeCO_3$[c] Cross Section[d]	$Fe(OH)_x$ + others[c] Surface	$Fe(OH)_x$ + others[c] Cross Section[d]
Direct Methanation	500	600	150	Aqueous	87	93	3.5	3.5	10	3.8
				Gaseous	75		3.7		22	
Direct Methanation	370	600	500	Aqueous	78	--	3.4	--	19	--
				Gaseous	85	87	5.9	6	9.2	7
Direct Methanation, begun at 500 °F for 118 hours, completed at 370 °F	500 & 370	600	500	Aqueous	78	89	2.9	2.9	19	7.9
				Gaseous	92		4.8		3.6	

[a]A scanning electron microscope fitted with energy-dispersive x-ray (EDX) and 4-crystal wavelength-dispersive (WDX) spectrometers was used to examine the scale on the coupons tested and determine the detailed quantitative elemental chemistry. Analyses were obtained from typical areas of scale. See B.1.1.134 for other corrosion data for these coupons for the same tests.

[b]See B.1.1.134 for details of the test method. Trap specimens were not examined here and only two specimens exposed in gaseous phase were examined in cross section.

[c]Estimated amounts of scale products are based on the elemental analysis. EDX results indicated that all S present was tied up as FeS. It was assumed that all C present was in $FeCO_3$ and that the remaining Fe, and O were in the form of hydrated iron oxides, $Fe(OH)_2$ and $Fe(OH)_3$. Amounts are weight percent.

[d]Average quantitative elemental analysis from a representative cross-section of the corrosion scale.

[e]Sample showed 4.5% nitrogen.

CORROSION RATES[a] OF ALLOYS SUBJECTED TO COAL LIQUIDS[b] FROM COAL LIQUEFACTION PILOT PLANTS[c][45,46]

		Corrosion Rate,[a] mils/year					
Coal Liquid[b]	Temperature °F	Carbon Steel A515, Gr. 70	5Cr-1/2Mo A387, Gr. 5	410 SS	316 SS	Hastelloy C-276	Incoloy 825
No. 1--SRC-I, Wilsonville	425	9.1	5.9	1.2	nil[d]	nil[d]	nil[d]
Decanter Oil with		5.2	4.8	1.4	nil		
Na_2CO_3, Coal = Kentucky	500	15.1	13.0	4.1	nil	nil	nil
No. 9, Dotiki Mine		15.8	13.8	4.4	nil		
	575	14.4	24.0	1.5	nil	nil	nil
		6.6	23.1	2.2	nil		
	650	31.1	13.4	9.2	1.8	<0.1	<0.1
		32.1	12.7	9.4	1.6		
No. 2--SRC-I, Wilsonville	350	nil	2.1	1.0	nil	nil	nil
T104 Overhead with		4.5	2.5	1.6	nil		
Na_2CO_3, Coal = Kentucky	425	4.5	8.1	5.4	0.8	nil	nil
No. 9, Dotiki Mine		5.1	8.2	6.3			
	500	18.6	16.9	8.4	nil	nil	nil
		12.8	16.0	6.6	nil		
No. 3--SRC-I, Wilsonville	350	4.3	0.3	0.3	nil	nil	
T105 Overhead with		4.1	0.3	0.5	nil	nil	
Na_2CO_3, Coal = Kentucky	425	17.9		<0.1	nil	0.2	
No. 9, Dotiki Mine		15.7	1.3	nil	nil	nil	
	500	19.8	8.7	0.1	0.2	0.3	
		25.6		0.1	0.4	0.2	
No. 4--SRC-I, Wilsonville	425	4.9	0.2	0.1	<0.1	0.1	
Process Solvent, no		4.7	<0.1	0.1	0.2	<0.1	
Na_2CO_3, Coal = Kentucky	500	5.4	0.7	0.1	<0.1	nil	
No. 9, Dotiki Mine		5.9	1.0	0.3	0.2	0.2	
	575	9.4	6.0	0.7	0.2	0.1	
		8.9	8.7	1.2	nil	<0.1	
No. 5--SRC-I, Wilsonville	425	3.7	2.3	<0.1	<0.1	nil	
T105 Bottoms with		3.6	2.8	0.2	0.2	0.2	
Na_2CO_3, Coal = Kentucky	500	10.6		0.3	nil	nil	
No. 9, Dotiki Mine		10.8	2.6	0.3	nil	nil	
	575	21.9	7.4	0.2	0.3	0.2	
		22.0	9.8	0.1	0.1	0.3	
	650	33.4	23.6	1.7	0.7	0.1	0.3
		35.9	25.0	1.6	0.8		
No. 6--SRC-I, Ft. Lewis	425	8.9	7.0	5.4	0.1	nil	0.1
Wash Solvent Column Feed		8.9	7.0	5.8	<0.1		
Point (Light Ends Column	500	23.1	17.0	9.6	0.3	<0.1	0.3
Bottoms), Coal = Kentucky		22.4	16.2	9.7	0.5		
No. 9 and No. 11 Blend	575	48.8	24.7	10.3	1.8	0.2	<0.1
		48.6	24.9	10.5	1.7		
	650	43.0	21.7	2.6	1.2	nil	nil
		42.3	23.5	1.1	0.9		
No. 7--SRC-I, Ft. Lewis	350	6.5	3.9	<0.1	0.2	0.1	
Wash Solvent Column		7.0	1.9	<0.1	0.2	0.1	
Overhead Point, Coal =	425	16.1	10.0	nil	nil	nil	
Kentucky No. 9 and No. 11		15.1	10.2	<0.1	nil	nil	
Blend	500	20.1	21.4	1.8	nil	nil	
		19.4	20.8	1.9	nil	nil	
	575	19.1	14.4	8.0	3.0	0.2	0.6
		19.1	13.7	7.7	3.0		
No. 8--SRC-I, Ft. Lewis	500	27.8	18.3	3.1	nil	nil	
Wash Solvent Column		27.3	19.2	3.6	nil	nil	
Bottoms Point, Coal =	575	51.7	22.5	0.7	nil	nil	
Kentucky No. 9 and No. 11		42.2		1.0	nil	nil	
Blend	650	130.8	20.5	9.2	0.8	nil	
		125.6	32.5	10.5	0.5	nil	

(Table Continued)

CORROSION RATES[a] OF ALLOYS SUBJECTED TO COAL LIQUIDS[b] FROM COAL LIQUEFACTION PILOT PLANTS[c][45,46], Continued

		Corrosion Rate,[a] mils/year					
Coal Liquid[b]	Temperature °F	Carbon Steel A515, Gr. 70	5Cr-1/2Mo A387, Gr. 5	410 SS	316 SS	Hastelloy C-276	Incoloy 825
No. 9--SRC-II, Ft. Lewis	425	5.3	5.9	3.8	1.1	0.2	0.1
Wash Solvent Column		5.2	5.7	3.5	<0.1		
Feed Point, Coal =	500	9.3	8.4	5.4	0.2	0.1	nil
Kentucky Powhattan No. 6		9.2	8.0	5.2	nil		
	575	17.7	9.8	4.1	1.4	1.1	1.2
		16.7	10.2	3.8	1.4		
	650	20.9	16.5	nil	0.5	0.1	0.1
		20.3	16.9	nil	0.5		
No. 10--SRC-II, Ft. Lewis	350	5.1	2.8	12.2	6.0	nil	nil
Wash Solvent Column		5.8	2.6	16.1	2.0		
Overhead Point, Coal=	425	9.6	10.3	13.1	0.2	nil	nil
Kentucky Powhattan No. 6		9.7	10.7	13.5	nil		
	500	22.5	21.5	3.7	0.3	0.2	0.1
		24.6	23.2	3.2	0.4		
	575	15.0	11.1	5.3	1.1	nil	<0.1
		16.2	11.3	5.3	1.0		
No. 11--SRC-II, Ft. Lewis	350				nil	<0.1	<0.1
Middle Distillate, Com-					<0.1		
posite Mixture from	500	4.1	9.2	0.5	nil	<0.1	<0.1
Storage Tank, not asso-		4.7	10.4	0.4	<0.4		
ciated with specific coal							
No. 12--SRC-II, Ft. Lewis	500	5.0	3.9	1.1	0.6	0.5	0.4
Wash Solvent Column		4.6	3.6	1.7	0.6		
Bottoms Point, Coal =	575	27.3	36.8	17.0	0.8	0.5	0.6
Kentucky Powhattan No. 6		30.6	40.0	12.4	0.7		
	650	14.8	2.9	0.9	<0.1	nil	nil
		16.4	2.7	0.4	nil		
No. 13--SRC-II, Ft. Lewis	500	0.5	0.5	0.6	<0.1	0.1	<0.1
Heavy Distillate, Com-		0.5	0.4	0.2	0.1		
posite Mixture from	650	4.7	0.7	0.7	0.7	<0.1	nil
Storage Tank, not asso-		5.0	1.3	0.8	0.8		
ciated with specific coal							
No. 14--SRC-II, Ft. Lewis	425	8.6	7.4	1.7	0.1	0.1	0.1
Light Ends Column Fee		9.0	7.6	1.1	0.2		
Point, Coal = Kentucky	575				0.2	nil	nil
Powhattan No. 6					1.1		
No. 15--H-Coal, Trenton	500	0.7	0.7	0.3	0.2	<0.1	0.2
Vacuum Still Overhead,		0.3	0.4	0.4	nil		
Coal = Wyodak Lignite	650	7.8	3.6	0.5	0.5	0.4	0.7
		8.2	5.1	0.6	0.2		
No. 16--H-Coal, Trenton	500	3.4	3.4	0.8	0.5	0.3	0.4
Vacuum Still Overhead,		3.5	4.4	1.1	<0.1		
Coal = Kentucky No. 11	575	2.6	1.7	1.6	<0.1	<0.1	<0.1
		2.4	1.5	1.5	<0.1		
	650	25.1	7.5	3.5	0.3	<0.1	<0.1
		22.4	7.7	2.6	0.3		
No. 17--H-Coal, Trenton	350	1.7	nil	nil	nil	nil	nil
Atmospheric Still		1.0	<0.1	<0.1	0.2		
Overhead, Coal =	500	5.4	2.9	1.1	nil	<0.1	nil
Wyodak Lignite		5.9	3.6	0.7	<0.1		
No. 18--H-Coal, Trenton	350	5.6	0.9	0.3	<0.1	0.1	0.1
Atmospheric Still		5.8	1.0	0.3	<0.1		
Overhead, Coal =	500	10.4	10.4	2.2	<0.1	0.2	0.2
Kentucky No. 11		10.0	10.4	1.7	0.2		
	575	15.4	15.3	9.5	0.5	<0.1	0.1
		15.1	12.5	9.5	0.6		

(Table Continued)

CORROSION RATES[a] OF ALLOYS SUBJECTED TO COAL LIQUIDS[b] FROM COAL LIQUEFACTION PILOT PLANTS[c][45,46], Continued

Coal Liquid[b]	Temperature °F	Corrosion Rate,[a] mils/year Carbon Steel A515, Gr. 70	5Cr-1/2Mo A387, Gr. 5	410 SS	316 SS	Hastelloy C-276	Incoloy 825
No. 19--H-Coal, Trenton	500	1.4	1.0	0.6	0.2	0.2	0.2
Atmospheric Still		1.3	1.0	0.6	0.4		
Bottoms, Coal =	575	1.4	0.9	0.5	0.1	<0.1	<0.1
Wyodak Lignite		1.5	0.9	0.5	<0.1		
	650	2.5	1.0	0.5	nil	0.1	0.1
		2.4	0.6	0.3	<0.1		
No. 20--H-Coal, Trenton	500	4.7	1.7	0.5	<0.1	nil	nil
Atmospheric Still		4.3	1.7	0.5	<0.1		
Bottoms, Coal =	650	11.9	6.6	2.0	0.1	nil	nil
Kentucky No. 11		14.8	8.4	2.5	<0.1		
No. 21--Exxon Donor Solvent	350	3.0	1.0	0.5	0.3	0.3	0.3
(ECLP), Baytown		1.4	1.5	0.5	0.4		
Atmospheric Reflux	425	6.1	6.1	0.8	0.1	nil	<0.1
Naphtha, Coal =		6.2	7.2	1.1	0.1		
Illinois No. 6	500	8.7	7.2	1.8	<0.1	nil	nil
		9.8	7.9	2.9	nil		
	575	10.3	13.6	3.1	2.1	0.2	0.2
		10.3	12.5	2.1	2.1		
No. 22--Exxon Donor Solvent	500	2.3	1.0	0.5	0.2	<0.1	<0.1
(ECLP), Baytown		2.8	1.1	0.5	0.2		
Heavy Atmospheric Gas	650	11.1	14.2	5.1	1.7	<0.1	nil
Oil, Coal = Illinois No. 6		10.4	10.4	5.1	2.0		
No. 23--Exxon Donor Solvent	425	0.7	0.1	0.1	<0.1	<0.1	<0.1
(ECLP), Baytown		0.7	0.1	nil	0.1		
Light Atmospheric Gas	500	2.5	1.9	1.5	1.1	0.1	0.1
Oil, Coal = Illinois No. 6		2.4	1.6	1.2	0.2		
	575	5.6	2.4	1.3	0.1	nil	nil
		5.1	1.8	0.9	0.2		
No. 24--Exxon Donor Solvent	425	7.0	8.8	0.6	nil	nil	nil
(ECLP), Baytown		7.4	7.9	1.3	0.3		
Light Vacuum Gas Oil,	500	9.9	8.1	3.4	0.2	0.1	<0.1
Coal = Illinois No. 6		9.4	7.7	3.8	0.1		
	575	64.5	34.2	6.4	1.7	0.2	0.2
		71.6	33.8	9.9	1.5		
	650	74.1	47.0	8.6	3.5	<0.1	nil
		76.0	47.5	8.1	3.6		
No. 25--Exxon Donor Solvent	500	1.2	1.1	<0.1	0.1	0.1	0.1
(ECLP), Baytown		1.0	2.6	0.3	0.2		
Product Solvent,	650	2.2	1.5	0.4	0.5	nil	0.2
Coal = Illinois No. 6		2.7	2.3	0.6	0.2		
No. 26--Exxon Donor Solvent	500	4.8	3.9	1.1	<0.1	<0.1	<0.1
(ECLP), Baytown		5.3	4.1	1.4	0.4		
Light Atmospheric Gas	575	14.5	10.5	3.1	0.3	nil	<0.1
Oil, Coal = Illinois No. 6		12.6	10.5	4.4	0.8		
	650	20.3	13.8	10.2	1.6	<0.1	nil
		20.8	15.0	10.5	1.5		
No. 27--Exxon Donor Solvent	500	4.7	2.4	0.8	1.0	0.5	0.5
(CLPP), Baytown	650	14.1	8.5	1.0	0.2	0.2	0.1
Solvent Hydrogenation		14.7	10.5	1.6	0.2		
Feed, Coal = Big Brown							
Texas Lignite							
No. 28--H-Coal, Catlettsberg	500	0.3	0.3	0.3	nil	<0.1	nil
Start-up Oil, Coal =		0.3	0.4	0.3	<0.1		
Illinois No. 6	650	10.0	8.6	0.9	0.2	nil	nil
		11.8	8.1	1.5	<0.1		

(Table Continued)

CORROSION RATES[a] OF ALLOYS SUBJECTED TO COAL LIQUIDS[b] FROM COAL LIQUEFACTION PILOT PLANTS[c][45,46], Continued

Coal Liquid[b]	Temperature °F	Corrosion Rate,[a] mils/year: Carbon Steel A515, Gr. 70	5Cr-1/2Mo A387, Gr. 5	410 SS	316 SS	Hastelloy C-276	Incoloy 825
No. 29--H-Coal, Catlettsberg	425	0.5	0.1	0.2	nil	nil	nil
Fractionation Column		0.6	0.2	0.2	nil		
Bottoms, Coal =	500	1.0	1.2	0.5	<0.1	<0.1	<0.1
Illinois No. 6		1.0	1.5	0.7	<0.1		
	575	2.5	1.8	0.7	0.3	<0.1	<0.1
		2.8	2.2	0.8			
No. 30--H-Coal, Catlettsberg	425	13.6	10.8	8.2	<0.1	<0.1	nil
Light Oil, Coal =		12.7	13.0	8.4	0.1		
Illinois No. 6	500	10.7	9.2	3.7	0.1	<0.1	<0.1
		12.0	8.8	4.5	0.1		
	575	8.3	6.2	4.1	0.5	0.2	<0.1
		8.6	6.6	4.4			
No. 31--H-Coal, Catlettsberg	350	3.1	9.1	1.5	nil	nil	nil
Fractionation Column		3.6	9.1	0.6	nil		
Side Draw, Coal =	500	7.3	7.1	5.0	0.1	<0.1	<0.1
Illinois No. 6		6.8	7.1	6.0	<0.1		
No. 32--H-Coal, Catlettsberg	350	0.8	1.0	0.3	nil	<0.1	<0.1
Q207 Bottoms,		0.9	1.0	0.3	<0.1		
Coal = Illinois No. 6	500	3.7	3.5	1.8	<0.1	<0.1	<0.1
		4.0	3.5	2.0	0.1		
No. 33--Exxon Donor Solvent	500	4.7	2.4	0.8	1.0	0.5	0.5
(CLPP), Baytown		4.5	3.7	1.0	nil		
Solvent Hydrogenation	650	14.1	8.5	1.0	0.2	0.2	0.1
Feed, Coal = Big Brown		14.9	10.5	1.6	0.2		
Texas Lignite							
No. 34--Exxon Donor Solvent	500	2.1	1.0	0.3	nil	nil	nil
(ECLP), Baytown		2.0	0.9	0.3	nil		
Bottoms Recycle Mode,	650	35.9	14.7	0.8	1.0	<0.1	nil
Heavy Vacuum Gas Oil,							
Coal = Illinois No. 6							
No. 35--Exxon Donor Solvent	425	3.5	0.4	0.3	<0.1	nil	nil
(ECLP), Baytown		4.6	0.4	0.3	<0.1		
Bottoms Recycle Mode,	500	4.0	3.4	0.3	<0.1	nil	<0.1
Light Vacuum Gas Oil,		3.9	3.7	0.3	<0.1		
Coal = Wyoming Subbitu-	575	5.4	2.3	0.5	<0.1	<0.1	<0.1
minous		5.2	2.1	0.4	<0.1		
No. 36--Exxon Donor Solvent	500	10.5	5.9	1.5	0.2	<0.1	<0.1
(ECLP), Baytown		10.2	6.3	1.4	0.2		
Bottoms Recycle Mode,	575	35.4	13.4	2.0	0.1	<0.1	nil
Light Vacuum Gas Oil,							
Coal = Illinois No. 6							

[a]Values are annual rates extrapolated linearly from metal loss of one test coupon in 100 hour exposures to the test liquids. Test coupons were prepared for testing and evaluated in accordance with ASTM Standard Recommended Practice G-1. Metal loss was determined gravimetrically. In most tests duplicate specimens were exposed and metal loss determined. Where only one value appears above either only one specimen was exposed or the second specimen was reserved for other examination. Carbon steel, 5Cr-1/2Mo steel, and 410 SS were exposed together in one test vessel and 316 SS, Hastelloy C-276, and Incoloy 825 were exposed together in a second vessel.

[b]Coal liquids are here identified as to process, location, and the type of coal used. The portion of the plant from which the liquid was taken is also given. See Section B.1.1.137 for analyses of the as-received liquids. Analyses of liquids not included in B.1.1.137 follow:

Species	Number 14	Number 27	Number 36
Total Sulfur, wt %	0.14	not available	0.36
Hydrogen Sulfide Sulfur, wt %	<0.0001	not available	<0.0001
Mercaptan Sulfur, wt %	0.044	<0.005	0.050
Phenol, % OH^-	1.40	not available	0.89
Phenol % as p-Cresol	8.9	not available	5.67

(Table Continued)

CORROSION RATES[a] OF ALLOYS SUBJECTED TO COAL LIQUIDS[b] FROM COAL LIQUEFACTION PILOT PLANTS[c][45,46], Continued

Footnotes continued

Acid no. mg KOH/g	<0.05	0.01	not available
Base no. mg KOH/g	<0.05	<0.05	not available
Water ppm	489	not available	not available
Total Cl^- ppm	36	not available	not available
Water Soluble Chlorides ppm	59	not available	36
Total Nitrogen, wt %	1.07	0.39	not available
Boiling Range, °F	425-575	>575	425-575

Analysis for Coal Liquid Number 34 not available, boiling range given as >575 °F.
Tests were conducted in accordance with NACE Standard TM-01-69. SRC = Solvent Refined Coal, SRC-I is the process producing solid product, SRC-II is the process producing liquid product.

[c]Pilot plants are identified in the first column under Coal Liquids. Tests and all transfer of liquids were carried out under an inert gas atmosphere (argon-helium mix) to avoid oxygen contamination. Initially autoclave pressures were maintained at 1000 psig but it was found that gases were being absorbed into the test liquids. The pressure was then set to produce a total of 300 psig at the test temperature. Glass liners were used to line the autoclaves when chemical analyses of the liquids run in unlined vessels differed from the chemical analyses of the as-received liquids and when the corrosion rate of 316 SS exceeded 3 mils/year. Test temperatures were based on the boiling range of the liquid and the normal operating temperature in the plant at the location from which the liquid was extracted.

[d]nil = no measurable weight change.

RANKING OF CORROSION RATES[a] FOR FOUR ALLOYS AND CHEMICAL ANALYSES OF COAL LIQUEFACTION LIQUIDS[b][45,46]

Coal Liquid Number[b]	Corrosion[a] mils/year	Total S[c] wt %	H_2S sulfur[d] wt %	Mercaptan[e] S, wt%	Phenol[f] % OH	Acid No.[g] mgKOH/g	Base No.[g] mgKOH/g	Water, ppm[h]	Total Cl[i] ppm	H_2O-soluble[j] Cl, ppm	Total N[k] wt %	Boiling Range, °F
CARBON STEEL, A515 Gr. 70												
28	0.3	0.09	<0.0001	<0.005	0.10	<0.05	<0.05	95	13	0	0.21	>575
13	0.5	0.50	<0.0001	<0.005	0.55	<0.05	<0.05	526	<10	0	1.23	>575
15	0.5	0.02	<0.0001	0.006	0.40	<0.05	<0.05	138	<10	0	0.35	>575
29	1.0	0.12	<0.0001	0.009	0.64	0.1	<0.05	349	14	20	1.03	425-575
25	1.1	0.03	<0.0001	<0.005	0.63	<0.05	4.38	382	15	16	0.21	>575
19	1.4	0.02	<0.0001	0.007	0.37	<0.05	0.1	94	<10	8	0.45	>575
23	2.5	0.12	<0.0001	0.036	1.32	<0.05	<0.05	490	10	7	0.10	425-575
22	2.6	0.27	<0.0001	0.043	0.76	<0.05	0.09	507	<10	7	0.24	>575
16	3.5	0.11	<0.0001	0.009	0.31	0.1	<0.05	371	256	70	0.76	>575
32	3.8	0.14	<0.0001	0.023	0.83	0.1	<0.05	292	65	47	0.50	<425
35	4.0	0.04	<0.0001	0.005	0.76	<0.05	<0.05	123	16	0	0.31	425-575
11	4.4	0.29	<0.0001	0.021	2.71	<0.05	<0.05	393	12	28	0.98	<425
20	4.5	0.08	<0.0001	<0.005	0.33	0.4	<0.05	305	335	290	0.62	>575
33	4.6	0.05	<0.0001	<0.005	0.80	0.1	<0.05	689	24	0	0.39	>575
12	4.8	0.45	<0.0001	0.015	0.63	<0.05	<0.05	64	<10	14	1.16	>575
26	5.1	0.21	0.008	0.084	2.03	<0.05	<0.05	739	95	91	0.11	425-575
17	5.7	0.06	<0.0001	0.010	1.03	<0.05	<0.05	588	<10	5	0.35	<425
4	5.7	0.45	<0.0001	0.026	1.11	0.1	<0.05	310	95	116	0.76	425-575
31	7.1	0.09	<0.0001	0.030	2.25	0.1	<0.05	375	102	95	0.47	<425
21	9.3	1.06	0.21	0.442	1.99	<0.05	<0.05	1012	<10	7	0.16	>575
9	9.3	0.39	<0.0001	0.026	1.50	<0.05	<0.05	200	50	63	1.26	425-575
24	9.7	0.61	<0.0001	0.092	1.02	<0.05	<0.05	133	53	73	0.78	425-575
18	10.2	0.24	0.049	<0.005	1.03	<0.05	5.97	476	10	8	0.59	<425
5	10.7	0.38	<0.0001	0.039	1.27	<0.05	0.05	1080	13	19	0.84	425-575
30	11.3	0.09	<0.0001	0.030	2.13	<0.05	<0.05	733	144	135	0.39	425-575
1	15.1	0.50	0.090	0.070	1.51	<0.05	0.11	1411	<10	6	0.91	425-575
2	15.7	0.68	0.01	0.410	0.31	<0.05	2.6	166	<10	10	1.29	<425
7	19.8	0.29	<0.0001	0.021	5.01	0.1	<0.05	410	132	128	0.63	<425
3	22.7	0.40	<0.0001	0.006	4.96	0.3	ND[1]	4700	<10	5	0.51	<425
6	22.8	0.38	<0.0001	0.044	2.82	0.3	<0.05	64	235	235	1.01	425-575
10	23.6	0.27	<0.0001	0.063	3.86	0.3	<0.05	73	187	191	1.24	<425
8	27.6	0.42	<0.0001	0.034	1.06	0.1	<0.05	430	325	298	1.02	>575
5Cr-1/2Mo STEEL, A387, Gr. 5												
28	0.4	0.09	<0.0001	<0.005	0.10	<0.05	<0.05	95	13	0	0.21	>575
13	0.5	0.50	<0.0001	<0.005	0.55	<0.05	<0.05	526	<10	0	1.23	>575

(Table Continued)

RANKING OF CORROSION RATES[a] FOR FOUR ALLOYS AND CHEMICAL ANALYSES OF COAL LIQUEFACTION LIQUIDS[b][45,46]
Continued

Coal Liquid Number[b]	Corrosion[a] mils/year	Total S[c] wt %	H_2S sulfur[d] wt %	Mercaptan[e] S, wt %	Phenol[f] % OH	Acid No.[g] mgKOH/g	Base No.[g] mgKOH/g	Water, ppm[h]	Total Cl[i] ppm	H_2O-soluble[j] Cl, ppm	Total N[k] wt %	Boiling Range, °F
5Cr-1/2Mo STEEL, A387, Gr. 5, Continued												
15	0.5	0.02	<0.0001	0.006	0.40	<0.05	<0.05	138	<10	0	0.35	>575
4	0.9	0.45	<0.0001	0.026	1.11	0.1	<0.05	310	95	116	0.76	425-575
19	1.0	0.02	<0.0001	0.007	0.37	<0.05	0.1	94	<10	8	0.45	>575
22	1.1	0.27	<0.0001	0.043	0.76	<0.05	0.09	507	<10	7	0.24	>575
29	1.4	0.12	<0.0001	0.009	0.64	0.1	<0.05	349	14	20	1.03	425-575
20	1.7	0.08	<0.0001	<0.005	0.33	0.4	<0.05	305	335	290	0.62	>575
23	1.8	0.12	<0.0001	0.036	1.32	<0.05	<0.05	490	10	7	0.10	425-575
25	1.9	0.03	<0.0001	<0.005	0.63	<0.05	4.38	382	15	16	0.21	>575
5	2.6	0.38	<0.0001	0.039	1.27	<0.05	0.05	1080	13	19	0.84	425-575
33	3.1	0.05	<0.0001	<0.005	0.80	0.1	<0.05	689	24	0	0.39	>575
17	3.3	0.06	<0.0001	0.010	1.03	<0.05	<0.05	588	<10	5	0.35	<425
32	3.5	0.14	<0.0001	0.023	0.83	0.1	<0.05	292	65	47	0.50	<425
35	3.6	0.04	<0.0001	0.005	0.76	<0.05	<0.05	123	16	0	0.31	425-575
12	3.8	0.45	<0.0001	0.015	0.63	<0.05	<0.05	64	<10	14	1.16	>575
16	3.9	0.11	<0.0001	0.009	0.31	0.1	<0.05	371	256	70	0.76	>575
26	4.0	0.21	0.008	0.084	2.03	<0.05	<0.05	739	95	91	0.11	425-575
31	7.1	0.09	<0.0001	0.030	2.55	0.1	<0.05	375	102	95	0.47	<425
21	7.6	1.06	0.21	0.442	1.99	<0.05	<0.05	1012	<10	7	0.16	425-575
24	7.9	0.61	<0.0001	0.092	1.02	<0.05	<0.05	133	53	73	0.78	425-575
9	8.2	0.39	<0.0001	0.026	1.50	<0.05	<0.05	200	50	63	1.26	425-575
3	8.7	0.40	<0.0001	0.006	4.96	0.3	ND[l]	4700	<10	5	0.51	<425
30	9.0	0.09	<0.0001	0.030	2.13	<0.05	<0.05	733	144	135	0.39	425-575
11	9.8	0.29	<0.0001	0.021	2.71	<0.05	<0.05	393	12	28	0.98	<425
18	10.4	0.24	0.049	<0.005	1.03	<0.05	5.97	476	10	8	0.59	<425
1	13.4	0.50	0.090	0.070	1.51	<0.05	0.11	1411	<10	6	0.91	425-575
2	16.5	0.68	0.01	0.410	0.31	<0.05	2.6	166	<10	10	1.29	425-575
6	16.6	0.38	<0.0001	0.044	2.82	0.3	<0.05	64	235	235	1.01	425-575
8	18.8	0.42	<0.0001	0.034	1.06	0.1	<0.05	430	325	298	1.02	>575
7	21.1	0.29	<0.0001	0.021	5.01	0.1	<0.05	410	132	128	0.63	<425
10	22.4	0.27	<0.0001	0.063	3.86	0.3	<0.05	73	187	191	1.24	<425
410 STAINLESS STEEL												
3	0.1	0.40	<0.0001	0.006	4.96	0.3	ND	4700	<10	5	0.51	<425
4	0.2	0.45	<0.0001	0.026	1.11	0.1	<0.05	310	95	116	0.76	425-575
25	0.2	0.03	<0.0001	<0.005	0.63	<0.05	4.38	382	15	16	0.21	>575
5	0.3	0.38	<0.0001	0.039	1.27	<0.05	0.05	1080	13	19	0.84	425-575

(Table Continued)

RANKING OF CORROSION RATES[a] FOR FOUR ALLOYS AND CHEMICAL ANALYSES OF COAL LIQUEFACTION LIQUIDS[b][45,46]
Continued

Coal Liquid Number[b]	Corrosion[a] mils/year	Total S[c] wt %	H_2S sulfur[d] wt %	Mercaptan[e] S, wt %	Phenol[f] % OH	Acid No.[g] mgKOH/g	Base No.[g] mgKOH/g	Water, ppm[h]	Total Cl[i] ppm	H_2O-soluble[j] Cl, ppm	Total N[k] wt %	Boiling Range, °F
-410 STAINLESS STEEL, Continued-												
28	0.3	0.09	<0.0001	0.005	0.10	<0.05	<0.05	95	13	0	0.21	>575
35	0.3	0.04	<0.0001	0.005	0.76	<0.05	<0.05	123	16	0	0.31	425-575
13	0.4	0.50	<0.0001	<0.005	0.55	<0.05	<0.05	526	<10	0	1.23	>575
15	0.4	0.02	<0.0001	0.006	0.41	<0.05	<0.05	138	<10	0	0.35	>575
11	0.5	0.29	<0.0001	0.021	2.71	<0.05	<0.05	393	12	28	0.98	<425
20	0.5	0.08	<0.0001	<0.005	0.33	0.4	<0.05	305	335	290	0.62	>575
19	0.6	0.02	<0.0001	0.007	0.37	<0.05	0.1	94	<10	8	0.45	>575
29	0.6	0.12	<0.0001	0.009	0.64	0.1	<0.05	349	14	20	1.03	425-575
16	0.9	0.11	<0.0001	0.009	0.31	0.1	<0.05	371	256	70	0.76	>575
17	0.9	0.06	<0.0001	0.010	1.03	<0.05	<0.05	588	<10	5	0.35	<425
33	0.9	0.05	<0.0001	<0.005	0.80	0.1	<0.05	689	24	0	0.39	>575
26	1.3	0.21	0.008	0.084	2.03	<0.05	<0.05	739	95	91	0.11	425-575
12	1.4	0.45	<0.0001	0.015	0.63	<0.05	<0.05	64	<10	14	1.16	>575
23	1.5	0.12	<0.0001	0.036	1.32	<0.05	<0.05	490	10	7	0.10	425-575
7	1.8	0.29	<0.0001	0.021	5.01	0.1	<0.05	410	132	128	0.63	<425
32	1.9	0.14	<0.0001	0.023	0.83	0.1	<0.05	292	65	47	0.50	<425
18	2.0	0.24	0.049	<0.005	1.03	<0.05	5.97	476	10	8	0.59	<425
21	2.4	1.06	0.21	0.442	1.99	<0.05	<0.05	1012	<10	7	0.16	425-575
8	3.3	0.42	<0.0001	0.034	1.06	0.1	<0.05	430	325	298	1.02	>575
10	3.4	0.27	<0.0001	0.063	3.86	0.3	<0.05	73	187	191	1.24	<425
24	3.4	0.61	<0.0001	0.092	1.02	<0.05	<0.05	133	53	73	0.78	425-575
1	4.1	0.50	0.090	0.070	1.51	<0.05	0.11	1411	<10	6	0.91	425-575
30	4.1	0.09	<0.0001	0.030	2.13	<0.05	<0.05	733	144	135	0.39	425-575
22	5.1	0.27	<0.0001	0.043	0.76	<0.05	0.09	507	<10	7	0.24	>575
9	5.3	0.39	<0.0001	0.026	1.50	<0.05	<0.05	200	50	63	1.26	425-575
31	5.5	0.09	<0.0001	0.030	2.25	0.1	<0.05	375	102	95	0.47	<425
2	7.5	0.68	0.01	0.410	0.31	<0.05	2.6	166	<10	10	1.29	425-575
6	9.6	0.38	<0.0001	0.044	2.82	0.3	<0.05	64	235	235	1.01	425-575
-316 STAINLESS STEEL-												
1	nil[m]	0.50	0.090	0.070	1.51	<0.05	0.11	1411	<10	6	0.91	425-575
2	nil	0.68	0.010	0.410	0.31	<0.05	2.6	166	<10	10	1.29	<425
5	nil	0.38	<0.0001	0.039	1.27	<0.05	0.05	1080	13	19	0.84	425-575
7	nil	0.29	<0.0001	0.021	5.01	0.1	<0.05	410	132	128	0.63	<425
8	nil	0.42	<0.0001	0.034	1.06	0.1	<0.05	430	325	298	1.02	>575
11	<0.1	0.29	<0.0001	0.021	2.71	<0.05	<0.05	393	12	28	0.98	<425

(Table Continued)

RANKING OF CORROSION RATES[a] FOR FOUR ALLOYS AND CHEMICAL ANALYSES OF COAL LIQUEFACTION LIQUIDS[b][45,46]
Continued

Coal Liquid Number[b]	Corrosion[a] mils/year	Total S[c] wt %	H_2S sulfur[d] wt %	Mercaptan[e] S, wt %	Phenol[f] % OH	Acid No.[g] mgKOH/g	Base No.[g] mgKOH/g	Water, ppm[h]	Total Cl[i] ppm	H_2O-soluble[j] Cl, ppm	Total N[k] wt %	Boiling Range, °F
-316 STAINLESS STEEL, Continued-												
13	<0.1	0.50	<0.0001	<0.005	0.55	<0.05	<0.05	526	<10	0	1.23	>575
17	<0.1	0.06	<0.0001	0.010	1.03	<0.05	<0.05	588	<10	5	0.35	<425
28	<0.1	0.09	<0.0001	0.005	0.10	<0.05	<0.05	95	13	0	0.21	>575
20	<0.1	0.08	<0.0001	<0.005	0.33	0.4	<0.05	305	335	290	0.62	>575
21	<0.1	1.06	0.21	0.442	1.99	<0.05	<0.05	1012	<10	7	0.16	>575
29	<0.1	0.12	<0.0001	0.009	0.64	0.1	<0.05	349	14	20	1.03	425-575
31	<0.1	0.09	<0.0001	0.030	2.25	0.1	<0.05	375	102	95	0.47	<425
32	<0.1	0.14	<0.0001	0.023	0.83	0.1	<0.05	292	65	47	0.50	<425
35	<0.1	0.04	<0.0001	0.005	0.76	<0.05	<0.05	123	16	0	0.31	425-575
4	0.1	0.45	<0.0001	0.026	1.11	0.1	<0.05	310	95	116	0.76	425-575
9	0.1	0.39	<0.0001	0.026	1.50	<0.05	<0.05	200	50	63	1.26	425-575
15	0.1	0.02	<0.0001	0.006	0.40	<0.05	<0.05	138	<10	0	0.35	>575
18	0.1	0.24	0.049	<0.005	1.03	<0.05	5.97	476	10	8	0.59	<425
30	0.1	0.09	<0.0001	0.030	2.13	<0.05	<0.05	733	144	135	0.39	425-575
16	0.2	0.11	<0.0001	0.009	0.31	0.1	<0.05	371	256	70	0.76	>575
25	0.2	0.03	<0.0001	<0.005	0.63	<0.05	4.38	382	15	16	0.21	>575
22	0.2	0.27	<0.0001	0.043	0.76	<0.05	0.1	507	<10	7	0.24	>575
24	0.2	0.61	<0.0001	0.092	1.02	<0.05	<0.05	133	53	73	0.78	425-575
3	0.3	0.40	<0.0001	0.006	4.96	0.3	ND	4700	<10	5	0.51	<425
10	0.3	0.27	<0.0001	0.063	3.86	0.3	<0.05	73	187	191	1.24	<425
19	0.3	0.02	<0.0001	0.007	0.37	<0.05	0.1	94	<10	8	0.45	>575
26	0.3	0.21	0.008	0.084	2.03	<0.05	<0.05	739	95	91	0.11	425-575
6	0.4	0.38	<0.0001	<0.044	2.82	0.3	<0.05	64	235	235	1.01	425-575
33	0.5	0.05	<0.0001	0.005	0.80	0.1	<0.05	689	24	0	0.39	>575
12	0.6	0.45	<0.0001	0.015	0.63	<0.05	<0.05	64	<10	14	1.16	>575

[a]Values are annual rates extrapolated linearly from metal loss determined gravimetrically. In most cases the values are the average of two specimens. Exposure to liquids was at 500 °F for 100 hours. Test coupons were prepared for testing and evaluated in accordance with ASTM Standard Recommended Practice G-1.

[b]Coal liquids are identified by number. See Section B.1.1.136 for identification of process, location of plant, type of coal used, and portion of plant from which liquid was taken. Tests were conducted in accordance with NACE Standard TM-01-69. See footnote c of Section B.1.1.136 for information about corrosion testing and data at temperatures other than 500 °F.

[c]Total sulfur determined using a modification of ASTM D-2622, an x-ray spectrographic method using energy-dispersive x-ray fluorescence analysis. Tests for elementary sulfur, reactive polysulfidic sulfur, and for disulfides were found to yield low and essentially constant amounts. Results are not included.

[d]Hydrogen sulfide sulfur determined by ASTM D-2385, Cadmium sulfate-iodometric titration.

(Table Continued)

RANKING OF CORROSION RATES[a] FOR FOUR ALLOYS AND CHEMICAL ANALYSES OF COAL LIQUEFACTION LIQUIDS[b][45,46]
Continued

Footnotes continued

[e]Mercaptans determined by ASTM D-3227, potentiometric method.

[f]Phenols determined by a modified version of ASTM D-2668, infrared absorption method.

[g]Acid and Base numbers determined by ASTM D-664, potentiometric titration of organic acids and bases.

[h]Water was determined by a chromatographic technique.

[i]Total chloride was determined by energy-dispersive x-ray fluorescence analysis.

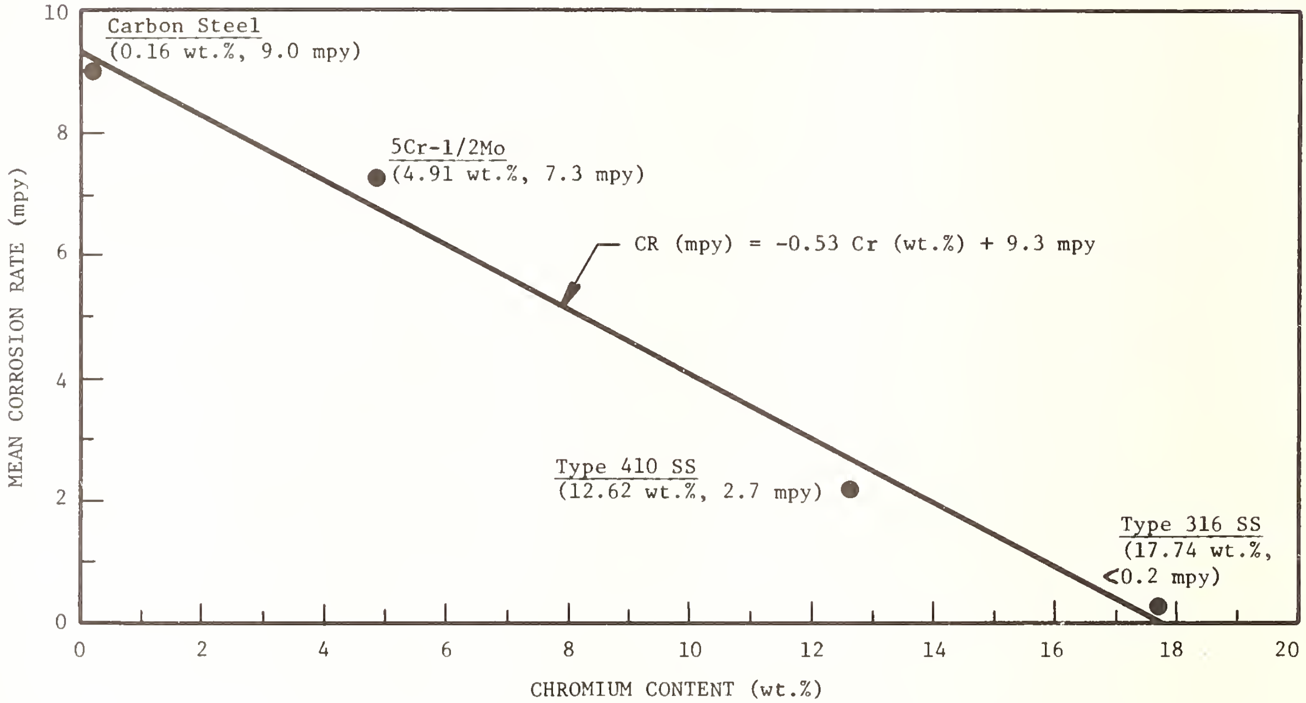
[j]Water-soluble chloride determined by extraction with water and titration with silver nitrate.

[k]Total nitrogen determined by cheminluminescence method. Nitrogen in the sample is oxidized to NO and then to activated NO_2 with ozone. Activated NO_2 reverts to normal NO_2 liberating light, the intensity of which is proportional to the total nitrogen in the sample.

[l]ND = not determined.

[m]nil = no measureable weight.

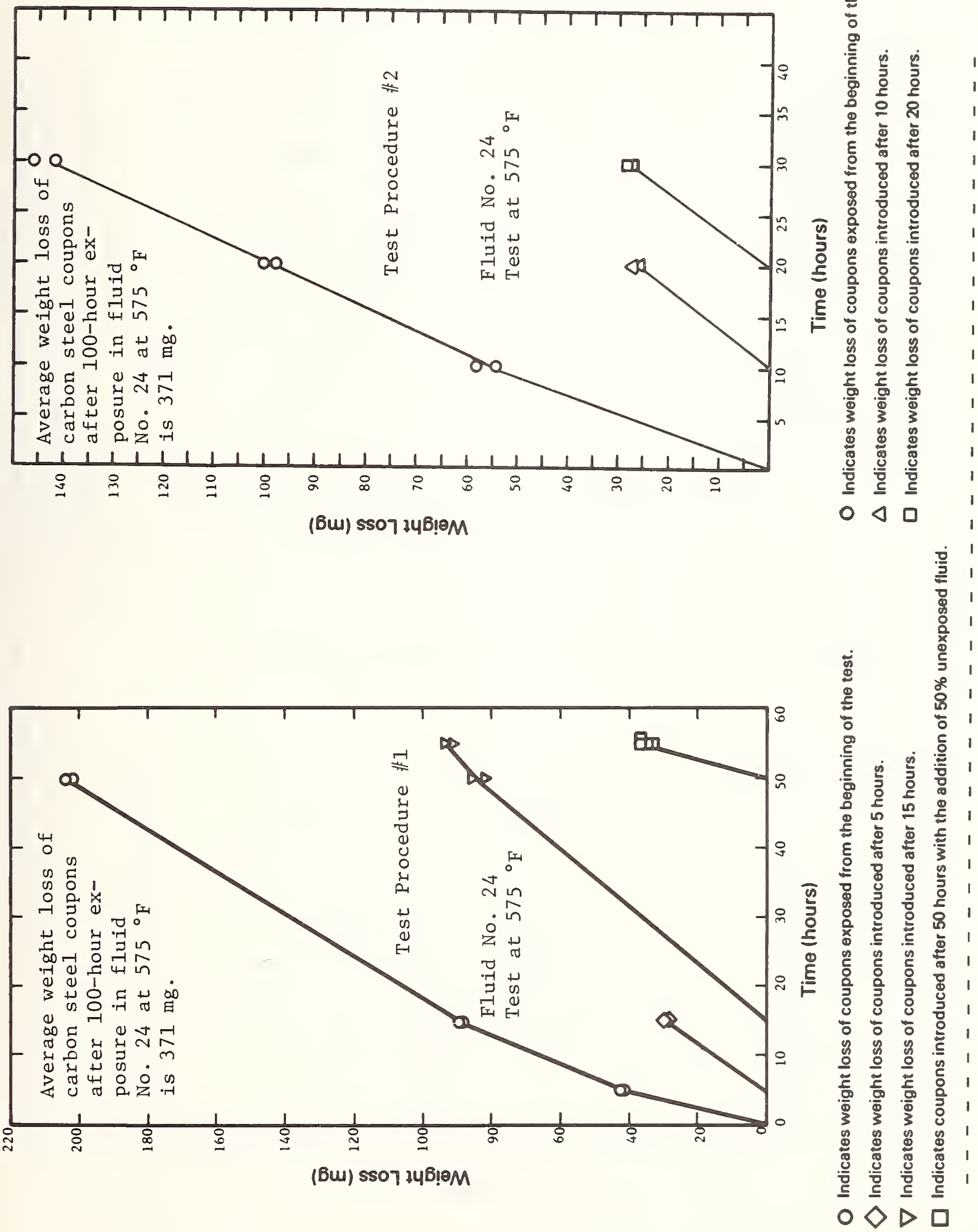
MEAN CORROSION RATES[a] OF ALLOYS[b] IN COAL LIQUEFACTION LIQUIDS AT 500 °F VERSUS ALLOY CHROMIUM CONTENT[45,46]



[a]Mean corrosion rates based on data of Sections B.1.1.137. See footnotes of Section B.1.1.137 for methods of testing in liquids taken from several coal liquefaction pilot plants.

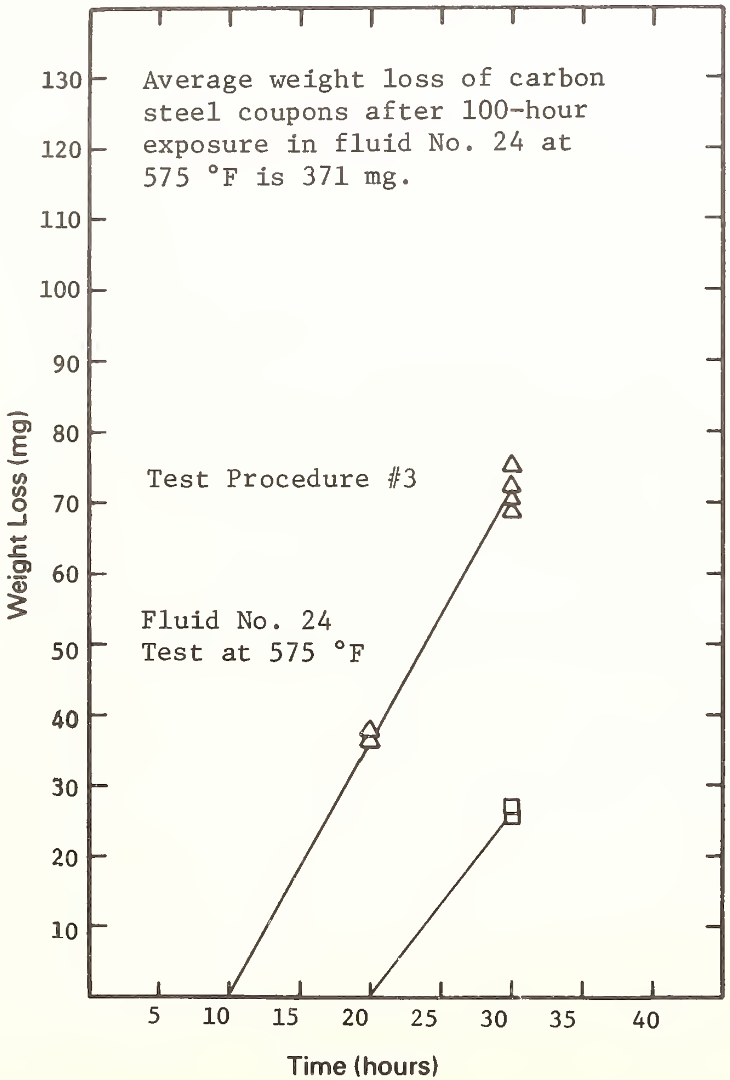
[b]Carbon steel (A515 Gr. 70), 5Cr-1/2Mo steel (A387 Gr. 5), 410 stainless steel, 316 stainless steel.

WEIGHT LOSS[a] OF CARBON STEEL[b] VERSUS TIME IN COAL LIQUEFACTION LIQUIDS[c] [45,46]



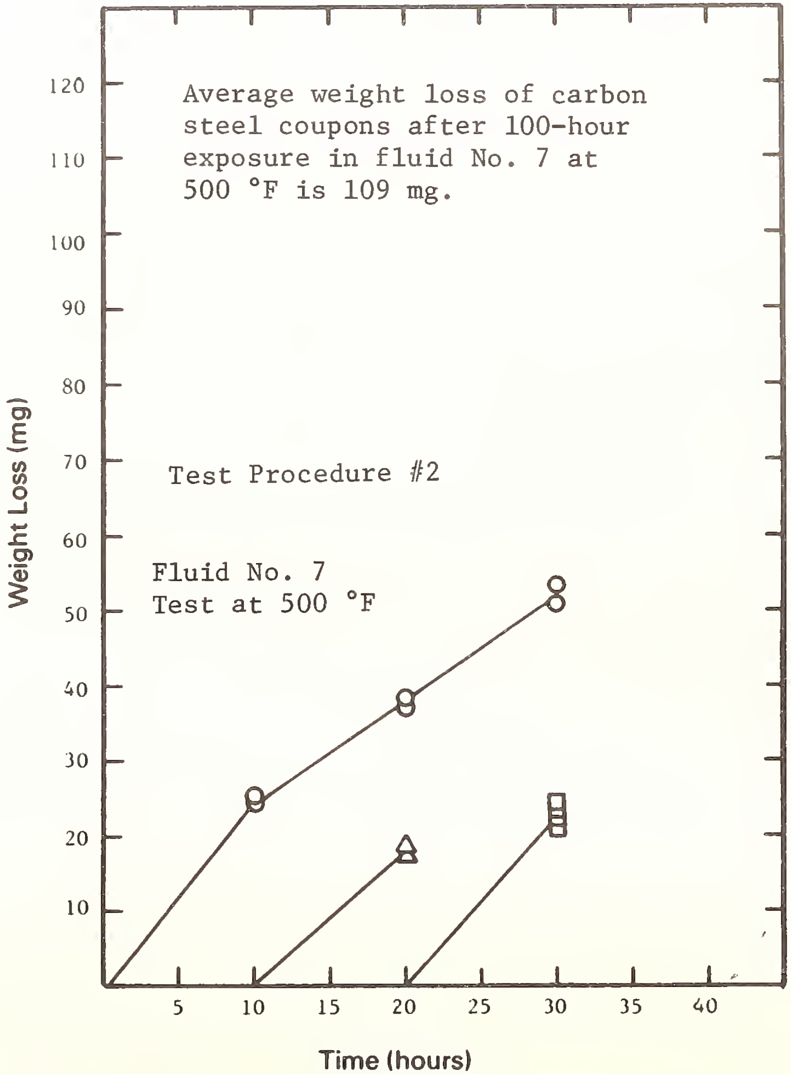
(Data Continued)

WEIGHT LOSS[a] OF CARBON STEEL[b] VERSUS TIME IN COAL LIQUEFACTION LIQUIDS[c] [45,46], Continued



△ Indicates weight loss of coupons introduced after 10 hours.

□ Indicates weight loss of coupons introduced after 20 hours.



○ Indicates weight loss of coupons exposed from the beginning of the test.

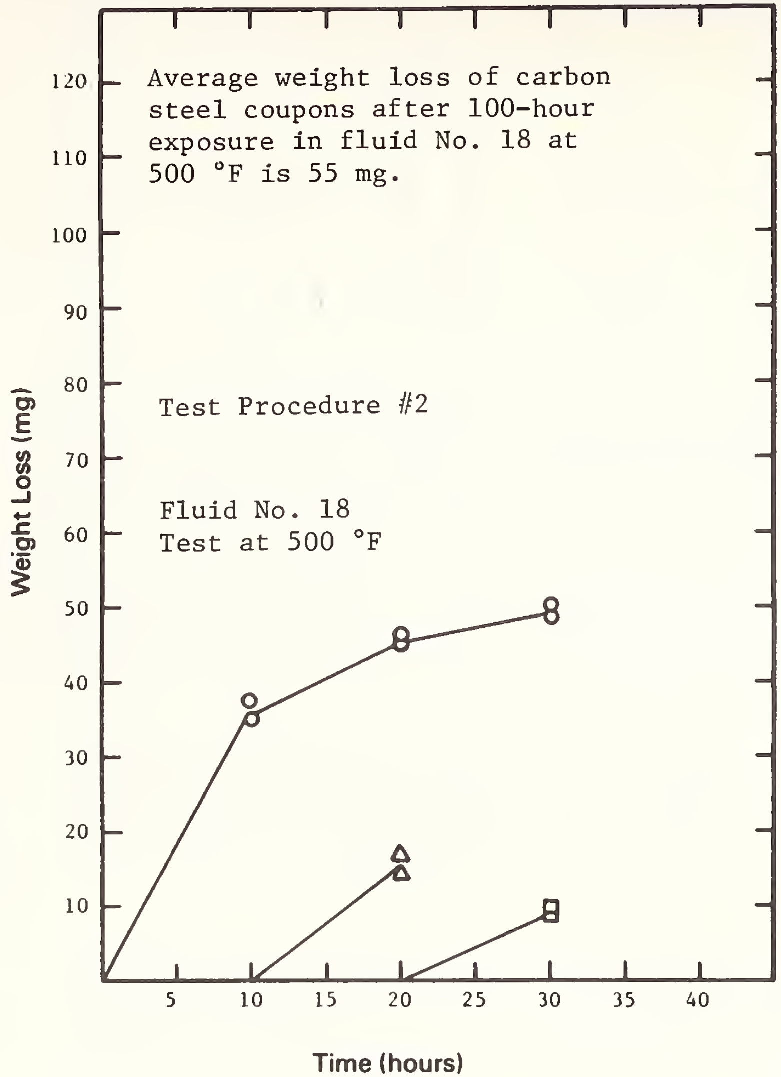
△ Indicates weight loss of coupons introduced after 10 hours.

□ Indicates weight loss of coupons introduced after 20 hours.

- -

(Data Continued)

WEIGHT LOSS[a] OF CARBON STEEL[b] VERSUS TIME IN COAL LIQUEFACTION LIQUIDS[c][45,46], Continued



○ Indicates weight loss of coupons exposed from the beginning of the test.

△ Indicates weight loss of coupons introduced after 10 hours.

□ Indicates weight loss of coupons introduced after 20 hours.

[a] See Sections B.1.1.136 and B.1.1.137 for the type of testing being done. For these tests six coupons were exposed at a time in the autoclaves according to the following procedures:

Test Procedure #1--After 5 hours exposure, the autoclave was cooled to room temperature. Two of the coupons were removed, cleaned, weighed, and replaced by 2 fresh coupons. The autoclave was deaerated with argon and reheated to 575 °F. After 10 more hours (total 15 hours) exposure the autoclave was again opened, cooled. Two more original coupons were removed as well as the two inserted at the beginning of the 10-hour period. All 4 coupons were cleaned and weighed. Four fresh coupons were inserted, the autoclave deaerated and reheated and the test continued for another 35 hours (total 50 hours). The last 2 original coupons and 2 of the 4 inserted at the beginning of the 35-hour period were removed. Four fresh coupons were inserted, 50 % of the solution was replaced with fresh, and the test continued for 5 more hours. All coupons were then removed, cleaned, and weighed.

Test Procedure #2--This procedure differs from #1 in that 2 of the original coupons were removed after 10 hours and were replaced by 2 fresh ones for 10 more hours (total 20 hours). Two more original as well as the 2 new ones were removed and 4 fresh ones inserted. After 10 more hours exposure (total 30 hours) all coupons were removed for cleaning and weighing.

Test Procedure #3--This procedure differs from #1 in that the first 10-hour period included heating the liquid in the glass-lined autoclave with no coupons, then following procedure #2 for a total of 20 hours.

[b] Carbon steel, A515 Gr. 70.

[c] See Sections B.1.1.136 and B.1.1.137 for source of liquids and analyses. The fluid numbers on these figures correspond to the liquid numbers in B.1.1.136.

CORROSION TESTS[a] OF CARBON STEEL[b] IN SYNTHETIC COAL LIQUEFACTION SOLUTIONS[45,46]

Test No.	Temperature °F	Component Concentrations: Tetralin[c] wt %	Phenol[d] wt %	Total Nitrogen[e] wt %	Water-Soluble Cl^-[f], ppm	Corrosion Rate, mils/yr
1	350	76.6	19.9	0.36	0[g]	0.0
2	350	76.6	20.1	0.35	10[g]	0.8
3	350	76.6	19.4	0.47	114[h]	21.8
4	350	76.6	19.7	0.34	241[h]	4.4
5	350	76.6	19.8	0.34	648	220.2
6	350	76.6	19.5	0.36	602	216.6
7	500	76.6	19.8	0.34	0[g]	3.8
8	500	76.6	21.0	0.36	0[g]	0.0
9	500	76.6	19.9	0.35	261[h]	64.2
10	500	76.6	19.6	0.35	173[h]	24.5
11	500	76.6	20.9	0.33	691	194.2
12	500	76.6	18.9	0.45	368	111.4
13	350	100.0	0.0[i]	0.0[i]	0[i]	1.5
14	500	100.0	0.0[i]	0.0[i]	0[i]	2.5
15	350	96.8	0.0[i]	0.40[i]	800[i]	35.7
16	500	96.8	0.0	0.38	84	90.4
17	350	79.4	19.6	0.03	654	123.2
18	500	79.4	19.4	0.03	584	26.2
19[j]	350	76.1	20.3[i]	0.40[i]	761	210.7
20[j]	500	76.1	20.3[i]	0.40[i]	499	97.5
21[j]	350	78.9	20.3[i]	0.03[i]	696	42.5
22[j]	350	99.2	0.0[i]	0.03[i]	6	10.6
23	350	99.7	0.0[i]	0.03[i]	355	95.3
24[j]	350	96.4	0.0[i]	0.40[i]	358	91.3
25[j]	350	79.0	20.3[i]	0.03[i]	0[i]	3.6
26[j]	350	96.7	0.0[i]	0.40[i]	0[i]	0.9
27	275	76.6	20.3[i]	0.40[i]	746	250.4
28	425	76.6	20.3[i]	0.40[i]	194	83.9
		n-Hexadecane[k] wt %	Phenol[l] wt %	Total Nitrogen[m] wt %	Water-Soluble Cl^-[n], ppm	Corrosion Rate, mils/yr
29	350	68.94	27.05	0.43	0	0.0
30	350	68.94	27.05	0.43	0	0.0
31	350	68.84	27.04	0.44	330	125.3
32	350	68.84	27.04	0.44	330	143.5
33	350	68.79	27.04	0.44	900	543.9
34	350	68.79	27.04	0.44	900	468.9
35	500	68.94	27.05	0.43	0	0.6
36	500	68.94	27.05	0.43	0	0.0
37	500	68.84	27.04	0.44	330	118.8
38	500	68.84	27.04	0.44	330	191.2

(Table Continued)

CORROSION TESTS[a] OF CARBON STEEL[b] IN SYNTHETIC COAL LIQUEFACTION SOLUTIONS[45,46], Continued

Test No.	Temperature °F	Component Concentrations: n-Hexadecane[k] wt %	Phenol[l] wt %	Total Nitrogen[m] wt %	Water-Soluble Cl^-[n], ppm	Corrosion Rate, mils/yr
39	500	68.79	27.04	0.44	900	536.1
40	500	68.79	27.04	0.44	900	382.1
41[o]	500	68.79	27.04	0.44	900	123.4
42	500	68.92	27.06	0.44	330[p]	3.2
43	500	68.97	27.11	0.44	900[p]	5.3

[a]Tests were conducted with synthetic solutions to determine the effect of amine hydrochloride concentration, temperature, and solution boiling point. Tests 1-28 used tetralin as the hydrocarbon solvent with boiling point 405 °F, tests 29-43 used n-hexadecane with boiling point 549 °F. The other constituents used are noted in the following footnotes. In both sets of tests phenol concentration was adjusted to obtain an OH concentration of ~3.2 wt % and the amine and/or amine hydrochloride concentration was adjusted to a total nitrogen concentration of ~0.40 wt %. Each test was for 25 hours except test 41 which was for 100 hours. The solution volume was 1.1 liter and only one coupon was exposed per test. The corrosion rates given in the last column of the table are linearly extrapolated values based on the one specimen exposed for 25 hours. See footnotes of Sections B.1.1.136 and B.1.1.137 for other information about the test methods.

[b]One carbon steel (A515 Gr. 70) coupon (3/4 x 3/4 x 1/16 inch) was exposed per test.

[c]As-mixed value, determined from the weights of species mixed.

[d]Added as p-cresol, pre-test value determined by chemical analysis of solution removed from the autoclave before test at or near ambient temperature after stirring for 30 minutes. 20.3 wt % p-cresol = 3.19 wt % OH.

[e]Added as meta-toluidine and/or meta-toluidine hydrochloride, pre-test value, see footnote d.

[f]Added as meta-toluidine hydrochloride, pre-test value, see footnote d.

[g]No chloride added, pre-test value, see footnote d.

[h]300 ppm chloride added as meta-toluidine, pre-test value, see footnote d.

[i]By weight as mixed, analysis not completed.

[j]Water added to these test solutions to a concentration of 0.5 wt % water. Other solutions were not analyzed for water.

[k]As-mixed value, determined from the weights of species mixed.

[l]As-mixed, added as α-naphthol. 27.05 wt % α-naphthol = 3.19 wt % OH.

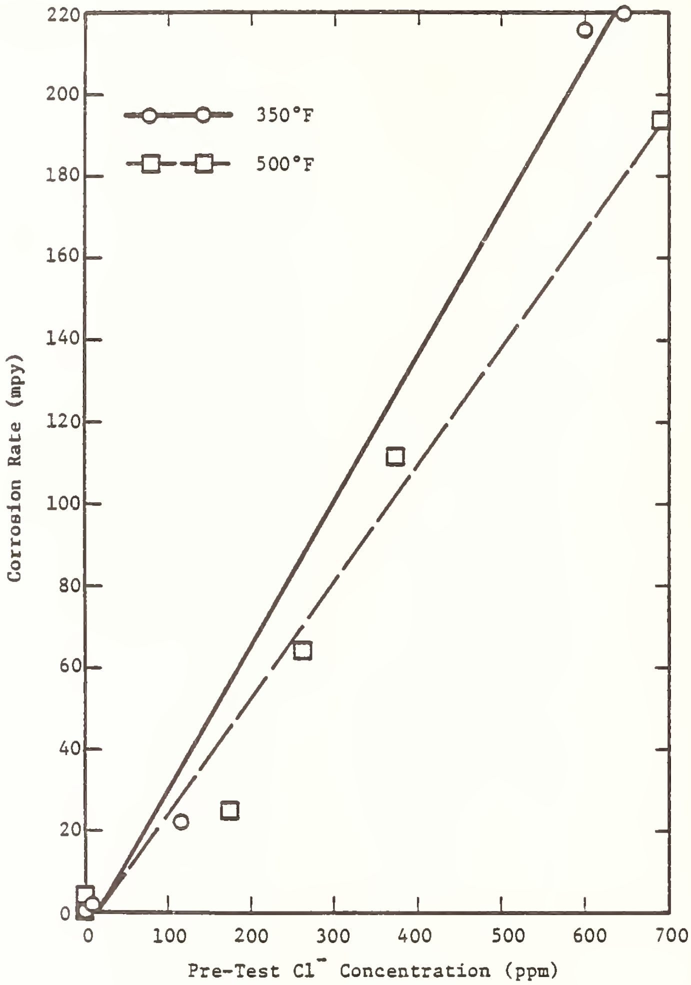
[m]As-mixed, added as quinoline and quinoline hydrochloride.

[n]As-mixed, added as quinoline hydrochloride.

[o]Test duration 100 hours.

[p]Chloride added as NaCl.

EFFECT OF CHLORIDE CONCENTRATION[a] OF SYNTHETIC COAL LIQUEFACTION TEST SOLUTIONS[b] ON CORROSION RATE OF CARBON STEEL[c][45,46]



[a]Pre-test concentration, determined by chemical analysis of the as-mixed test solution at or near room temperature.

[b]Test solutions consisted of tetralin to which para-cresol, meta-toluidine, and meta-toluidine hydrochloride were added. See Section B.1.1.140, tests 1 through 18 for data from which this figure was plotted.

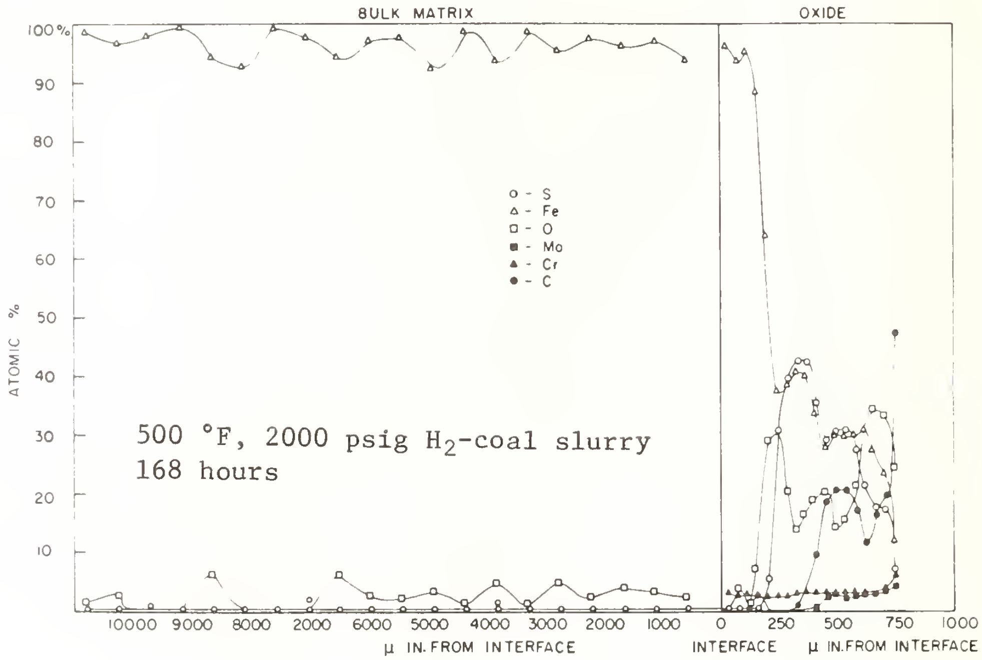
[c]Carbon steel, A515 Gr. 70.

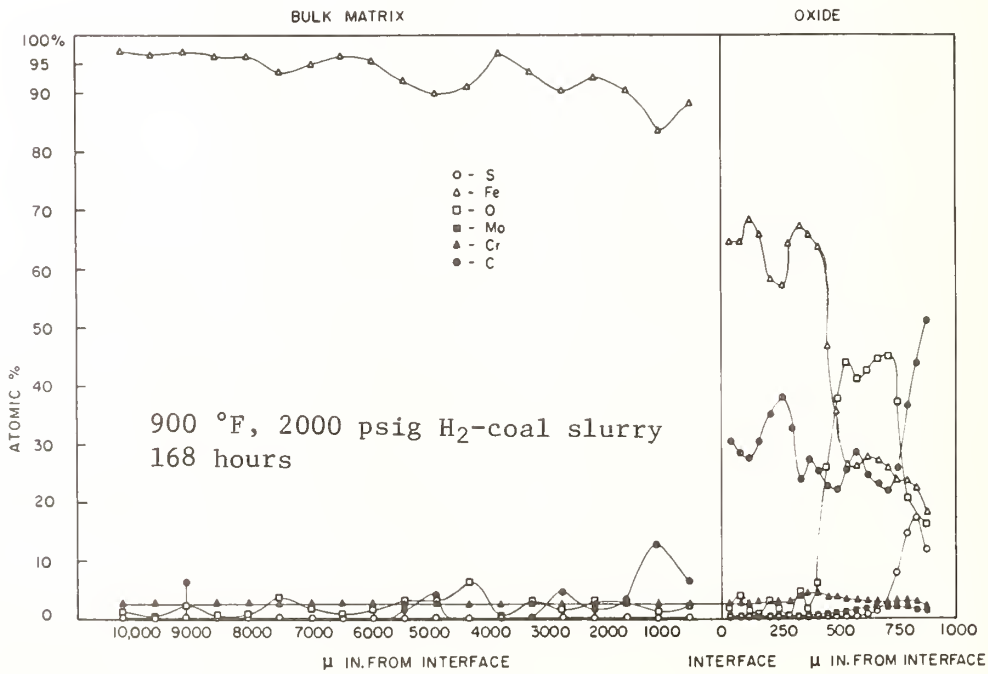
CORROSION TESTING[a] OF SOME ALLOYS[48]

Alloy	Weight Change (gm/cm^2)	Loss of Substrate Thickness (in.)	Scale Thickness (in.)	Penetration (in.)
1015 Carbon Steel	+0.253	0.059	32×10^{-3}	--
	+0.171	0.020	49×10^{-3}	--
Incoloy 800	+0.001	0.002	0.1×10^{-3}	0.5×10^{-3}
	+0.061	0.002	0.1×10^{-3}	1×10^{-3}
304 SS	+0.024	0.002	0.5×10^{-3}	2×10^{-3}
	+0.003	0.004	3×10^{-3}	5×10^{-3}
Stellite 6B	+0.007	0.018	0.1×10^{-3}	4×10^{-3}
	+0.003	0.002	0.3×10^{-3}	2×10^{-3}

[a]Corrosion tests were performed at 816 °C (1500 °F) in a simulated coal gasification atmosphere (CO 18, CO_2 12, CH_4 5, H_2 24, H_2O 39, NH_3 1, H_2S 1, all volume percent; calculated equilibrium potentials, oxygen 5.4×10^{-19}, sulfur 3.5×10^{-7}, and carbon activity 0.0214). Test time was 150 hours at atmospheric pressure. Two separate tests were conducted and the data combined in this single table.

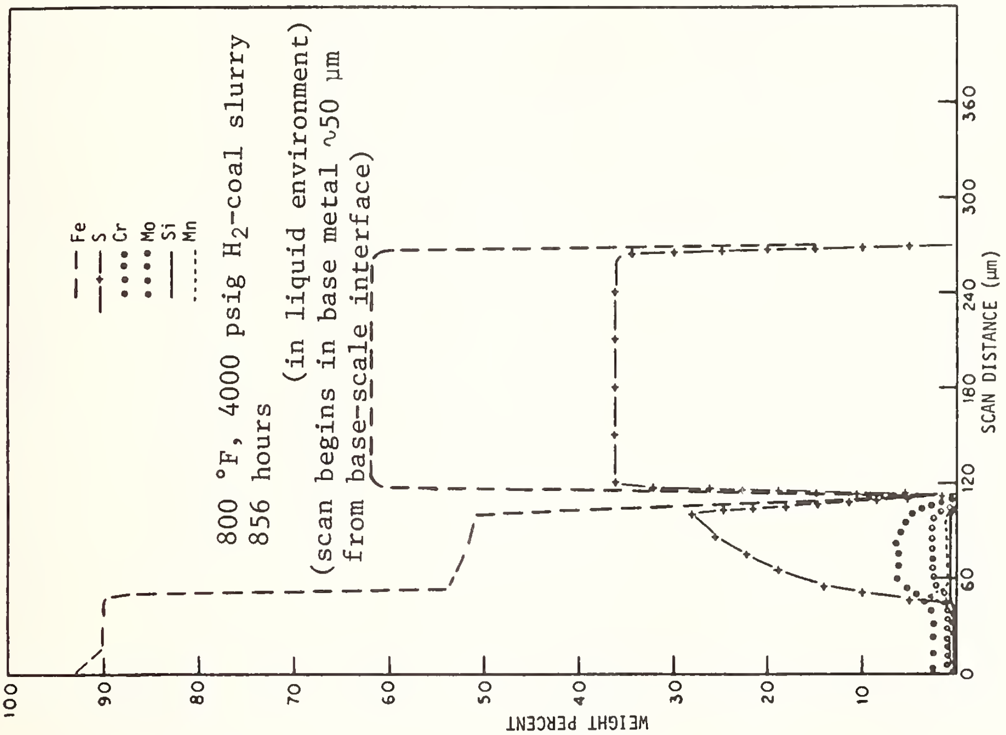
ANALYSES[a] OF SCALE FORMED ON 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN-COAL SLURRY ENVIRONMENT[c][47]

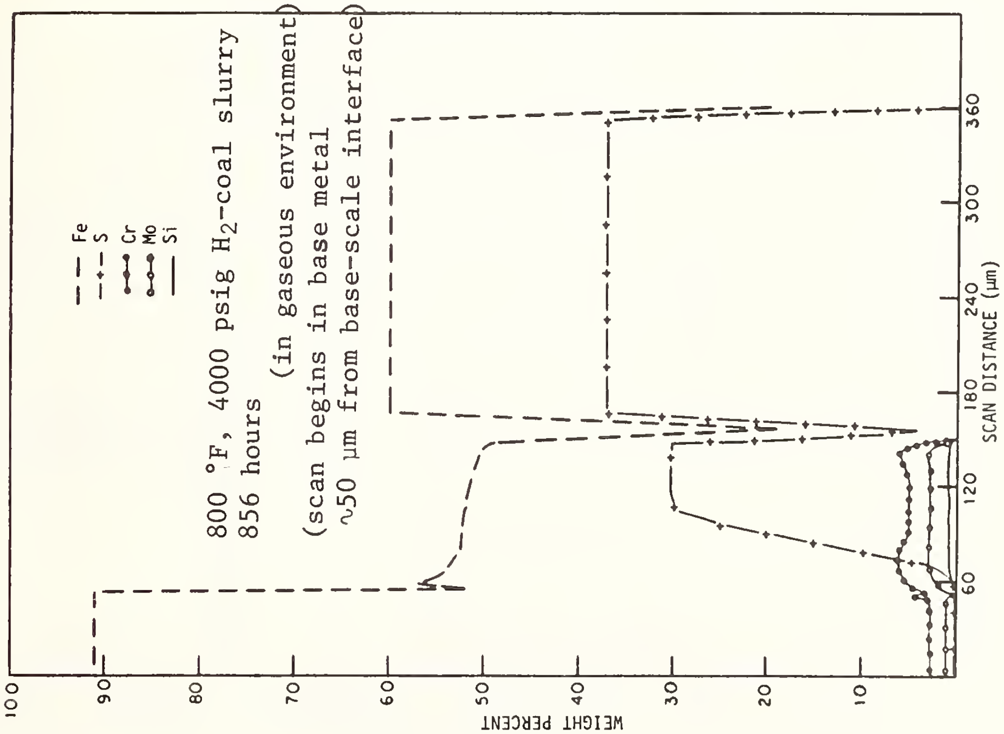




(Data Continued)

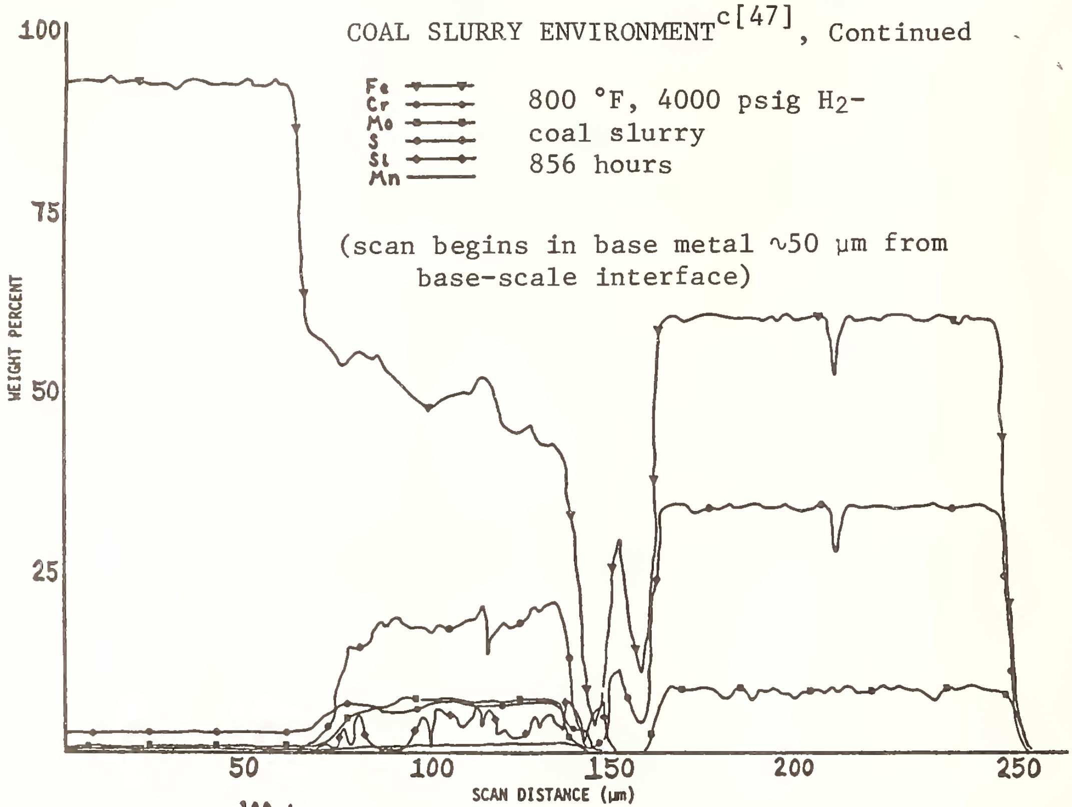
ANALYSES[a] OF SCALE FORMED ON 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN-COAL SLURRY ENVIRONMENT[c][47], Continued

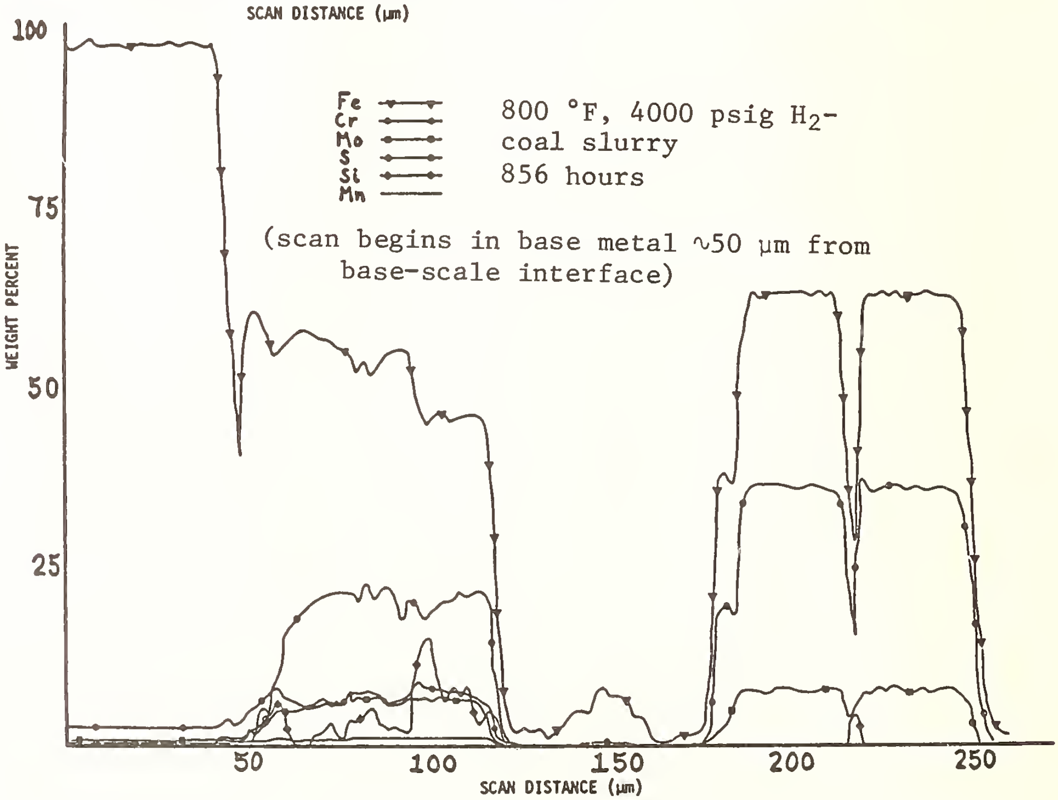




(Data Continued)

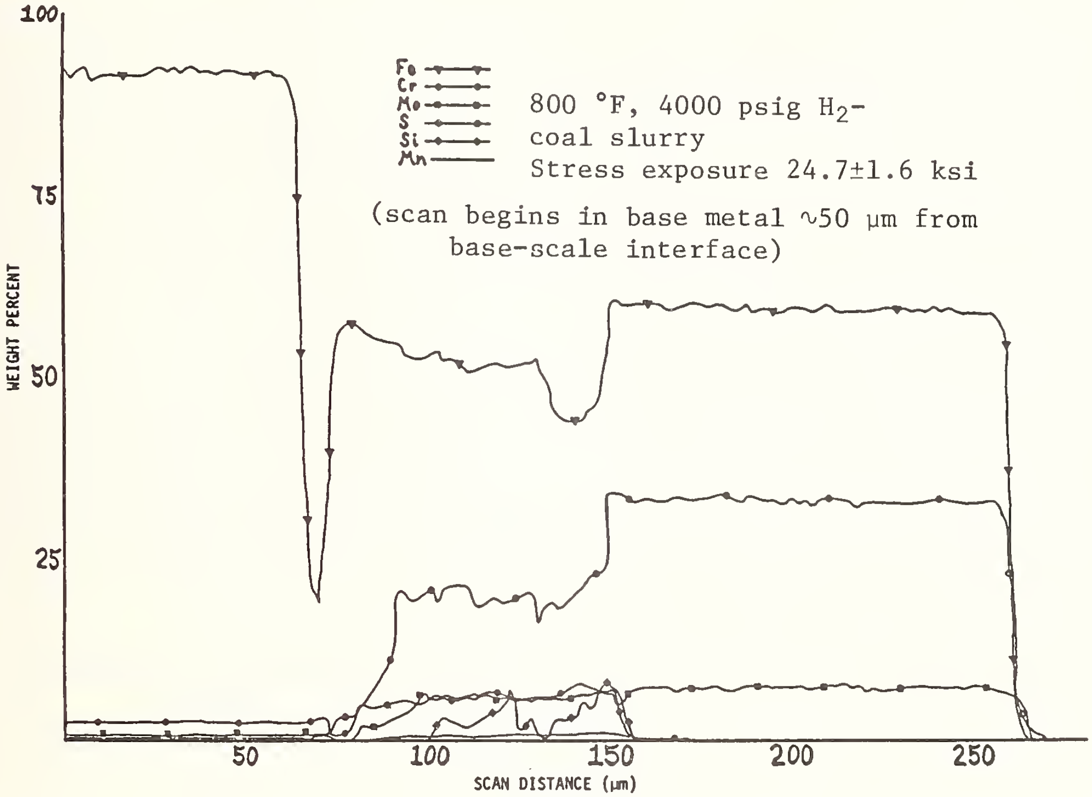
ANALYSES[a] OF SCALE FORMED ON 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN-COAL SLURRY ENVIRONMENT[c][47], Continued





(Data Continued)

ANALYSES[a] OF SCALE FORMED ON 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN-COAL SLURRY ENVIRONMENT[c][47], Continued



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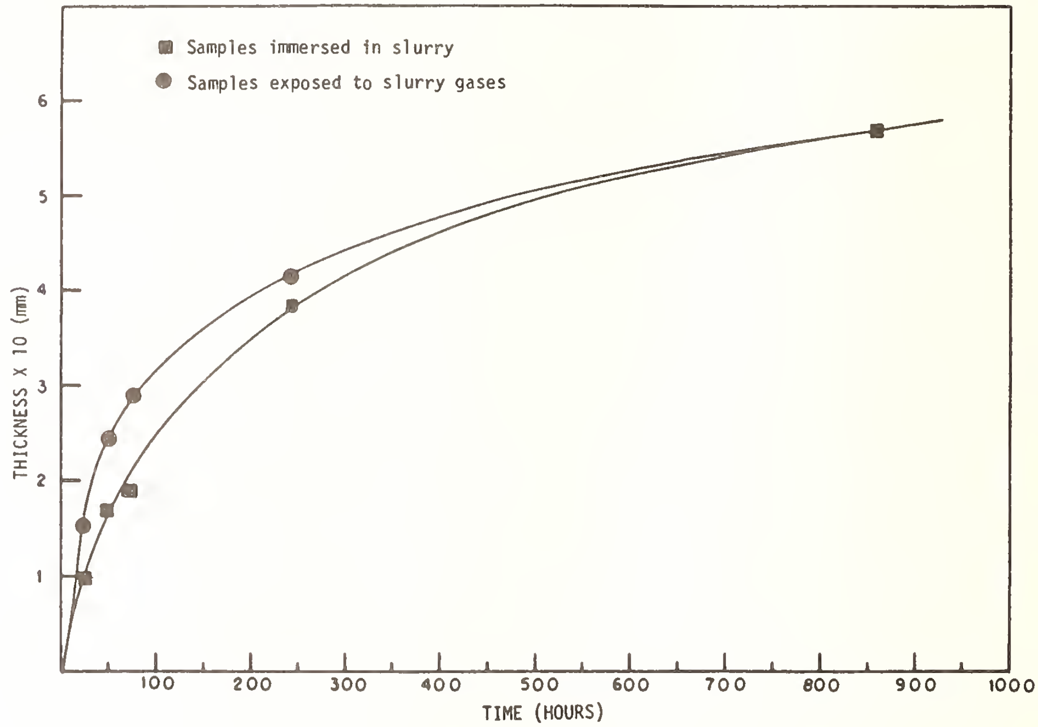
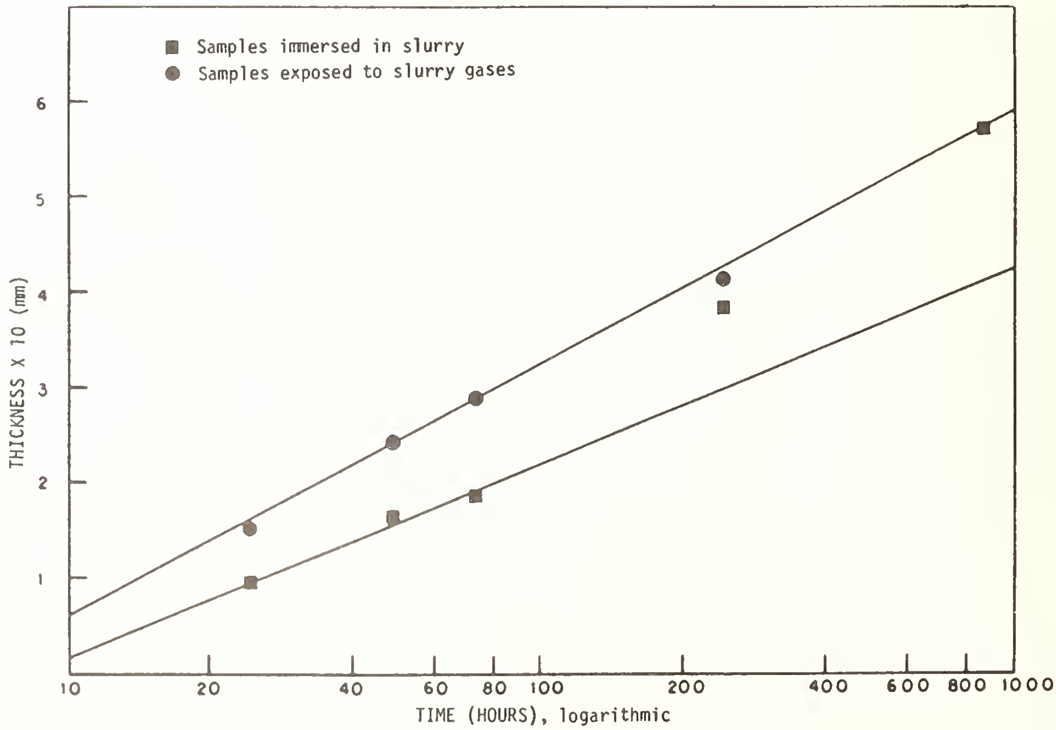
[a]Electron microprobe scans of exposed tensile specimens which were sectioned longitudinally, mounted in conducting Bakelite, mechanically polished, and etched. (Oxide scale layers were also scraped off and analyzed by x-ray fluorescence. The results corroborated the electron microprobe data.)

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled. For the stress exposure the specimen was loaded in tension via precompressed loading ring.

[c]Coal slurry is 35 vol % of -100 mesh Kentucky bituminous and 65 % solvent. The solvent is centrifuged Synthoil product from Pittsburgh Energy Technology Center run FB-61 using the same Kentucky bituminous. Solvent analysis (in wt %): oils 64.4, asphaltenes 32.3, organic benzene insolubles 3.3.

CORROSION SCALE THICKNESS[a] VERSUS TIME FOR 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN-COAL SLURRY ENVIRONMENT[c] [47]





(Data Continued)

CORROSION SCALE THICKNESS[a] VERSUS TIME FOR 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN-COAL SLURRY ENVIRONMENT[c][47], Continued

Footnotes

[a]After exposure specimens were cleaned with acetone and mounted in conducting Bakelite, ground mechanically and polished. Scale thickness was measured microscopically, six measurements of each samples being made at random. The values for each two like samples were averaged.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held at 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled. One inch cylindrical specimens, 0.212 inch diameter, were prepared from longitudinal sections of plate.

[c]Specimens were exposed to coal slurry in hydrogen atmosphere at 4000 psig at 800 °F. Duplicate samples were immersed in the slurry and duplicate samples were also suspended above the slurry in the gaseous phase. The coal slurry is 35 vol % of -100 mesh Kentucky bituminous and 65 % solvent. The solvent is centrifuged Synthoil product from Pittsburgh Energy Technology Center run FB-61 using the same Kentucky bituminous. Solvent analysis (wt %): oils 64.4, asphaltenes 32.3, organic benzene insolubles 3.3.

HYDROGEN ATTACK[a] OF 2-1/4 Cr-1 Mo STEEL[b][47,50]

Type of Exposure[c]	Temperature °F	Pressure psig	Time hr	Hydrogen Attack[a]
Simple	900	4000	350	no
Stress exposure	900	4000	350	no
Prestrained	900	4000	350	no
Simple	900	4000	1000	yes
Stress exposure	900	4000	1000	yes
Prestrained	900	4000	1000	yes
Simple	950	2000	350	no
Stress exposure	950	2000	350	no
Prestrained	950	2000	350	no
Simple	950	4000	100	no
Stress exposure	950	4000	100	no
Prestrained	950	4000	100	no
Simple	950	4000	350	no
Stress exposure	950	4000	350	yes
Prestrained	950	4000	350	yes
Simple	975	2000	350	no
Stress exposure	975	2000	350	yes
Prestrained	975	2000	350	no
Simple	1000	750	350	no
Stress exposure	1000	750	350	no
Prestrained	1000	750	350	no
Simple	1000	1300	350	yes
Stress exposure	1000	1300	350	yes
Prestrained	1000	1300	350	yes
Simple	1000	2100	350	yes
Stress exposure	1000	2100	350	yes
Prestrained	1000	2100	350	yes
Simple	1000	4000	250	yes
Stress exposure	1000	4000	250	yes
Prestrained	1000	4000	250	yes
Simple	1000	4000	500	yes
Stress exposure	1000	4000	500	yes
Simple	1050	750	350	yes
Stress exposure	1050	750	350	yes
Prestrained	1050	750	350	yes
Simple	1100	750	350	yes
Stress exposure	1100	750	350	yes
Prestrained	1100	750	350	yes

(Table Continued)

HYDROGEN ATTACK[a] OF 2-1/4 Cr-1 Mo STEEL[b][47,50], Continued

Type of Exposure[c]	Temperature °F	Pressure psig	Time hr	Hydrogen Attack[a]
Simple[d]	1000	4000	168	?
Simple[d]	1000	4000	500	yes
Stress exposure[d]	1000	4000	500	yes

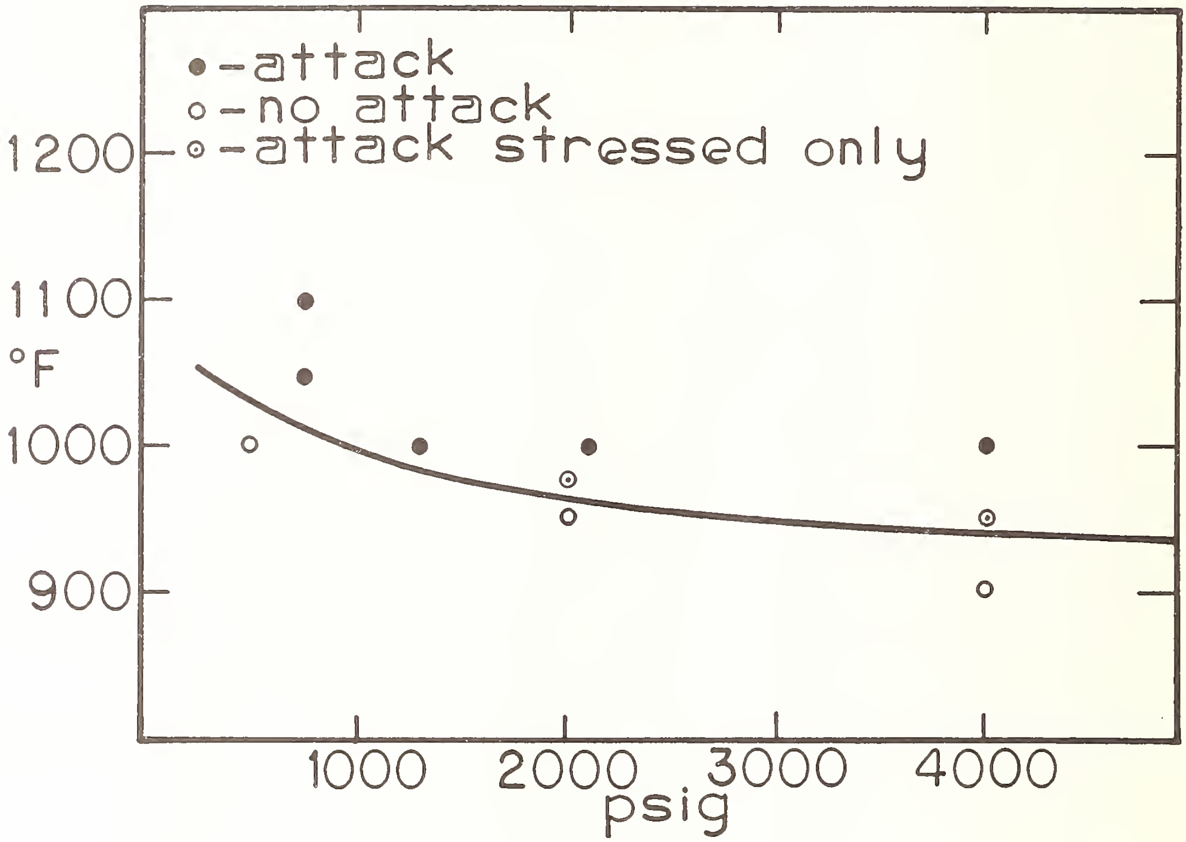
[a]Attack was said to have occurred if scanning electron microscope examination revealed the presence of bubbles anywhere in the exposed sample.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled. Notch-bar cylindrical specimens were prepared from longitudinal sections of the plate. See Sections B.3.1.88 and B.3.1.89 for descriptions of the specimens.

[c]The specimens were exposed to the hydrogen atmosphere at the indicated temperatures and pressures. Stress-exposed specimens were loaded in tension via precompressed stainless steel loading rings during the exposure. See Section B.3.1.90 for the stress values and the mechanical properties of these specimens. The specimens labelled prestrained were prestrained in air at room temperature (ε_p = 0.92%). Prestrained specimens were not stress exposed.

[d]These specimens were smooth-bar cylindrical specimens (see Sections B.3.1.88 and B.3.1.89 for descriptions). See Section B.3.1.90 for the stress exposure values and the mechanical properties.

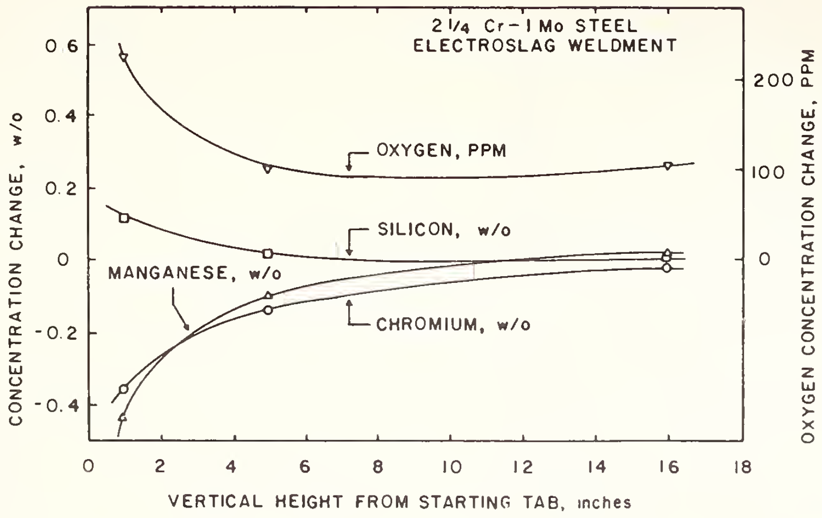
NELSON CURVE[a] FOR 2-1/4 Cr-1 Mo STEEL[b][47,50]

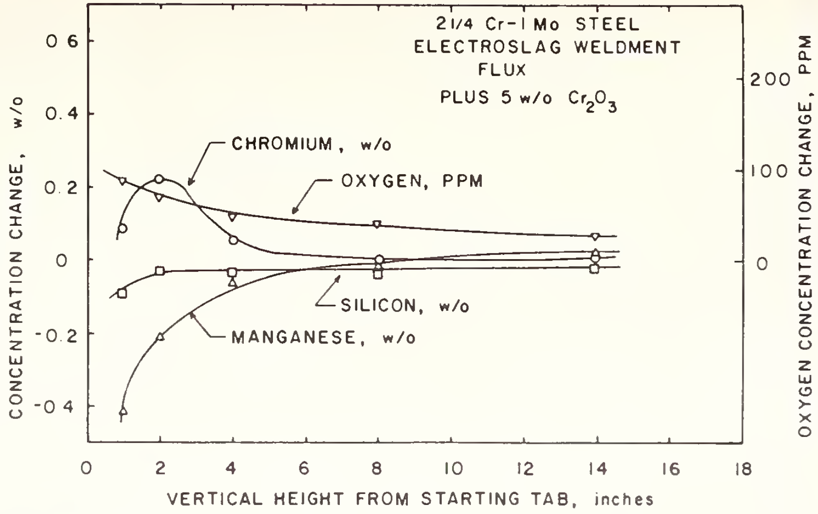


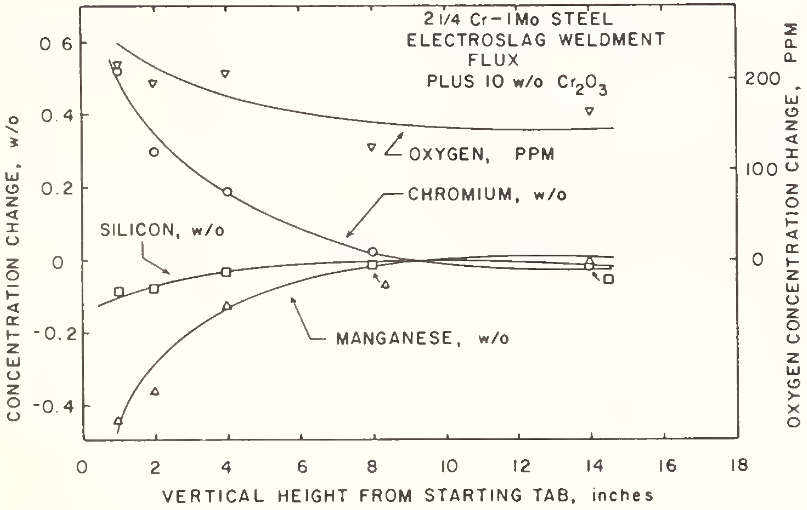
[a]See Section B.1.1.145 for the data from which this curve was derived. The data for the 350 hour exposures were used.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled.

EFFECT OF Cr ADDITION TO OXIDE-BASED FLUX[a] FOR ELECTROSLAG WELDING OF 2-1/4 Cr-1 Mo STEEL[b][55]



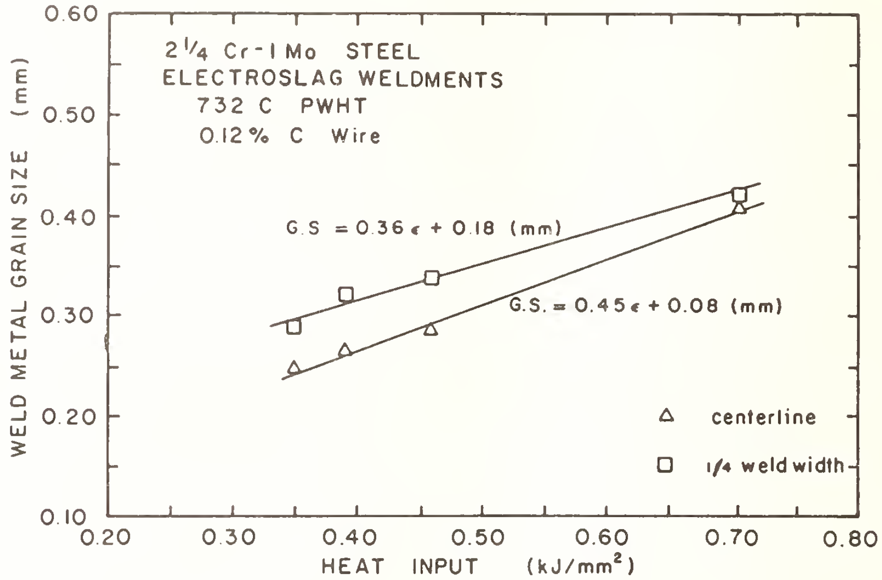




[a] Oxide-base flux is Linde 123, composition (wt %): 35 SiO_2, 7 MnO, 22CaO, 7 MgO, 15 Al_2O_3, 1 TiO_2, 1 FeO, 12 CaF_2. Additions of 5 % Cr_2O_3 and 10 % Cr_2O_3 were made to the commercial flux.

[b] 4-inch (102-mm) thick plate.

EFFECT OF HEAT INPUT ON WELD METAL GRAIN SIZE[a] OF ELECTROSLAG WELDMENTS[b] OF 2-1/4 Cr-1 Mo STEEL[c][55]



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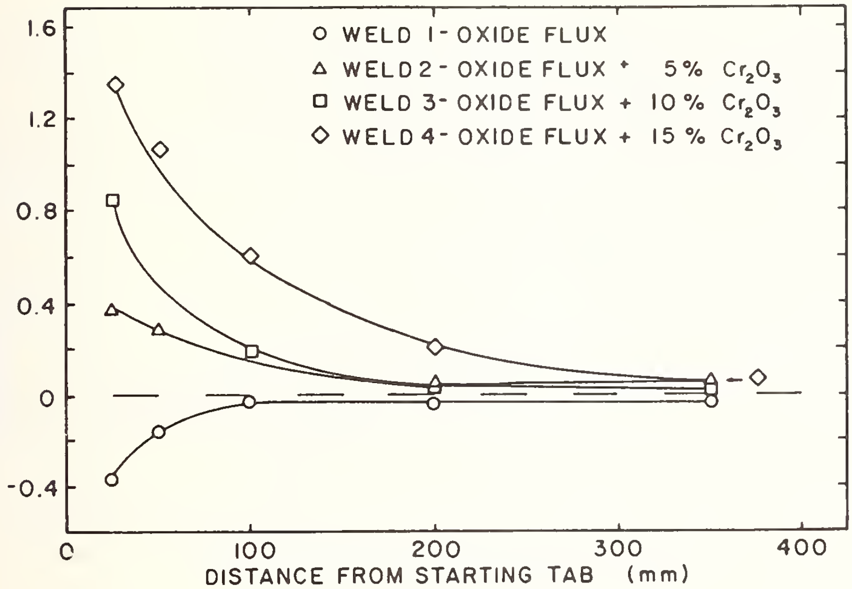
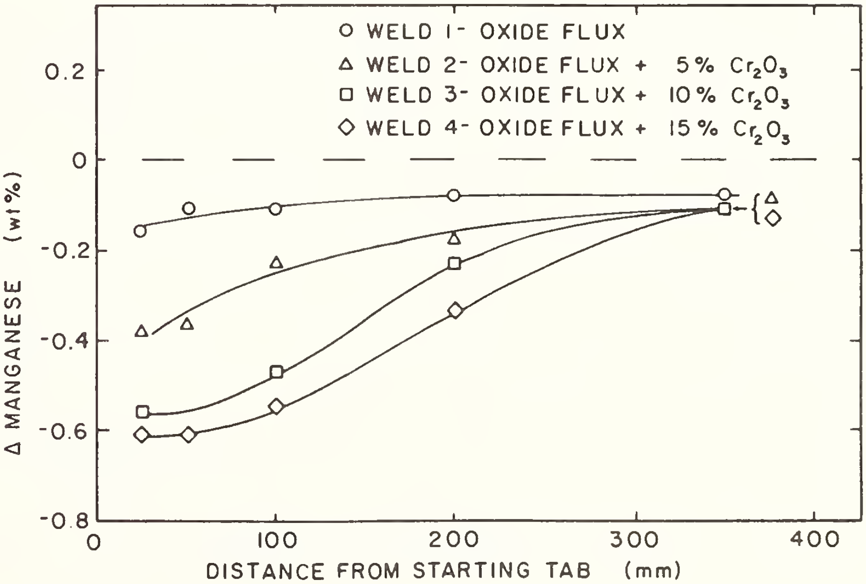
[a]Micrographs were taken on a plane parallel to the welding direction viewed in a direction parallel to the plate thickness. Heat input controls the direction of columnar grains: low heat input = major axes of columns are nearly perpendicular to the welding direction; high heat input = major axes of columns are nearly parallel to the welding direction. Specimens from the fusion zone centerline and 1/4-width position were prepared with the plane of polish perpendicular to the major axes of the columnar grains. Columnar grain size (G.S.) is plotted as a function of heat input, ε.

[b]The oxide-base flux (Linde 124) composition is (wt %) 35 SiO_2, 7 MnO, 22 CaO, 7 MgO, 15 Al_2O_3, 1 TiO_2, 1 FeO, 12 CaF_2. Carbon content of wire used was 0.12 %. Weldments were post-weld heat treated (PWHT) at 732 °C.

[c]4-inch (102-mm) thick plate.

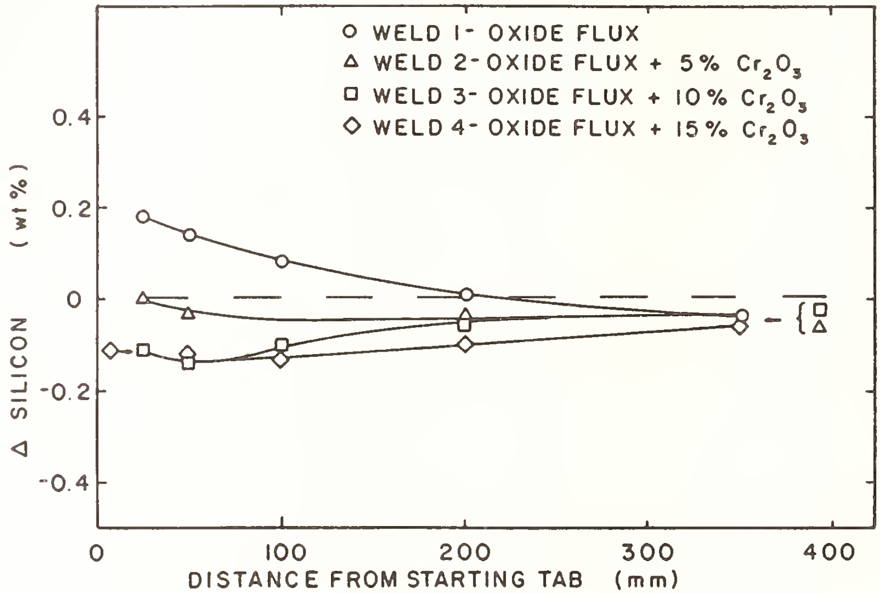
CHANGE IN FUSION ZONE CHEMISTRY[a] WITH FLUX COMPONENTS[b] FOR ELECTROSLAG WELDMENTS OF 2-1/4 Cr-1 Mo STEEL[c][55]

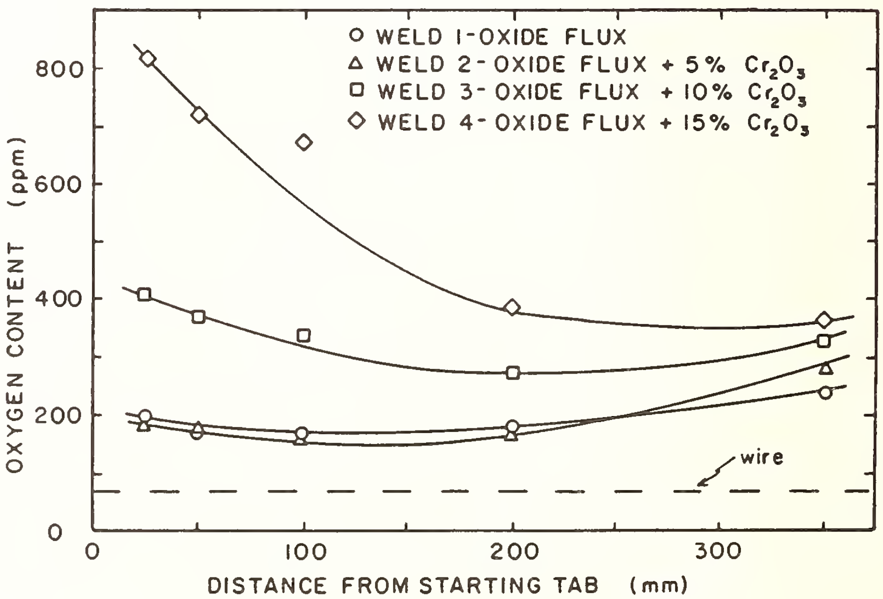




(Data Continued)

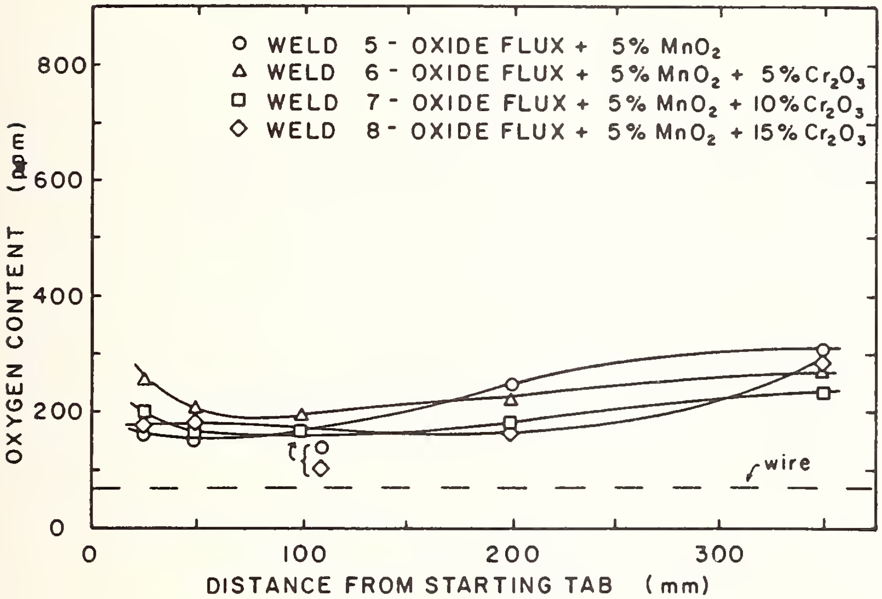
CHANGE IN FUSION ZONE CHEMISTRY[a] WITH FLUX COMPONENTS[b] FOR ELECTROSLAG WELDMENTS OF 2-1/4 Cr-1 Mo STEEL[c][55], Continued

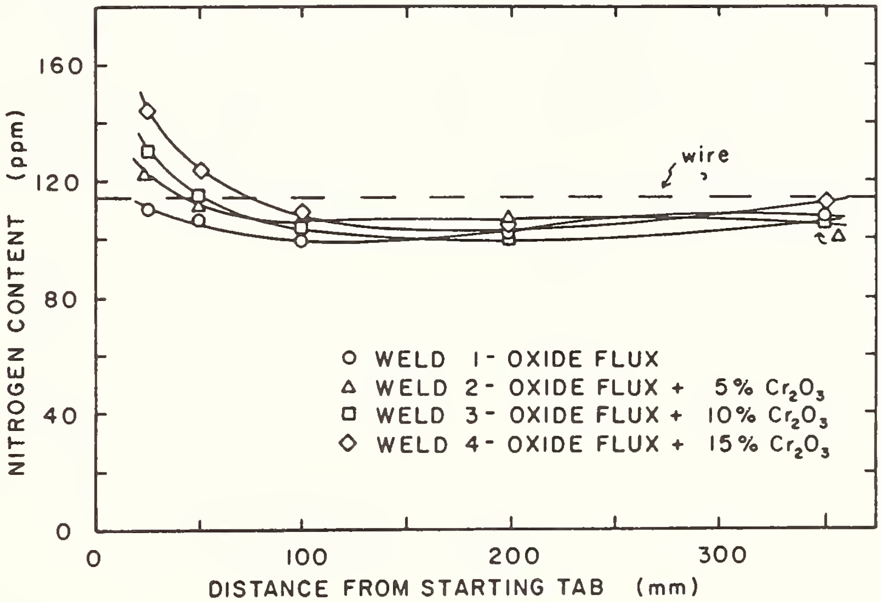




(Data Continued)

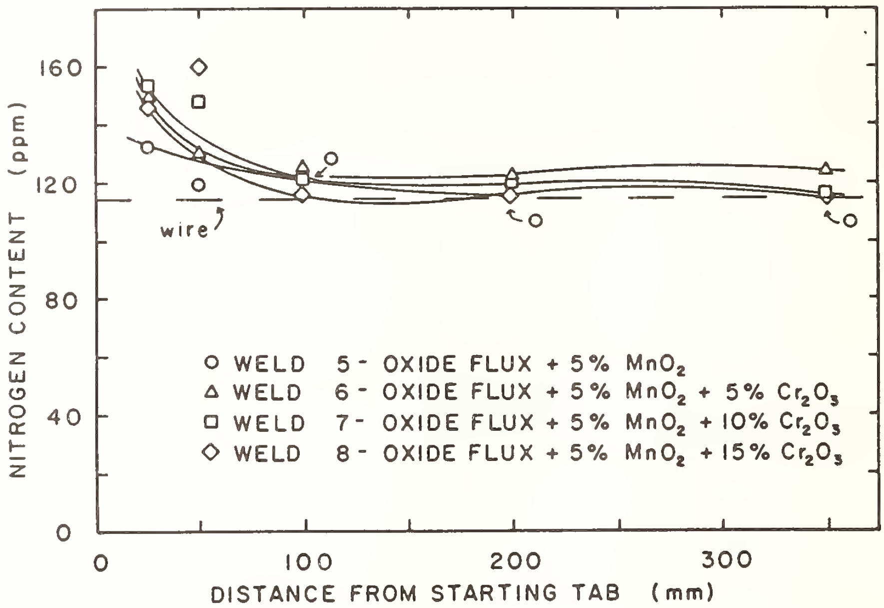
CHANGE IN FUSION ZONE CHEMISTRY[a] WITH FLUX COMPONENTS[b] FOR ELECTROSLAG WELDMENTS OF 2-1/4 Cr-1 Mo STEEL[c][55], Continued





(Data Continued)

CHANGE IN FUSION ZONE CHEMISTRY[a] WITH FLUX COMPONENTS[b] FOR ELECTROSLAG WELDMENTS OF 2-1/4 Cr-1 Mo STEEL[c] [55], Continued

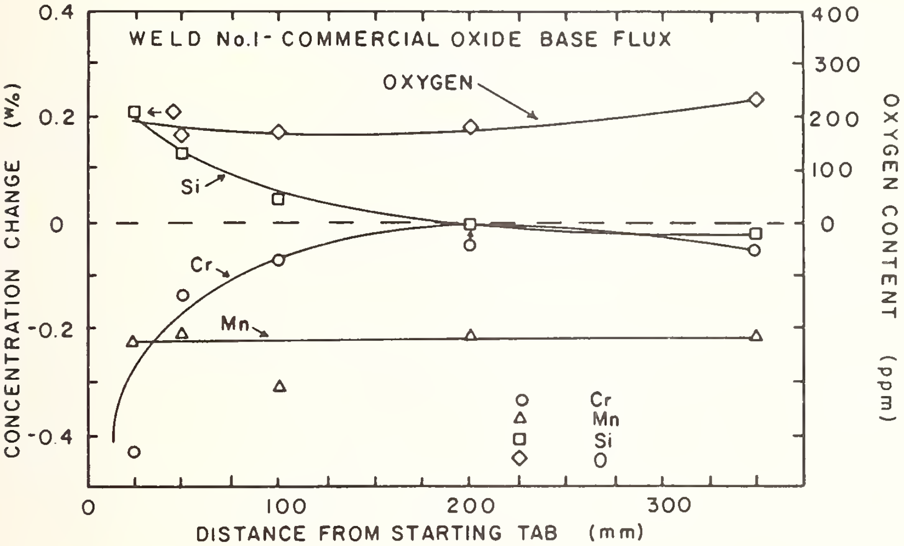


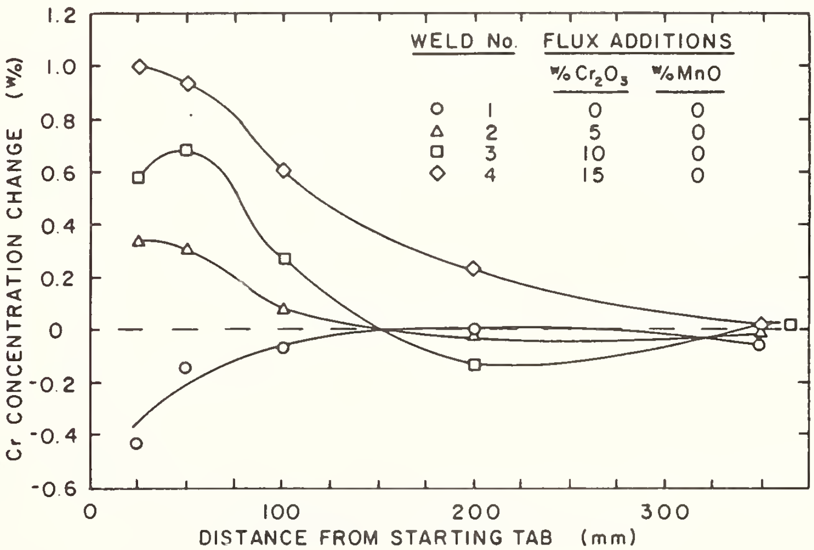
[a]Chemical analyses were made of welds at varying heights from the base of the welds. The changes of Cr, Mn, and Si concentration with distance for varying weld flux compositions are plotted. Oxygen and nitrogen concentrations are given as functions of the distance.

[b]The oxide-base flux (Linde 124) composition is (wt %) 32 SiO_2, 7 MnO, 22 CaO, 7 MgO, 15 Al_2O_3, 1 TiO_2, 1 FeO, 12 CaF_2. Varying amounts of Cr_2O_3 and MnO_2 were added to the base flux for the different welds as indicated on the figures.

[c]4-inch (102-mm) thick plate.

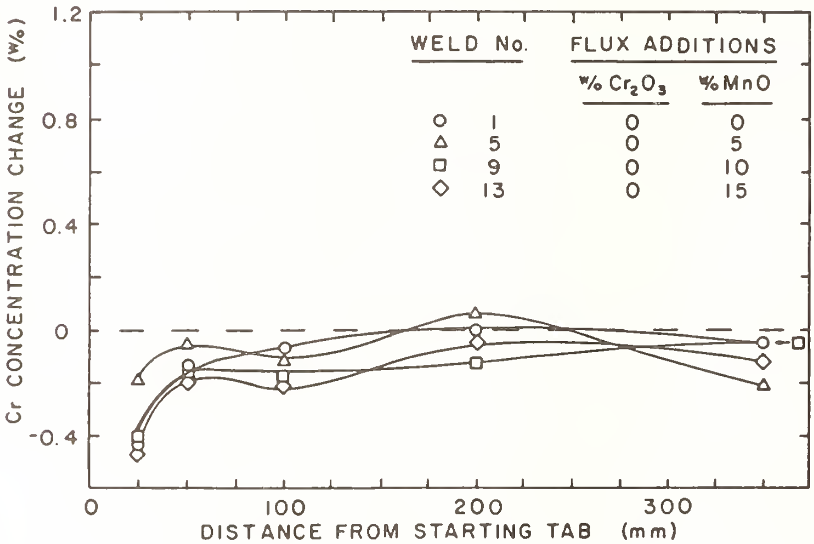
INFLUENCE OF FLUX COMPOSITIONS[a] ON WELD METAL CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDMENTS[b] ON 2-1/4 Cr-1 Mo STEEL[55]

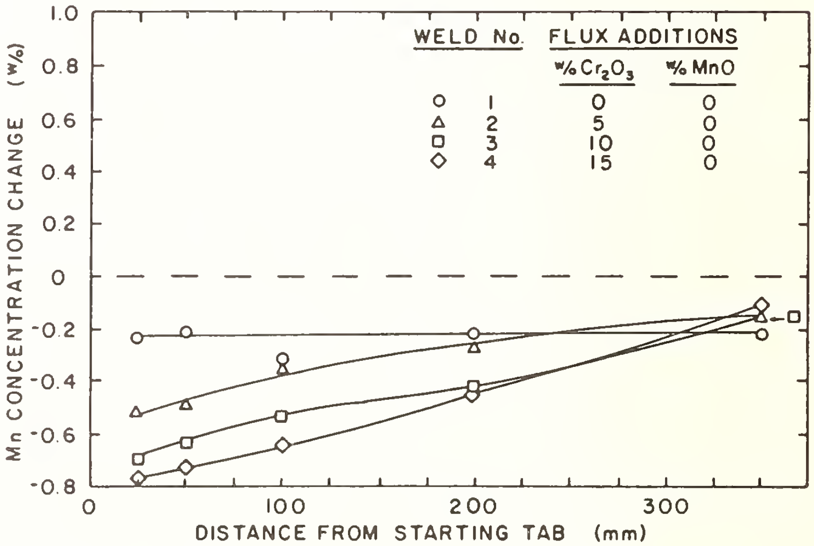




(Data Continued)

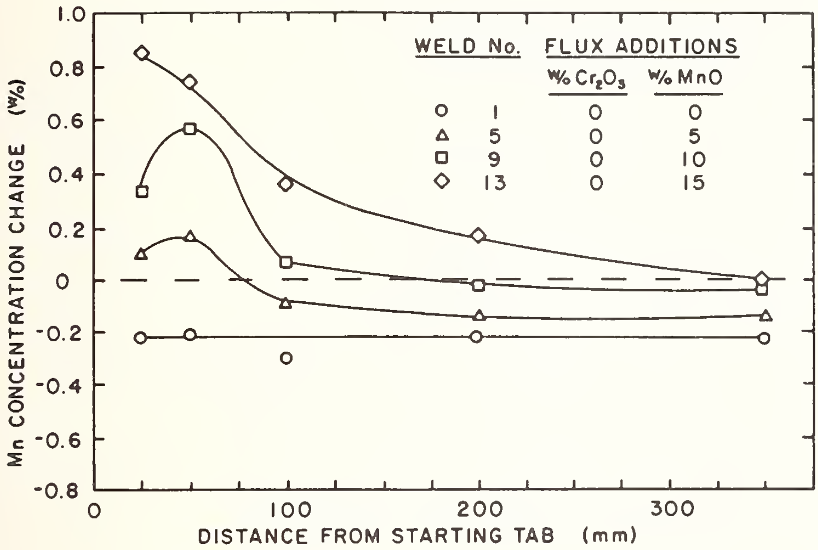
INFLUENCE OF FLUX COMPOSITIONS[a] ON WELD METAL CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDMENTS[b] ON 2-1/4 Cr-1 Mo STEEL[55], Continued

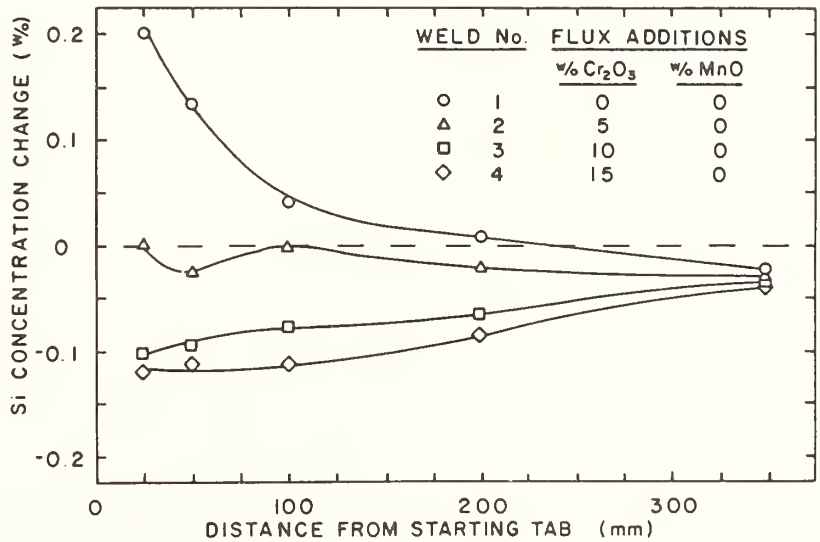




(Data Continued)

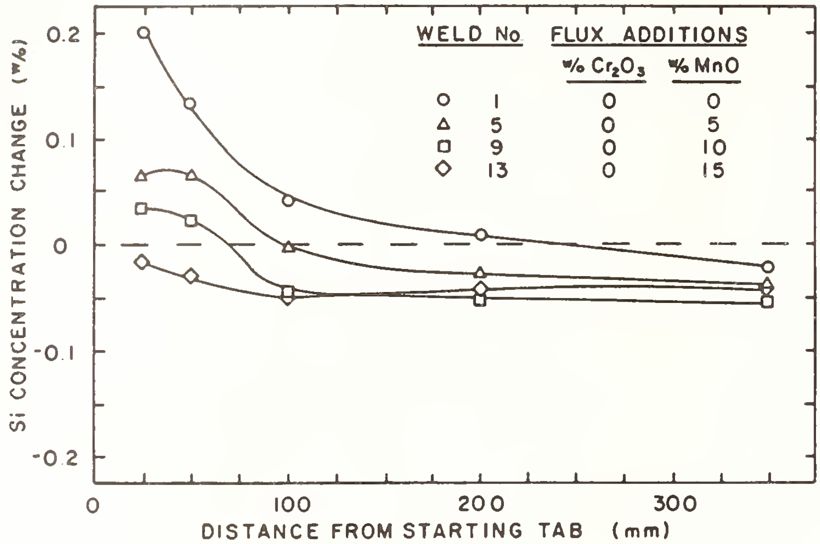
INFLUENCE OF FLUX COMPOSITIONS[a] ON WELD METAL CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDMENTS[b] ON 2-1/4 Cr-1 Mo STEEL[55], Continued

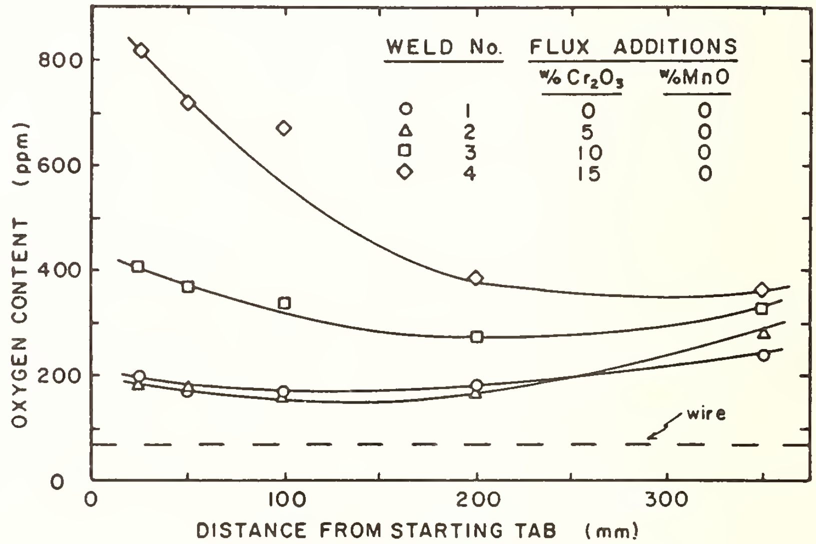




(Data Continued)

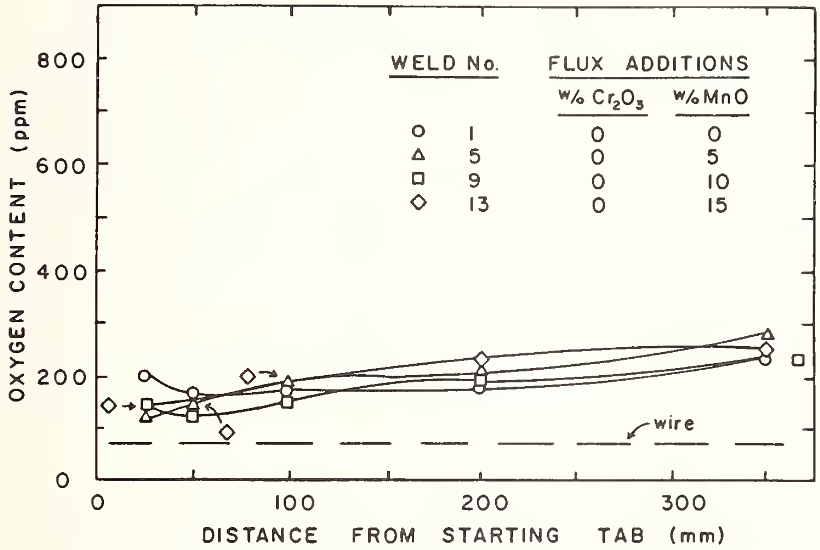
INFLUENCE OF FLUX COMPOSITIONS[a] ON WELD METAL CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDMENTS[b] ON 2-1/4 Cr-1 Mo STEEL[55], Continued

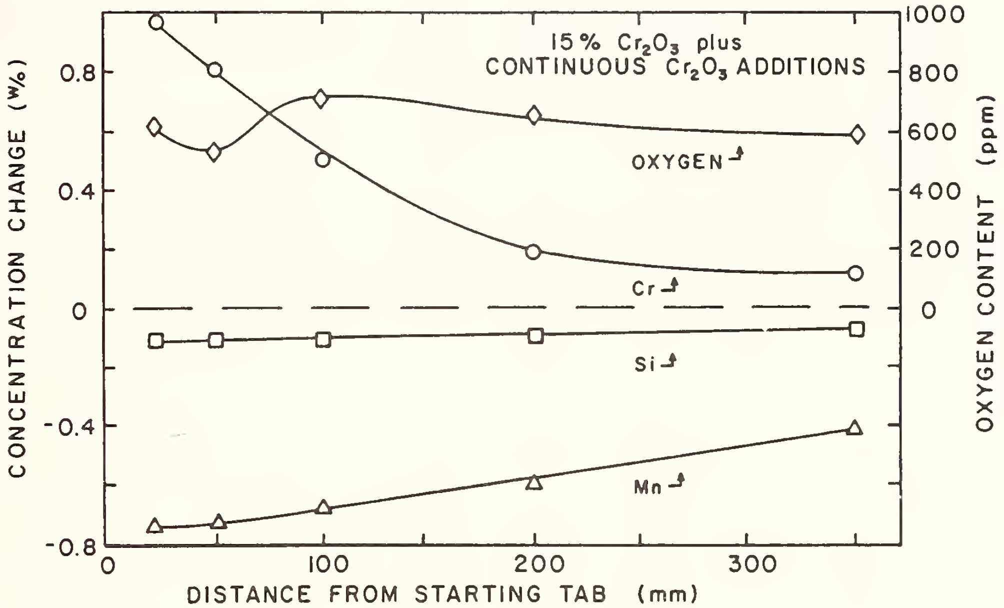




(Data Continued)

INFLUENCE OF FLUX COMPOSITIONS[a] ON WELD METAL CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDMENTS[b] ON 2-1/4 Cr-1 Mo STEEL[55], Continued





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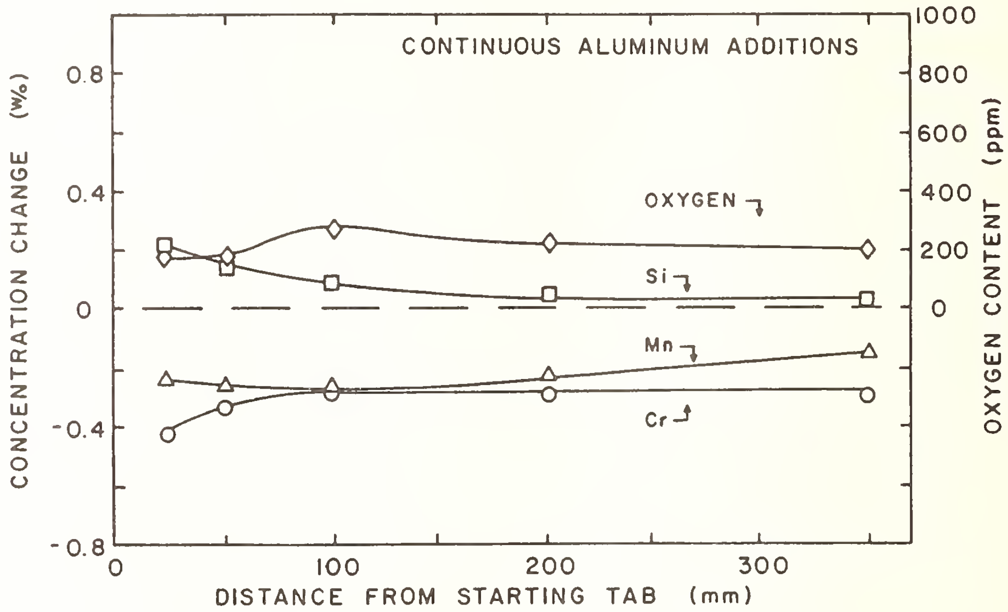
(Data Continued)

INFLUENCE OF FLUX COMPOSITIONS[a] ON WELD METAL CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDMENTS[b] ON 2-1/4 Cr-1 Mo STEEL[55], Continued



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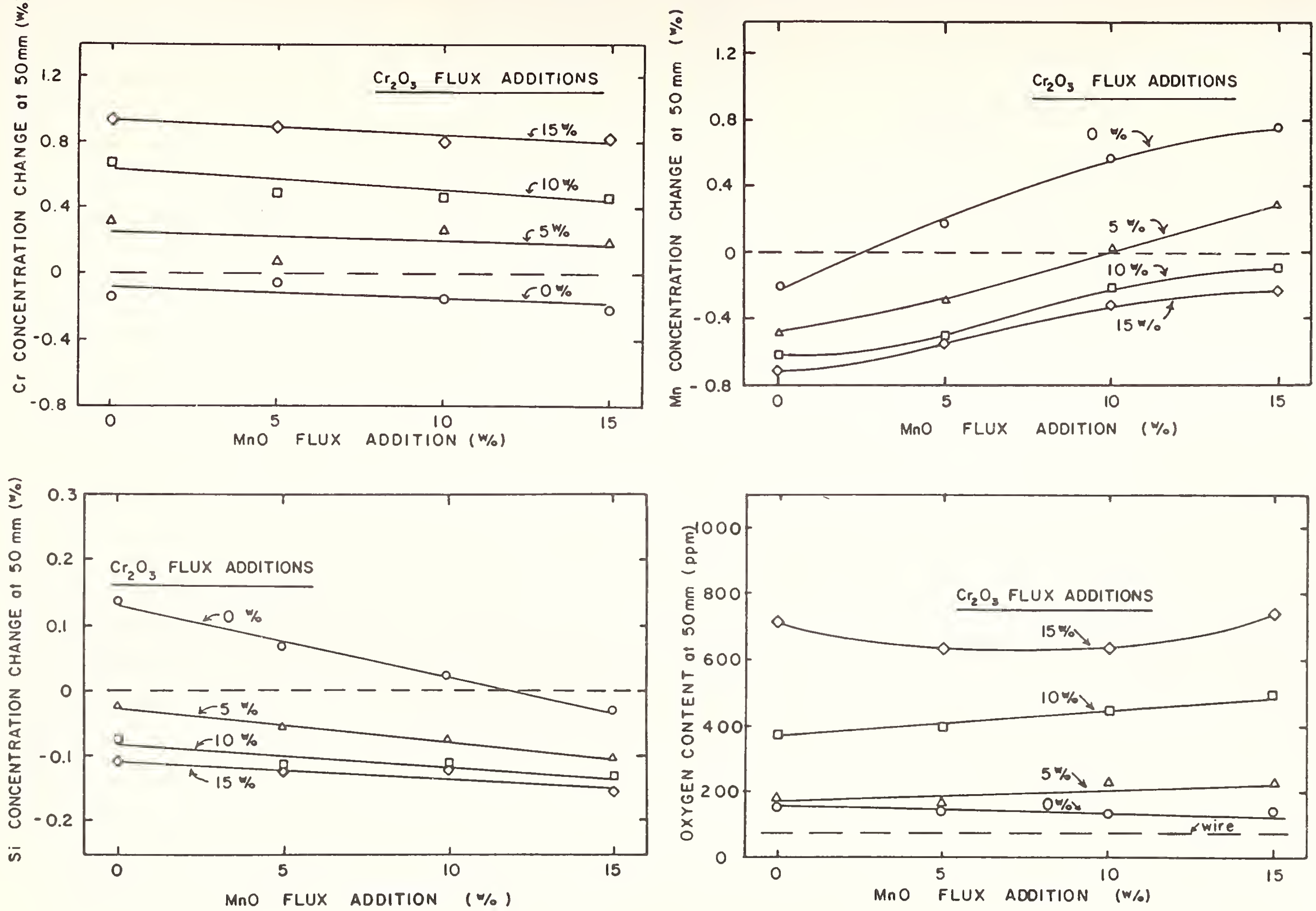
[a]Oxide-base flux composition (wt %): 35 SiO_2, 20 CaO, 6.5 MnO, 5 MgO, 15 CaF_2, 15 Al_2O_3, 3.5 miscellaneous. Varying amounts of chromium and manganese oxide were added to the base flux as indicated on the above figures. The last two figures show the effect of an initial addition of 15% chromium oxide with a continuous addition during the welding and the effect of a continuous addition of aluminum during welding.

[b]D.C. electroslag welds were produced in a cylindrical water-cooled crucible. Weld diameter of 58 mm (2.3 in.) was used to match the fill ratio and weld velocity of 100 mm (4 in.) thick weld. The starting tab was 2-1/4 Cr-1 Mo steel. The welding was done in reverse polarity mode, constant 20 KW power input, currents 500-600 amperes, potentials 30-40 volts, electrode velocity 115 mm/s (4.5 in./s), weld time ∿34 min, weld length ∿400 mm (15.7 in.).

CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDS[a] AT THE POINT OF MAXIMUM CHEMICAL INFLUENCE[b] FOR A VARIETY OF FLUX ADDITIONS[55]



(Data Continued)

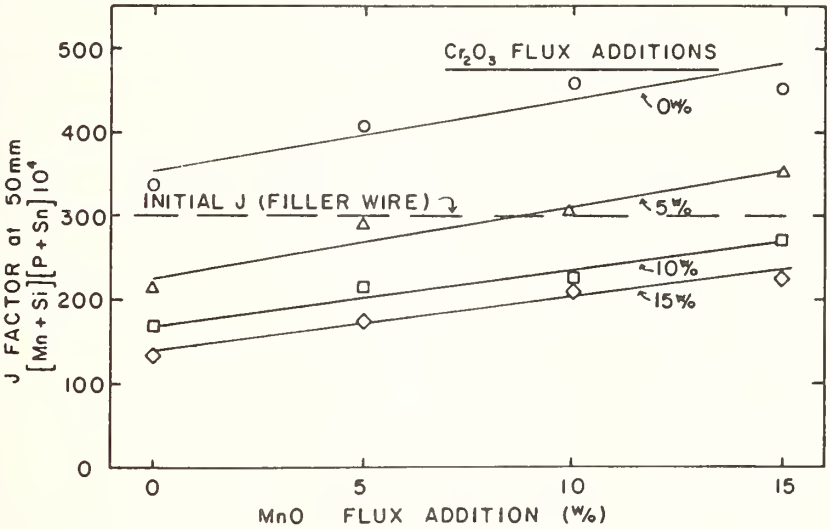
CHEMISTRY OF EXPERIMENTAL ELECTROSLAG WELDS[a] AT THE POINT OF MAXIMUM CHEMICAL INFLUENCE[b] FOR A VARIETY OF FLUX ADDITIONS[55], Continued

Footnotes

[a] See Section B.1.1.150 for the description of the experimental work and the flux compositions as well as the data on which these plots are based.

[b] The maximum chemical influence of flux additions is observed at 50 mm from the starting tab. Since the influence of flux additions decreases with time, an estimate of the influence of continuous flux additions is very useful. This estimate can be made by comparing all of the welds (see B.1.1.150) at this point of maximum chemical influence for both chromium and manganese oxide additions.

TEMPER EMBRITTLEMENT SUSCEPTIBILITY[a] AS INFLUENCED BY FLUX CHEMISTRY[b] OF 2-1/4 Cr-1 Mo STEEL ELECTROSLAG WELDMENTS[55]



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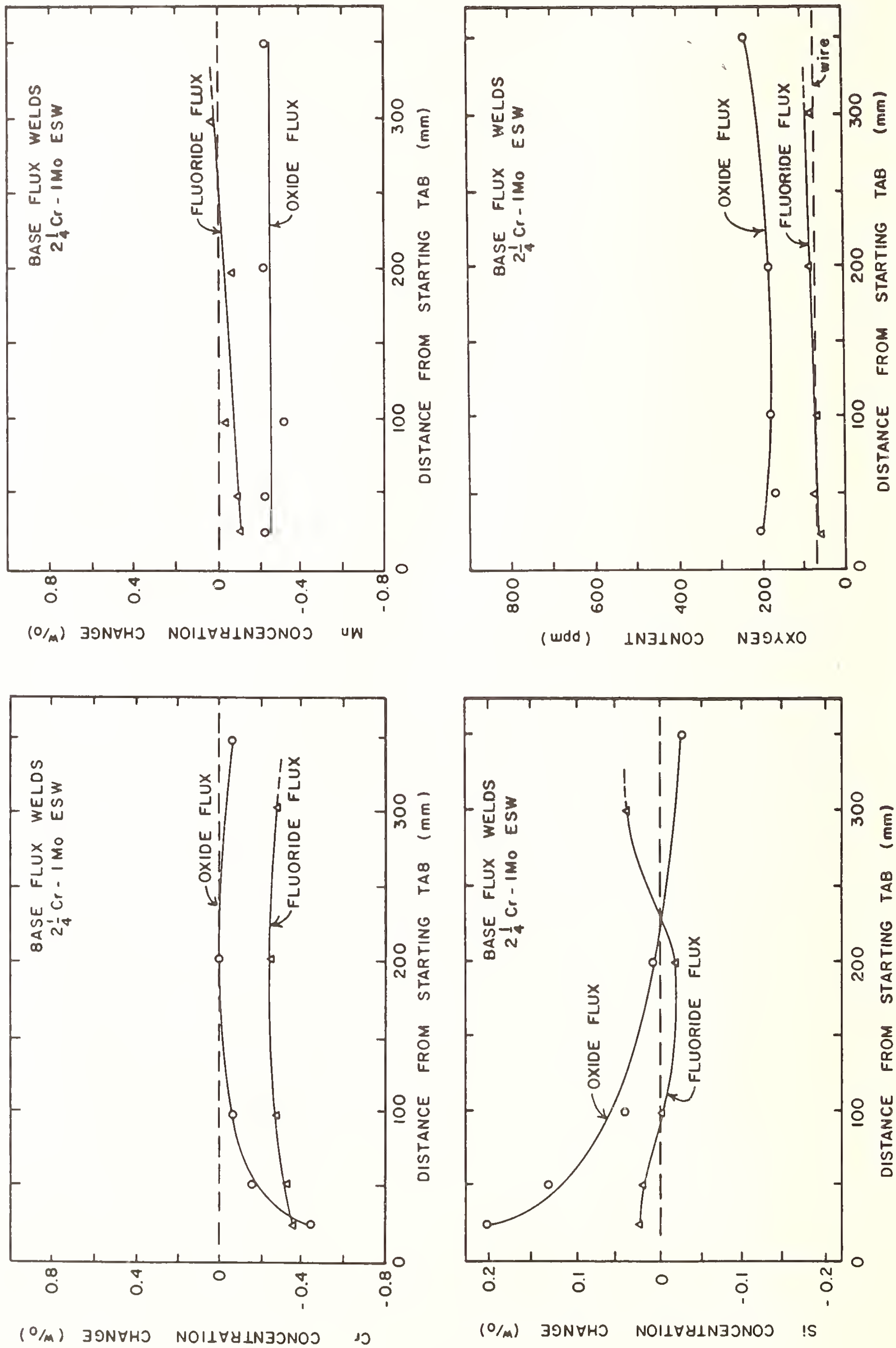
[a]Temper embrittlement factor (J-Factor or "Watanabe Number") based on alloy chemistry. For 2-1/4 Cr-1 Mo steel:

$$J = (\text{wt\% Mn} + \text{wt\% Si})(\text{wt\% P} + \text{wt\% Sn}) \times 10^4.$$

A J <200 indicates resistance to temper embrittlement as measured by changes in Charpy impact transition temperature after embrittling heat treatment. The J factors plotted were calculated based on chemical analyses of welds at a height of 50 mm from the starting tab of the experimental weldments of Section B.1.1.150. See also B.1.1.151.

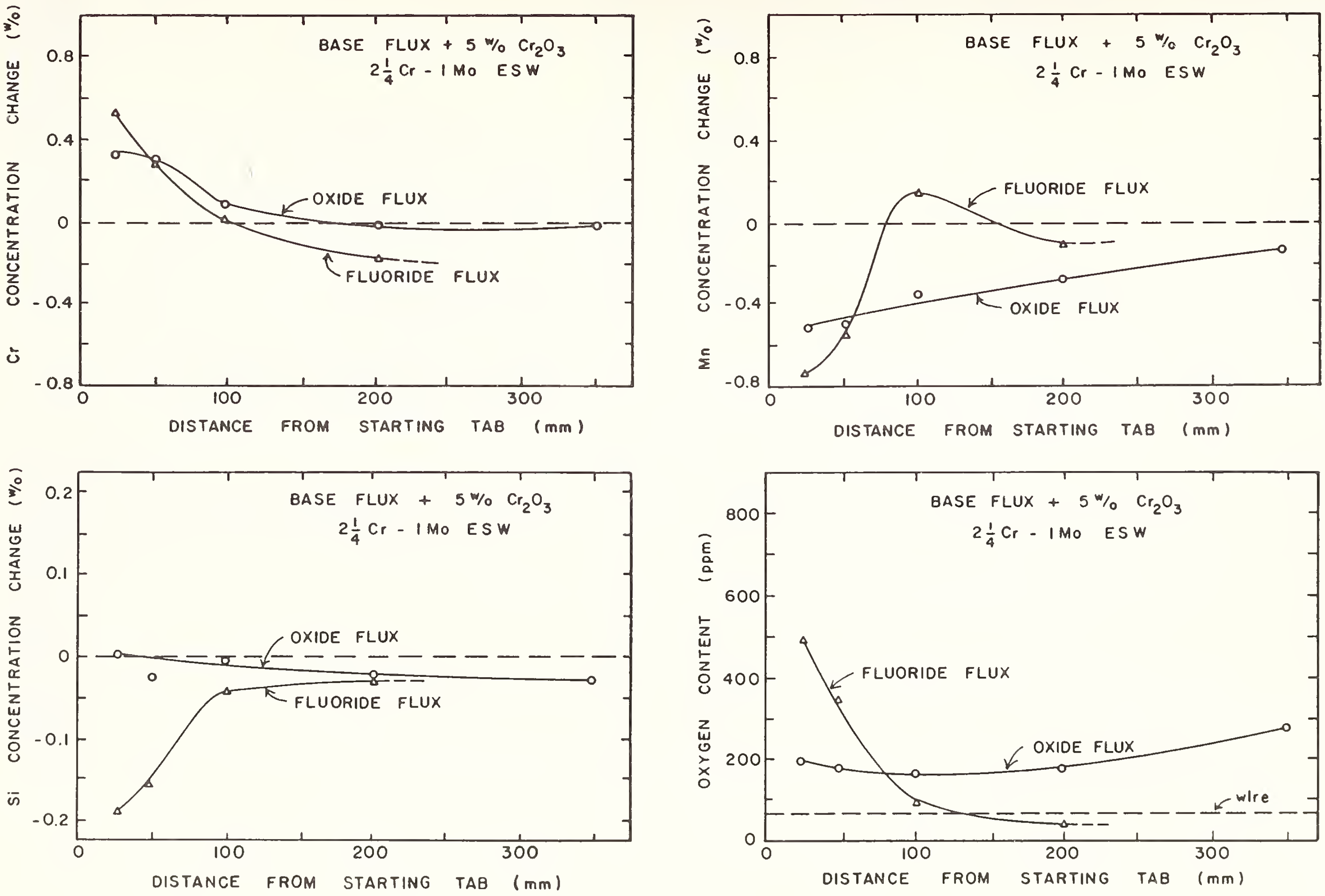
[b]See B.1.1.150 for flux chemistry of experimental weldments and the chromium and manganese additions.

EFFECT OF OXIDE- AND FLUORIDE-BASED FLUXES[a] AND FLUX ADDITIONS ON THE CHEMISTRY[b] OF EXPERIMENTAL ELECTROSLAG WELDS[c] OF 2-1/4 Cr-1 Mo STEEL[55]



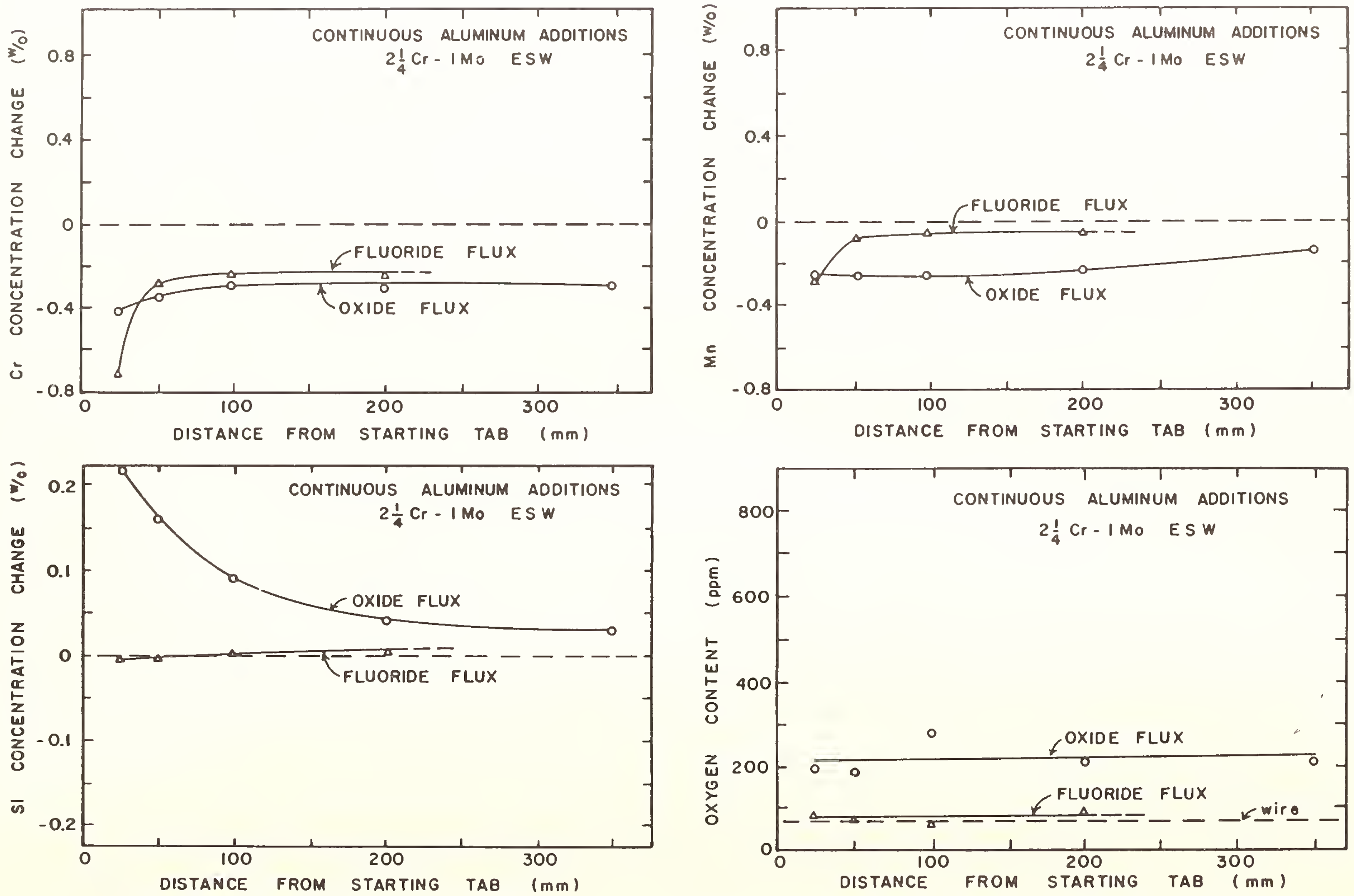
(Data Continued)

EFFECT OF OXIDE- AND FLUORIDE-BASED FLUXES[a] AND FLUX ADDITIONS ON THE CHEMISTRY[b] OF EXPERIMENTAL ELECTROSLAG WELDS[c] OF 2-1/4 Cr-1 Mo STEEL[55], Continued



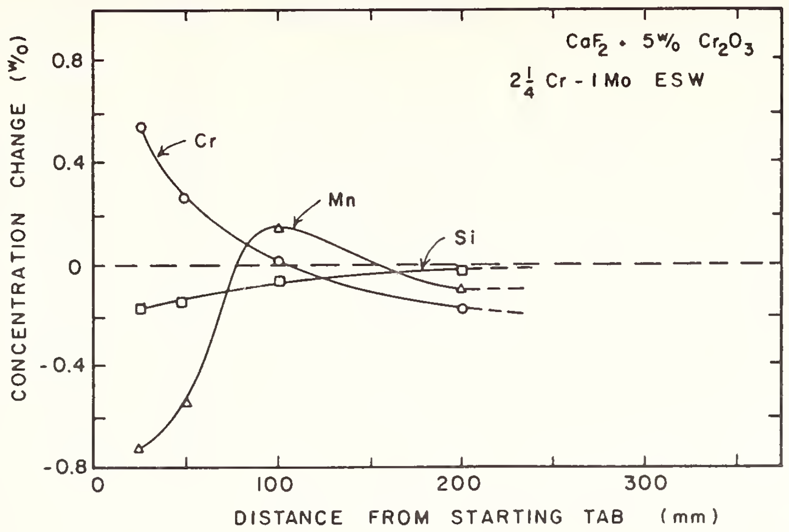
(Data Continued)

EFFECT OF OXIDE- AND FLUORIDE-BASED FLUXES[a] AND FLUX ADDITIONS ON THE CHEMISTRY[b] OF EXPERIMENTAL ELECTROSLAG WELDS[c] OF 2-1/4 Cr-1 Mo STEEL[55], Continued



(Data Continued)

EFFECT OF OXIDE- AND FLUORIDE-BASED FLUXES[a] AND FLUX ADDITIONS ON THE CHEMISTRY[b] OF EXPERIMENTAL ELECTROSLAG WELDS[c] OF 2-1/4 Cr-1 Mo STEEL[55], Continued



[a]Oxide-base flux (Linde 124) composition (wt%): 32 SiO_2, 7 MnO, 22 CaO, 7 MgO, 15 Al_2O_3, 1 TiO_2, 1 FeO, 12 CaF_2. Fluoride flux is analytical reagent grade CaF_2. Flux additions were 5 % Cr_2O_3 and continuous aluminum additions.

[b]Welds were sectioned at various distances from the starting tab and chemistries determined by emission spectroscopy.

[c]D.C. electroslag welds were produced in a cylindrical water-cooled crucible. Weld diameter of 58 mm (2.3 in.) was used to match the fill ratio and weld velocity of 100 mm (4 in.) thick weld. The starting tab was 2-1/4 Cr-1 Mo steel. The welding was done in reverse polarity mode, constant 20 KW power input, currents 500-600 amperes, potentials 30-40 volts, electrode velocity 115 mm/s (4.5 in./s), weld time ∿34 min, weld length ∿400 mm (15.7 in.).

HYDROGEN-ASSISTED CRACKING SENSITIVITY[a] OF CHROMIUM-MOLYBDENUM STEELS[57]

Specimen	Shielding Gas	Preheat[b] Temperature		Postweld[c] Hold	Bend Temperature		Strain	Results[d]
-9 Cr-1 Mo and Modified 9 Cr-1 Mo Steel[e]-								
ESR-Mod 1[e]	5% H_2-95% Ar	21°C	70°F	--	21°C	70°C	4%	No cracks
ESR-Mod 1	5% H_2-95% Ar	21	70	--	0	32	4	Cracked after 2 1/2 min.
Standard	100% Ar	29	85	--	29	85	4	No cracks
Standard	100% Ar	29	85	--	0	32	4	No cracks
ESR-Mod 1	100% Ar	29	85	--	29	85	4	No cracks
ESR-Mod 1	100% Ar	29	85	--	0	32	4	No cracks
Standard	5% H_2-95% Ar	29	85	--	0	32	4	Cracked after 4 min.
ESR-Mod 1	5% H_2-95% Ar	29	85	--	0	32	4	Cracked after 2 1/2 min.
AOD-Mod 1	5% H_2-95% Ar	29	85	--	0	32	4	Cracked after 3 min.
ESR-Mod 2	5% H_2-95% Ar	29	85	--	0	32	4	Cracked after 2 min.
AOD-Mod 2	5% H_2-95% Ar	29	85	--	0	32	4	Cracked after 5 min.
Standard	5% H_2-95% Ar	30	86	--[f]	30	86	4	No cracks
All heats	5% H_2-95% Ar	30	86	--[f]	30	86	1	Cracked
AOD-Mod 2	5% H_2-95% Ar	30	86	--[f]	30	86	1	No cracks
All heats	5% H_2-95% Ar	100	212	DCRT(15 min)	30	86	4	No cracks
Standard	5% H_2-95% Ar	30	86	--[f]	0	32	4,2,1	Cracked
All heats	5% H_2-95% Ar	30	86	--[f]	0	32	4,2,1	Cracked
Standard	5% H_2-95% Ar	100	212	DCRT(15 min)	0	32	4	No cracks
All heats	5% H_2-95% Ar	100	212	DCRT(15 min)	0	32	4	Cracked
All heats	5% H_2-95% Ar	100	212	DCRT(15 min)	0	32	2	Cracked
All heats	5% H_2-95% Ar	100	212	DCRT(15 min)	0	32	1	No cracks
ESR-Mod 1 & AOD-Mod 2	5% H_2-95% Ar	200	392	DCRT(18 min)	0	32	4	No cracks
AOD-Mod 1 & ESR-Mod 2	5% H_2-95% Ar	200	392	DCRT(18 min)	0	32	4	Cracked
AOD-Mod 1 & ESR-Mod 2	5% H_2-95% Ar	200	392	DCRT(18 min)	0	32	2	No cracks
AOD-Mod 1 & ESR-Mod 2	5% H_2-95% Ar	300	572	DCRT(20 min)	0	32	4	No cracks

(Table Continued)

HYDROGEN-ASSISTED CRACKING SENSITIVITY[a] OF CHROMIUM-MOLYBDENUM STEELS[57], Continued

Specimen	Shielding Gas	Preheat[b] Temperature		Postweld[c] Hold	Bend Temperature		Strain	Results[d]
-12 Cr-1 Mo Steel, HT9[g]-								
All the same heat	5% H_2-95% Ar	21°C	70°F	--	21°C	70°F	4%	Cracked
	5% H_2-95% Ar	29	85	--	29	85	4,2,1	Cracked
	5% H_2-95% Ar	93	200	--	29	85	4,2	Cracked
	5% H_2-95% Ar	204	400	--	29	85	4	Cracked
	5% H_2-95% Ar	316	600	--	29	85	4,2,1	Cracked
	5% H_2-95% Ar	371	700	700°F/2 h	29	85	4	Cracked
	5% H_2-95% Ar	371	700	700°F/2 h	29	85	2	Cracked after 1 min.
	5% H_2-95% Ar	371	700	700°F/2 h	29	85	1	Cracked after 2 min.
	100% Ar	371	700	700°F/2 h	29	85	4	Cracked
	100% Ar	371	700	700°F/2 h	29	85	2	No cracks
	100% Ar	371	700	700°F/2 h	29	85	1	No cracks
	5% H_2-95% Ar	30-315°C[h]		DCRT(2-20min)	30	86	4,2,1	Cracked
	5% H_2-95% Ar	375	707	DCRT(25 min)	30	86	4	Cracked
	5% H_2-95% Ar	375	707	DCRT(25 min)	30	86	2,1	No cracks
	5% H_2-95% Ar	375	707	DCRT(25 min)	0	32	2	Cracked
	5% H_2-95% Ar	375	707	DCRT(25 min)	0	32	1	No cracks
	5% H_2-95% Ar	375	707	DCRT, 375°C/2 h	30	86	4	Cracked
	5% H_2-95% Ar	375	707	DCRT, 375°C/2 h	30	86	2	No cracks
	5% H_2-95% Ar	375	707	750°C/2 h	30	86	4	No cracks
- 12 Cr-2 Mo Steel[i]-								
All the same heat	100% Ar	24	75	--	24	75	4	No cracks
	5% H_2-95% Ar	24	75	--	24	75	4	Cracked
	5% H_2-95% Ar	29	84	--	24	75	1	Cracked after 38 min.
	5% H_2-95% Ar	200	392	--	24	75	4	Cracked
	5% H_2-95% Ar	300	572	--	24	75	2	Cracked, time not known
	5% H_2-95% Ar	300	572	--	24	75	1	Cracked after 604 min.
	5% H_2-95% Ar	400	752	--	24	75	1	Cracked after 840 min.

(Table Continued)

HYDROGEN-ASSISTED CRACKING SENSITIVITY[a] OF CHROMIUM-MOLYBDENUM STEELS[57], Continued

Footnotes

[a]Hydrogen sensitivity as measured by the presence of cracking under strain after a standard gas tungsten-arc welding procedure with hydrogen in the shielding gas. Welds are deposited on 3-mm thick coupons at 80-100 A, 10 V, at a speed of 127 mm/min., using a 1.58-mm diameter 2% thoriated tungsten electrode. The shielding gas used in these tests was either pure argon or 5% hydrogen-95% argon. Five minutes after welding the specimens are strained by bending along the direction of the weld. The augmented strain on the top surface of the weld is inversely proportional to the bending direction. The strain level is controlled by the bending radius.

[b]Many of the welds were done on specimens at ambient temperatures (21-30 °C) but a number were preheated before the welds were applied.

[c]Most of the specimens were not subjected to a postweld heat treatment but were simply allowed to cool in the fixture, direct cool to room temperature (DCRT). For a few samples the times were specified, but for most no time was given.

[d]Where the single word "cracked" appears, the specimen cracked during bending. If time elapsed after bending before cracks appeared that time is given.

[e][Specifications for standard composition (wt%): Cr 8.0-10.0, Mo 0.90-1.20, C 0.15-0.20, Mn 0.30-0.65, P 0.03-0.05, S 0.03-0.06, Si 0.25-1.00.] Specified composition ranges for modified alloy: Cr 8-9, Mo-0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-0.25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001. Specimens from four different heats appear in the table. Two heats were electroslag remelted (ESR) after argon-oxygen-decarburization (AOD), two heats were only processed by argon-oxygen-decarburization. Mod = modified. The numbers 1 and 2 refer to the heats. Si content for the four modifications (wt%): ESR-Mod 1, Si 0.11; ESR-Mod 2, Si 0.40; AOD-Mod 1, Si 0.41, AOD-Mod 2, Si 0.28. All alloys were normalized at 1038 °C, held 1 hour, air-cooled, then tempered to 760 °C, held 1 hour, air-cooled.

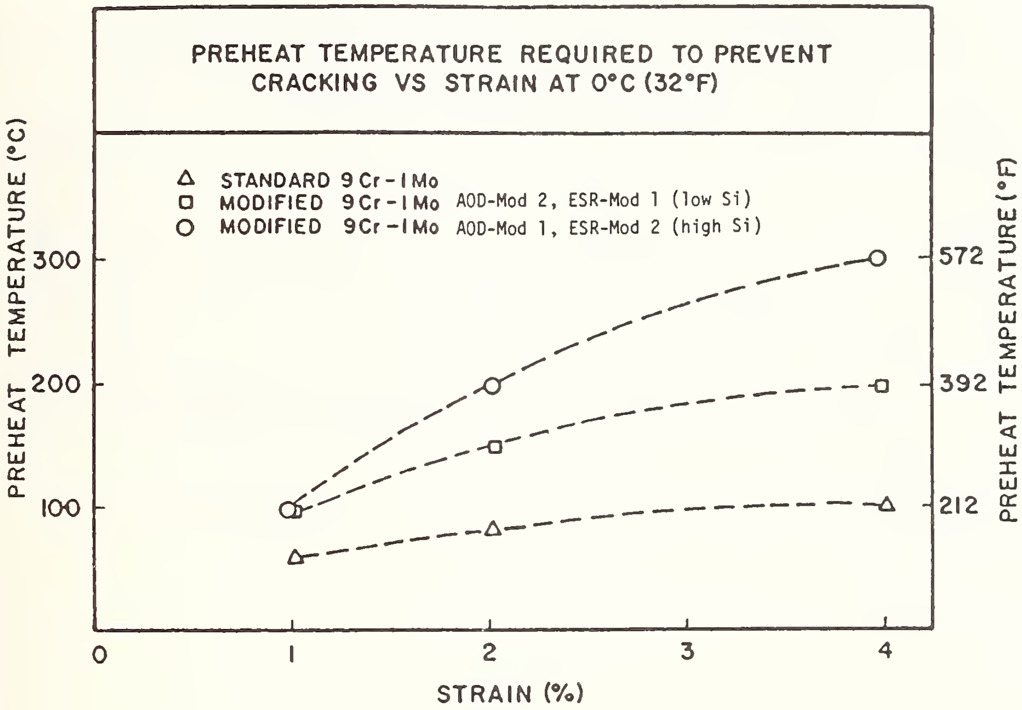
[f]DCRT time was given as 2 minutes.

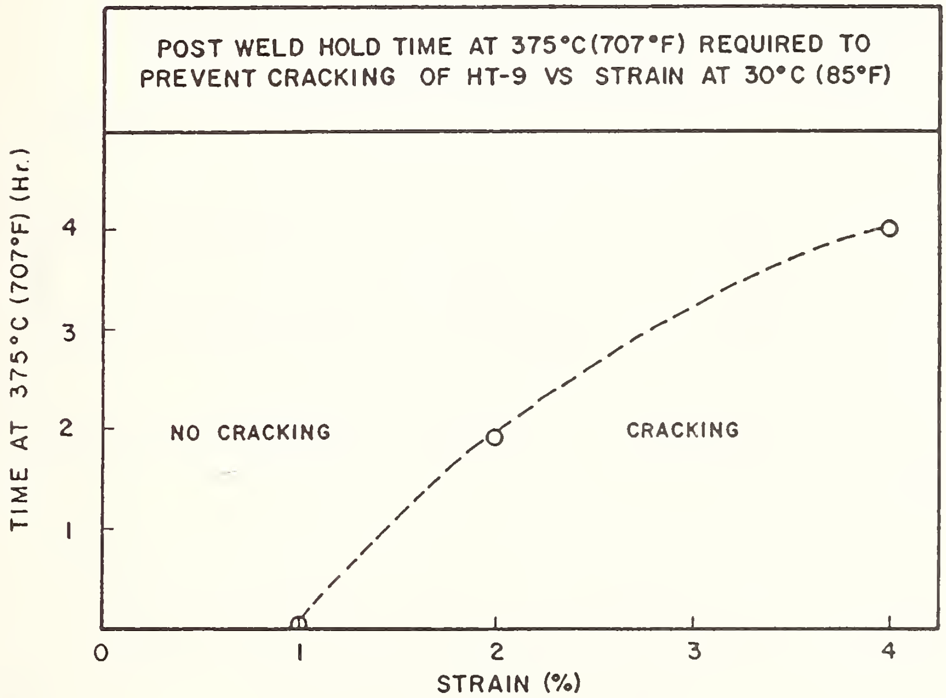
[g]HT9 composition (wt%): 11.65 Cr, 1.02 Mo, 0.20 C, 0.61 Mn, 0.016 P, 0.007 S, 0.26 Si, 0.54 Ni, 0.29 V, 0.01 Nb/Ta, <0.01 Ti, 0.09 Co, 0.03 Cu, 0.009 Al, 0.01 B, 0.61 W, 0.004 As, 0.001 Sn,0.002 Zr, 0.041 N, 0.013 O. Alloy was normalized at 1038 °C and tempered at 760 °C as in footnote e.

[h]Specimens were tested over the range of temperatures with no difference in results.

[i]Composition (wt%): 11.90 Cr, 1.99 Mo, 0.086 C, 0.73 Mn, 0.012 P, 0.009 S, 0.28 Si, 1.01 Ni, 0.22 V, 0.007 Al, other elements analysis not available.

EFFECT OF PREHEATING AND POST WELD HOLD ON THE HYDROGEN-ASSISTED CRACKING SENSITIVITY[a] OF Cr-Mo STEELS[b][57]





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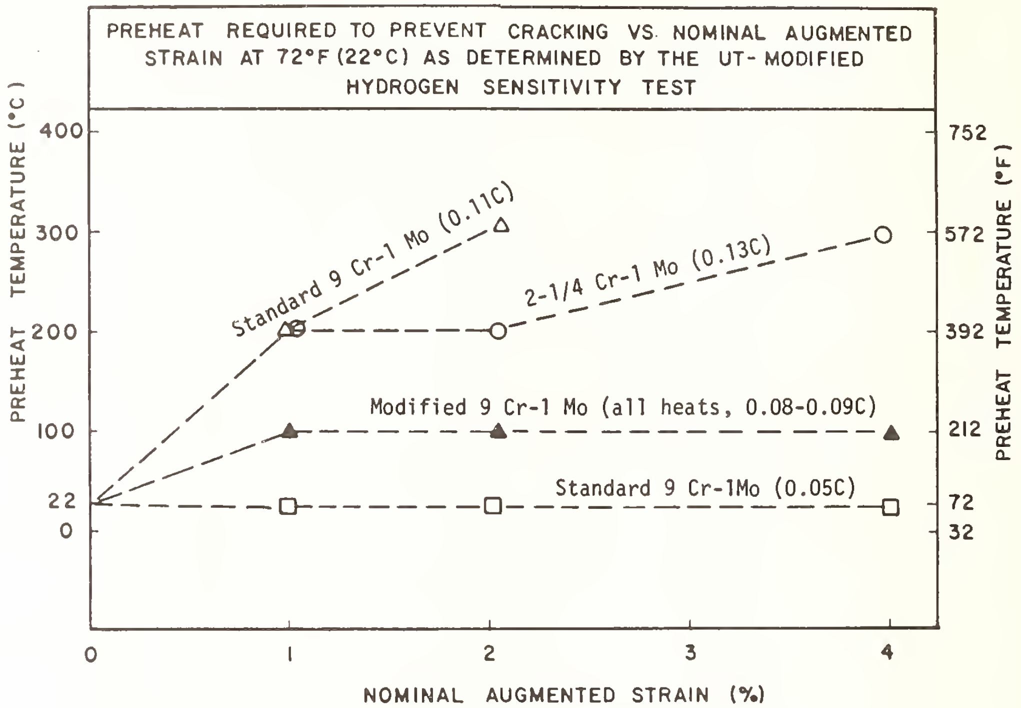
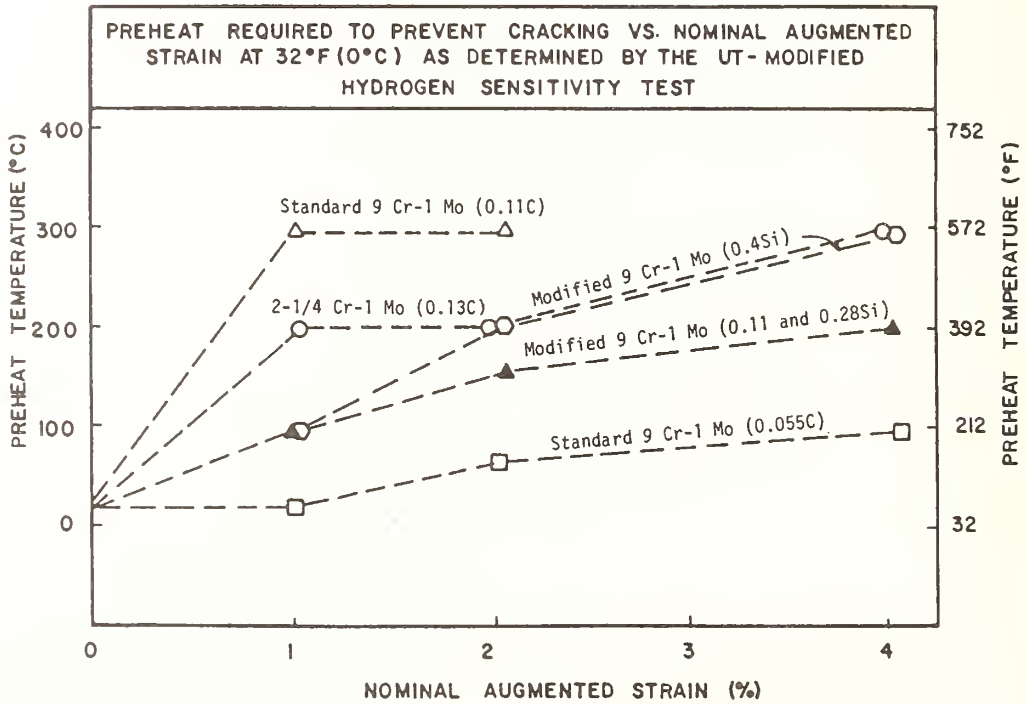
(Data Continued)

EFFECT OF PREHEATING AND POST WELD HOLD ON THE HYDROGEN-ASSISTED CRACKING SENSITIVITY[a] OF Cr-Mo STEELS[b][57], Continued





(Data Continued)

EFFECT OF PREHEATING AND POST WELD HOLD ON THE HYDROGEN-ASSISTED CRACKING SENSITIVITY[a] OF Cr-Mo STEELS[b][57], Continued

Footnotes

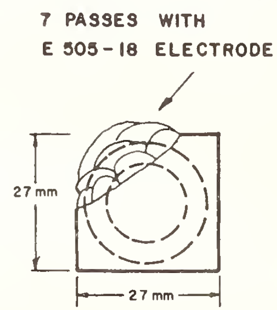
[a]Hydrogen sensitivity as measured by the presence of cracking under strain after a standard gas tungsten-arc welding procedure with hydrogen in the shielding gas. See Section B.1.1.154, footnote a, for a description of the procedure, a standard Battelle test modified by the University of Tennessee (UT) personnel.

[b]See Section B.1.1.154 for compositions of standard 9 Cr-1 Mo steel and the modified heats of 9 Cr-1 Mo, and for the 12 Cr-1 Mo steel (HT9). Composition given for the 2-1/4 Cr-1 Mo steel (wt%): 2.15 Cr, 1.09 Mo, 0.13 C, 0.45 Mn, 0.013 P, 0.021 S, 0.23 Si, 0.20 Ni, 0.01 V, 0.05 Co, 0.13 Cu, other elements analysis not available. All alloys were normalized at 1038 °C, and tempered at 760 °C before testing.

SULFIDE STRESS CRACKING TESTS[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b][57]

Specimen	Post Weld Heat Treated[c]	Notch Position[d]	Stress[e] MPa	Stress ksi	Stress YF	Rockwell C[d,f] BM	Rockwell C HAZ	Rockwell C WM	Time to Failure hours	HAZ Cracking
1	no	HAZ	552	80	1	19	42	38	24[g]	yes
2	no	HAZ	552	80	1	19	42	38	24[g]	yes
3	yes	HAZ	552	80	1	14	21	18	18.5-21.5	yes
4	no	BM	552	80	1	19	42	38	15.5[g]	yes
5	no	BM	276	40	½	19	42	38	no failure after 458 hours	no[h]
6	yes	HAZ	276	40	½	14	21	18	no failure after 458 hours	no
7	no	HAZ	276	40	½	19	42	38	48[g]	yes
8	no	WM	276	40	½	19	42	38	48[g]	no[h]
9	no	HAZ	138	20	¼	19	42	38	24[g]	yes
10	no	WM	138	20	¼	19	42	38	24-54	yes
11	no	none	138	20	¼	19	42	38	4-24	yes
12	no	none	138	20	¼	19	42	38	4-24	yes

[a]C-ring blanks were made by making multiple shielded metal arc welds over an alloy test block in the rolling direction (see diagram). Preheat temperature was 204 °C (400 °F). Standard C-ring stress-corrosion samples were machined according to ASTM G38-73. Samples were notched either in the base metal, weld metal, or the heat-affected zone and stressed to yield, half-yield, or quarter-yield. They were then immersed in a saturated hydrogen sulfide standard NACE solution (945 ml water + 50 g NaCl + 4.8 ml acetic acid) in a corrosion cell. After exposure the specimens were examined at the notch root for cracking. Some specimens were post weld heat treated.



[b]Argon-oxygen-decarburization melt process. Composition (wt%): 8.46 Cr, 1.02 Mn, 0.083 C, 0.46 Mn, 0.010 P, 0.004 S, 0.41 Si, 0.09 Ni, 0.198 V, 0.072 Nb/Ta, 0.005 Ti, 0.055 Co, 0.03 Cu, 0.002 Al, 0.05 W, 0.051 N, B, As, Sn, Zr, all <0.001.

[c]Post weld heat treatment temperature 732 °C (1350 °F).

[d]HAZ = heat-affect zone, BM = base metal, WM = weld metal.

[e]YF = yield fraction. Stress to yield is 552 MPa.

[f][Note that the minimum value of the Rockwell C hardness scale is 20.]

[g]Upper limit value.

[h]No HAZ cracks in unstressed regions.

CORROSION RATES[a] FOR ALLOYS[b] EXPOSED TO SIMULATED $ZnCl_2$ RECOVERY CONDITIONS[c] OF $ZnCl_2$ HYDROCRACKING PROCESS[d][64]

Cold Leg Exposures				Hot Leg Exposures			
Alloy	Temperature °C	Corrosion Rate[a] mm/yr	Corrosion Rate[a] mils/yr	Alloy	Temperature °C	Corrosion Rate[a] mm/yr	Corrosion Rate[a] mils/yr
140 HOUR EXPOSURE							
Hastelloy B-2	700	28.47	1121	Hastelloy B-2	975	e	
Alloy 800 (CrAl)[f]	500	23.7	933	Hastelloy N	975	e	
MA 956	500	20.5	807	Hastelloy N	950	30.3	1193
Stellite 6B	700	17.6	693	Alloy 600	925	20.4	804
Haynes 25	500	13.6	536	Hastelloy S	950	13.9	546
Haynes 188	500	11.5	451	Inconel 671	975	11.0	433
Multimet	500	10.3	406	Hastelloy C-276	950	8.69	342
Alloy 800 (CrAl)[f]	700	10.2	403	Alloy 800 (CrAl)[f]	975	7.7	303
Alloy 800	500	6.4	251	MP 35 N, Multiphase	975	4.7	185
Hastelloy N	600	5.6	222	Alloy 690	925	4.7	185
Hastelloy G-3	500	5.6	221	Alloy 617	975	3.0	118
Hastelloy C-276	600	5.21	205	Alloy 617	975	2.5	98
Hastelloy S	600	5.1	202	Stellite 6B	975	2.2	85
Alloy 825	500	4.9	193	Haynes 25	975	2.14	84
Alloy 601	500	4.6	183	Alloy 800 (CrAl)[f]	975	2.0	78
Hastelloy C-276	500	2.67	105	Stellite 6B	975	1.9	74
Alloy 617	500	2.6	103	Haynes 188	975	1.7	66
Alloy 625	500	2.3	91	Haynes 25	975	1.57	62
500 HOUR EXPOSURE							
Hastelloy N	650	>14.4[e]	>565	MA 956	925	>9.3[e]	>366
Stellite 6B	800	17.1	672	MA 956	925	>9.3[e]	>366
Stellite 6B	700	16.7	658	Haynes 25	950	4.8	189
Alloy 800 (CrSi)[g]	500	12.2	479	Haynes 188	950	4.0	159
Haynes 25	750	11.9	468	Alloy 600	970	2.9	113
Alloy 690	600	10.0	394	Alloy 825	970	2.2	85
Alloy 625	650	8.6	339	Haynes 188	970	2.0	79
Hastelloy G	650	8.2	324	Multimet	970	1.9	76
Multimet	600	4.3	170	Alloy 601	925	1.9	73
Hastelloy G	560	3.6	144	Multimet	925	1.8	72
Alloy 625	560	3.6	143	Haynes 25	970	1.7	66
Alloy 600	560	2.6	103	MP 35 N, Multiphase	950	1.6	61
MP 35 N, Multiphase	750	1.9	77	Alloy 617	950	1.4	56
Hastelloy C-276	800	1.0	41	Alloy 800 (CrSi)[g]	925	1.2	49
Hastelloy C-276	700	0.9	35	Stellite 6B	950	1.2	48
Alloy 617	800	0.7	29	Udimet 720	970	1.2	47
Alloy 617	700	0.6	22	Alloy 800 (CrSi)[g]	925	1.0	38
Udimet 720	750	0.2	9.4	Udimet 720	950	0.8	32
75 HOUR EXPOSURE							
Titanium	765	h		Titanium	925	i	
Hastelloy G-3	750	5.73	225.5	Multimet	975	4.25	167.4
Inconel 617	600	5.61	221.0	Inconel 671	975	4.11	161.8
Inconel 625	600	4.74	186.6	Multimet	925	3.65	143.7
Hastelloy N	635	3.57	140.5	Alloy 800 (CoAl)[j]	950	2.72	107.2
Inconel 600	600	2.96	116.5	MP 35 N, Multiphase	975	2.64	104.1
Hastelloy S	635	2.18	85.8	Hastelloy G-3	925	1.94	76.2
Inconel 600	670	2.13	83.9	Stellite 6B	975	1.75	68.9
Hastelloy B-2	745	1.74	68.3	Haynes 188	950	1.47	57.8
Inconel 690	635	1.57	61.8	Haynes 25	965	1.42	55.8
Hastelloy C-276	765	0.96	37.9	Udimet 720	975	1.10	43.5
MP 35 N, Multiphase	750	0.45	17.8	Inconel 617	950	0.87	34.1

(Table Continued)

CORROSION RATES[a] FOR ALLOYS[b] EXPOSED TO SIMULATED $ZnCl_2$ RECOVERY CONDITIONS[c] OF $ZnCl_2$ HYDROCRACKING PROCESS[d][64], Continued

Cold Leg Exposures				Hot Leg Exposures			
Alloy	Temperature °C	Corrosion Rate[a] mm/yr	mils/yr	Alloy	Temperature °C	Corrosion Rate[a] mm/yr	mils/yr
75 HOUR EXPOSURE, Continued							
Inconel 625	670	0.39	15.4	Hastelloy G-3	975	0.77	30.4
Inconel 617	750	0.39	15.2	Stellite 6B	895	0.67	26.3
Hastelloy C-276	745	0.38	15.0	Udimet 720	895	0.55	21.6
Udimet 720	765	0.35	13.6	MP 35 N, Multiphase	895	0.55	21.5
Inconel 617	670	0.23	8.90	Alloy 800 (CoAl)[j]	965	0.39	15.2
Udimet 720	745	0.02	0.71	Inconel 617	965	0.17	6.5

[a]Corrosion rates are linearly extrapolated to annual values (based on the assumption of uniform removal of material). Alloys are ranked for each exposure in decreasing order of corrosion rate. For some alloys more than one specimen apparently was included in each test.

[b]Alloys are designated by the terms actually used in the original tables in the original reports for the most part. In the earlier reports "Alloy 617" was used and then "Inconel 617" for example. This inconsistency was kept in this summary table.

[c]Tests were conducted in quartz loops. Zinc chloride vapor was circulated with dry air and 5% HCl. The quartz loops required the exclusion of hydroxyl ions.

[d]The Conoco Zinc Chloride Hydrocracking Process for coal liquefaction uses zinc chloride to catalyze the hydrogenation of coal in the reactor. The zinc chloride is recovered in a fluidized sand bed regenerator containing air and HCl at 1000 °C. This process stream is then condensed at 370 °C and oxygen and sulfur are separated as H_2O and H_2S.

[e]Sample completely consumed.

[f]Lockheed supplied the alloy with the CrAl coating.

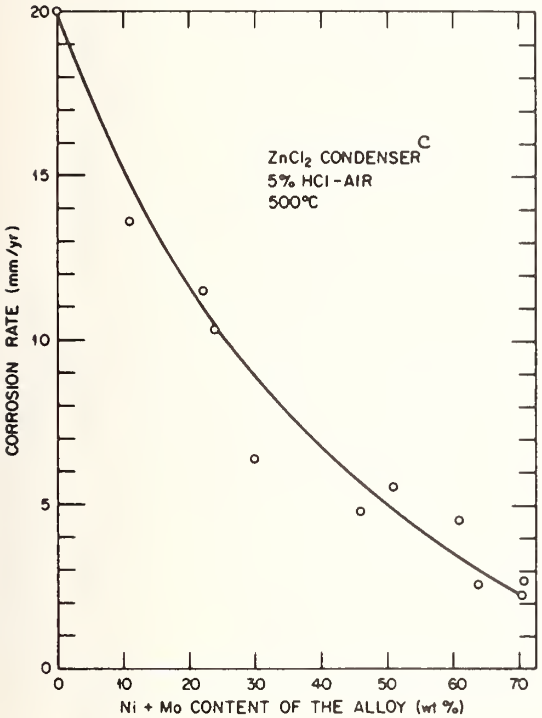
[g]Lockheed supplied the alloy with the CrSi coating.

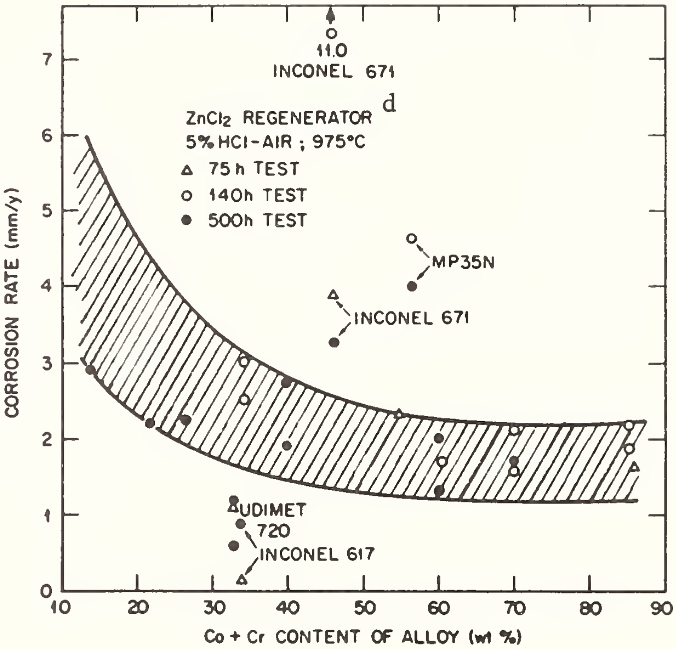
[h]Specimen gained weight due to scale formation but disintegrated on contact, <60 mm/yr.

[i]Specimen gained weight due to oxide formation but was completely consumed, <60 mm/yr.

[j]Lockheed supplied the alloy with the CoAl coating.

CORRELATION OF THE CORROSION RATES WITH THE ELEMENTAL COMPONENTS[a] OF ALLOYS TESTED IN $ZnCl_2$ HYDROCRACKING PROCESS SIMULATED $ZnCl_2$ RECOVERY CONDITIONS[b][64]





[a]At 500 °C there was no correlation found with either Cr or Co content. At 975 °C there was no correlation found with either Ni or Mo content.

[b]See Section B.1.1.157 for a description of the process and the test conditions and some of the data plotted above.

[c]Data from the 500 h test in Section B.1.1.157 are plotted.

[d]Data for 75 and 140 hour tests plotted above are from Sections B.1.1.157 but the 500 hour data are from another test not included in B.1.1.157.

LABORATORY STRESS CORROSION CRACKING[a] OF ALLOYS AS A FUNCTION OF AGING CONDITIONS[b][65,66]

Alloy	Penetration Rate, mm/yr (mils/yr)[a] 400°C(752°F)[b]	500°C(932°F)[b]	600°C(1112°F)[b]	Penetration Rate, mm/yr (mils/yr)[a] 400°C(752°F)[b]	500°C(932°F)[b]	600°C(1112°F)[b]
	10 HOUR AGING			100 HOUR AGING		
304 SS	0.887 (34.94)	1.594 (62.73)	11.789 (464.12)	0.87 (34.2)	1.55 (61.6)	15.60 (614.0)
304L SS	0.627 (24.66)	0.483 (19.00)	2.187 (86.10)	0.75 (29.5)	0.87 (34.3)	1.55 (61.0)
316 SS	0.552 (21.72)	0.509 (20.03)	3.146 (123.85)	0.46 (18.3)	0.79 (30.9)	4.84 (190.4)
316L SS	0.601 (23.68)	0.458 (18.02)	1.115 (43.89)	0.66 (26.0)	0.84 (32.9)	3.97 (156.4)
317 SS	0.272 (10.72)	0.386 (15.21)	1.716 (67.57)	0.32 (12.7)	0.34 (13.4)	2.99 (117.9)
317LM SS	0.334 (13.16)	0.341 (13.42)	1.282 (50.33)	0.37 (14.7)	0.39 (15.3)	4.51 (177.6)
321 SS	0.828 (32.59)	0.870 (34.26)	12.468 (490.88)	0.89 (35.1)	1.22 (48.1)	6.16 (242.4)
347 SS	0.579 (22.78)	0.504 (19.84)	0.562 (22.13)	0.49 (19.5)	0.51 (20.0)	1.01 (39.8)
310 SS	0.123 (4.85)	0.142 (5.58)	2.839 (111.77)	0.11 (4.3)	0.48 (19.0)	0.94 (37.1)
E-Brite 26-1	2.781 (109.50)	0.422 (16.60)	0.350 (13.78)	0.30 (11.9)	2.06 (80.9)	0.33 (13.1)
Carpenter 20Cb-3	0.136 (5.35)	0.141 (5.55)	0.290 (11.42)			
Incoloy 800	0.217 (8.55)	0.440 (17.30)	1.313 (51.69)	0.32 (12.8)	0.47 (18.3)	2.53 (99.6)
Incoloy 825	1.623 (63.89)	0.225 (8.86)	0.321 (12.66)	0.19 (7.3)	0.25 (9.8)	0.69 (27.3)
Hastelloy G-3	0.236 (9.29)	0.221 (8.71)	0.628 (24.71)	0.18 (7.0)	0.31 (12.0)	1.39 (54.7)
Hastelloy C-276	5.077 (199.86)	6.621 (260.66)	8.303 (326.91)	6.45 (254.1)	6.19 (243.9)	21.14 (832.1)
	1000 HOUR AGING			5000 HOUR AGING		
304 SS	2.06 (81.1)	3.53 (138.8)	c	1.34 (52.7)	6.87 (270.3)	c
304L SS	0.67 (26.4)	3.75 (147.5)	c	0.86 (33.9)	5.36 (210.8)	c
316 SS	0.69 (27.2)	1.38 (54.2)	9.31 (366.3)	0.82 (32.4)	1.97 (77.7)	c
316L SS	0.63 (24.6)	1.46 (57.3)	8.89 (350.1)	0.88 (34.5)	2.45 (96.6)	c
317 SS	0.48 (18.8)	0.43 (16.8)	1.89 (74.5)	0.38 (15.1)	0.79 (31.0)	c
317LM SS	0.38 (14.9)	0.69 (27.2)	41.99 (1653.0)	0.37 (14.5)	0.68 (26.7)	c
321 SS	1.28 (50.5)	3.87 (152.3)	1.65 (64.9)	1.40 (55.1)	5.98 (235.5)	c
347 SS	0.44 (17.2)	0.45 (17.9)	c	0.67 (26.5)	1.45 (57.1)	c
310 SS	0.26 (10.0)[d]	2.53 (99.5)	0.24 (9.3)	0.29 (11.5)	1.91 (75.3)	c
E-Brite 26-1	0.66 (26.0)	8.58 (337.9)	0.75 (29.5)	0.81 (31.8)	c	3.33 (130.9)
Carpenter 20Cb-3				0.22 (8.8)	0.20 (7.9)	3.63 (143.0)
Incoloy 800	0.33 (12.8)	1.01 (39.7)	11.40 (448.8)	0.37 (14.7)	1.57 (61.8)	13.24 (521.2)
Incoloy 825	0.15 (5.8)	0.35 (13.7)	1.55 (61.2)	0.21 (8.3)	0.57 (22.5)	
Hastelloy G-3	0.21 (8.4)	0.57 (22.3)	4.07 (160.0)	0.31 (12.3)	0.75 (29.6)	8.02 (315.7)
Hastelloy C-276	6.63 (261.2)	5.09 (200.3)	20.96 (825.0)	8.87 (349.2)	5.10 (200.9)	13.66 (537.8)
Ferralium				6.62 (260.4)	73.41 (2890.)	c
Inconel 625				1.97 (77.4)	3.48 (137.1)	c

[a]ASTM E262 Practice B was used to determine the relative degree of sensitization by measuring the susceptibility of alloys to intergranular attack. The samples were exposed to boiling 50% sulfuric acid-ferric sulfate solution for 120 hours. The degree of attack is reported as penetration rate (the 120 h attack extrapolated linearly to one year) for an average of three specimens exposed.

[b]The alloys were aged at 400, 500, and 600 °C for 10, 100, 1000, and 5000 hours.

[c]Specimens completely corroded during test.

[d]Specimens cracked in two during test.

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS OF THE BAYTOWN EXXON COAL LIQUEFACTION PILOT PLANT[65,66,67]

			Corrosion Rate,[a] mm/yr (mils/yr)							
Exposure Site	Environment[b]	Exposure Time, h	Carbon Steel	2-1/4 Cr-1 Mo	5 Cr-1 Mo	304 SS welded	304 SS sensitized [as received]	347 SS welded	Ferralium[c]	Incoloy 825
Liquefaction overhead, piping from separator recycle	Sour water, 40-65 °C, 13.8 MPa	1245					<0.01 (0.3) [0.01 (0.4)]		<0.01 (0.3)	<0.01 (0.3)
		2660					<0.01 (0.2) [<0.01 (0.1)]			<0.01 (0.1)
		1896	0.01 (0.40)		0.01 (0.45)	<<0.01 (0.07)			<<0.01 (0.09)	
	38 °C given	4944	<0.003(<0.1)	<0.003 (<0.1)		<0.003(<0.1)			<0.003(<0.1)	
Liquefaction overhead, piping into separator condenser	Sour water-hydrocarbon, 290 °C, 13.8 MPa	1245					0.08 (3.0) [0.09 (3.6)]		0.03 (1.1)	0.02 (0.8)
		2660					d [0.08 (3.2)]		e	0.01 (0.4)
		1896			0.50 (19.7)	0.04 (1.66)		0.04 (1.68)	<0.01 (0.22)	
	260 °C given	4944		0.291 (11.4)		0.035(1.4)		0.039(1.5)	<0.003(<0.1)	
Hydrogenation overhead piping into hot separator vapor condensor	Sour water-hydrocarbon[f]	1320	0.12 (4.6)				0.01 (0.4) [0.02 (0.6)]		0.03 (1.1)	0.01 (0.4)
		2645	0.07 (2.7)				<0.01 (0.2) <0.01 (0.3)		e	<0.01(0.15)
		1896	0.01 (0.38)		0.02 (0.69)	<0.01 (0.17)		<0.01 (0.24)	<<0.01 (0.08)	
		4944	0.012 (0.5)	0.006 (0.2)		<0.003(<0.1)		<0.003(<0.1)	<0.003(<0.1)	
Hydrogenation overhead piping from sour water scrubber	Sour water[f]	1320	0.09 (3.5)				<0.01 (0.1) [<0.01 (0.3)]		<0.01 (0.2)	<0.01 (0.3)
		2645	0.03 (1.0)				e [<0.01 (0.2)]		e	<0.01 (0.3)
		1896	0.06 (2.46)		0.02 (0.69)	<<0.01 (0.06)		<<0.01 (0.08)	<<0.01 (0.07)	
		4944	0.009 (0.4)	0.010 (0.4)		<0.003(<0.1)		<0.001(<0.1)	<0.003(<0.1)	
Solvent fractionator overhead, piping into reflux drum	Sour water-hydrocarbon, 120 °C, 0.34 MPa	1320	0.07 (2.9)				0.01 (0.5) 0.03 (1.2)			
		2645	0.01 (0.6)				<0.01 (0.1) [<0.01 (0.1)]			
		1896	0.11 (4.46)		0.21 (8.17)	0.02 (0.64)				
	107 °C given	4944	0.012 (0.5)	0.010 (0.4)		<0.003(<0.1)				
Solvent fractionator overhead piping from condenser	Sour water-hydrocarbon, 120 °C, 0.34 MPa	1320	0.01 (0.6)				<0.01 (0.1) [<0.01 (0.3)]			
		2645	0.03 (1.0)				<0.01 (0.2) [<0.01 (0.1)]			
		1896	0.02 (0.61)		0.02 (0.61)	<<0.01 (0.05)				
Solvent fractionator piping into distillate condenser	Sour water-hydrocarbon, 66 °C, 0.3 MPa	4944	0.004 (0.1)	<0.003 (<0.1)		<0.003(<0.1)				

[a]U-Bend specimens were exposed in the pilot plant in various locations indicated for the given times which apparently are the actual hours of full operation and do not include any holding time. The rate was linearly extrapolated from the corrosion loss for the test time (loss in mm calculated from weight loss)

[b]Only general conditions of the environment are given. For some 4944 hour tests a different temperature was given from that given for the other tests.

[c]Trade name of Langley Alloys Limited; nominal composition (wt%): 25.5 Cr, 5.2 Ni, 3.5 Mo, 1.7 Cu, 0.04 C, 0.45 Si, 0.80 Mn, 0.17 N, balance Fe.

[d]Corrosion rate could not be determined.

[e]Sample gained weight.

[f]Temperature and pressure are proprietary.

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE FORT LEWIS SOLVENT REFINED COAL LIQUEFACTION (SRC-II) PILOT PLANT[65,66]

		High-Pressure Separator (Flash Drum) at 330-430 °C			Intermediate-Pressure Separator (Flash Drum) at 280-380 °C		
Alloy	Weld Filler Metal[c]	Exposure Time, h[d]	Corrosion Rate, mm/yr	Type of Attack[e]	Exposure Time, h[d]	Corrosion Rate, mm/yr	Type of Attack[e]
410 SS		2707	0.45	P	2808	0.06	GS
410 SS	410 SS	736	0.30	TC	800	0.05	P
410 SS	410 SS	2707	0.44	TC	2808	0.07	TC
410 SS	410 SS				4 months	0.14	
18Cr-2Mo					2800	<0.01	N
18Cr-2Mo					4 months	0.01	
18Cr-2Mo	26Cr-1Mo	2707	0.02	N	2808	<0.01	IC[f]
E-Brite 26-1		736	<0.01	N	800	<0.01	N
E-Brite 26-1		2707	g	N	2808	g	N
E-Brite 26-1	26Cr-1Mo	2800	<<0.01	IC[f]	2800	g	N
E-Brite 26-1	26Cr-1Mo				4 months	<0.003	
304 SS	308 SS	736	0.13	N	800	0.03	N
304 SS	308 SS				4 months	0.03	
304L SS	308L SS	2800	0.03	GS	2800	<<0.01	N
304L SS	308L SS	2707	0.13	IP			
304L SS	308L SS	4 months	0.06				
310S SS					2800	h	N
310S SS	310 SS	2800	<<0.01	P			
316 SS		736	0.21	N	800	0.07	N
316 SS	316 SS	736	0.22	N	800	0.05	N
316L SS	316ELC				2808	0.02	N
317L SS	317L SS				2800	<<0.01	N
321 SS		2800	0.03	GS	2800	<0.01	N
321 SS	347 SS	736	0.12	N	800	0.08	N
321 SS	347 SS	2707	0.09	IP	2808	0.04	N
321 SS	347 SS	4 months	0.11		4 months	0.04	
347 SS		736	0.11	N	800	0.05	N
347 SS		2707	0.06	IP	2808	0.01	N
347 SS	347 SS	736	0.09	N	800	0.04	P
347 SS	347 SS	2800	0.02	GS	2800	<<0.01	N
347 SS	347 SS	4 months	0.06		4 months	0.03	
332 SS		2800	0.02	P			
332 SS	Inconel 82				2800	0.01	N
Incoloy 800H		736	0.12	N	800	0.05	N
Incoloy 800H		2707	0.03	S	2808	0.02	N
Incoloy 800H	Inconel 82	736	0.11	IC	800	<0.01	N
Incoloy 800H	Inconel 82	4 months	0.17				
Incoloy 825		2707	0.04	N	2808	g	N
Inconel 600		2800	h	S			
Inconel 600	Inconel 82				2800	h	S
Inconel 600	Inconel 82	2707	1.73	S,GS	2808	1.48	S,GS
Inconel 625		2800	<<0.01	IC			
Hastelloy C-276	C-276	2800	<<0.01	TC,S	2800	<<0.01	N
Carpenter 20Cb-3	320	2800	0.03	IC			
5Cr-1Mo (0.13 Nb)		4 months	1.27		4 months	0.86	
5Cr-1Mo (0.38 Nb)		4 months	0.95		4 months	0.87	
7Cr-1Mo (0.14 Nb)		4 months	1.36				
7Cr-1Mo (0.37 Nb)		4 months	1.28				
9Cr-1Mo		4 months	0.34		4 months	0.13	
9Cr-1Mo (modified)[i]		4 months	1.13		4 months	0.36	

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE FORT LEWIS SOLVENT REFINED COAL LIQUEFACTION (SRC-II) PILOT PLANT[65,66], Continued

		Recycle Condensate Separator at ambient temperature to 180 °C			Dissolver Vessel at 330-450 °C		
Alloy	Weld Filler Metal[c]	Exposure Time, h[d]	Corrosion Rate, mm/yr	Type of Attack[e]	Exposure Time, h	Corrosion Rate, mm/yr	Type of Attack[e]
410 SS		4340	<0.01	N			
410 SS	410 SS	1175	<0.01	TC	2600	g	N
410 SS	410 SS	4340	<0.01	TC			
410 SS	410 SS	4 months	<0.003				
18Cr-2Mo		4500	g	N			
E-Brite 26-1		1175	<0.01	N			
E-Brite 26-1		4340	g	N			
E-Brite 26-1		4 months	<0.003				
E-Brite 26-1	26Cr-1Mo	4500	<<0.01	N	2600	g	N
304 SS		4500	<<0.01	N			
304 SS		4 months	<0.003				
304 SS	308 SS	1175	0.01	N	2600	0.03	P
304 SS	308 SS	4500	<<0.01	N	2600	g	N
310 SS					2600	g	N
310 SS	310 SS	4500	<<0.01	N	2600	g	N
316 SS		1175	<0.01	N	2600	0.05	N
316 SS	316 SS	1175	<0.01	N	2600	0.02	N
316L SS	316 ELC	4340	<<0.01	N			
317L SS					2600	0.03	N
317L SS	317L SS	4500	<<0.01	N	2600	0.04	N
321 SS		4500	<<0.01	P	2600	0.06	N
321 SS	347 SS	1175	<0.01	N	2600	0.08	N
321 SS	347 SS	4340	g	N			
321 SS	347 SS	4 months	<0.003				
347 SS		1175	<0.01	N	2600	0.04	N
347 SS		4340	g	N			
347 SS	347 SS	1175	<0.01	N	2600	<<0.01	N
347 SS	347 SS	4500	<<0.01	N			
347 SS	347 SS	4 months	<<0.003				
332 SS		4500	<<0.01	N			
332 SS	Inconel 82				2600	0.30	N
Incoloy 800H		1175	<0.01	N	2600	0.29	TC,S
Incoloy 800H		4340	<<0.01	N			
Incoloy 800H	Inconel 82	1175	<0.01	N	2600	0.35	TC,S
Incoloy 825		4340	g	N			
Inconel 600	Inconel 82	4340	g	N	26C0	h	S
Inconel 625	Inconel 82				2600	0.03	TC,S
Carpenter 20Cb-3	320	4500	<<0.01	N	2600	0.09	N
Hastelloy G-3		4340	<<0.01	N			
5Cr-1Mo (0.13 Nb)		4 months	0.003				
5Cr-1Mo (0.38 Nb)		4 months	0.003				
9Cr-1Mo		4 months	0.003				
9Cr-1Mo (modified)[i]		4 months	0.003				

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE FORT LEWIS SOLVENT REFINED COAL LIQUEFACTION (SRC-II) PILOT PLANT[65,66], Continued

		Wash Solvent Column at 180-280 °C		
Alloy	Weld Filler Metal[c]	Exposure Time, h	Corrosion Rate, mm/yr	Type of Attack[e]
E-Brite 26-1	26Cr-1Mo	1334	2.39	GS
316 SS	316 SS	1334	1.05	GS
316L SS	316 ELC	1334	0.87	GS
317L SS	317L SS	1334	0.91	P
321 SS	347 SS	1334	0.91	GS
Incoloy 825		1334	0.54	GS
Inconel 625	Inconel 82	1334	0.33	GS
Carpenter 20Cb-3	320	1334	0.34	GS
Hastelloy G-3		1334	0.39	GS

[a]U-bend specimens and welded U-bends were exposed in the various locations for the given times. Times are apparently the actual hours of full operation and do not include holding times, except for the 4-month exposure. The rate was linearly extrapolated from the corrosion loss (calculated from weight loss) for the test times.

[b]Locations are given as stated in the original reports. Specific conditions were not given as to pressure, or chemical environment, and only nominal temperature ranges.

[c]Filler metal is given for welded specimens. If the specimen is a plain U-bend this column is blank.

[d]One series of the test results did not specify the number of hours but simply stated that the specimens were exposed from June through September. These results carry the 4 month label and the holding times are therefore included.

[e]GS = general surface attack, IC = intergranularly cracked, IP = intergranular penetrations, N = no attack, P = pitted slightly, S = sulfidized, TC = transgranularly cracked. Where this column is blank, no information was given in the source tables.

[f]Suspected anomaly.

[g]Specimen gained weight.

[h]Specimen completely corroded.

[i]Modified alloy contains Nb, V, and N.

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE WILSONVILLE SOLVENT REFINED COAL PILOT PLANT[65,66]

Location--Fractionation Column for 5341 hours

Alloy	Temperature Range, °C[c]	Corrosion Rate, mm/yr[d]	Type of Attack[e]
E-Brite 26-1	190-220	<0.02	N
E-Brite 26-1	220-260	f	GS,P
E-Brite 26-1	290-310	g	N
304L SS	190-220	<0.02	N
304L SS	220-260	0.48	TC,P
304L SS	290-310	g	N
310S SS	190-220	<0.02	N
310S SS	220-260	0.38	TC
310S SS	290-310	<0.01	N
316 SS	190-220	<0.02	N
316 SS	220-260	0.47	GS
316 SS	290-310	g	N
317L SS	190-220	<0.02	N
317L SS	220-260	0.55	GS
317L SS	290-310	g	N
321 SS	190-220	<0.02	N
321 SS	220-260	0.38	TC,P
321 SS	290-310	<0.01	TC,P
347 SS	190-220	<0.02	N
347 SS	220-260	0.43	TC,P
347 SS	290-310	<0.01	TC,P
Incoloy 800H	190-220	<0.02	N
Incoloy 800H	220-260	0.26	TC
Incoloy 800H	290-310	0.30	S
Inconel 600	190-220	<0.02	N
Inconel 600	220-260	0.01	IP
Inconel 600	290-310	<0.01	IP
Carpenter 20Cb-3	190-220	<0.02	N
Carpenter 20Cb-3	220-260	0.01	IP
Carpenter 20Cb-3	290-310	<0.01	N

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE WILSONVILLE SOLVENT REFINED COAL PILOT PLANT[65,66], Continued

Location--Dissolver Vessel (near the top) for 12,267 hours[h]

Alloy	Weld Filler Metal[i]	Corrosion Rate[d] mm/yr	Corrosion Rate[d] mils/yr	Type of Attack[e]
VAPOR PHASE				
Hastelloy C-276	C-276	<0.01	<0.04	S
Inconel 600	Inconel 82	0.010	0.40	MM
Inconel 625	Inconel 82	0.001	0.04	IC
410 SS	410 SS	0.171	6.71	TC
304L SS	308L SS	0.019	0.74	IC
316 SS	316 SS	0.008	0.32	MM
Incoloy 800H	Inconel 82	0.008	0.32	IC
317L SS	317L SS	0.022	0.88	MM
310 SS	310 SS	0.009	0.38	TC
347 SS	347 SS	0.015	0.60	MM
VAPOR-LIQUID INTERFACE				
Hastelloy C-276		<0.01	<0.04	N
Inconel 600		j	j	j
Inconel 625		<0.01	<0.04	IC
Incoloy 800H	Inconel 82	0.007	0.29	TC
310 SS		0.010	0.41	TC
310 SS	310 SS	0.009	0.37	TC
347 SS		0.015	0.61	MM
321 SS	347 SS	0.005	0.18	TC
332 SS		0.006	0.24	TC
Carpenter 20Cb-3		0.004	0.16	TC
LIQUID PHASE				
410 SS		0.265	10.42	GS
304L SS		0.013	0.52	TC
316 SS		0.004	0.16	TC
Incoloy 800H		0.013	0.50	MM
317L SS		0.006	0.25	TC
317L SS	317L SS	0.003	0.14	IC
347 SS	347 SS	0.011	0.42	MM
321 SS		0.008	0.33	TC
304 SS		0.014	0.56	TC
316 SS	316 SS	g	g	IC

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE WILSONVILLE SOLVENT REFINED COAL PILOT PLANT[65,66], Continued

Location--Dissolver Vessel Bottom

Alloy	Weld Filler Metal[i]	Corrosion Rate[d] mm/yr	Corrosion Rate[d] mils/yr	Corrosion Rate[d] mm/yr	Corrosion Rate[d] mils/yr
Exposed		9958 hours		1850 hours	
7Cr-1Mo steel		>0.66[j]	>26[j]	1.87	74
7Cr-1Mo steel		>0.66[j]	>26[j]	1.79	71
9Cr-1Mo (modified)[k]		>0.67[j]	>26[j]	1.31	52
9Cr-1Mo steel		>0.66[j]	>26[j]	1.14	45
Sandvik HT9		0.325	12.8	0.84	33
Sanicro 41X				0.24	9.4
410 SS		0.278	10.9	0.23	9.2
321 SS		0.123	4.8	0.10	4.0
321 SS	347 SS	0.106	4.2	g	g
304L SS		0.080	3.1	0.06	2.3
304L SS	308L SS	0.077	3.0	0.05	2.1
332 SS	Inconel 82	0.056	2.2	g	g
347 SS	347 SS	0.054	2.1	0.05	1.9
304 SS	308 SS	0.053	2.1	0.04	1.4
347 SS		0.053	2.1	0.03	1.2
332 SS		0.045	1.8	g	g
316L SS		0.040	1.6	0.05	1.9
Sandvik 3RE14		0.039	1.5	0.05	2.1
316L SS	316ELC	0.036	1.4	0.04	1.5
Sanicro 28		0.07	0.3	g	g
310 SS	310 SS	0.004	0.2		

Location--High-Pressure Separator for 12,267 hours

Alloy	Weld Filler Metal[i]	Corrosion Rate[d] mm/yr	Corrosion Rate[d] mils/yr
5Cr-1Mo steel		0.358	14.1
5Cr-1Mo steel		0.330	13.0
7Cr-1Mo steel		0.271	10.7
7Cr-1Mo steel		0.261	10.3
9Cr-1Mo steel		0.221	8.7
9Cr-1Mo (mod.)[k]		0.213	8.4
321 SS	347 SS	0.018	0.7
Incoloy 800H	Inconel 82	0.015	0.6
347 SS	347 SS	0.010	0.4
304 SS	308 SS	0.008	0.3

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS PARTS[b] OF THE WILSONVILLE SOLVENT REFINED COAL PILOT PLANT[65,66], Continued

Location--High-Pressure Letdown Vessel (Flash Drum) for 6158 hours -

Alloy	Corrosion Rate[d] mm/yr	mils/yr
Carbon steel	>1.00	>39
5Cr-1Mo steel	0.229	9.0
7Cr-1Mo steel	0.209	8.2
9Cr-1Mo steel (modified)[k]	0.176	6.9
347 SS	0.024	1.0
316 SS	0.05	0.2
304 SS	0.003	0.1
317L SS	<0.003	<0.1
Ferralium[l]	<0.003	<0.1
310 SS	<0.003	<0.1

[a]U-bend specimens and welded U-bends were exposed in the various locations for the given times. Times are apparently the actual hours of full operation and do not include holding times.

[b]Locations are given as stated in the original reports. Specific conditions were not given as to pressure, temperature, or chemical environment.

[c]U-bends were exposed at different levels in the column and therefore were subjected to different temperature ranges.

[d]Corrosion rates were linearly extrapolated from the corrosion loss (calculated from weight loss) for the test times.

[e]GS = general surface attack, IC = intergranularly cracked, IP = intergranular penetrations, MM = mixed mode, N = no attack, P = pitted slightly, S = sulfidized, TC = transgranularly cracked.

[f]Specimen completely corroded.

[g]Specimen gained weight.

[h]Specimens were placed in the vessel near the top in such a way that they were exposed to the three different phases defined in the table. The nominal temperature for the exposure was given as 450 °C.

[i]Filler metal is given for welded specimens. If the specimen is a plain U-bend this column is blank.

[j]Specimen disappeared.

[k]Modified alloy contains Nb, V, and N.

[l]Trade name of Langley Alloys Limited; nominal composition (wt %): 25.5 Cr, 5.2 Ni, 3.5 Mo, 1.7 Cu, 0.04 C, 0.45 Si, 0.80 Mn, 0.17 N, balance Fe.

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] OF THE CATLETTSBURG COAL LIQUEFACTION (H-COAL) PILOT PLANT[65,66,67]

Data from the first exposure for five months of noncontinuous service

Weight Loss,[c] g/cm^2 (Type of Attack)[d]

Alloy	Weld[e] Filler Metal	Reactor, 22.4 MPa (3250 psi), 455 °C (850 °F) Vapor	Liquid	Fractionator, 0.08 MPa (12 psi), 150-280 °C (305-535 °F) Top	Middle	Bottom
HT9		0.082	0.087			
410 SS	410 SS	0.042	0.058	<0.001(TC,P)	0.002(TC,P)	0.081(TC)
304 SS		f	0.010	f (P)	<0.001	<0.001(P)
304 SS	308 SS	f	0.009	f (P)	<0.001	<0.001
316 SS		f	0.007	f	f (P)	<0.001
316 SS	316 SS	f	0.006	f	f	0.0
317L SS	317L SS			f	f	f
347 SS	347 SS	f	0.008			
310 SS	310 SS	<0.001	0.003			
Carpenter 20Cb-3	320	f	0.009			
Incoloy 800H	Inconel 82	0.020	0.026			
Incoloy 825				f	f	f
Inconel 625	Inconel 82			f	f	f
Hastelloy G-3				f	f	<0.001
Hastelloy C-276	C-276			f	f	f

Alloy	Weld Filler Metal	High-Pressure Flash Drum, 8.3MPa(1200psi), 400°C(750°F) Vapor	Liquid	Low-Pressure Flash Drum, 0.37MPa(55psi), 385°C(730°F) Vapor	Liquid
Carbon steel				0.164	0.105
HT9		0.041(GS)	f (GS)		
410 SS	410 SS	0.034(GS)	0.032(GS)	0.015	0.007
304 SS		f	f	f	f
304 SS	308 SS	f (GS)	f (P)	f	f
316 SS		f	f	f	f
316 SS	316 SS	f	f	f	f
347 SS	347 SS	f (GS)	f (P)	f	f
310 SS	310 SS	f	f	f	f
Carpenter 20Cb-3	320	0.005	0.004		
Incoloy 800H	Inconel 82	0.010	0.007	<0.001	<0.001

Alloy	Weld Filler Metal	Reactor Effluent Vapor Separator, 22.2 MPa (3225 psi), 260 °C (500 °F) Vapor	Liquid	Reactor Effluent Separator, 20.7 MPa (3000 psi), 455 °C (850 °F) Vapor	Liquid
Carbon steel		0.227(GS,P)	0.144(GS)		
HT9		0.210(P)	0.001(P)	0.080	0.041
410 SS	410 SS	0.252(P)	0.008(TC)	0.040	0.023
304 SS		0.015(IC,TC)	<0.001	f	f
304 SS	308 SS	0.011(TC,P)	<0.001(TC)	f	f
316 SS		0.011	<0.001(TC)	f	f
316 SS	316 SS	0.011(TC)	<0.001	f	f
347 SS	347 SS	0.012	<0.001	f	0.012
310 SS	310 SS	0.007(TC)	f	f	<0.001
Carpenter 20Cb-3	320			0.010	0.031
Incoloy 800H	Inconel 82	0.025(IC)	<0.001	0.022	0.026

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] OF THE CATLETTSBURG COAL LIQUEFACTION (H-COAL) PILOT PLANT[65,66,67], Continued

Data from a second exposure for 13 months (142 days of operation with coal)

		Corrosion Rate,[a] mm/yr				
		Reactor, 20.7 MPa (3000 psi), 455 °C (850 °F)		Fractionator, 0.08 MPa (12 psi), 150-280 °C (305-535 °F)		
Alloy	Weld[e] Filler Metal	Vapor	Liquid	Top	Middle	Bottom
HT9		0.07	0.50			
410 SS	410 SS	0.10	0.19	<<0.01	<<0.01	<<0.01
304 SS		0.11	0.08	<<0.01	<<0.01	<<0.01
304 SS	308 SS	0.07	0.08	<<0.01	<<0.01	<<0.01
316 SS		0.02	0.13	<<0.01	<<0.01	<<0.01
316 SS	316 SS	0.34	0.36	0.01	0.01	<<0.01
317L SS	317L SS			<<0.01	f	<<0.01
347 SS	347 SS	0.07	0.07			
310 SS	310 SS	0.11	0.02			
Carpenter 20Cb-3	320	0.50	0.25			
Incoloy 800H	Inconel 82	0.53	0.37			
Incoloy 825				<<0.01	f	<<0.01
Inconel 625	Inconel 82			<<0.01	f	0.00
Hastelloy G-3				<<0.01	f	f
Hastelloy C-276	C-276			<<0.01	f	<<0.01

		High-Pressure Flash Drum, 8.3MPa(1200psi), 400°C(750°F)		Low-Pressure Flash Drum, 0.34MPa(50psi), 380°C(715°F)	
Alloy	Weld Filler Metal	Vapor	Liquid	Vapor	Liquid
Carbon steel				1.50	0.17
HT9		0.18	0.06	0.06	0.02
9Cr-1Mo (modified)[g]				0.12	0.03
410 SS	410 SS	0.05	0.01	0.04	0.00
304 SS		0.07	0.01	0.01	<0.01
304 SS	308 SS	0.04	0.01	0.01	f
316 SS		0.15	0.01	0.01	f
316 SS	316 SS	0.15	0.11	0.01	0.01
347 SS	347 SS	0.06	0.01	0.01	<0.01
310 SS	310 SS	<0.01	<0.01		
Carpenter 20Cb-3	320	0.07	0.02		
Incoloy 800H	Inconel 82	0.11	0.01	0.01	<0.01

		Reactor Effluent Vapor Separator, 20.7 MPa (3000 psi), 260 °C (500 °F)		Reactor Effluent Separator, 20.7 MPa (3000 psi), 455 °C (850 °F)	
Alloy	Weld Filler Metal	Vapor	Liquid	Vapor	Liquid
Carbon steel		h	h		
HT9		h	h	0.42	0.20
9Cr-1Mo (modified)[g]		h	h		
410 SS	410 SS	0.47	0.01[i]	0.16	0.16
304 SS		0.44	0.01[i]	0.16	0.14
304 SS	308 SS	0.42	0.01[i]	0.08	0.07
316 SS		0.46	0.01[i]	0.13	0.06
316 SS	316 SS	h	h	0.41	0.15
347 SS	347 SS	0.50	0.02[i]	0.06	0.06
310 SS	310 SS			<0.01	f
Carpenter 20Cb-3	320			0.27	0.10
Incoloy 800H	Inconel 82	0.77	<0.01[i]	0.42	0.27

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] OF THE CATLETTSBURG COAL LIQUEFACTION (H-COAL) PILOT PLANT[65,66,67], Continued

Data from an exposure for 456 hours with operation of Wyodak subbituminous coal - - - - - - - - - - -

		Corrosion Rate,[a] mm/yr				
		Reactor, 20.7 MPa (3000 psi), 455 °C (850 °F)		Fractionator, 0.08 MPa (12 psi), 150-280 °C (305-535 °F)		
Alloy	Weld[e] Filler Metal	Vapor	Liquid	Top	Middle	Bottom
Carbon steel				0.044	0.096	0.061
2-1/4 Cr-1 Mo		3.75	3.61	0.014	0.003	0.034
5 Cr-1 Mo						0.023
9 Cr-1 Mo				<0.003		<0.003
18 Cr-1 Mo		0.044	0.041			
410 SS		0.289	0.359	0.005	0.010	0.003
Ferralium[j]	Not given, but welded	0.016	0.009	f	0.007	f
304 SS	308 SS	0.020	0.022	f	0.005	<0.003
316 SS	316 SS	0.005	0.007	f	0.005	0.003
321 SS	347 SS	0.029	0.027		f	
347 SS	347 SS	0.017	0.022	f	0.010	0.003
Carpenter 20Cb-3		0.048	0.010			
Incoloy 825	Not given, but welded	0.052	0.006	f	f	0.007
Inconel 600				f	f	

		High-Pressure Flash Drum, 8.3MPa(1200psi), 400°C(750°F)		Low-Pressure Flash Drum, 0.34MPa(50psi), 380°C(715°F)	
Alloy	Weld Filler Metal	Vapor	Liquid	Vapor	Liquid
2-1/4 Cr-1 Mo		2.34	0.53	0.615	0.149
18 Cr-1 Mo		0.030	0.012	0.010	0.010
410 SS		0.204	0.106	0.071	0.036
Ferralium[j]	Not given, but welded	0.014	0.008	0.009	0.008
304 SS	308 SS	0.023	0.010	0.005	0.008
316 SS	316 SS	0.007	0.003	0.006	0.009
321 SS	347 SS	0.020	0.014	0.007	0.007
347 SS	347 SS	0.014	0.015	0.006	0.007
Carpenter 20Cb-3		0.016	0.006	0.007	0.007
Incoloy 825	Not given, but welded	0.005	0.010	0.007	0.008

		Reactor Effluent Vapor Separator, 20.7 MPa (3000 psi), 260 °C (500 °F)		Reactor Effluent Separator, 20.7 MPa (3000 psi), 455 °C (850 °F)	
Alloy	Weld Filler Metal	Vapor	Liquid	Vapor	Liquid
2-1/4 Cr-1 Mo		0.292	0.045	3.53	2.54
18 Cr-1 Mo		0.027	0.009	0.056	0.044
410 SS		0.067	0.030	0.138	0.345
Ferralium[j]	Not given but welded	0.003	0.007	0.006	<0.003
304 SS	308 SS	0.028	0.009	0.016	0.018
316 SS	316 SS	f	f	<0.003	0.005
347 SS	347 SS	0.033	<0.003	0.016	0.005
Carpenter 20Cb-3		<0.003	<0.003	0.031	0.003
Incoloy 825	Not given, but welded	0.005	0.004	0.033	0.005
Inconel 625		f	f	0.003	0.014

(Table Continued)

STRESS-CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] OF THE CATLETTSBURG COAL LIQUEFACTION (H-COAL) PILOT PLANT[65,66,67], Continued

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[a]U-bend specimens and welded U-bends were exposed in the various locations. Corrosion rate was linearly extrapolated from the corrosion loss (calculated from weight loss) for the time of operation with coal. See footnote c for explanation of weight loss data given.

[b]Chemical environment not given.

[c]Weight loss is given because there was a question as to the length of operating time to be used in calculating corrosion rate. The plant operated on both coal and oil and some operation took place at below-normal temperatures during the test period.

[d]GS = general surface attack, IC = intergranular cracking, P = pitting, TC = transgranular cracking.

[e]Filler metal is given for welded specimens. If the specimen is a plain U-bend this column is blank.

[f]Specimen gained weight.

[g]Modified alloy contains Nb, V, and N.

[h]Specimen totally lost.

[i]Specimen mechanically damaged.

[j]Trade name of Langley Alloys Limited; nominal composition (wt %): 25.5 Cr, 5.2 Ni, 3.5 Mo, 1.7 Cu, 0.04 C, 0.45 Si, 0.80 Mn, 0.17 N, balance Fe.

CORROSION DATA[a] FOR ALLOYS EXPOSED[b] IN THE BAYTOWN EXXON DONOR SOLVENT COAL LIQUEFACTION PILOT PLANT[66,67,68]

Alloy	Corrosion Rate,[a] mm/year (mils/year) Tray 20	Tray 21	Tray 23	Tray 25	Tray 26
FIRST EXPOSURE, 1896 HOURS[c]					
Carbon steel	2.69 (108)	4.54 (179)	4.86 (191)	1.47 (58)	0.58 (23)
410 SS	0.46 (18)	2.62 (103)	2.10 (83)	0.045 (1.8)	0.010 (0.4)
321 SS	<0.003 (<0.1)	0.009 (0.4)	0.166 (6.5)	<0.003 (<0.1)	<0.003 (<0.1)
310 SS (aluminized)	0.010 (0.4)	0.008 (0.3)	0.011 (0.4)	0.017 (0.7)	0.016 (0.6)
Inconel 600	d	0.003 (0.1)	<0.003 (<0.1)	d	d
Inconel 601	<0.003 (<0.01)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
304 SS	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	0
316 SS	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Incoloy 825	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
316L SS	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Ferralium[e]	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Haynes 20 Mod	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Zirconium	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
347 SS	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	d
Titanium	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Inconel 625	<0.003 (<0.1)	<0.003 (<0.1)	d	<0.003 (<0.1)	d
Hastelloy C-276	<0.003 (<0.1)	<0.003 (<0.1)	0	<0.003 (<0.1)	<0.003 (<0.1)
SECOND EXPOSURE, 4920 HOURS					
Carbon steel	>4.20 (>165)	>4.23 (>166)	>4.22 (>166)	>4.20 (>165)	0.86 (34)
410 SS	0.605 (24)	4.04 (159)	1.96 (77)	0.025 (1.0)	0.004 (0.2)
304 SS	0.040 (1.6)	0.277 (10.9)	0.146 (5.7)	<0.003 (<0.1)	<0.003 (<0.1)
321 SS	0.041 (1.6)	0.196 (7.7)	0.131 (5.2)	<0.003 (<0.1)	<0.003 (<0.1)
316 SS	0.031 (1.2)	0.153 (6.0)	0.140 (5.5)	<0.003 (<0.1)	0.003 (0.1)
316L SS	0.020 (0.8)	0.131 (5.2)	0.072 (2.8)	<0.003 (<0.1)	<0.003 (<0.1)
317LM SS	0.022 (0.9)	0.119 (4.7)	0.069 (2.7)	<0.003 (<0.1)	0.003 (0.1)
Ferralium[e]	0.022 (0.9)	0.094 (3.7)	0.048 (1.9)	<0.003 (<0.1)	0.003 (0.1)
Haynes 20 Mod	0.003 (0.1)	0.037 (1.4)	0.012 (0.5)	<0.003 (<0.1)	<0.003 (<0.1)
304 SS (aluminized)	0.003 (0.1)	0.010 (0.4)	0.011 (0.4)	0.007 (0.3)	0.005 (0.2)
Incoloy 825	0.003 (0.1)	0.019 (0.7)	0.006 (0.2)	<0.003 (<0.1)	<0.003 (<0.1)
Inconel X-750	<0.003 (<0.1)	0.008 (0.3)	0.005 (0.2)	<0.003 (<0.1)	<0.003 (<0.1)
Inconel 600	<0.003 (<0.1)	0.008 (0.3)	0.006 (0.2)	<0.003 (<0.1)	<0.003 (<0.1)
Titanium	0.004 (0.2)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Hastelloy C-276	<0.003 (<0.1)	<0.003 (<0.1)	0.003 (0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Zirconium	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)
Inconel 625	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)	<0.003 (<0.1)

[a]Coupons were cleaned and weighed after exposure and corrosion rates were calculated from weight loss, linearly extrapolated assuming uniform removal of material, to obtain annual rates. In the original reports the authors noted that corrosion of 410 SS in the 4920-hour exposure was not uniform.

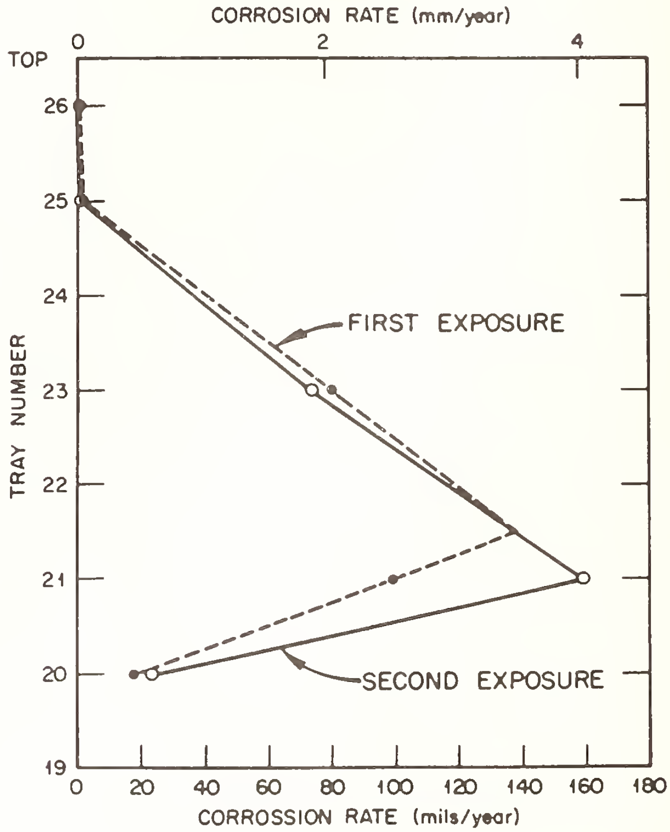
[b]Coupons were exposed at different levels in the atmospheric fractionator, the tray numbers indicate the levels. Operating conditions and chemical environment are not given. The exposure time is apparently time for full operation of the plant and does not include hold times.

[c]The plant operated for about 1 week on Illinois No. 6 (bituminous) and for about 10 weeks on Wyodak subbituminous during this exposure period.

[d]Weight gain indicates the presence of a tightly adherent scale not removed by ultrasonic cleaning.

[e]Trade name of Langley Alloys Limited; nominal composition (wt%): 25.5 Cr, 5.2 Ni, 3.5 Mo, 1.7 Cu, 0.04 C, 0.45 Si, 0.80 Mn, 0.17 N, balance Fe.

CORROSION RATES[a] OF 410 SS EXPOSED IN THE FRACTIONATOR COLUMN OF THE BAYTOWN EXXON DONOR SOLVENT COAL LIQUEFACTION PILOT PLANT[67]



[a]See Section B.1.1.164 for the data plotted here. The first and second exposure labels of the plot correspond to the first and second exposures in B.1.1.164 and the plant tray designations for locations in the Fractionator are the same.

CORROSION DATA[a] FOR ALLOYS EXPOSED[b] IN THE ATMOSPHERIC FRACTIONATOR OF THE CATLETTSBURG COAL LIQUEFACTION (H-COAL) PILOT PLANT[66,67,68]

Alloy	Corrosion Rate,[a] mm/year (mils/year)									
	Tray 9		Tray 10		Tray 11		Tray 12		Tray 13	
First Exposure---1176 hours for Trays 9, 10, 12, and 13; 1080 hours for Tray 11										
Carbon steel		(582.0)		(803.6)		(759.9)		(700.4)		(295.0)
409 SS		(45.1)		(261.6)		(300.1)		(210.5)		(0.2)
347 SS		(32.1)		(29.9)		(21.7)		(19.3)		(<0.1)
321 SS				(15.8)				(20.7)		
Monel 400		(12.9)		(11.5)		(4.5)		(5.9)		(4.4)
317 SS		(2.4)		(7.0)		(7.4)		(1.2)		(<0.1)
Carpenter 20Cb-3		(1.3)		(1.4)		(4.5)		(1.4)		(<0.1)
Sanicro 2205		(0.2)		(1.3)		(1.5)		(1.8)		(<0.1)
Sandvik 2RE69		(<0.1)		(0.5)		(1.3)		(0.6)		(<0.1)
Inconel 600		(0.5)		(0.5)		(<0.1)		(0.3)		(<0.1)
Incoloy 825		(<0.1)		(0.4)		(0.7)		(0.1)		(0.1)
Hastelloy B-2		(0.3)		(0.3)		(<0.1)		(0.3)		(0.3)
RA 333		(0.2)		(0.1)		(<0.1)		(<0.1)		(0.2)
Crucible 6M		(0.2)		(0.1)		(0.1)		(0.1)		(0.2)
Haynes 20 Mod		(<0.1)		(<0.1)		(<0.1)		(0.3)		(<0.1)
Haynes 263		(0.1)		(<0.1)		(0.2)		(0.1)		(<0.1)
Titanium		(0.1)		(<0.1)		(<0.1)		(<0.1)		(0.1)
Alloy 904L		(<0.1)				(<0.1)				(<0.1)
Hastelloy C-4		(<0.1)		(<0.1)		(<0.1)		(<0.1)		(<0.1)
Inconel 625		(<0.1)		(<0.1)		(<0.1)		(<0.1)		(<0.1)
Hastelloy G		(<0.1)		(<0.1)		(<0.1)		(<0.1)		(<0.1)
Second Exposure---2160 hours for all trays										
Carbon steel	15.8	(620)	10.5	(414)	11.0	(435)	6.32	(249)	3.54	(139)
410 SS	1.86	(73)	0.526	(21)	0.438	(17)	0.068	(2.7)	0.019	(0.8)
Monel 400	0.304	(12)	0.166	(6.5)	0.196	(7.7)	0.182	(7.2)	0.137	(5.4)
304 SS	0.264	(10)	0.314	(12)	0.281	(11)	0.010	(0.4)	0.003	(0.1)
347 SS	0.301	(12)	0.135	(5.3)	0.155	(6.1)	0.022	(0.9)	0.003	(0.1)
321 SS	0.145	(5.7)	0.141	(5.5)	0.063	(2.5)	0.050	(2.0)	0.003	(0.1)
317 SS	0.048	(1.9)	0.065	(2.6)	0.056	(2.2)	0.006	(0.2)	0.003	(0.1)
316L SS	0.017	(0.7)	0.084	(3.3)	0.056	(2.2)	0.005	(0.2)	0.003	(0.1)
Sandvik 2RE69	0.008	(0.3)	0.068	(2.7)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)
Alloy 904L	0.003	(0.1)	0.016	(0.6)	0.009	(0.3)	0.006	(0.2)	0.003	(0.1)
Sanicro 2205	0.013	(0.5)	0.003	(0.1)	0.013	(0.5)	0.003	(0.1)	0.003	(0.1)
Inconel 600	0.007	(0.3)	0.004	(0.2)	0.005	(0.2)	0.005	(0.2)	0.003	(0.1)
RA 333	0.003	(0.1)	0.007	(0.3)	0.005	(0.2)	0.006	(0.2)	0.003	(0.1)
Carpenter 20Cb-3	0.007	(0.3)	0.005	(0.2)	0.005	(0.2)	0.003	(0.1)	0.003	(0.1)
Incoloy 825	0.004	(0.1)	0.005	(0.2)	0.003	(0.1)	0.004	(0.1)	0.003	(0.1)
Crucible 6M	0.003	(0.1)	0.003	(0.1)	0.005	(0.2)	0.004	(0.1)	0.003	(0.1)
Titanium	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)
Hastelloy C-4	0.003	(0.1)	0.003	(0.1)	0.004	(0.1)	0.003	(0.1)	0.003	(0.1)
Inconel 625	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)
Haynes 20 Mod	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)	0.003	(0.1)

[a]Coupons were cleaned and weighed after exposure and corrosion rates were calculated from weight loss, linearly extrapolated assuming uniform removal of material, to obtain annual rates.

[b]Coupons were exposed at different levels in the fractionator, the tray numbers assigned by the plant indicating the levels. Operating conditions and chemical environment not given. The exposure time is apparently time for full operation of the plant and does not include hold times.

CORROSION DATA[a] FOR ALLOYS EXPOSED[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[69]

Location	Conditions[c]	Alloy	First Exposure[b] Exposure Time, h	Corrosion Rate mm/yr	mils/yr	Second Exposure[b] Exposure Time, h	Corrosion Rate mm/yr	mils/yr
Dissolver--	430-450 °C	316 SS	4015	0.05	2.1	5730	0.04	1.4
Vapor phase	(805-845 °F)	347 SS		0.00	0.0		e	
	12-17 MPa (1700-2450	410 SS		0.10	3.9		0.03	1.1
	psig)	Carpenter 20Cb-3		0.01	0.4		0.01	0.5
	40-60 SRC[d]	304 SS		0.00	0.0		e	
	5-25 organic liquid	Incoloy 800		0.03	1.3		0.04	1.7
	3-8 water	RA 330		0.01	0.3		0.01	0.2
	5-25 unreacted coal	22Cr-13Ni-5Mn		0.00	0.0		e	
	7-12 ash	26Cr-1Mo steel		e			0.06	2.2
	4-12 hydrocarbon gases							
	1.0-4 $CO + CO_2$							
	0.5-4 H_2S							
High-pressure	310-340 °C	26Cr-1Mo steel	4015	e		5730	0.00	0.0
Separator--	(590-650 °F)	304L SS		0.02	0.8		0.01	0.2
Vapor phase	All other conditions,	316 SS		0.02	0.6		0.02	0.6
	same as dissolver	410 SS		e			0.03	1.0
	above	22Cr-13Ni-5Mn		0.01	0.3		0.01	0.2
Solvent De-	38 °C (100 °F)	1018 Carbon steel	4015	0.02	0.7	5730	0.00	0.0
canter--Liquid	0.17 MPa (10 psig)	304L SS		e			0.00	0.0
vapor inter-	ammonia, organic	410 SS		0.00	0.0		0.00	0.0
face	liquid, decanter oil,							
	decanter water, vent gas							
Reclaim Tank--	260-315 °C (500-600 °F)	1018 Carbon steel	4015	0.07	2.9	5730	0.01	0.2
Liquid phase	0.90 MPa (115 psig)	304L SS		0.00	0.0		e	
	cresol insolubles, ash,	410 SS		0.00	0.0		0.00	0.0
	SRC[d], distillate							
Vacuum Column	93-102 °C (200-215 °F)	1018 Carbon steel	4015	0.06	2.3	5730	0.01	0.2
top manway--	2-27 kPa (0.3-3.9 psia)	304L SS		0.00	0.0		0.00	0.0
Vapor phase	product, overhead	410 SS		<0.11	0.1		0.00	0.0
	light solvent, wash							
	solvent, recycle pro-							
	cess solvent							
Vacuum Column	300-325 °C (590-615 °F)	1018 Carbon steel	4015	0.65	25.7	5730	0.64	25.1
bottom manway--	Other conditions as	304L SS		0.00	0.0		e	
Vapor phase,	given above for top	410 SS		0.01	0.4		0.01	0.2
maybe liquid	manway							
Fractionation	190-220 °C	316 SS	2350	0.00	0.0	5730	0.00	0.0
Column top	(380-430 °F)	Carpenter 20Cb-3		0.03	1.2		0.00	0.0
manway--liquid	0.13-0.14 MPa (4-5	304L SS		0.00	0.0		0.00	0.0
phase	psig)	321 SS		0.00	0.0		0.00	0.0
	Column feed:	RA 330		0.00	0.0		0.00	0.0
	0-2 light organic sol-	410 SS		0.01	0.2		0.00	0.0
	vent, 15-30 wash sol-	1018 Carbon steel		0.05	2.1		0.03	1.3
	vent, 60-85 process	Incoloy 800		0.01	0.2		0.00	0.0
	solvent							
Fractionation	250-260 °C	316 SS	2350	0.18	7.0	5730	0.13	5.2
Column middle	(480-500 °F)	304L SS		0.18	7.2		0.04	1.4
manway--liquid	same pressure as above;	321 SS		0.14	5.6		0.03	1.0
phase	overhead product: 11	410 SS		0.21	8.4		0.06	2.4
	light organic liquid,	1018 Carbon steel		0.23	9.1		0.08	3.1
	81-85 wash solvent,	Incoloy 800		0.27	10.5		0.03	1.3
	4-8 process solvent							
Fractionation	290-300 °C (550-570 °F)	316 SS	2350	0.01	0.0		e	
Column bottom	same pressure as above;	304L SS		0.00	0.0		e	
manway--liquid	bottom product: 1 light	321 SS		0.03	1.1			
phase	organic liquid, 2-5	410 SS		0.13	5.3		0.05	1.8
	wash solvent, 94-97	1018 Carbon steel		0.77	30.5		0.83	32.6
	process solvent	Incoloy 800		0.02	0.8		0.05	2.1

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[69], Continued

			First Exposure[b]			Second Exposure[b]		
Location	Conditions[c]	Alloy	Exposure Time, h	Corrosion Rate mm/yr	Corrosion Rate mils/yr	Exposure Time, h	Corrosion Rate mm/yr	Corrosion Rate mils/yr
Light Solvent Surge Tank--Liquid phase	110 °C (230 °F) top 290 °C (560 °F) bottom 0.90 MPa (115 psig) wash solvent from the vacuum column	316 SS	4015	0.00	0.0	5730	e	
		304 SS		0.01	0.2		0.00	0.0
		321 SS		0.01	0.3		0.00	0.0
		410 SS		0.01	0.2		0.00	0.0
		1018 Carbon steel		0.12	4.7		0.07	2.6
		Incoloy 800		<0.01	0.1		0.00	0.0

[a]Corrosion rates determined by weight loss of exposed specimens after cleaning in organic solvent to remove residual process material and brushing to remove loose scale and other deposits. In spite of the cleaning, many coupons retained their corrosion scale. Annual rates were calculated assuming uniform removal of material.

[b]Alloy coupons were exposed for the first period, cleaned (see footnote a), crosssection samples taken for metallographic examination and then the coupons were re-inserted in the plant test locations for the second exposure. During the first exposure period Utah Emergy coal was used followed by Indiana V, and during the second period only Indiana V was used.

[c]Concentration of components where given are in weight percent.

[d]SRC = solvent refined coal.

[e]Specimen gained weight.

SCALE CHARACTERISTICS[a] FOR ALLOYS EXPOSED[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[69]

Location	Conditions[c]	Alloy	Scale Characteristics[a]
Dissolver--Vapor phase	430-450 °C (805-845 °F)	316 SS	Scale and subsurface attack <25 μm thick, also slight intergranular attack.
	12-17 MPa (1700-2450 psig) 40-60 SRC[d] 5-25 organic liquid	347 SS	Dual-layer scale ∿70 μm thick (inner layer, Cr and Fe with some S and Si; outer layer, Fe and some Ni sulfides), subsurface attack, slight intergranular attack.
	3-8 water 5-25 unreacted coal 7-12 ash	410 SS	Multilayered irregular scale 0.025-0.28 mm thick (outer layer Fe and S; inner S, Fe, and Cr), scale cracked throughout.
	4-12 hydrocarbon gases	Carpenter 20Cb-3	Irregular outer layer and subsurface attack.
	1.0-4 $CO + CO_2$ 0.5-4 H_2S	304 SS	Multiphase, variable thickness scale on irregular surface (outer scale contains Ca, Si, Ti, Mn; subsurface contains Fe and S, no Cr.
		Incoloy 800	Subsurface attack, surface scale (inner layer Cr, Fe, and S; outer layer mostly NiS).
		RA 330	Some subsurface penetration.
		22Cr-13Ni-5Mn	Thin scale, some subsurface attack.
		26Cr-1Mo steel	Subsurface corrosion.
High-Pressure Separator--Vapor phase	310-340 °C (590-650 °F) all other conditions, same as dissolver above	26Cr-1Mo steel 304L SS 316 SS 410 SS 22Cr-13Ni-5Mn	Results similar to those found in the Dissolver.
Solvent Decanter--Liquid-vapor interface	38 °C (100 °F) 0.17 MPa (10 psig) ammonia, organic liquid, decanter oil, decanter water, vent gas		For all alloys, mostly grain boundary or pitting attack, thin surface scales formed.
		1018 Carbon steel	Multilayer scale with stringers up to 50 μm long.
		304L SS	Pits ∿100 μm deep, no thick outer scale.
		410 SS	Multiphase single layer, subsurface pits and stringers 30 μm deep.
Reclaim Tank--Liquid phase	260-315 °C (500-600 °F) 0.90 MPa (115 psig) cresol insolubles, ash, SRC[d], distillate	1018 Carbon steel	Multiphased scale (layers of Fe and S; banded region with Cr, Si, and S; another region with Fe, Si, Mn, Ti, and Al), subsurface attack to ∿30 μm.
		304L SS	Multilayer scale, deeper penetration of surface, intergranular penetration.
		410 SS	Subsurface cracking extending from multilayer scale (Fe, S, some Cr).
Vacuum Column top manway--Vapor phase	93-102 °C (200-215 °F) 2-27 kPa (0.3-3.9 psia) product, overhead light solvent, wash solvent, recycle process solvent	1018 Carbon steel	Scale Fe, S, and O; complex multiphase subsurface; subsurface damage and pitting to 130 μm.
		304L SS	Complex scale, deep penetration (Fe, Cr, O); pits and penetrations up to 60 μm.
		410 SS	Subsurface scale and dendritic deposits below the original surface (Ti, some Si, Ca, Cr, Mn, K).
Vacuum Column bottom manway--Vapor phase, maybe liquid	300-325 °C (590-615 °F) Other conditions as given above for top manway	1018 Carbon steel	Little penetration, compared to top manway location.
		304L SS	Shallow penetration, more scale (Fe, Cr, and O).
		410 SS	Subsurface scales; Ti and O in a dendritic deposit with Fe, S, and Cr.
Fractionation Column top manway--liquid phase	190-220 °C (380-430 °F) 0.13-0.14 MPa (4-5 psig) Column feed: 0-2 light organic solvent, 15-30 wash solvent, 60-85 process solvent	316 SS	Clean surface, subsurface intergranular cracks.
		Carpenter 20Cb-3	Multiphase scale, subsurface penetration.
		304L SS	Clean surface, pits up to 100 μm.
		321 SS	Subsurface attack.
		RA 330	Small amount of irregular scale.
		410 SS	Multiphase scale, subsurface penetration.
		1018 Carbon steel	Multiphase scale, subsurface penetration.
		Incoloy 800	Clean surface.

(Table Continued)

SCALE CHARACTERISTICS[a] FOR ALLOYS EXPOSED[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[69], Continued

Location	Conditions[c]	Alloy	Scale Characteristics[a]
Fractionation Column middle manway--liquid phase	250-260 °C (480-500 °F)		For all alloys there was greater surface attack and subsurface penetration than at the top manway level.
	same pressure as above;	316 SS	Multiphase multilayer scale and pitting.
	overhead product: 11	304L SS	Multilayer scale, surface penetration.
	light organic liquid,	321 SS	Same as at top manway level but surface scale thicker.
	81-85 wash solvent,	410 SS	Penetration is to 150 μm.
	4-8 process solvent	1018 Carbon steel	Pitting up to 40 μm.
		Incoloy 800	Deeper penetration of complex sulfides and oxides of Cr, Ni, Fe; extensive sulfidation.
Fractionation Column bottom manway--liquid phase	290-300 °C (550-570 °F) same pressure as above; bottom product: 1 light organic liquid, 2-5 wash solvent, 94-97 process solvent		For all alloys the surface scale was similar but less than in the upper parts of the vessel; subsurface penetration was decreased; there was some penetration and pitting. 316 SS showed some cracking and pitting.
Light Solvent Surge Tank--Liquid phase	110 °C (230 °F) top 290 °C (560 °F) bottom 0.90 MPa (115 psig) wash solvent from the vacuum column		For all alloys there was the same amount of scale on the coupons as occurred in the Vacuum Column and the Fractionation Column but less subsurface penetration.

[a]See Section B.1.1.167 for the corrosion rates for these alloys for these exposures. Metallographic and electron microprobe examination of the coupons took place after the first exposure (see footnote b). Micrographs were taken after the second exposure to document any significant changes. The above results are a composite of the two examinations which did not generally show great differences between the exposures.

[b]Alloys were exposed for two periods (see Section B.1.1.167). After the first exposure the coupons were cleaned, samples taken for metallographic examination and then the coupons were re-inserted in the plant test locations for the second exposure. During the first exposure period Utah Emergy coal was used followed by Indiana V. During the second exposure only Indiana V was used.

[c]Concentration of components where given are in weight percent.

[d]SRC = solvent refined coal.

CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[66,68]

	Data after first 1128 hours			Data after total 3552 hours			No Time Given[c]	
	Weight Change	Corrosion Rate[a]		Weight Change	Corrosion Rate[a]		Corrosion Rate[a]	
Alloy	g	mm/yr	mils/yr	g	mm/yr	mils/yr	mm/yr	mils/yr
TOP MANWAY FRACTIONATION COLUMN								
410 SS				+0.0073				
Sandvik 2RE69				+0.0003			<0.001	<0.01
SC-1				+0.0001			<0.001	<0.01
Titanium				+0.0001			<0.001	<0.01
Hastelloy G				0.0			<0.001	<0.01
Hastelloy C-276				-0.0001			<0.001	<0.01
Haynes 20 Mod				-0.0001			<0.001	<0.01
Nitronic 50				-0.0006				
Hastelloy G-3				-0.0006			<0.001	<0.01
Nyby Monit				-0.0010			<0.001	<0.01
304 SS				-0.0014			<0.001	0.01
26Cr-1Mo stabilized				-0.0016			<0.001	<0.01
18Cr-2Mo steel				-0.0032	0.002	0.01	<0.001	0.02
317 SS				-0.0430	0.002	0.1	<0.005	0.19
Carbon steel				-0.2064	0.012	0.5		
Inconel 625							<0.001	<0.01
Alloy 904L							<0.001	<0.01
Incoloy 825							<0.001	<0.01
321 SS							<0.001	<0.01
MIDDLE MANWAY FRACTIONATION COLUMN								
Hastelloy C-276	-0.004	0.0007	0.03	-0.0027		0.1	<0.001	0.01
Hastelloy G-3	-0.256	0.044	1.7	-0.3340	0.018	0.7	0.007	0.28
Hastelloy G	-0.243	0.042	1.6	-0.3604	0.020	0.8	0.008	0.32
Titanium	-0.571	0.224	8.8	-0.5743	0.072	2.8		
Incoloy 825				-0.1530[d]	0.014	0.6	0.031	1.22
Haynes 20 Mod	-0.582	0.167	6.6	-1.7860	0.163	6.4	0.043	1.72
321 SS				-2.0763[d]	0.195	7.7	0.169	6.66
317LM SS				-4.4160[d]	0.337	14.8	0.297	11.70
317 SS	-4.782	0.851	33.5	-8.1440	0.460	18.1	0.275	10.83
Sandvik 2RE69	-2.795		22.2	-8.1470	0.522	20.6	0.319	12.59
304 SS	-6.525	1.234	48.5	-11.6721	0.701	27.6	0.337	13.30
Nitronic 50				-3.7036	0.732	28.8		
410 SS	-12.523	2.020	79.5	-18.1673	1.062	41.8		
Nyby Monit	-13.366	2.978	117.3	-16.3671	1.158	45.6		
SC-1	-18.190	4.106	161.7					
Carbon steel	-25.105	4.576	180.2	-33.9571	1.966	77.4		
12Cr-2Mo steel	-24.090	5.014	197.4					
26Cr-1Mo stabilized	-31.774	6.228	245.2					
Inconel 625							0.006	0.25
Carpenter 20Cb-3							0.043	1.70
Monel 400							0.065	2.54
Alloy 904L							0.066	2.58
310 SS							0.454	17.89
BOTTOM MANWAY FRACTIONATION COLUMN								
Hastelloy C-276				+0.0096			0.002	0.08
Hastelloy G-3				+0.0069			<0.001	<0.01
SC-1				+0.0062			<0.001	<0.01
18Cr-2Mo steel				+0.0059			<0.001	<0.01
Titanium				+0.0048			<0.001	<0.01
Nyby Monit				+0.0038			<0.001	<0.01

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[66,68], Continued

Alloy	Data after first 1128 hours: Weight Change g	Data after total 3352 hours: Weight Change g	Corrosion Rate[a] mm/yr	Corrosion Rate[a] mils/yr	No Time Given[c]: Corrosion Rate[a] mm/yr	Corrosion Rate[a] mils/yr
BOTTOM MANWAY FRACTIONATION COLUMN, Continued						
Hastelloy G		+0.0033			<0.001	<0.01
317 SS		-0.0013	0.0001	<0.01	<0.001	<0.01
304 SS		-0.0366	0.002	0.09	0.006	0.25
26Cr-1Mo stabilized		-0.0844	0.005	0.02	<0.001	<0.01
Nitronic 50		-0.0628	0.012	0.05		
Sandvik 2RE69		-1.2425	0.080	3.1	0.131	5.15
Carbon steel		-8.9234	0.517	20.3		
410 SS		-10.9374	0.640	25.2		
Incoloy 825					<0.001	<0.01
Inconel 625					<0.001	<0.01
Haynes 20 Mod					<0.001	<0.01

Alloy	No Time Given[c]: Weight Change g	Time Given-6 months: Corrosion Rate[a] mm/yr	mils/yr	Exposure-3526 h: Corrosion Rate[a,e] mm/yr	mils/yr
TOP OF VACUUM COLUMN					
Hastelloy G	+0.0049	<0.003	<0.01	<0.001[e]	<0.05[e]
410 SS	+0.0040	<0.003	<0.01	<0.001	<0.05
29Cr-4Mo steel	+0.0040	d		<0.001	<0.05
18Cr-2Mo steel	+0.0037	d		<0.001	<0.05
Sandvik 2RE69	+0.0029	0.0	0.0		
Incoloy 800	+0.0028	d		<0.001	<0.05
Titanium	+0.0028	d		<0.001	<0.05
Inconel 600	+0.0027	d		<0.001	<0.05
304 SS	+0.0025	d			
316 SS	+0.0025	d		<0.001	<0.05
317 SS	+0.0024	<0.003	<0.01	<0.001	<0.05
Hastelloy C-276	+0.0023	<0.003	<0.01	<0.001	<0.05
Incoloy 825	+0.0023	d		<0.001	<0.05
347 SS	+0.0018	d		<0.001	<0.05
321 SS	+0.0018	d		<0.001	<0.05
Carbon steel	-0.0125	0.003	0.01	0.013	0.5
304L SS				<0.001	<0.05
MIDDLE OF VACUUM COLUMN					
29Cr-4Mo steel	+0.0114				
317 SS	+0.0103				
18Cr-2Mo steel	+0.0062				
Hastelloy C-276	+0.0054				
Hastelloy G	+0.0038				
Sandvik 2RE69	+0.0028				
Incoloy 825	+0.0026				
304 SS	+0.0020				
Incoloy 800	+0.0008				
347 SS	+0.0007				
Titanium	+0.0006				
316 SS	+0.0005				
321 SS	-0.0026				
Inconel 600	-0.0179				
410 SS	-0.0226				
Carbon steel	-11.2169				

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[66,68], Continued

Alloy	Time Given-6 months Corrosion Rate[a] mm/yr	mils/yr	Exposure-1596 h Corrosion Rate[a] mm/yr	mils/yr	Exposure-3526 h Corrosion Rate[a,e] mm/yr	mils/yr
BOTTOM OF VACUUM COLUMN						
Haynes 263	<0.003	<0.1	<0.003	<0.1		
Crutemp 25	<0.003	<0.1	<0.003	<0.1		
Titanium	<0.003	<0.1	<0.003	<0.1		
Sandvik 2RE69	<0.003	<0.1	<0.003	<0.1		
321 SS	<0.003	<0.1	<0.003	<0.1	<0.001[e]	<0.05[e]
347 SS	<0.003	<0.1	<0.003	<0.1	<0.001	<0.05
304 SS	<0.003	<0.1	<0.003	<0.1		
Hastelloy G	<0.003	<0.1	<0.003	<0.1		
18Cr-2Mo steel	<0.003	<0.1	<0.003	<0.1	<0.001	<0.05
317 SS	<0.003	<0.1	<0.003	<0.1		
29Cr-4Mo steel	<0.003	<0.1	0.004	0.2	<0.001	<0.05
Inconel 600	<0.003	<0.1	0.005	0.2		
410 SS	<0.003	<0.1	0.006	0.2	0.003	0.14
304 SS (Alonized)[f]	0.004	0.2	0.012	0.5	0.021	0.8
9Cr-1Mo steel	0.02	0.8	0.054	2.1		
7Cr-1Mo steel	0.04	1.7	0.118[g]	4.3		
Carbon steel	0.36	14.	1.34	53.	0.41[h]	16
Incoloy 825			<0.003	<0.1		
304L SS					<0.001	<0.05
409 SS					0.001	0.05
7Cr-1Mo steel (0.14 Nb)					0.023	0.9
7Cr-1Mo steel (0.37 Nb)					0.032	1.2
5Cr-1Mo steel (0.13 Nb)					0.032	1.3
9Cr-1Mo steel (modified)					0.034	1.3
5Cr-1Mo steel (0.38 Nb)					0.043	1.7

Alloy	No Time Given[c] Weight Change g	Exposure-12,267 h Corrosion Rate[a] mm/yr	mils/yr
HIGH-PRESSURE SEPARATOR VESSEL			
Sandvik 2RE69	+0.0059	<0.003	<0.1
SC-1	-0.0007	<0.003	<0.1
26Cr-1Mo stabilized	-0.0040	<0.003	<0.1
E-Brite 26-1	-0.0149		
29Cr-4Mo steel	-0.0284	<0.003	<0.1
Hastelloy G-3	-0.2735	0.008	0.3
317LM SS	-0.7241	0.016	0.6
317L SS	-0.9131	0.027	1.1
Incoloy 825	-0.9598	0.027	1.1
316L SS	-1.6112	0.042	1.6
347 SS	-1.6137	0.041	1.6
304L SS	-2.1553	0.048	1.9

(Table Continued)

CORROSION DATA[a] FOR ALLOYS EXPOSED IN VARIOUS LOCATIONS[b] IN THE WILSONVILLE SOLVENT REFINED COAL LIQUEFACTION PLANT[66,68], Continued

Alloy	Exposure-12,267 h Corrosion Rate[a] mm/yr	mils/yr
SOLVENT DECANTER VESSEL		
SC-1	d	
Titanium	d	
26Cr-1Mo steel stabilized	d	
18Cr-2Mo steel	d	
410 SS	d	
304L SS	0.003	0.1
316 SS	0.003	0.1
Carbon steel	0.003	0.1
26Cr-1Mo steel	0.003	0.1

Alloy	HYDROTREATER MELT TANK Exposure-2901 h Corrosion Rate[a] mm/yr	mils/yr	HYDROTREATER PRODUCT RECYCLE TANK Exposure-2901 h Corrosion Rate[a] mm/yr	mils/yr
2-1/4 Cr-1 Mo steel	0.0093	0.37	0.0038	0.15
Carbon steel	0.0092	0.36	0.0107	0.42
5Cr-1Mo steel	0.0037	0.15	0.0058	0.23
9Cr-1Mo steel	0.0037	0.14	0.0022	0.09
7Cr-1Mo steel	0.0035	0.14	0.0031	0.12
410 SS	0.0015	0.06	0.0007	0.03
409 SS	0.0007	0.03	0.0015	0.06
Incoloy 825	0.0005	0.02	0.0003	0.01
316 SS	0.0003	0.01	0.0002	<0.01
304 SS	0.0003	0.01	0.0002	<0.01

[a]For some tests only coupon weight changes were reported, for others annual corrosion rates were calculated from weight loss assuming uniform removal of material. In some cases the conversion between mm and mils is not correct. However, since it was not always possible to determine which value was in error, both values are given as reported in the original tables of the reports, except for one set of data which is so noted.

[b]Conditions were not given as to temperature, pressure, or chemical environment and in some cases the exposure times were omitted. For general conditions for some locations in the plant see Section B.1.1.167.

[c]No time period given for the exposure.

[d]Specimen gained weight.

[e]Extra zeros appear to have been inserted in the mm values for this data set in the original table, i.e. 0.0001 was given but it is assumed that 0.001 was meant so the mm values have been changed.

[f]Aluminum coating [presumably applied by Alon Processing, Inc.].

[g]Misprinted in original as 0.0118.

[h]Misprinted in original as 0.0041.

CORROSION RATES[a] FOR ALLOYS EXPOSED IN WASH SOLVENT COLUMN LOCATIONS[b] IN THE FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[66,68]

	Corrosion Rates[a]							
	Light Ends Column Reboiler Shell				Wash Solvent Column Reboiler Shell			
	No Time Given		Exposed--3163 h		No Time Given		Exposed--3190 h	
Alloy	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
Titanium			0	0			d	
Hastelloy C-276	<0.003	<0.1	<0.001	<0.001			d	
Hastelloy N			0.001	0.04	d		0.001	0.05
Hastelloy B-2			0.001	0.03			0.001	0.02
321 SS			0.007	0.3			0.005	0.2
Haynes 263			0.009	0.4			0.004	0.2
304 SS (alonized)[c]			0.019	0.8			d	
Inconel X-750			0.055	2.2			0.023	0.9
Udimet 720			0.064	2.5			0.068	2.7
Incoloy 801			0.074	2.9			0.256	10.
Inconel 600	<0.003	<0.1	0.076	2.9	d		0.199	7.8
Haynes 20 Mod	0.005	0.2			d			
Inconel 625			<0.001	<0.001	d		d	
Carpenter 20Cb-3	0.02	0.8			d			
Incoloy 825	0.01	0.5			d			
Crucible 6M	<0.003	<0.1			d			
Alloy 904L			0.016	0.6	d		0.004	0.2
Monel 400	0.30	12.						
Crutemp 25	0.03	1.1			d			
317LM SS	0.02	0.8			d			
Inconel 671					d			
316 SS	0.01	0.4	0.026	1.1	d		0.001	0.03
304 SS	0.02	0.8	0.031	1.2			0.010	0.4
410 SS	0.45	18.	0.349	14.	1.14	45.	1.01	40.
Incoloy 800	0.19	7.4	0.390	15.			0.355	14.
Nickel			1.23	48.			0.212	8.3
Carbon steel			3.15	124.			0.841	33.
Inconel 601			0.152	5.9			0.979	39.
Aluminum	3.90	154.			2.60	102.		
Hastelloy G					d			

	Middle of the Wash Solvent Column			
	No Time Given		Exposed--6 months[e]	
	mm/yr	mils/yr	mm/yr	mils/yr
Carbon steel	1.48			
405 SS	0.75			
410 SS			0.97	38.
304 SS	0.37		1.06	42.
316 SS			0.75	30.
316L SS	0.21			
317 SS	0.17			
317LM SS			0.47	18.
Carpenter 20Cb-3			0.07	2.7
Incoloy 800	1.2			
Incoloy 825	0.05			
Haynes 20 Mod			0.05	2.0
Hastelloy G	0.01		0.02	1.0
Hastelloy C-276	<0.01		d	
Inconel 625			0.14	5.5
Inconel 671			0.49	19.
Hastelloy N			<0.003	<0.1
Inconel 600			0.01	0.4
Crutemp 25			0.47	18.
Aluminum			>5.45	>215.

(Table Continued)

CORROSION RATES[a] FOR ALLOYS EXPOSED IN WASH SOLVENT COLUMN LOCATIONS[b] IN THE FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[66,68], Continued

	Corrosion Rates[a]					
	Middle of the Wash Solvent Column					
	Exposed--1334 h		Exposed--2156 h		Exposed--3190 h	
Alloy	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
Carbon steel	10.84	427.			4.99	196.
410 SS	3.33	131.	0.89	35.	3.45	136.
26Cr-1Mo stabilized	9.43	371.				
SC-1	5.21	205.				
304 SS	1.50	59.	0.29	12.	1.31	52.
304 SS (Alonized)[c]					0.88	34.
310 SS			0.08	3.0		
316 SS	0.93	37.	0.20	7.7	1.01	40.
317 SS	1.14	45.				
317LM SS	1.05	41.	0.10	3.7		
321 SS	0.86	34.	0.06	2.5	0.17	6.8
Alloy 904L			0.08	3.2	0.41	16.
Carpenter 20Cb-3			0.35	14.		
Incoloy 800					2.72	107.
Incoloy 825	0.37	14.	0.17	6.6		
Haynes 20 Mod			0.01	0.39		
Hastelloy G	0.65	26.	<0.01	0.12		
Hastelloy G-3	0.49	19.				
Hastelloy C-276	<0.01	0.1	<0.01		<0.0003	<0.01
Haynes 263			0.02	0.73	0.083	3.3
Titanium	<0.01	0.1	<0.01		0.36	14.
Monel 400			0.23	9.1		
Inconel 625			<0.01		0.008	0.3
Inconel 671			<0.01	0.14		
Hastelloy B-2					<0.003	<0.1
Hastelloy N					<0.003	<0.1
Inconel X-750					0.078	3.1
Inconel 601					0.085	3.4
Inconel 600					0.14	5.6
Udimet 720					0.39	15.
Nickel					0.61	24.
Incoloy 801					1.09	>43.

	Top of the Wash Solvent Column					
	No Time Given		No Time Given		Exposed--6 months[e]	
Alloy	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
Carbon steel					2.0	
405 SS					1.3	
410 SS			1.42	56.		
304 SS	0.89	35.	0.92	36.	0.27	
316 SS	0.84	33.	0.70	27.		
316L SS					0.46	
317 SS					0.52	
317LM SS			0.45	11.		
Alloy 904L	0.18	7.0	0.24	9.6		
Carpenter 20Cb-3	0.14	5.7	0.11	4.4		
Incoloy 800	1.27	50.	1.78	70.	0.35	
Incoloy 825	0.06	2.2	0.21	8.2	0.04	
Haynes 20 Mod			0.07	2.7		
Hastelloy G			0.11	4.2	<0.01	
Hastelloy C-276		d	<0.003	<0.1	<0.01	
Monel 400			0.23	9.0		
Inconel 625	0.11	4.2	0.03	1.0		

(Table Continued)

CORROSION RATES[a] FOR ALLOYS EXPOSED IN WASH SOLVENT COLUMN LOCATIONS[b] IN THE FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[66,68], Continued

	Corrosion Rates[a]					
	Data continued from bottom of previous page					
Alloy	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
Inconel 671	0.50	20.				
Hastelloy N	<0.003	<0.1				
Inconel 600	d		d			
Crutemp 25	0.41	16.	0.39	15.		
Aluminum			>5.43	>214.		
RA 333	0.003	0.1				
Molybdenum	<0.003	<0.1				
Crucible 6M	0.17	6.6	0.16	6.3		

	Top of the Wash Solvent Column							
	Exposed--1334 h		Exposed--2156 h		Exposed--2156 h		Exposed--3491 h	
	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
Carbon steel							4.74	187.
410 SS			2.13	84.	1.00	40.	2.18	86.
26Cr-1Mo stabilized	2.39	94.					3.17	125.
SC-1							2.02	79.
304 SS			1.0	39.	1.05	41.	0.92	36.
304 SS (Alonized)[c]			0.53	21.				
310 SS	0.93	37.	0.67	26.	0.77	30.		
316 SS	1.05	42.	0.76	30.	1.07	42.	0.98	38.
316L SS	0.87	34.						
317 SS							0.69	27.
317LM SS	0.91	36.	0.68	27.	1.07	42.	0.69	27.
321 SS	0.91	36.	0.26	10.	0.65	26.	0.45	18.
Alloy 904L			0.55	22.	1.07	42.		
Carpenter 20Cb-3	0.34	14.	0.54	21.	1.22	48.		
Incoloy 825	0.54	21.	0.49	19.	0.97	38.	0.35	14.
Haynes 20 Mod			0.14	5.5	0.26	10.		
Hastelloy G			0.18	7.2	0.04	1.5	0.25	9.8
Hastelloy G-3	0.39	15.					0.22	8.8
Hastelloy C-276			<0.01	<0.01	0.10	4.0	<0.01	0.02
Haynes 263			<0.02	0.72	<0.01	0.10		
Titanium			<0.01	<0.01	<0.01	<0.01	0.03	1.3
Monel 400			0.32	13.	0.28	11.		
Inconel 625	0.33	13.	0.18	6.9	0.01	0.48		
Inconel 671			0.40	16.	0.35	14.		

	Top of the Wash Solvent Column			
	Exposed--3190 h		Exposed--3190 h	
	mm/yr	mils/yr	mm/yr	mils/yr
Carbon steel	>10.7	>422.	6.4	250.
410 SS	2.63	103.	1.09	82.
304 SS	2.22	88.	1.37	54.
304 SS (Alonized)[c]	1.17	46.	1.41	55.
316 SS	1.52	60.	0.89	35.
321 SS	0.55	22.	1.08	43.
Alloy 904L	0.58	23.	0.47	19.
Incoloy 800	1.81	71.	2.92	115.
Hastelloy C-276	<0.003	<0.1	<0.0003	<0.01
Haynes 263	0.073	2.9	0.10	3.9
Titanium	<0.003	<0.1	0.009	0.4
Inconel 625	0.063	2.5	0.06	2.4

(Table Continued)

CORROSION RATES[a] FOR ALLOYS EXPOSED IN WASH SOLVENT COLUMN LOCATIONS[b] IN THE FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[66,68], Continued

	Corrosion Rates[a]			
	Continued from bottom of previous page			
Alloy	mm/yr	mils/yr	mm/yr	mils/yr
Hastelloy B-2	<0.003	<0.1	<0.003	<0.1
Hastelloy N	<0.003	<0.1	<0.003	<0.1
Inconel X-750	0.074	2.9	0.13	5.1
Inconel 601	0.095	3.7	0.28	11.
Inconel 600	0.20	7.7	0.33	13.
Udimet 720	0.89	35.	1.10	43.
Nickel	0.60	24.	0.49	19.
Incoloy 801	>1.00	>39.	1.08	43.

[a]Coupons were cleaned and weighed after exposure and corrosion rates were calculated from weight loss, linearly extrapolated assuming uniform removal of material, to obtain annual rates.

[b]Coupons were exposed at different locations of the wash solvent column. In earlier reports some distinction was made between locations in the top of the column for instance. Since in a summary table in the original reports for some of the above data the distinction was omitted it was decided to follow the more general grouping of exposures for this table.

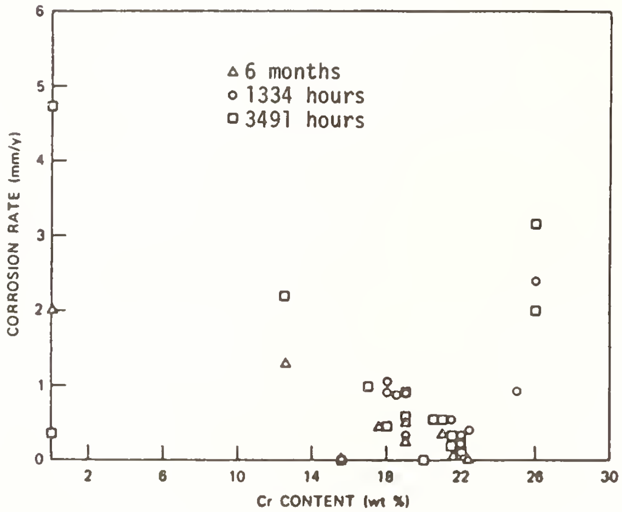
[c]Aluminum coating [presumably applied by Alon Processing, Inc.].

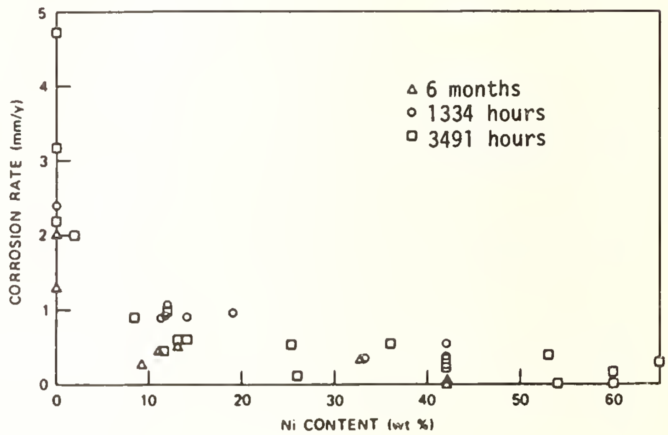
[d]Specimen gained weight.

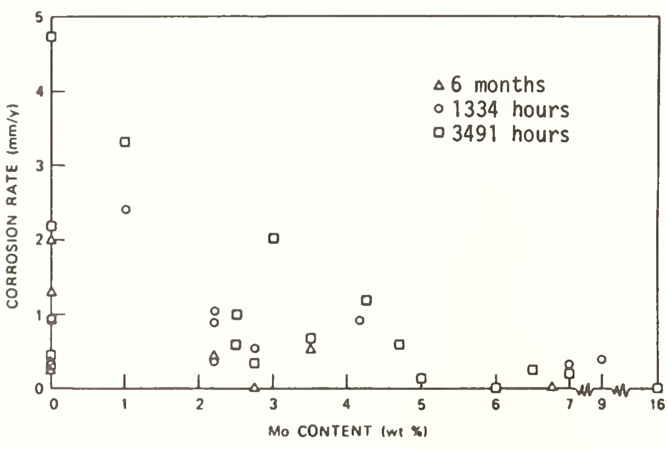
[e]Only dates for placement of the coupons in the plant are given, no exposure time.

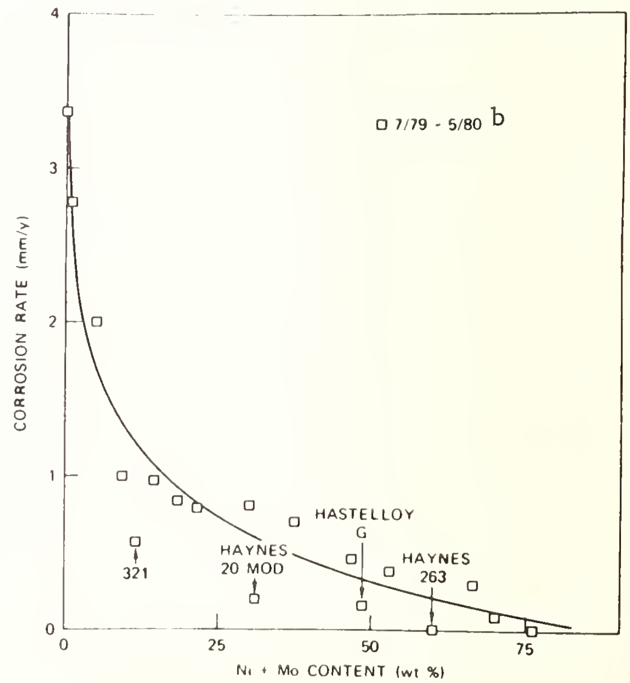
EFFECT OF CHEMICAL CONSTITUENTS ON CORROSION RATES[a] OF ALLOYS EXPOSED IN THE WASH SOLVENT COLUMN OF THE FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[68]

Exposures in the top of the wash solvent column- - - - - - - - - - - - - -







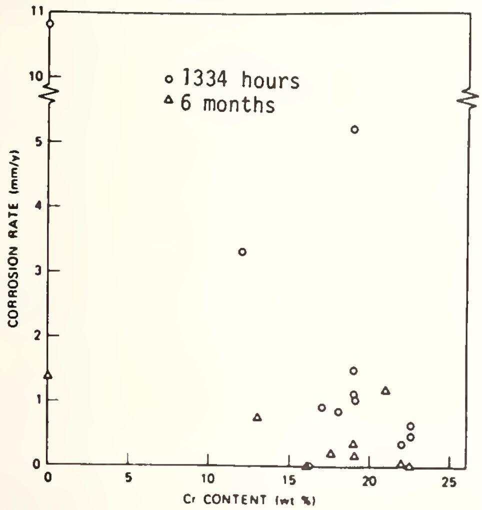


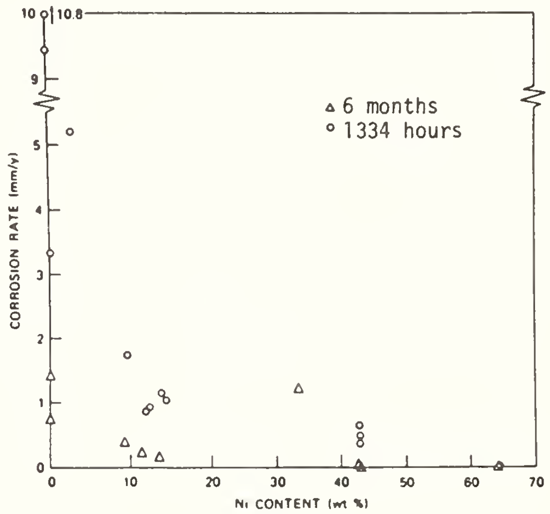
- -

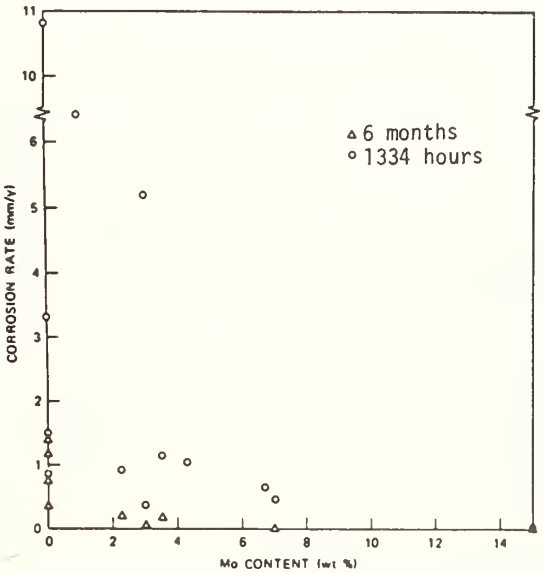
(Data Continued)

EFFECT OF CHEMICAL CONSTITUENTS ON CORROSION RATES[a] OF ALLOYS EXPOSED IN THE WASH SOLVENT COLUMN OF THE FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[68], Continued

Exposures in the middle of the wash solvent column- - - - - - - - - - - - - - -







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[a]See preceding Section B.1.1.170 for data plotted above.

[b]Dates of exposure cover two periods in the original data tables and the exposure time is therefore not easily defined with respect to the data in B.1.1.170.

CORROSION SCALE ANALYSIS[a] OF ALLOYS IN COAL LIQUEFACTION PILOT PLANT FRACTIONATION AREAS[68]

Constituent[a]	Fort Lewis[b] 317 SS	Wilsonville Fractionation Column[c]: Top Manway Carbon Steel	Middle Manway 304 SS: Scale	Middle Manway 304 SS: Dust below Scale	Tray 11 316 SS
Fe[d]	4.5	65	12	15	10
Ni[d]	28	0.2	23	24	36
Cr[d]	8.9	0.4	11	12	2.4
Mo[d]	5.1	0.2	1.0	1.0	7.6
S[e]	40	40	34	36	34
Cl[f]	0.90	0.035	0.43	0.49	0.134
C[g]	17	1.7	4.9	5.4	4.7
N[g]	0.90	0.10	0.22	0.35	0.32
H[g]	1.11	1.10	0.77	0.52	0.45
SO_4^{-2}[h]	<0.4				
Cu	1.0	0.3	0.5	0.4	0.3
Si	0.7	0.1	0.5	0.4	0.2
Co	0.3	<0.02	0.3	0.2	1.5
Ti	0.3	0.01	0.3	≤0.01	0.2
Mn	0.03	0.4	0.1	0.1	0.1

[a]Samples of scale from fractionation area vessels were collected before the customary steam cleaning. Unless otherwise noted the analysis is semiquantitative spectrographic analysis, +100 %, -50 %.

[b]Location is from above the middle manway of the wash solvent column of the Fort Lewis Solvent Refined Coal Plant.

[c]Plant is the Wilsonville Solvent Refined Coal Plant.

[d]Photoemission analysis, ±5%.

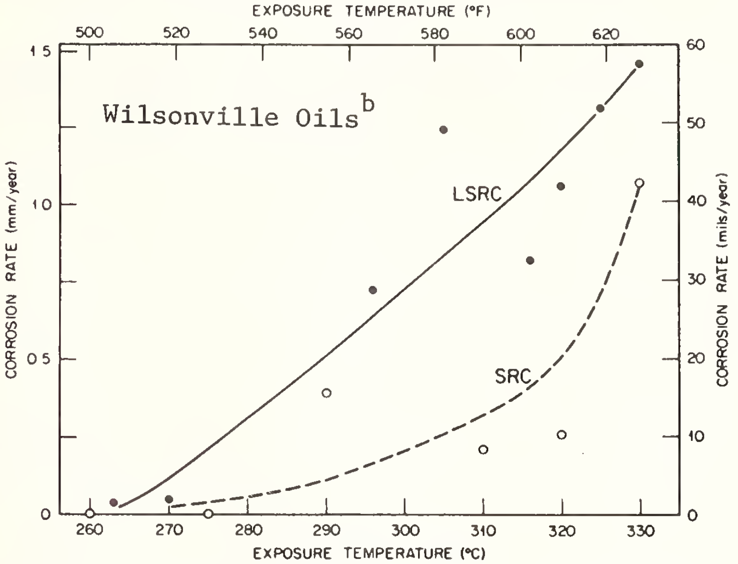
[e]Leco sulfur, ±2%.

[f]Neutron activation analysis, ±3%.

[g]Perkin-Elmer C,H,N microanalyzer, ±2.5%.

[h]$BaSO_4$ gravimetric technique.

CORROSION RATES[a] FOR LABORATORY EXPOSURE OF CARBON STEEL TO SOLVENT REFINED COAL OILS[b] [66,67,68]



Source of Oil[b]	Test Temperature	Test Time	Location of Sample	Corrosion Rate[a] mm/yr	mils/yr
Wilsonville SRC	295 °C	21 h	In oil	0.41	16
			In vapor	0.10	4
Wilsonville SRC	320	20	In oil	0.25	10
			In vapor	0.08	3
Wilsonville SRC	338	5.75	In oil	1.07	42
			In vapor	0.41	16
Wilsonville LSRC	263	20	In oil	0.05	2
			In vapor	0	0
Wilsonville LSRC	305	20	In oil	1.24	49
			In vapor	0.53	21
Wilsonville LSRC	317	5	In oil	0.81	32
Wilsonville LSRC	325	19	In oil	1.32	52
			In vapor	0.33	13
Wilsonville LSRC	330	21	In oil	1.47	58
			In vapor	1.14	45
Fort Lewis SRC I	177	94	In oil	0.007	0.3
Process solvent			Above oil	0.003	0.1
Fort Lewis SRC I	260	92	In oil	0.67	26.4
Process solvent	255		Above oil	0.24	9.4

[a]Corrosion rates calculated from weight loss, linearly extrapolated assuming uniform removal of material. Tests static, oils not flowing.

[b]SRC = solvent refined coal, LSRC = light solvent refined coal, no analysis. Fort Lewis solvent, 125.5 μg/mL Cl, 0.55 mg KOH/g, 0.82 % N, 0.30 % S, <0.1 μg/mL S^{-2}.

CORROSION RATES[a] OF CARBON STEEL AND 304 SS EXPOSED TO DISTILLATE PRODUCT[b] OF FORT LEWIS SOLVENT REFINED COAL PILOT PLANT[67]

Alloy	As-Received Distillate mm/yr	As-Received Distillate mils/yr	Water-Washed Distillate mm/yr	Water-Washed Distillate mils/yr
First Experiment[c]				
Carbon steel	4.42	174	0.56	22
304 SS	3.92	154	0	0
Second Experiment[d]				
Carbon steel	8.80	345	0[e]	0
304 SS	6.79	267	0[e]	0

[a] Corrosion rates were calculated from weight loss, linearly extrapolated from the 5-hour exposure time assuming uniform removal of material to obtain annual rate.

[b] Material is identified as middle distillate from the plant. The exposure was for 5 hours at an average temperature of 215 °C (420 °F).

[c] In the first experiment, the as-received distillate was used as well as distillate which had been water washed. The oil was mixed with equal volume of water, centrifuged to break the emulsion, and the filtered to further separate the oil and water. Finally, it was heated to drive off retained water.

[d] The same water washing procedure was used on both the as-received distillate and the already water-washed material, i.e. one test was run with double-washed distillate.

[e] Slight weight gain.

CORROSION DATA[a] FOR LABORATORY EXPOSURE OF CARBON STEEL AND 304 SS TO SOLVENT REFINED COAL LIQUEFACTION PROCESS LIQUIDS[b][67]

Source of Oil[b]	Cl Content	Additive[c]	Corrosion Rate,[a] mm(mils)/yr Carbon Steel	304 SS
Solvent decanter vessel	0.1 ppm	None	0.10(4)	0.05 (2)
Vacuum column overhead	0.1	None	0.64(25)	0.10 (4)
		5%	11.3 (433)	0.64 (25)
Vacuum column tray 3	46.5	None	d	d
		5%	6.4 (252)	0.005(2)
Vacuum column tray 8	239	None	0.33(13)	d
		5%	(32)	d
Light solvent recovery column bottoms	22	None	0 (0)	0 (0)
		10%	10.3 (404)	5.5 (217)

[a]Corrosion rates were calculated from weight loss, linearly extrapolated assuming uniform removal of material, to obtain annual rate.

[b]Oils are identified only by plant location and by chlorine content.

[c]The additive was aqueous condensate from the V-164 vessel which is fed by the solvent decanter vessel and the vacuum column. The chlorine content is very high, 12,340 ppm.

[d]Specimen gained weight.

CORROSION DATA[a] FOR ADMIRALTY BRASS EXPOSED TO SOLVENT REFINED COAL OILS[b][67]

Source of Oil[b]	Test Temperature		Test Time	Location of Sample	Corrosion Rate[a] mm/yr	mils/yr
Fort Lewis SRC I	90°C	194°F	73 h	In oil	0.08	2.99
Process Solvent	68	154		Above oil	0.04	1.4
Fort Lewis SRC II	93	199	75	In oil	0.01	0.34
Heavy distallate	60	140		Above oil	0.01	0.55
Fort Lewis SRC I	121	250	72	In oil	0.27	10.67
Process solvent	93	200		Above oil	0.03	1.07
Fort Lewis SRC I	121	250	97	In oil	0.27	10.71
Process Solvent				In oil	0.31	12.16
Fort Lewis SRC I	161	320	6.5	In oil	0.62	24.6
Process solvent				Above oil	0.06	2.4

[a] Corrosion rates were calculated from weight loss, linearly extrapolated assuming uniform removal of material, to obtain annual rates.

[b] Oils used are from the bottom of the wash solvent column of the Fort Lewis solvent refined coal pilot plant. They are identified as process solvent during SRC I operation and heavy distillate during SRC II operation. Analysis of oils:

	Process Solvent	Heavy Distillate
Cl, μg/mL	125.5	<2.0
Neutralization No., mg KOH/g	0.55	0.78
N, %	0.82	1.06
S, %	0.30	0.44
S^{-2}, μg/mL	<0.1	<1

CARBIDE ANALYSES[a] OF 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN[c] [61]

Carbide Precipitates	As-Received	Hydrogen Exposed[c]	Hydrogen Exposed and Creep Tested[c]
Fe_3C	Many, inside grains and on boundaries	Few, on boundaries	None observed
$M_{23}C_6$, M=(Fe,Cr,Mo)	Many, inside grains and on boundaries	Many, inside grains and on boundaries	Many
M_6C	None observed	None observed	None observed
M_7C_3	None observed	None observed	Few
Fe_2MoC	None observed	Few, on boundaries	?
Mo_2C	Many, inside grains, generally in ferritic areas, not in bainitic	Many, inside grains, generally in ferritic areas, not in bainitic	Many

[a]By electron diffraction methods.

[b]A387 Grade 22 steel, normalized and tempered 12-inch plate. Heat treatment: austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. Bainitic and proeutectoid ferrite microstructure.

[c]Exposure to hydrogen for 20 days at 600 °C and 13.8 MPa pressure hydrogen. Exposure took place in an autoclave fitted with a creep stand.

GRAIN BOUNDARY CAVITY DENSITY[a] DUE TO HYDROGEN EXPOSURE[b] OF 2-1/4 Cr-1 Mo STEEL[c] [61,62]

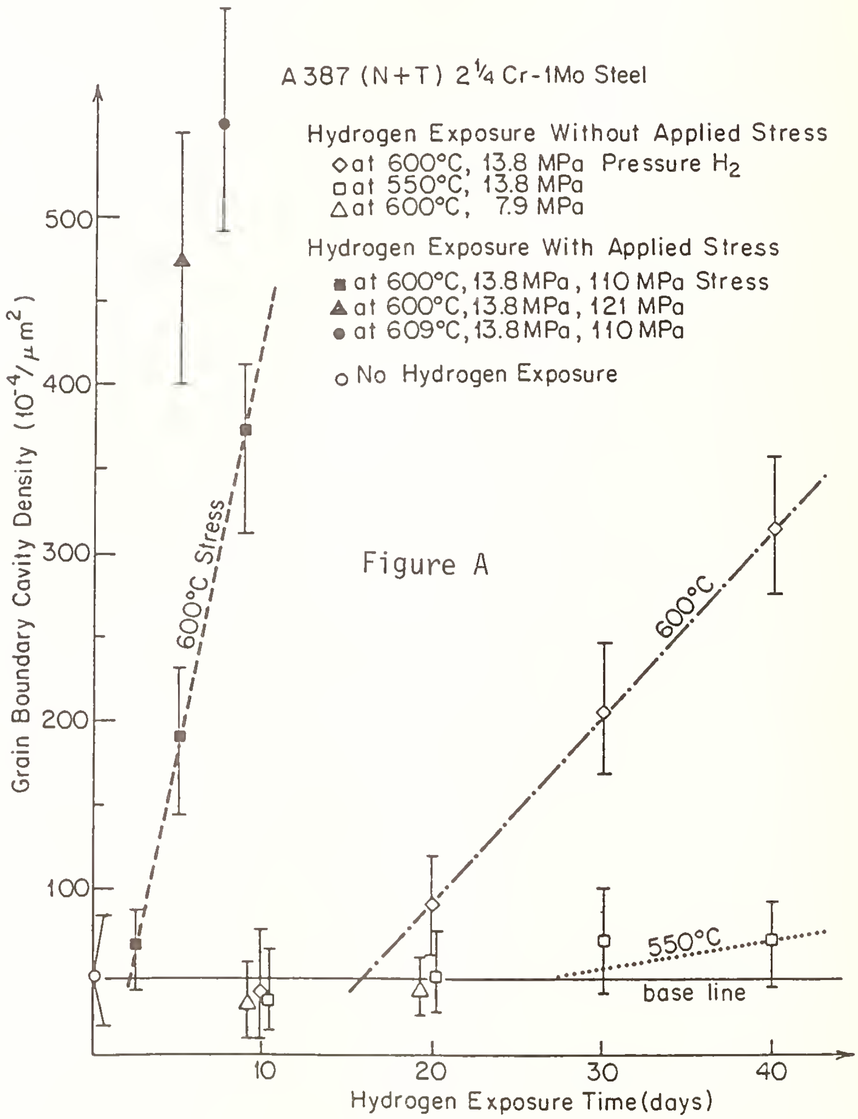


Figure A

(Data Continued)

GRAIN BOUNDARY CAVITY DENSITY[a] DUE TO HYDROGEN EXPOSURE[b] OF 2-1/4 Cr-1 Mo STEEL[c][61,62], Continued

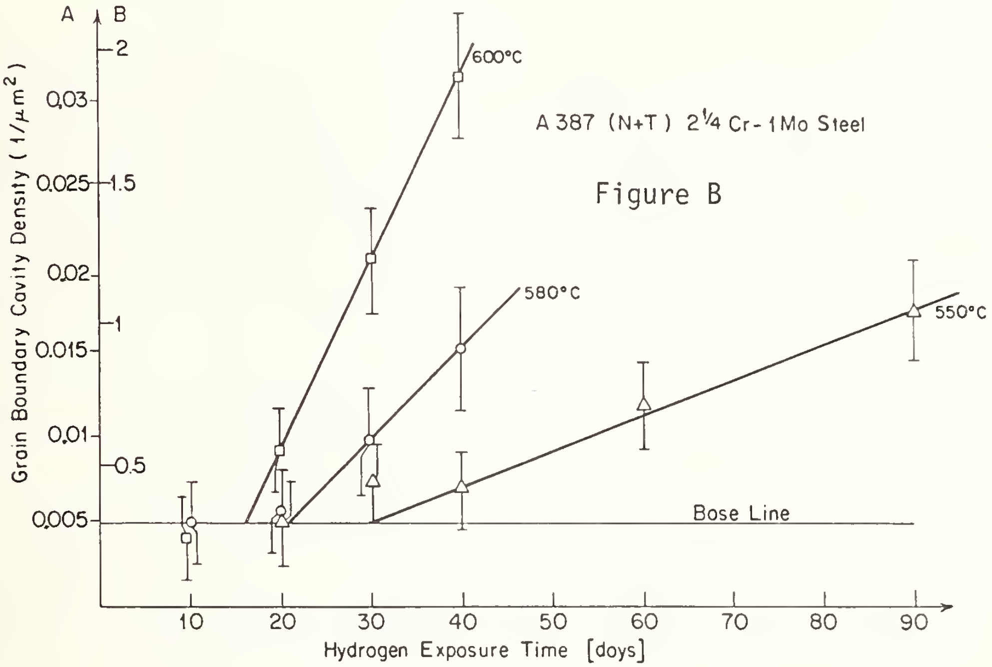


Figure B

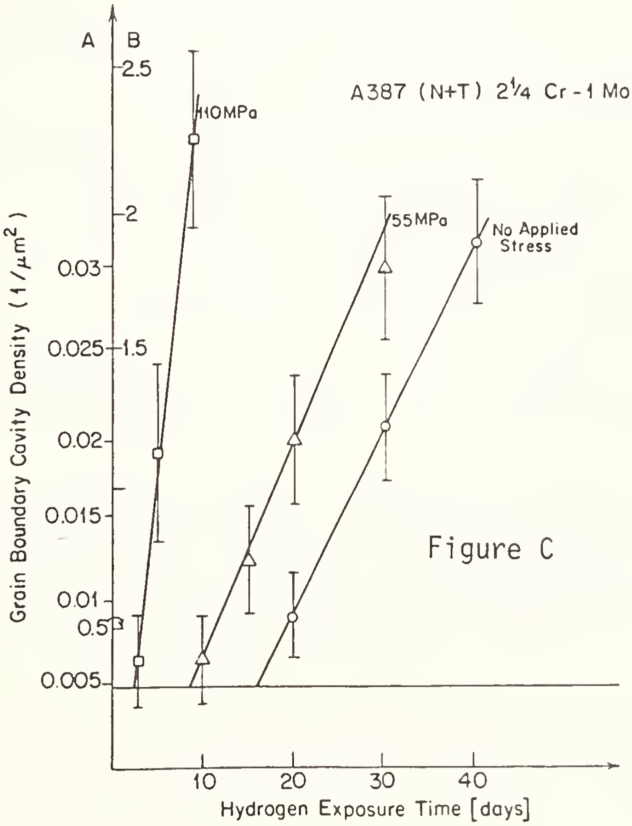


Figure C

(Data Continued)

GRAIN BOUNDARY CAVITY DENSITY[a] DUE TO HYDROGEN EXPOSURE[b] OF 2-1/4 Cr-1 Mo STEEL[c][61,62], Continued

Footnotes

[a]Cavities measured using scanning electron micrographs of intergranularly fractured surfaces of creep specimens (notched and fractured in liquid nitrogen). Specimens were sectioned, polished, and etched 15 seconds in 2% nital. Two matched surfaces were examined side by side to identify true cavities as opposed to cavities resulting from pull out of precipitate particles. Stereo images were used to orient grain boundary planes relative to applied stress axis. Mean area of cavities was based on examination of ∿100 cavities to overcome variations in widely separated sections of plate from which the specimens were made. Two corrections to the number density SEM count were necessary. One, a geometrical correction to account for cavities at grain boundaries normal or nearly so to applied stress axis. Two, a correction to account for the coalescence after creep growth of several bubbles formed on one particle. After H_2 exposure specimens were subjected to creep growth treatment consisting of holding the specimens at 110 MPa at 600 °C for several days.

- Figure A shows the results of hydrogen exposure under a variety of conditions followed by creep growth treatment. The cavity density number is not corrected for geometry or coalescence. The base line was measured after creep growth treatment and has the same value with or without hydrogen exposure. The number density of methane bubbles nucleated during exposure is the difference between the observed number density and the base line value.
- Figure B shows more data for hydrogen exposure at various temperatures.
- Figure C shows the effect of applied stress during hydrogen exposure at 600 °C. The ordinates of Figures B and C carry two scales. The A scale is for an uncorrected density count. The B scale is corrected for both geometry and coalescence as outlined above.

The nucleation rate and incubation time values determined from Figures B and C for hydrogen pressures of 13.8 MPa are:

Temperature (°C)	600	580	550	600	600
Applied stress (MPa)				55	110
Nucleation rate ($1/\mu m^2$ day)	0.0664	0.0324	0.0121	0.0762	0.3
Incubation time (days)	16	21	31	8.5	2.5

[b]Specimens were loaded in autoclaves (fitted with a creep stand) which were first evacuated to 10^{-3} torr, brought to the desired temperature in a split furnace and loaded with hydrogen to the prescribed pressure, 13.8 MPa (2000 psi), except for the one test noted in Figure A for 7.9 MPa. Round tension specimens, 19 mm gauge length, 1.8 mm gauge diameter, were used.

[c]A387 Grade 22 steel, normalized and tempered 12-inch plate. Heat treatment: austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. Bainitic and proeutectoid ferrite microstructure.

GRAIN BOUNDARY CAVITY DENSITY[a] DUE TO HYDROGEN EXPOSURE[b] OF 2-1/4 Cr-1 Mo QUENCHED AND TEMPERED STEEL[c] [61,62]

Figure A

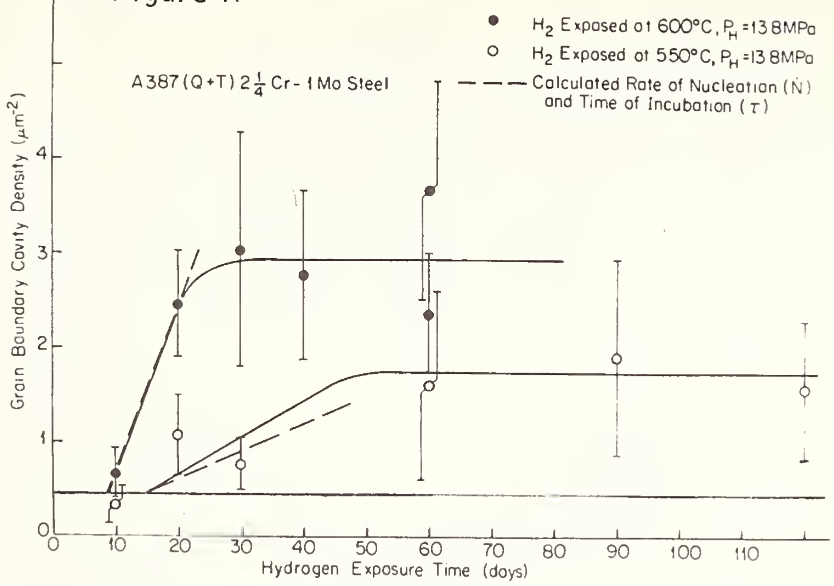
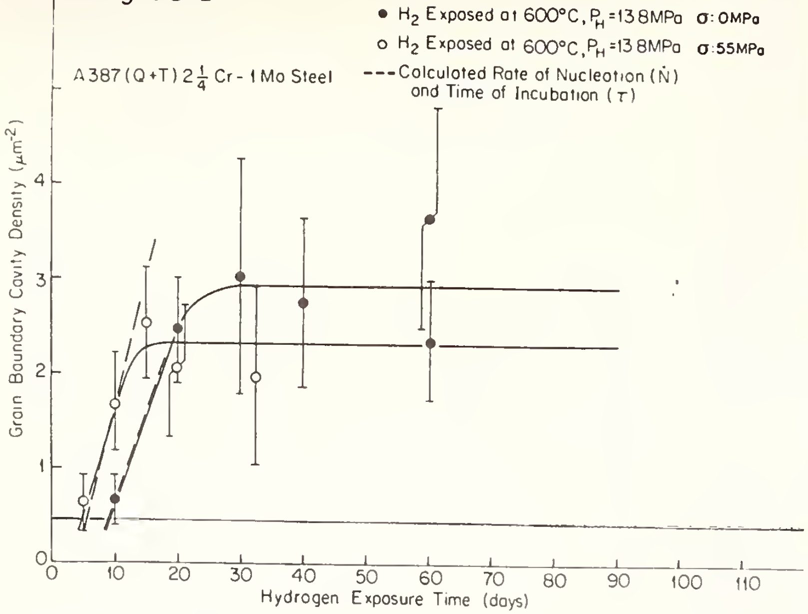


Figure B



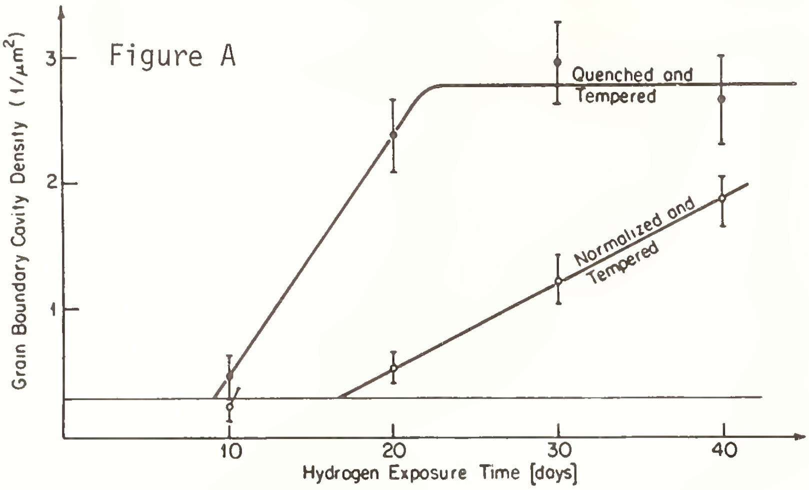
Temperature (°C)	550	600	600
Applied stress (MPa)			55
Nucleation rate (1/μm² day)	0.039	0.20	0.22
Incubation time (days)	15	8.8	5

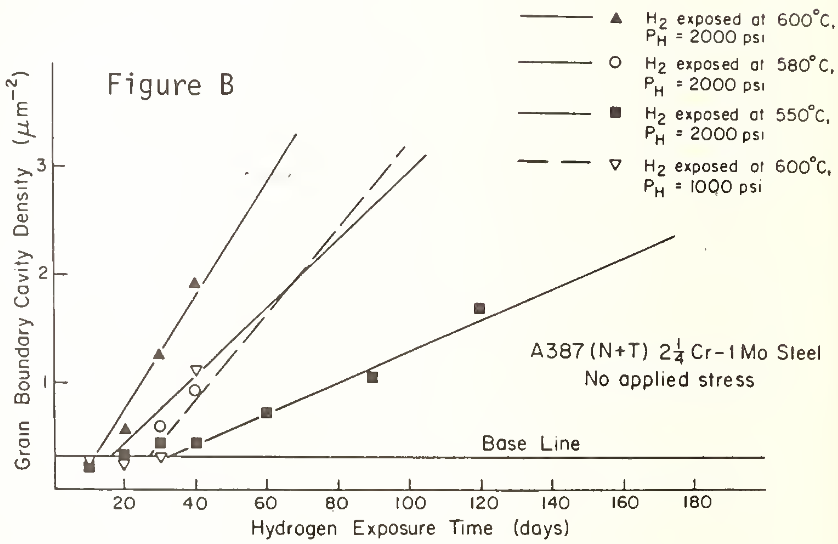
[a] See footnote a of Section B.1.1.178 for methods used. Figure A shows the effect of temperature. Figure B shows the effect of applied stress (σ) during exposure.

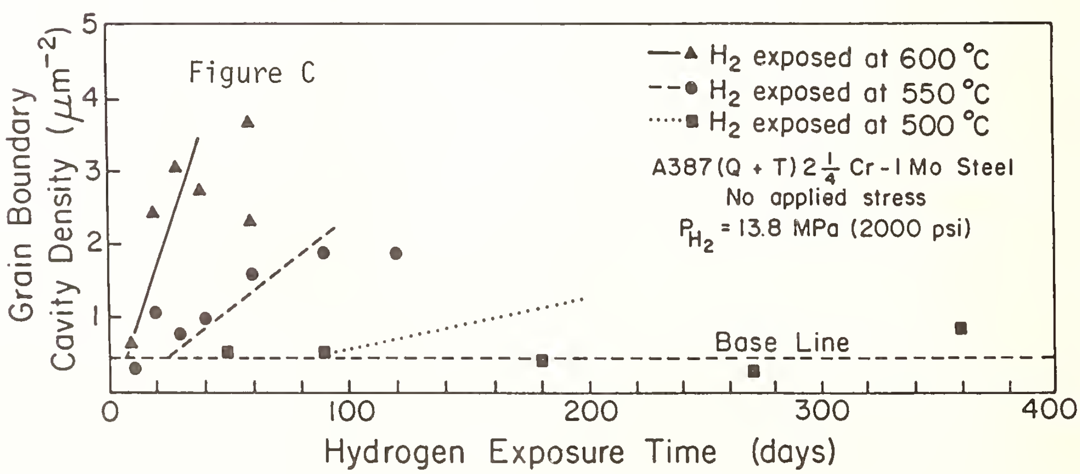
[b] Specimens were loaded in autoclaves (fitted with creep stands) which were first evacuated to 10^{-3} torr, brought to the desired temperature in a split furnace and loaded with hydrogen to the prescribed pressure, 13.8 MPa (2000 psi). Round tension specimens, 19 mm gauge length, 1.8 mm gauge diameter, were used.

[c] A387 Grade 22 steel, quenched and tempered 12-inch plate. Heat treatment: austenitized 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched. Bainitic microstructure with no proeutectoid ferrite.

COMPARISON OF HYDROGEN EXPOSURE[a] CAVITY DENSITY DATA[b] FOR 2-1/4 Cr-1 Mo STEEL WITH DIFFERENT HEAT TREATMENTS[c] [61,62]







(Data Continued)

COMPARISON OF HYDROGEN EXPOSURE[a] CAVITY DENSITY DATA[b] FOR 2-1/4 Cr-1 Mo STEEL WITH DIFFERENT HEAT TREATMENTS[c][61,62], Continued

Figure D

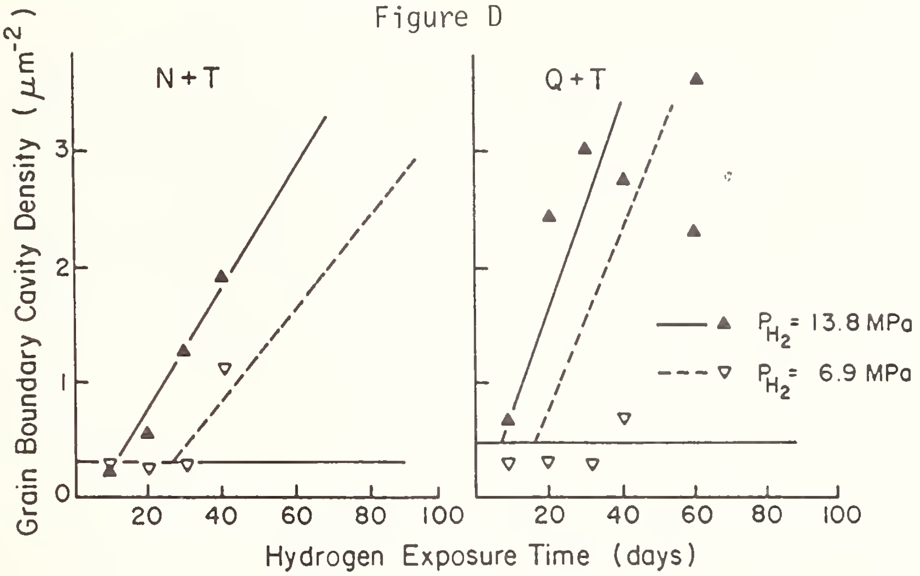
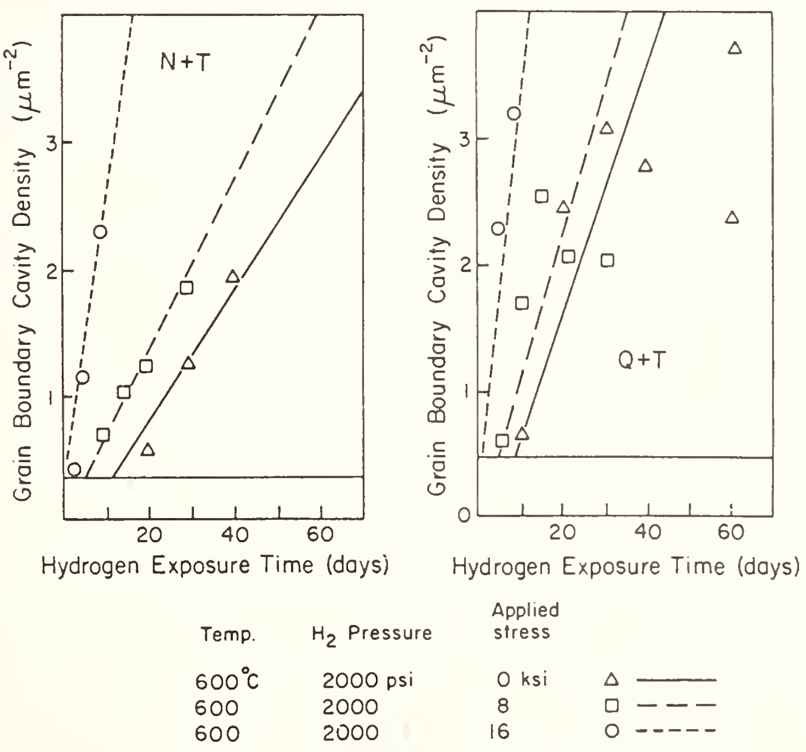


Figure E



(Data Continued)

COMPARISON OF HYDROGEN EXPOSURE[a] CAVITY DENSITY DATA[b] FOR 2-1/4 Cr-1 Mo STEEL WITH DIFFERENT HEAT TREATMENTS[c][61,62], Continued

Footnotes

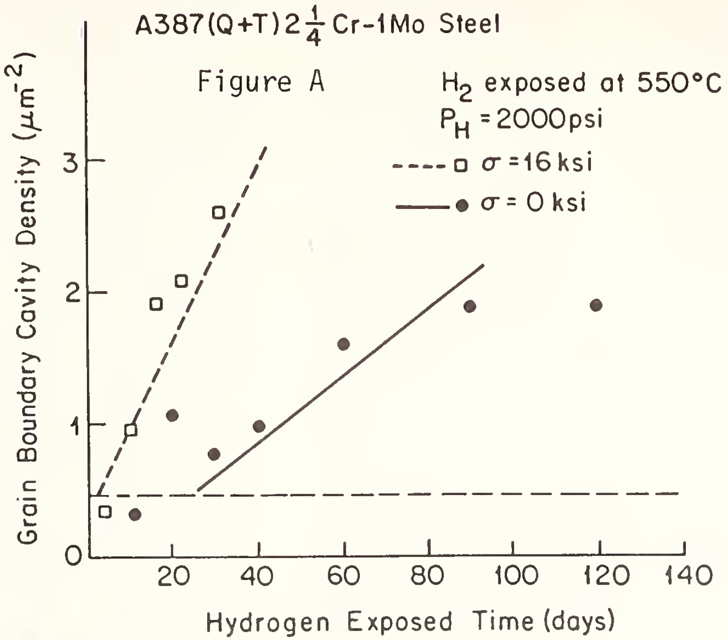
[a]Specimens were loaded in autoclaves (fitted with creep stands) which were first evacuated to 10^{-3} torr, brought to the desired temperature in a split furnace and loaded with hydrogen to the prescribed pressure. Round tension specimens, 19 mm gauge length, 1.8 mm gauge diameter, were used.

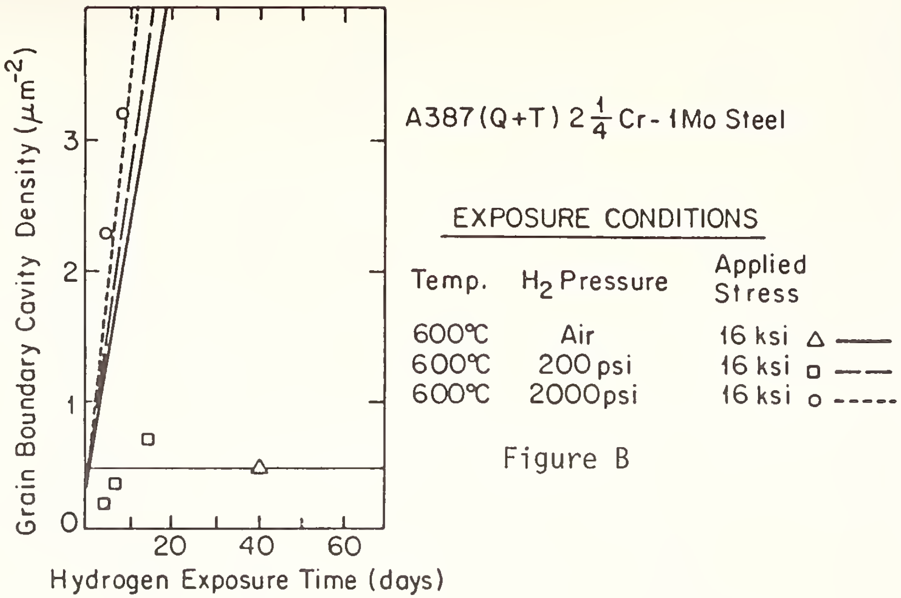
[b]See footnote a of Section B.1.1.178 for methods of creep growth treatment after hydrogen exposure, of cavity density count, and the corrections applied. In Figures B, C, D, and E, the symbols are data points and the lines are calculated values.

-Figure A compares specimens exposed at 600 °C under 13.8 MPa hydrogen pressure with no applied stress.
-Figures B and C have data for specimens tested at various temperatures and no applied stress.
-Figure D (double figure) compares data for different hydrogen pressures, 13.8 MPa (2000 psi) and 6.9 MPa (1000 psi).
-Figure E (double figure) compare data for different applied stress levels during hydrogen exposure, zero stress, 55 MPa (8000 psi), and 110 MPa (16,000 psi).

[c]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Specimens were taken from the surface of 12-inch thick plate. Heat treatments: quenched and tempered plate was austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched; normalized and tempered plate was austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. The Q + T material had a bainite microstructure (no proeutectoid ferrite) and the N + T material showed a bainite and proeutectoid ferrite microstructure.

HYDROGEN EXPOSURE[a] CAVITY DENSITY DATA[b] FOR 2-1/4 Cr-1 Mo STEEL[c] UNDER APPLIED STRESS[61,62]



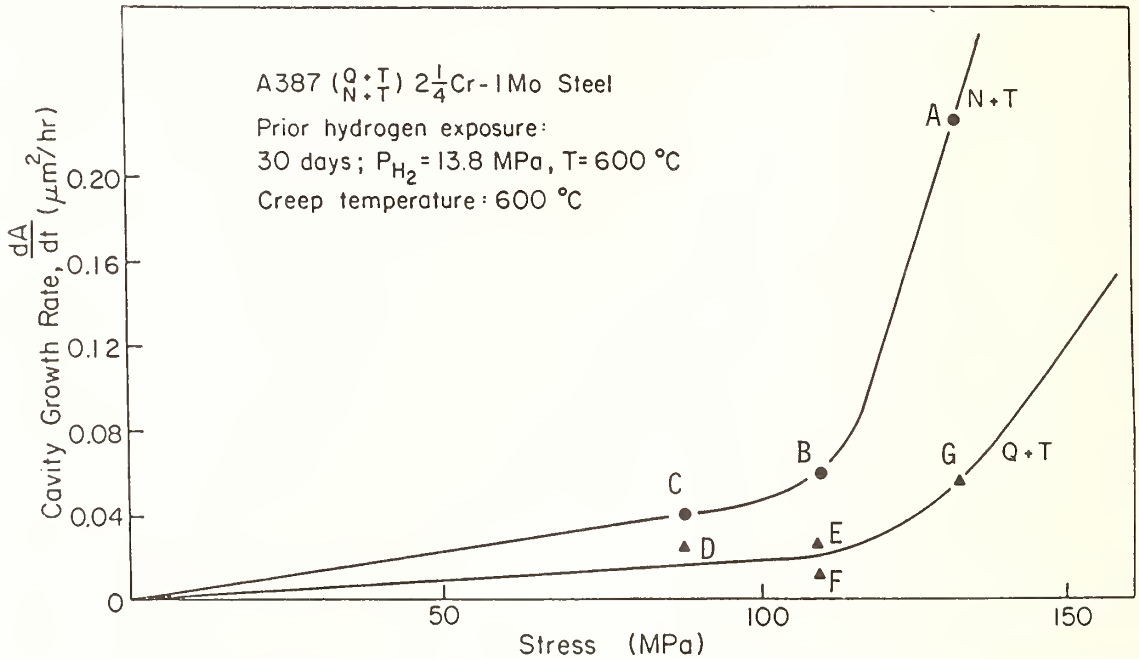


[a]Specimens were loaded in autoclaves (fitted with creep stands) which were first evacuated to 10^{-3} torr, brought to the desired temperature in a split furnace and loaded with hydrogen to the prescribed pressure. Round tension specimens, 19 mm gauge lenght, 1.8 mm gauge diameter, were used.

[b]See footnote a of Section B.1.1.178 for methods of creep growth treatment after hydrogen exposure, of cavity density count, and the corrections applied. In Figures A and B the symbols are data points, the lines are calculated values.
-Figure A show the effect of applied stress (σ), 110 MPa (16 ksi), at 550 °C during hydrogen exposure.
-Figure B shows data for constant applied stress under varied hydrogen pressure.

[c]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Specimens were taken from the surface of 12-inch thick plate. Heat treatment for quenched and tempered material: austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched. Material had a bainitic microstructure with no proeutectoid ferrite.

HYDROGEN EXPOSURE[a] CAVITY GROWTH RATE[b] FOR 2-1/4 Cr-1 Mo STEEL[c][61,62]



Sample	dA/dt (μm^2/hr)	Density (μm^{-2})	Applied Stress		Time to Failure
A	0.249	0.0085	19.2 ksi	132 MPa	84 hours
B	0.06	0.0194	16.0	110	162
C	0.04	0.0121	12.8	88	396
D	0.013	0.028	12.8	88	497
E	0.019	0.030	16.0	110	376
F	0.0060	0.098	16.0	110	312
G	0.056	0.041	19.2	132	85

[a]See footnote a of B.1.1.181 for hydrogen exposure.

[b]The above data were determined by creep-to-rupture tests on material subjected to hydrogen exposure at 600 °C, 13.8 MPa pressure for 30 days. The creep tests were performed in air at 600 °C. See footnote a of B.1.1.178 for determination of Grain Boundary Cavity Density. The average cavity density was estimated in regions far (>0.4 cm) from the rupture site. Using time-to-rupture and observed cavity density, the average cavity growth rate (dA/dt, where A = cavity cross-sectional area) was estimated. It was assumed that the specimen ruptured when the diameter of a bubble reached half the bubble separation.

[c]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Specimens were taken from the surface of 12-inch thick plate. Heat treatments: quenched and tempered plate was austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched; normalized and tempered plate was austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. The Q + T material had a bainite microstructure (no proeutectoid ferrite) and the N + T material showed a bainite and proeutectoid ferrite microstructure.

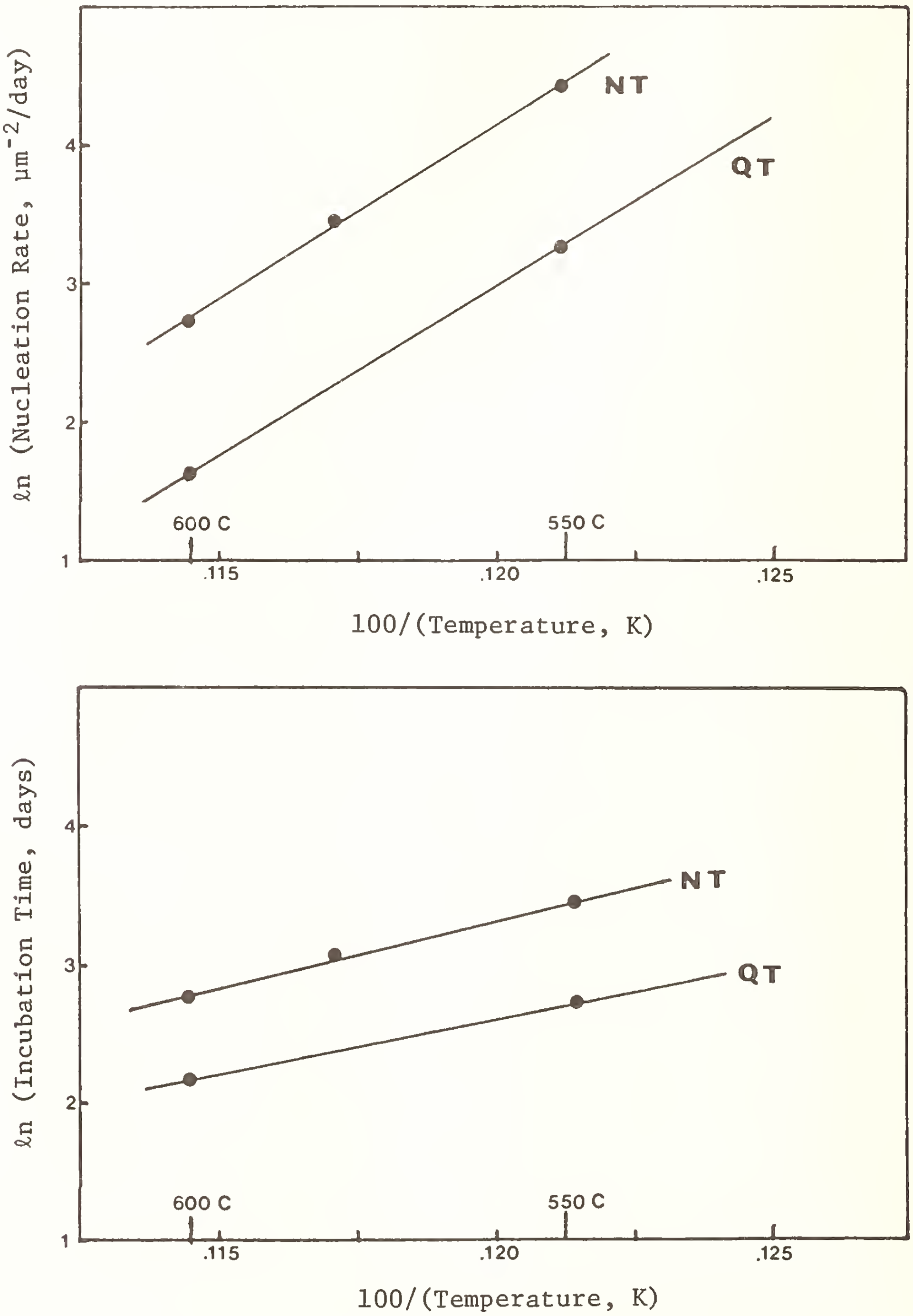
METHANE BUBBLE FORMATION DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b][61,62]

Exposure Conditions °C	P_{H_2} MPa	Applied Stress MPa	Nucleation Rate $\mu m^{-2} day^{-1}$	Incubation Time days
NORMALIZED AND TEMPERED				
600	13.8		0.0664	16
580	13.8		0.0324	21
550	13.8		0.0121	30
600	6.9		0.070	30
600	13.8	55	0.0762	8.5
500	13.8	110	0.30	2.5
QUENCHED AND TEMPERED				
600	13.8		0.20	8.8
550	13.8		0.039	15
500	13.8		--	>270
600	6.9		--	>30 but <40
600	13.8	55	0.22	5
600	13.8	110	0.40	0.5

[a]See Sections B.1.1.178 through B.1.1.182 for the data from which this table is derived. The nucleation rates and incubation times are taken from the various plots of grain boundary cavity density versus hydrogen exposure time.

[b]See footnote c of Section B.1.1.182 for analysis and heat treatments for the normalized and tempered and quenched and tempered A387 Grade 22 steel.

TEMPERATURE DEPENDENCE OF METHANE BUBBLE NUCLEATION RATE[a] AND INCUBATION TIME[a] FOR 2-1/4 Cr-1 Mo STEEL[b][61,62]



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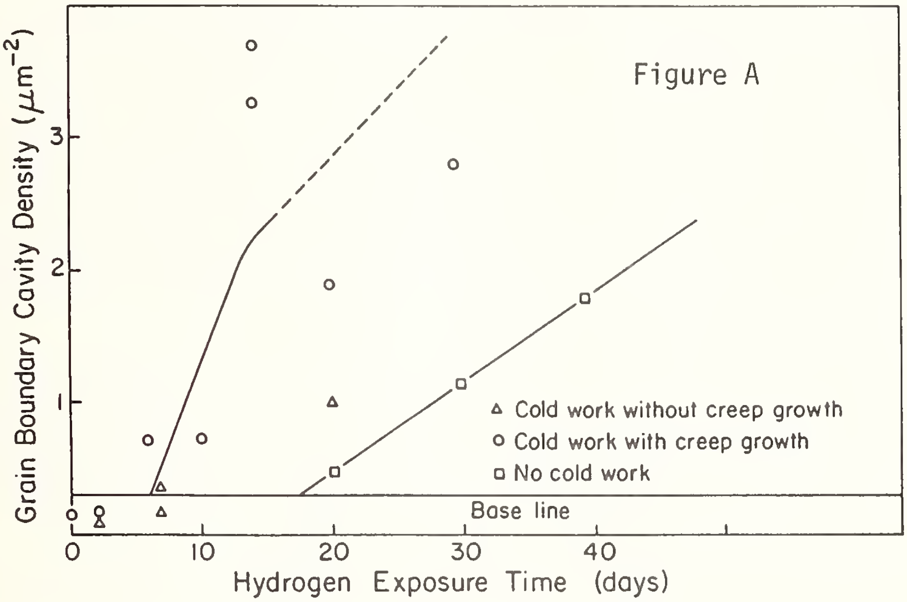
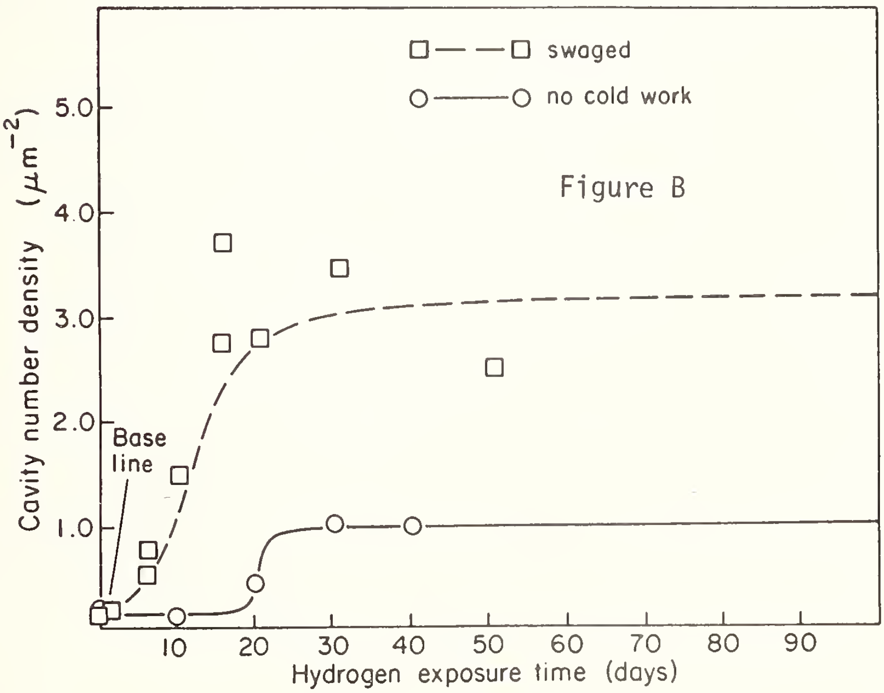
[a] See Section B.1.1.183 for the data plotted here.

[b] See footnote c of Section B.1.1.182 for analysis and heat treatments for the normalized and tempered (NT) and quenched and tempered (QT) A387 Grade 22 steel.

EFFECT OF COLD-WORKING[a] OF 2-1/4 Cr-1 Mo STEEL[b] ON GRAIN BOUNDARY CAVITY DENSITY[c][61,62]





(Data Continued)

EFFECT OF COLD-WORKING[a] OF 2-1/4 Cr-1 Mo STEEL[b] ON GRAIN BOUNDARY CAVITY DENSITY[c][61,62], Continued

Footnotes

[a]Specimens were machined from a 3/8 inch bar which had been swaged down from a 1.2 inch bar, corresponding to 44 % nominal strain.

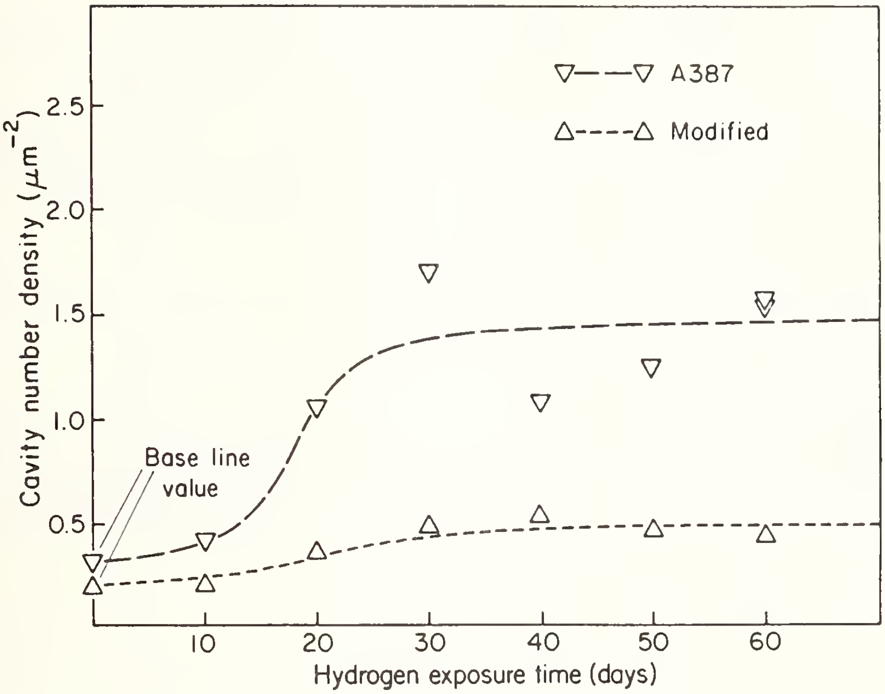
[b]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Normalized and tempered 12 inch thick plate had been austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. Microstructure was bainitic with proeutectoid ferrite. Specimens were round tension specimens, 19 mm gauge length, 1.8 mm gauge diameter, taken from the surface of the plate.

[c]See footnote a of Section B.1.1.178 for method of determination of grain boundary cavity density after hydrogen exposure. Specimens were exposed to hydrogen at 13.8 MPa and 600 °C in autoclaves fitted with creep stands and given creep growth treatment after exposure. The creep growth treatment consisted of holding the specimens at 110 MPa applied stress at 600 °C for several days.

-Figure A compares data for cold-worked (swaged) steel with and without creep growth treatment with data for steel which has not been cold-worked but with creep growth treatment.

-Figure B compares further data for cold-worked (swaged) steel with the unswaged, both subjected to creep growth treatment after hydrogen exposure.

COMPARISON OF THE EFFECT OF HYDROGEN EXPOSURE[a] ON 2-1/4 Cr-1 Mo STEEL[b] AND A MODIFIED STEEL[c][62]



[a]Specimens were exposed to hydrogen at 13.8 MPa and 600 °C in autoclaves fitted with creep stands. After exposure they were subjected to creep growth treatment consisting of holding the specimens at an applied stress of 110 MPa and 600 °C for several days. See footnote a of Section B.1.1.178 for determination of grain boundary cavity density.

[b]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Quenched and tempered material had been austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched. Microstructure was bainitic only. Creep specimens, 19 mm gauge length, 1.8 mm gauge diameter, were taken from the surface of the 12-inch thick plate.

[c]Modified 2-1/4 Cr-1 Mo steel produced in Japan. Analysis (wt %): 0.10 C, 0.02 Si, 0.54 Mn, 0.009 P, 0.007 S, 0.11 Ni, 2.30 Cr, 0.097 Mo, 0.21 V, 0.0022 Ti, 0.022 B, 0.01 Al, 0.005 Sn, 0.005 As, 0.0004 Sb, 0.0094 N. Heat treatment: austenitized at 950 °C for 7 hours, water quenched, and tempered at 650 °C for 15 hours. Grain size is 51 μm compared to the 27 μm of the A387 in footnote b. Microstructure is bainitic.

EFFECT OF VARIED CONSTITUENT CONTENT ON CARBIDE FORMATION[a][79]

Constituent[b] wt %	Tempering Parameter[c]	Fe_3C	M_7C_3	Mo_2C	M_6C	$M_{23}C_6$
Mn 0.1	19.1		X	X	few	--
0.5	19.5		X	X	--	--
0.6	19.5		X	X	X	possible
1.1	19.8		X	few	X	--
1.0	19.9		A	C		B
1.0	20.5		A	C	D	B
Comments: above A>B>C>D; increasing Mn leads to preferential nucleation of M_6C						
Si 0.05 (Mn 0.6)	19.5		X	X	X	--
0.5	19.5		X	X	--	--
0.45 (Mn 0.6)	19.5		X	X	few	
0.90 (Mn 0.6)	20.0		some	few	majority	--
Comments: in general, increasing Si reduces Mo_2C and accelerates earlier nucleation of M_6C						
C 0.02	19.9		A	C		B
0.025	untempered	X	--	--	--	--
0.06	19.9	--	A	C	--	B
0.09	19.9	--	A	C	--	B
0.12	19.8	--	X	X	--	--
0.12	19.5		X	X	few	--
0.20	19.8		some	--	X	--
Comments: increasing C content, increases dissolution of Mo_2C (and $M_{23}C_6$), reduces relative formation of M_7C_3, and accelerates earlier nucleation of M_6C						
Mo 0.3	19.1	?	X	--	X	
0.9	19.5	--	X	X	few	
1.6	19.8	--	few	X[d]	X	
0.3 (Mn 0.5) (Si 0.5)	19.5	X	X	--	--	
0.9 (Mn 0.5) (Si 0.5)	19.5	--	X	X	--	
1.6 (Mn 0.5) (Si 0.5)	19.5	--	X	X	--	
Comments: promotion of M_6C with increasing % Mn, increasing Mo increases volume fraction of Mo_2C						
Cr 0.8	19.1	possible	--	X[e]	--	--
2.25	19.5	--	X	X	few	--
3.5	20.0	--	X[f]	--	X	--
0.8 (Mn 0.5) (Si 0.5)	19.1	X	--	X	--	--
2.25 (Mn 0.5) (Si 0.5)	19.5	--	X	X	--	--
3.5 (Mn 0.5) (Si 0.5)	20.0	--	X	--	X	X
Comments: little effect of Mn and Si in promoting M_6C; increasing Cr leads to accelerated nucleation of M_6C						

[a]Identification of carbides is based upon electron diffraction patterns,

(Table Continued

EFFECT OF VARIED CONSTITUENT CONTENT ON CARBIDE FORMATION[a] [79], Continued

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carbide morphologies as seen in scanning transmission electron microscopic examination of carbide extraction replicas, and carbide chemistries.

[b]Steels are Cr-Mo steels for pressure vessel use. The following are analyses for the other major alloying elements in weight percent for the various sets of data:

Varying Element	Other Constituents
Mn	1.0 Mo, 2.25 Cr, 0.12 C, 0.45 Si
Si	1.0 Mo, 2.25 Cr, 0.12 C, 0.6 Mn
C	1.0 Mo, 2.25 Cr, 0.6 Mn, 0.45 Si
Mo	2.25 Cr, 0.12 C, 0.6 Mn, 0.45 Si
Cr	1.0 Mo, 0.6 Mn, 0.45 Si, 0.12 C

Any variation from the above compositions is noted in the constituents column above.

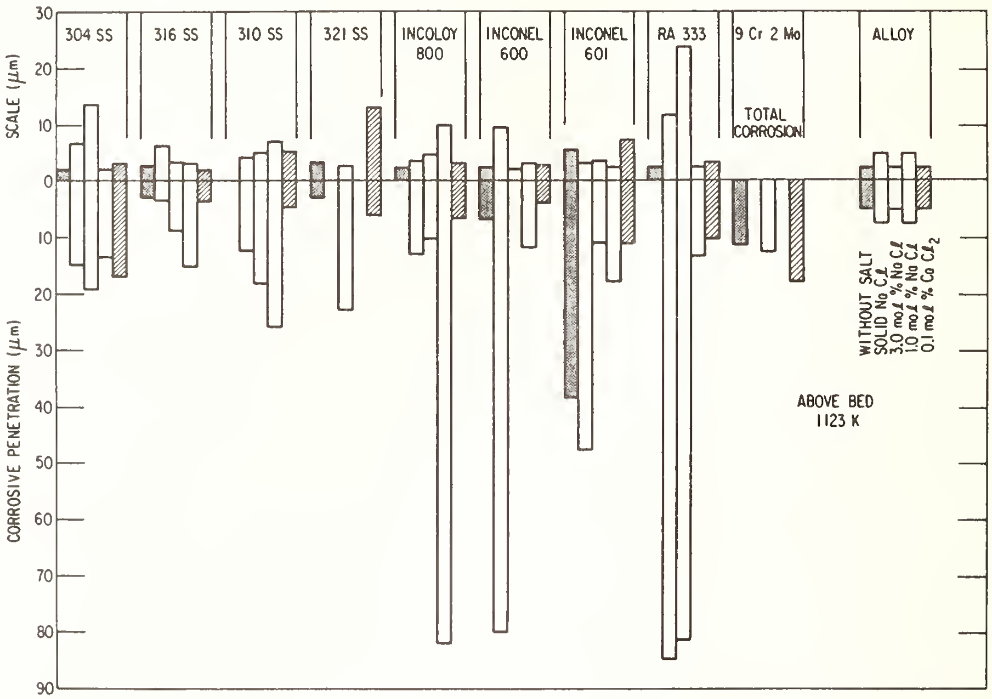
[c]Tempering parameter is $T(20 + \log t) \times 10^{-3}$ where T is temperature in Kelvins and t is tempering time in hours.

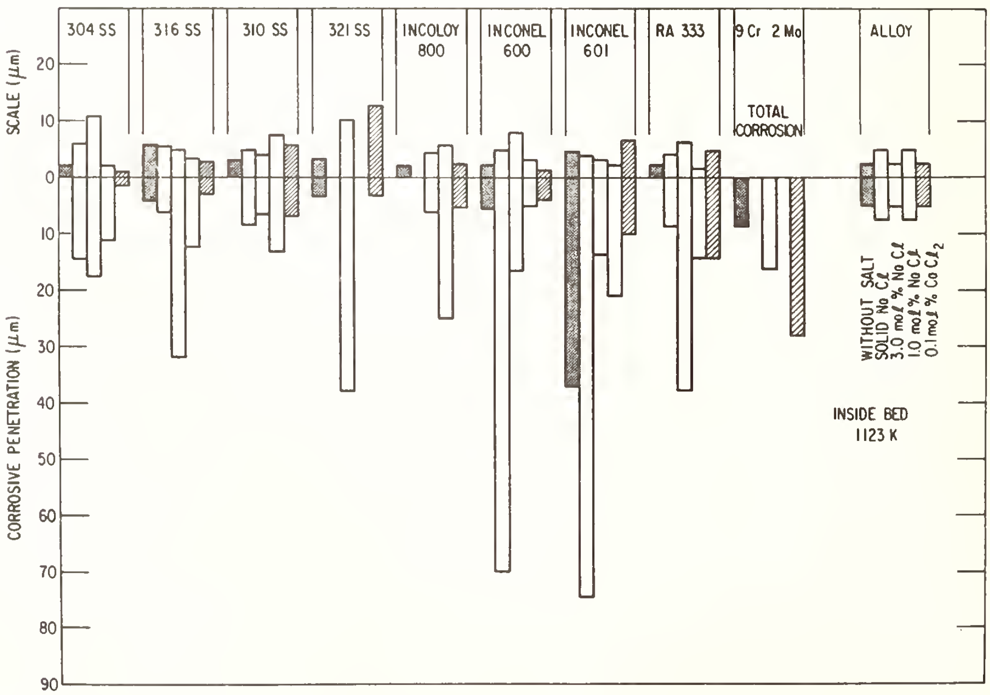
[d]More Mo_2C.

[e]Primarily Mo_2C.

[f]M_7C_3 on grain boundaries.

CORROSION[a] OF ALLOYS SUBJECTED TO A SALT-CONTAINING FLUIDIZED BED ATMOSPHERE[b][84]





(Data Continued)

CORROSION[a] OF ALLOYS SUBJECTED TO A SALT-CONTAINING FLUIDIZED BED ATMOSPHERE[b][84], Continued

Footnotes

[a]Average thickness of surface scale and corrosive penetration as determined by metallographic examination. [Note: in the original report, figure captions are interchanged between these two figures.]

[b]A process development unit in which the vessel is equipped with an overflow tube which maintains a constant bed level. Coupons were exposed in and above the fluidized bed at 1123 K for 100 hours. The nominal operating conditions for the bed are: 855 °C (1571 °F), 152 kPa (1.5 atm), 1 m/s (3.3 ft/s) fluidizing velocity, 895 mg/s (7.1 lb/h) coal feed rate for Eastern bituminous coal, 428 mg/s (3.4 lb/h) limestone feed rate based on Greer limestone (Ca/S molar ration = 3.), fluidized bed height 813 mm (32 in.), 6.8 mm^3/s (14.4 scfm). The various runs indicated in the figures had the following chemistry:

Run	Bed Condition	Fluidizing Gas
Without salt	Fully sulfated dolomite	5% O_2, 200 ppm SO_2, balance N_2
Solid NaCl	Fully sulfated dolomite with 1.5 g solid NaCl introduced every 4 hours	5% O_2, 200 ppm SO_2, balance N_2
3.0 Mol% NaCl	Dolomite treated with NaCl	5% O_2, 3200 ppm SO_2, balance N_2
1.0 Mol% NaCl	Dolomite treated with NaCl	5% O_2, 3200 ppm SO_2, balance N_2
0.1 Mol% $CaCl_2$	Limestone treated with $CaCl_2$	5% O_2, 3200 ppm SO_2, balance N_2

CORROSION DATA[a] FOR ALLOY COUPONS[b] EXPOSED IN THE FLUIDIZED BED[c] OF AN ATMOSPHERIC FLUIDIZED-BED COMBUSTOR[d][84]

Probe Location[c]	Mean Temperature °C	Material[b]	Surface-Scale Thickness, μm Top	Bottom	Side	Corrosive Penetration, μm Top	Bottom	Side	Remarks
Run 1, no additional treatment, Ca/S molar ratio 3.4									
102 mm above gas distributor plate	848	Inconel 601	1.7	2.0	2.0	5.3	5.3	4.1	Some grain-boundary attack, ∿50 μm deep
		Inconel 671	3.1	3.4	2.5	6.4	8.5	6.6	Preferential corrosive attack of one phase ∿15 μm deep
		Hastelloy X	e	1.2	1.2	5.1	4.2	8.5	
		Type 310 SS	1.5	1.4	2.6	17.1	11.5	21.2	Internal corrosion mainly sulfides
		Haynes 188	2.0	e	1.9	9.3	8.5	9.2	
		RA 333	1.5	e	2.4	12.7	10.7	15.2	
		Type 347 SS	1.0	e	1.9	6.0	6.4	7.3	
610 mm above gas distributor plate	844	Inconel 625	1.4	1.7	1.4	7.8	9.3	7.4	
		Inconel 718	e	3.1	2.0	5.4	5.1	5.9	
		Incoloy 800	1.7	e	2.7	11.0	21.2	8.8	
		Type 310 SS	e	e	1.6	9.1	12.9	12.7	Internal corrosion mainly sulfides
		Inconel 617	3.2	e	3.3	16.5	16.1	9.3	Some grain-boundary attack ∿40 μm deep
		Type 304 SS	3.8	1.7	3.1	20.3	11.4	11.9	
		Type 316 SS	2.7	2.9	2.7	9.1	25.0	8.5	
Run 2, 0.3 mol% $CaCl_2$ added, Ca/S molar ratio 3.5									
610 mm above gas distributor plate	844	Inconel 601	e	2.0	2.0	7.4	6.7	3.0	Some grain-boundary attack ∿33 μm deep
		Inconel 671	e	5.6	6.7	63.0	77.5	11.5	
		Hastelloy X	e	e	2.0	20.7	10.7	7.3	
		Type 310 SS	1.3	e	2.0	7.6	11.0	9.8	Internal corrosion mainly sulfides
		Haynes 188	e	e	1.3	11.3	13.3	8.6	
		RA 333	2.3	e	1.7	8.5	13.5	7.6	
		Type 347 SS	e	3.0	3.4	5.3	9.7	10.2	
102 mm above gas distributor plate	819	Inconel 625	1.3	1.3	2.1	9.8	9.1	8.8	
		Inconel 718	2.0	1.7	1.5	5.9	5.9	5.1	
		Incoloy 800	3.7	1.2	1.2	5.3	7.8	7.6	
		Type 310 SS	3.4	3.0	2.3	27.1	15.4	14.6	Internal corrosion mainly sulfides
		Inconel 617	3.3	5.3	3.3	18.7	19.5	14.4	Some grain-boundary attack ∿25 μm deep
		Type 304 SS	2.2	3.0	2.1	13.5	11.1	10.1	
		Type 316 SS	3.4	2.5	2.5	12.3	8.0	12.7	
Run 3, 0.5 mol% NaCl added, Ca/S molar ratio 3.6									
610 mm above gas distributor plate	851	Inconel 601	e	e	3.8	32.2	40.2	38.1	
		Inconel 671	e	7.6	6.8	51.9	97.4	80.4	
		Hastelloy X	1.9	1.7	1.7	14.8	10.6	15.6	
		Type 310 SS	2.0	2.0	2.7	15.2	10.2	15.2	Internal corrosion mainly sulfides
		Haynes 188	1.7	e	1.2	11.8	8.5	12.3	
		RA 333	e	e	2.9	22.0	37.2	37.7	Corrosion attack in some regions ∿80 μm deep
102 mm above gas distributor plate	852	Type 347 SS	e	e	2.5	11.0	10.1	9.3	
		Inconel 625	2.5	e	2.4	17.8	16.9	9.8	
		Inconel 718	2.5	2.4	2.0	7.1	8.5	5.8	
		Incoloy 800	e	e	3.4	22.9	19.5	24.6	
		Type 310 SS	e	e	2.9	33.9	31.3	23.7	Internal corrosion mainly sulfides
		Inconel 617	2.6	e	2.4	27.5	32.8	34.8	
		Type 304 SS	2.2	e	2.4	10.8	9.3	11.8	
		Type 316 SS	e	e	3.1	8.1	9.8	18.6	

(Table Continued)

CORROSION DATA[a] FOR ALLOY COUPONS[b] EXPOSED IN THE FLUIDIZED BED[c] OF AN ATMOSPHERIC FLUIDIZED-BED COMBUSTOR[d][84]
(Continued)

Probe Location[c]	Mean Temperature °C	Material[b]	Surface-Scale Thickness, μm Top	Bottom	Side	Corrosive Penetration, μm Top	Bottom	Side	Remarks
Run 4, 1.9 mol% Na_2CO_3, Ca/S molar ratio 2.0									
610 mm above gas distributor plate	855	Inconel 601	2.7	2.1	3.0	6.8	12.3	16.6	Some grain-boundary attack ~50 μm deep
		Inconel 671	7.6	4.7	3.1	50.8	46.6	f	Corrosion behavior not uniform
		Hastelloy X	3.0	3.0	2.9	-	10.2	12.9	
		Type 310 SS	3.4	3.4	3.2	13.5	17.8	12.8	Internal corrosion mainly sulfides
		Haynes 188	2.1	1.8	2.1	8.0	9.8	9.5	Some grain-boundary attack ~24 μm deep
		RA 333	2.0	e	2.4	9.8	11.8	10.2	
		Type 347 SS	2.7	2.7	2.4	10.2	9.8	9.3	Internal corrosion mainly sulfides
102 mm above gas distributor plate	854	Inconel 625	3.8	3.1	4.1	21.1	22.9	23.7	
		Inconel 718	2.2	2.2	2.7	11.0	10.2	14.6	
		Incoloy 800	3.4	3.6	3.6	21.2	25.0	19.5	
		Type 310 SS	3.4	3.2	3.4	18.2	18.2	19.1	
		Inconel 617	3.2	3.6	3.6	25.4	21.2	26.5	
		Type 304 SS	2.9	2.4	3.0	18.6	16.2	22.0	
		Type 316 SS	3.4	3.4	3.4	16.1	22.2	23.3	

[a]From metallographic examination.

[b]Coupons were ~8 mm thin disk specimens used with uncooled corrosion-coupon holders. Materials are listed for each exposure according to the stacking sequence on the probe: first coupon is towards the pipe bushing, the last one is near the end cap. Specimens were exposed for 100 hours.

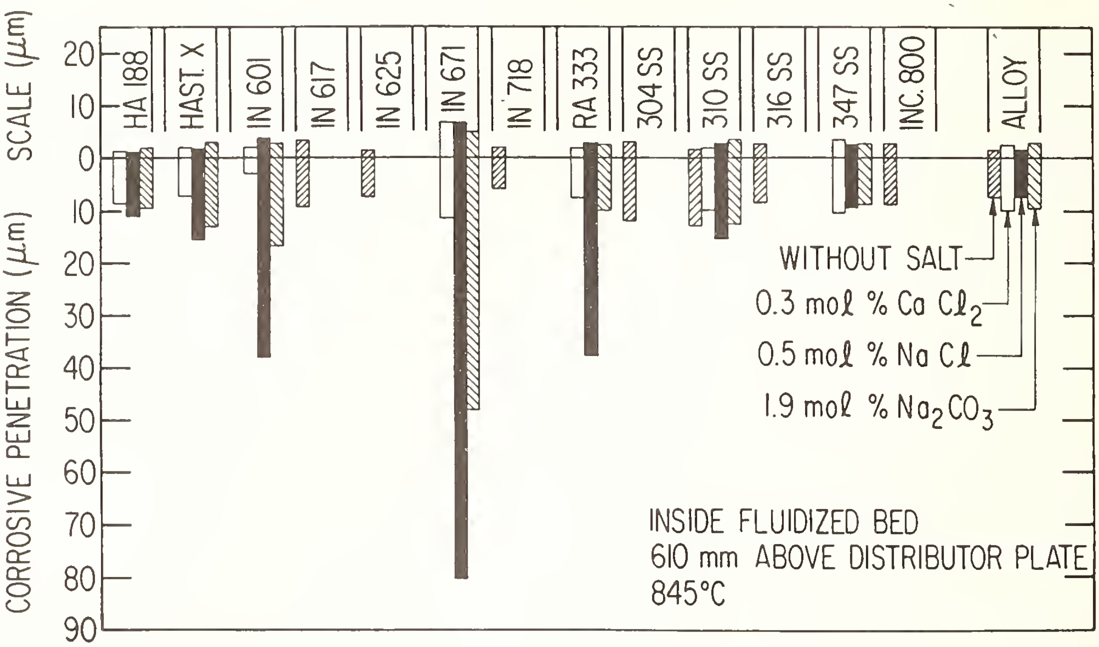
[c]The actual locations of the probes were within the fluidized bed itself, the bed height being 813 mm.

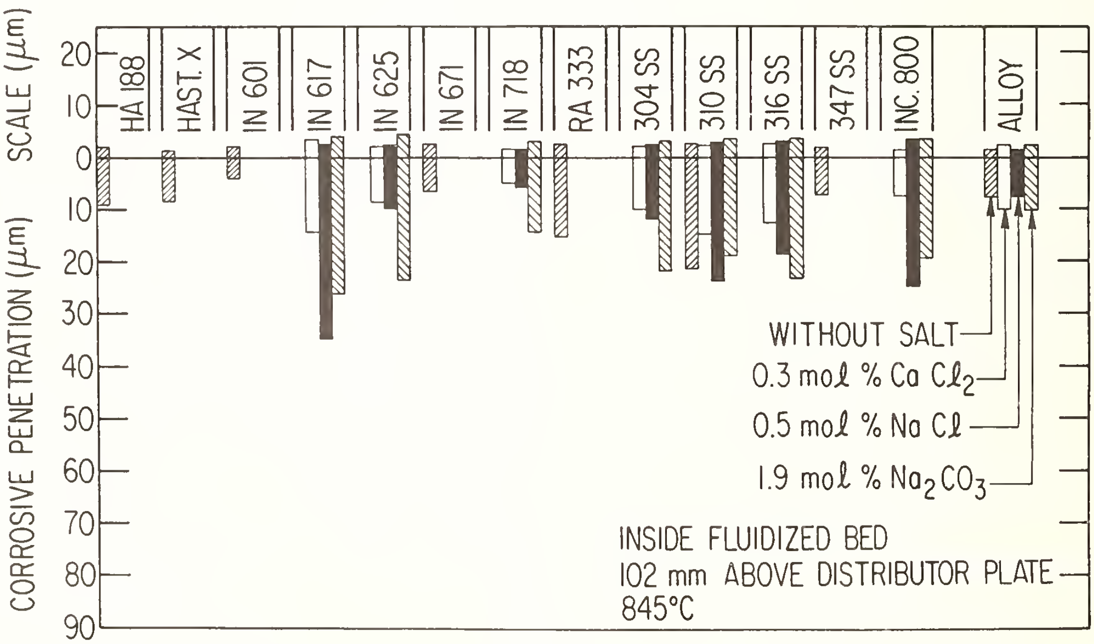
[d]A process development unit combustor. Bed temperature 850 °C, pressure 101.3 kPa (1 atm), fluidizing velocity 1 m/s, excess O_2 is 3% in dry off-gas, coal is Sewickley -12 + 100 mesh with 5.46% S, sorbent is Grove limestone, -10 + 30 mesh, 95.3% $CaCO_3$. These conditions provide a calcium-to-sulfur ratio which maintains 700 ppm SO_2 in the dry off-gas.

[e]Surface scale spalled.

[f]Extensive corrosion on one side of the specimen and very little internal corrosive penetration on the other.

CORROSION DATA[a] FOR UNCOOLED SPECIMENS EXPOSED IN A FLUIDIZED BED[84]





[a] See Section B.1.1.189 for the data plotted here and for the experimental conditions.

CORROSION DATA[a] FOR AIR-COOLED ALLOY COUPONS[b] EXPOSED IN THE FLUIDIZED-BED[c] OF AN ATMOSPHERIC FLUIDIZED-BED COMBUSTOR[d][84]

Probe Location[c]	Average Temperature K	Material[b]	Surface-scale Thickness, μm	Corrosive Penetration, μm	Total Corrosive Attack, μm	Remarks
Run 1, no additional treatment, Ca/S molar ratio 3.4						
508 mm above gas distributor plate	1000[e]	Type 304 SS	2.3	2.7	5.0	
	876	Type 446 SS	2.1	2.2	4.3	
	925	2¼Cr-1Mo Steel	-	-	171.9	Maximum corrosion ∿320 μm
	950	Incoloy 800	3.2	3.6	6.8	Interaction between surface scale and deposits
	970	9Cr-1Mo Steel	-	-	18.4	Maximum corrosion ∿35 μm
	985	Type 316 SS	2.4	4.1	6.5	
	1000	Type 309 SS	5.6	5.9	11.5	Interaction between surface scale and deposits
305 mm above gas distributor plate	900[e]	Type 321 SS	2.9	2.1	5.0	
	876	Inconel 601	2.6	4.7	7.3	Maximum corrosive attack ∿15 μm
	925	Type 310 SS	4.9	6.9	11.8	Interaction between surface scale and deposits
	950	Incoloy 800	2.5	3.9	6.4	Interaction between surface scale and deposits
	970	Inconel 617	2.5	2.6	5.1	
	985	RA 333	2.4	4.5	6.9	
Run 2, 0.3 mol% $CaCl_2$ added, Ca/S molar ratio 3.5						
508 mm above gas distributor plate	780	Type 446 SS	2.1	2.8	4.9	
	800	Type 304 SS	1.2	1.6	2.8	
	817	2¼Cr-1Mo Steel	-	-	142.3	Maximum corrosion ∿160 μm
	833	Incoloy 800	2.3	3.5	5.8	
	848	9Cr-1Mo Steel	-	-	12.9	Maximum corrosion ∿25 μm
	856	Type 316 SS	1.2	2.1	3.3	
	870	Type 309 SS	2.0	3.5	5.5	
305 mm above gas distributor plate	840	Inconel 601	1.7	1.8	3.5	
	870	Type 321 SS	2.1	2.0	4.1	
	896	Type 310 SS	2.3	5.0	7.3	
	919	Incoloy 800	1.7	3.7	5.4	
	936	Inconel 617	2.2	2.6	4.8	
	950	RA 333	3.0	6.2	9.2	Internal corrosion mainly sulfides
	958	Type 309 SS	2.0	4.1	6.1	
Run 3, 0.5 mol% NaCl added, Ca/S molar ratio 3.6						
508 mm above gas distributor plate	850	Type 446 SS	3.0	3.2	6.2	Intergranular attack
	861	Type 304 SS	2.4	1.7	4.1	
	873	2¼Cr-1Mo Steel	-	-	101.0	Maximum corrosion ∿140 μm
	885	Incoloy 800	2.4	4.0	6.4	
	895	9Cr-1Mo Steel	-	-	16.5	Maximum corrosion ∿40 μm
	903	Type 316 SS	1.8	2.3	4.1	
	907	Type 321 SS	2.2	3.5	5.7	
305 mm above gas distributor plate	802	Inconel 601	1.9	1.7	3.6	Corrosion in some regions ∿10 μm
	823	Type 321 SS	3.1	3.2	6.3	Intergranular attack
	843	Type 310 SS	2.5	1.0	3.5	
	862	Type 304 SS	1.6	1.2	2.8	
	873	Inconel 617	2.7	3.8	6.5	
	878	RA 333	2.0	1.7	3.7	Corrosion in some regions ∿10 μm
Run 4, 1.9 mol% Na_2CO_3, Ca/S molar ratio 2.0						
305 mm above gas distributor plate	802	Type 446 SS	2.4	1.0	3.4	
	823	Type 304 SS	2.2	1.7	3.9	
	843	2¼Cr-1Mo Steel	-	-	119.5	Maximum corrosion ∿180 μm
	862	Incoloy 800	2.6	3.0	5.6	
	873	9Cr-1Mo Steel	-	-	13.2	Maximum corrosion ∿25 μm
	878	Type 316 SS	2.2	2.1	4.3	
	878	Type 309 SS	2.7	3.8	6.5	

(Table Continued)

CORROSION DATA[a] FOR AIR-COOLED ALLOY COUPONS[b] EXPOSED IN THE FLUIDIZED-BED[c] OF AN ATMOSPHERIC FLUIDIZED-BED COMBUSTOR[d][84], Continued

Probe Location[c]	Average Temperature K	Material[b]	Surface-scale Thickness, μm	Corrosive Penetration, μm	Total Corrosive Attack, μm	Remarks
Run 4, Continued						
508 mm above gas distributor plate	890	Inconel 601	2.1	1.4	3.5	
	901	Type 321 SS	2.3	1.9	4.2	
	913	Type 310 SS	2.1	2.1	4.7	
	923	Incoloy 800	2.5	3.1	5.6	Interaction between surface scale and deposits
	933	Inconel 617	1.3	1.4	2.7	
	940	RA 333	2.1	3.2	5.3	
	948	Type 309 SS	4.2	5.3	9.5	Interaction between surface scale and deposits

[a]From metallographic examination.

[b]Coupons were tubular rings, 22.2 mm diameter and 22.2, used with air-cooled corrosion probes. Materials are listed for each exposure according to the stacking sequence on the probe: first coupon is towards the pipe bushing, the last one is near the end cap. Specimens were exposed for 100 hours.

[c]The actual locations of the probes were within the fluidized bed itself, the bed height being 813 mm.

[d]A process development unit combustor. Bed temperature 850 °C, pressure 101.3 kPa (1 atm), fluidizing velocity 1 m/s, excess O_2 is 3% in dry off-gas, coal is Sewickley -12 + 100 mesh with 5.46% S, sorbent is Grove limestone, -10 + 30 mesh, 95.3% $CaCO_3$. These conditions provide a calcium-to-sulfur ratio which maintains 700 ppm SO_2 in the dry off-gas.

[e][The order of the alloys is that given in the reports in one table but the temperatures of the specimens would indicate that a few of the coupons were actually in a different order.]

RESULTS OF HYDROGEN EXPOSURE OF DEVELOPMENTAL PRESSURE VESSEL STEELS[40]

Alloys	Prior heat treatment	Results of 1000 hr exposure to H_2 at 1500 psi, 550°C[a]
A542 (2¼Cr-1Mo)[b] A542 (2¼Cr-1Mo)+1Mn A542 (2¼Cr-1Mo)+0.5Mn+0.5Ni	All Aust. 1 hr at 1000°C, oil quench, tempered at 650°C for 4 hrs	One sample of 2¼Cr-1Mo showed one macroscopic blister and one micro-crack. No sign of attack on other samples of the same material or on alloy modified samples.
A533B[c] A533B+1Cr A533B+1Cr+1Mn A533B+1Cr+1Mn+1Si	All Aust. 1 hr at 1000°C, oil quench, tempered at 650°C for 4 hrs	All showed macroscopic attack consisting of blisters and cracks.
Fe+0.15C+0.5Mn Fe+0.15C+0.5Mn+2Cr	Aust. 1 hr at 1000°C, tempered 1 hr at 625°C	Blisters observed on plain carbon steel, but no visible attack on modifications containing Cr, Mo or W.
Fe+0.15C+0.5Mn+2Mo Fe+0.15C+0.5Mn+2W	Aust. 1 hr at 1150°C, tempered 1 hr at 625°C	

[a] None of the samples showed visible evidence of attack after 500 hours exposure.

[b] 2¼Cr-1Mo base composition: 0.15C, 0.42Mn, 0.91Mo, 0.10Ni, 2.18Cr, 0.30Si, 0.009S, 0.015P, 0.019Al, 0.09Cu, bal Fe.

[c] Mn-Mo-Ni base composition: 0.22C, 1.32Mn, 0.57Mo, 0.65Ni, 0.20Si, 0.007S, 0.009P, 0.036Al, 0.07Cu, bal Fe.

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EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43]

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			1650			1650
Pressure, psi			atmospheric			1000
Velocity, ft/s		-20+40 mesh	100		-20+40 mesh	100
Time, hr			100			50
Volume % H_2S			1.0			1.0
Incoloy 800 47Fe-31Ni-21Cr	0.2 0.2 0.2 0.3	130.1 118.2 1.0 165.5	Very heavy erosion, possible melting Large deep erosion area on E/C[g] surface; general attack on back surface Pitting and general attack on back surface Severe attack with signs of melting	0.2	10.8	Large E/C[g] areas, rest of sample covered with small pits
Incoloy 800(Al)[h]	0.5	0.9	Pitting of coating in eroded areas	0.7	5.4	General specimen discoloration only
Inconel 601 16Fe-60Ni-23Cr	0.1 0.5	1.0 31.6	Some edge attack on reverse side Intact scale E/C surface and general attack all surfaces	0.7	53.3	Large E/C area damage and whole E/C surface very rough
310 SS 52Fe-20Ni-25Cr	0.4 0.3 0.2	1.7 9.1 14.5	Some edge attack on reverse side Pits all surfaces Pits all surfaces; deep pits back side	0.3	2.0	Large E/C area damage, back of specimen pitted
310 SS (Al)[h]	0.5	1.2	Few minor pits on both surfaces	0.2	0.7	General specimen discoloration only
RA 333 16Fe-45Ni-26Cr	-	0.5	No visible attack	2.8	11.0	All of E/C surface rough, back had some pits
LM-1866 Fe-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
446 SS 75Fe-24Cr	0.3 0.5 0.8	5.6 11.9 1.2	No visible attack Pits all surfaces Few pits E/C surface; few large shallow pits back surface	0.6	1.9	Small E/C area with a compact scale still present after cleaning
Inconel 671 48Ni-50Cr	0.5 0.4 0.3 0.6	0.9 0.9 0.9 1.1	No visible attack Slight pitting back of specimen Melt pits back surface Melt pits back surface	0.7	3.8	Small E/C damage area
Crutemp 25 47Fe-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
Haynes 188 Co-23Ni-22Cr	0.2 0 0	0.5 0.7 0.2	Minor edge corrosion, reverse side Few pits all surfaces and general attack one corner back surface Few pits and general attack in one corner of back surface	5.9	49.8	Badly corroded with melting
Co-Cr-W No. 1 Co-30Cr-12W				0.6	0.8	Sample discoloration under E/C impact area
Stellite 6B 57Co-28Cr-3Ni	0.1	0.6	No signs of corrosion			
Wiscalloy 30/50W Fe-49Ni-28Cr	1.0	3.0	Slight pitting on E/C surface; many large pits on back surface			
HK-40 Fe-20Ni-28Cr	0.2	6.2	Pitting attack on E/C surface			
Alloy X 20Fe-45Ni-22Cr-9Mo	3.7	22.6	Localized pitting on E/C surface; severe attack on back face			
Sanicro 32X Fe-32Ni-22Cr	0.3	113.8	Extensive localized E/C			
Multimet N155 29Fe-20Ni-21Cr-20Co	0.2	3.2	Pitting attack all surfaces			
Haynes 150 Co-18Fe-28Cr	0.2	0.7	No signs of corrosion			
Supertherm T63WC Fe-36Ni-28Cr-15Co-5W	0.7	4.7	Extensive corrosion on back surface			
HL-40 47Fe-19Ni-31Cr	0.1	4.0	Fine pitting attack under E/C stream; slight pits on back surface			
329 SS Fe-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][11,43]
(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		-20+40 mesh	100		-20+40 mesh	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		-20+40 mesh	100		-20+40 mesh	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 still 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 edge 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 melting, 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	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				0.1	4.2	Slight E/C pits & edge attack back surface
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[c] [11,43]
(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			1000			1000
Velocity, ft/s		-20+40 mesh	100		-20+40 mesh	50
Time, hr			50			50
Volume % H_2S			0.1			1.0
Incoloy 800	11.4	62.3	Very deep erosion pit, possible melting	0.4	33.6	Localized E/C area; some back surface corrosion
Incoloy 800(Al)	1.6	3.6	Some discoloration and roughening of coating	0.9	1.9	No visible E/C
Inconel 601	0.4	169.5	Very deep erosion damage, minimal corrosion	5.1	135.1	Deep localized E/C; some back surface corrosion
310 SS	2.2	8.1	Small erosion pit	1.0	5.0	Limited shallow pitting
310 SS(Al)	2.1	3.6	Bottom surface, some corrosion on coating	0.3	1.3	No visible E/C
RA 333	3.2	8.1	Erosion pit, reverse surface corrosion	0.9	90.4	Deep E/C and corrosion, both surfaces
LM-1866	0.4	0.8	Some edge corrosion	14.9	16.9	Some general E/C
446 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
Crutemp 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		-20+40 mesh	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
	D.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	D.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			
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	1.4	6.4	Area of E/C			
Alloy X	D.6	2.1	Localized small pits on erosion surface			
Sanicro 32X	0.7	15.7	Localized significant E/C			
Multimet N155	D.6	4.6	Some pitting of erosion surface			
Haynes 150	0.7	2.2	Few small pits on erosion surface			
Supertherm T63WC	D.8	2.8	Limited E/C, localized back surface corrosion			

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43]
(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	-20+40 mesh		100		-20+40 mesh	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 impingement 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; significant 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
Temperature, °F			1650			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s	-30+50 mesh		50		-30+50 mesh	50
Time, hr			250			250
Volume % H_2S			1.0			1.0
Incoloy 800	0.6	6.0		1.6	9.4	
Incoloy 800(Al)	0.6	4.1				
Inconel 601	0.4	4.9				
310 SS	0.4	0.8				
310 SS (Al)	0.5	7.8				
RA 333	0.5	3.0				
LM-1866	0.3	4.6				
446 SS	0.9	4.3				
Inconel 671	0.5	1.0		0.6	1.5	
Crutemp 25	1.2	4.3				
Haynes 188	<0.2	0.6				
Co-Cr-W No. 1	<0.2	0.6				
Stellite 6B				0.2	1.0	
Wiscalloy 30/50W				0.9	1.9	
HK-40				<0.2	14.5	
Alloy X				0.2	0.7	
Sanicro 32X				0.2	1.2	
Multimet N155				0.5	1.1	
Haynes 150				0.6	4.8	
HL-40				1.1	1.8	
329 SS				1.1	2.6	
Fe-31Cr-36Ni				0.5	9.0	
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s	-30+50 mesh		50		-30+50 mesh	50
Time, hr			250			5
Volume % H_2S			1.0			1.0
Incoloy 800	1.2	97.2	Extensive attack	0.3	1.8	Light general attack under erosion stream
Incoloy 800(Al)	0.7	4.7	Localized pitting E/C surface			
Inconel 601	1.5	16.5	Heavy general attack all surfaces	<0.2	68.0	Large E/C pit and general edge attack all surfaces
310 SS	0.8	33.8	Large pit E/C surface	0.5	3.5	Few pits E/C surface
310 SS (Al)	0.4	1.4	Surface discoloration E/C surface			
RA 333	4.0	32.0	General attack all surfaces			
LM-1866	1.1	11.1	Light general attack E/C surface			
446 SS	1.2	18.7	Localized pits E/C surface	0.4	1.4	No signs of attack
Inconel 671	0.4	6.4	Small pit E/C surface, corroded area on back	0.6	1.1	Fine pitting all surfaces
Crutemp 25	2.8	44.3	General attack all surfaces, large pits E/C side			
Haynes 188	0.4	6.6	Fine pitting E/C surface	0.5	6.5	Small E/C area
Co-Cr-W No. 1	0.4	0.9	Fine pits all surfaces, localized E/C pit			

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO COARSE FMC CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43]
(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		-30+50 mesh	100		-30+50 mesh	100
Time, hr			5			5
Volume % H_2S			1.0			none, N_2 atmosphere
Incoloy 800	0.7	6.2	Small E/C area, light general attack on back	0.2	0.7	No signs of attack
	<0.2	55.9	Large E/C area			
Inconel 601	0.9	126.9	Large E/C pit; general attack all surfaces	<0.2	1.1	No signs of attack
	0.4	64.9	Large E/C area			
310 SS	0.4	0.9	No signs of attack	<0.2	0.9	Slight edge attack
	0.4	95.9	Large E/C area			
446 SS	0.3	4.3	Pitting E/C surface	<0.2	0.6	No signs of attack
	<0.2	0.6	No signs of attack			
Inconel 671	0.6	1.6	Pitting all surfaces	0.4	1.4	No signs of attack
	0.5	1.5	Fine pits all surfaces			
Haynes 188	0.3	1.8	Pitting all surfaces	<0.2	0.6	No signs of attack
	0.3	16.3	Small E/C area			
Temperature, °F			1800			1800
Pressure, psi			300			600
Velocity, ft/s		-30+50 mesh	100		-30+50 mesh	100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	0.7	269.2	Sample penetrated	1.4	128.9	Major E/C pit
	1.1	115.1	Major E/C pit with intact scale in it			
Incoloy 800(Al)	0.2	138.7	Coating failed, E/C pit	0.2	0.8	Intact dark scale all surfaces
Inconel 601	0.5	167.5	Large E/C melt area	1.9	231.9	Sample completely penetrated
310 SS	0.2	141.7	Three deep E/C pits	0.6	5.1	Pitting all surfaces
310 SS (Al)	0.5	49.0	Coating pitted, E/C pit	0.5	1.5	Shallow pits all surfaces
RA 333	3.1	224.1	Complete penetration	0.2	0.8	General attack all surfaces
LM-1866	1.1	2.6	Light pitting	0.1	2.6	Light general attack E/C surface
446 SS	0.7	13.7	Edge attack top edge	1.0	3.0	Fine pits all surfaces
Inconel 671	1.0	38.0	Edge attack top edge	0.5	1.0	Fine pits back surface
	0.7	1.2	Fine pits all surfaces			
Crutemp 25	0.7	181.2	Three deep E/C pits	0.5	85.0	Large pit E/C surface
Haynes 188	0.5	69.0	Three shallow E/C melt pits	0.4	19.4	Localized pits E/C surface
Co-Cr-W No. 1	0.3	12.3	Slight E/C pit top edge	0.3	0.8	Light pits all surfaces
Stellite 6B	0.4	3.9	Fine E/C area			
Wiscalloy 30/50W	<0.2	29.0	Edge attack all surfaces and E/C pit			
HK-40	0.6	85.6	Large E/C pit, fine pits E/C surface, spot attack back surface			
Alloy X	<0.2	188.1	Deep E/C pit and edge attack all surfaces			
Sanicro 32X	0.7	153.7	Large E/C area with intact scale			
Multimet N155	1.0	224.0	Very deep E/C pit and fine pits back surface			
Haynes 150	0.7	131.2	Large E/C melt pit and fine pits back surface			
Supertherm T63WC	1.5	53.5	Large E/C area and pits all surfaces			
HL-40	2.2	26.2	Pits all surfaces and E/C area pit			
329 SS	0.8	1.3	Fine pits all surfaces, edge attack back surface			
Temperature, °F			1800			1800
Pressure, psi			1000			1000
Velocity, ft/s		-30+50 mesh	50		-30+50 mesh	100
Time, hr			5			5
Volume % H_2S			1.0			1.0
Incoloy 800	1.0	39.5	Large E/C area	1.0	39.5	General E/C area and pits all surfaces
Inconel 601	0.2	6.7	General attack all surfaces and E/C pit	0.3	16.8	Two melt pits E/C surface
310 SS	0.3	0.8	Fine pits all surfaces	0.3	0.8	Fine pits E/C surface
446 SS	0.1	0.6	Light edge attack	0.3	2.3	Fine pits E/C surface and top edge
Inconel 671	0.7	1.2	General attack back surface	0.7	1.2	No signs of attack
Haynes 188	0.4	1.4	Light attack back surface	0.3	0.8	Fine pits E/C surface

[a] Alloy samples 1 x 1 x 1/4 in were subjected to erosion in coal gasification atmosphere (2 tests were 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] Char from Western Kentucky coal prepared by COED process, either -20+40 mesh (840 to 420 μm) or -30+50 mesh (600 to 300 μm) used in all tests but one. That test was run with fine FMC char, -100+140 mesh (149 to 105 μm). The size erodent used is indicated on each test.

[c] Coal gasification atmosphere input gas (volume %): 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; compositions given for alloys the first time they appear in the 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,j] IN COAL GASIFICATION ATMOSPHERE[d] [11,43]

Alloy/ Composition[e]	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments
Erodent			Dolomite[b]			Dolomite[b]
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			100
Time, hr			50			50
Volume % H_2S			0.1			1.0
Incoloy 800 47Fe-31Ni-21Cr	0.4	0.8	No visible erosion	0.4	0.6	No visible attack
Incoloy 800(Al)[h]	0.7	0.8	Slight pitting	0.3	0.6	Minor tarnishing of erosion side
Inconel 601 16Fe-60Ni-23Cr	0.1	0.3	No visible erosion	0.4	0.5	No visible attack
310 SS 52Fe-20Ni-25Cr	0.2	0.3	No visible erosion	0.3	0.5	No visible attack
310 SS(Al)[h]	0.8	1.2	Slight pitting	0.6	1.0	Discoloration of aluminide coating
RA 333 16Fe-45Ni-26Cr	0.3	0.4	No visible erosion	0.4	0.5	No visible attack
LM-1866 Fe-18Cr-5Al	--	0.1	No visible erosion	0.2	0.7	Significant edge corrosion
446 SS 75Fe-24Cr	0.2	0.4	No visible erosion	0.3	0.6	No visible attack
Inconel 671 48Ni-50Cr	0.6	0.8	No visible erosion	0.5	0.8	Slight pitting on erosion surface
Crutemp 25 47FE-25Ni-25Cr	--	0.3	No visible erosion	0.4	0.6	Pitting on erosion surface
Haynes 188 Co-23Ni-22Cr	0.3	0.4	No visible erosion	0.3	0.6	No visible attack
Erodent			Alumina[c]			Alumina[c]
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			50			100
Time, hr			50			50
Volume % H_2S			1.0			0.5
Incoloy 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
Incoloy 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
Inconel 601	0.2	0.7	Back surface pitting attack	0.2	7.7	General attack E/C surface
310 SS	0.5	2.5	E/C surface many small pits	0.2	20.2	General attack E/C surface
310 SS(Al)	0.3	1.3	Slight discoloration only	0.5	1.5	Intact dark scale E/C and back surface
RA 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
LM-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,j] IN COAL GASIFICATION ATMOSPHERE[d][11,43]
(Table Continued)

Alloy/ Composition[e]	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments
Erodent			Alumina[c]			Alumina[c]
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[c]			Alumina[j]
Temperature, °F			1800			1800
Pressure, psi			atmospheric			300
Velocity, ft/s			200			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	24.1	84.1	Very extensive E/C, some corrosion	2.6	115.6	Large E/C pit, intact scale all surfaces
Incoloy 800(Al)	4.1	49.6	Extensive E/C, coating penetrated locally	0.7	96.2	Large E/C pit, coating penetrated
Inconel 601	12.2	77.2	Very extensive E/C, some corrosion	0.2	49.2	E/C pit & general attack all surfaces
310 SS	10.0	57.0	Extensive E/C, some corrosion	0.7	110.7	Large E/C pit, light attack all surfaces
310 SS(Al)	3.6	43.6	Extensive E/C, coating penetrated locally	0.3	63.3	Large E/C pit
RA 333	16.7	60.2	Extensive E/C, some corrosion	0.7	112.7	Large E/C pit, intact scale all surfaces
LM-1866	3.8	12.3	Significant E/C	<0.2	6.5	Shallow E/C pit
446 SS	7.4	33.4	Extensive E/C, some corrosion	1.6	21.1	Shallow E/C pit
Inconel 671	3.0	24.0	Significant E/C	1.1	9.6	Shallow E/C pit and edge attack
Crutemp 25	21.4	141.4	Very extensive E/C, some corrosion	1.1	101.1	Large E/C pit and general attack
Haynes 188	14.5	82.5	Very extensive E/C, some corrosion	0.4	18.4	Shallow E/C pit and back general attack
Co-Cr-W No. 1				0.4	25.9	Shallow E/C pit and edge attack

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY DOLOMITE[b] AND ALUMINA[c,j] IN COAL GASIFICATION ATMOSPHERE[d][11,43]
(Table Continued)

Alloy/ Composition[e]	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments	Average[f] Corrosion mils	Maximum[g] Erosion/ Corrosion mils	Comments
Erodent			Alumina[j]			Alumina[j]
Temperature, °F			1800			1800
Pressure, psi			600			1000
Velocity, ft/s			100			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	0.9	58.9		0.4	89.4	Large E/C pit with intact scale
Incoloy 800(Al)	<0.2	1.0		0.4	124.4	Large E/C pit coating penetrated with intact scale in bottom of pit
Inconel 601	1.1	190.8		0.4	148.4	Large E/C pit with scale still attached
310 SS	0.9	67.6		0.5	94.5	Large E/C pit
310 SS (Al)	<0.2	2.6		0.3	95.8	Large E/C pit coating penetrated
RA 333	0.5	122.8		0.7	164.7	Large E/C pit with intact scale
LM-1866	1.1	10.3		<0.2	41.1	Large E/C pit
446 SS	1.7	9.7		0.6	57.6	Large E/C pit
Inconel 671	1.0	6.5		1.1	33.6	Large shallow E/C pit
Crutemp 25	0.8	85.3		0.7	98.2	Large E/C pit
Haynes 188	1.2	34.2		1.7	44.7	Large E/C area with intact scale over all of pit
Co-Cr-W No. 1	0.4	25.6		0.5	40.5	Large shallow E/C pit

[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.

[j]Coarse alumina, -30 + 50 mesh.

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COARSE HUSKY CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43]

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			1650			1650
Pressure, psi			atmospheric			1000
Velocity, ft/s			100			100
Time, hr			100			50
Volume % H_2S			1.0			1.0
Incoloy 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
Incoloy 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
Inconel 601 16Fe-60Ni-23Cr	0.4	2.4	Few pits all surfaces	0.1	137.6	Large erosion pit
310 SS 52Fe-20Ni-25Cr	0.2	1.8	Slight E/C area and pits on back surface	0.9	2.4	Small erosion area
310 SS (Al)[h]	0.1	1.1	Sample discoloration	0.3	1.5	General corrosion over all surfaces
RA 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
LM-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
446 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 surfac
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 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 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][11,43]

(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 edges
310 SS	0.3	0.7	Some pitting on erosion side	0.3	0.5	Faint outline visible of impingement area
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 surface
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
Haynes 188	0.5	0.7	Edge corrosion on both sides	0.4	0.6	Corrosion visible on lower edge of sample
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 surface 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 corrosion
310 SS (Al)	1.1	4.0	Extensive loss of coating on erosion side	2.1	3.1	Some blackening and roughening of coating
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; corrosion 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 surfaces
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][11,43]

(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
Inconel 671	0.5	1.0	Pitting attack on erosion side	0.6 0.8	1.2 1.3	Edge corrosion on reverse surface 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				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
Temperature, °F			1500			
Pressure, psi			1000			
Velocity, ft/s			100			
Time, hr			50			
Volume % H_2S			1.0			
Incoloy 800	0.4	0.9	No signs of attack			
Incoloy 800(Al)	0.2	1.7	Dark intact surface scale			
Inconel 601	0.1	4.6	Pitting E/C surface			
310 SS	0.5	1.0	No signs of attack			
310 SS (Al)	0.3	1.3	Dark intact surface scale			
RA 333	0.4	2.4	Extensive pitting E/C surface			
LM-1866	0.2	1.2	Dark scale E/C surface only			
446 SS	0.4	0.9	No signs of attack			
Inconel 671	0.4	0.9	No signs of attack			
Crutemp 25	0.5	1.0	No signs of attack			
Haynes 188	0.3	0.8	Dark scale E/C surface, edge attack back surface			
Co-Cr-W No. 1	0.2	0.8	No signs of attack			

[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. Last test at 1500 °F used mesh -30 +50.

[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 tnickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in uneroded area.

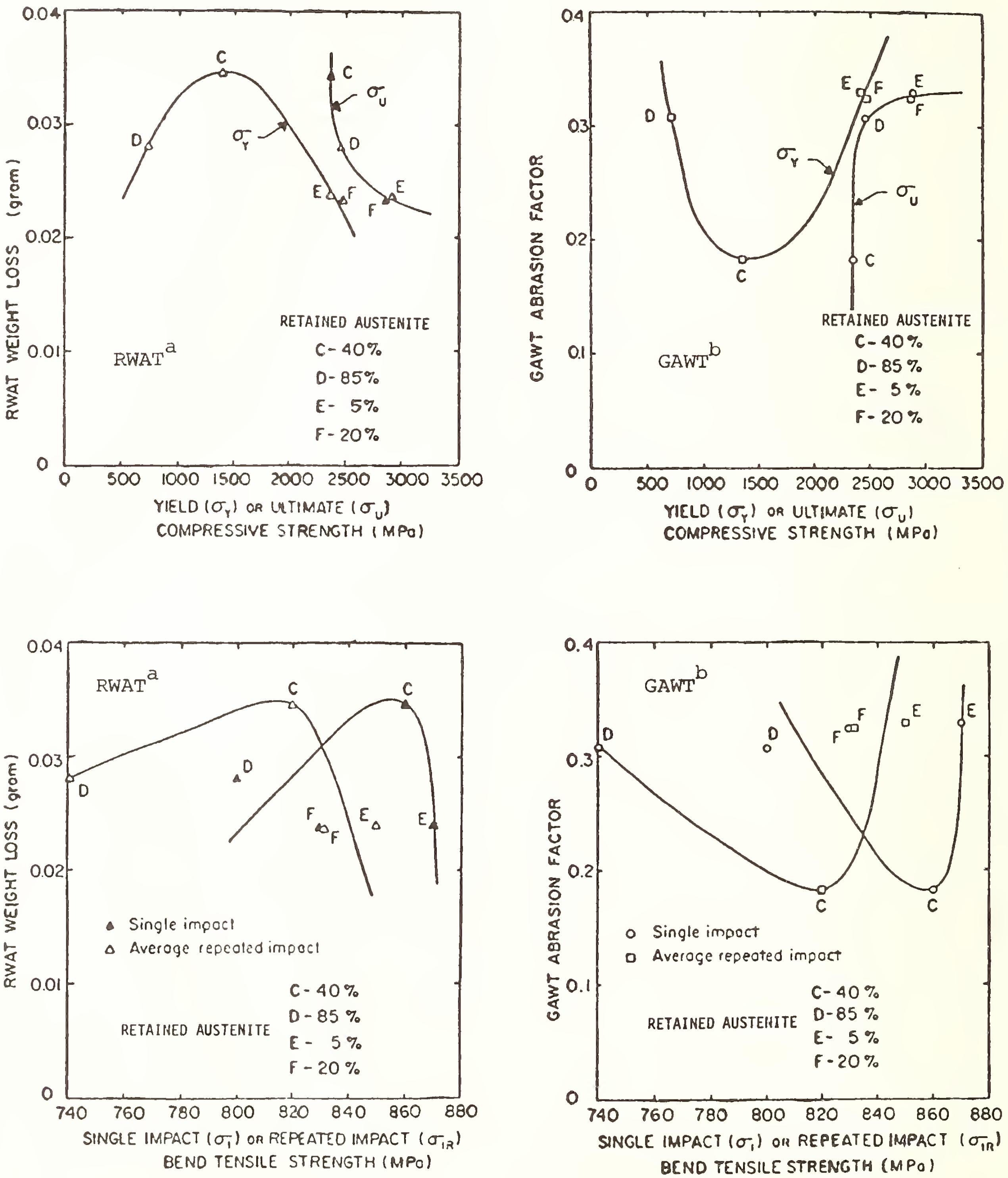
[e]Maximum effect on the one side of the sample exposed to both erosion and corrosion; calculated from thickness measurements (by micrometer) of samples before exposure and after exposure and cleaning; measurements after exposure made in eroded area and pits.

[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]



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(Data Continued)

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 (corresponds to VASCO MA steel)	Austenitized at 1000 °C for 1 hour, oil quenched	as quenched	0.437
		200	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[e]
		400	0.570[e]
		450	-
		500	0.540[e]
		550	0.514
		600	0.453
		650	0.495[e]
Experimental Cr-Si-Mo Steels			
0.3 C, 2.0 Cr, 1.5 Si, 0.3 Mo, balance Fe (corresponds to a commercial ESCO steel)	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

(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, continued			
		300	0.61
		400	0.64
		500	0.68
Same as preceding alloy	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
Same as preceding alloy	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
Same as preceding alloy	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 (Al and Si added to commercial aircraft quality 4340 in induction furnace under argon)	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[f]
	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

(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]
-Modified Ultra-High Strength Steel, continued-			
	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, as received			
AISI 1020 (standard for wear factors)			1.0
01			0.589
AISI 4340			0.620
300M			0.575
Commercial Steel with additional heat treatment-			
0.4 C, 5 Cr, 1.3 Mo, 0.5 V, 1 Si, balance Fe (H-11, hot work tool steel)	Normal heat treatment (1 hour/inch thickness at 815 °C, 15 min/inch thickness at 1010 °C, air-cooled) followed by triple tempering with liquid N_2 refrigeration before each temper	200	0.57
		300	0.59
		400	0.60
		500	0.56
		550	0.53
		600	0.63[e]
		650	0.71[e]

[a]Determined in a pin-on-disc apparatus, see B.2.1.40 for description.

[b]Prepared as 11.3 kg ingots in an induction furnace under argon atmosphere from 99.9% pure raw 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 treatment. Sample pins (1/4 inch diameter) were machined from the specimen blanks.

[c]Tempered for 1 hour, unless otherwise indicated, followed by a water quench.

[d]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.

[e]Value estimated from reported graphical results.

[f]Value conflicts with graphical results indicating a value ∿0.53.

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY SPENT CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c][11,43]

Alloy[d]	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Comments	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Comments
Temperature, °F			1650			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			100
Time, hr			100			100
Volume % H_2S			1.0			1.0
Incoloy 800	0.1	0.6	Very light discoloration	0.7	6.7	Edge attack all surfaces
	<0.2	1.1	Fine pits back and side surfaces	0.4	13.9	Edge and pitting attack all surfaces
Incoloy 800 (Al)[h]	0.2	2.2	Coating loss in E/C[g] area	0.8	2.3	Dark scale intact all surfaces
Inconel 601	0.2	0.7	No sign of attack	0.4	0.9	Light general attack E/C[g] surface
310 SS	0.4	1.4	Small area of dark scale E/C surface	1.0	1.5	Light pitting E/C surface
310 SS (Al)[h]	0.6	1.6	Slight coating loss E/C surface	0.8	2.3	Localized adherent scale all surfaces
RA 333	0.2	1.2	Area of limited attack E/C surface	0.2	0.8	Light edge attack back surface
LM-1866	0.2	0.3	No sign of attack	0.5	2.5	Localized E/C area
446 SS	0.2	1.2	Small area of dark scale E/C surface	0.9	2.4	Light pitting attack all surfaces
Inconel 671	0.1	1.1	No sign of attack	0.8	1.3	Edge attack back surface
	0.7	1.7	Melt attack back surface	1.2	1.7	No sign of attack
Crutemp 25	0.2	1.2	Small area of dark scale E/C surface	0.1	2.1	Light pitting E/C surface
Haynes 188	0.2	0.3	No sign of attack	0.4	1.4	Light pitting E/C surface
Co-Cr-W No. 1	0.2	0.8	Small area of dark scale E/C surface	0.3	0.8	Limited attack
Stellite 6B	0.3	0.8	Pits on side surfaces	0.4	0.9	No sign of attack
Wiscalloy 30/50W	13.6	13.6	Major metal loss back surface	0.6	25.6	General attack all surfaces
HK-40	0.6	7.6	General attack all surfaces	0.6	13.6	Big pits all surfaces
Alloy X	2.4	14.4	Major attack all surfaces	<0.2	26.0	Edge attack E/C side and bad general attack back surface
Sanicro 32X	0.2	0.7	Pits back and side surfaces	<0.2	34.9	Major deep pits all surfaces
Multimet N155	0.4	0.9	Pitting attack back surface	0.3	0.8	Pits all surfaces
Haynes 150	0.2	0.7	No sign of attack	<0.2	0.5	Shallow E/C area
Supertherm T63WC	0.2	0.7	Edge attack all edges	0.2	11.2	Bad edge and general attack all surfaces
HL-40	0.2	0.7	Pits back and side surfaces	<0.2	0.5	No sign of attack
329 SS	0.3	0.8	No sign of attack	0.8	1.8	Dark intact scale E/C surface
Temperature, °F			1650			1800
Pressure, psi			1000			1000
Velocity, ft/s			100			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	2.5	26.8		0.4	35.9	Large E/C area
Incoloy 800 (Al)	0.2	1.0		0.2	0.8	Dark intact scale all surfaces
Inconel 601	1.6	38.8		0.4	85.4	Large E/C area
310 SS	1.4	3.8		0.2	1.7	Fine pits all surfaces
310 SS (Al)	0.4	0.8		0.4	1.4	Dark intact scale all surfaces
RA 333	3.8	48.2		0.4	20.4	Pitting all surfaces
LM-1866	0.2	1.7		0.2	1.2	Edge attack back side
446 SS	0.6	2.2		0.8	3.8	Edge attack all surfaces
Inconel 671	0.8	12.5		0.7	3.2	Dark scale E/C surface, edge pitting E/C surface
Crutemp 25	0.8	2.9		0.3	0.8	Fine pits all surfaces
Haynes 188	5.6	44.7		0.4	37.4	
Co-Cr-W No. 1	<0.2	1.0		0.2	0.2	Discoloration E/C surface

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY SPENT CHAR[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43]
(Table Continued)

Alloy[d]	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Comments	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Comments
Temperature, °F			1800			1800
Pressure, psi			300			600
Velocity, ft/s			100			100
Time, hr			50			50
Volume % H_2S			1.0			1.0
Incoloy 800	0.6	42.6	Large E/C area	0.6	24.6	Large E/C area with intact scale
Incoloy 800 (Al)	0.2	1.2	Dark intact scale E/C surface	0.4	1.4	Dark intact scale all surfaces
Inconel 601	0.8	38.8	Large E/C area	0.5	4.5	Surface attacked outside of erosion stream
310 SS	0.4	31.4	Large E/C area	0.7	48.2	Large E/C area
310 SS (Al)	<0.2	0.3	Dark intact scale all surfaces	0.3	1.3	Dark intact scale all surfaces
RA 333	0.4	4.4	Small E/C area	0.5	8.5	Surface attacked outside of erosion stream
LM-1866	<0.2	<0.2	No sign of attack	<0.2	0.5	Small pit E/C surface
446 SS	0.7	4.2	Few pits all surfaces	0.7	1.2	Light pitting all surfaces
Inconel 671	0.9	1.4	Dark scale all surfaces	0.6	1.1	Light pits E/C surface
Crutemp 25	0.2	53.2	Large E/C area	0.6	34.1	Large E/C surface with intact scale
Haynes 188	0.5	2.5	Fine pits E/C surface	0.4	1.4	Fine pits E/C surface
Co-Cr-W No. 1	0.3	3.3	Dark scale E/C surface	<0.2	5.4	Small E/C area
Temperature, °F			1800			1800
Pressure, psi			atmospheric			atmospheric
Velocity, ft/s			100			100
Time, hr			100			100
Volume % H_2S			0.1			0.5
Incoloy 800	0.2	0.7		0.5	10.4	
Incoloy 800 (Al)	<0.2	2.6		<0.2	3.7	
Inconel 601	0.2	1.7		<0.2	1.4	
310 SS	0.5	1.0		<0.2	1.3	
310 SS (Al)	<0.2	2.0		<0.2	3.5	
RA 333	0.2	0.7		0.4	1.4	
LM-1866	0.4	1.4		<0.2	2.4	
446 SS	0.9	1.9		0.9	1.7	
Inconel 671	0.6	1.6		0.4	1.3	
Crutemp 25	0.4	1.4		0.3	1.4	
Haynes 188	0.5	1.0		0.4	0.7	
Co-Cr-W No. 1	<0.2	0.6		<0.2	0.3	

[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; some materials were included in more than one test.

[b] Spent char is Montana Rosebud coal which has been through the BI-GAS gasifier; particle size -30+50 mesh (600 to 300 μm).

[c] Coal gasification atmosphere input gas (volume %): 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] Approximate values for major constituents only (weight %): Incoloy 800, 47Fe-31Ni-21Cr; Inconel 601, 16Fe-60Ni-23Cr; 310 SS, 52Fe-20Ni-25Cr; RA 333, 16Fe-45Ni-26Cr; LM-1866, Fe-18Cr-5Al; 446 SS, 75Fe-24Cr; Inconel 671, 48Ni-50Cr; Crutemp 25, 47Fe-25Ni-25Cr; Haynes 188, Co-23Ni-22Cr; Co-Cr-W No. 1, Co-30Cr-12W; Stellite 6B, 57Co-28Cr-3Ni; Wiscalloy 30/50W, Fe-49Ni-28Cr; HK-40, Fe-20Ni-28Cr; Alloy X, 20Fe-45Ni-22Cr-9Mo; Sanicro 32X, Fe-32Ni-22Cr; Multimet N155, 29Fe-20Ni-21Cr-20Co; Haynes 150, Co-18Fe-28Cr; Supertherm T63WC, Fe-36Ni-28Cr-15Co-5W; HL-40, 47Fe-19Ni-31Cr; 329 SS, Fe-4Ni-27Cr. Where no number precedes an element, e.g., Fe, that element constitutes the balance of the alloy.

[e] 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.

[f] 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.

[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 COKE[b] IN COAL GASIFICATION ATMOSPHERE[c][11,43]

Alloy[d]	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils
Temperature, °F	900		900		1200		1200			
Pressure, psi	atmospheric		250		atmospheric		250			
Velocity, ft/s	50[g]		50		50		50			
Time, hr	200		100		200		100			
Incoloy 800	<0.2	0.3	<0.2	4.2	0.2	0.7	0.3	1.2		
	0.2	0.3	0.5	4.6	0.3	0.8	0.3	1.0		
310 SS	<0.2	0.2	0.2	3.7	0.1	0.6	0.6	2.3		
	0.2	0.3	<0.2	3.4	0.4	1.6	0.7	1.6		
446 SS	<0.2	0.2	0.5	4.1	0.6	2.0	0.7	2.6		
	0.2	0.2	0.2	2.8	0.5	1.5	0.3	1.3		
Stellite 6B	<0.2	0.2	0.3	1.7	0.2	0.6	0.6	1.1		
	0.2	0.3	0.3	1.5	0.2	0.3	0.3	0.9		
Temperature, °F	1500		1500		1500		1500		1500	
Pressure, psi	atmospheric		atmospheric		250		500		1000	
Velocity, ft/s	50		50		50		50		50	
Time, hr	100		200		100		100		100	
Incoloy 800	<0.2	0.4	0.3	10.4	0.3	1.8	0.7	1.2	1.9	12.9
	<0.2	1.5	0.5	33.8	0.3	0.9	0.5	1.0	1.6	12.5
			0.3	0.7	0.6	0.9	0.8	1.3		
310 SS	<0.2	0.2	0.3	0.8	0.6	1.0	0.3	1.2	2.4	48.0
	<0.2	0.5	0.4	0.8	0.4	0.9	0.6	1.6	0.9	62.3
			0.3	0.9	0.6	1.0	0.4	0.9		
446 SS	<0.2	0.3	0.2	0.7	0.4	0.9	0.6	1.6	0.9	4.9
	<0.2	0.7	0.4	0.8	0.3	0.8	0.8	1.3	0.6	12.6
			0.4	0.9	0.4	0.8	0.6	1.6		
Stellite 6B	<0.2	<0.2	0.3	0.8	0.3	0.6	0.5	1.1	0.2	1.2
	<0.2	<0.2	0.6	1.1	0.4	0.5	0.5	1.0	<0.2	1.0
			0.7	1.2	0.3	0.8	0.6	1.7		
Temperature, °F	1800		1800		1800		1800			
Pressure, psi	250		750		1000		1000			
Velocity, ft/s	50		50		50		100			
Time, hr	100		100		100		50			
Incoloy 800	0.7	1.8	0.2	1.3	0.4	0.4	0.2	98.5		
	0.5	1.2	<0.2	0.8	<0.2	0.2				
Incoloy 800(Al)[h]							0.7	5.2		
Inconel 601							0.3	212.3		
310 SS	1.2	5.0	<0.2	0.7	0.2	0.2	0.2	72.8		
	1.2	3.7	<0.2	0.6	<0.2	0.2				
310 SS (Al)[h]							0.3	3.1		
RA 333							0.9	86.4		
LM-1866							<0.2	0.9		
446 SS	0.8	3.6	0.6	1.3	0.6	0.6	0.6	10.8		
	1.3	2.4	0.7	1.1	0.7	0.7				
Inconel 671							<0.2	1.2		
Crutemp 25							0.2	64.0		
Haynes 188							<0.2	23.7		
Co-Cr-W No. 1							<0.2	1.1		
Stellite 6B	0.2	0.8	<0.2	0.8	<0.2	0.2				
	0.3	0.7	<0.2	0.6	<0.2	0.4				
Temperature, °F	1800		1800		1800					
Pressure, psi	atmospheric		atmospheric		atmospheric					
Velocity, ft/s	25		25		25					
Time, hr	50[i]		100[i]		200[i]					
Incoloy 800	0.2	0.4	0.6	1.7	0.9	1.3				
Incoloy 800 (Al)	0.5	0.8	1.0	1.3	1.3	1.7				
Inconel 601	0.1	0.4	0.7	1.2	1.0	2.0				
310 SS	0.3	0.5	0.8	2.0	1.2	2.0				
310 SS (Al)	0.6	1.0	1.0	1.5	1.0	1.5				
RA 333	0.5	0.5	0.4	2.1	1.1	2.1				
LM-1866	0.2	0.5	0.7	1.0	1.1	3.3				
446 SS	0.5	0.5	1.0	1.7	1.4	2.2				

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COKE[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43], Continued

Alloy[d]	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils
Inconel 671	0.8	0.8	1.0	1.5	1.2	1.5				
Crutemp 25	0.4	0.4	0.7	1.8	1.1	1.6				
Haynes 188	0.4	0.4	0.6	2.8	0.8	2.9				
Co-Cr-W No. 1	0.2	0.5	0.3	0.5	0.5	0.7				
Temperature, °F	-1800-		-1800-		-1800-					
Pressure, psi	atmospheric		atmospheric		atmospheric					
Velocity, ft/s	50		50		50					
Time, hr	50[i]		100[i]		200[i]					
Incoloy 800	1.0	14.1	1.2 <0.2 <0.2	17.4 0.3 0.2	1.0	83.4				
Incoloy 800 (Al)	0.7	2.4	0.8	4.5	0.4	29.4				
Inconel 601	0.7	8.7	1.6	18.8	0	24.5				
310 SS	0.7	7.7	1.0 0.3 0.3	8.5 0.2 0.3	1.5	66.5				
310 SS (Al)	0.6	1.7	0.9	2.9	0.9	29.9				
RA 333	0.7	18.6	1.0	20.7	10.1	89.1				
LM-1866	0.9	1.7	1.7	4.7	2.6	27.1				
446 SS	1.3	8.4	1.5 0.3 0.3	9.6 0.4 0.6	3.7	29.7				
Inconel 671	0.9	1.6	1.0	1.8	3.9	63.9				
Crutemp 25	0.8	7.8	1.1	9.5	0.4	65.4				
Haynes 188	0.7	4.9	1.0	5.0	0.7	16.7				
Co-Cr-W No. 1	0.4	0.7	0.5	1.1	0.8	13.8				
Stellite 6B			0.3 0.4	0.3 0.4						
Temperature, °F	-1800-		-1800-		-1800-		-1800-		-1800-	
Pressure, psi	atmospheric		atmospheric		atmospheric		atmospheric		atmospheric	
Velocity, ft/s	100		100		100		150		150	
Time, hr	50[i]		100[i]		200[i]		40[i]		100[i]	
Incoloy 800	0.4	5.1	0.6 0.5	3.6 46.7	2.5	89.4	0.1	49.1	0.7	54.1
Incoloy 800 (Al)	0.3	0.9	<0.2 <0.2	1.4 0.8	0.7	2.5	0.6	2.6	0.8	10.8
Inconel 601	0.9	5.7	0.7 <0.2	4.2 0.4	2.0	24.2	<0.2	18.2	0.3	32.3
310 SS	0.5	5.6	0.6 <0.2	5.6 0.3	3.4	89.6	0.3	17.5	1.0	21.3
310 SS (Al)	0.7	1.2	0.2 <0.2	1.7 1.4	1.5	2.0	<0.2	1.0	1.0	3.0
RA 333	0.4	1.9	0.8 0.5	2.8 12.0	1.7	16.1	<0.2	42.6	<0.2	41.0
LM-1866	0.3	5.7	0.6 <0.2	8.1 4.8	4.5	5.6	<0.2	13.8	2.0	12.1
446 SS	0.7	5.5	1.7 1.6	8.7 3.2	8.6	25.4	0.3	14.7	1.4	17.4
Inconel 671	0.6	3.7	0.6 0.4	1.1 1.0	6.7	19.3	0.4	0.9	0.9	1.9
Crutemp 25	5.5	8.9	1.3 5.2	7.8 55.6	2.2	126.8	<0.2	15.0	0.7	15.8
Haynes 188	0.5	5.8	0.4 <0.2	0.9 0.7	0.7	4.3	<0.2	1.3	0.2	11.2
Co-Cr-W No. 1	<0.2	1.3	0.3 <0.2	1.8 0.3	<0.2	0.3	0.4	2.4	0.4	2.4

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COKE[b] IN COAL GASIFICATION ATMOSPHERE[c] [11,43], Continued

Alloy[d]	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils	Average[e] Corrosion mils	Maximum[f] Erosion/ Corrosion mils
Temperature, °F	1800		1800		1800			
Pressure, psi	500		500		500			
Velocity, ft/s	25		25		25			
Time, hr	50[i]		100[i]		200[i]			
Incoloy 800	0.7	1.4	1.2	1.8	5.5	11.8		
Incoloy 800 (Al)	1.4	2.4	2.1	4.1	1.6	2.2		
Inconel 601	0.6	1.2	0.9	1.1	1.4	10.7		
310 SS	0.6	1.9	0.9	1.1	1.4	8.0		
310 SS (Al)	1.0	3.6	2.1	2.5	2.8	3.4		
RA 333	0.2	1.2	0.9	2.0	3.6	18.0		
LM-1866	0.3	1.1	1.0	2.4	0.5	3.5		
446 SS	0.3	0.7	1.2	4.3	3.3	11.2		
Inconel 671	0.9	1.3	1.2	1.4	1.6	1.9		
Crutemp 25	0.5	1.8	1.0	2.5	1.6	10.0		
Haynes 188	0.5	1.2	0.5	1.4	0.6	2.0		
Co-Cr-W No. 1	0.4	0.5	0.4	0.7	0.4	0.9		
Temperature, °F	1800		1800		1800			
Pressure, psi	500		500		500			
Velocity, ft/s	50		50		50			
Time, hr	50[i]		100[i]		200[i]			
Incoloy 800	2.0	10.0	3.2 0.2 <0.2	17.4 0.5 0.3	6.0	43.5		
Incoloy 800 (Al)	0.4	1.0	<0.2	2.6	1.1	2.8		
Inconel 601	0.2	6.7	0.9	10.4	0.6	12.0		
310 SS	1.2	4.1	2.1 <0.2 0.3	20.6 0.2 0.4	1.9	28.0		
310 SS (Al)	0.2	3.8	1.9	3.9	2.0	4.4		
RA 333	2.7	18.1	4.5	21.0	2.6	22.7		
LM-1866	<0.2	1.5	1.1	7.6	1.8	7.2		
446 SS	0.6	1.1	6.3 0.3 0.6	8.3 0.5 0.7	6.5	8.9		
Inconel 671	<0.2	1.8	1.3	3.5	1.2	2.7		
Crutemp 25	1.5	10.6	2.0	12.5	4.9	25.1		
Haynes 188	0.5	1.0	1.3	1.6	1.0	2.5		
Co-Cr-W No. 1	<0.2	1.7	0.4	1.9	0.5	1.6		
Stellite 6B			<0.2 <0.2	<0.2 <0.2				
Temperature, °F	1800		1800		1800		1800	
Pressure, psi	500		500		500		500	
Velocity, ft/s	100		100		100		100	
Time, hr	50[i]		100[i]		150[i]		200[i]	
Incoloy 800	2.7	74.2						
Incoloy 800 (Al)	1.2	2.5	0.6	9.6	1.2	11.1	0.7	91.1
Inconel 601	0.2	80.2						
310 SS	0.4	28.3	1.5	102.9	1.7	105.9	0.7	133.7
310 SS (Al)	0.5	1.0	0.7	6.9	1.5	8.5	1.2	4.6
RA 333	0.6	8.7	0.7	15.6	2.2	15.3	1.5	96.9
LM-1866	0.2	1.4	0.9	78.0	1.9	79.9	3.3	124.6
446 SS	0.9	4.0	1.9	88.4	9.2	88.2	9.7	97.1
Inconel 671	1.0	2.2	1.6	11.0	1.8	13.3	4.6	16.5
Crutemp 25	1.1	30.8	1.8	95.0				
Haynes 188	0.5	15.3	1.0	27.6	3.7	26.7	4.2	30.6
Co-Cr-W No. 1	<0.2	0.4	<0.2	9.8	0.6	10.3	0.7	13.7

(Table Continued)

EROSION/CORROSION METAL LOSS[a] OF ALLOYS SUBJECTED TO EROSION BY COKE[b] IN COAL GASIFICATION ATMOSPHERE[c][11,43], Continued

Footnotes

[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; some materials were included in more than one test.

[b]Metallurgical coke, particle size -30+50 mesh (600 to 300 μm).

[c]Coal gasification atmosphere input gas (volume %): 12 CO_2, 18 CO, 24 H_2, 5 CH_4, 1 NH_3, 1.0 H_2S, balance H_2O.

[d]Approximate values for major constituents only (weight %): Incoloy 800, 47Fe-31Ni-21Cr; Inconel 601, 16Fe-60Ni-23Cr; 310 SS, 52Fe-20Ni-25Cr; RA 333, 16Fe-45Ni-26Cr; LM-1866, Fe-18Cr-5Al; 446 SS, 75Fe-24Cr; Inconel 671, 48Ni-50Cr; Crutemp 25, 47Fe-25Ni-25Cr; Haynes 188, Co-23Ni-22Cr; Co-Cr-W No. 1, Co-30Cr-12W; Stellite 6B, 57Co-28Cr-3Ni. Where no number precedes an element, e.g., Fe, that element constitutes the balance of the alloy.

[e]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.

[f]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.

[g]In table on page D-19 of the annual report for 1982 (see reference [11]), the velocity is misprinted as 500 ft/s.

[h]Aluminum coating applied to specimens by pack diffusion process by Alon Processing Inc. (Alonized).

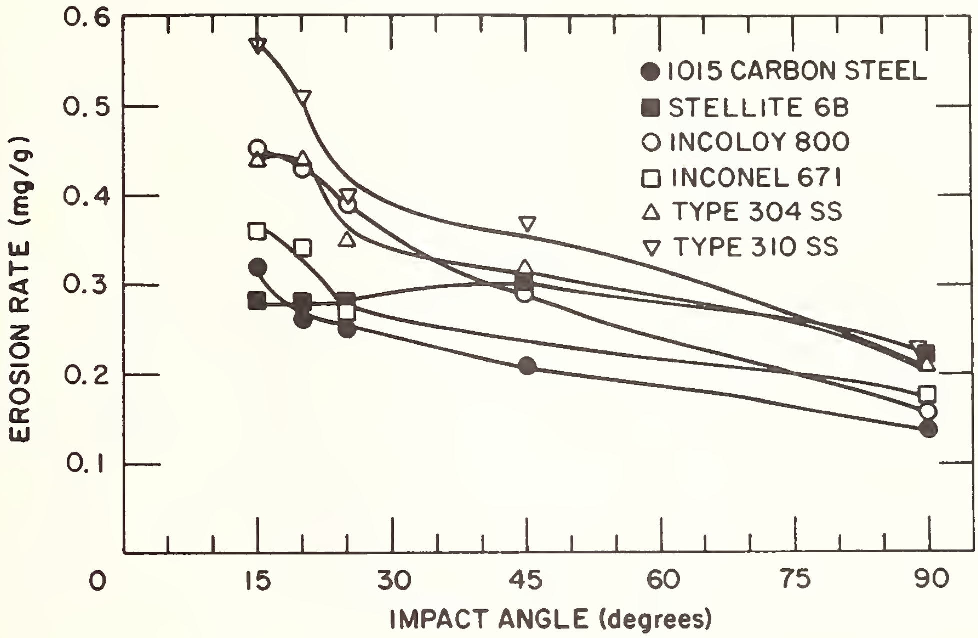
[i]Where test conditions are identical but the times differ and increase indicate tests which were interrupted to examine the degree of erosion/corrosion at the stated times. Specimens were reinserted to continue the tests.

RELATIVE EROSION RESISTANCE[a] OF SOME ALLOYS[48]

	Low Impact Angle (15°)	High Impact Angle (90°)
Most Resistant	Stellite 6B	1015 Carbon Steel
	1015 Carbon Steel	Incoloy 800
	Inconel 671	Inconel 671
	304 SS	304 SS
	Incoloy 800	Stellite 6B
Least Resistant	310 SS	310 SS

[a]Erosion tests were performed at ambient temperature in air using 60 μm Al_2O_3 with an impact velocity of 70 m/s at impact angles of 15°, 20°, 25°, 45°, and 90°. [Test time was not given.]

EROSIVE WEAR[a] OF SEVERAL ALLOYS AS A FUNCTION OF IMPACT ANGLE[48]



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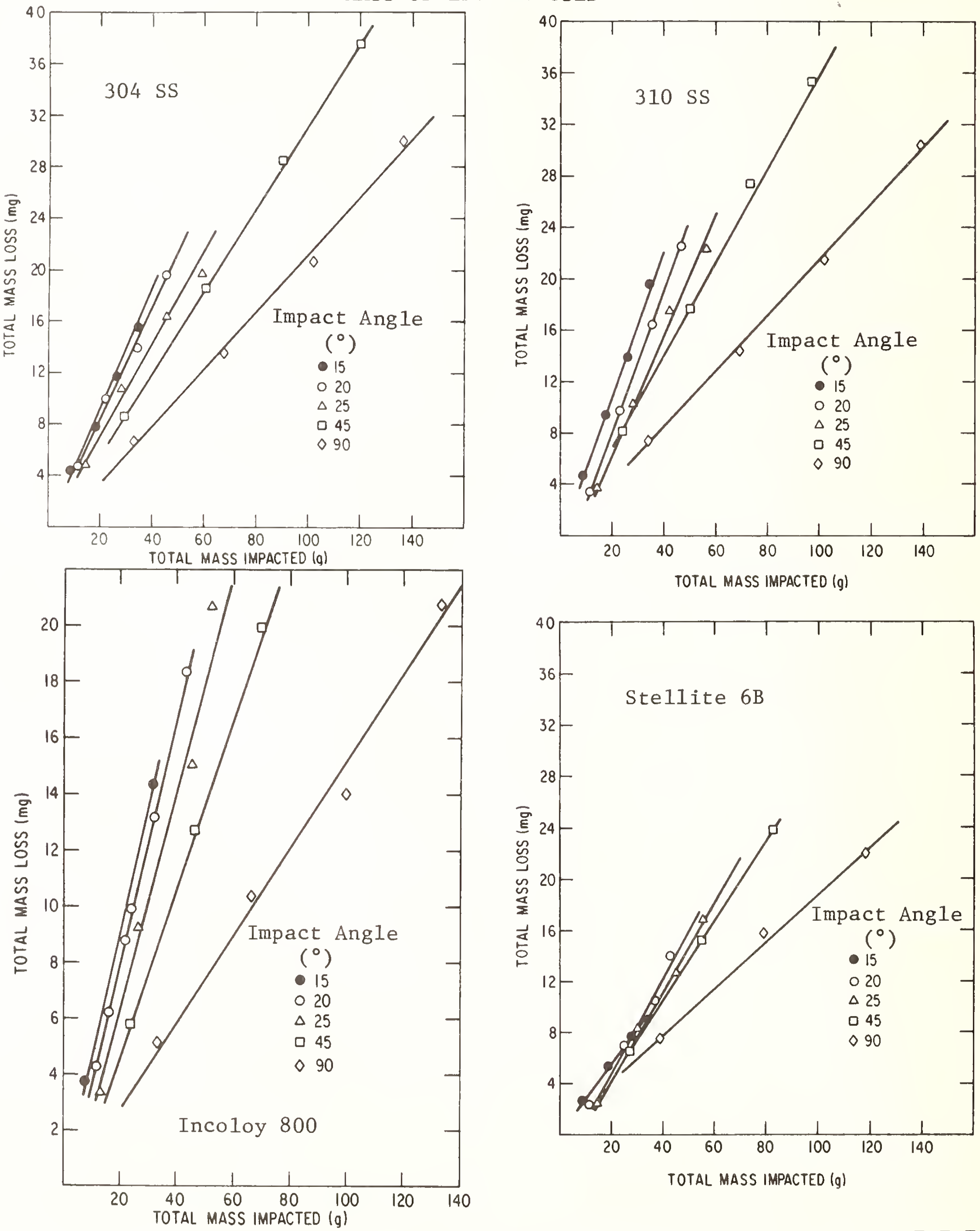
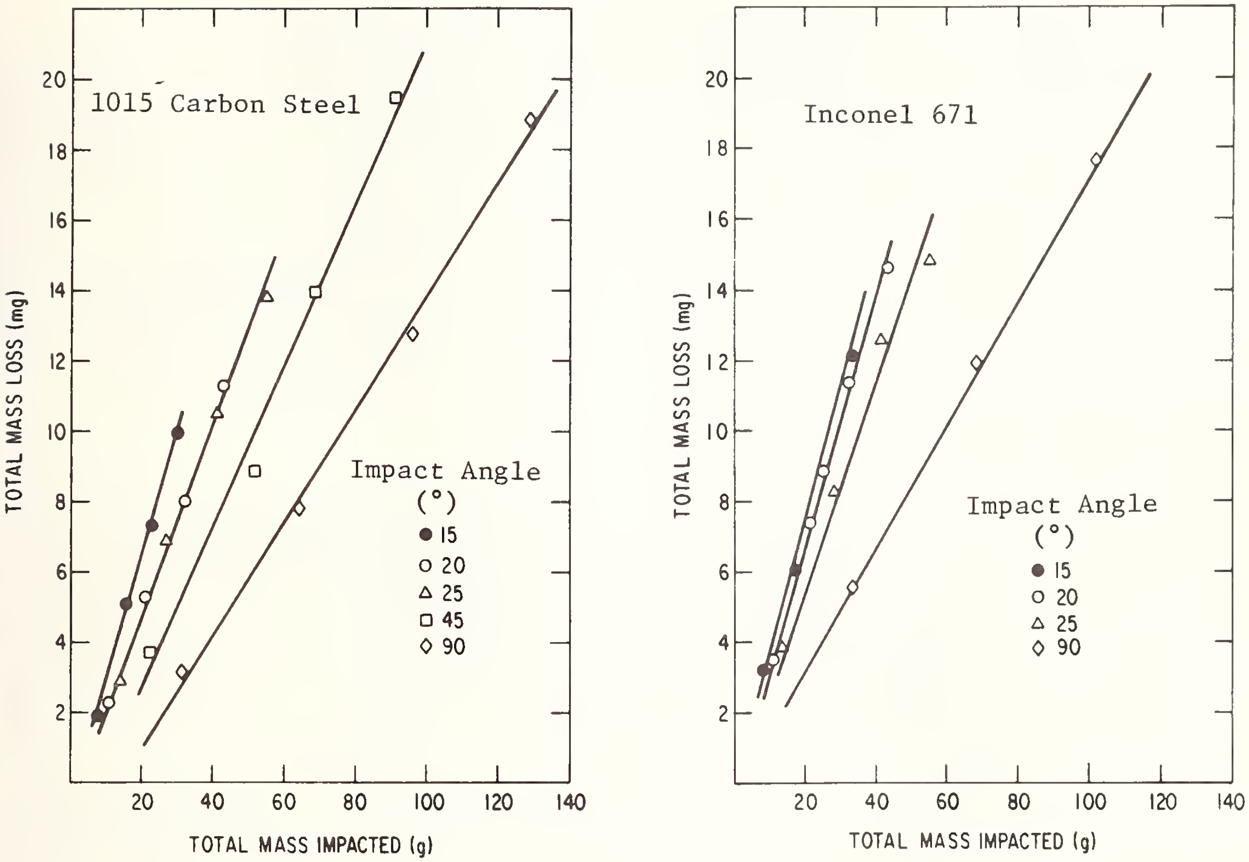
[a]Erosion tests were performed at ambient temperatures in air using 60 µm Al_2O_3 with an impact velocity of 70 m/s at impact angles of 15°, 20°, 25°, 45°, and 90°. [Test time was not given.]

MASS LOSS OF SEVERAL ALLOYS AT VARIOUS IMPACT ANGLES AS A FUNCTION OF MASS OF ERODENT USED[a][48]



(Data Continued)

MASS LOSS OF SEVERAL ALLOYS AT VARIOUS IMPACT ANGLES AS A FUNCTION OF MASS OF ERODENT USED[a][48], Continued



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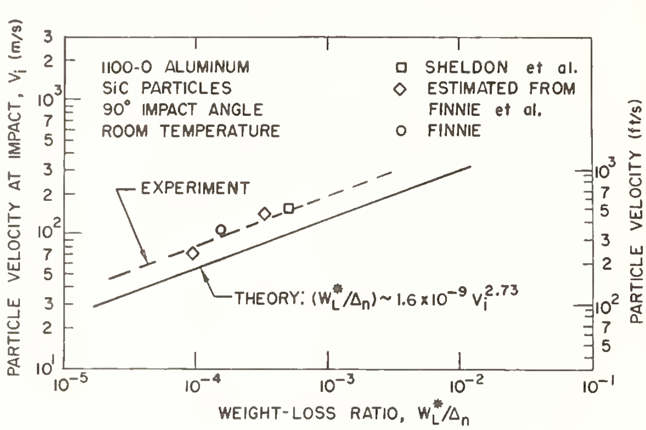
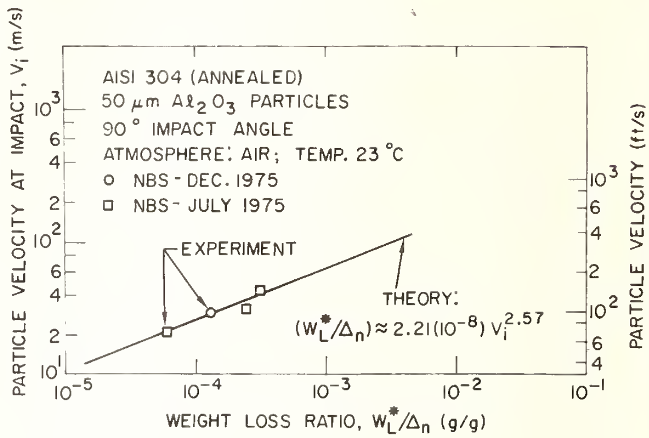
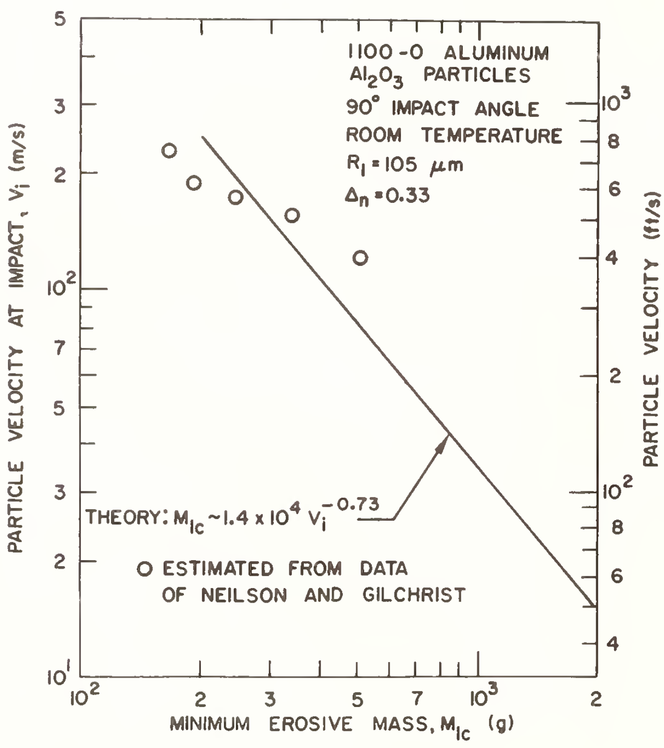
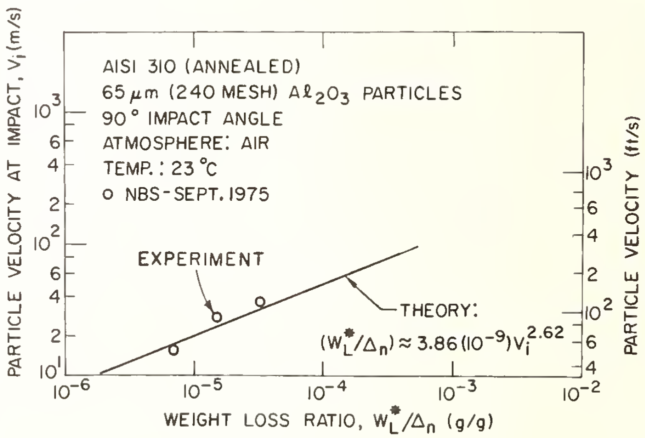
[a]Erosion tests were performed at ambient temperature in air using 60 μm Al_2O_3 with an impact velocity of 70 m/s at impingement angles of 15°, 20°, 25°, 45°, and 90°. [Time of tests not given.] Data are plotted as total mass loss of specimen as a function of the total mass of erodent impacted at each impact angle.

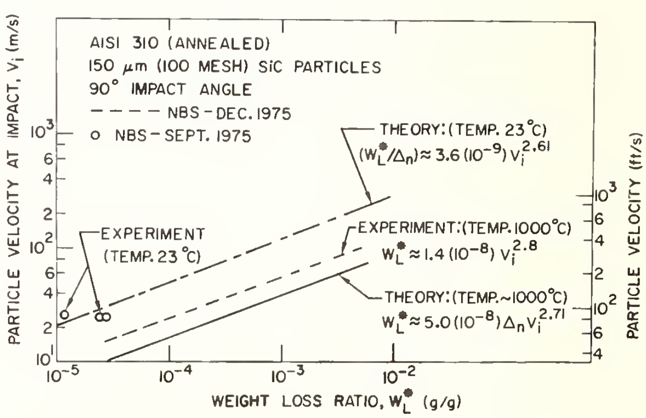
EXPERIMENTAL[a] AND CALCULATED WEIGHT LOSS RATIOS[b] FOR SEVERAL ALLOYS AS A FUNCTION OF IMPACT VELOCITY OF ERODENT AND TEMPERATURE[48]









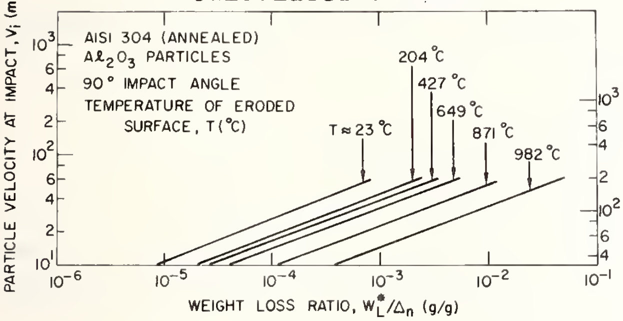


(Data Continued)

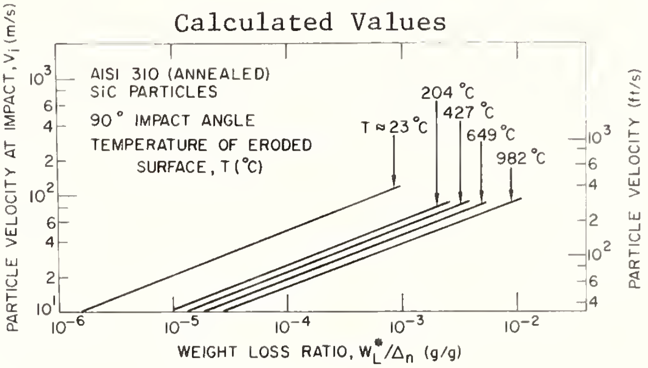
EXPERIMENTAL[a] AND CALCULATED WEIGHT LOSS RATIOS[b] FOR SEVERAL ALLOYS AS A FUNCTION OF IMPACT VELOCITY OF ERODENT AND TEMPERATURE[48],

Continued

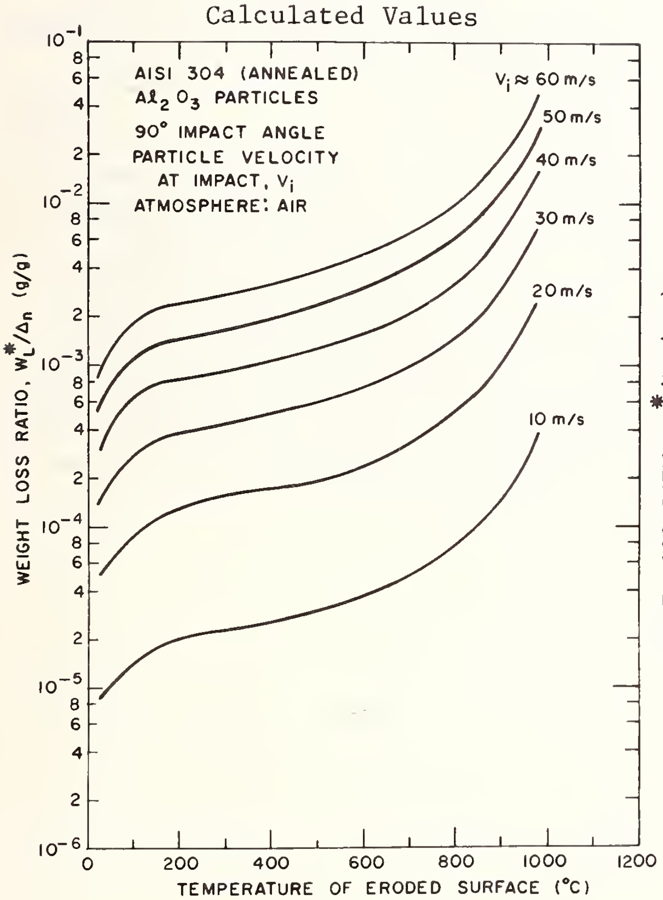
Calculated Values



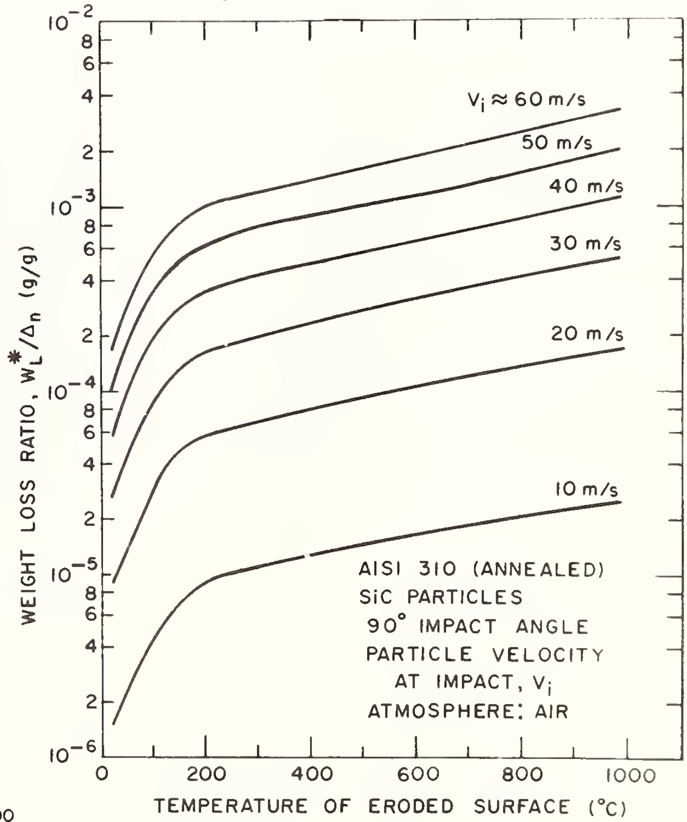
Calculated Values



Calculated Values



Calculated Values



(Data Continued)

EXPERIMENTAL[a] AND CALCULATED WEIGHT LOSS RATIOS[b] FOR SEVERAL ALLOYS AS A FUNCTION OF IMPACT VELOCITY OF ERODENT AND TEMPERATURE[48],

Continued

Footnotes

[a]Experimental data designated on the diagrams are taken from the following sources--

Diagram Designation	Reference
Sheldon et al.	G.L. Sheldon and I. Finnie, Trans. ASME, 88B, 387-392 (1966).
Finnie et al.	I. Finnie, J. Wolak, and Y. Kabil, J. Materials, 2(3), 682-700 (1967).
Finnie	I. Finnie, Proc. Soc. for Experimental Stress Analysis, Vol. XVII, No. 2, 65-70 (1960).
Neilson and Gilchrist	J.H. Neilson and A. Gilchrist, Wear, 2, 111-122 (1968).
NBS	A.W. Ruff, J.P. Young, and L.K. Ives, in "Materials Research for Clean Utilization of Coal", Quarterly Progress Reports, FE-1749-3, July-September 1975, FE-1749-6, December 1975, from the National Bureau of Standards, see reference [21].

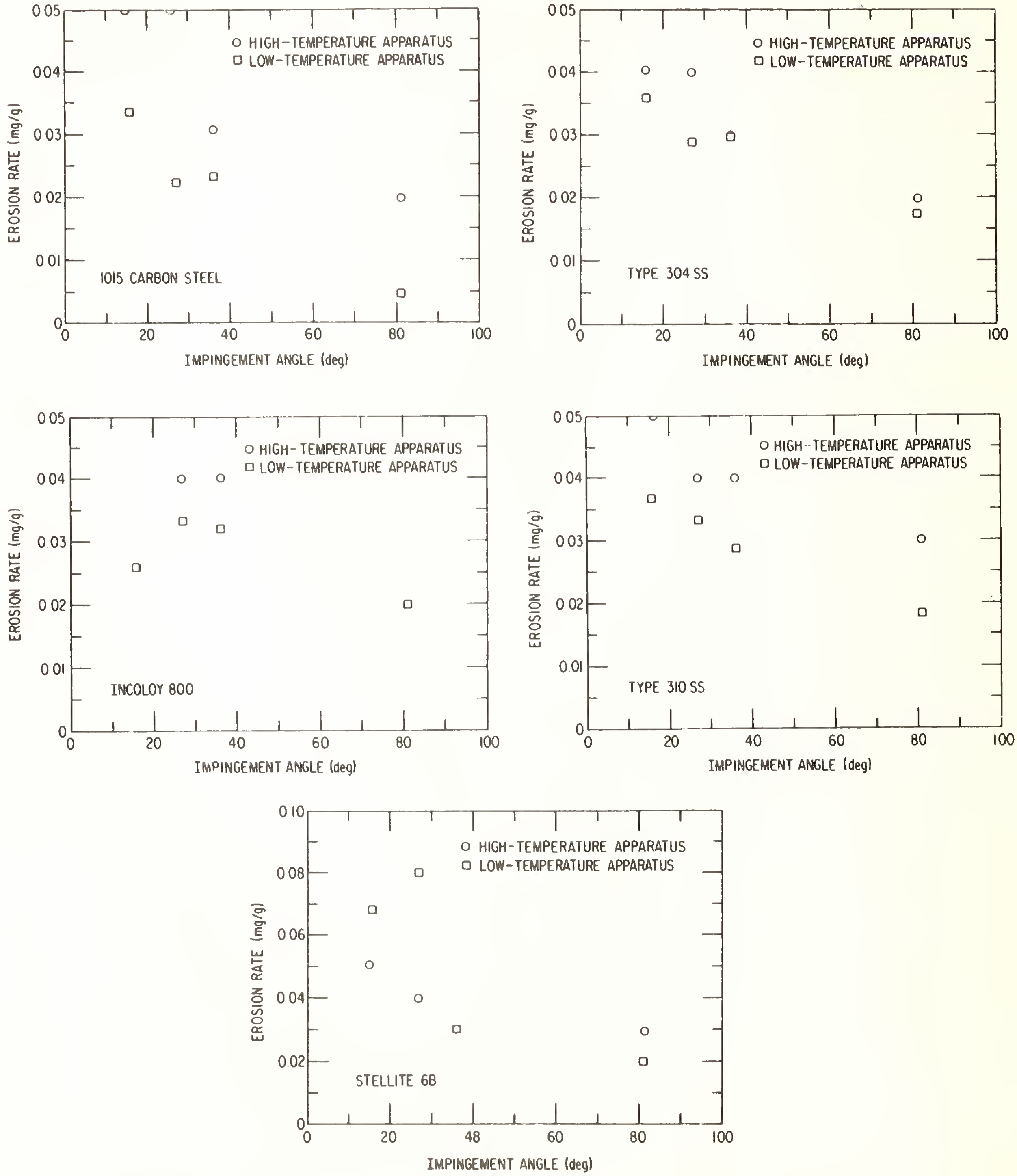
[b]Analytical models were developed for determining material loss by erosion. Theoretical predictions for weight loss by erosion are compared with experimental data for variation of particle velocity and minimum erodent mass. Theoretical predictions for weight loss by erosion at several temperatures are also given. The weight loss ratio, W_L^* is the ratio of the total weight loss of the eroded surface to the total weight of the erodent. The fractional weight of the eroding particles (determined experimentally to be between 1/3 and 1/2) that actually impact the surface is denoted by Δ_n. The value of W_L^*/Δ_n for a ductile metallic surface is a function of the mass densities of the erodent and the eroded material, the flow stress of the eroded surface, and material constants related to the plastic strain range and the number of cycles to failure for completely reversed axial load.

EROSION TESTING[a] OF SOME ALLOYS[48]

	Erosion Rate (mg/g)					
Impingement Angle	6°	16°	24°	26°	36°	81°
Alloy						
1015 Carbon Steel	0.09	0.05	0.06		0.03	
		0.05		0.05	0.03	0.02
		0.03L		0.02L	0.02L	0.01L
304 SS	0.06	0.03	0.04		0.03	
		0.05		0.04	0.04	0.02
		0.04L		0.03L	0.03L	0.02L
Incoloy 800	0.06	0.05	0.05		0.04	
		0.06		0.05	0.04	0.03
		0.03L		0.03L	0.03L	0.02L
310 SS	0.03	0.04	0.04		0.03	
		0.06		0.05	0.04	0.03
		0.04L		0.03L	0.03L	0.02L
Stellite 6B	0.06	0.04	0.04		0.03	
		0.06		0.04	0.04	0.03
		0.07L		0.08L	0.03L	0.02L

[a]Erosion tests were performed at ambient temperature in air using 150 μm Al_2O_3 with an impact velocity of 22 m/s at impingement angles from 6° to 81°. Erosion rates (mass loss/mass impacted) were calculated from specimen weight loss. [Test times not given, probably >50 hours.] These data result from equipment calibration tests. Two tests were run in apparatus intended for high-temperature testing, one test (designated by the letter L above) was run in apparatus intended for low- or ambient-temperature testing. See Section B.2.1.51 for these same data plotted.

EROSION RATE[a] VERSUS IMPINGEMENT ANGLE FOR SOME ALLOYS[48]



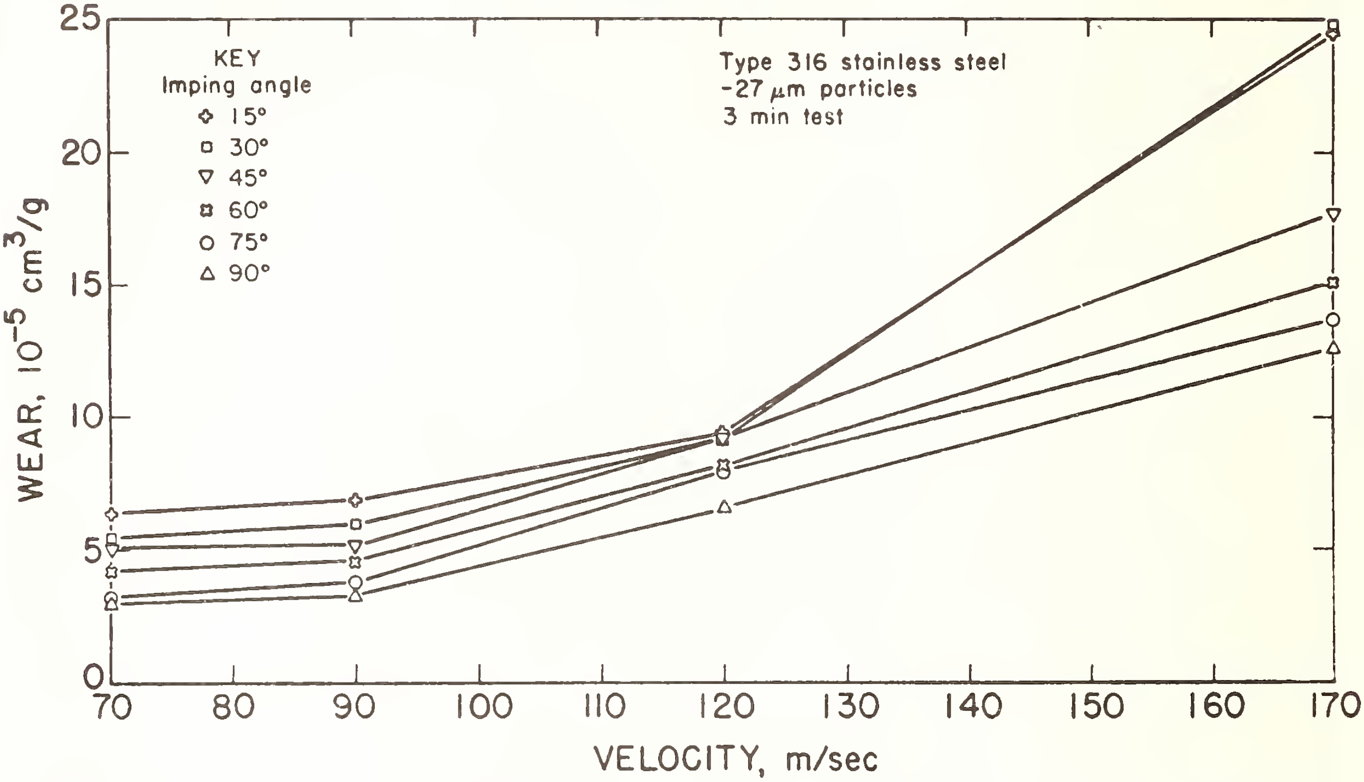
[a]See Section B.2.1.50 for these same data in tabular form.

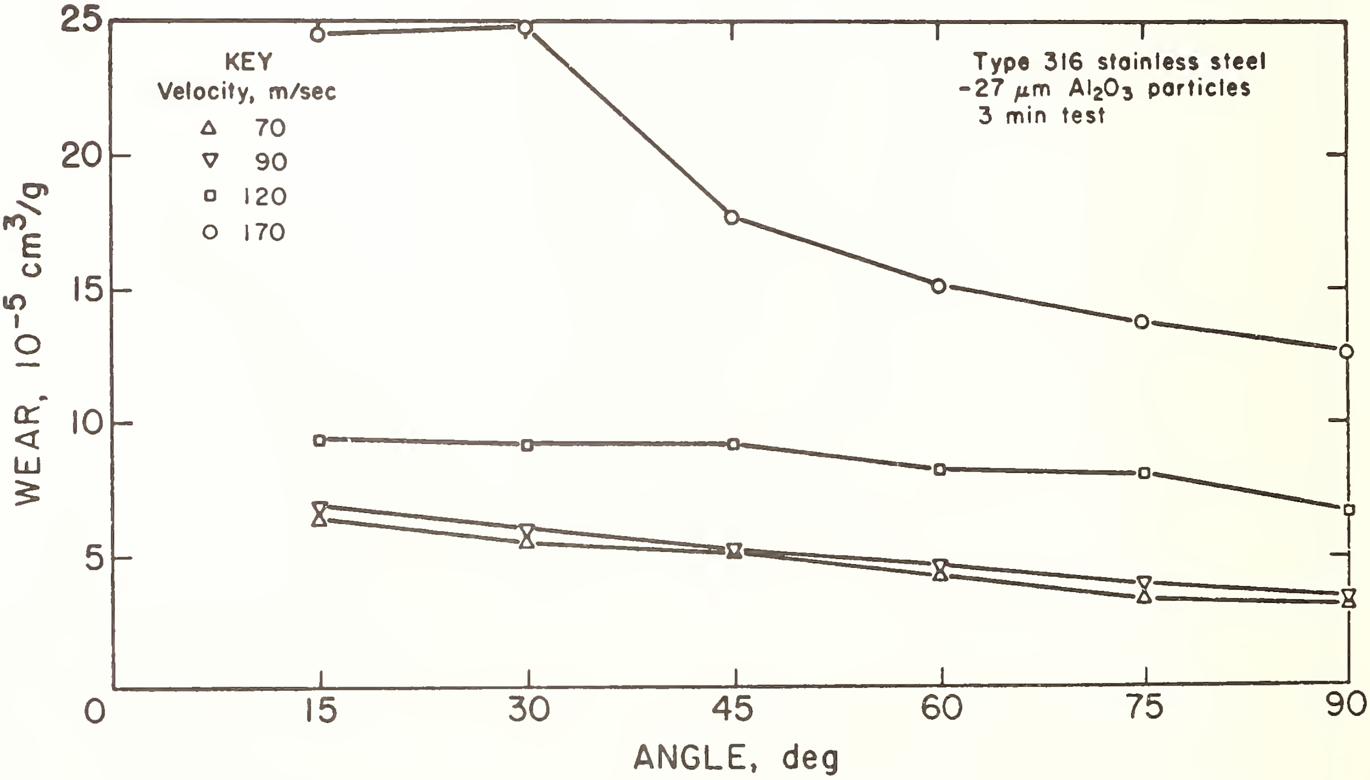
EROSION-CORROSION TESTING[a] OF SOME ALLOYS[48]

Impingement Angle	Erosion-Corrosion (mg/g) 16°	26°	36°	81°
Alloy				
1015 Carbon Steel	0.03	0.01	0.01	0.00
304 SS	0.09	0.06	0.06	0.06
Incoloy 800	0.07	0.07	0.07	0.09
310 SS	0.06	0.07	0.07	0.10
Stellite 6B	0.08	0.07	0.06	0.08

[a]Erosion-Corrosion tests were performed at 816 °C (1500 °F) in a simulated coal gasification atmosphere (CO 18, CO_2 12, CH_4 5, H_2 24, H_2O 39, NH_3 1, H_2S 1, all volume percent; calculated equilibrium potentials, oxygen $5.4x10^{-19}$, sulfur $3.5x10^{-7}$, and carbon activity 0.0214) using 150 µm Al_2O_3 with an impact velocity of 22 m/s at impingement angles from 16° to 81°. Test time was 24 hours.

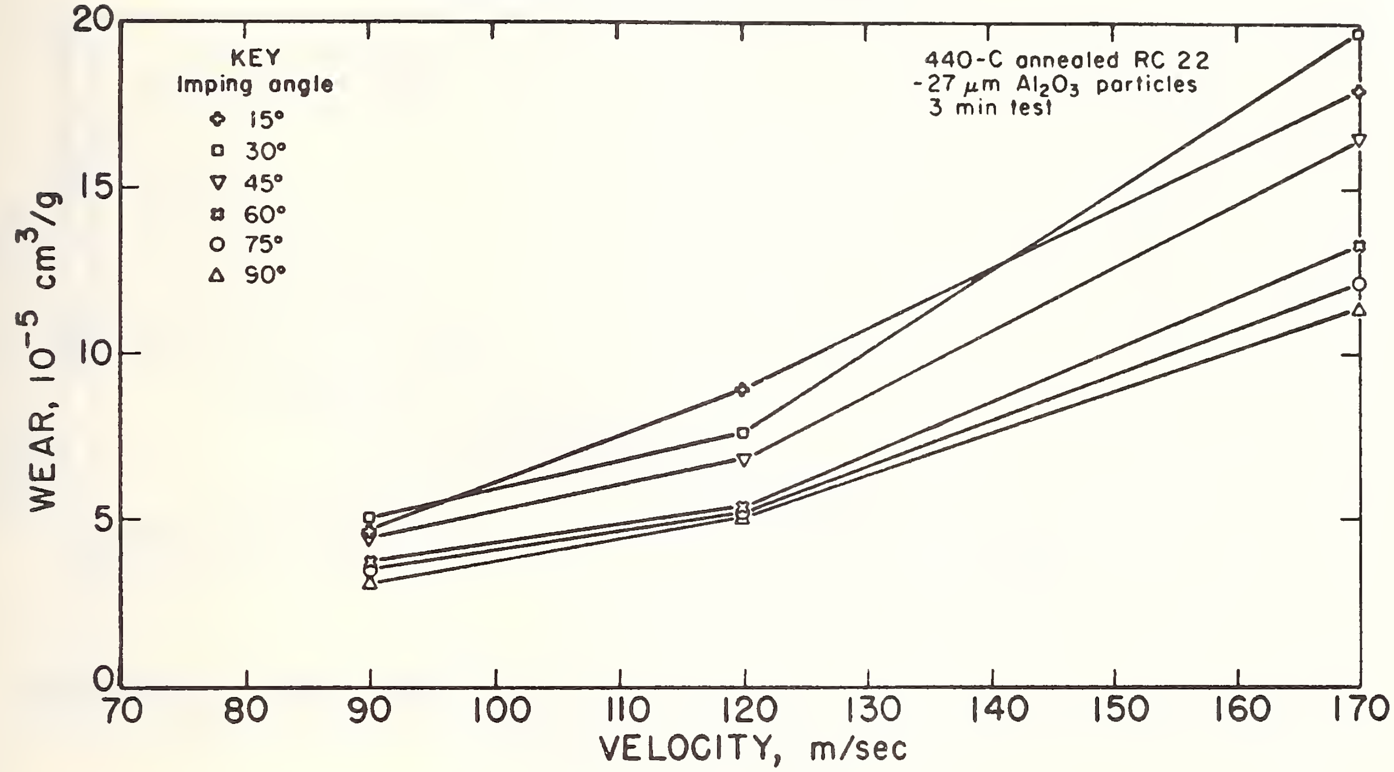
EROSION DATA[a] FOR SEVERAL ALLOYS[b] AT VARIOUS PARTICLE VELOCITIES AND IMPINGEMENT ANGLES[1]

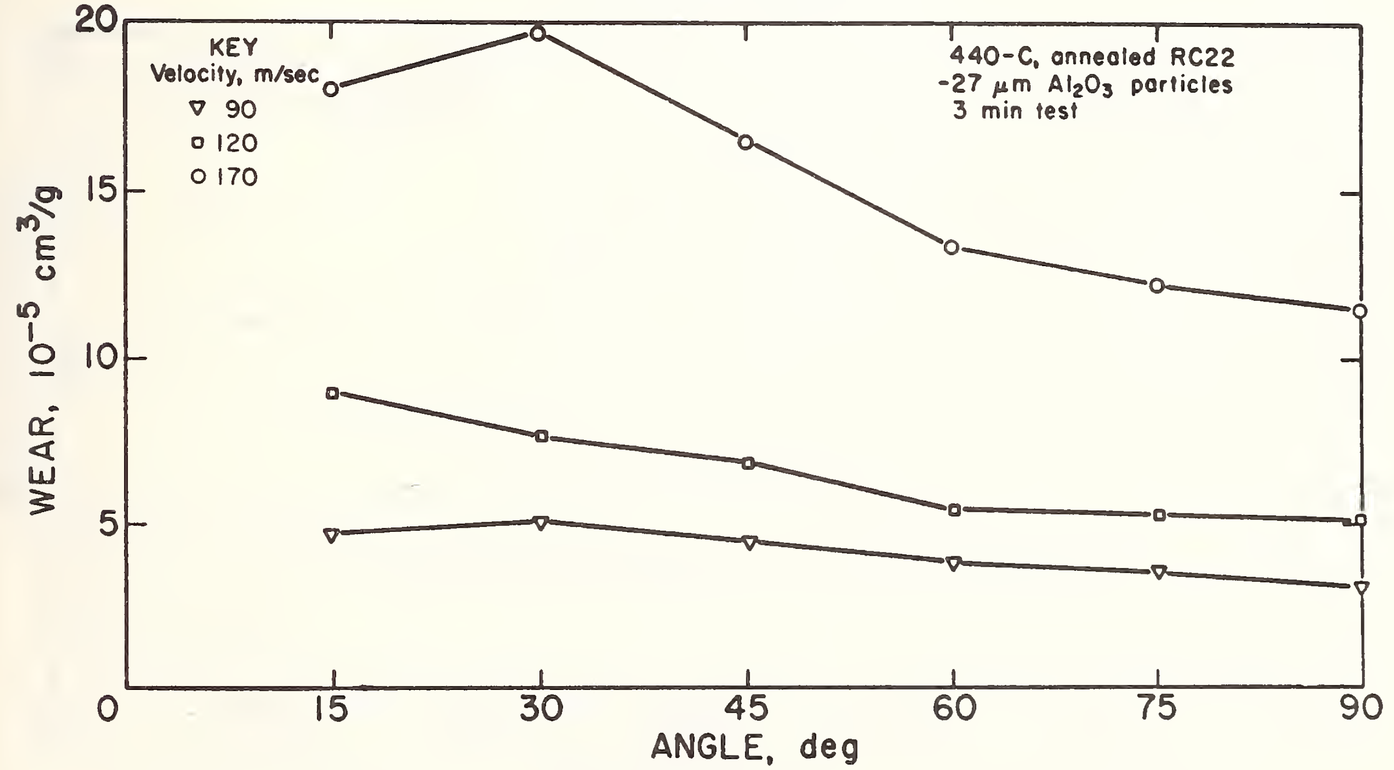




(Data Continued)

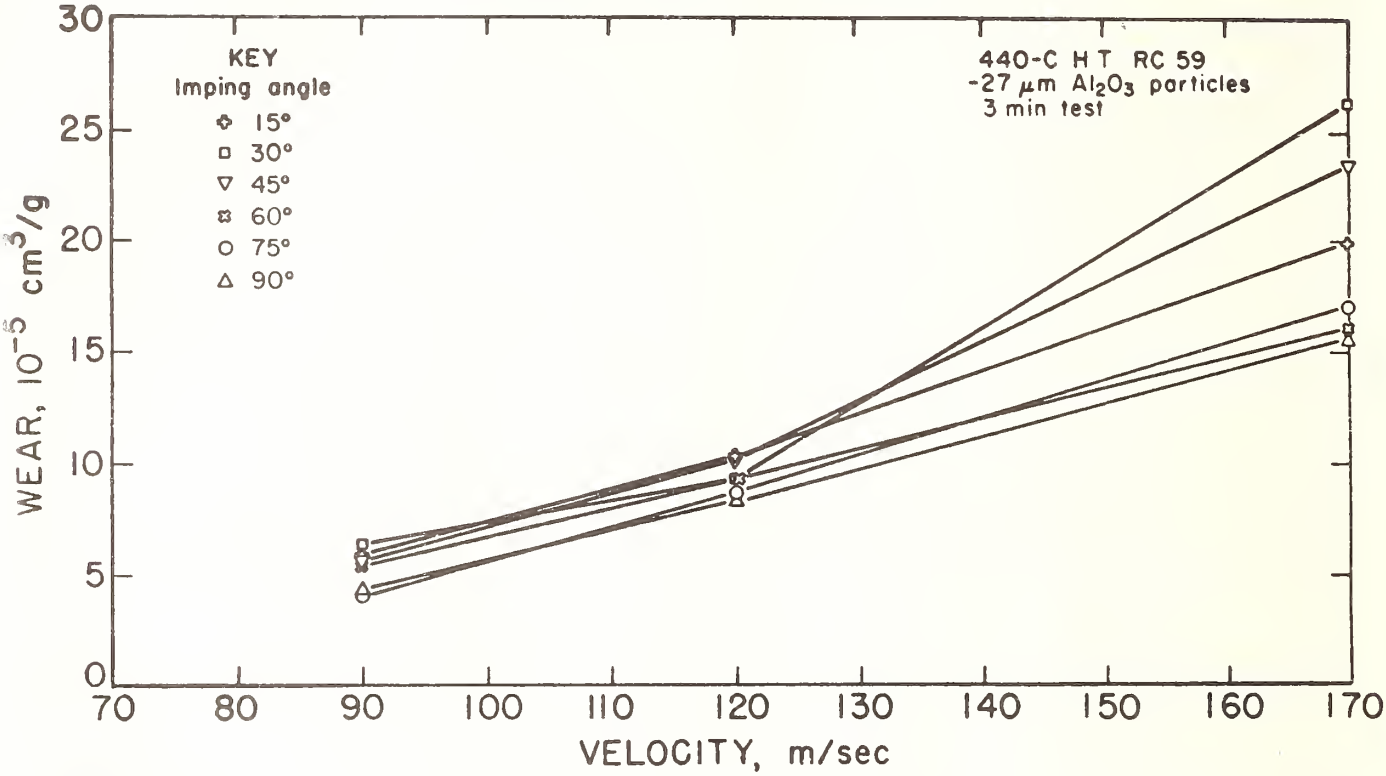
EROSION DATA[a] FOR SEVERAL ALLOYS[b] AT VARIOUS PARTICLE VELOCITIES AND IMPINGEMENT ANGLES[1], Continued

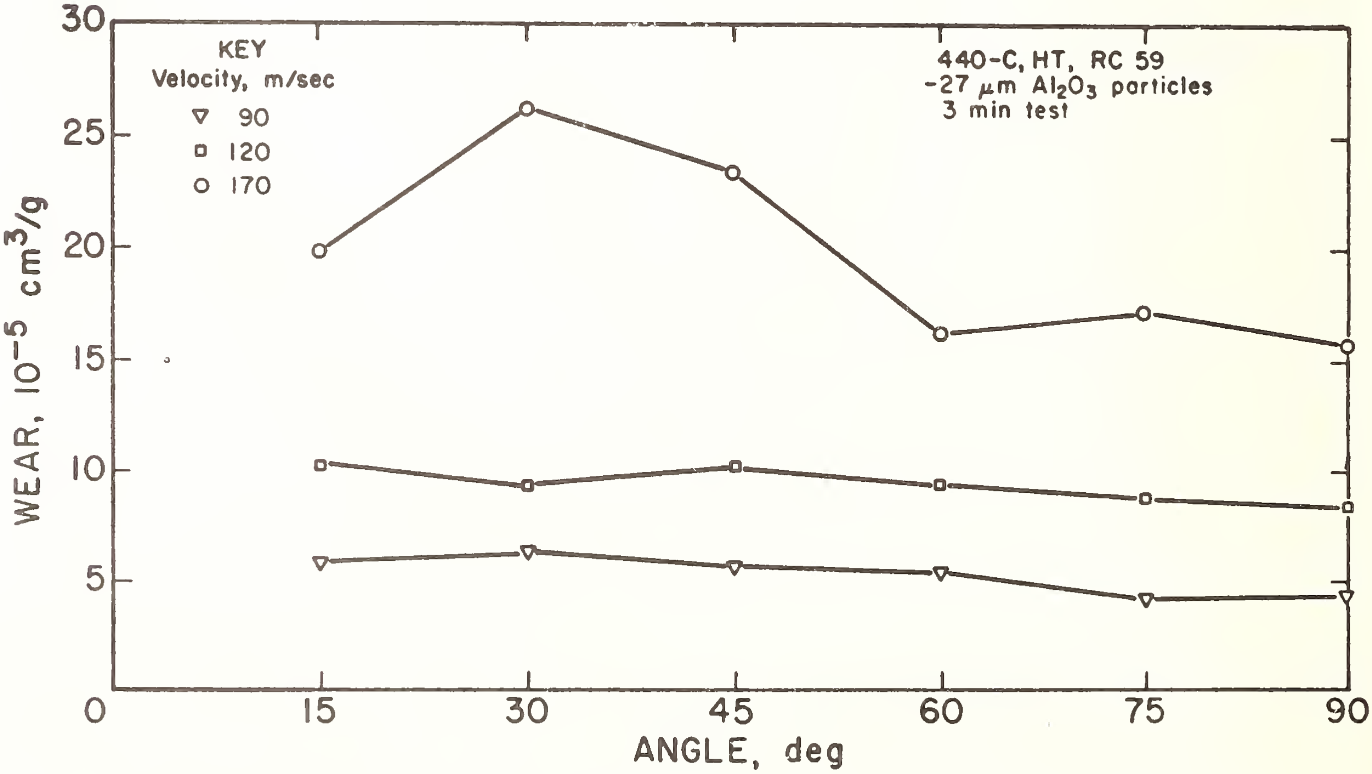




(Data Continued)

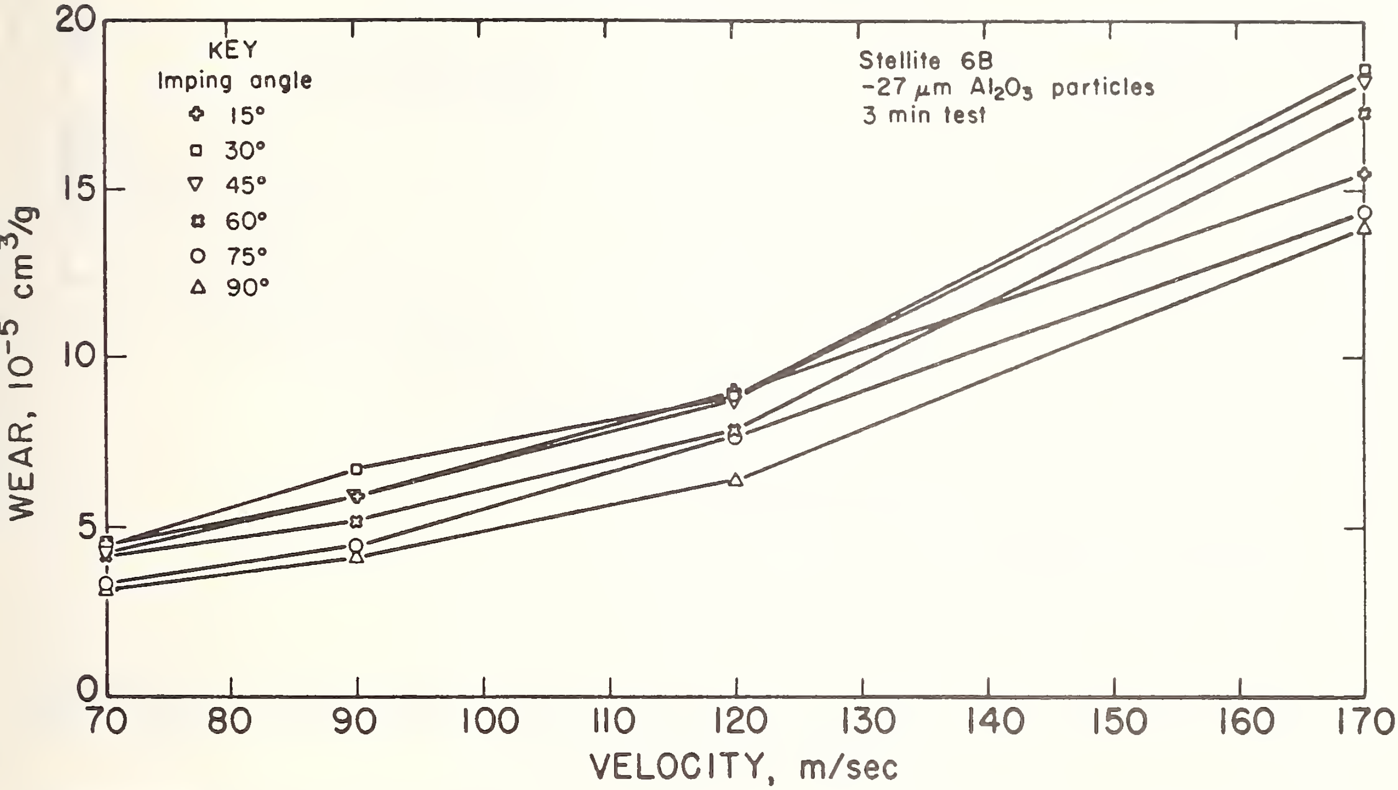
EROSION DATA[a] FOR SEVERAL ALLOYS[b] AT VARIOUS PARTICLE VELOCITIES AND IMPINGEMENT ANGLES[1], Continued

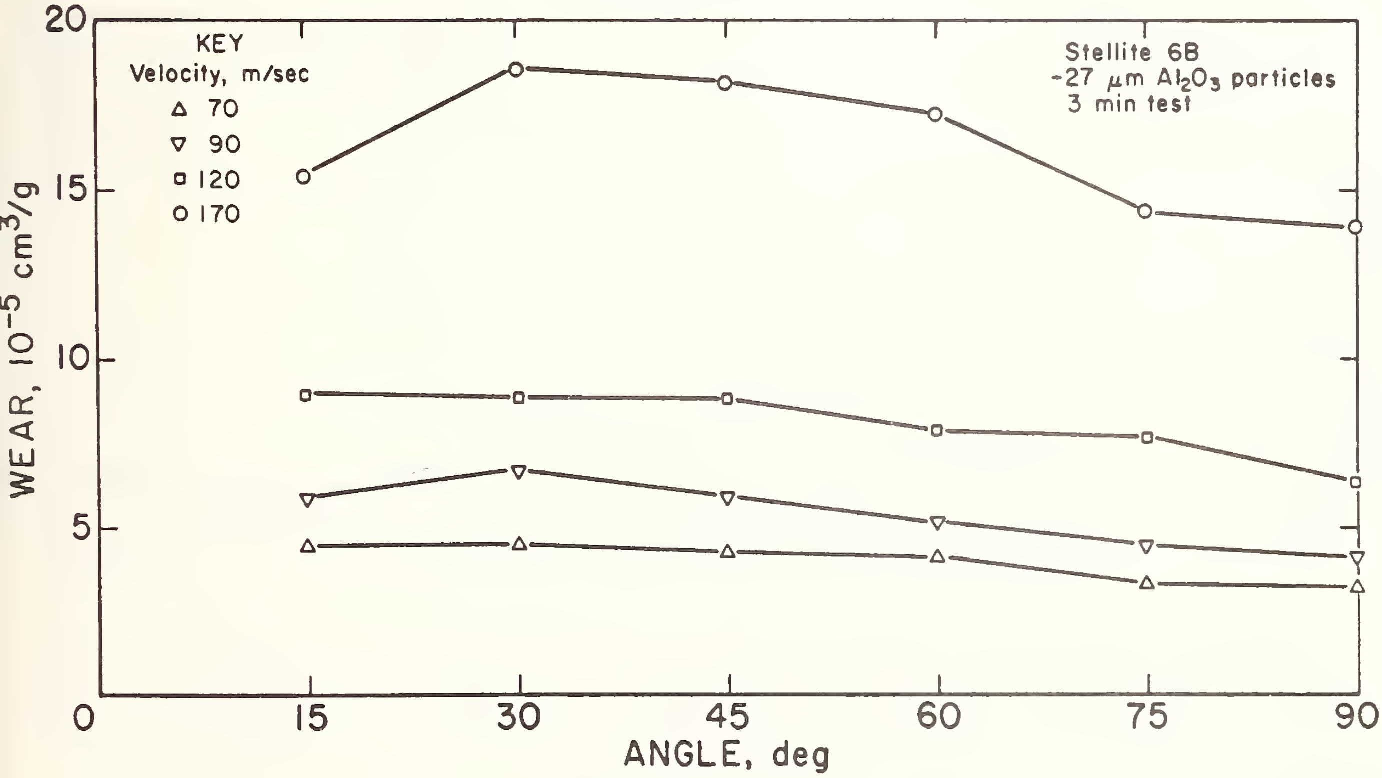




(Data Continued)

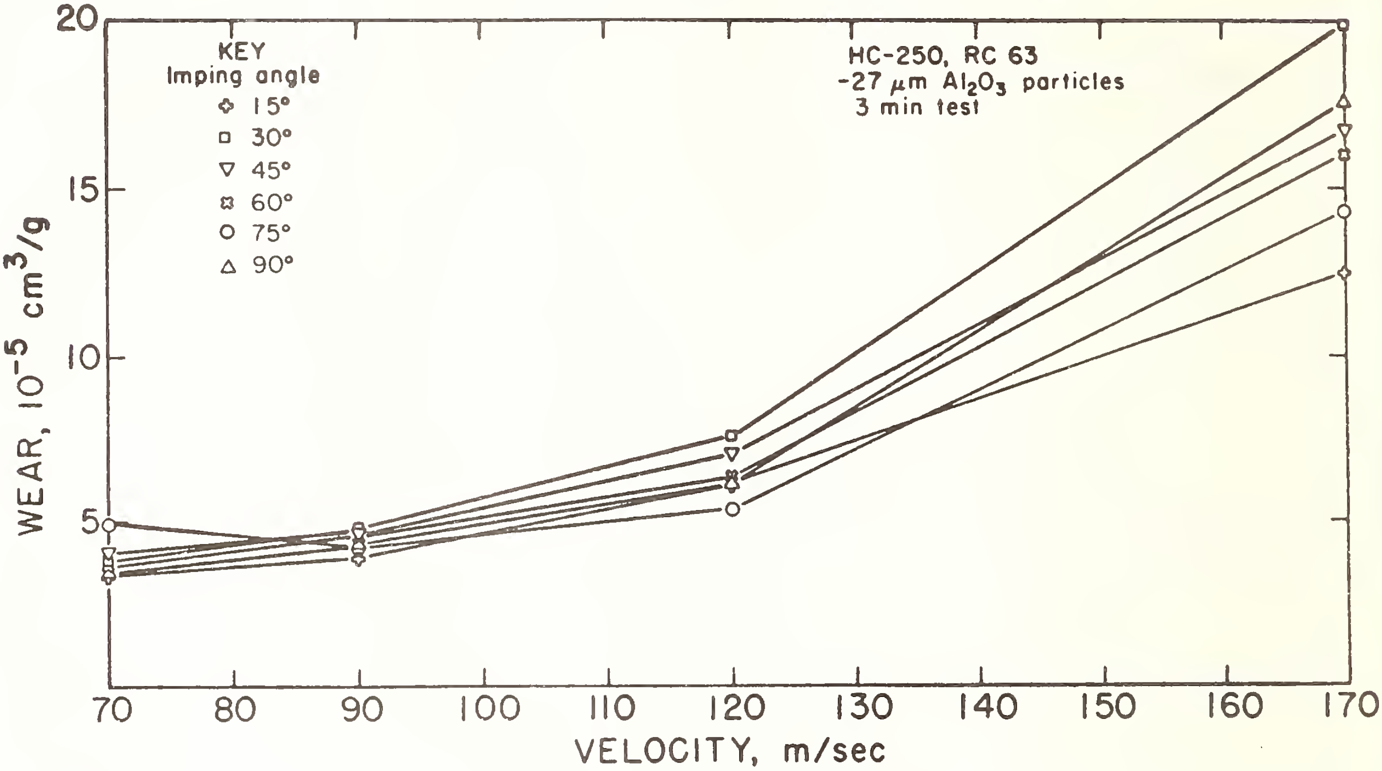
EROSION DATA[a] FOR SEVERAL ALLOYS[b] AT VARIOUS PARTICLE VELOCITIES AND IMPINGEMENT ANGLES[1], Continued

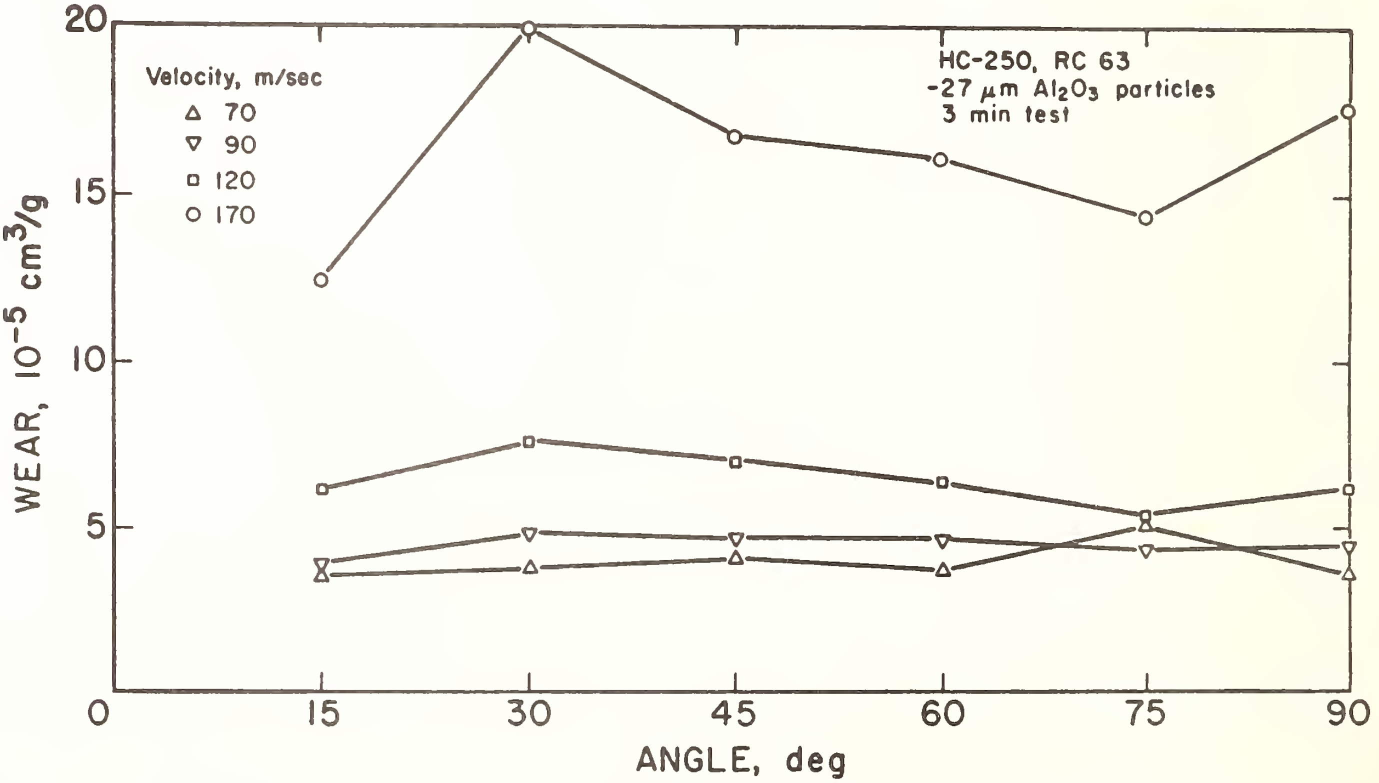




(Data Continued)

EROSION DATA[a] FOR SEVERAL ALLOYS[b] AT VARIOUS PARTICLE VELOCITIES AND IMPINGEMENT ANGLES[1], Continued





(Data Continued)

EROSION DATA[a] FOR SEVERAL ALLOYS[b] AT VARIOUS PARTICLE VELOCITIES AND IMPINGEMENT ANGLES[1], Continued

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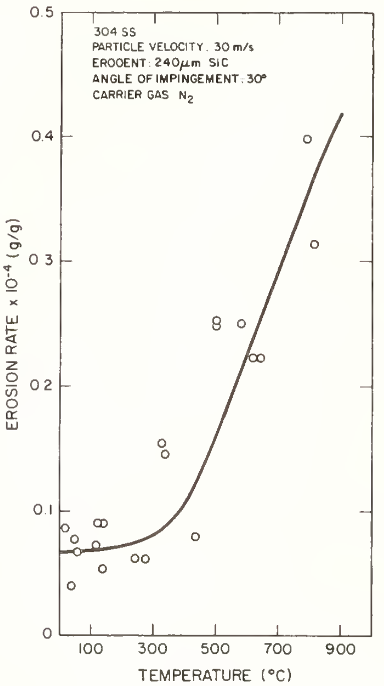
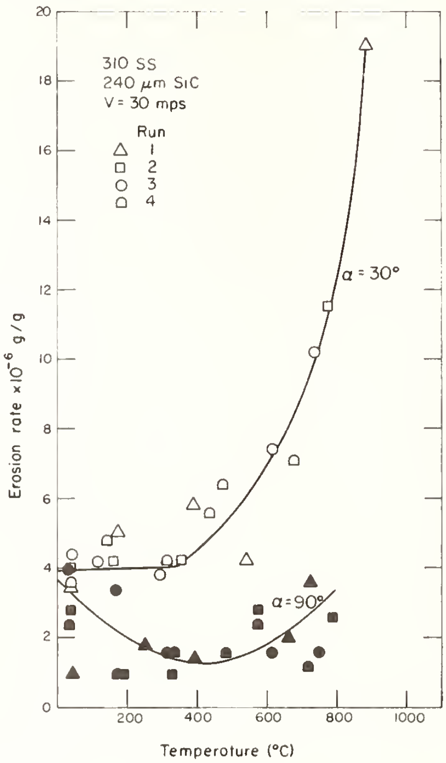
[a]Erosion testing was performed on 1/2-inch square specimens subjected to erosion by 27 μm Al_2O_3 in three minute tests in N_2 atmosphere. The abrasive flow was 5 g/min. There were 4 different particle velocities and 6 impingement angles. The wear value plotted is the volume of alloy removed divided by the weight of Al_2O_3 expended.

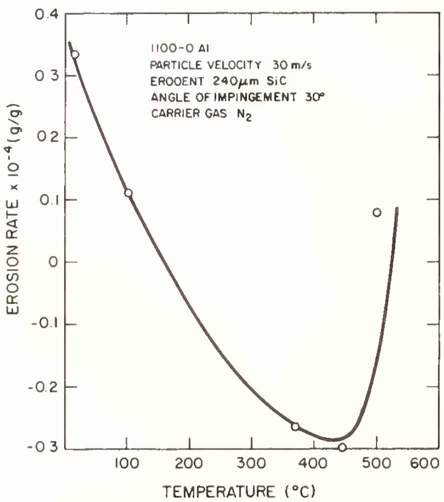
[b]The alloys are 316 stainless steel; 440 C stainless steel annealed, Rockwell Hardness C 22 and heat-treated, Rockwell Hardness C 59; Stellite 6B; and cast alloy HC-250.

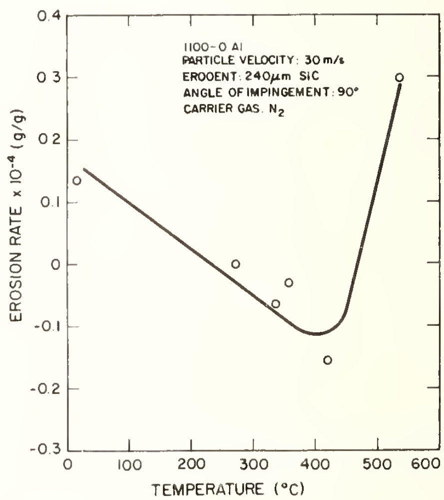
EFFECT OF TEMPERATURE AND IMPINGEMENT ANGLE ON THE EROSION[a] OF STAINLESS STEELS[b] AND ALUMINUM[c] [53]





For 310 SS four separate test runs were made over the test temperature range with a different specimen for each test.





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[a] Specimens were polished with 240 grit SiC before exposure. The specimens were eroded by 240 μm SiC in nitrogen gas, particle velocity 30 m/s (~100 ft/s), impingement angles (α) were 30° and 90°. 500 g of SiC were used for each test. After testing, specimens were removed from the apparatus at temperature, cooled under nitrogen, cleaned with alcohol in an ultrasonic cleaner, and weighed. The erosion rate is the weight loss of the specimens per weight of erodent used.

[b] 310 SS and 304 SS.

[c] Aluminum alloy 1100-0.

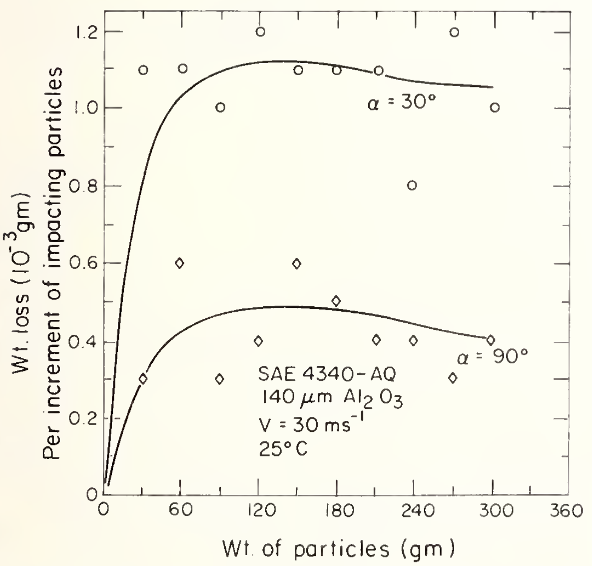
EFFECT OF DUCTILITY[a] ON THE EROSION[b] OF TWO STEELS[53]

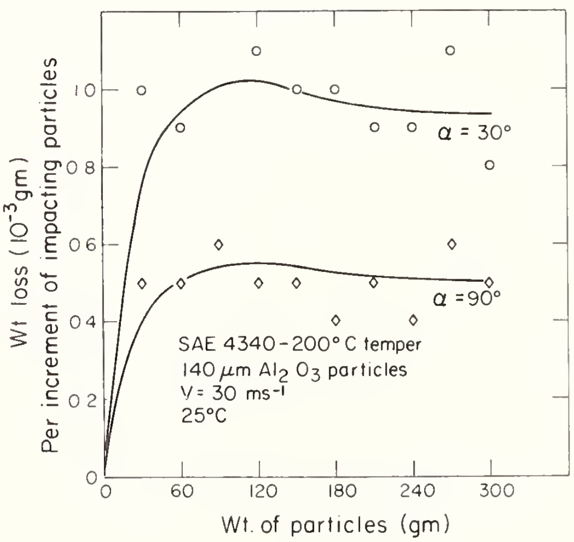
1020 CARBON STEEL

Test Temperature (°C)	% Elongation	Steady State Erosion (mg)[c]
25	25	0.75
(-18 °C, ductile-brittle temperature transition)		
∿-78[d]	1-5	2.50

4340 STEEL

Heat Treatment	Ultimate Tensile Strength	Rockwell C Hardness	K_{IC}	Elongation	Charpy Impact Strength	Erosion[e]
As-quenched (AQ)	307 ksi	60	34	8 %	10 ft-lb	1.03 mg
200 °C temper	273	53	58	11	16	0.97
500 °C temper	182	39	62	14	12	0.97
Spheroidize anneal	∿100	∿19		∿25		0.90





[a] As indicated by test temperature or properties after heat treatment.

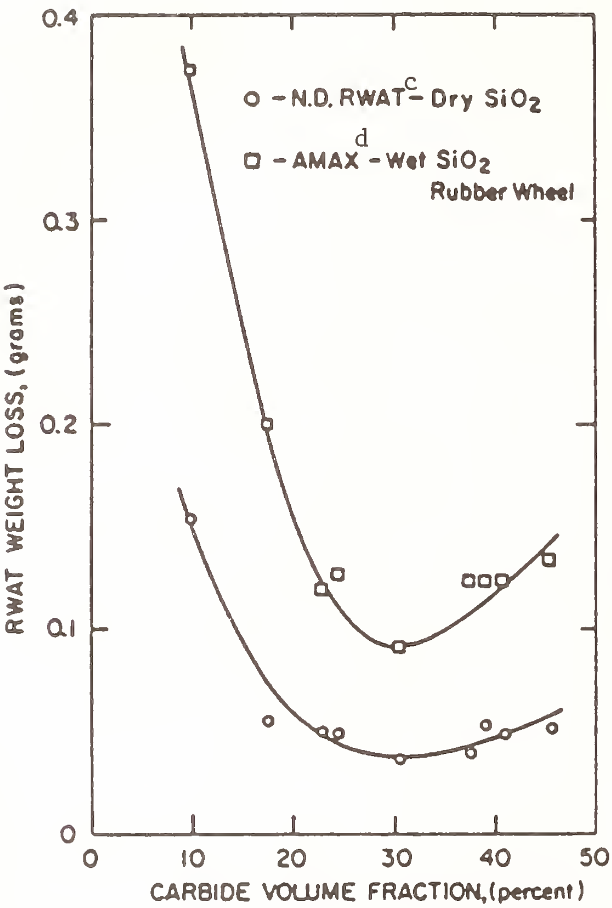
[b] Duplicate samples were eroded by Al_2O_3 in nitrogen atmosphere at particle velocity of 30 m/s. Particle size 140 μm.

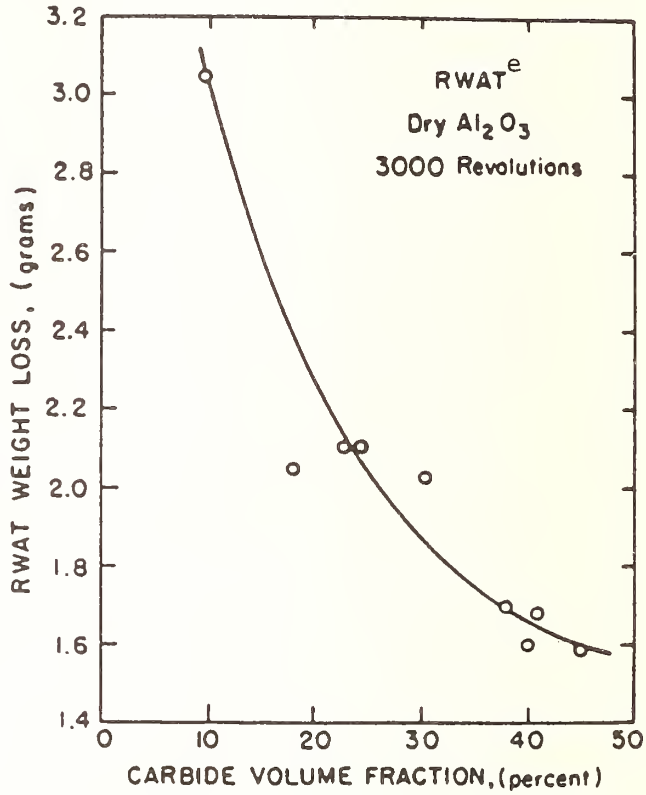
[c] Per 150 mg of erodent at 90° impingement angle.

[d] Specimens were secured to 1-inch thick blocks of dry ice.

[e] Statistical average of weight loss per 30 g of erodent, 30° impingement angle.

ABRASION TESTING[a] OF EXPERIMENTAL HIGH Cr-Mo WHITE CAST IRONS[b] WITH VARYING CARBIDE CONTENT[28]





[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 x 25.4 x 76.2 mm). The abrasives used are -50+70 mesh semi-rounded Ottawa silica sand and an angular alumina ∿70 mesh. The wheel rotates at a constant speed of 200 rpm (surface rate 2.38 m/s), applied load is 13 kg corresponding to a nominal stress of 0.41 MPa. Results are reported as specimen weight loss per 3000 revolutions. The flow rate of abrasive is maintained at 130 g/min.

[b]Alloys provided by Climax Molybdenum Research Laboratories. Wear samples were cut from as-cast blocks on an abrasive cut-off wheel in which the blocks were completely submerged in coolant and then surface ground with the grinding parallel to the wear direction.

Heat No.	% Cr	% Mo	% C	Hardness Rc	Carbide Volume Fraction %
1	12.8	2.39	1.38	36	9.8
2	17.8	2.35	1.89	52	17.4
3	17.6	2.39	2.58	48	24.3
4	18.7	2.39	2.48	48	22.7

(Data Continued)

ABRASION TESTING[a] OF EXPERIMENTAL HIGH Cr-Mo WHITE CAST IRONS[b] WITH VARYING CARBIDE CONTENT[28], Continued

Footnotes continued

Heat No.	% Cr	% Mo	% C	Hardness Rc	Carbide Volume Fraction %
5	21.0	2.36	2.79	50	30.4
6	23.4	2.47	3.50	55	37.6
7	24.1	2.47	3.41	55	41.1
8	24.6	2.45	3.93	53	45.5
9	25.7	2.45	3.81	54	38.8

Other elements present include Si, Mn, Cu, and Ni.

[c]Testing done at Notre Dame. Wear decreases in the hypereutectic composition range because massive M_7C_3 protrude from the worn surface and become vulnerable to cracking.

[d]Testing done at Climax Laboratories with SiO_2 slurry.

[e]Alumina particles cut the carbides effectively so the wear resistance increases monotonically for that abrasive.

SINGLE POINT SCRATCH TEST ABRASIVE WEAR DATA[a] FOR Co-BASE ALLOYS[b][28]

Alloy Specimen[b]	Surface Condition	Load g	Scratch Width, μm Carbide Phase	On The Matrix	Average
#6, fine carbides (sintered at 1160 °C)	Metallographically polished	10	2.55	4.79	3.67
		50	9.82	14.28	12.05
		100	17.85	23.44	20.65
		200	30.60	34.71	32.66
#6, coarse carbides (sintered at 1203 °C)	Metallographically polished	10	20.76	4.25	3.51
		50	9.78	12.75	11.27
		100	17.00	25.50	21.25
		200	28.05	36.13	32.09
#6, samples from SiO_2 RWAT test[c]	Worn	10	no scratch	no scratch	--
		50	--	9.35	9.35
		100	--	13.25	13.25
		200	--	20.40	20.40
#19, fine carbides (sintered at 1204 °C)	Metallographically polished	10	d	d	8.93
		50	d	d	14.24
		100	d	d	22.59
		200	d	d	33.58
#19, coarse carbides (sintered at 1238 °C)	Metallographically polished	10	3.67	7.65	5.66
		50	8.54	16.93	12.74
		100	17.64	25.73	21.69
		200	31.88	36.55	34.22
#19, samples from SiO_2 RWAT test[c]	Worn	10	no scratch	no scratch	--
		50	--	7.37	7.37
		100	--	13.46	13.46
		200	--	16.98	16.98

Scanning Electron Microscope General Observations

1. Ploughing of the matrix phase to the sides of the scratch groove, showing that the entire groove volume is not removed by the cutting.
2. Some plastic flow of the carbide phase.
3. Appearance (almost always) of coarse slip bands at the edge of the scratch and possible cracking of the matrix phase along slip bands.
4. Large cracks in the large M_7C_3 carbide phase, usually perpendicular to the scratch direction.
5. Separation of the carbide-matrix interface in heavily cracked large carbides.
6. Smeared layers of matrix phase overlying the carbides in the fine carbide materials.

(Data Continued)

SINGLE POINT SCRATCH TEST ABRASIVE WEAR DATA[a] FOR Co-BASE ALLOYS[b][28],

Continued

Footnotes

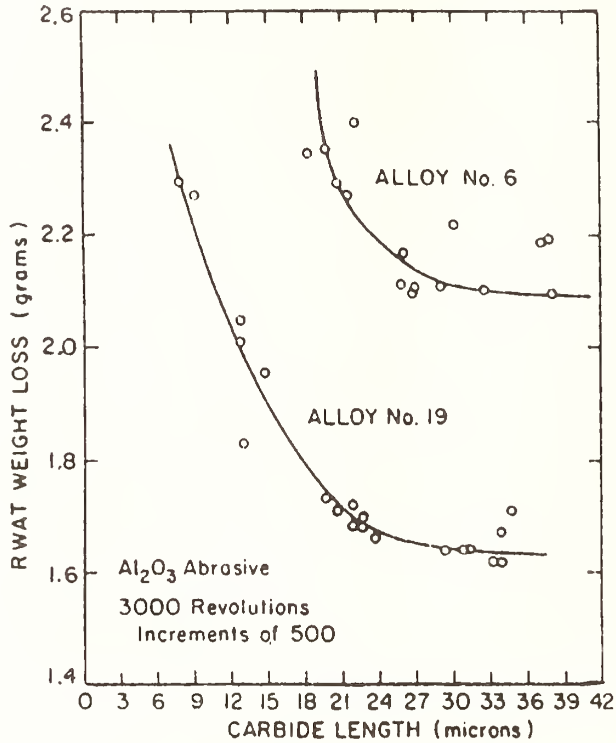
[a]Single point scratch test done with a Bergsman microhardness apparatus with the standard Vickers diamond pyramid indentor. Various weights were used to provide the scratch test load. Scratches were examined by optical metallography and scanning electron microscope techniques.

[b]Cobalt-base superalloys prepared by powder metallurgy techniques from Cabot Corporation. Composition: #6, 28.46Cr-1.16Ni-0.98Si-1.73Fe-0.04Mn-0.13Mo-4.42W-1.35C-0.57B-balance Co, carbide volume fraction 26.5%, microhardness VHN 185; #19, 31.42Cr-2.00Ni-0.40Si-1.82Fe-0.10Mn-6.97Mo-10.08W-2.36C-0.19B-balance Co, carbide volume fraction 32.0%, microhardness VHN 220. #19 has W-rich M_6C phases in addition to Cr-rich M_7C_3 phases. Carbide size was controlled by sintering temperature as indicated above. Sintering time was 2 hours.

[c]See B.2.1.29 and B.2.1.30 for description and results of the RWAT test. These samples were worn from having been used in the earlier abrasion tests.

[d]Carbides so fine that the scratch width was much greater than the carbide size.

ABRASION TESTS[a] OF Co-BASE ALLOYS[b] PREPARED WITH VARIOUS CARBIDE SIZES[c][28]



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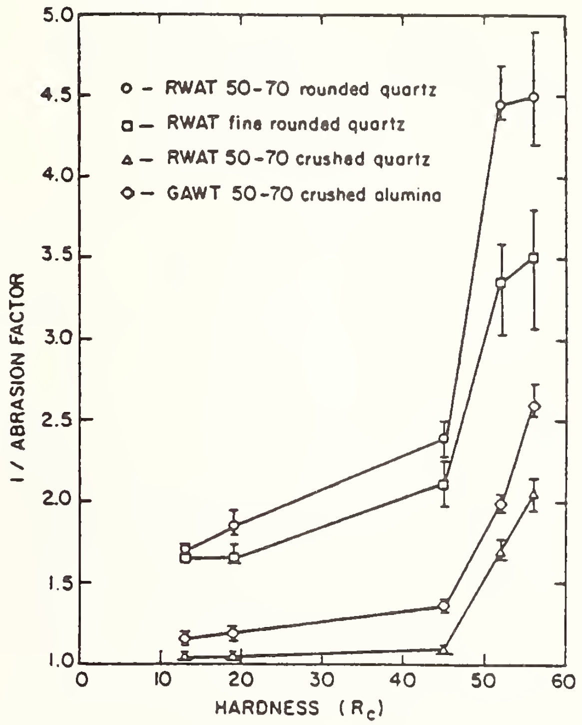
[a]Wear resistance was measured by a Rubber Wheel Abrasive Test (RWAT); a uniform stream of abrasive (~70 mesh Al_2O_3) is gravity fed between a rotating rubber wheel and a test specimen (12.7 x 25.4 x 76.2 mm). The wheel rotates at a constant speed of 200 rpm, applied load is 30 lb corresponding to a stress of 60 psi. The flow rate of 130 g/min is maintained for 3000 revolutions, reached in increments of 500. The wear is recorded as total sample weight loss in 3000 revolutions. Weight loss standard deviation is ±0.1 g.

[b]Cobalt-base superalloys prepared by powder metallurgy techniques from Cabot Corporation. Composition: #6, 28.4Cr-1.16Ni-0.98Si-1.73Fe-0.04Mn-0.13Mo-4.42W-1.35C-0.57B-balance Co, carbide volume fraction 26.5%; #19, 31.42Cr-2.00Ni-0.40Si-1.82Fe-0.10Mn-6.97Mo-10.08W-2.36C-0.19B-balance Co, carbide volume fraction 32.0%. #19 has W-rich M_6C phases in addition to Cr-rich M_7C_3 phases.

[c]Carbide size controlled by sintering temperature. For #6: Fine, 1160 °C, Medium, 1182 °C, Coarse, 1204 °C. For #19: Fine, 1204 °C, Medium, 1221 °C, Coarse, 1238 °C. Sintering time 2 hours. Carbide size standard deviation ±0.1 μm.

EFFECT OF HEAT TREATING[a] AND DIFFERENT ABRASIVES ON LOW-STRESS ABRASION[b] OF 1045 STEEL[c][28]



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[a]The steel was heat treated to a variety of hardness levels as plotted on the abscissa above. [Note that the lower limit of the Rockwell C hardness scale is 20.]

[b]Low-stress abrasion testing was done using both SiO_2 and Al_2O_3. The test methods used were the RWAT (Rubber Wheel Abrasive Test) and the GAWT (Gouging Abrasive Wheel Test). See Section B.2.1.29 for a description of these tests. The ordinate above, 1/Abrasion Factor, is a measure of wear resistance relative to an annealed 1020 hot-rolled steel standard.

[c]Untempered 1045 steel.

COMPARISON OF HARDNESS, TOUGHNESS, AND WEAR FOR CAST AND FORGED EXPERIMENTAL STEELS[a] [41]

Alloy[a]	Hardness[b] R_C	Charpy Impact Toughness[b] ft-lb	3-Body Wear Ratio[b,c]
Base+1 Al+1 Si+0.4 V			
Cast	54.5	2.5	0.51
Forged	55	17	0.56
AISI 4340+1.5 Al+1.5 Si			
Cast	49	9.3	0.50
Forged	51	20	0.45

[a] Base alloy composition: 0.36 C, 0.5 Mn, 1.0 Cr, 3.0 Ni, 2.0 Mo, balance Fe.

[b] All values for cast materials are for equiaxed zone.

[c] Three-body wear was determined using a specimen disc 3.75 inches in diameter, 0.25 in thick, with a central hole 5/16 inches in diameter. After heat treatment the surfaces of the disc were ground (to 0.11 in thickness) to remove the decarburized layer. The apparatus contained an acrylic tube (containing 120 grit SiC and fitting into a horizontal beam and plunger with weights) sitting on the disc specimen which rotates beneath it. The conditions provided an effective load of 2.5±0.3 kg applied to the specimen. Wear was analyzed by plotting the weight loss against the number of cycles, least squares fitting of a straight line, and reporting the slope as wear per 100 cycles.

$$\text{Volume Wear Rate} = \frac{\text{Weight Loss}}{\text{Density x Distance x Load}}$$

$$\text{Wear Ratio} = \frac{\text{Wear Rate of Specimen}}{\text{Wear Rate of Standard}}$$

1020 steel was used as the standard. Two specimens were used for each test.

EFFECT OF ALLOY CARBIDE PRECIPITATION IN AN EXPERIMENTAL SECONDARY HARDENING STEEL[a][41]

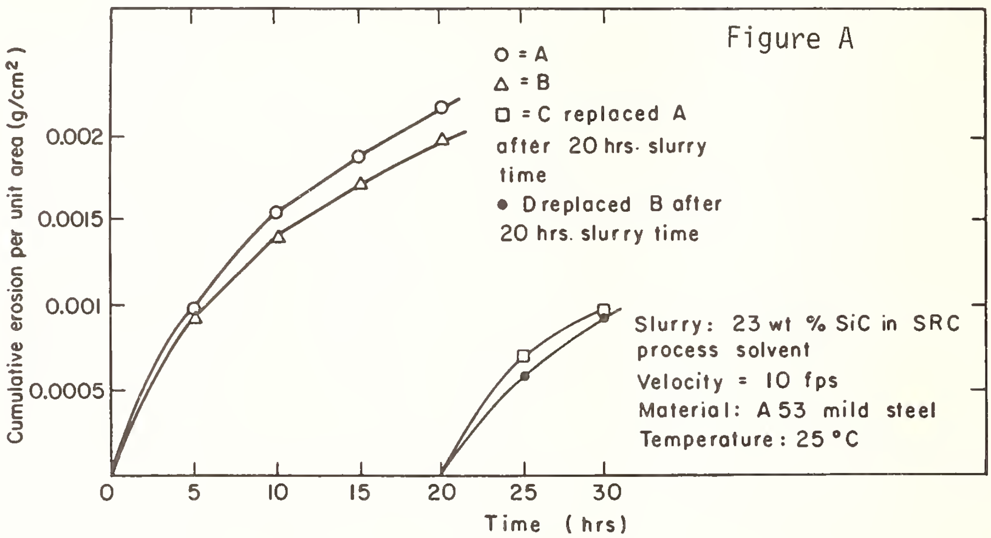
	No Alloy Carbides	Alloy Carbides
Heat Treatment	1050 °C austenitized 200 °C tempered	1050 °C austenitized 550 °C tempered
Hardness, R_c	56.9	54.2
Impact Toughness, ft-lb	17	36.5
Tensile Strength, ksi	306.0	274.3
Yield Strength, ksi	213.8	223.3
% Elongation	10	12
2-Body Wear Ratio[b]	0.6105	0.5563
3-Body Wear Ratio[c]	0.456	0.409

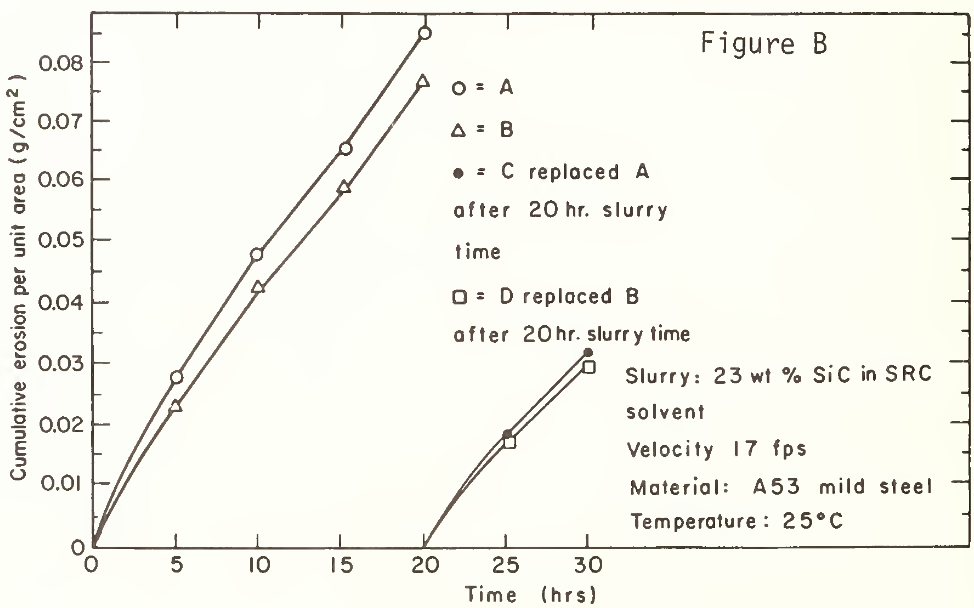
[a]Composition of the experimental steel (wt%): 0.39 C, 1.92 Mo, 3.87 Cr, 0.49 W, 0.45 V, 0.5 Mn, balance Fe.

[b]For description of 2-body wear testing see B.2.1.40.

[c]For description of 3-body wear testing see B.2.1.60.

EFFECT OF USED SLURRY[a] AND SLURRY VISCOSITY[b] ON THE EROSION[c] OF MILD STEEL[52]





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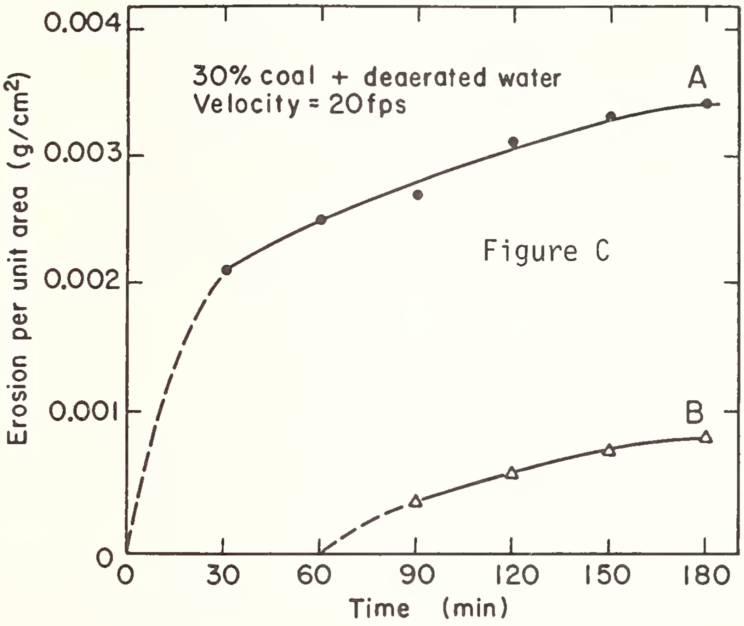
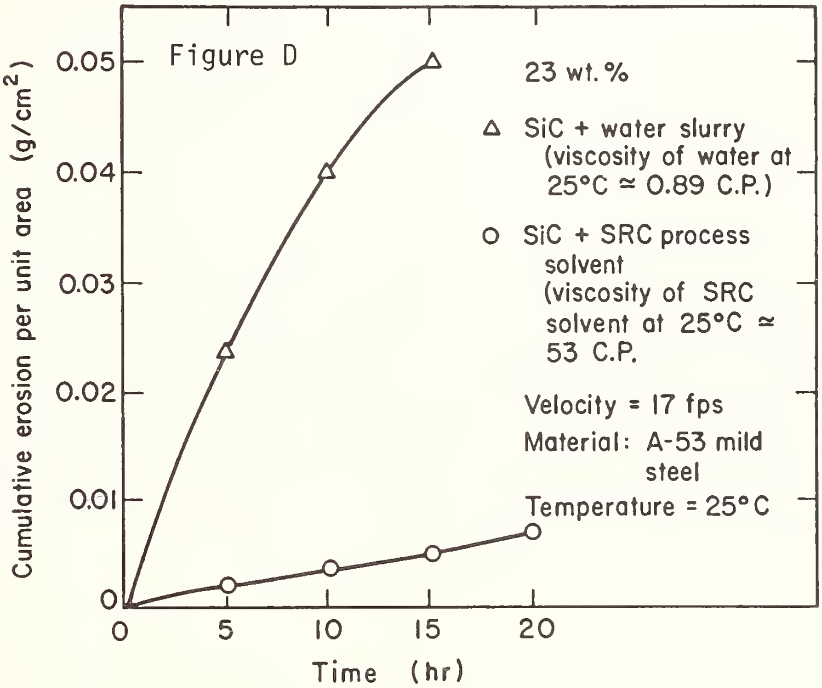
EFFECT OF USED SLURRY[a] AND SLURRY VISCOSITY[b] ON THE EROSION[c] OF MILD STEEL[52], Continued





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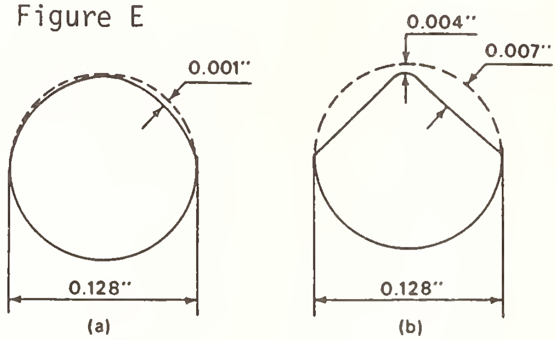
EFFECT OF USED SLURRY[a] AND SLURRY VISCOSITY[b] ON THE EROSION[c] OF MILD STEEL[52], Continued

Figure E



Cylindrical samples cross sections after:

a) 20 hours in 23% SiC + SRC process solvent at the velocity of 17 fps.

b) 4 hours and 20 minutes in 23% SiC + deaerated water at the velocity of 20 fps.

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[a]Figures A and B show the erosive effect of slurry used for 20 hours of testing on new specimens inserted into the test unit. The difference in slopes of the A and B curves at the end of the test and of the C and D curves at the beginning of the test is attributed to specimen geometry of new and eroded samples (see Figure E). Figure C shows the effect (specimen B replaced A after 60 minutes exposure) using coal-water slurry. The slopes of the two curves are not very different. Coal, being less erosive than the SiC used in the other tests, did not change specimen geometry drastically.

[b]Figure D shows the effect of varying slurry viscosity (C.P. = centipoise).

[c]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens 1/8-inch outer diameter by 2 inches long. Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The pot operates in a recirculating slurry mode. Air is excluded from the slurry by the introduction of nitrogen at a pressure slightly higher than 1 atm. The process solvent used is the Solvent Refined Coal Tacoma plant starter solvent (Koppers coal tar distillate blend). The coal is the same as that used at the Wilsonville Solvent Refined Coal plant.

EFFECT OF VELOCITY[a] ON SLURRY EROSION[b] OF MILD STEEL[52]

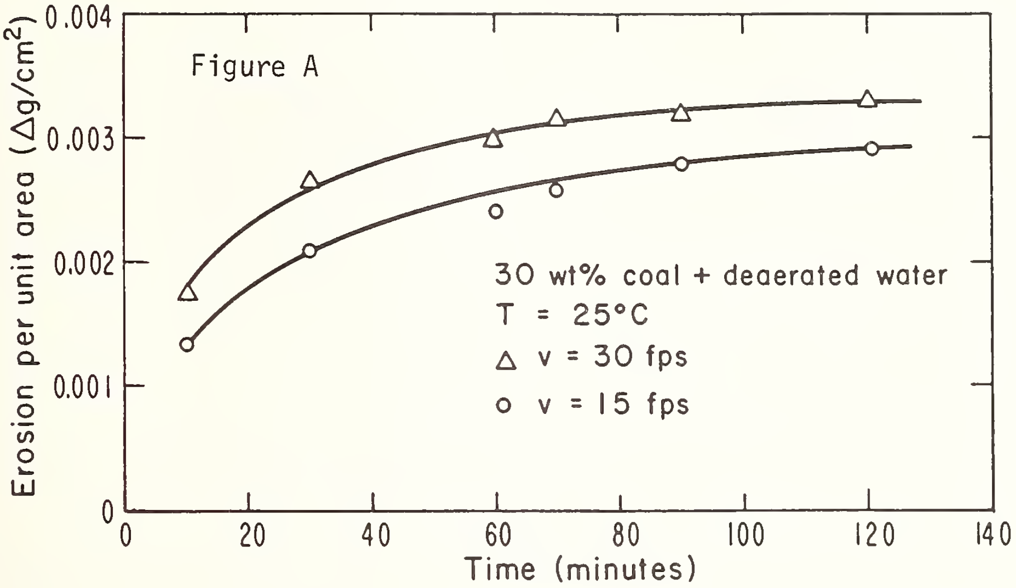
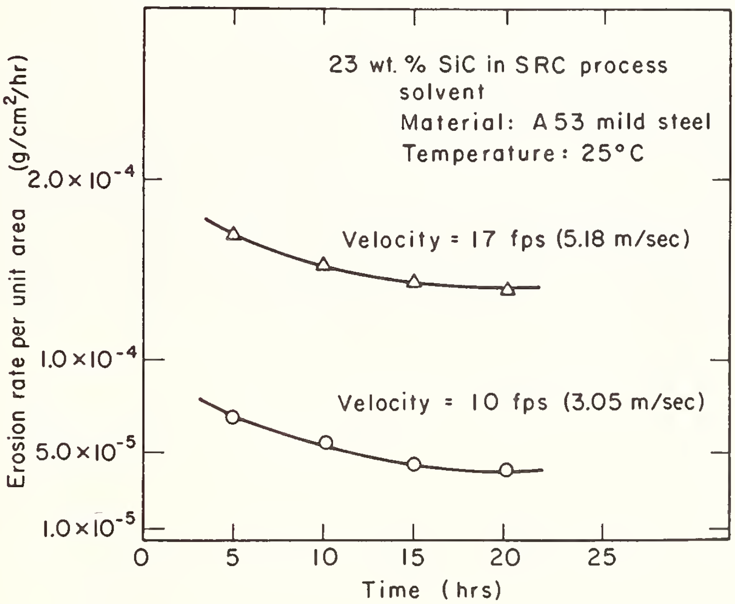


Figure B



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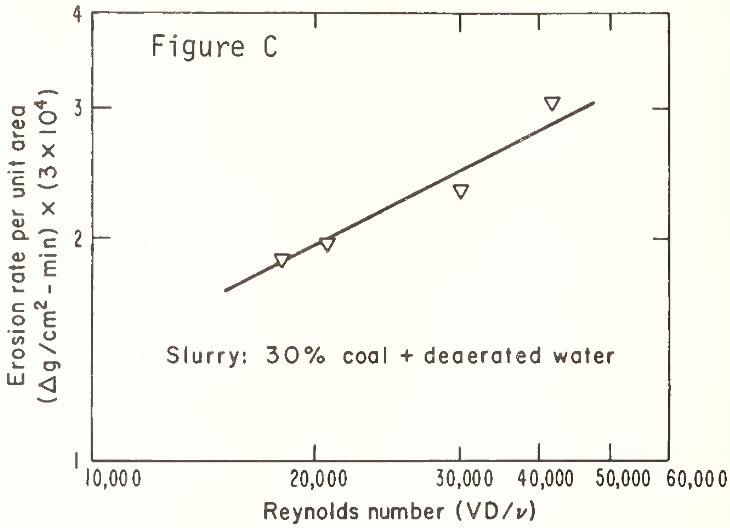
EFFECT OF VELOCITY[a] ON SLURRY EROSION[b] OF MILD STEEL[52], Continued



[a]Figure A shows the effect of velocity on cumulative erosion; Figure B shows the effect on erosion rate. Figure C shows the effect of the fluid flow field around the specimen. The Reynolds number is proportional to the ratio of the inertial force to the viscous force in a flow system (V = velocity, D = fluid density, ν = fluid viscosity).

[b]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens (1/8-inch outer diameter by 2 inches long). Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The pot operates in a recirculating slurry mode. Air is excluded from the slurry by the introduction of nitrogen at a pressure slightly higher than 1 atm. The process solvent used is the Solvent Refined Coal Tacoma plant starter solvent (Koppers coal tar distillate blend). The coal is the same as that used at the Wilsonville Solvent Refined Coal plant.

SLURRY EROSION TESTING OF MILD STEEL BY JET IMPINGEMENT[a] AND THE EFFECT OF VELOCITY AND IMPINGEMENT ANGLE[b][52]

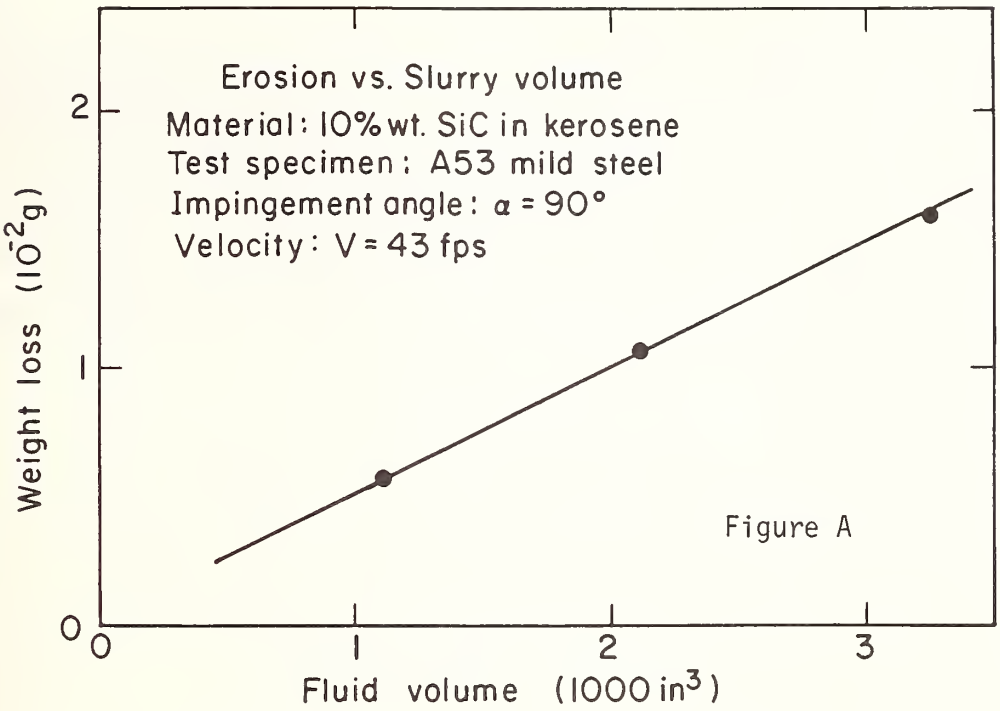


Figure A

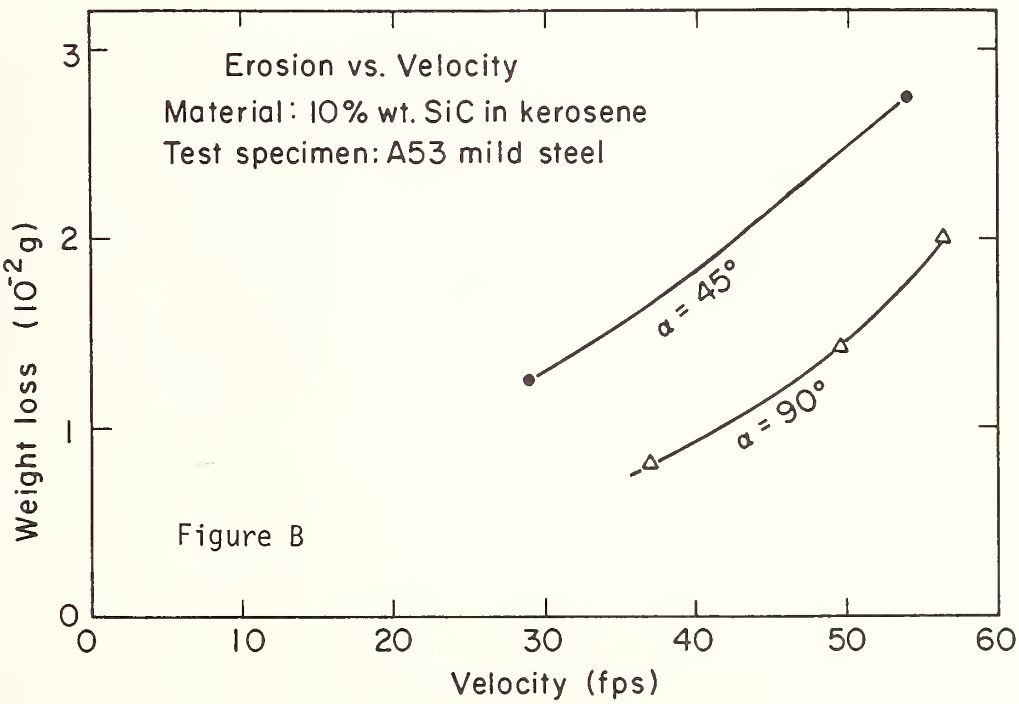


Figure B

(Data Continued)

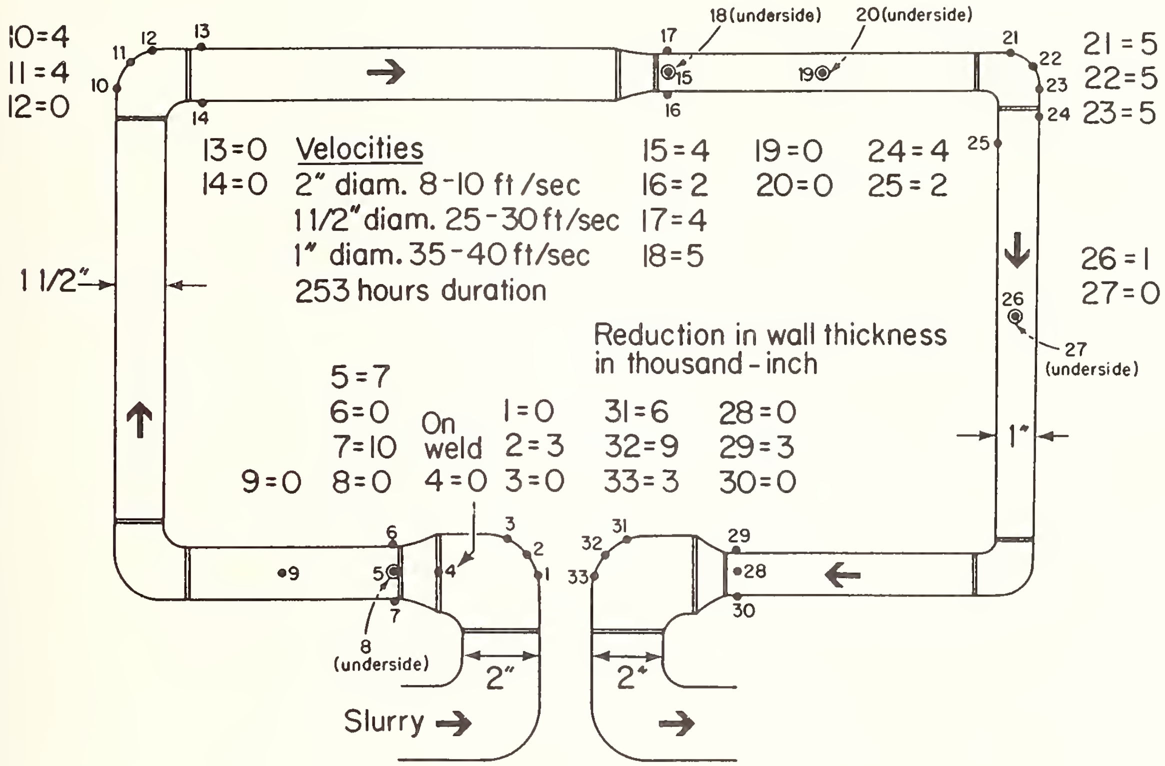
SLURRY EROSION TESTING OF MILD STEEL BY JET IMPINGEMENT[a] AND THE EFFECT OF VELOCITY AND IMPINGEMENT ANGLE[b][52], Continued

Footnotes

[a]Slurry erosion testing was performed with a jet impingement tester. A pressurized gas-fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The tester operates in a once-through slurry mode (as opposed to the circulating slurry mode, see Sections B.2.1.62 and B.2.1.63). Figure A shows a constant erosion rate, indicating that there was no breakdown of particles in these tests which do not recirculate the slurry.

[b]Figure B shows the effect of velocity at different impingement angles.

RECIRCULATING SLURRY LOOP EROSION[a] OF MILD STEEL[53]



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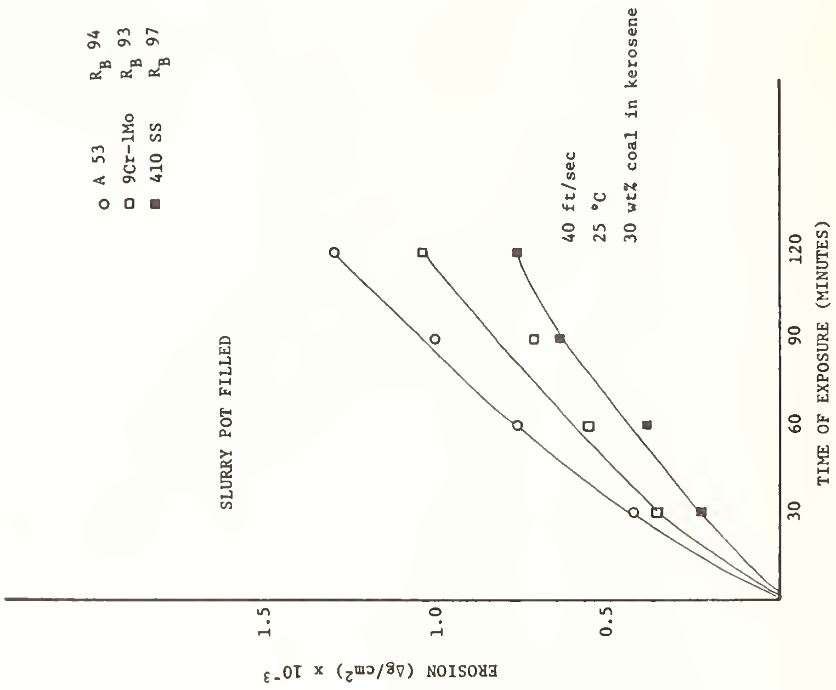
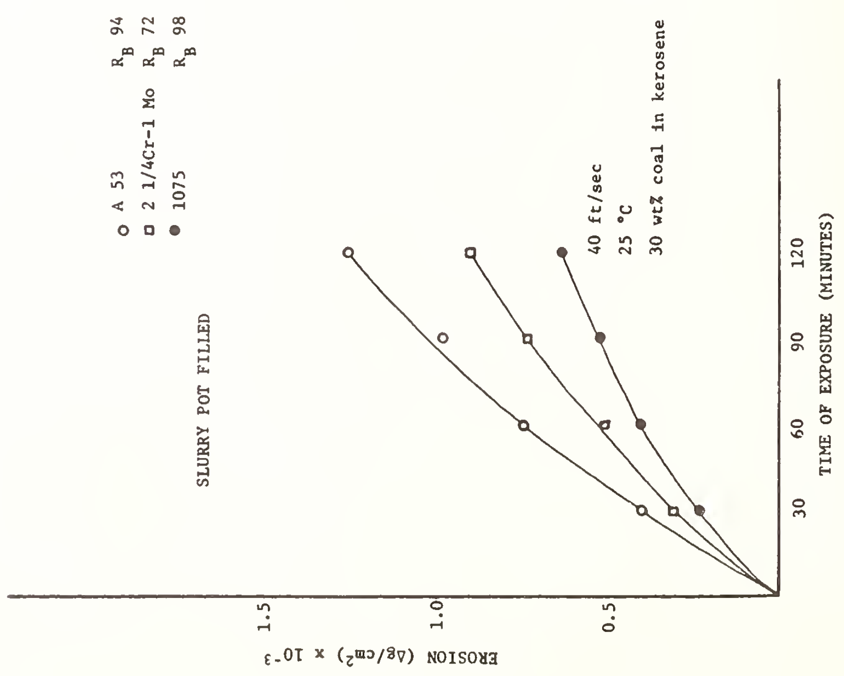
[a]A side loop was fabricated of A-53 mild steel for erosion testing. The coal used was the same -200 mesh Illinois # 6 coal used in the Wilsonville Solvent Refined Coal pilot plant. The slurry consisted of 30 wt % coal in kerosene. The slurry was circulated for 253 hours. The tests were at ambient temperatures but the pipe wall temperatures increased to 90 °C because of the frictional heating of the moving slurry. The reduction in wall thickness, measured with an ultrasonic thickness gauge, is recorded on the above diagram in thousandths of an inch against the tube wall location, i.e., 10 = 4 indicates that location 10 was reduced in wall thickness by 0.004 inch.

SLURRY EROSION TESTING[a] OF VARIOUS ALLOYS[53]





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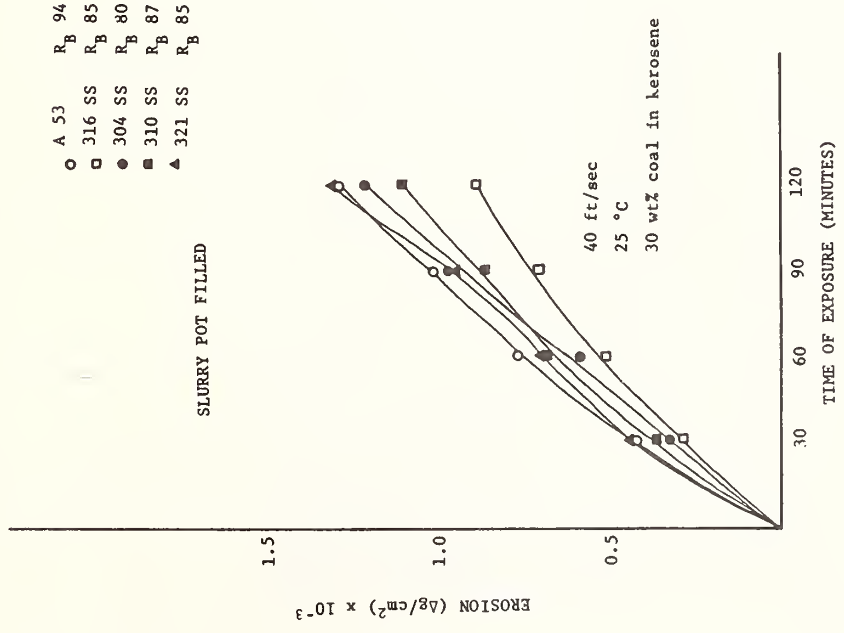
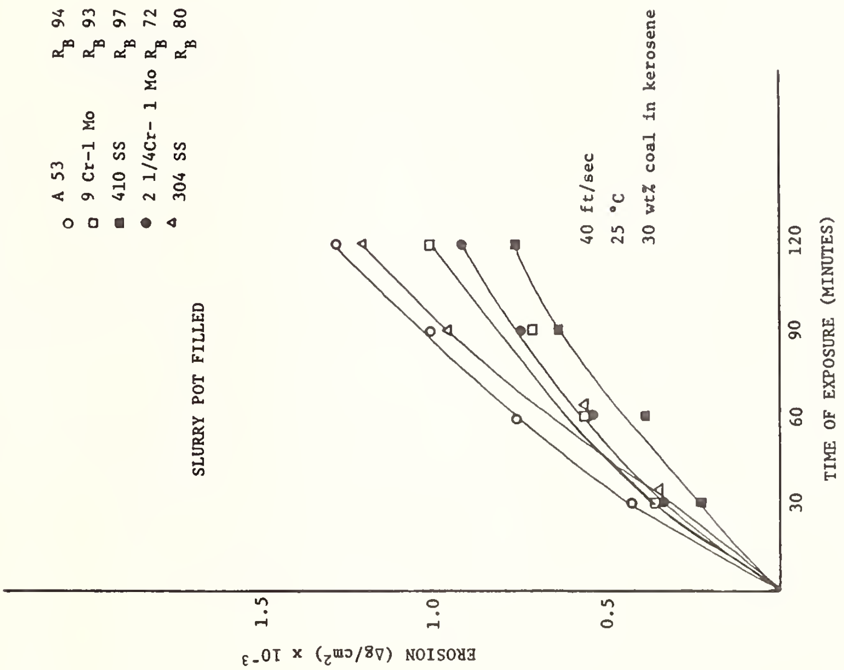
SLURRY EROSION TESTING[a] OF VARIOUS ALLOYS[53], Continued



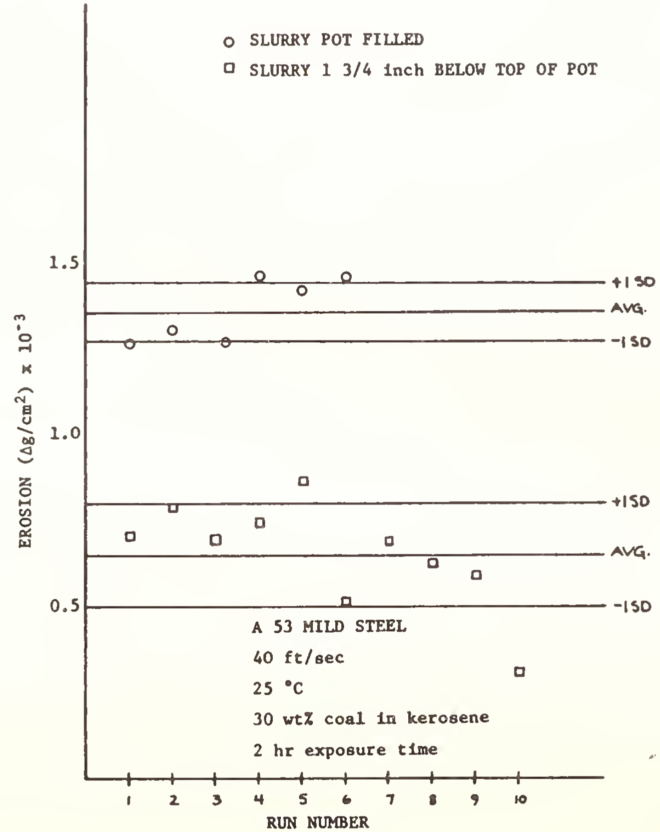


(Data Continued)

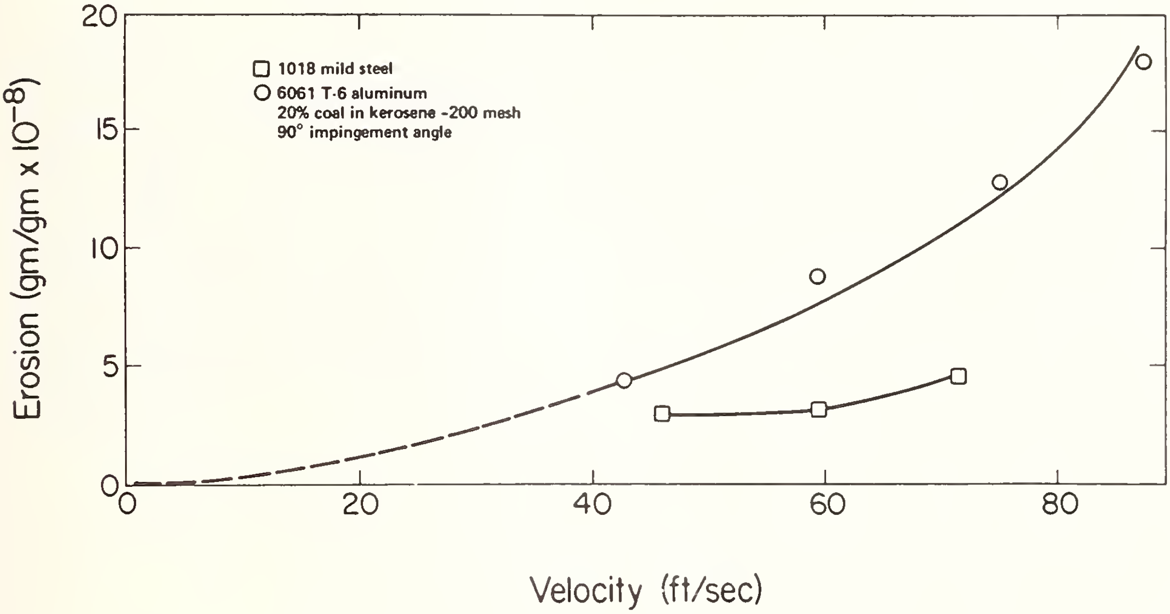
SLURRY EROSION TESTING[a] OF VARIOUS ALLOYS[53], Continued

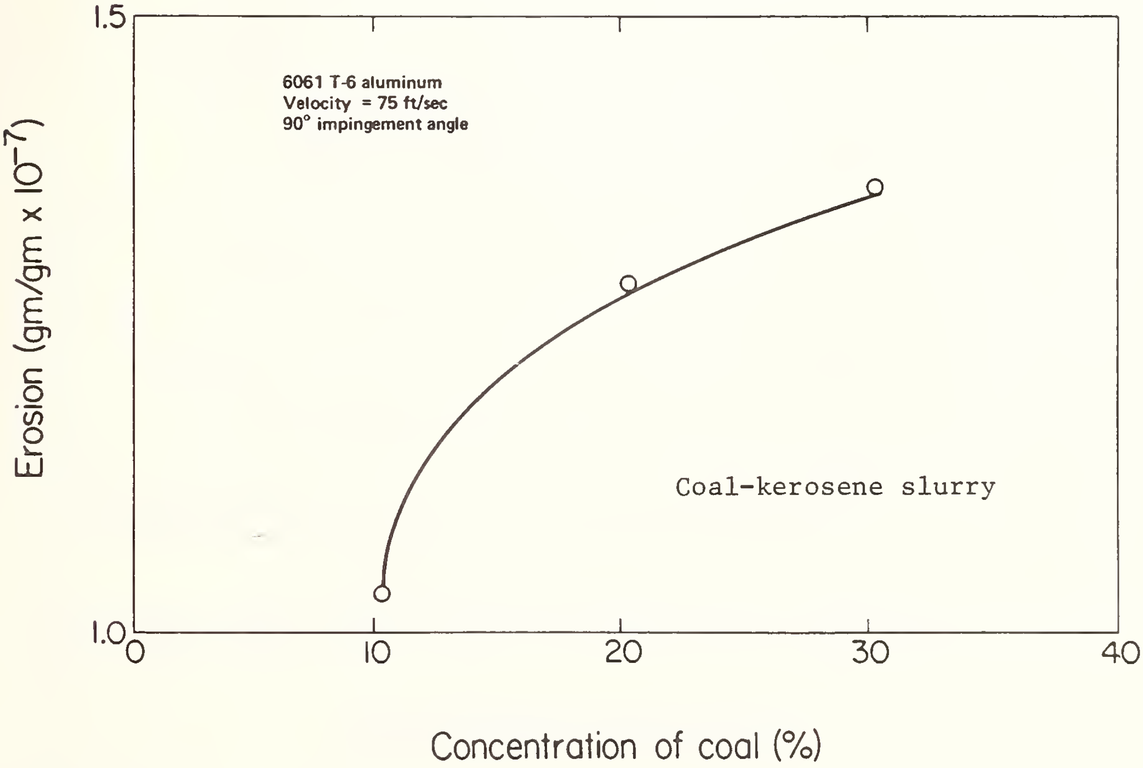
Footnote

[a]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens (1/8-inch outer diameter by 2 inches long). Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The pot operates in a recirculating slurry mode. The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. The slurry medium was kerosene. Cumulative erosion is plotted against test time. Reproducibility of the slurry pot testing was found to be better when air was excluded by filling the pot completely with slurry (see the adjacent figure). Apparently air above the slurry is stirred in and forms cushions around the coal particles reducing their erosive potential.



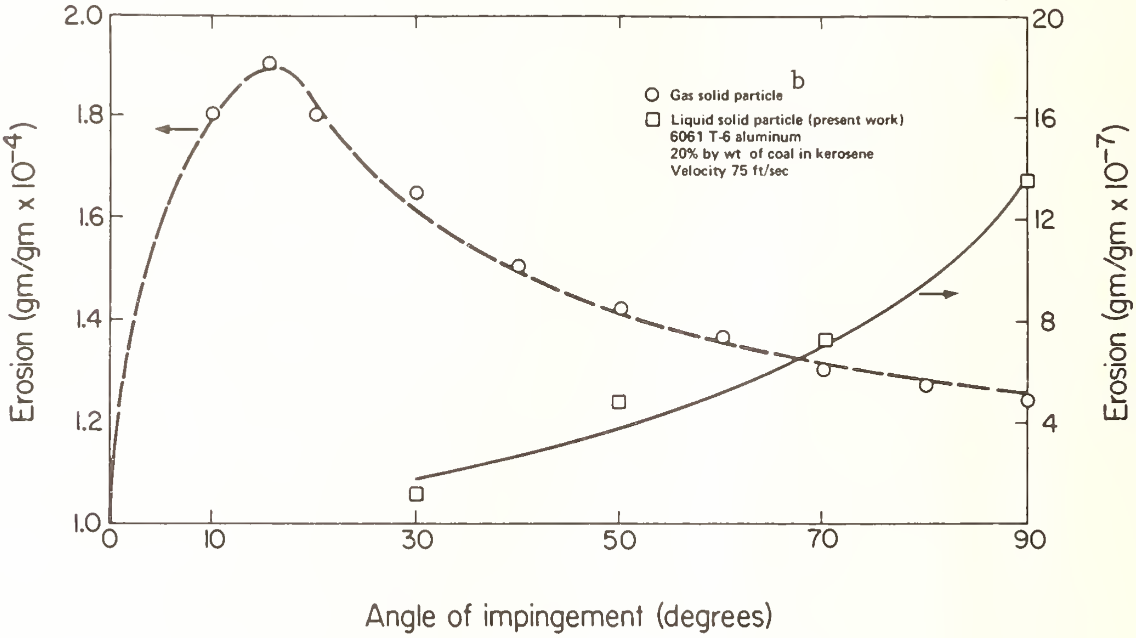
EFFECT OF VELOCITY, COAL CONCENTRATION, IMPINGEMENT ANGLE, AND VARIOUS ERODENT PARTICLES ON SLURRY EROSION[a][53]

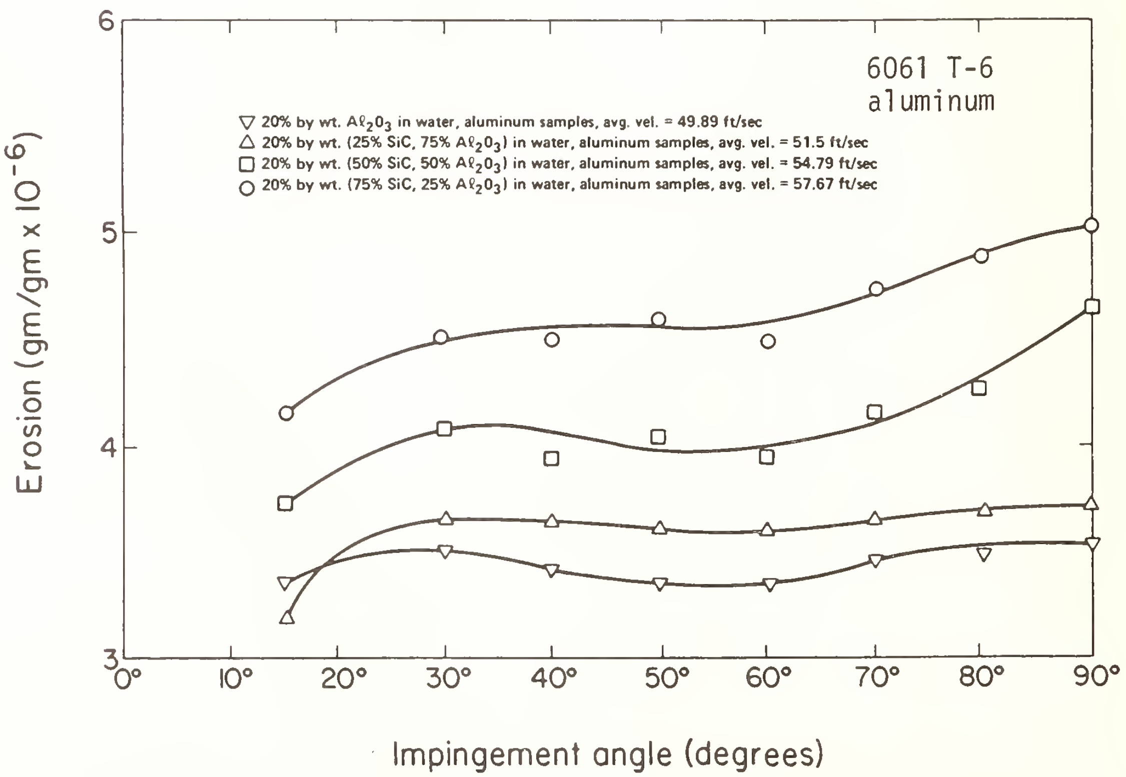




(Data Continued)

EFFECT OF VELOCITY, COAL CONCENTRATION, IMPINGEMENT ANGLE, AND VARIOUS ERODENT PARTICLES ON SLURRY EROSION[a] [53], Continued





(Data Continued)

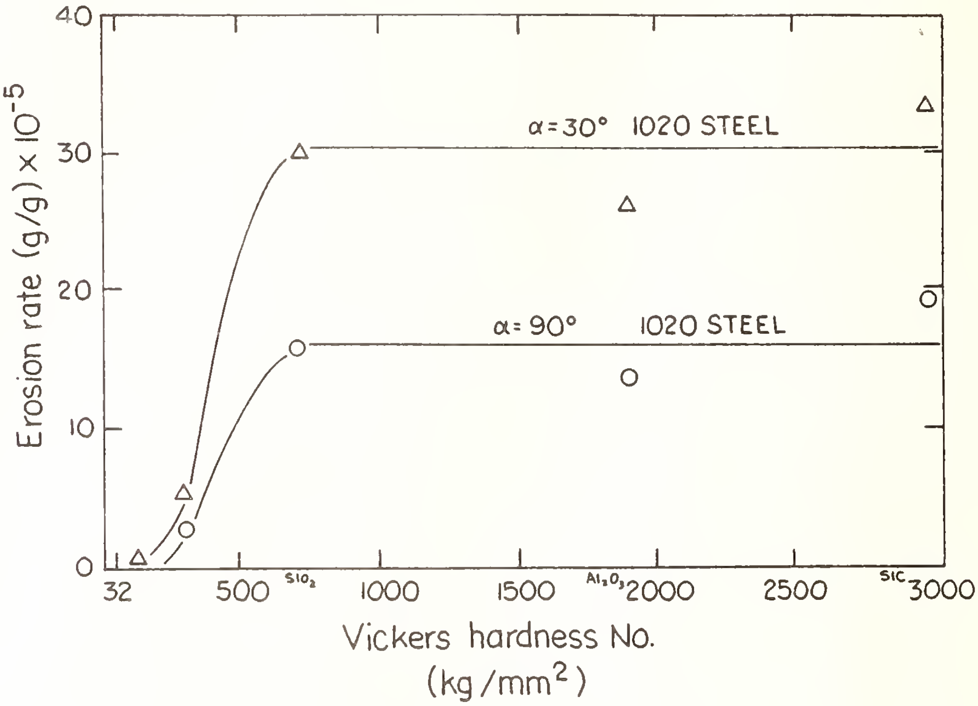
EFFECT OF VELOCITY, COAL CONCENTRATION, IMPINGEMENT ANGLE, AND VARIOUS ERODENT PARTICLES ON SLURRY EROSION[a][53], Continued

Footnotes

[a]Slurry erosion testing was performed with a jet impingement tester. A pressurized gas fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The tester operates in a once-through slurry mode (see Section B.2.1.64). The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. Typically 20 gallons of slurry were directed at a specimen in a 10-15 minute test. The weight loss of the specimens divided by the weight of the coal in the amount of slurry used is calculated to give the erosion data plotted above.

[b]Literature data; classic curve for gas-solid particle erosion of a ductile metal.

EFFECT OF ERODENT HARDNESS[a] ON EROSION RATE[b] OF 1020 STEEL[53]



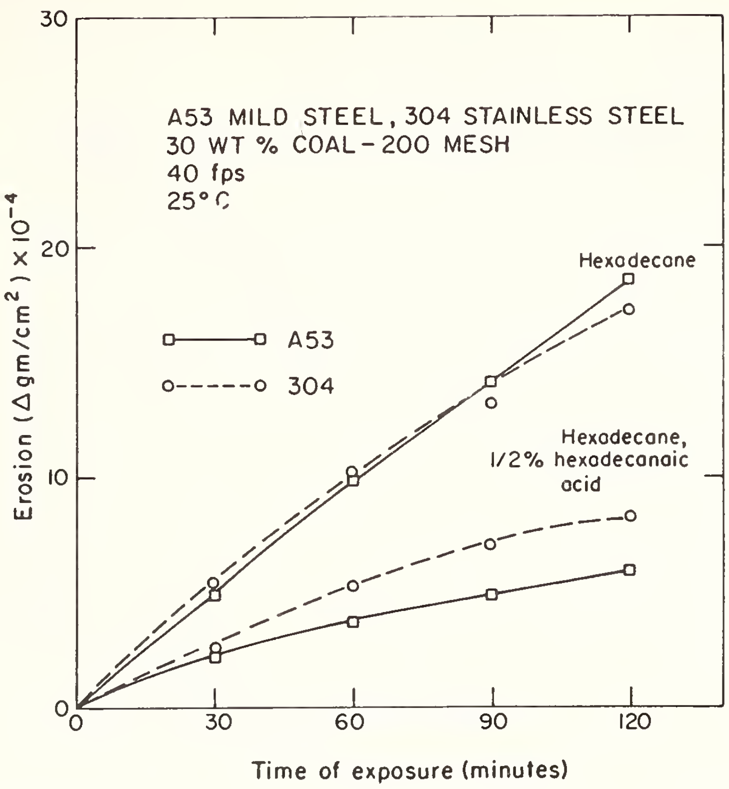
[a]Erodents used were the following:

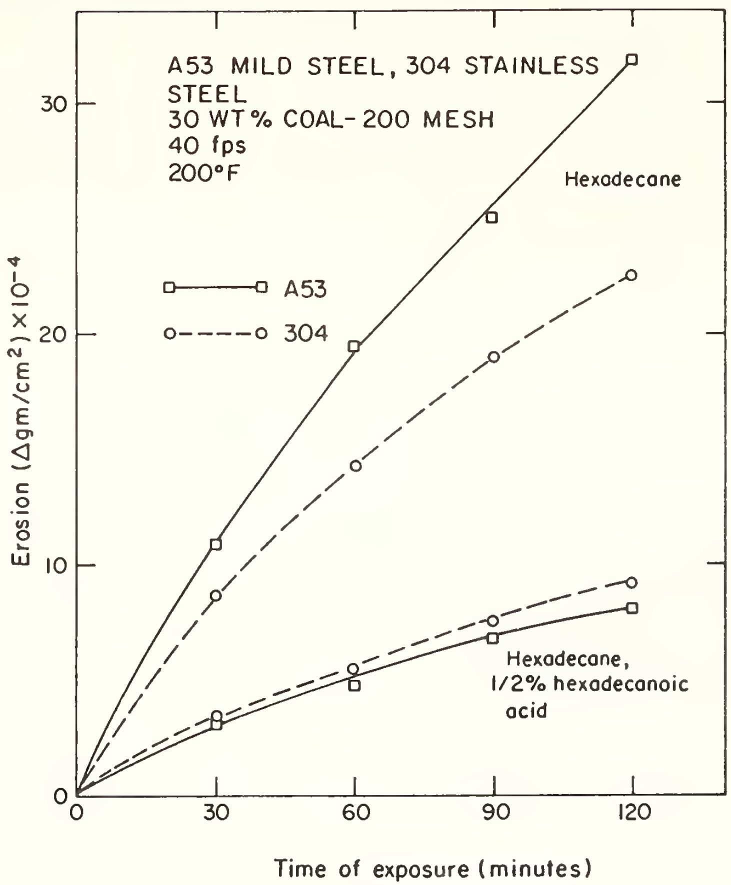
Erodent	Mohs Hardness	Vickers Hardness (kg/mm^2)
Calcite, $CaCO_3$	3	115
Apatite, $Ca_5(OH,F,Cl)(PO_4)_3$	5	300
Sand, SiO_2	7	700
Alumina, Al_2O_3	9	1900
Silicon carbide, SiC	>9	3000

Average particle size was 250 μm.

[b]Specimens were eroded at particle velocity of 60 m/s at 30° and 90° impingement angles (α) in a tester using air as the carrier gas. The nozzle diameter was 0.8 cm, the nozzle-to-specimen distance 1.3 cm. The erosion rate is the weight loss of specimen divided by the weight of erodent used.

EFFECT OF LUBRICITY[a] OF SLURRY ON EROSION[b] OF STEELS[53]





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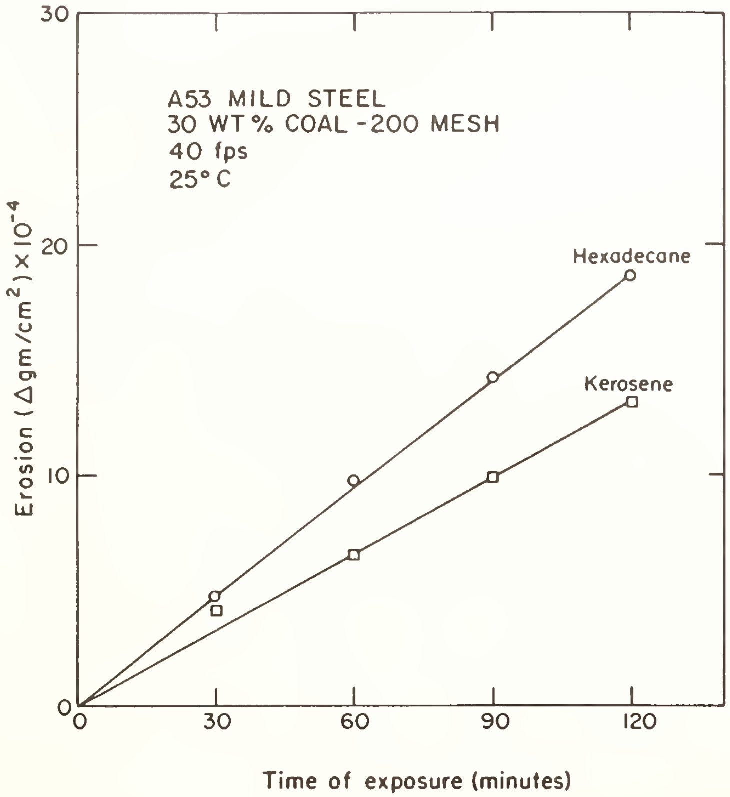
EFFECT OF LUBRICITY[a] OF SLURRY ON EROSION[b] OF STEELS[53], Continued



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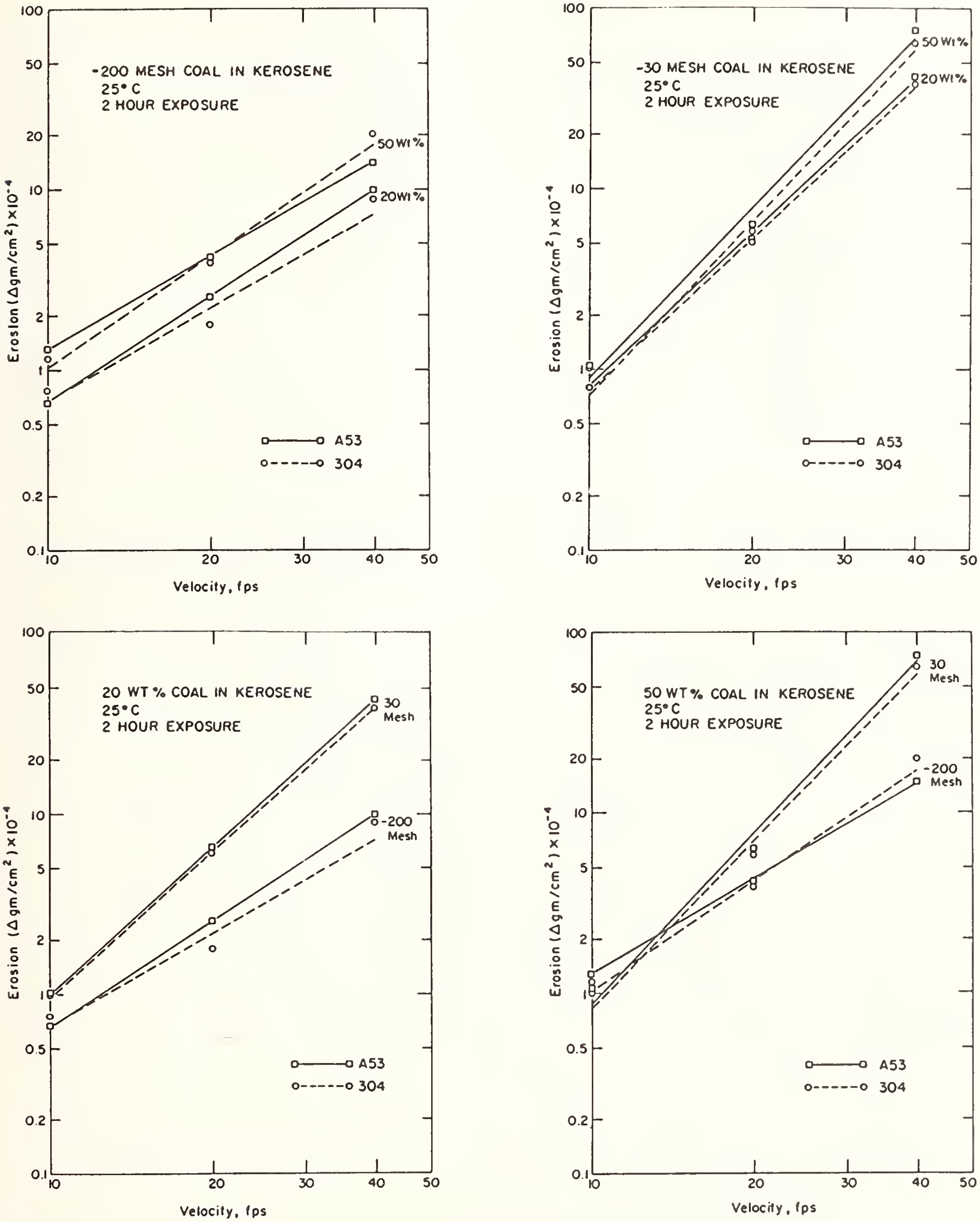
[a]Kerosene, hexadecane, and hexadecane with 1/2 % hexadecanoic acid added were used as the liquid medium of the slurry to study the effect of increasing the lubricity of the medium. The effect of temperature can be seen by comparing the first two figures.

[b]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens (1/8-inch outer diameter by 2 inches long). Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The pot operates in a recirculating slurry mode. The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant.

EFFECT OF COAL PARTICLE SIZE,[a] COAL CONCENTRATION,[b] AND VELOCITY[c] ON THE SLURRY EROSION[d] OF STEELS[e][53]



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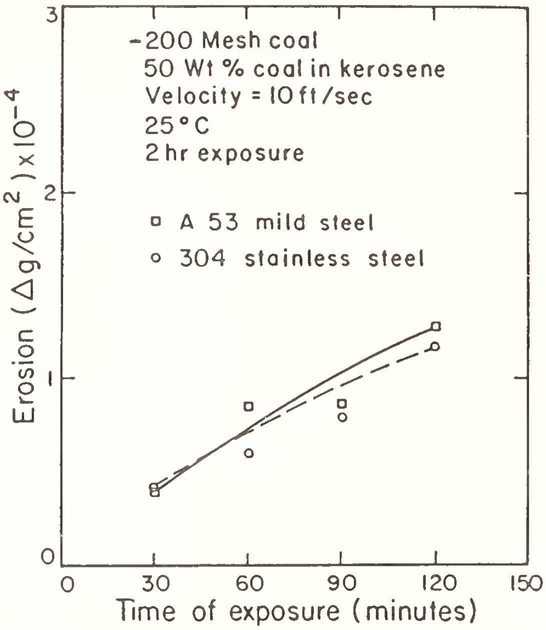
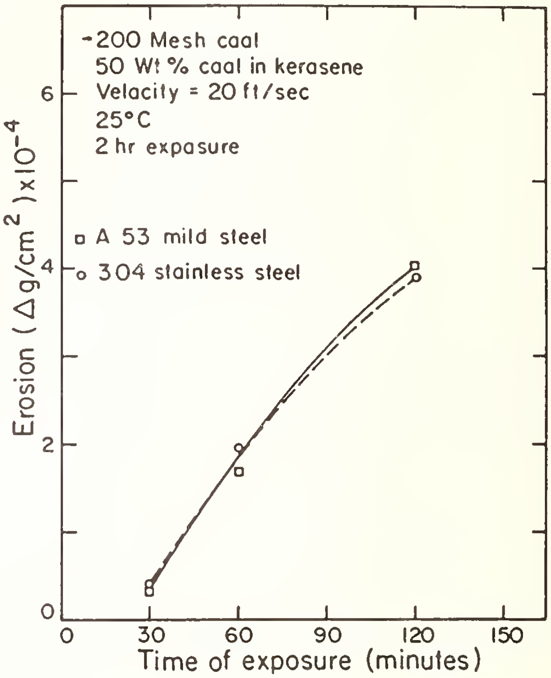
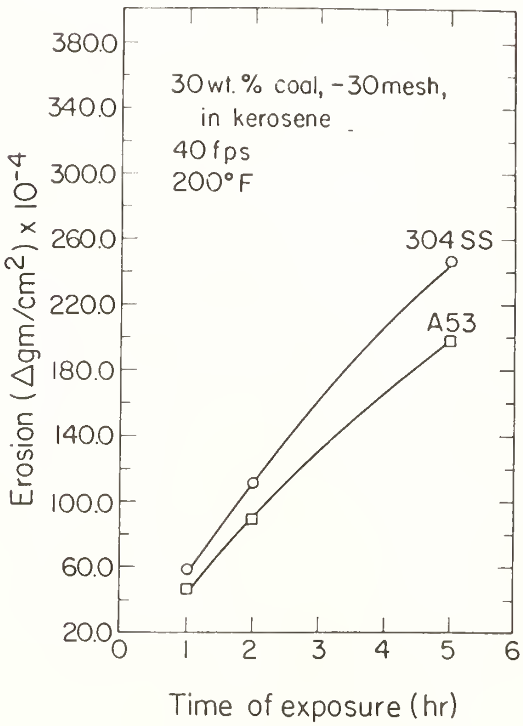
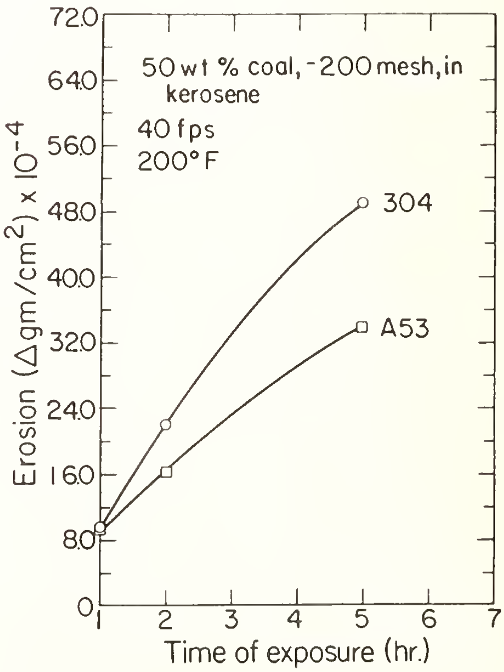
EFFECT OF COAL PARTICLE SIZE,[a] COAL CONCENTRATION,[b] AND VELOCITY[c] ON THE SLURRY EROSION[d] OF STEELS[e][53], Continued









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EFFECT OF COAL PARTICLE SIZE,[a] COAL CONCENTRATION,[b] AND VELOCITY[c] ON THE SLURRY EROSION[d] OF STEELS[e][53], Continued

Footnotes

[a]Illinois #6 coal (same coal used in Wilsonville Solvent Refined Coal plant) was used, in -200 mesh and in -30 mesh sizes.

[b]Two coal concentrations for the slurry were used: 20 weight percent and 50 weight percent.

[c]Tests were made at velocities of 10, 20, and 40 feet/second.

[d]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens (1/8-inch outer diameter by 2 inches long). Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The pot was kept full to exclude air from the slurry (see Section B.2.1.66).

Figure A shows the reproducibility of the slurry pot tests on the two alloys tested in a 20 wt% coal-kerosene slurry at 25 °C.

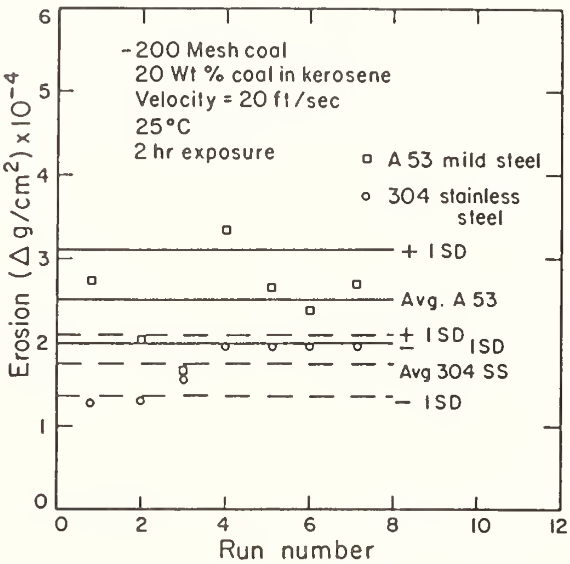


Figure A

Figure B shows the reproducibility of tests using fresh and used slurry. The tests were made with specimens of 1018 steel, 5 cm long by 3 mm diameter rods, eroded for four hours in a 30 wt % -200 mesh coal-kerosene slurry at 10 m/s velocity at 25 °C. The used material refers to a rod which had already been subjected to 4 hours of erosion previously. Initial differences in the curves are probably due to initial roughness of specimens, once polished by the slurry the rates are much the same. There is apparently little comminution of coal particles.

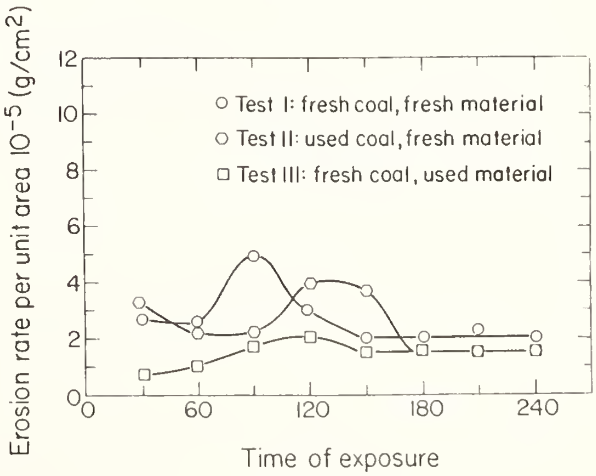
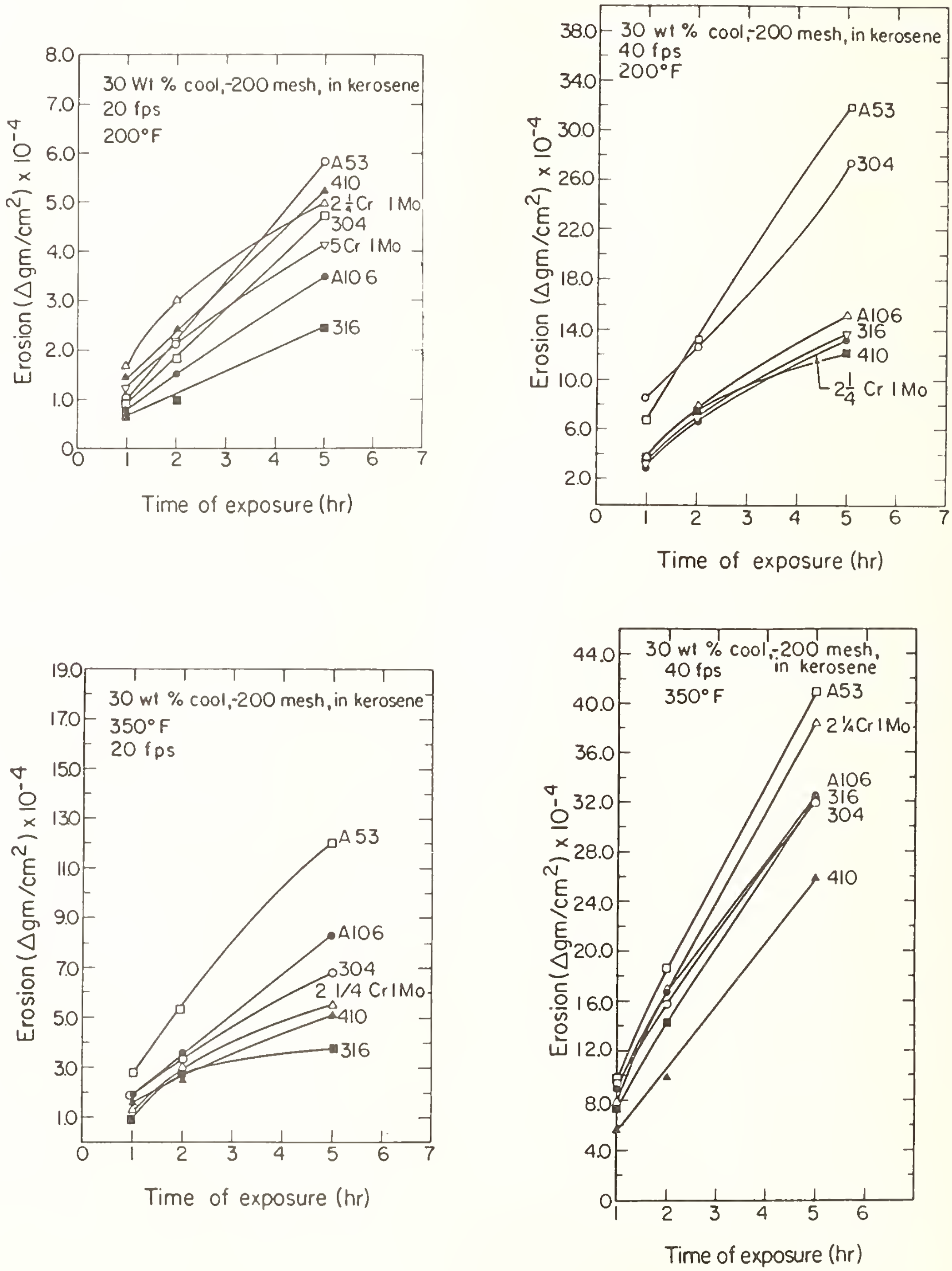


Figure B

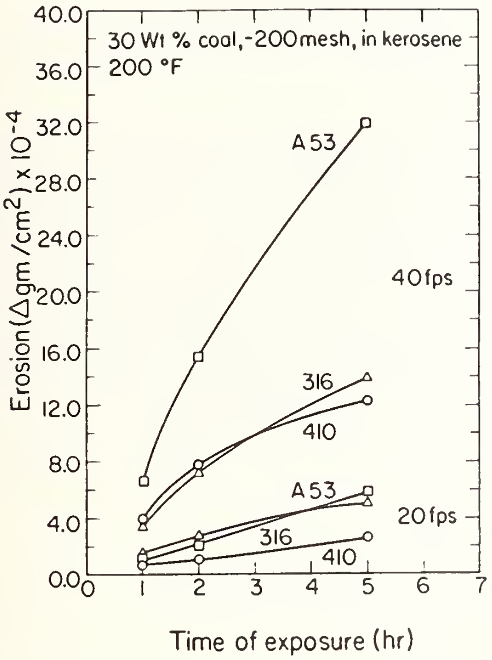
[e]A53 mild steel and 304 stainless steel.

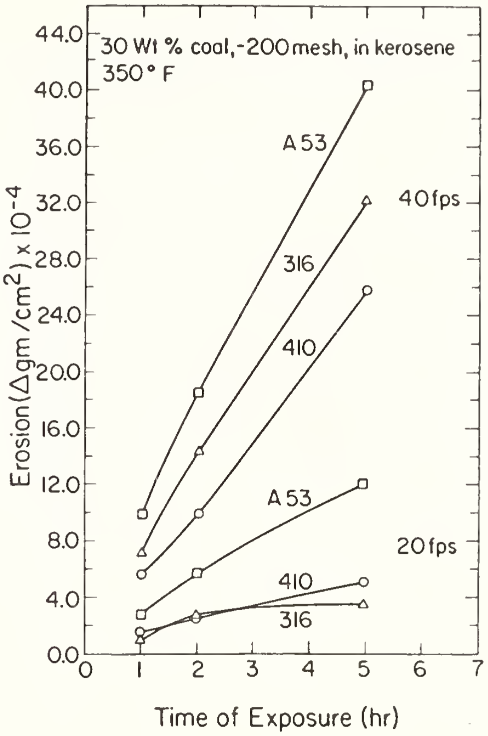
EFFECT OF VELOCITY,[a] TEMPERATURE,[b] AND EXPOSURE TIME,[c] ON SLURRY EROSION[d] OF SEVERAL ALLOYS[e][53]

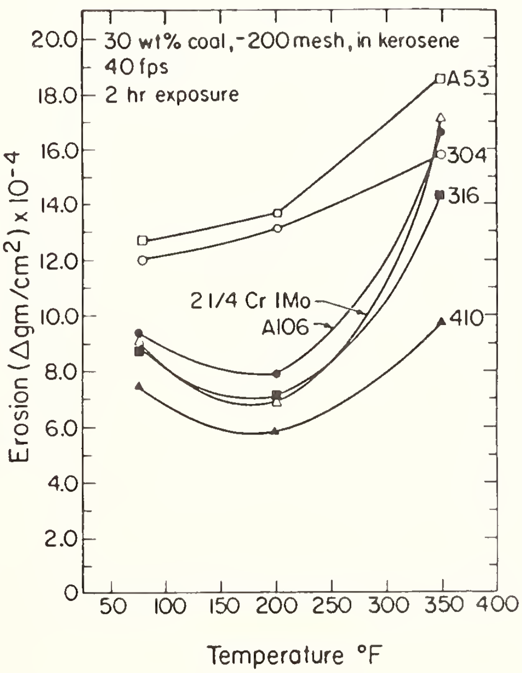


(Data Continued)

EFFECT OF VELOCITY,[a] TEMPERATURE,[b] AND EXPOSURE TIME,[c] ON SLURRY EROSION[d] OF SEVERAL ALLOYS[e][53], Continued







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(Data Continued)

EFFECT OF VELOCITY,[a] TEMPERATURE,[b] AND EXPOSURE TIME,[c] ON SLURRY EROSION[d] OF SEVERAL ALLOYS[e][53], Continued

Footnotes

[a]Tests were run at 20 and 40 feet/second velocity.

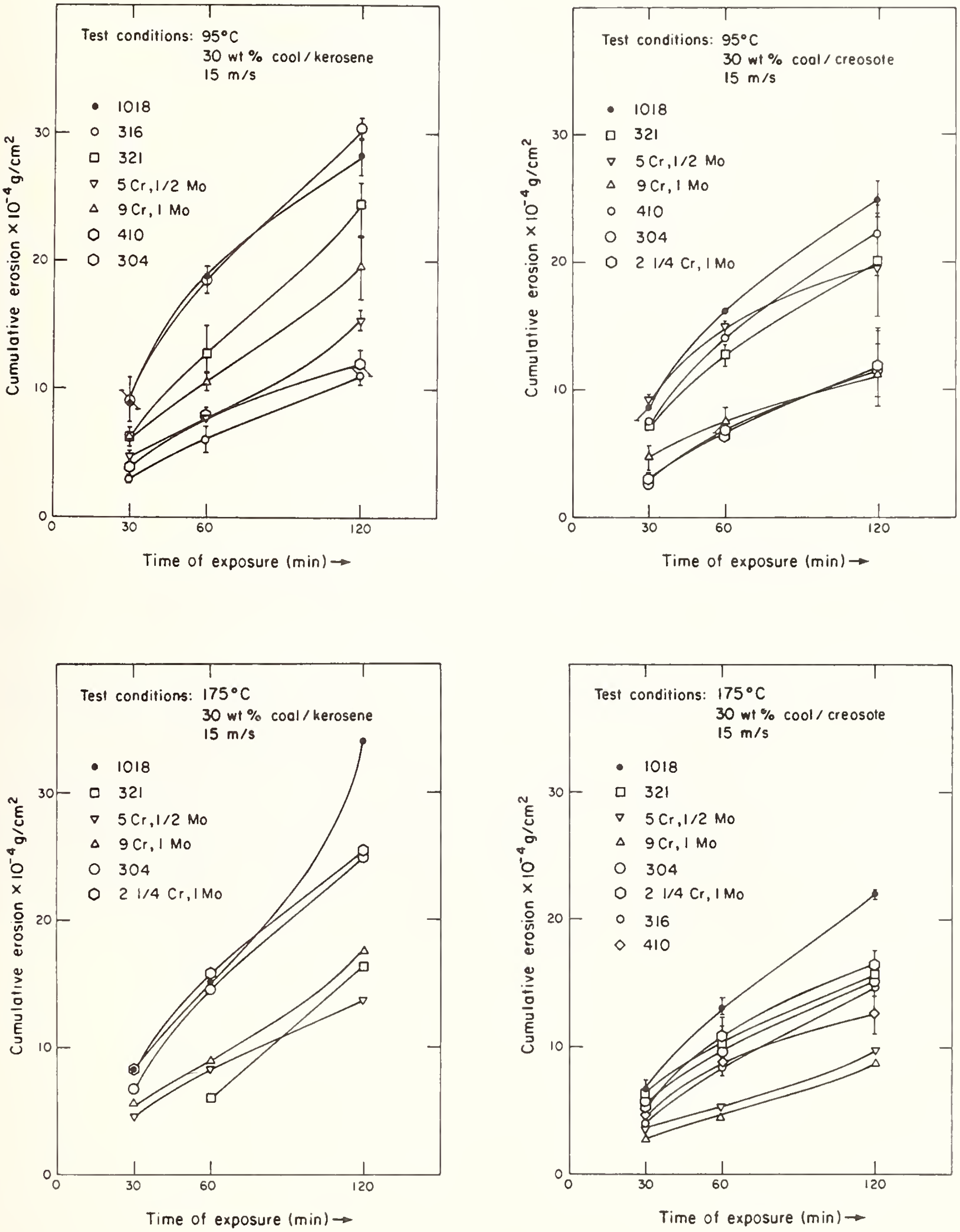
[b]Tests were run at ambient temperature (25 °C, 77 °F) and at 200 and 350 °F.

[c]Tests were of 1, 2, and 5 hour durations.

[d]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens (1/8-inch outer diameter by 2 inches long). Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. The pot was kept full to exclude air from the slurry (see Section B.2.1.66). The slurry pot was modified to operate at elevated temperatures. A reflux condenser returned the vapors to the pot when it was operated above 300 °F. See footnote d of Section B.2.1.70 for data on the reproducibility of tests at 25 °C.

[e]A53 mild steel, A106 carbon steel, 304, 316, and 410 stainless steels, 2-1/4 Cr-1 Mo steel, and 5 Cr-1 Mo steel.

EFFECT OF SLURRY LIQUID[a] ON SLURRY EROSION[b] OF SEVERAL ALLOYS[c][53]



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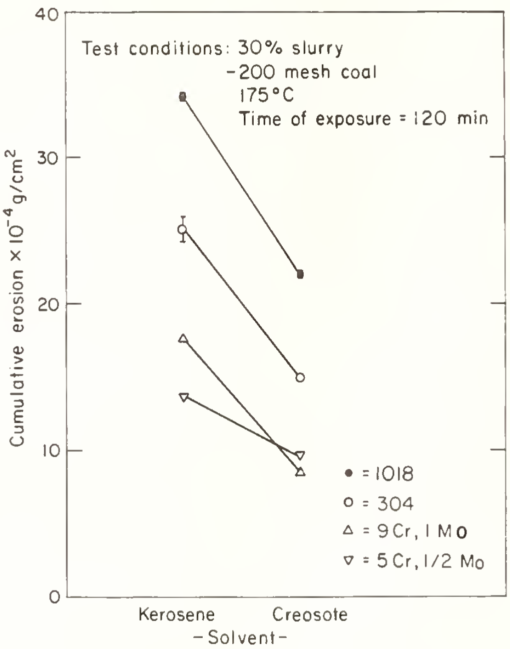
(Data Continued)

EFFECT OF SLURRY LIQUID[a] ON SLURRY EROSION[b] OF SEVERAL ALLOYS[c] [53], Continued



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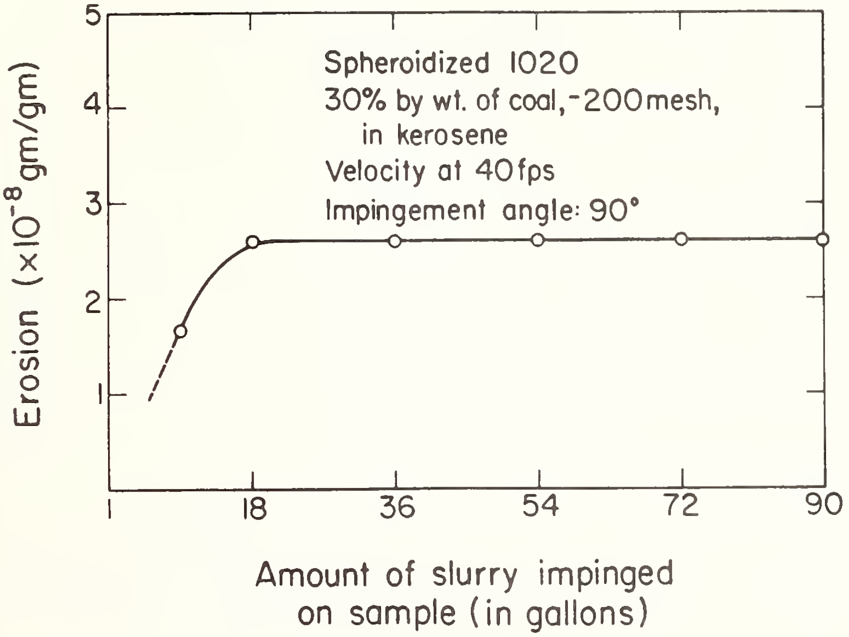
[a]Slurry consisted of 30 weight percent coal (the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant) in kerosene or creosote oil.

[b]Erosion testing was performed in a 2-liter slurry pot with circulating cylindrical specimens (1/8-inch outer diameter by 2 inches long). Specimens were suspended vertically in the pot at selected radii from a central stirring shaft. The pot was kept full to exclude air from the slurry (see Section B.2.1.66). The slurry pot was modified to operate at elevated temperatures. A reflux condenser returned the vapors to the pot. The above tests were run at 95 °C (203 °F) and 175 °C (347 °F).

[c]1018 carbon steel, 304, 316, 321, and 410 stainless steels, 2-1/4 Cr-1 Mo, 5 Cr-1 Mo, and 9 Cr-1 Mo steels.

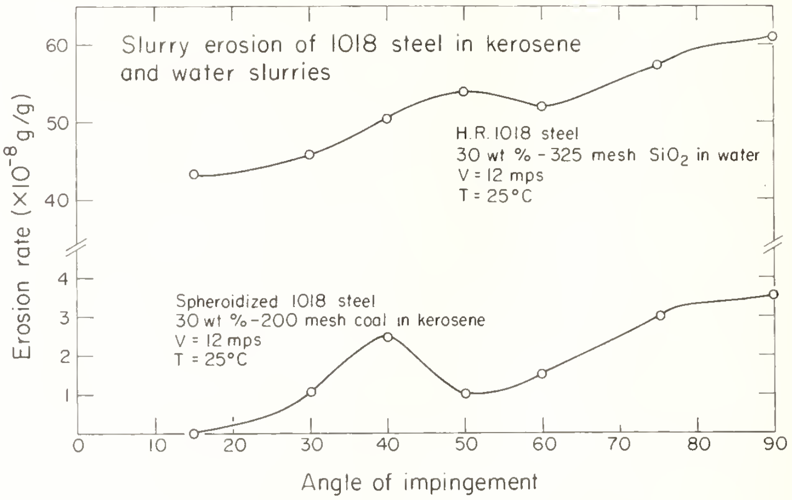
EFFECT OF SUCCEEDING QUANTITIES[a] OF SLURRY ON EROSION BY JET IMPINGEMENT[b][53]



[a]Eighteen gallons of slurry were used per test on the same specimen. Each succeeding 18 gallons on that specimen resulted in the same amount of erosion of the 1020 steel used in the test.

[b]A pressurized gas fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The tester operates in a once-through slurry mode. The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. The tests at 40 ft/s took 11 minutes each to use 18 gallons of slurry.

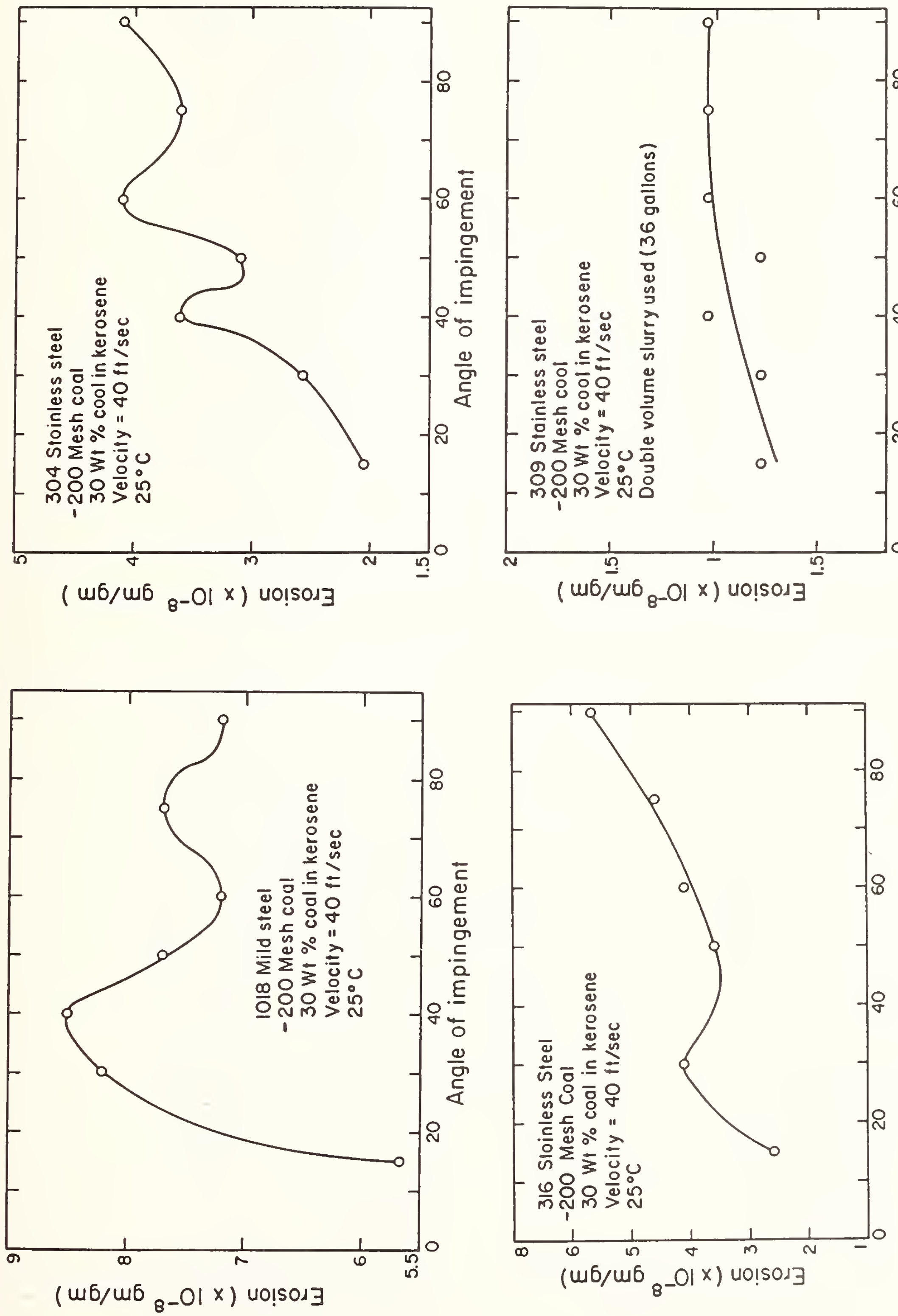
EFFECT OF A LOW-VISCOSITY MEDIUM[a] ON JET IMPINGEMENT SLURRY TESTING[b][53]



[a]To determine the erosion behavior of ductile materials in slurries of lower viscosity than kerosene, water was used with -325 mesh SiO_2 (-200 mesh coal could not be suspended evenly in water). The smaller particle sand would have the same erosiveness as the larger particle coal.

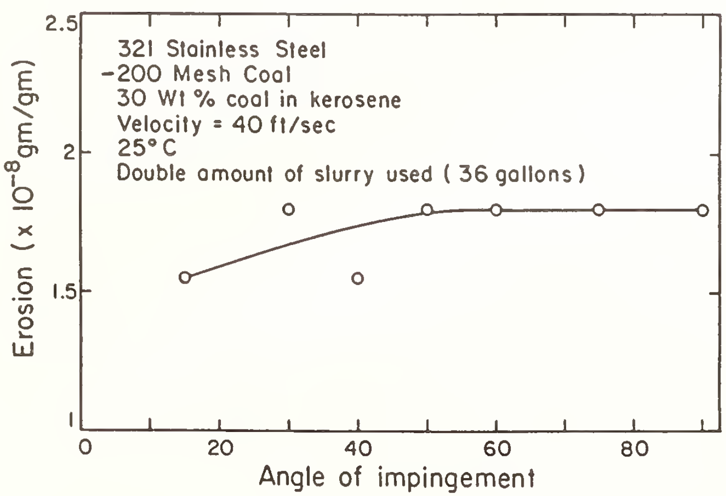
[b]A pressurized gas fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The tester operates in a once-through slurry mode. Nine gallons of slurry were used in each test. Specimens were polished with 320 grit SiC before testing. The coal used is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant.

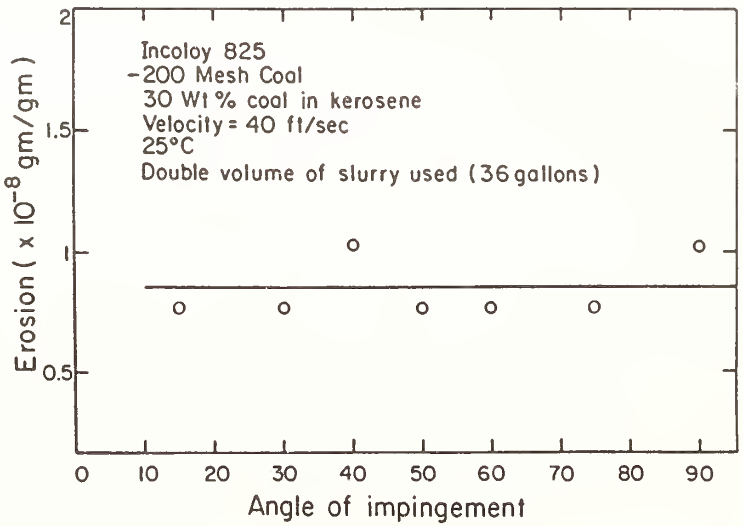
EFFECT OF IMPINGEMENT ANGLE ON THE SLURRY EROSION[a] OF SEVERAL ALLOYS[b][53]



(Data Continued)

EFFECT OF IMPINGEMENT ANGLE ON THE SLURRY EROSION[a] OF SEVERAL ALLOYS[b][53], Continued





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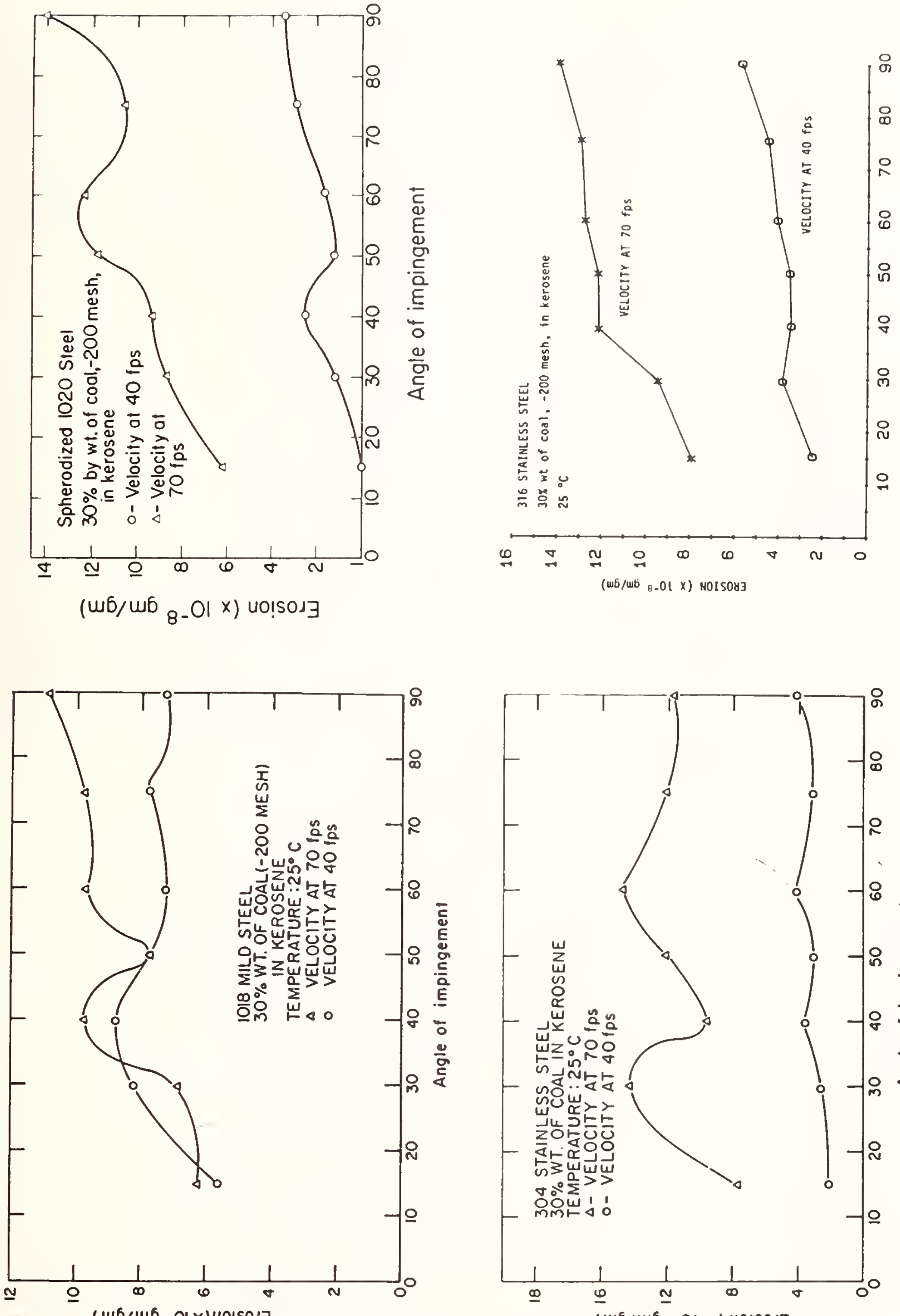
[a]Slurry erosion testing was performed with a jet impingement tester. A pressurized gas fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The tester operates in a once-through slurry mode (see Section B.2.1.64 and Sections B.2.1.71 and B.2.1.72 for slurry pot erosion testing of some of the same alloys). The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. Eighteen gallons of slurry were used for each test. At 40 ft/s each test took 11 minutes. The erosion plotted above is the weight loss of the sample divided by the weight of the coal in 18 gallons of slurry. In order to have measurable erosion for three of the alloys, double the amount of slurry had to be used in each test.

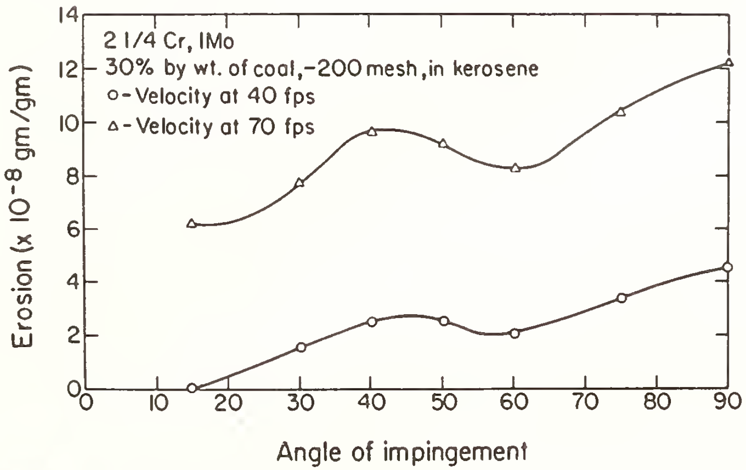
[b]Specimens were polished with 600 grit SiC before testing.

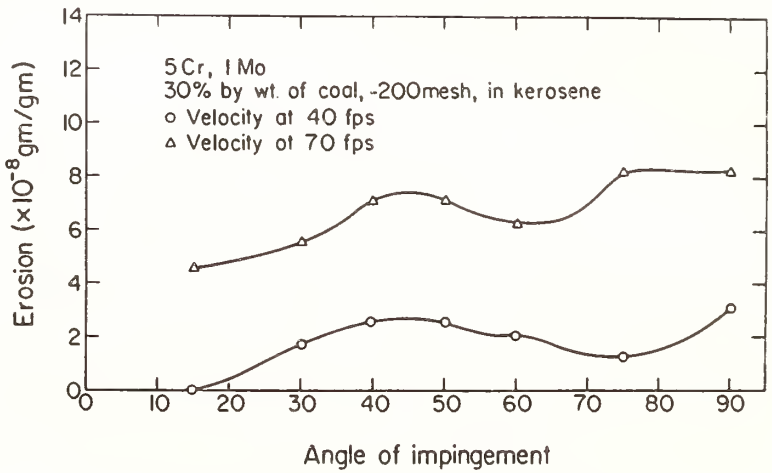
EFFECT OF VELOCITY[a] AND IMPINGEMENT ANGLE ON THE SLURRY EROSION[b] OF SEVERAL ALLOYS[c] [53]



(Data Continued)

EFFECT OF VELOCITY[a] AND IMPINGEMENT ANGLE ON THE SLURRY EROSION[b] OF SEVERAL ALLOYS[c][53], Continued



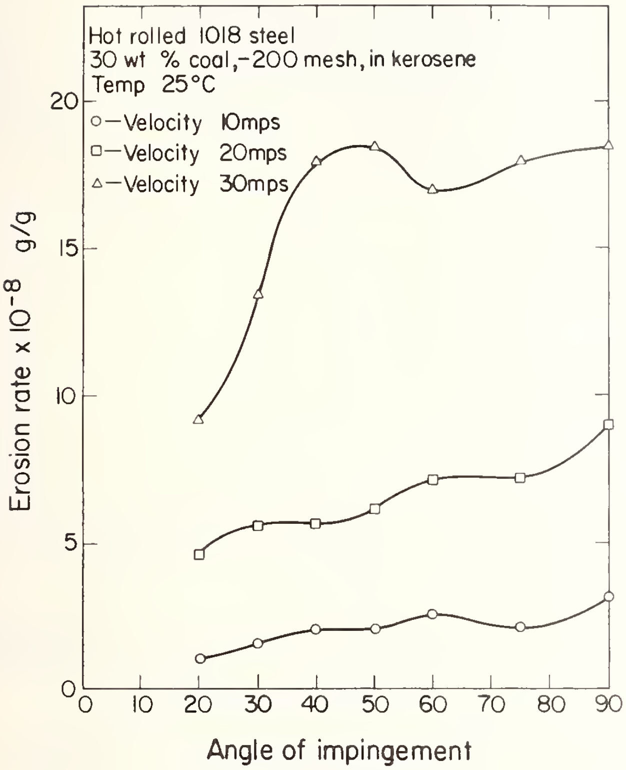


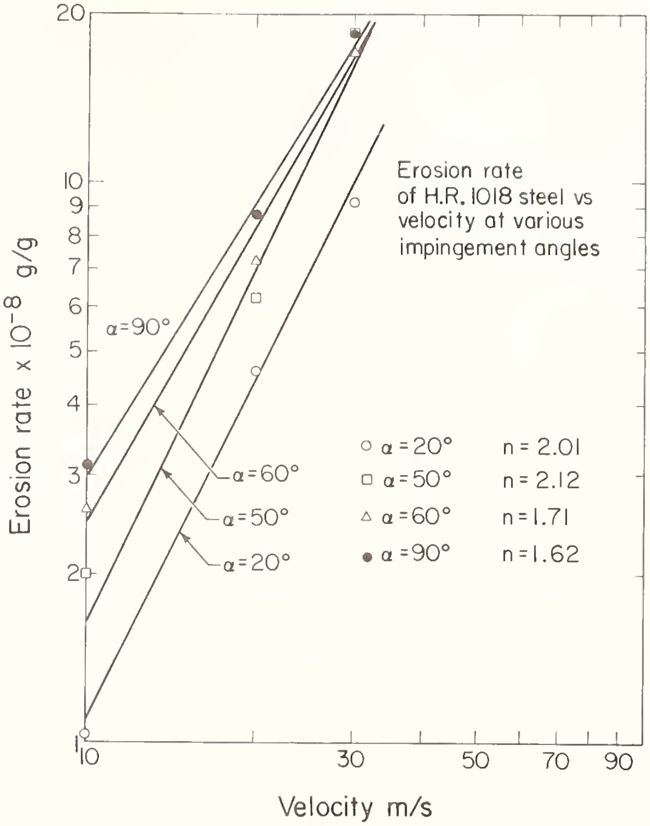
[a]Two velocities were used, 40 and 70 feet/second.

[b]Slurry erosion testing was performed with a jet impingement tester. A pressurized gas fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The tester operates in a once-through slurry mode (see Section B.2.1.64 and Sections B.2.1.72 and B.2.1.72 for slurry pot erosion testing of some of the same alloys). The coal is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. Eighteen gallons of slurry were used for each test. At 40 ft/s each test took 11 minutes. The erosion plotted above is the weight loss of the sample divided by the weight of the coal in 18 gallons of slurry.

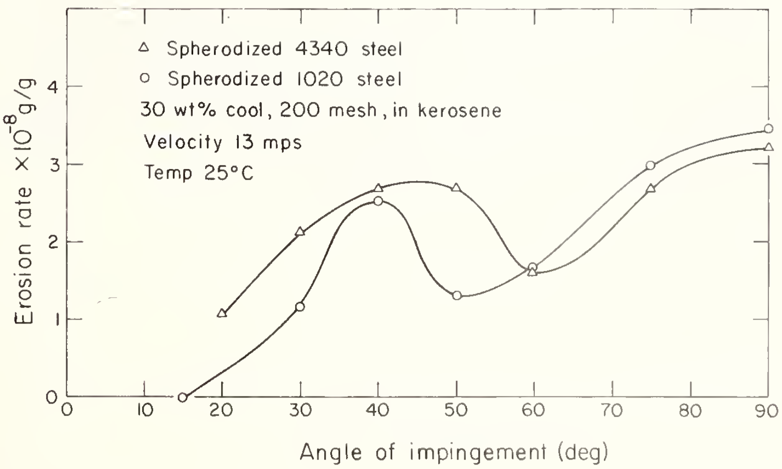
[c]Specimens were polished with 600 grit SiC before testing.

SLURRY EROSION[a] BEHAVIOR OF VARIOUS HEAT-TREATED STEELS[53]



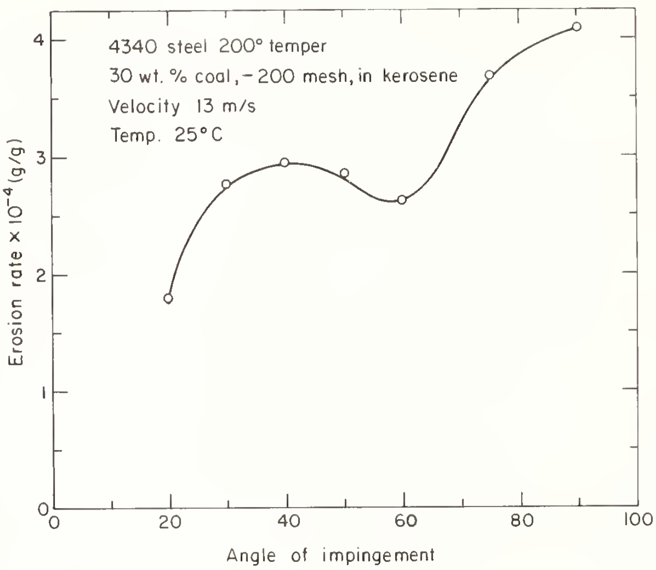


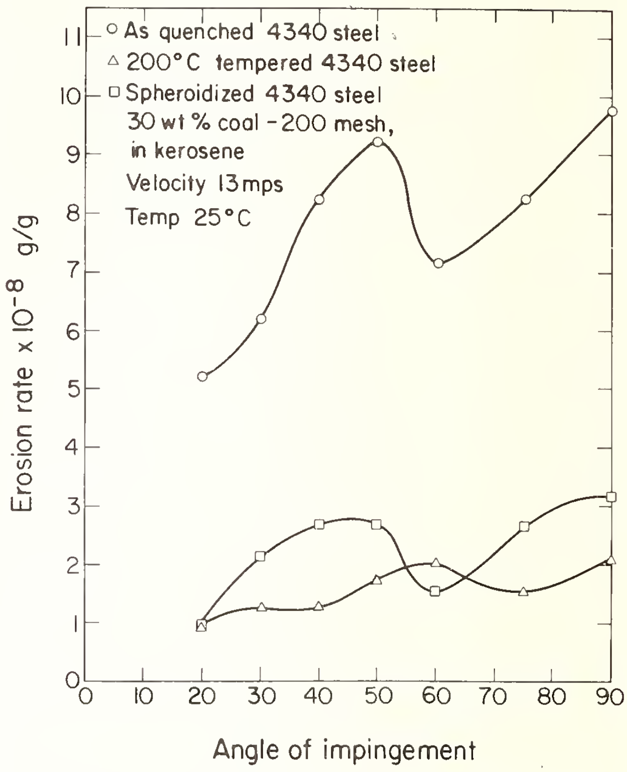
n = velocity exponent



(Data Continued)

SLURRY EROSION[a] BEHAVIOR OF VARIOUS HEAT-TREATED STEELS[53]





[In text of original report a 500 °C temper is referred to with respect to the above set of tests.]

[a] Slurry erosion testing was performed with a jet impingement tester. A pressurized gas fed slurry flow from a 3 mm diameter nozzle impinged a jet stream on a flat surface specimen at a fixed distance and angle from the nozzle. The coal used is the same -200 mesh Illinois #6 coal used in the Wilsonville Solvent Refined Coal plant. The erosion plotted above is the weight loss of the sample divided by the weight of the coal in the amount of slurry used for each test.

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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

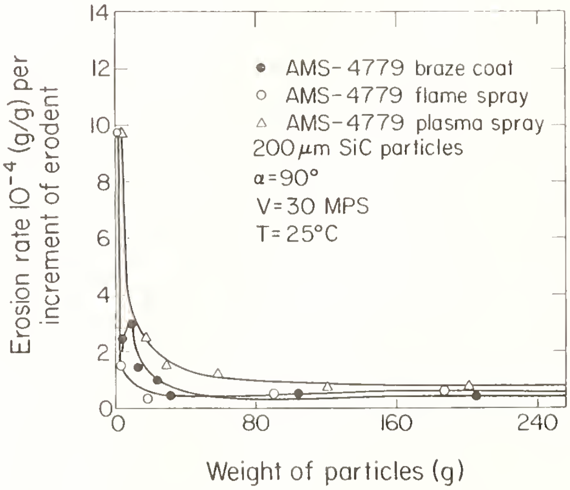
[a]Test temperature was controlled at 980 °C (1800 °F), pressure was maintained at 240 KPa (35 psi), and char particle velocity averaged 39 m/s (125 ft/s). Char used was FMC char from Western Kentucky coal. Gas composition was close to the following with variations due to problems with ammonia and steam 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.

EROSION TESTS[a] ON NICKEL BASE ALLOYS[b] FOR COATINGS AND CLADDINGS[53]

Material[b]	Steady State Erosion Rate X 10^{-6} g/cc[a] Braze Coat[c]	Flame Spray[c]	Plasma Spray[c]
AMS-4775	5.13	d	8.85
AMS-4777	5.27	5.90	9.79
AMS-4779	5.37	6.08	6.44
AMS-4777 + 40 wt% WC[e]	7.51	--	--
AMS-4777 + 25 wt% WC	7.62	--	--
AMS-4777 + 10 wt% WC	7.10	--	--



[a]Erosion tests were performed at 25 °C using 200 µm SiC, nitrogen atmosphere, particle velocity of 30 m/s, and 90° impingement angle. After testing, specimens were cleaned with alcohol in an ultrasonic cleaner, and weighed. Values are steady state rates after 250 g of SiC except for AMS-4777 + 40 wt% WC where the rate is after 130 g SiC. Steady state erosion rates normalized for density of specimen material.

[b]Alloys supplied by Wesco Division of GTE are multiphase, incorporating hard, boron-containing second phases in the matrix alloy. Compositions: AMS-4775, 73.4Ni, 14.3Cr, 4.3Si, 4.7Fe, 3.3B, Ni-Cr-B and Cr-C 2nd phases, >>40% in microstructure; AMS-4777, 83.0Ni, 7.0Cr, 4.0Si, 3.0Fe, 3.0B, Ni-Cr-B 2nd phase, >40% in microstructure; AMS-4779, 94.7Ni, 3.5Si, 1.8B, Ni-B 2nd phase, ~40% in microstructure. One alloy AMS-4777 was modified by the addition of varying amounts of WC.

[c]Materials were applied to a low carbon steel substrate. Braze coats were prepared by melting a thin layer of alloy (>10 mils) and brazing to substrate with braze metal of same composition. Coats containing WC were brazed with Ag-Cu eutectic. Flame spray and plasma spray methods were commercial processes. Alloy coatings >10 mils thick, alloy + WC coatings 4 mils thick.

(Data Continued)

EROSION TESTS[a] ON NICKEL BASE ALLOYS[b] FOR COATINGS AND CLADDINGS[53],

Continued

Footnotes continued

[d]AMS-4775 flame spray coating too thin.

[e]Tungsten carbide addition consists of WC and W_2C mixture.

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EFFECT OF TEST AND EXPOSURE TEMPERATURE AND COAL GASIFICATION ATMOSPHERE[a] ON TENSILE PROPERTIES[b] OF SOME WELDED ALLOYS [10]

Material Condition/ Pretreatment[c]	Test Condition[d]	Welded Incoloy 800H[e] YS ksi	UTS ksi	El. %	RA %	FL[f]	Welded Incoloy 800H Al[g,h] YS ksi	UTS ksi	El. %	RA %	FL[f]	Welded 310 SS[i] YS ksi	UTS ksi	El. %	RA %	FL[f]
as welded	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]
1200 °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
1200 °F, CGA[a]	80 °F	50.5	76.2	7.4	0.9	W						46.2	89.6	34.8	55.6	B
1500 °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
1800 °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

Material Condition/ Pretreatment[c]	Test Condition[d]	Welded RA 333[l] YS ksi	UTS ksi	El. %	RA %	FL[f]	Welded Haynes 188[m] YS ksi	UTS ksi	El. %	RA %	FL[f]	Welded INCO 657[o] YS ksi	UTS ksi	El. %	RA %	FL[f]
as welded	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]
1200 °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
1200 °F, CGA	80 °F	57.5	101.8	18.0	17.3	B	82.6	149.6	32.4	30.9	B					
1500 °F, air	80 °F	38.1	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]
1800 °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

[a] 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, % NH_3, 0.5% H_2S.

[b] Specimens are ASTM standard, 0.505 in diameter, 2-in long gauge section; values reported are for duplicate specimens except where otherwise marked; tests conducted on specimens with weldment in center of gauge length; properties shown are for base metal/weldment composite.

[c] 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).

[d] All tests were performed in air at the indicated temperatures.

[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).

[f] FL = failure location; B = base metal, w = weld metal.

[g] 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 tensile specimens by Alon Processing, Inc. (Alonized).

[h] Yield and Ultimate Tensile Strengths of aluminized samples calculated using diameter of uncoated specimen; reduction in area calculated using diameter of uncoated specimen and final diameter of coated specimen less twice the coating thickness.

[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] All four properties are the average for three specimens.

[k] For one specimen most of necking occurred in base metal although failure location was in weld metal; reduction in area value is average for the two specimens where failure occurred in base metal.

[l] 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).

[m] 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).

[n] Failure occurred in base metal in one specimen , in weld metal in other.

[o] 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).

[p] Specimen 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]				Vacuum Aged[d]			Tested at Indicated Temperatures after Exposure at Indicated Temperatures and Pressures: Atmosphere 1, 34 atm[e]			Atmosphere 1, 102 atm[e]			Atmosphere 2, 34 atm[f]			Atmosphere 2, 102 atm[f]		
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	1800°F	1382°F	1600°F	1800°F
0.2% YIELD STRENGTH[b], MPa																		
18-18-2[g]																		
331.2		57.2		100.0	42.6	23.6	141.9	76.3	52.1	130.2	68.3	36.4[h]	141.7[i]	77.1	52.2	161.7[j]	73.4	34.5
(201.5)	(113.1)	(93.8)	(40.0)															
INCOLOY 800[g]																		
332.4	175.1	72.4		95.8	60.8	30.6	143.0	75.2	41.1	142.4	75.2	37.4[h] 38.5[k]	142.0	80.0	43.7[i]	139.6	69.3	49.8
(365.7)	(161.8)	(92.8)	(51.0)															
310 SS[g]																		
292.3	129.4	64.9		102.1	66.3	33.3	122.6	85.6	50.2	114.8	76.4	39.7[h]	121.9	85.1	43.6	133.1	77.9	48.5
(268.4)	(119.4)	(87.6)	(59)															
INCONEL 671[g]																		
563.5	260.9	90.1		93.8	48.0	29.3	250.6	108.1	52.6	242.9	103.2	48.7[h]	233.8	105.0	50.1	251.0	119.8	69.8
(482.9)																		
ULTIMATE TENSILE STRENGTH[b], MPa																		
18-18-2																		
588.7		79.0		190.3	94.9	47.0	193.7	101.7	72.2	186.1	91.6	47.9	187.8	97.2	63.6	447.6[j]	87.3	52.4
(531.2)	(240.8)	(104.2)	(75.2)															
INCOLOY 800																		
595.8	204.9	94.9		203.7	99.4	50.3	181.3	91.3	53.5	180.8	91.3	49.1 51.4[k]	178.3	91.7	53.9	187.5	92.9	59.1
(620.9)	(231.5)	(120)	(65.9)															
310 SS																		
564.8	201.0	103.1		231.6	106.1	52.2	196.9	114.1	67.7	200.7	103.0	48.2	205.2	111.6	55.4	212.3	107.9	63.2
(563.4)	(269.1)	(158.7	(89.7)															
INCONEL 671																		
848.7	313.4	141.7		251.4	93.6	56.6	288.8	136.0	67.7	282.6	131.8	64.7	278.5	132.3	62.2	291.1	143.1	86.7
(862.4)																		
% UNIFORM STRAIN[b]																		
18-18-2																		
				9.8	3.7	24.6	11.0	13.6	9.3	13.1	12.1	13.3	13.5	11.5	10.4	42.1[j]	14.2	13.8
INCOLOY 800																		
				14.8	12.3	19.7	12.7	12.9	16.0	14.4	18.0	23.1 22.0[k]	13.6	7.7	18.8	12.0	14.2	13.5
310 SS																		
				7.4	12.5	22.1	14.2	11.5	11.2	16.7	14.3	16.8	18.9	11.9	13.0	14.1	12.0	11.4
INCONEL 671																		
				4.9	2.5	2.2	8.8	9.3	7.8	9.2	9.5	10.8	11.8	9.2	8.8	7.0	6.9	4.4
% TOTAL ELONGATION[b]																		
18-18-2																		
68		71		84.4	56.1	139.0	44.1	60.2	55.9	52.5	49.3	50.6	61.6	50.8	93.4	47.9[j]	48.0	60.7
(63)	(46)	(55)	(74)															
INCOLOY 800																		
46	89	122		91.0	120.6	64.0	59.8	99.3	74.1	85.8	73.4	93.5 88.1[k]	100.4	82.3	68.7	54.5	67.8	55.9
(38)	(46)	(119)	(113)															
310 SS																		
65	48	81		38.9	80.0	89.8	33.8	59.8	45.9	45.9	50.3	57.8	43.5	53.4	66.9	30.3	45.3	51.5
(52)	(29)	(43)	(53)															
INCONEL 671																		
45	64	156		102.1	281.7	147.6	33.4	73.5	35.5	62.1	84.4	50.6	85.9	110.9	54.1	33.8	43.5	32.5
(25)																		

(Continued)

EFFECT OF EXPOSURE[a] TO COAL GASIFICATION ATMOSPHERES ON THE UNIAXIAL TENSILE PROPERTIES[b] OF VARIOUS ALLOYS[7], Continued

Footnotes

[a]Specimens in as-machined condition were exposed to the coal gasification atmospheres given in footnotes e and f 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 testing machine, crosshead speed 0.025 in./min, at ambient conditions and at the indicated temperatures. Tests at elevated temperatures were conducted under 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 specimens, data for exposed samples are for duplicate specimens except where noted.

[c]Values in parentheses are literature values quoted in the reports, not data generated by the authors.

[d]Aged in vacuum for 1000 hours at the specified temperatures and tested at temperature (data from Argonne National Laboratory).

[e]Composition of atmosphere no. 1:

	Input, 1 atm, 77°F (mole %)	Equilibrium at 34 atm			Equilibrium at 102 atm		
		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(solid)		22.6	12.0	1.4	25.4	18.0	8.3
log $P(O_2)$(P in atm)		-19.19	-17.31	-16.10	-18.67	-16.68	-15.34
log $P(S_2)$		-6.05	-5.55	-5.07	-5.61	-5.15	-4.75
log a_c		1.00	1.00	1.00	1.00	1.00	1.00

[f]Composition of atmosphere no. 2:

	Input, 1 atm, 77°F (mole %)	Equilibrium at 34 atm			Equilibrium at 102 atm		
		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(solid)		24.0	13.7	3.5	26.7	19.5	10.1
log $P(O_2)$(P in atm)		-19.21	-17.32	-16.11	-18.68	-16.70	-15.35
log $P(S_2)$		-6.32	-5.83	-5.35	-5.93	-5.42	-5.08
log a_c		1.00	1.00	1.00	1.00	1.00	1.00

[g]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; 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.

[h]Specimens were slightly deformed after exposure to corroding atmospheres.

[i]Data are for a single specimen.

[j]Tensile testing done at 754 °F by mistake.

[k]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]

Alloy[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]												
USS 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
Incoloy 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
310 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
Inconel 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]												
USS 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
Incoloy 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
310 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
Inconel 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]												
USS 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
Incoloy 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
310 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
Inconel 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

[a]As-machined specimens were exposed for 1000 hours in the coal gasification atmospheres at the indicated temperatures and pressures. Similar specimens were aged in vacuum for 1000 hours at the appropriate temperatures. All specimens were tensile tested on a standard laboratory tensile testing machinge, crosshead speed 0.025 in/min. Specimens conformed to the 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 properties for the exposed specimens with the properties of the aged specimens; i.e. $(\%\ \text{ELONGATION})_{\text{exposed}} \div (\text{ELONGATION})_{\text{aged}}$ and $(\text{ULTIMATE TENSILE STRENGTH})_{\text{exposed}} \div (\text{ULTIMATE TENSILE STRENGTH})_{\text{aged}}$; therefore, the values for the aged specimens = 1.0.

[b]Composition of atmosphere no. 1:

	Input, 1 atm, 77°F (mole %)	Equilibrium at 34 atm 1382°F	1600°F	1800°F	Equilibrium at 102 atm 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

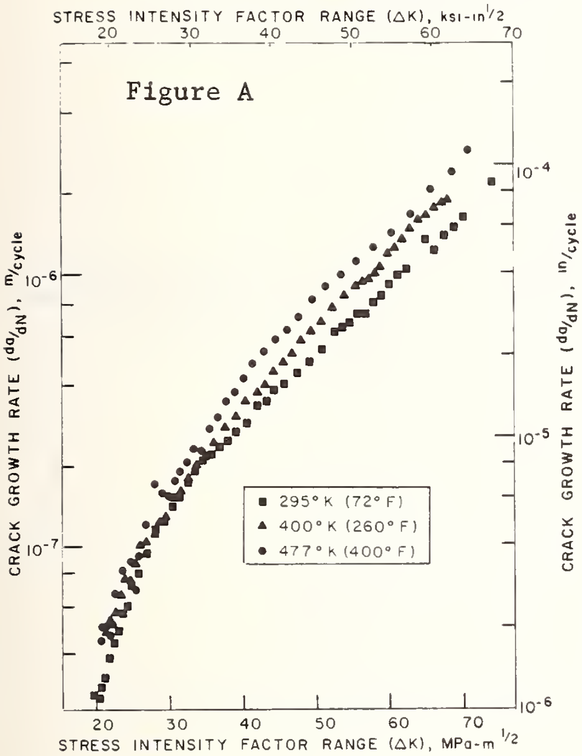
Composition of atmosphere no. 2:

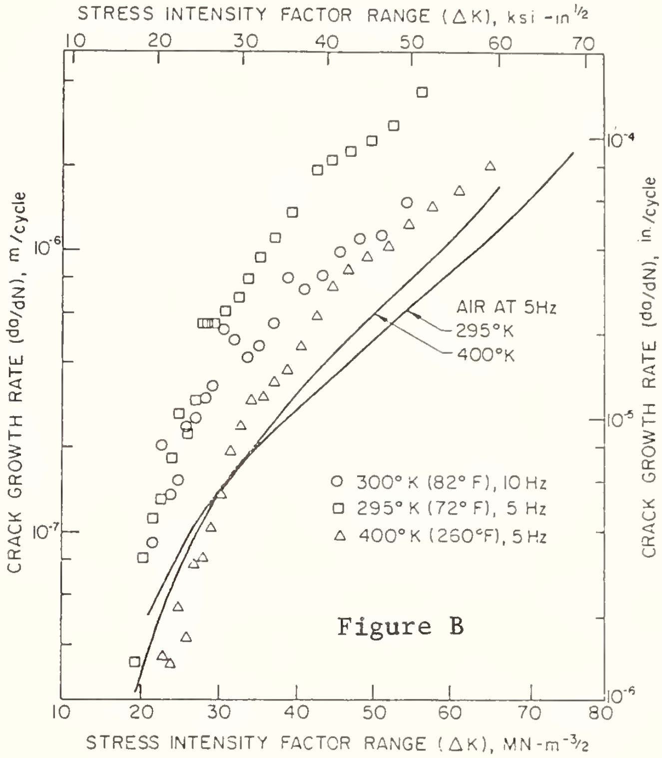
	Input, 1 atm, 77°F (mole %)	Equilibrium at 34 atm 1382°F	1600°F	1800°F	Equilibrium at 102 atm 1382°F	1600°F	1800°F
CO	33.42	10.4	26.4	42.7	6.2	16.9	31.7
CO_2	19.15	17.9	12.1	5.9	19.5	15.9	10.5
H_2	33.42	16.3	26.1	34.7	10.3	17.6	25.5
H_2O		21.1	13.9	7.6	24.7	19.2	13.3
H_2S	1.29	1.2	1.1	1.1	1.2	1.2	1.1
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.

[c]Alloy 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 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.

EFFECT OF TEMPERATURE ON FATIGUE CRACK GROWTH KINETICS[a] FOR 2-1/4 Cr-1 Mo STEEL (A542)[b] IN VARIOUS ENVIRONMENTS[29]





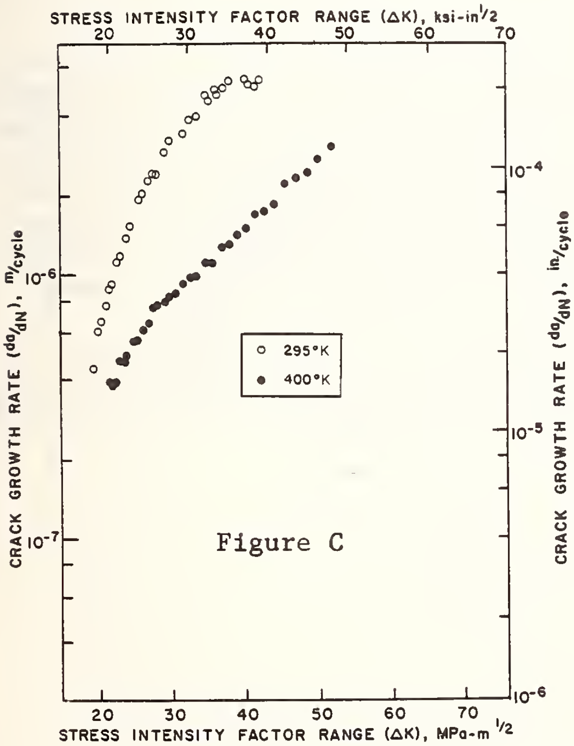


Figure A--Effect of temperature in air at 5 Hz.

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).

(Continued)

EFFECT OF TEMPERATURE ON FATIGUE CRACK GROWTH KINETICS[a] FOR 2-1/4 Cr-1 Mo STEEL (A542)[b] IN VARIOUS ENVIRONMENTS[29], Continued

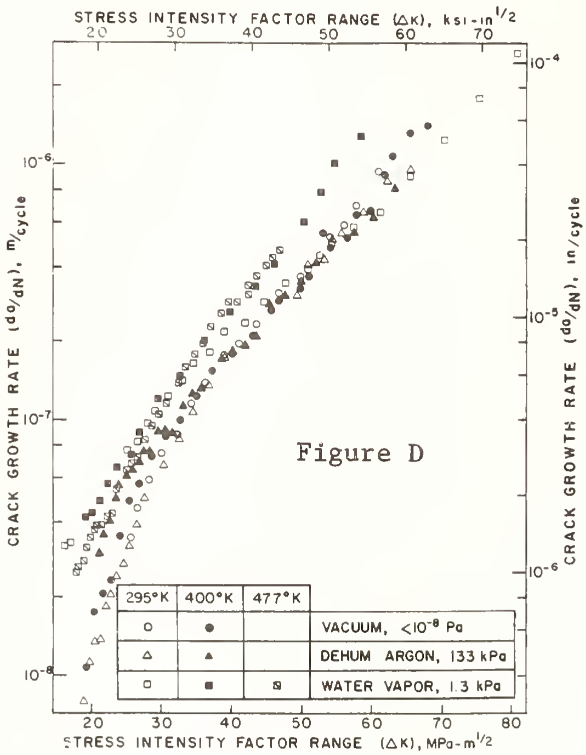


Figure D--Effect of temperature in vacuum, dehumidified argon, and in water vapor.

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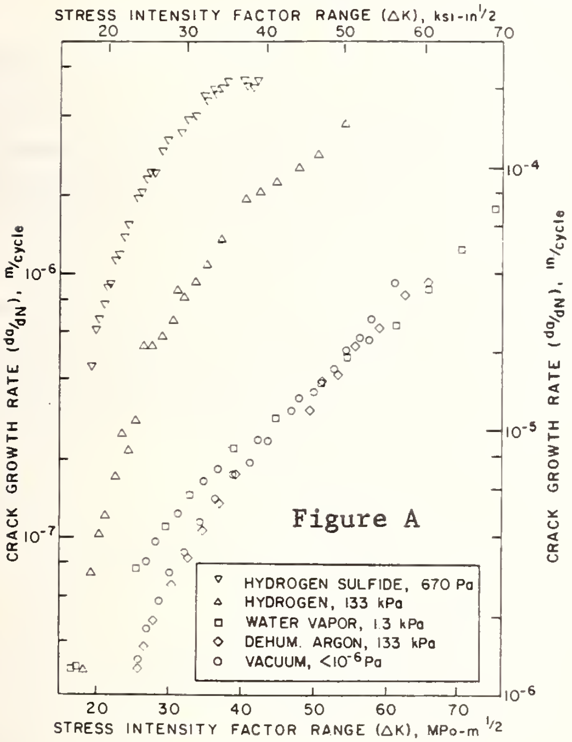
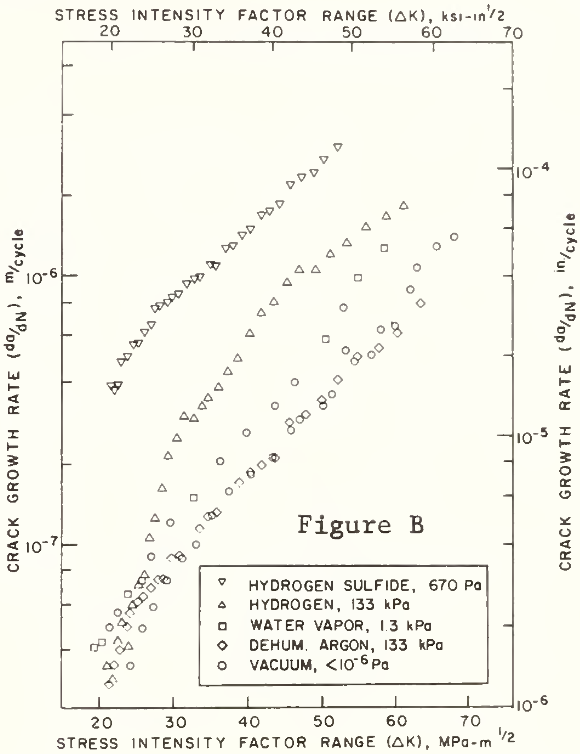
[a]Fatigue crack growth measurements performed on 25.4 mm thick compact tension specimens taken in longitudinal-transverse orientation from the rolled plate. The specimens were 63.5 mm wide and had a half-height to width ratio of 0.6. Specimens conform to ASTM E647-78T, and were pre-cracked in fatigue in air. Tests were carried out under constant-load-amplitude, sinusoidal loading at 5 Hz in a closed-loop electrohydraulic testing machine operated in load control. The minimum-to-maximum stress load ratio was 0.1. One set of tests was run at 10 Hz (see Figure B).

[b]The material was 2.54 cm thick plate heat treated to a yield strength of about 689 MPa (100 ksi). The plate, from an electric furnace heat, conforms to specifications for ASTM 542, Class 2.

EFFECT OF ENVIRONMENT AND PRESSURE ON FATIGUE CRACK GROWTH KINETICS[a] FOR 2-1/4 Cr-1 Mo STEEL (A542)[b][29]





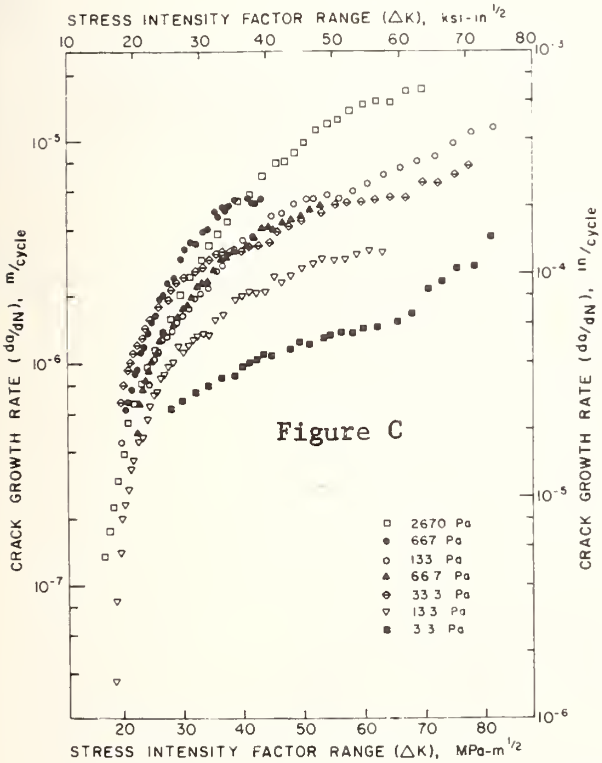


Figure A--Effect of environment at 295 K.

Figure B--Effect of environment at 400 K.

Figure C--Effect of pressure in hydrogen sulfide at 295 K.

(Continued)

EFFECT OF ENVIRONMENT AND PRESSURE ON FATIGUE CRACK GROWTH KINETICS[a]
FOR 2-1/4 Cr-1 Mo STEEL (A542)[b][29], Continued

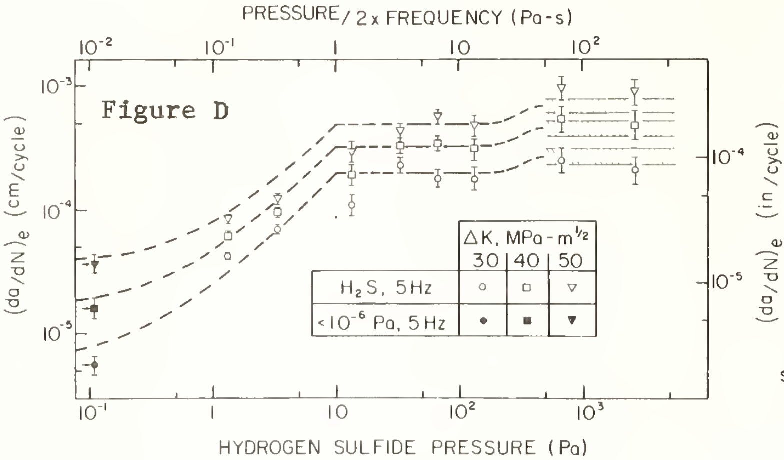


Figure D--Effect of pressure at 295 K in H_2S.

Figure E--Effect of carbon monoxide pressure in H_2S at 295 K.

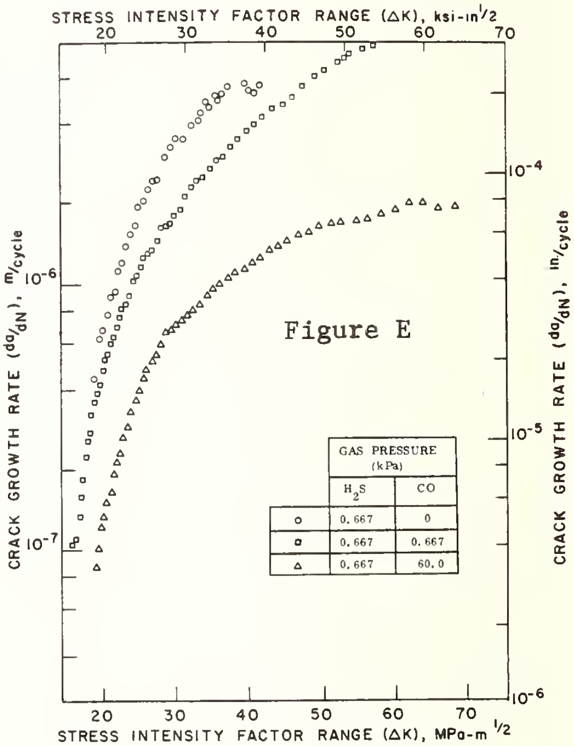
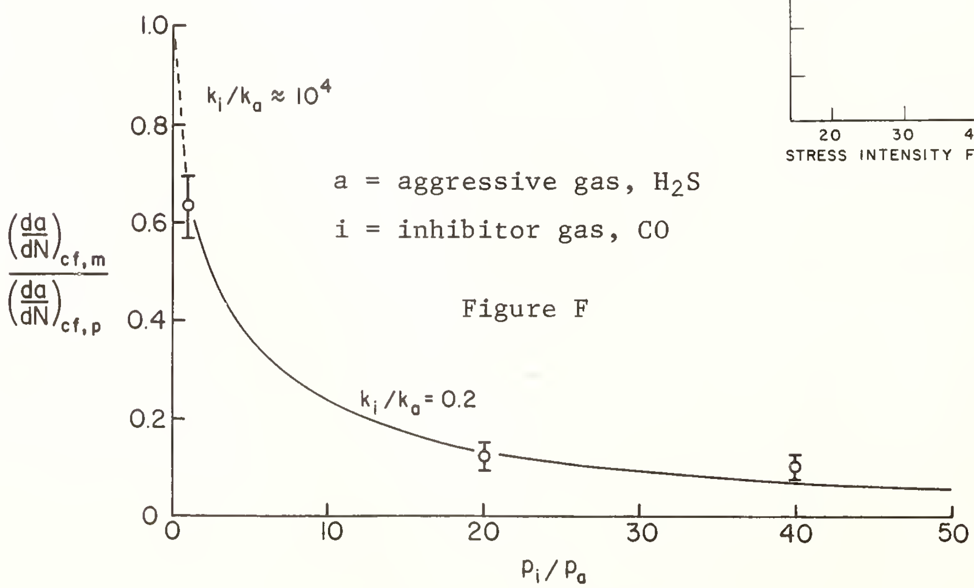


Figure F--Effect of carbon monoxide in reducing H_2S influence at ambient temperature.



(Continued)

EFFECT OF ENVIRONMENT AND PRESSURE ON FATIGUE CRACK GROWTH KINETICS[a]
FOR 2-1/4 Cr-1 Mo STEEL (A542)[b][29], Continued

Footnotes

[a]Fatigue crack growth measurements performed on 25.4 mm thick compact tension specimens taken in longitudinal-transverse orientation from the rolled plate. Specimens were 63.5 mm wide with a half-height to width ratio of 0.6. Specimens conform to ASTM E647-78T, and were pre-cracked in fatigue in air. Tests were carried out under constant-load-amplitude, sinusoidal loading at 5 Hz in a closed-loop electrohydraulic testing machine operated in load control. The minimum-to-maximum stress load ratio was 0.1.

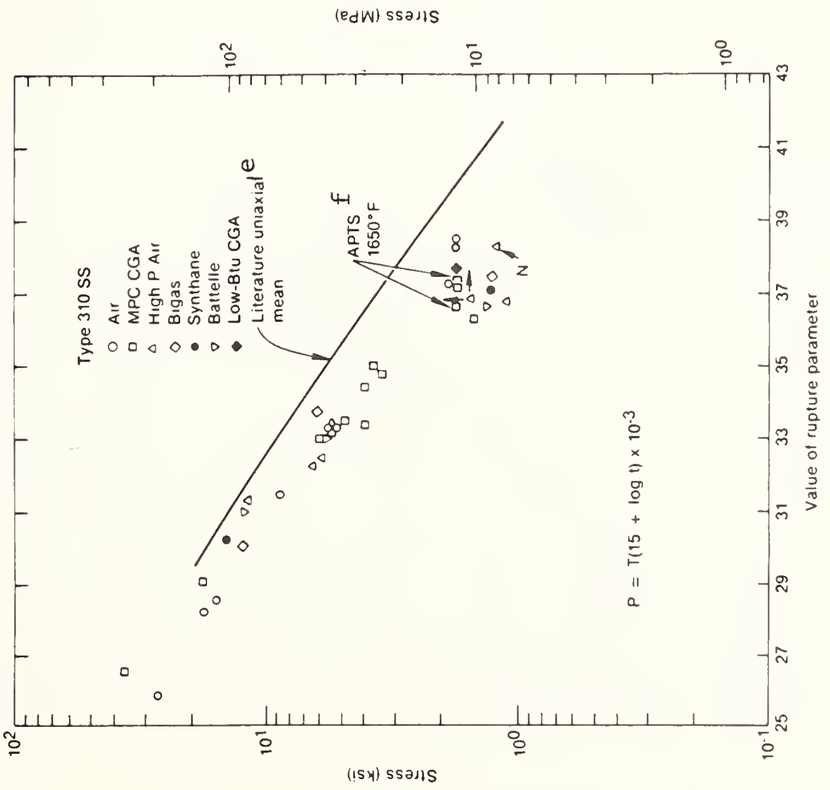
[b]The material was 2.54 cm thick plate heat treated to a yield strength of about 689 MPa (100 ksi). The plate, from an electric furnace heat, conforms to specifications for ASTM 542, Class 2.

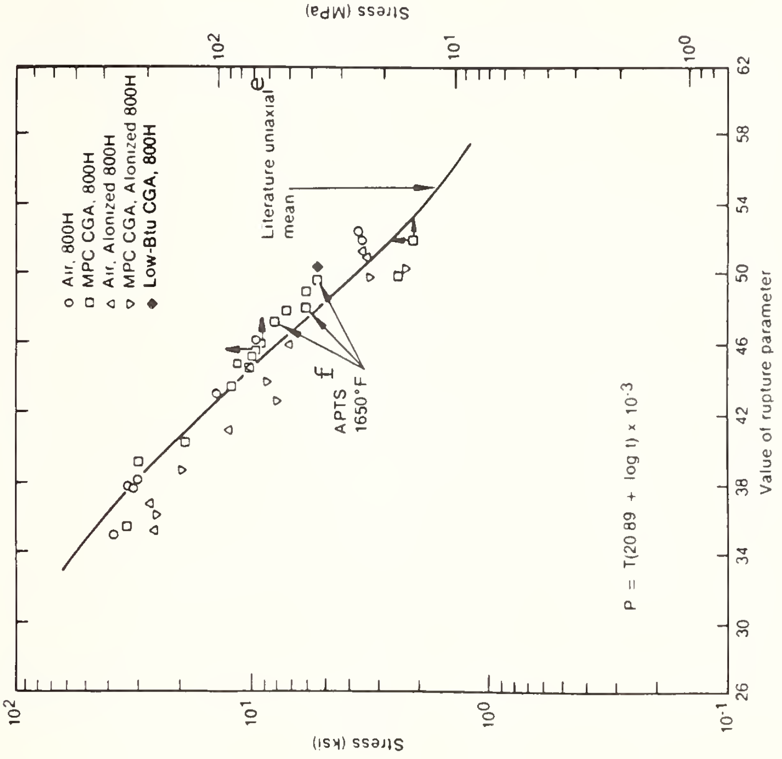
STRESS RUPTURE TESTS[a] OF SOME WELOEO ALLOYS IN AIR ANO IN COAL GASIFICATION ATMOSPHERE[b][10]

Environment	Temperature °F	Stress ksi	Time (hours) to 0.1% El.[c]	Time (hours) to 0.5% El.[c]	Time (hours) to 1.0% El.[c]	Time (hours) to Rupture	Elong. %	RA %	Minimum Creep Rate[c] %/hr	FL[d]
WELOEO INCOLOY 800H[e]										
air, 1 atm	1200	40.0	0.1	13.8	24.4	32.7	19.9	40.9	C.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	--	8
	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
WELOEO 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
WELOEO 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
WELOEO 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	8
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)

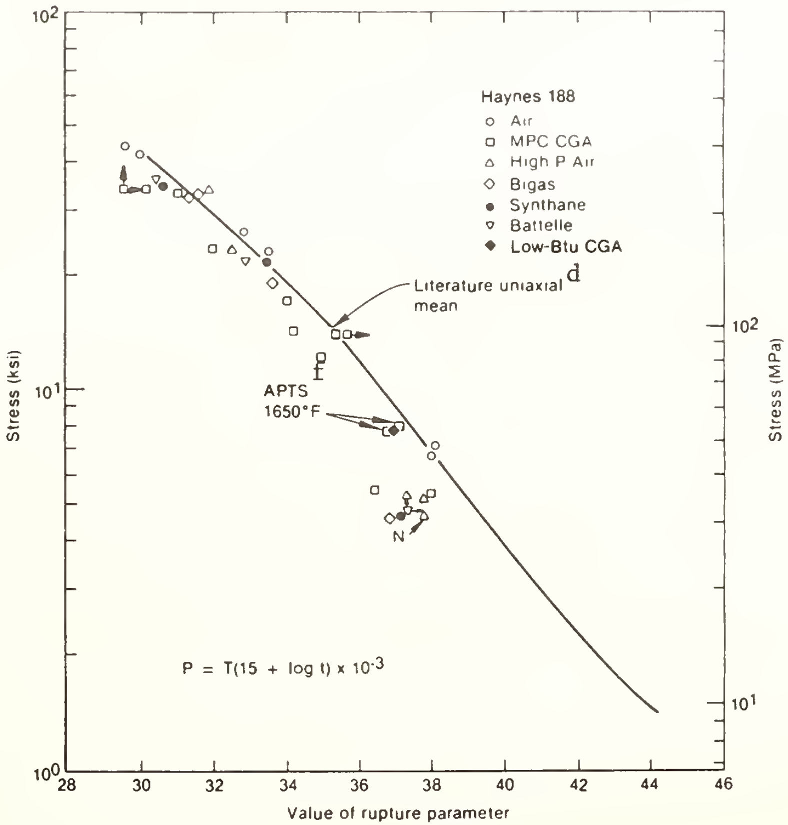
VARIATION OF BIAXIAL STRESS RUPTURE[a] PARAMETER FOR SEVERAL ALLOYS[b] IN AIR AND IN VARIOUS COAL GASIFICATION ATMOSPHERES[c] [14,54]

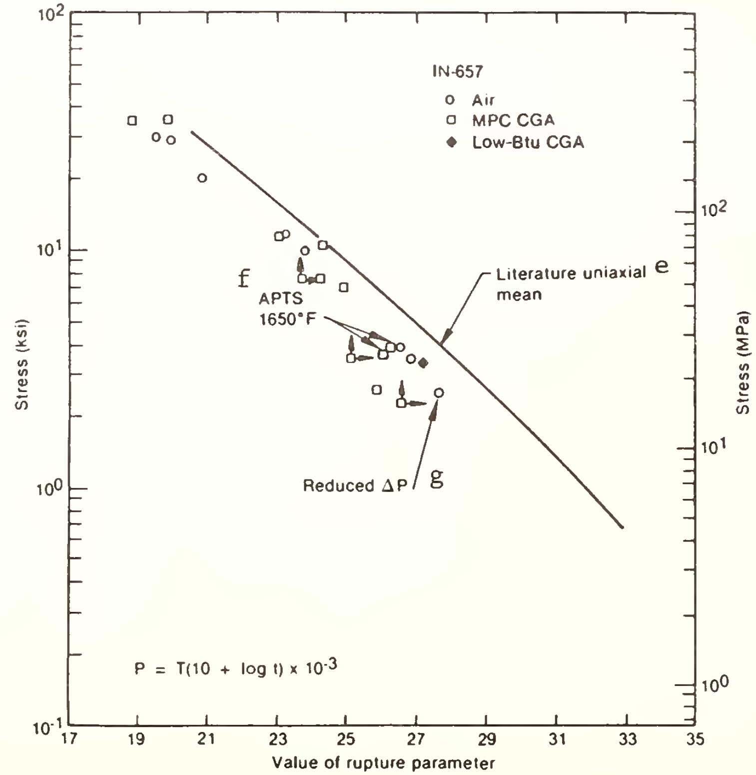




(Data Continued)

VARIATION OF BIAXIAL STRESS RUPTURE[a] PARAMETER FOR SEVERAL ALLOYS[b] IN AIR AND IN VARIOUS COAL GASIFICATION ATMOSPHERES[c][14,54], Continued





(Data Continued)

VARIATION OF BIAXIAL STRESS RUPTURE[a] PARAMETER FOR SEVERAL ALLOYS[b] IN AIR AND IN VARIOUS COAL GASIFICATION ATMOSPHERES[c][14,54], Continued

Footnotes

[a]Tubular specimens, approximately 1 cm in diameter by 11 cm long with the outside diameter of the central 7 cm portion reduced to form a gauge section, were pressurized to measure 100- and 500-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 rupture was measured by sensing a significant drop in specimen argon pressure. Biaxial stress rupture data obtained are plotted above. 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. Arrows appearing on some data points indicate a minimum value of stress and rupture life for that specimen. (Due to valve malfunction, gas pressure decreased, overloaded the specimen, and caused premature rupture.)

[b]See Section B.3.1.25, footnotes f, g, i, j, and l for alloy information. Note that a second specimen of 310 SS was included in the testing because of the banding of the Heat No. 24569. There was no real difference for the data for the second 310 SS (Jessop 19477), however, and the data are not differentiated in the above plot. Alonized = Al coating, pack diffusion process by Alon Processing Co.

[c]Air tests were run at 1 atmosphere except for the data designated High P Air (1000 psi) and all other gas tests were run at 1000 psi. Temperature range used was 1200-1800 °F. The input test gases were (in vol %): MPC CGA, 24H_2, 18CO, 12CO_2, 5CH_4, 40H_2O, 1NH_3, 0.5H_2S; Bigas, 15H_2, 12CO, 13CO_2, 7CH_4, 52H_2O, 1.06NH_3, 0.53H_2S; Synthane, 18H_2, 10CO, 18CO_2, 16CH_4, 37H_2O, 0.6NH_3, 0.3H_2S; Battelle, 48H_2, 26CO, 5CO_2, 6CH_4, 14H_2O, 0.6NH_3, 0.3H_2S; low-Btu (1650 °F) P_{O_2} 3×10^{-18}, P_{S_2} 3.7×10^{-7}, (1500 °F) P_{O_2} 1×10^{-19}, P_{S_2} 1.3×10^{-7} (atm).

[d]The mean line is from limited uniaxial data compiled by R.M. Horton.

[e]Lines drawn are mean values from plots of the available uniaxial stress rupture from several heats of each alloy (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).

[f]APTS = atmospheric pressure test system data points.

[g]Data gathered in test with an extra valve in the system to provide for smaller pressure fluctuation (±28 psi instead of usual ±40 psi).

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.

[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	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		Base	Clad
on Incoloy 800	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		
Material	Coal Feedstock[b]	Temperature (°F)[c]	Hours	Depth of Attack Mils	Midwall Hardness 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	
		1267	7468	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)

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]

Metallurgical Condition[d]	Cooling Rate[c] K/s	Cooling Rate[c] °R/s	Test Temperature °C	Test Temperature °F	Stresses, MPa (ksi) 0.2% Offset Yield	Stresses, MPa (ksi) Ultimate	Total[e] Elongation, % L/D=7	Total[e] Elongation, % L/D=4	Reduction in Area %
					Austenitized at 927 °C (1700 °F) for 1 hr				
Q	0.3	0.6	24	75	537 (77.9)	762 (110)	14.1		47
Q	0.3	0.6	343	650	582 (84.5)	865 (125)	10.0		36
Q	3	5	24	75	779 (113)	1007 (146)	11.5		57
Q	3	5	343	650	879 (127)	1090 (158)	11.2		50
Q, T	0.3	0.6	22	72	419 (60.8)	582 (84.4)	16.5		68
Q, T	0.3	0.6	343	650	401 (58.2)[f]	538 (78.1)	12.6		65
Q, T	3	5	22	72	532 (77.1)	645 (93.5)	15.5		67
Q, T	3	5	343	650	479 (69.5)	595 (86.3)	12.5		63
Q, T, SR (40 h)	0.3	0.6	22	72	385 (55.9)	552 (80.0)	18.4		68
Q, T, SR (40 h)	0.3	0.6	343	650	343 (52.6)[f]	515 (74.7)	13.4		65
Q, T, SR (40 h)	3	5	24	75	455 (66.2)	568 (82.4)	17.2		72
Q, T, SR (40 h)	3	5	343	650	421 (61.0)	538 (77.8)	12.3		66
Q, T, SR (120 h)	0.3	0.6	24	76	363 (52.7)	518 (75.1)	19.8	27.1	71
Q, T, SR (120 h)	0.3	0.6	343	650	328 (47.6)[f]	490 (71.0)	13.3	18.4	63
Q, T, SR (120 h)	3	5	22	72	426 (61.8)	543 (78.8)	18.8		72
Q, T, SR (120 h)	3	5	343	650	381 (55.3)	506 (73.4)	13.6		65
Q, T, SR (40 h),A(1000 h)	0.3	0.6	24	76	365 (53.1)	520 (75.5)	20.3	27.6	71
Q, T, SR (40 h),A(1000 h)	0.3	0.6	343	650	333 (48.4)	492 (71.4)	14.2	19.2	61
Q, T, SR (40 h),A(1000 h)	3	5	24	76	472 (68.5)	586 (85.0)	17.7	24.9	71
Q, T, 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				
Q	0.3	0.6	24	75	710 (103)	928 (135)	11.5		54
Q	0.3	0.6	343	650	790 (114)	1048 (152)	11.1		41
Q	3	5	22	72	759 (110)	980 (143)	11.5		58
Q	3	5	343	650	869 (126)	1064 (154)	11.0		50
Q, T	0.3	0.6	24	75	533 (77.3)	651 (94.4)	14.1		66
Q, T	0.3	0.6	343	650	484 (70.2)[f]	603 (87.5)	11.8		63
Q, T	3	5	22	72	534 (77.4)	645 (93.6)	15.4		72
Q, T	3	5	343	650	483 (70.0)	596 (86.4)	12.1		66
Q, T, SR (40 h)	0.3	0.6	24	75	469 (68.0)	588 (85.3)	16.3	22.9	69
Q, T, SR (40 h)	0.3	0.6	345	650	436 (63.2)[f]	548 (79.6)	12.2	17.3	62
Q, T, SR (40 h)	3	5	22	72	543 (78.8)	647 (93.8)	14.0	20.0	71
Q, T, SR (40 h)	3	5	343	650	485 (70.4)	582 (84.4)	11.5	16.8	64
Q, T, SR (120 h)	0.3	0.6	22	72	408 (59.3)	540 (78.3)	19.2	26.7	73
Q, T, SR (120 h)	0.3	0.6	345	650	379 (55.0)[f]	506 (73.4)	13.9	19.3	63
Q, T, SR (120 h)	3	5	22	72	423 (61.4)	543 (78.8)	17.5		72
Q, T, SR (120 h)	3	5	343	650	385 (55.9)	510 (73.9)	13.8		67
Q, T, SR (40 h),A(1000 h)	0.3	0.6	22	71	458 (66.5)	579 (84.0)	16.0	22.4	70
Q, T, SR (40 h),A(1000 h)	0.3	0.6	345	650	428 (62.1)	550 (79.8)	12.3	17.5	63
Q, T, SR (40 h),A(1000 h)	3	5	22	72	451 (65.4)	571 (82.8)	18.0	25.1	71
Q, T, SR (40 h),A(1000 h)	3	5	345	650	402 (58.3)	528 (76.6)	14.1	19.5	65

[a] 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.

[b] SA-387, gr. 22.

[c] Cooling 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 quenching after being austenitized; cooling rate 0.3 K/s (0.6 °R/s) simulates that at the 1/4-thickness depth.

[d] 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. Q denotes quench rate simulated by DATA TRAK; T denotes temper at 704 °C (1300 °F) for 1 h followed by air cooling; SR denotes stress relief at 677 °C (1250 °F) for 40 or 120 h, followed by air cooling; A denotes aging in air at 343 °C (650 °F) for 1000 h. Cooling after each additional heat treatment was on firebrick in still air.

[e] Ratio of gauge length (L) to gauge diameter (D) is 7; strain rate is 0.016/min. L/D=4 data are calculated from the L/D=7 data.

[f] These 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	°F	Upper Shelf Energy J	ft-lb
Surface	Longitudinal - parallel to rolling direction	-96	-140	140	103
	Transverse - perpendicular to rolling direction	-84	-120	112	82
1/4-thickness ∿63.5 mm (2.5 in)	Longitudinal	-73	-100	122	90
	Transverse	-62	-80	114	84
Midthickness ∿127 mm (5 in)	Longitudinal	-26	-15	106	78
	Transverse	-21	-5	91	67

Plate Depth[b]	Test Temperature °C	°F	Toughness Values, MPa$\sqrt{m}$ (ksi$\sqrt{in}$): Precracked Charpy V-Notch, K_{Icd} by Equivalent Energy, RW[c]	WR[d]	0.394T (10-mm Thick) Compact Tension in WR[c] Orientation: K_{Icd} by Equivalent Energy	$K_{(J)}$ by J-Integral	1T (25.4-mm thick) Compact Tension in WR[c] Orientation
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 ∿63.5 mm (2.5 in)	-184	-300			38 (35)	38 (35)	
	-129	-200	90 (82)	110 (100)	103 (94)	104 (95)	73 (67)
	-101	-150			156 (142)	157 (143)	
	-73	-100		202 (184)	166 (151)	169 (154)	155 (141)
	-18	0	223 (203)	225 (205)	200 (182)	202 (184)	273 (249)
	38	100		199 (181)			
	93	200	216 (197)				215 (195)
	176	350	193 (176)	185 (168)			
	260	500	196 (178)	169 (154)			
Mid-thickness ∿127 mm (5 in)	-129	-200	48 (44)	59 (54)			
	-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)			

[a] A542 Type B Class 1 low-alloy steel (Ni-Cr-Mo), 248 mm (9 3/4 in.) plate.

[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] 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 propagation parallel to RD.

EFFECT OF TEMPER EMBRITTLEMENT ON IMPACT PROPERTIES OF MODIFIED 2.25 Cr-1 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
Base + 1% Mn*	-	-50/8	-	105/-	58	-
Base + 0.5% Mn + 0.5% Ni*	-	-45/-6	-	98/-	39	-
2.25 Cr - 1 Mo Base steel*	-	-5/-2	-	105/117	3	-
Remelted base*	-	-5/-8	-	105/112	-3	-
Remelted base + 0.11% Ce + 0.03% La*	-	-5/-47	-	105/112	-37	-

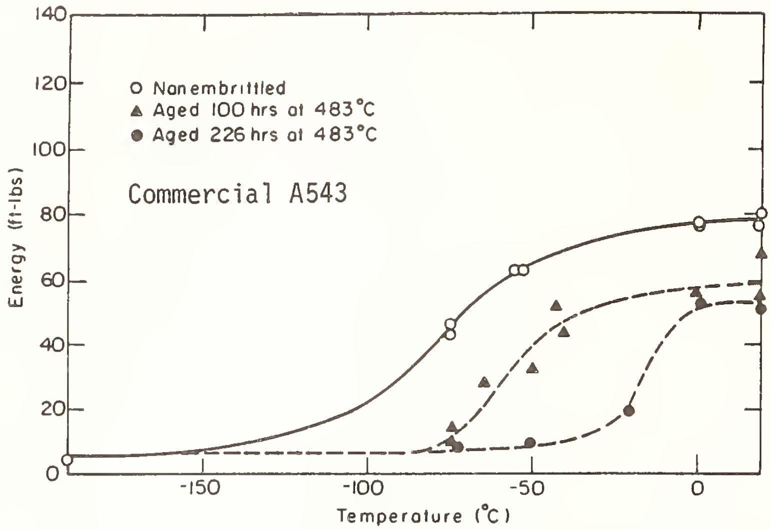
[a]Base alloy composition: ∿2.25 Cr, ∿1 Mo, ∿0.4 Mn, ∿0.2 Si, ∿0.1 C, balance Fe.

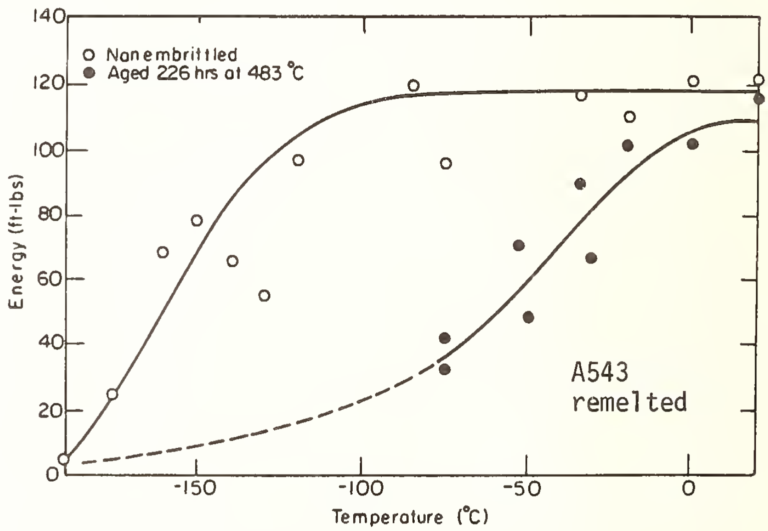
[b]Unembrittled alloys were austenitized at 1000 °C for 1 hour followed by either, oil quench, then tempering at 650 °C for 4 hours (unmarked alloys), or simulated cooling at 7 °C/min, then tempering at 700 °C for 4 hours (* marked alloys).

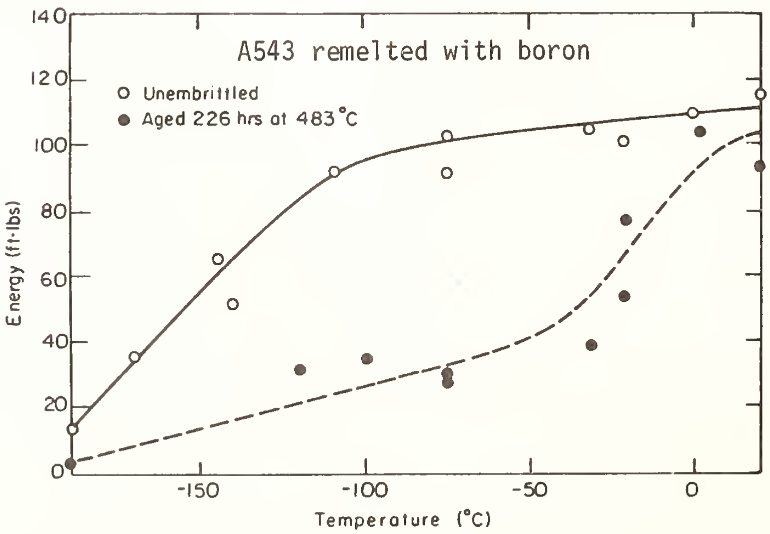
[c]Embrittling treatment consisted of holding the unembrittled alloys at 483 °C for 1000 hours.

[d]FATT = Fracture Appearance Transition Temperature.

CHARPY IMPACT TESTS OF A543 ALLOY[a] SUBJECTED TO ISOTHERMAL EMBRITTLEMENT[b][40]







(Data Continued)

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.

STRESS RUPTURE TESTS[a] OF WELD OVERLAYS[b] AT 982 °C (1800 °F)[8]

	Single Layer Overlay			Double Layer Overlay		
Weld Overlay[b]	Stress MPa(psi)	Life in Hours	% Elongation 38 mm (1.5 in.)	Stress MPa(psi)	Life in Hours	% Elongation 38 mm (1.5 in.)
AWS-ER309 Filler	13.8(2000)	52	15	13.8(2000)	72	21
on	10.3(1500)	189	16	8.6(1250)	630	23
304L SS--GMAW[c]	6.9(1000)	1084	23	7.6(1100)	846	21
AWS-ER309 Filler	13.8(2000)	54	27	13.8(2000)	47	27
on	10.3(1500)	104	17	10.3(1500)	139	21
304L SS--SAW[c]	6.9(1000)	342	22	5.9(850)	2352	31
	4.8(700)	4282	30			
AWS-ER309 Filler	13.8(2000)	65	21	13.8(2000)	74	19
on	10.3(1500)	205	23	10.3(1500)	268	20
304L SS--GTAW-HW[c]	8.6(1250)	611	22	8.6(1250)	609	21
	7.6(1100)	1331	27	7.6(1100)	861	21
Inconel Filler Metal	17.2(2500)	31	15	17.2(2500)	100	13
72 on	13.8(2000)	71	14	13.8(2000)	293	9
304L SS--GMAW	10.3(1500)	558	20	10.3(1500)	879	12
	9.3(1350)	922	26			
Inconel Filler Metal	13.8(2000)	35	15	13.8(2000)	48	15
72 on	10.3(1500)	131	10	10.3(1500)	118	13
304L SS--SAW	8.6(1250)	384	13	8.6(1250)	301	11
	6.9(1000)	497	11	6.9(1000)	653	16
Inconel Filler Metal	13.8(2000)	89	22	13.8(2000)	126	15
72 on	10.3(1500)	261	9	10.3(1500)	244	10
304L SS--GTAW-HW	8.6(1250)	1074	12	7.6(1100)	1109	13
				6.2(900)	2184	11
Inconel Filler Metal	20.7(3000)	66	17	20.7(3000)	73	16
72 on	13.8(2000)	223	15	13.8(2000)	256	30
310 SS--GMAW	10.3(1500)	835	18	9.0(1300)	938	10
	8.3(1200)	601	21			
Inconel Filler Metal	15.9(2300)	74	11	15.9(2300)	99	17
72 on	13.8(2000)	228	17	13.8(2000)	142	13
310 SS--SAW	10.3(1500)	522	20	10.3(1500)	400	15
	8.3(1200)	1143	18	7.9(1150)	1159	19
Inconel Filler Metal	15.9(2300)	144	11	19.0(2750)	157	21
72 on	13.8(2000)	240	18	15.9(2300)	306	13
310 SS--GTAW-HW	10.3(1500)	721	20	13.8(2000)	379	13
	9.3(1350)	807	17	10.3(1500)	847	9
Inconel Filler Metal	31.0(4500)	72	5	31.0(4500)	99	9
72 on	24.1(3500)	228	11	24.1(3500)	221	7
Incoloy 800H--GMAW	17.2(2500)	711	10	17.2(2500)	523	10
	15.2(2200)	1345	9	13.8(2000)	1408	10
Inconel Filler Metal	31.0(4500)	83	10	20.7(3000)	164	12
72 on	20.7(3000)	316	9	17.2(2500)	240	6
Incoloy 800H--SAW	17.2(2500)	526	6	13.8(2000)	468	7
	13.8(2000)	693	8	10.3(1500)	1023	7
Inconel Filler Metal	31.0(4500)	111	7	31.0(4500)	102	24
72 on	24.1(3500)	270	13	20.7(3000)	333	9
Incoloy 800H--GTAW-HW	20.7(3000)	432	17	17.2(2500)	521	13
	17.2(2500)	959	18	13.8(2000)	1366	11
R139 Filler Metal	17.2(2500)	48	20	17.2(2500)	62	12
on	13.8(2000)	165	19	13.8(2000)	183	11
304L SS--GMAW	9.6(1400)	785	21	9.6(1400)	1040	22
R139 Filler Metal	13.8(2000)	110	9	13.8(2000)	87	15
on	8.6(1250)	353	10	10.3(1500)	530	17
304L SS--SAW	6.9(1000)	915	14	9.3(1350)	637	11
	8.2(800)	2017	11	8.3(1200)	731	13

(Continued)

STRESS RUPTURE TESTS[a] OF WELD OVERLAYS[b] AT 982 °C (1800 °F)[8], Continued

	Single Layer Overlay			Double Layer Overlay		
Weld Overlay[b]	Stress MPa(psi)	Life in Hours	% Elongation 38 mm (1.5 in.)	Stress MPs(psi)	Life in Hours	% Elongation 38 mm (1.5 in.)
R139 Filler Metal	13.8(2000)	65	13	17.2(2500)	98	23
on	10.3(1500)	437	16	13.8(2000)	283	16
304L SS--GTAW-HW	8.3(1200)	831	13	10.3(1500)	1106	13
R139 Filler Metal	20.7(3000)	88	26	20.7(3000)	61	23
on	17.2(2500)	185	30	17.2(2500)	178	19
310 SS--GMAW	13.8(2000)	318	26	13.8(2000)	304	17
	9.0(1300)	1919	31	9.0(1300)	969	15
R139 Filler Metal	20.7(3000)	108	21	24.1(3500)	73	13
on	17.2(2500)	152	18	17.2(2500)	263	15
310 SS--SAW	12.1(1750)	675	23	12.1(1750)	753	15
	10.3(1500)	906	23	10.3(1500)	903	10
R139 Filler Metal	24.1(3500)	53	15	24.1(3500)	81	25
on	20.7(3000)	115	17	20.7(3000)	149	19
310 SS--GTAW-HW	17.2(2500)	194	20	17.2(2500)	210	20
	13.1(1900)	703	27	13.1(1900)	914	27
R139 Filler Metal	31.0(4500)	102	9	31.0(4500)	100	14
on	24.1(3500)	247	7	24.1(3500)	242	9
Incoloy 800H--GMAW	20.0(2900)	554	13	20.0(2900)	467	19
	16.2(2350)	1435	11	16.2(2350)	1519	13
R139 Filler Metal	31.0(4500)	73	13	31.0(4500)	81	9
on	24.1(3500)	202	8	24.1(3500)	203	8
Incoloy 800H--SAW	16.2(2350)	764	7	16.2(2350)	813	15
	14.5(2100)	1240	9	14.5(2100)	1243	5
R139 Filler Metal	31.0(4500)	98	11	37.1(5385)	44	12
on	24.1(3500)	253	9	31.0(4500)	86	8
Incoloy 800H--GTAW-HW	20.7(3000)	403	9	20.7(3000)	364	9
	16.9(2450)	852	12	15.9(2300)	1191	15

[a]Stresses were computed using the full width of the specimens, i.e., base metal plus overlay. Tests were conducted at 982 °C in air. Three or four tests were performed on each base alloy-weld metal-weld process combination. Specimens were 12.7 cm overall length, 3.81 cm reduced section length, 1.27 cm width of grip, 4.76 mm reduced section width, 3.17-4.76 cm total thickness (overlay thickness 0.4-1.06 cm on each side). [Note: in the original report, a diagram of the specimen gives the overlay thickness as 0.4-2.06 cm. These values are inconsistent with a table showing overlay thicknesses from 0.417 to 1.069 cm. The 2.06 cm value is unlikely.] Overlays were not machined before testing.

[b]Single and double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc, gas metal arc, and gas tungsten arc with a hot wire addition. Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based with 31% Cr, 15% Fe, and 3.25% Al.

[c]GMAW = gas metal arc welding process, SAW = submerged arc welding process, GTAW-HW = gas tungsten arc with hot wire welding process.

STRESS[a] TO PRODUCE RUPTURE IN WELD OVERLAYS[b] AT 982 °C (1800 °F)[8]

	Stress to Rupture in 100 h		Stress to Rupture in 1000 h	
Weld Overlay[b]	Single Layer MPa (psi)	Double Layer MPa (psi)	Single Layer MPa (psi)	Double Layer MPa (psi)
AWS-ER309 Filler on 304L SS--GMAW[c]	11.7 (1700)	13.1 (1900)	7.0 (1010)	7.4 (1075)
AWS-ER309 Filler on 304L SS--SAW[c]	10.3 (1500)	11.6 (1675)	5.9 (860)	6.9 (1000)
AWS-ER309 Filler on 304L SS--GTAW-HW[c]	10.3 (1500)	13.1 (1900)	7.9 (1150)	7.4 (1075)
Inconel Filler 72 on 304L SS--GMAW	13.6 (1975)	17.2 (2500)	9.1 (1325)	10.2 (1475)
Inconel Filler 72 on 304L SS--SAW	11.0 (1600)	11.0 (1600)	6.4 (925)	6.2 (900)
Inconel Filler 72 on 304L SS--GTAW-HW	13.3 (1925)	14.0 (2025)	8.6 (1250)	7.6 (1100)
Inconel Filler 72 on 310 SS--GMAW	17.9 (2600)	18.6 (2700)	9.7 (1400)	8.8 (1275)
Inconel Filler 72 on 310 SS--SAW	15.4 (2225)	15.9 (2300)	8.6 (1250)	8.1 (1175)
Inconel Filler 72 on 310 SS--GTAW-HW	17.7 (2575)	20.7 (3000)	9.0 (1300)	9.8 (1425)
Inconel Filler 72 on Incoloy 800H--GMAW	29.7 (4300)	31.0 (4500)	16.2 (2350)	15.2 (2200)
Inconel Filler 72 on Incoloy 800H--SAW	29.3 (4250)	24.7 (3575)	10.3 (1500)	10.3 (1500)
Inconel Filler 72 on Incoloy 800H--GTAW-HW	32.1 (4650)	31.0 (4500)	15.9 (2300)	14.8 (2150)
R139 Filler Metal on 304L SS--GMAW	15.2 (2200)	15.9 (2300)	9.3 (1350)	9.7 (1400)
R139 Filler Metal on 304L SS--SAW	13.8 (2000)	15.2 (2200)	6.6 (960)	6.7 (970)
R139 Filler Metal on 304L SS--GTAW-HW	15.7 (2275)	17.2 (2500)	7.8 (1125)	10.5 (1525)
R139 Filler Metal on 310 SS--GMAW	20.0 (2900)	19.3 (2800)	10.5 (1525)	8.8 (1275)
R139 Filler Metal on 310 SS--SAW	21.0 (3050)	22.4 (3250)	9.7 (1400)	9.7 (1400)
R139 Filler Metal on 310 SS--GTAW-HW	20.7 (3000)	22.4 (3250)	12.1 (1750)	12.1 (1750)

(Continued)

STRESS[a] TO PRODUCE RUPTURE IN WELD OVERLAYS[b] AT 982 °C (1800 °F)[8], Continued

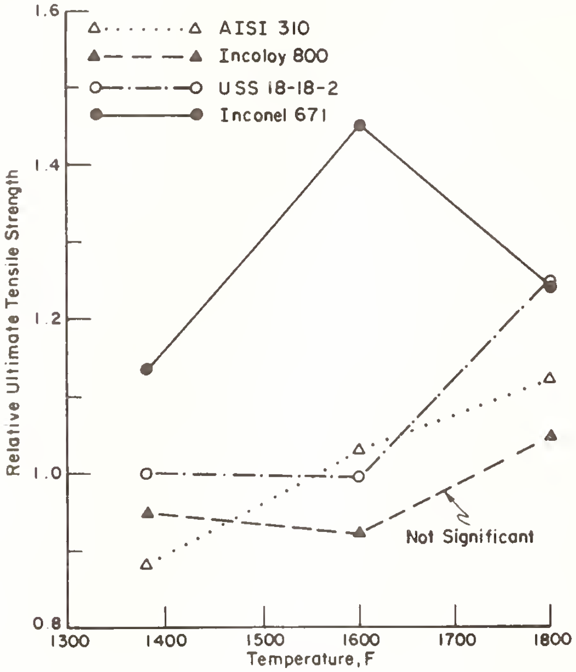
Weld Overlay[b]	Stress to Rupture in 100 h		Stress to Rupture in 1000 h	
	Single Layer MPa (psi)	Double Layer MPa (psi)	Single Layer MPa (psi)	Double Layer MPa (psi)
R139 Filler Metal on Incoloy 800H--GMAW	31.0 (4500)	31.0 (4500)	17.6 (2550)	17.6 (2550)
R139 Filler Metal on Incoloy 800H--SAW	29.0 (4200)	30.0 (4300)	15.0 (2175)	15.2 (2200)
R139 Filler Metal on Incoloy 800H--GTAW-HW	31.0 (4500)	29.3 (4250)	16.2 (2350)	16.6 (2400)

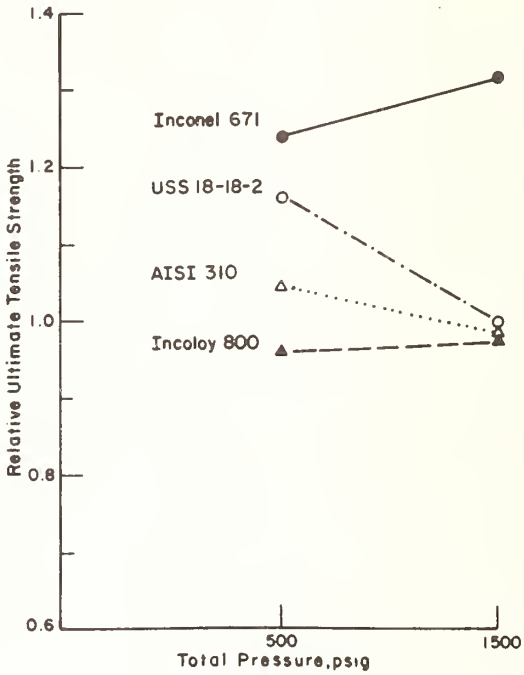
[a]Stresses were computed using the full width of the specimens, i.e., base metal plus overlay. Tests were conducted at 982 °C in air. Three or four tests were performed on each base alloy-weld metal-weld process combination. Specimens were 12.7 cm overall length, 3.81 cm reduced section length, 1.27 cm width of grip, 4.76 mm reduced section width, 3.17-4.76 cm total thickness (overlay thickness 0.4-1.06 cm on each side). [Note: in the original report, a diagram of the specimen gives the overlay thickness as 0.4-2.06 cm. These values are inconsistent with a table showing overlay thicknesses from 0.417 to 1.069 cm. The 2.06 cm value is unlikely.] Overlays were not machined before testing.

[b]Single and double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc, gas metal arc, and gas tungsten arc with a hot wire addition. Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based with 31% Cr, 15% Fe, and 3.25% Al.

[c]GMAW = gas metal arc welding process, SAW = submerged arc welding process, GTAW-HW = gas tungsten arc with hot wire welding process.

EFFECT OF COAL GASIFICATION TEST[a] TEMPERATURE, PRESSURE, AND SULFUR CONTENT ON THE AVERAGE RELATIVE UTS[b] OF FOUR ALLOYS[c] [7]





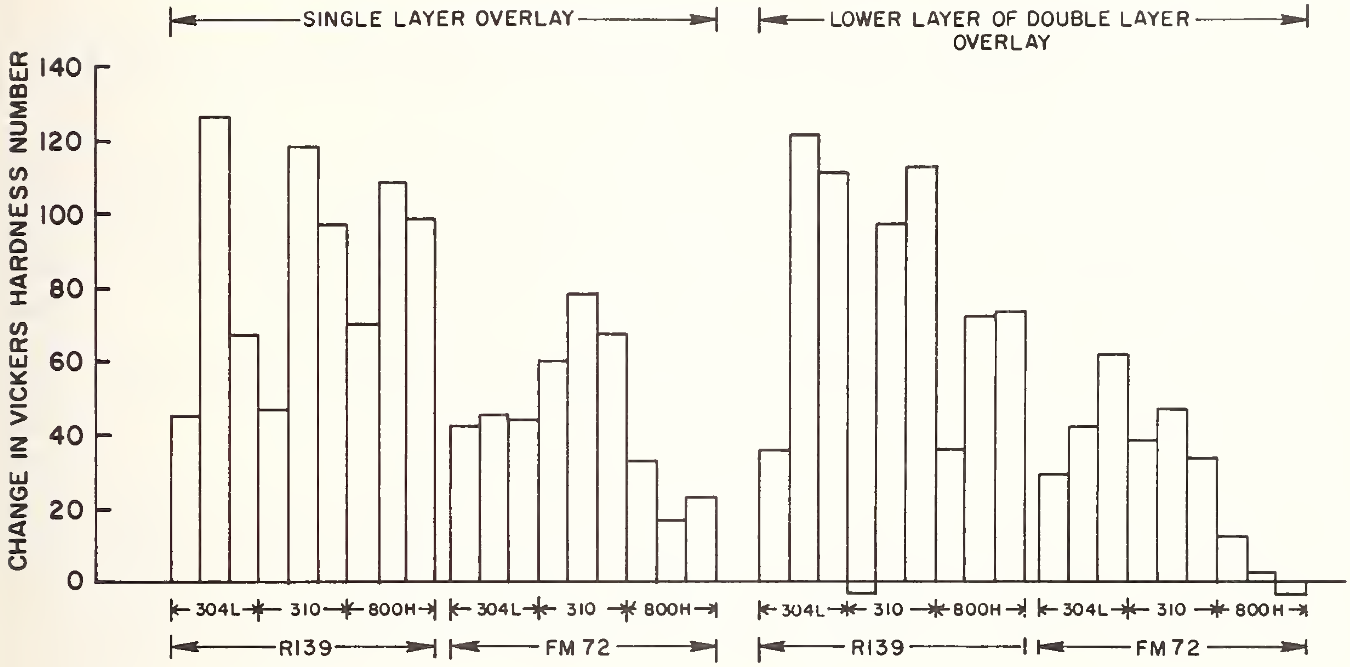
Test Variable	Value	Average Relative Ultimate Tensile Strength[b] 18-18-2	Incoloy 800	310 SS	Inconel 671
Temperature	1382 °F	1.00	0.95	0.88	1.14
	1600	1.00	0.92	1.03	1.45
	1800	1.25	1.05	1.12	1.24
Pressure	500 psig	1.16	0.96	1.04	1.24
	1000	1.00	0.98	0.98	1.32
Sulfur	1.0 %	1.06	0.98	1.02	1.31
	1.5	1.10	0.95	1.00	1.24

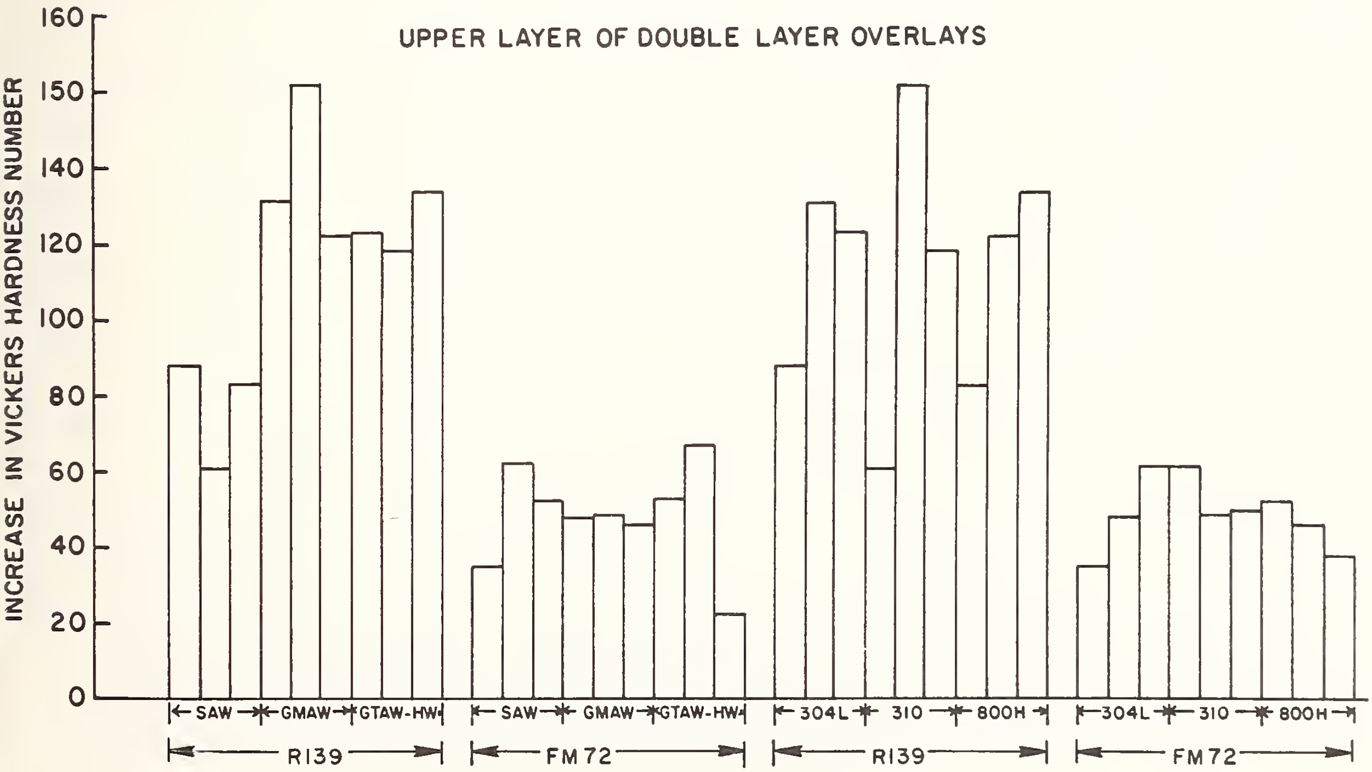
[a]See B.3.1.10 for test conditions.

[b]Ultimate tensile strength of specimens exposed to coal gasification atmospheres relative to the strength of specimens aged in vacuum for 1000 hours. Ultimate tensile strength data from B.3.1.10 was analyzed by statistical methods to find the effect of temperature, pressure, and sulfur content of the test gases. To obtain the average values given above and plotted in the graphs, the data of B.3.1.10 for each temperature was averaged over both levels of pressure and sulfur content, the averages being based on four runs each. The pressure data were averaged over all levels of temperature and sulfur content, averages based on six runs each. The sulfur data were averaged over all levels of temperature and pressure, averages based on six runs each. The resulting averages are listed and plotted above.

[c]See B.3.1.10 for alloy compositions.

CHANGE IN HARDNESS[a] OF WELDMENTS[b] AFTER EXPOSURE IN A COAL GASIFICATION ATMOSPHERE[c][8]





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CHANGE IN HARDNESS[a] OF WELDMENTS[b] AFTER EXPOSURE IN A COAL GASIFICATION ATMOSPHERE[c][8], Continued

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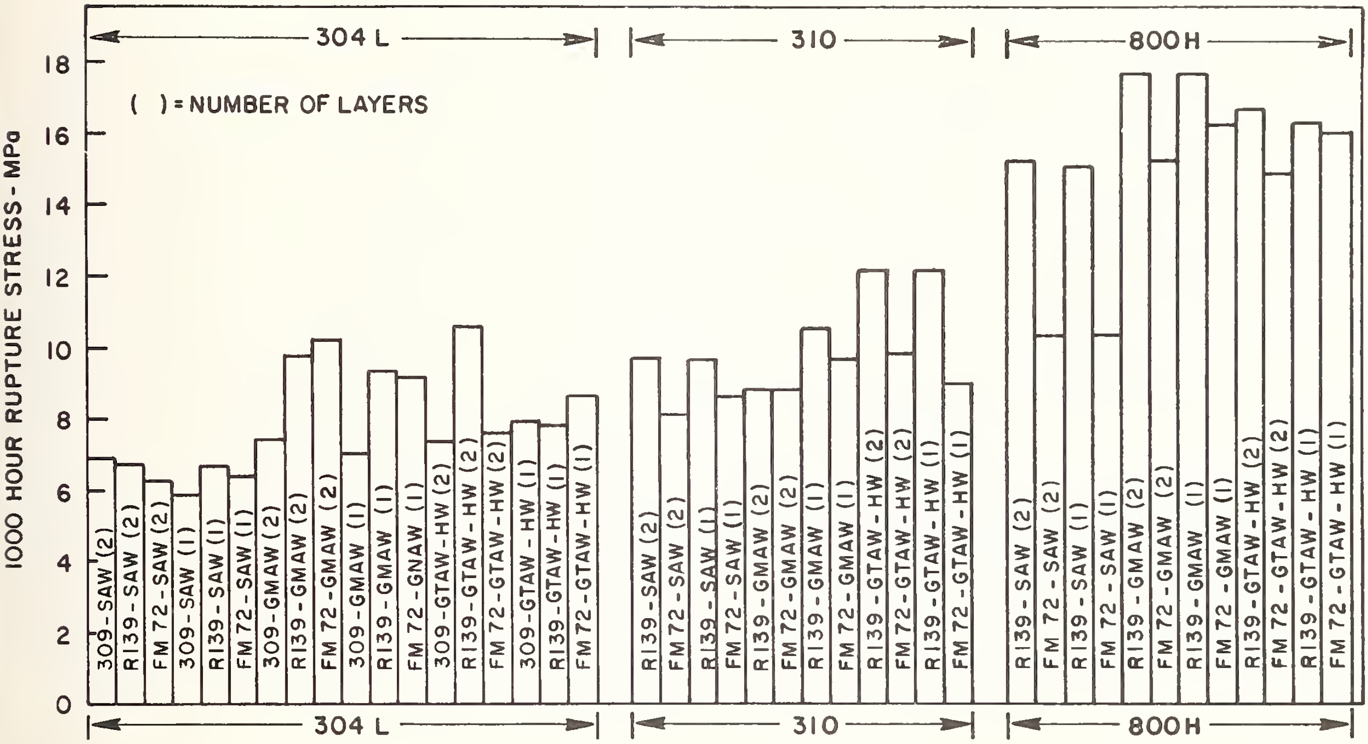
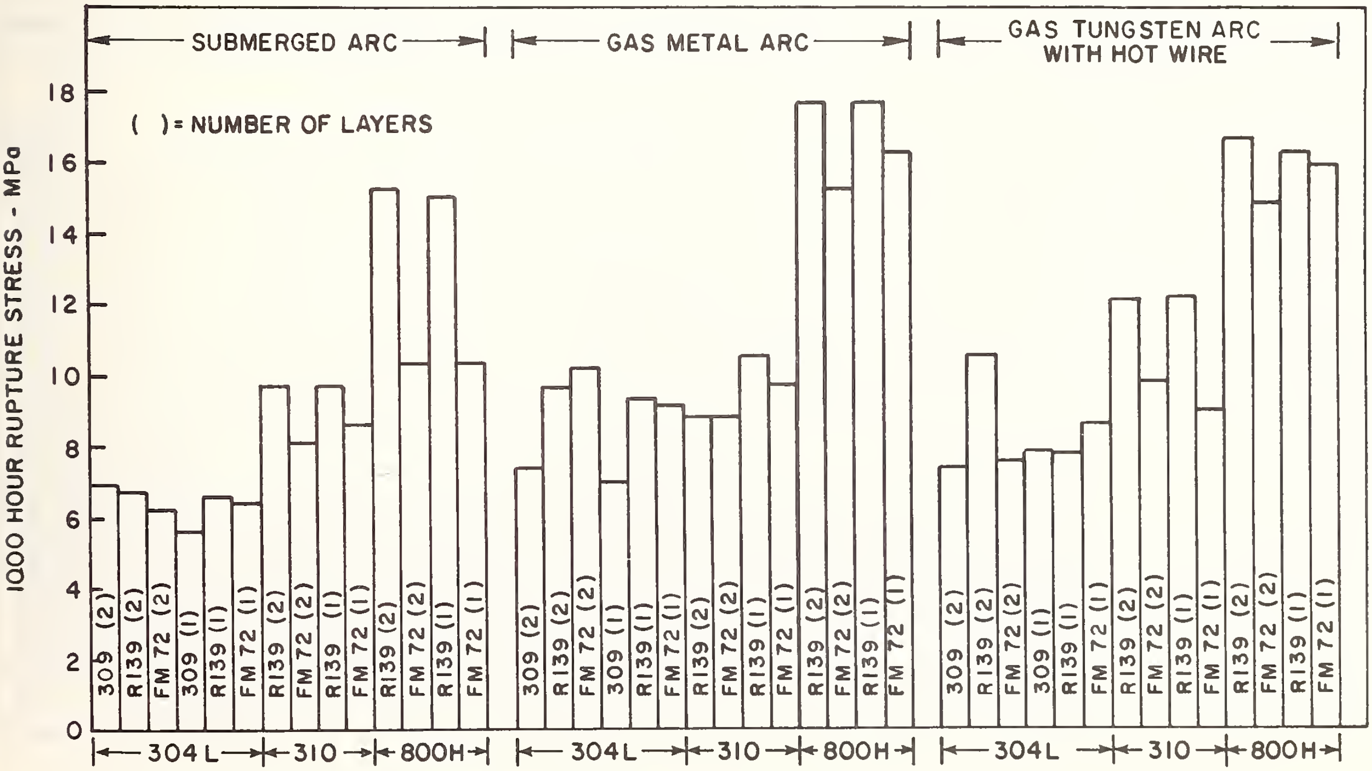
[a]Vickers hardness numbers (VHN) were determined on cross sections of surface ground and etched samples with a 10 kg load. A minimum of 5 readings were made in each area.

[b]Single and double layers of weld filler metals were deposited on substrates using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW). Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al. The substrates were 304L SS, 310 SS, and Incoloy 800H.

[c]Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, and 39% H_2O.

EFFECT OF SUBSTRATE,[a] WELD PROCESS,[b] AND WELD METAL COMPOSITION[c] ON THE STRESS RUPTURE[d] OF WELD OVERLAYS[e][8]





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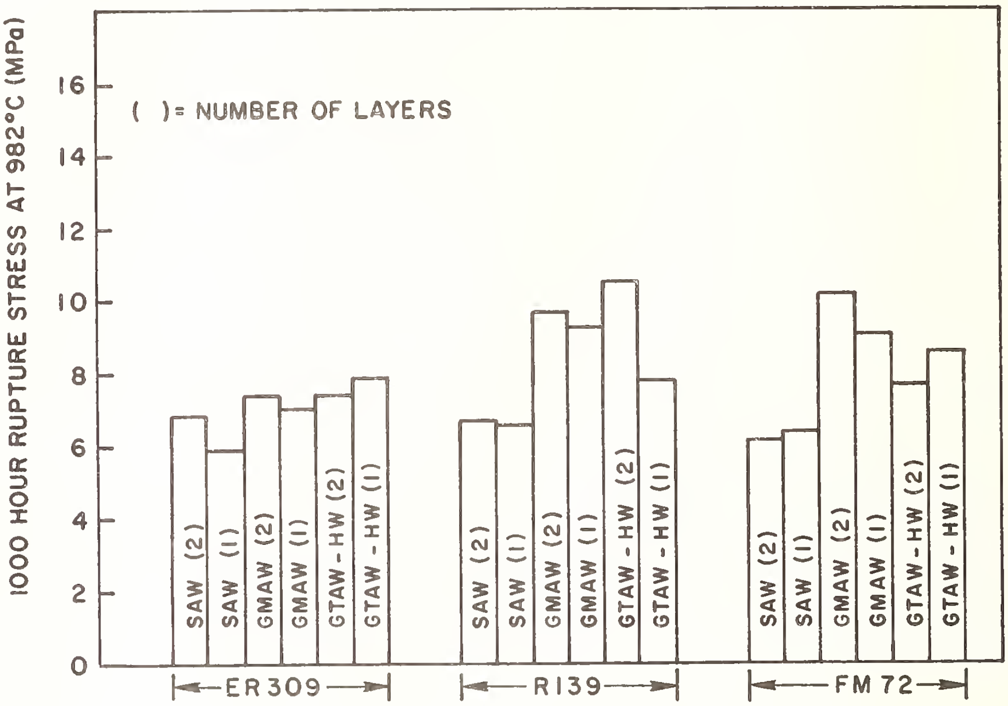
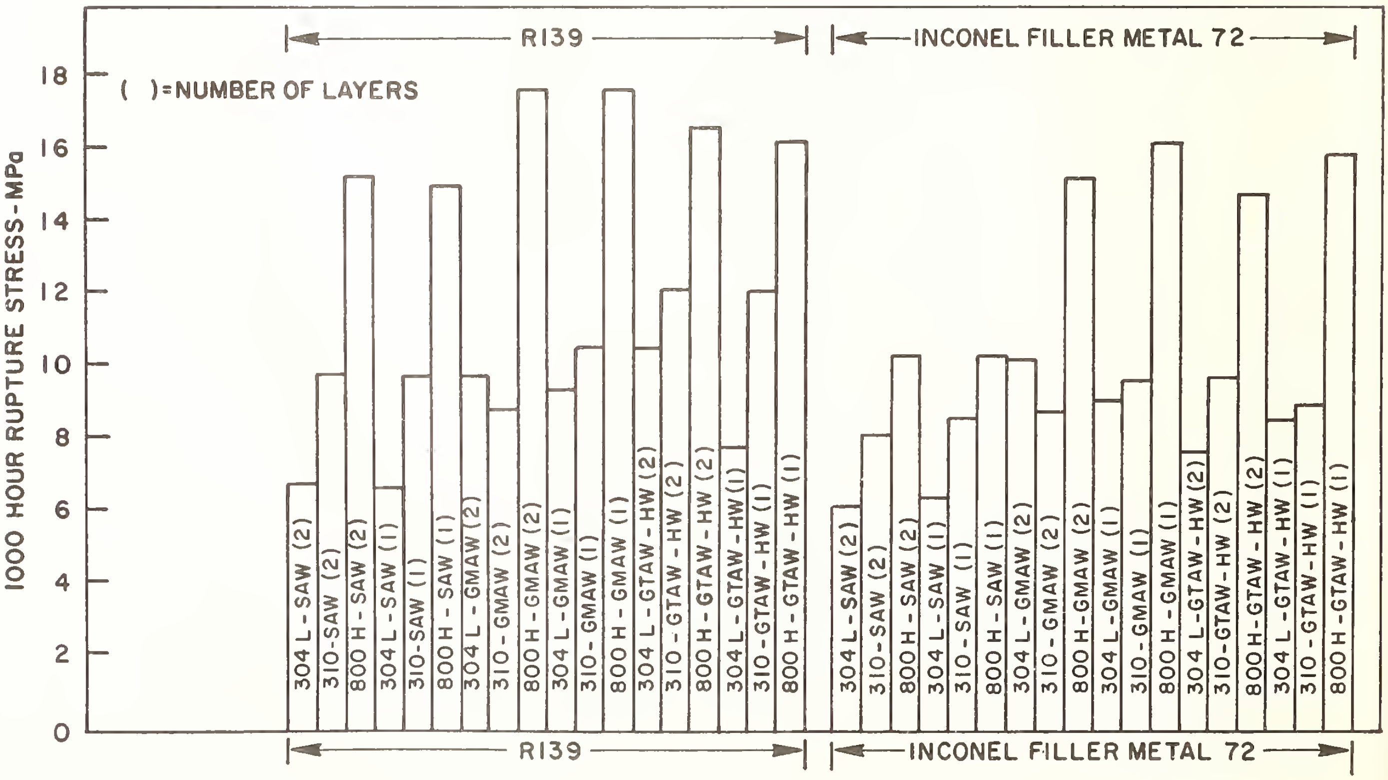
EFFECT OF SUBSTRATE,[a] WELD PROCESS,[b] AND WELD METAL COMPOSITION[c] ON THE STRESS RUPTURE[d] OF WELD OVERLAYS[e][8], Continued





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EFFECT OF SUBSTRATE,[a] WELD PROCESS,[b] AND WELD METAL COMPOSITION[c] ON THE STRESS RUPTURE[d] OF WELD OVERLAYS[e][8], Continued

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[a]Substrate alloys were 304L SS, 310 SS, and Incoloy 800H.

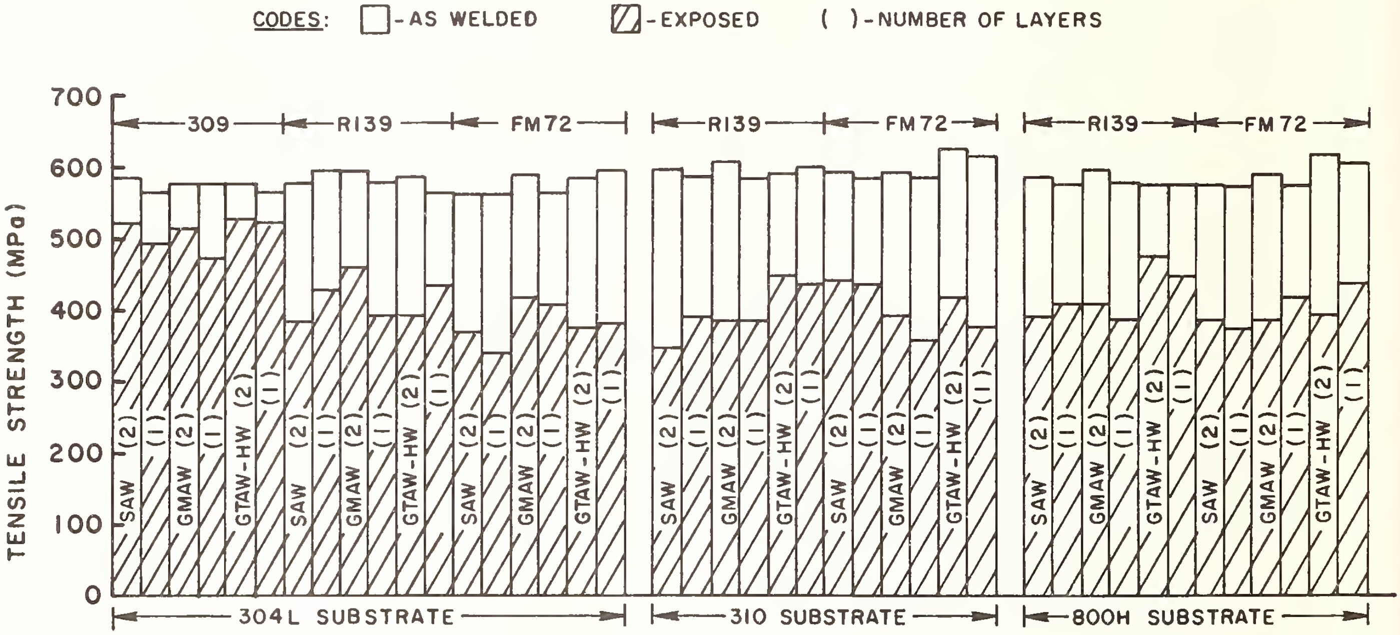
[b]Three weld processes were used: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW).

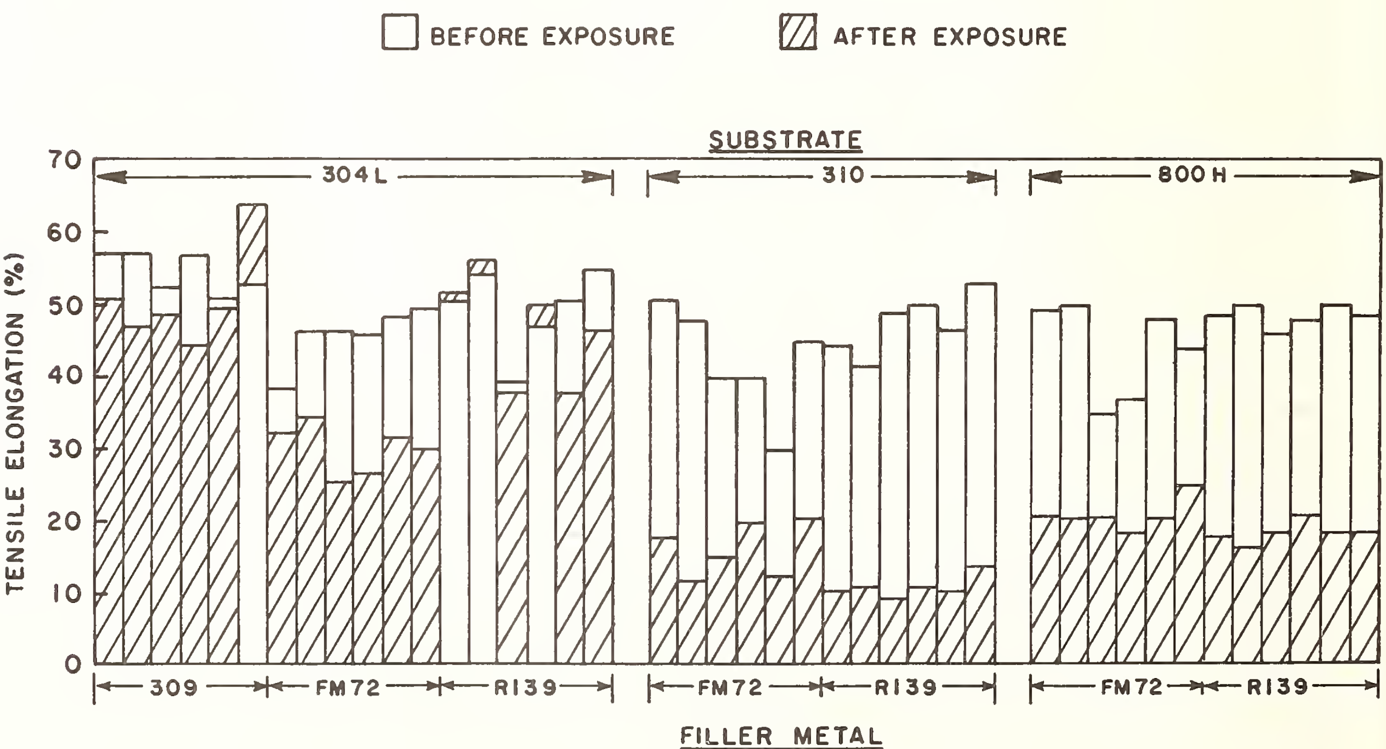
[c]The three weld metals used were AWS-ER309, Inconel Filler Metal 72, and R139 Filler Metal. Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

[d]Stresses were computed using the full width of the specimens, i.e., base metal plus overlay. Tests were conducted at 982 °C (1800 °F) in air. Three or four tests were performed on each base alloy-weld metal-weld process combination. Specimens were 12.7 cm overall length, 3.81 cm reduced section length, 1.27 cm width of grip, 4.76 mm reduced section width, 3.17-4.76 cm total thickness (overlay thickness 0.4-1.06 cm on each side). [Note: in the original report a diagram of the specimen gives the overlay thickness as 0.4-2.06 cm. These values are inconsistent with a table showing overlay thicknesses from 0.417 to 1.069 cm. The 2.06 cm value is unlikely.] Overlays were not machined before testing.

[e]Single and double layers of the weld filler metals were deposited on the substrates by each of the weld processes named in footnote b.

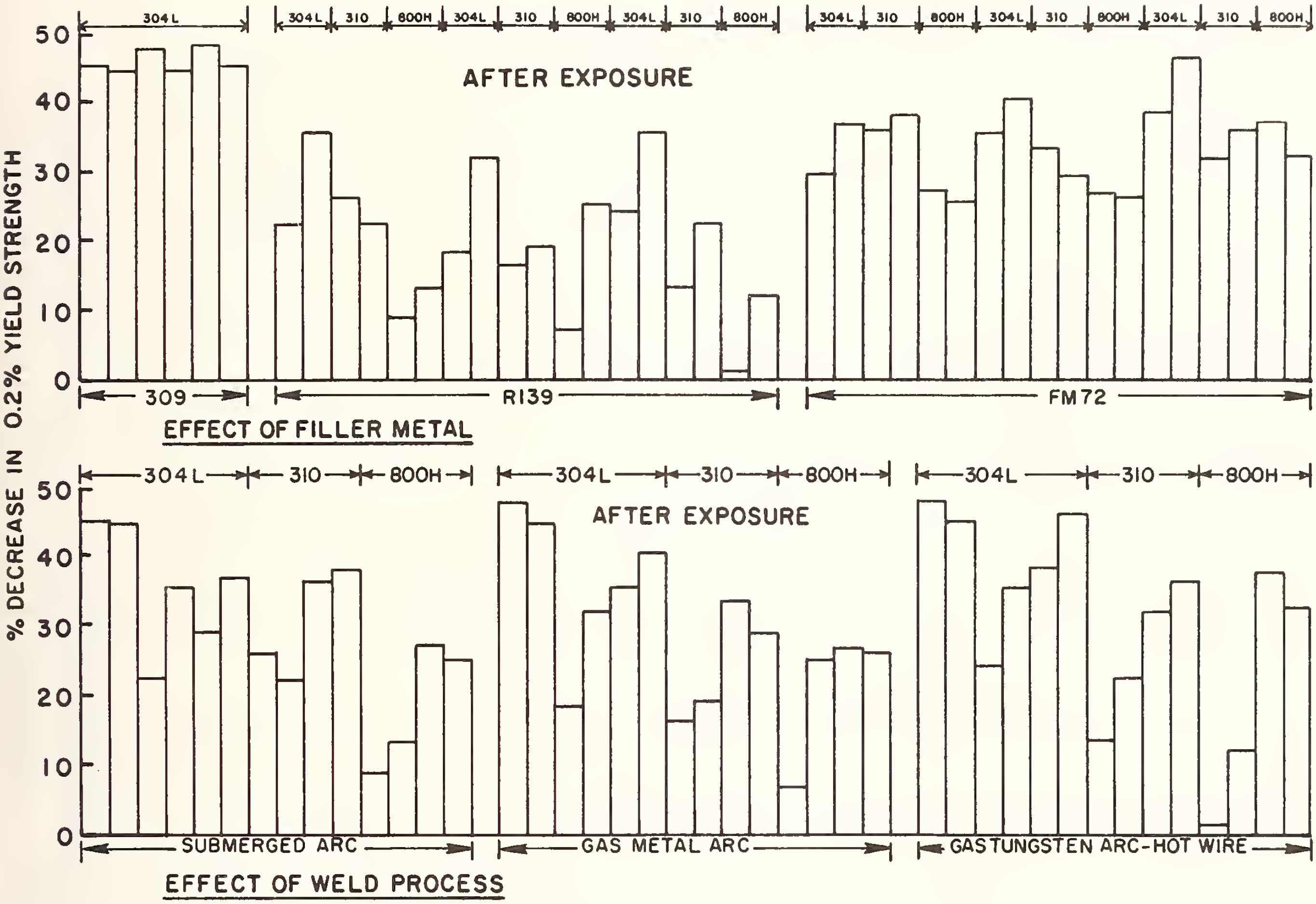
EFFECT OF SUBSTRATE,[a] WELD METAL,[b] WELD PROCESS,[c] AND COAL GASIFICATION EXPOSURE[d] ON THE MECHANICAL PROPERTIES[e] OF WELD OVERLAYS[8]





(Continued)

EFFECT OF SUBSTRATE,[a] WELD METAL,[b] WELD PROCESS,[c] AND COAL GASIFICATION EXPOSURE[d] ON THE MECHANICAL PROPERTIES[e] OF WELD OVERLAYS[8], Continued



[a]Substrate alloys were 304L SS, 310 SS, and Incoloy 800H.

[b]The weld metals used were AWS-ER309, Inconel Filler Metal 72, and R139 Filler Metal. Inconel Filler Metal 72 is Ni-based, 44% Cr, 0.7% Ti. R139 is Ni-based, 31% Cr, 15% Fe, and 3.25% Al.

[c]Single and double layers of the weld metals were overlayed using three weld processes: submerged arc (SAW), gas metal arc (GMAW), and gas tungsten arc with a hot wire addition (GTAW-HW).

[d]Specimens were exposed for 1000 hours at 982 °C (1800 °F). The composition of the input gas was 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 1% NH_3, 1% H_2S, 39% H_2O.

[e]Duplicate test were run in accordance with ASTM E-8. Crosshead speed was about 0.5 mm/min up to the 0.2% offset yield strength and 25.4 mm/min after yield strength was obtained. Yield strength was measured with the extensometer attached to the substrate. Specimens were 12.7 cm overall length, 3.81 cm reduced section length, 1.27 cm width of grip, 4.76 mm reduced section width, 3.17-4.76 cm total thickness (overlay 0.4-1.06 cm on each side). [Note: in original report a diagram gives the overlay thickness as 0.4-2.06 cm. These values are inconsistent with a table showing thicknesses from 0.417 to 1.069 cm. The 2.06 cm value is unlikely.] Overlays were not machined before tests.

EFFECT OF EXPOSURE[a] TO COAL GASIFICATION ATMOSPHERES[b] ON THE UNIAXIAL TENSILE PROPERTIES[c] OF FOUR ALLOYS[30]

	As-Received Material[d]			Tested at Indicated Temperatures after Exposure at the Same Temperatures											
				Atmosphere No. 1[b]			Atmosphere No. 2[b]			Atmosphere No. 3[b]			Atmosphere No. 4[b]		
	750 °C 1382 °F	871 °C 1600 °F	982 °C 1800 °F	750 °C 1382 °F	871 °C 1600 °F	982 °C 1800 °F	750 °C 1382 °F	871 °C 1600 °F	982 °C 1800 °F	750 °C 1382 °F	871 °C 1600 °F	982 °C 1800 °F	750 °C 1382 °F	871 °C 1600 °F	982 °C 1800 °F
0.2% YIELD STRENGTH, MPa[c]															
USS 18-18-2	63.5	36.8	30.4	57.6	SC[e]	26.7	43.7	SE[e]	SC[e]	--	SE[e]		--	SC[e]	
INCOLOY 800	91.0	30.7	29.7	53.3	--	27.1	40.5	41.3	SE	69.9	60.2		64.6	--	
310 SS	49.2	43.0	25.4	43.2	20.0	25.7	36.1	--	SE	--	--		--	--	
INCONEL 671	49.2	42.0	22.4	48.5	27.3	24.3	45.1	43.1	24.7	--	62.2		--	SC	
ULTIMATE TENSILE STRENGTH, MPa[c]															
USS 18-18-2	191.2	94.5	52.0	181.9	SC	41.7	182.6	SE	SC	163.9	SE		171.5	SC	
INCOLOY 800	226.7	119.7	59.7	204.2	51.4	47.9	200.0	75.7	SE	190.3	100.0		138.2	88.2	
310 SS	257.9	138.5	55.0	219.4	106.5	45.8	222.9	SE	SE	216.0	SE		188.9	97.9	
INCONEL 671	339.0	141.1	50.7	265.3	105.9	54.4	256.9	88.9	53.5	223.6	118.0		241.7	SC	
% UNIFORM STRAIN[c]															
USS 18-18-2	8	3	2.0	12.3	SC	16.0	9.8	SE	SC	6.9	SE		8.4	SC	
INCOLOY 800	4	4	11.1	10.8	2.4	8.6	8.8	2.5	SE	13.3	7.9		8.6	4.9	
310 SS	4	3	14.7	8.1	8.9	13.5	9.4	--	SE	7.4	--		7.9	5.9	
INCONEL 671	9	5	4.3	3.9	4.9	7.4	5.9	3.5	7.4	3.9	3.0		4.3	SC	
% TOTAL ELONGATION[c]															
USS 18-18-2	70	71	67.9	64.5	SC	86.1	62.5	SE	SC	43.8	SE		58.1	SC	
INCOLOY 800	136	123	120.1	100.4	8.4	52.9	70.4	46.4	SE	90.0	149.6		55.4	77.5	
310 SS	38	48	78.1	36.4	76	75.1	27.5	--	SE	38.9	--		29.0	66.9	
INCONEL 671	32	87	234.4	77	172	68.9	54.1	74.3	68.9	107.3	163.0		98.4	SC	

[a]Specimens were exposed to the atmospheres described in footnote b for 1000 hours at the indicated temperatures and at 1 atm pressure.

[b]Coal Gasification Atmospheres:

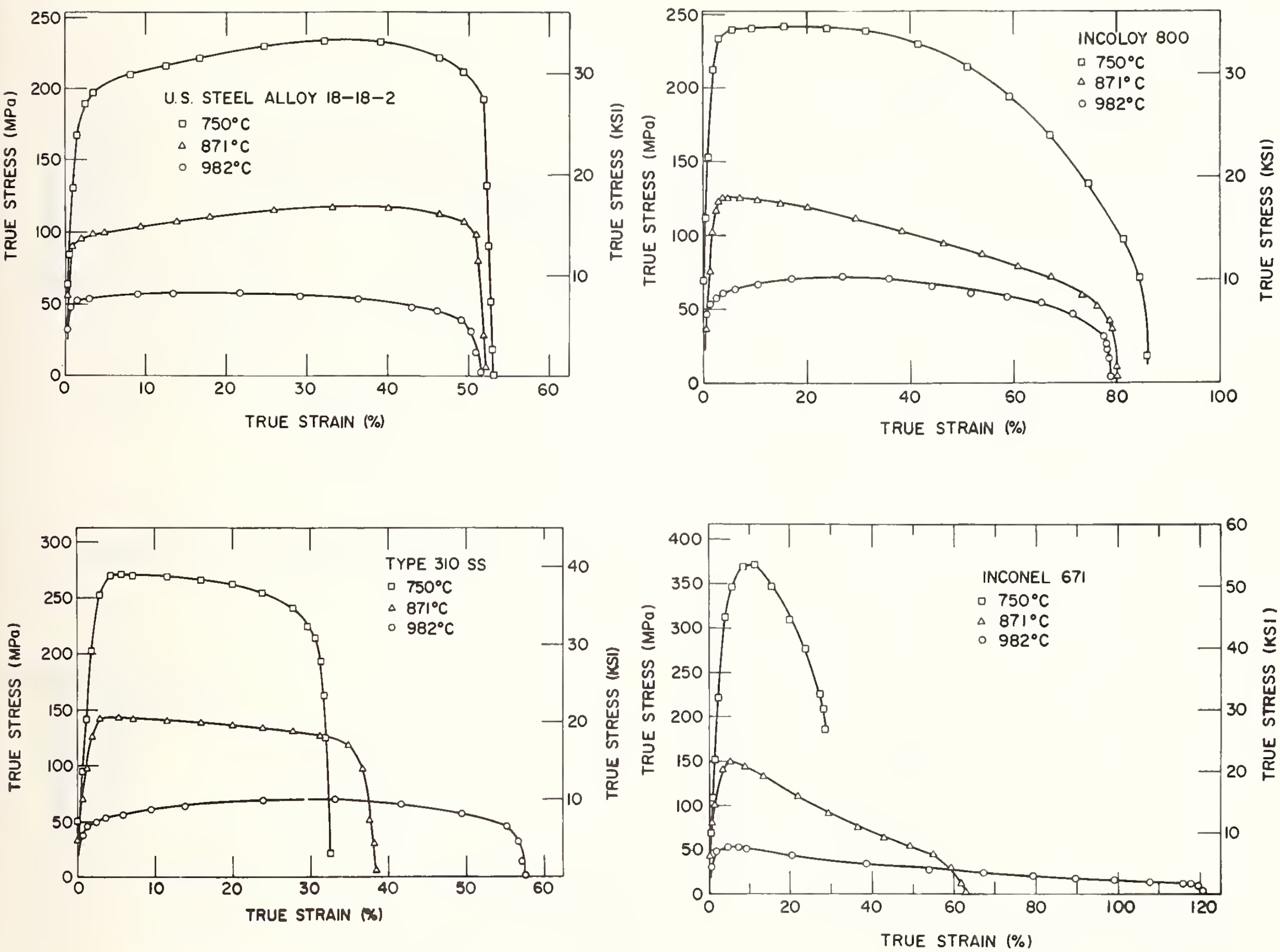
	Input Composition, Vol. %						P_{O_2}, atm			P_{S_2}, atm		
	CO	CO_2	CH_4	H_2	H_2O	H_2S	750 °C	871 °C	982 °C	750 °C	871 °C	982 °C
Atmosphere No. 1	11.7	15.4	10.0	13.0	48.9	1.0	1.7×10^{-20}	1.1×10^{-17}	1.3×10^{-15}	3.8×10^{-8}	4.0×10^{-7}	2.4×10^{-6}
Atmosphere No. 2	17.3	11.5	10.0	23.0	37.2	1.0	5.9×10^{-21}	3.6×10^{-18}	4.5×10^{-16}	2.7×10^{-8}	2.7×10^{-7}	1.5×10^{-6}
Atmosphere No. 3	26.0	14.9	10.0	26.0	22.1	1.0	2.2×10^{-21}	1.4×10^{-18}	1.8×10^{-16}	2.9×10^{-8}	2.8×10^{-7}	1.6×10^{-6}
Atmosphere No. 4	9.1	12.0	30.0	10.0	37.9	1.0	6.7×10^{-22}	3.2×10^{-19}	3.9×10^{-17}	9.9×10^{-9}	8.7×10^{-8}	4.8×10^{-7}

[c]Tensile specimens were fabricated according to ASTM E8-69; gauge length 20.3 mm, width 5.1 mm, thickness 2.54 mm. Specimens were tested at crosshead speed 8.33×10^{-3} mm/s in vacuum at the indicated temperatures.

[d]Alloy compositions in weight percent: USS18-18-2, 18.5 Cr, 17.8 Ni, 0.06 C, 0.011 S, 1.25 Mn, 2.05 Si, balance Fe; Incoloy 800, 21 Cr, 32.5 Ni, 0.05 C, 0.008 S, 0.75 Mn, 0.35 Si, 0.38 Al, 0.38 Ti, 46.0 Fe; 310 SS, 25 Cr, 20 Ni, 0.25 C, 1.5 Mn, 0.4 Si, balance Fe; Inconel 671, 48 Cr, 50 Ni, 0.05 C, 0.35 Ti.

[e]SC = sample corroded, SE = sample embrittled.

VARIATION OF TRUE STRESS-TRUE STRAIN DATA[a] FOR SEVERAL ALLOYS[b] AT THREE TEMPERATURES[30]



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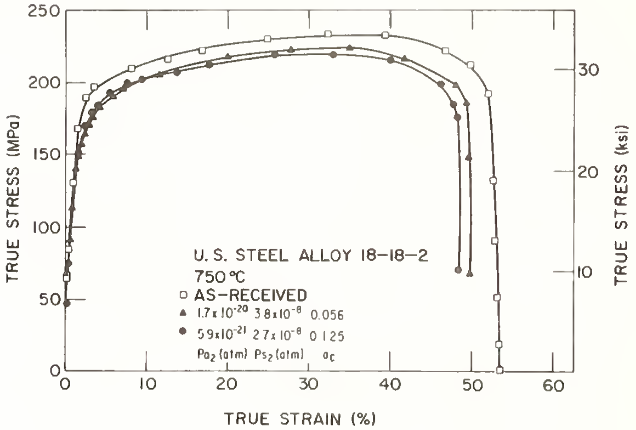
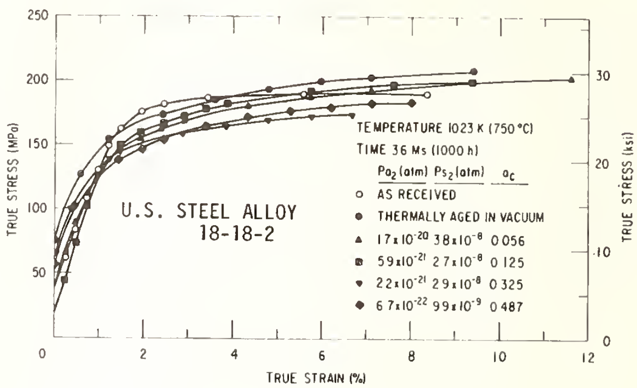
[a]From tensile testing data. Tensile specimens were fabricated according to ASTM E8-69; gauge length 20.3 mm, width 5.1 mm, thickness 2.54 mm. Specimens were tested at crosshead speed 8.33 x 10^{-3} mm/s in vacuum at the indicated temperatures.

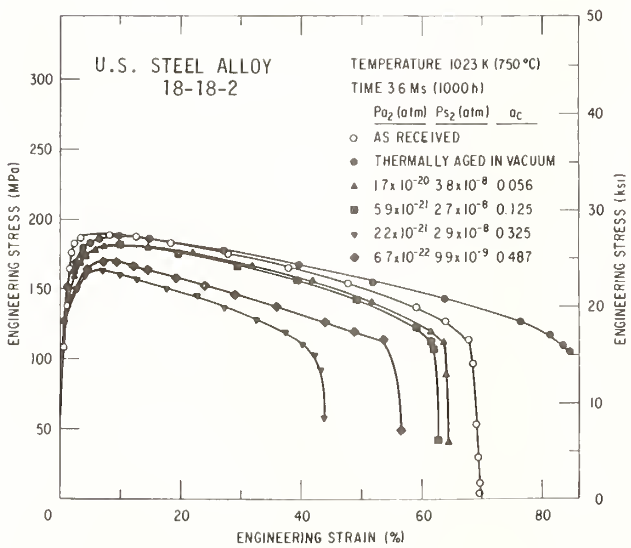
[b]Alloys were tested in the as-received condition. Alloys compositions in weight percent: USS 18-18-2, 18.5 Cr, 17.8 Ni, 0.06 C, 0.011 S, 1.25 Mn, 2.05 Si, balance Fe; Incoloy 800, 21 Cr, 32.5 Ni, 0.05 C, 0.008 S, 0.75 Mn, 0.35 Si, 0.38 Al, 0.38 Ti, 46.0 Fe; 310 SS, 25 Cr, 20 Ni, 0.25 C, 1.5 Mn, 0.4 Si, balance Fe; Inconel 671, 48 Cr, 50 Ni, 0.05 C, 0.35 Ti.

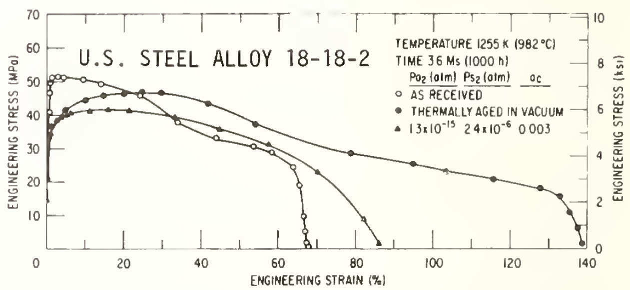
EFFECT OF COAL GASIFICATION ATMOSPHERES[a] ON STRESS-STRAIN DATA[b] FOR FOUR ALLOYS[c] AT SEVERAL TEMPERATURES[30]





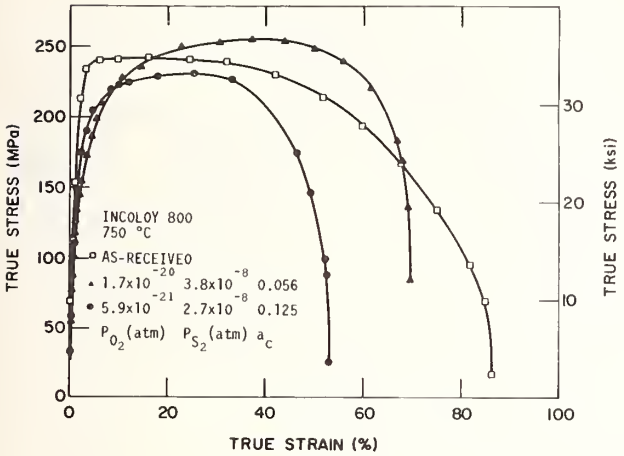
↑
True Stress-True Strain up to the Point of Maximum Engineering Stress

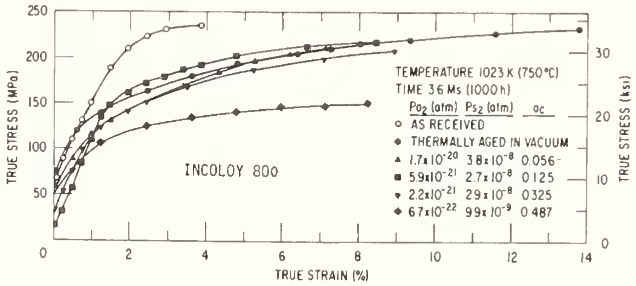




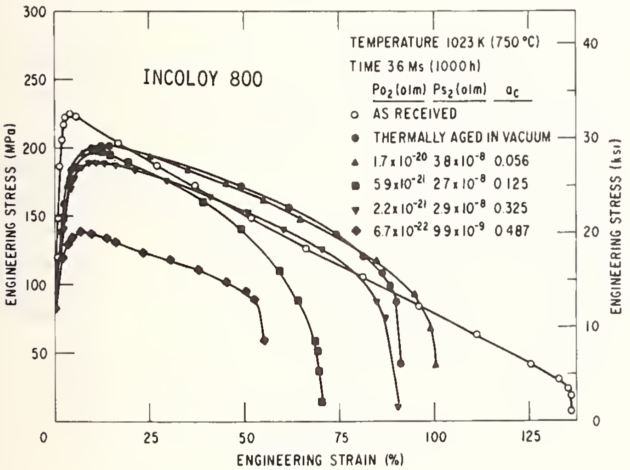
(Continued)

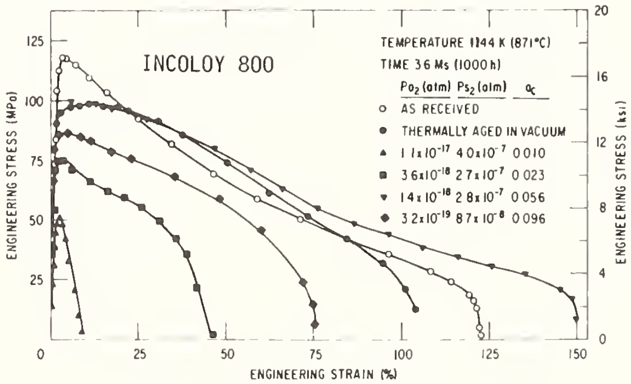
EFFECT OF COAL GASIFICATION ATMOSPHERES[a] ON STRESS-STRAIN DATA[b] FOR FOUR ALLOYS[c] AT SEVERAL TEMPERATURES[30], Continued

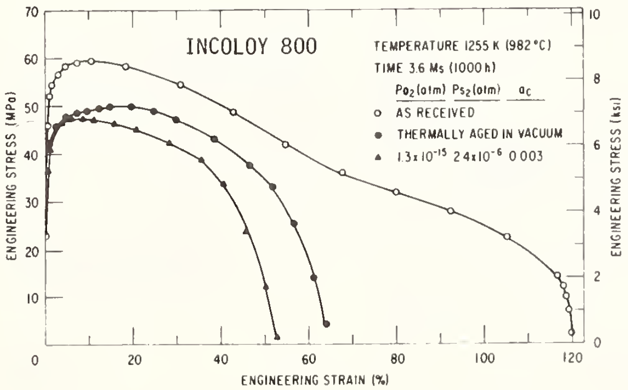




↑
True Stress-True Strain up to the Point of Maximum Engineering Stress







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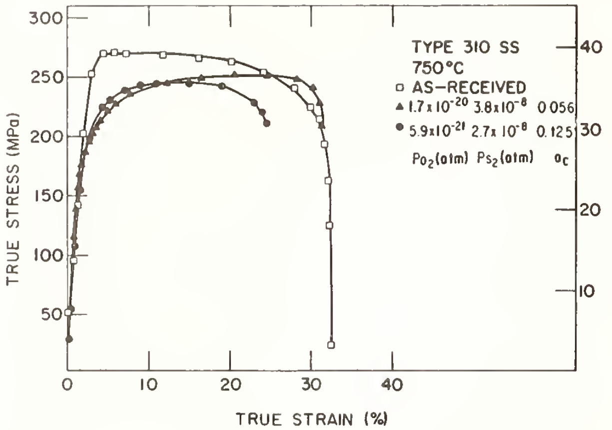
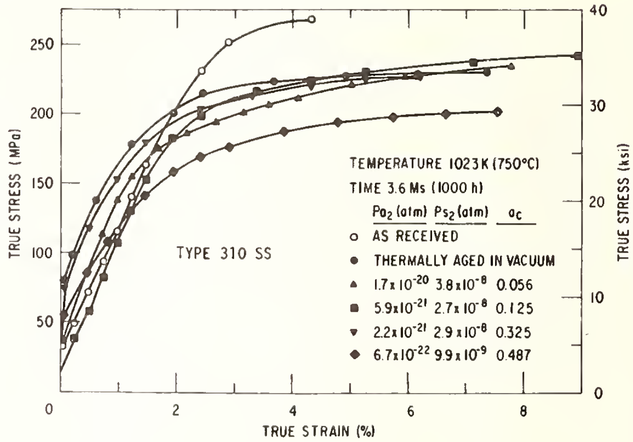
EFFECT OF COAL GASIFICATION ATMOSPHERES[a] ON STRESS-STRAIN[b] FOR FOUR ALLOYS[c] AT SEVERAL TEMPERATURES[30], Continued





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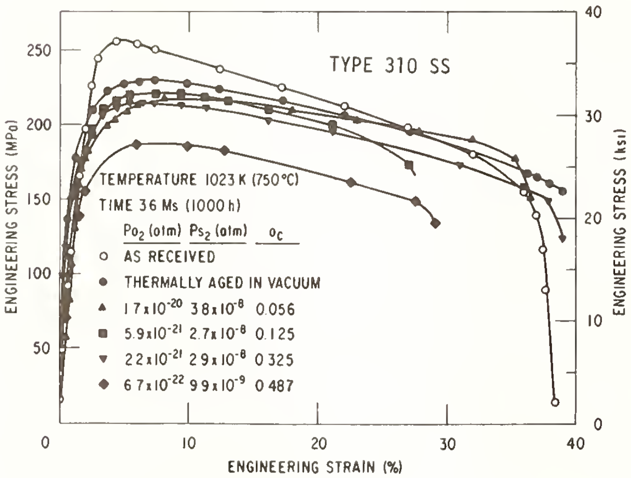
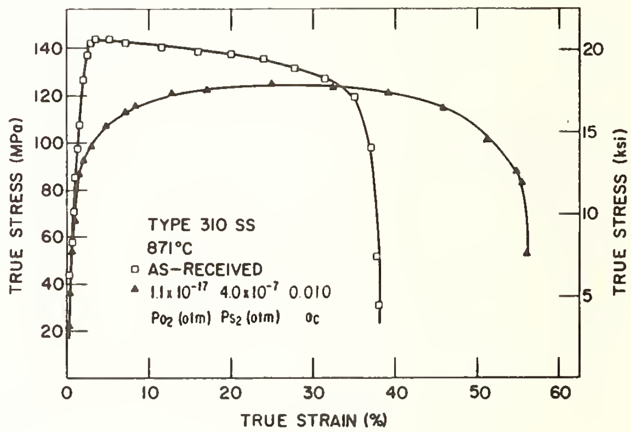
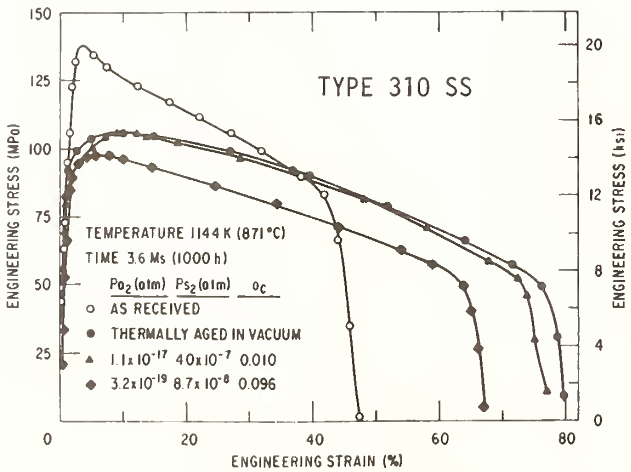
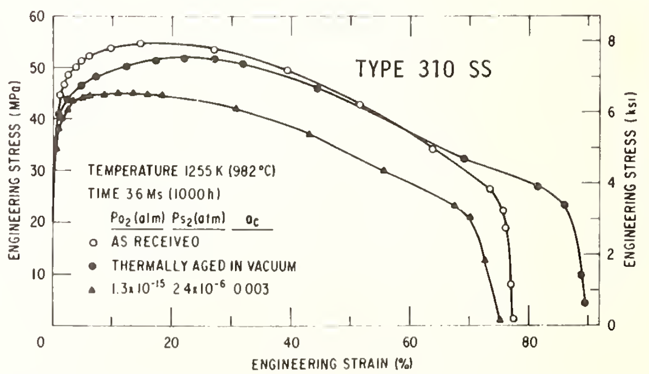
True Stress-True Strain up to the Point of Maximum Engineering Stress









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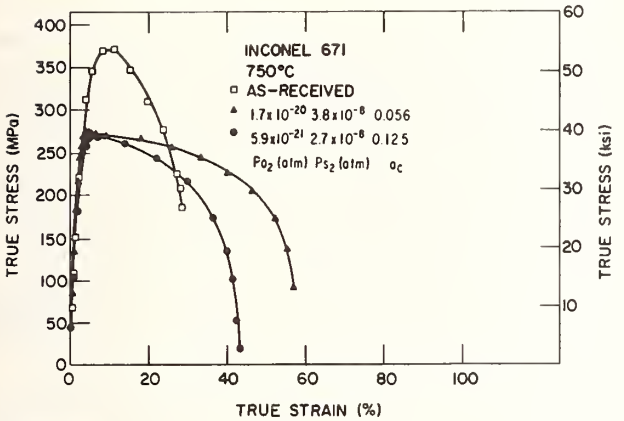
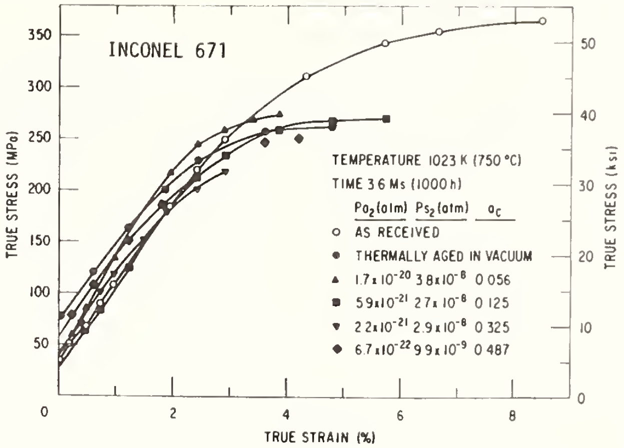
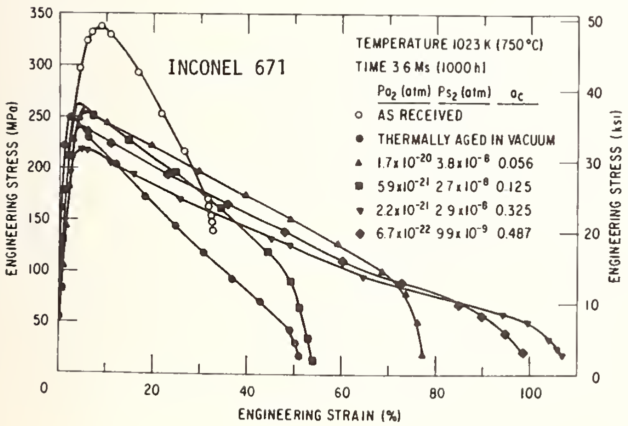
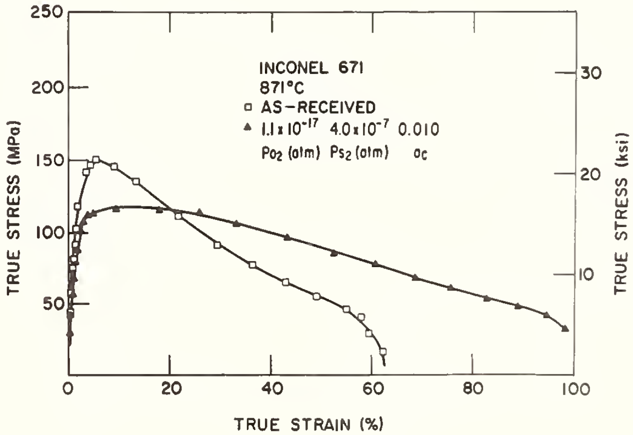
EFFECT OF COAL GASIFICATION ATMOSPHERES[a] ON STRESS-STRAIN DATA[b] FOR FOUR ALLOYS[c] AT SEVERAL TEMPERATURES[30], Continued

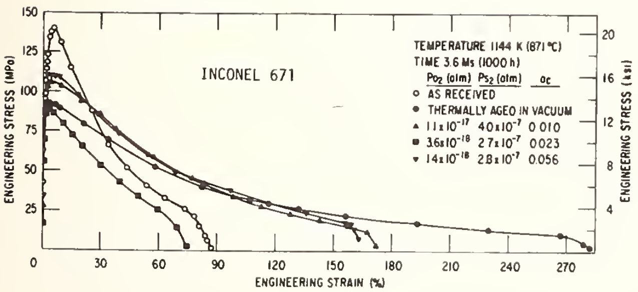


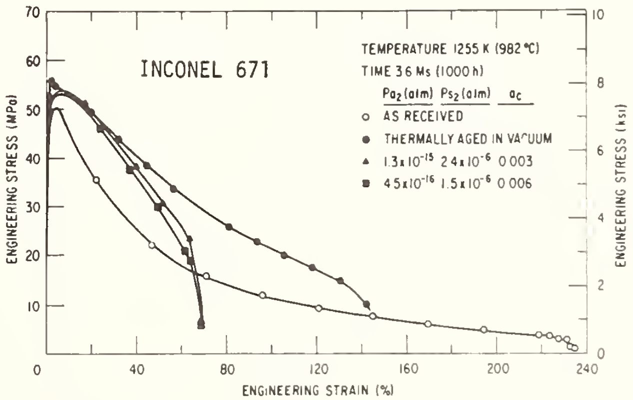


True Stress-True Strain up to the Point of Maximum Engineering Stress









(Continued)

EFFECT OF COAL GASIFICATION ATMOSPHERES[a] ON STRESS-STRAIN DATA[b] FOR FOUR ALLOYS[c] AT SEVERAL TEMPERATURES[30], Continued

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[a]Alloy specimens were exposed to simulated coal gasification atmospheres for 1000 hours at the indicated temperatures and at 1 atm pressure. The gas atmospheres correspond to those given in footnote b of Section B.3.1.84.

[b]True Stress-True Strain and Engineering Stress-Engineering Strain data were obtained from tensile testing data. Load-elongation data were converted to True Stress-True Strain by assuming a constant volume approximation. Tensile specimens were fabricated according to ASTM E8-69; gauge length 20.3 mm, width 5.1 mm, thickness 2.54 mm. Specimens were tested at crosshead speed 8.33 x 10^{-3} mm/s in vacuum at the indicated temperatures.

[c]Alloys were tested in as-received condition, after thermal aging in vacuum at the indicated temperatures for 1000 hours, and after the gas atmosphere exposures. Alloy compositions in weight percent: USS 18-18-12, 18.5 Cr, 17.8 Ni, 0.06 C, 0.011 S, 1.25 Mn, 2.05 Si, balance Fe; Incoloy 800, 21 Cr, 32.5 Ni, 0.05 C, 0.008 S, 0.75 Mn, 0.35 Si, 0.38 Al, 0.38 Ti, 46.0 Fe; 310 SS, 25 Cr, 20 Ni, 0.25 C, 1.5 Mn, 0.4 Si, balance Fe; Inconel 671, 48 Cr, 50 Ni, 0.05 C, 0.35 Ti.

HOT HARDNESS DATA[a] FOR ALLOYS USED IN EROSION/CORROSION TESTING[b][11,43]

	Hot Hardness, R_{15T}[a]					
Alloy	Ambient[c]	900 °F[c]	1200 °F[c]	1500 °F[c]	1650 °F[d]	1800 °F[d]
Incoloy 800	83.9	80.6	78.2	78.0	74.7	59.2
Inconel 601	82.0	79.4	78.8	76.2	76.0	60.9
310 SS	82.0	78.0	73.0	65.1	60.3	50.0
RA 333	81.5	78.6	76.0	75.0	74.1	55.8
LM-1866	90.8	89.0	82.7	68.3	59.9	--
Inconel 671	91.0	90.1	90.2	78.2	85.9	73.4
Haynes 188	87.7	85.1	84.4	83.5	83.4	75.9
446 SS	87.0	83.0	82.2	40.3	2.5	--
Crutemp 25	86.0	82.5	81.0	76.0	65.5	50.0
Stellite 6B	92.3	90.6	88.1	86.7	86.2	77.7

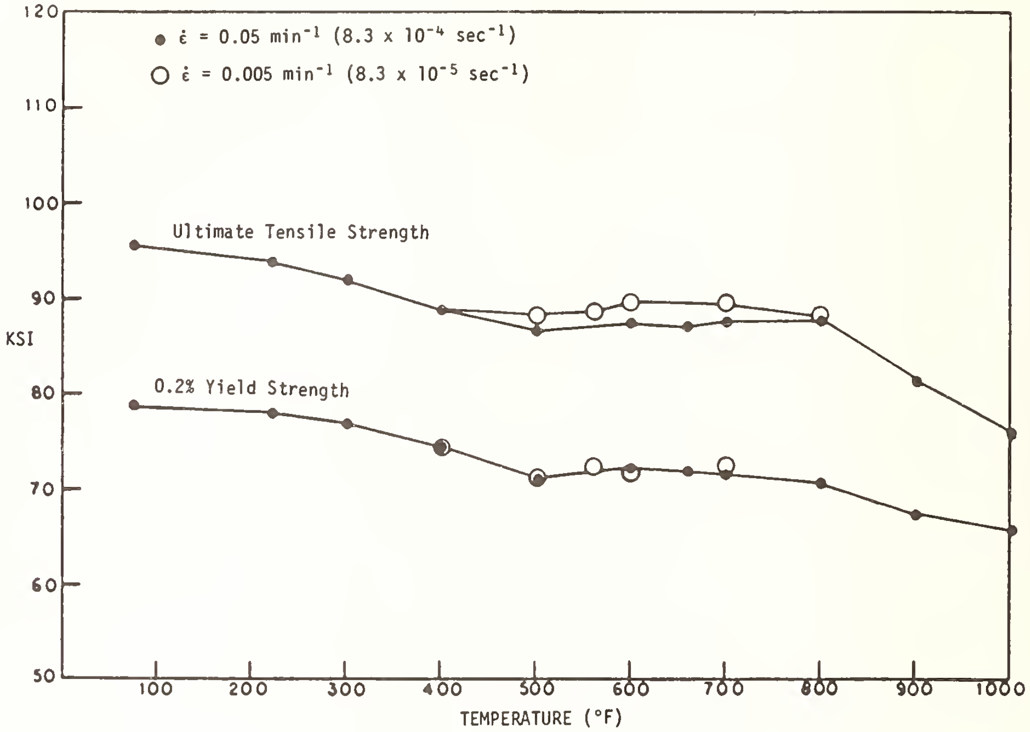
[a]Alloys were tested using a Wilson Hot Hardness Tester; calibration was checked with hardness standards at ambient temperature before the specimens were tested. All tests were in an argon environment using two types of indenter balls, either carbide or sapphire, both 1/16 in. diameter, with a major load of 15 kg. The Rockwell test scale used was the 15T scale.

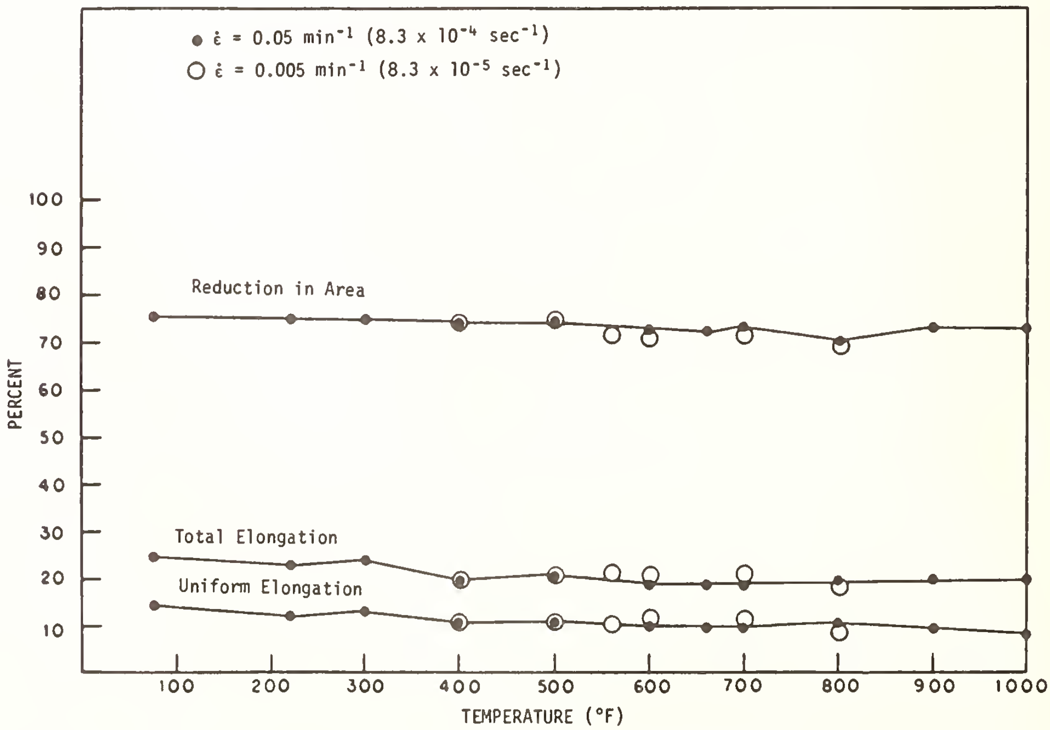
[b]See B.2.1.23, B.2.1.24, B.2.1.25, B.2.1.26, B.2.1.44, and B.2.1.45 for the erosion/corrosion data for these alloys.

[c]Tested with the carbide ball.

[d]Tested with the sapphire ball.

TEMPERATURE DEPENDENCE OF THE MECHANICAL PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEEL[b][47]





(Data Continued)

TEMPERATURE DEPENDENCE OF THE MECHANICAL PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEEL[b][47], Continued

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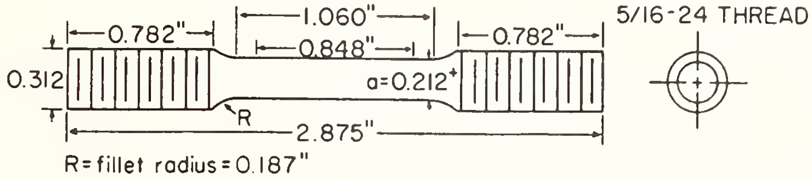
[a]Specimens were prepared from longitudinal sections of the plate. The speci-



mens were tensile tested at temperatures from 72 °F to 1000 °F on a TT-C Instron tensile machine at constant crosshead speed of 0.05 in/min. (Some specimens were tested at 0.005 in/min. Discontinuous yielding was noted in the 600-700 °F region so the specimens were tested at the slower speed in that temperature region. All data were calculated from stress-strain curves since these values at the point of fracture were within 1% of the values obtained using fiducial marks. Cross-sections and reduction in area were obtained by averaging measurements across three diameters.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled.

EFFECT OF TEMPERATURE, PRESSURE, AND H_2-COAL SLURRY[a] ON ROOM TEMPERATURE TENSILE PROPERTIES[b] OF 2-1/4 Cr-1 Mo STEEL[c][47]

Sample	Exposure Environment	Exposure Stress (ksi)[d]	0.2% Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	% Total Elongation	% Uniform Elongation	Reduction in Area (%)	Notch Tensile Strength (ksi)
ASTM Code Specifications			45.0 minimum	75.0 to 100.0	22 minimum	--	45 minimum	--
ASTM Specification Verification (longitudinal)	as-received	--	78.3 (5)[e]	94.2 (5)[e]	>22.5 (5)[e]	9.3 (5)[e]	72.5 (5)[e]	146.0 (5)[e]
ASTM Specification Verification (transverse)	as-received	--	79.2 (4)	94.5 (4)	>22.5 (4)	8.8 (4)	61.0 (4)	138.8 (4)
Base Data[f]	as-received	--	78.7 (10)	95.6 (10)	24.7 (10)	14.2 (10)	75.5 (10)	148.2 (10)
Tested at 500 °F[g]	as-received	--	69.2 (10)	84.5 (10)	21.1 (10)	11.7 (10)	74.2 (10)	129.6 (10)
Tested at 900 °F[g]	as-received	--	64.3 (10)	78.4 (10)	21.1 (10)	10.9 (10)	71.1 (10)	121.3 (10)
Exposed for 168 h	500 °F, 2000 psig Argon	--	79.6 (10)	96.4 (9)	24.5 (10)	14.3 (10)	75.8 (10)	148.6 (10)
Exposed for 168 h	900 °F, 2000 psig Argon	--	78.2 (10)	95.7 (10)	24.3 (10)	14.0 (10)	75.0 (10)	147.9 (10)
Exposed for 168 h	500 °F, 4000 psig Argon	--	80.0 (10)	96.8 (10)	23.7 (10)	13.6 (10)	75.0 (10)	146.4 (10)
Exposed for 1000 h	800 °F, 4000 psig Argon	--	79.1 (5)	97.0 (5)	24.3 (5)	14.0 (5)	74.7 (5)	149.8 (5)
Exposed for 168 h	900 °F, 4000 psig Argon	--	79.2 (10)	97.2 (10)	23.5 (10)	12.9 (10)	74.7 (10)	146.6 (10)
Stress exposed for 168 h	500 °F, 2000 psig Argon	46.1 ± 6.0	79.2 (9)	95.8 (10)	22.9 (10)	13.1 (10)	74.7 (10)	147.0 (10)
Stress exposed for 168 h	900 °F, 2000 psig Argon	19.1 ± 1.3	78.2 (10)	94.6 (10)	22.8 (10)	13.5 (10)	74.4 (9)	147.8 (10)
Stress exposed for 168 h	900 °F, 2000 psig Argon	41.4 ± 7.2	81.3 (10)	95.2 (9)	22.4 (9)	12.0 (10)	73.9 (10)	149.2 (9)
Stress exposed for 168 h	500 °F, 4000 psig Argon	48.6	80.7 (10)	94.7 (10)	22.1 (10)	11.9 (10)	75.1 (9)	148.0 (10)
Stress exposed for 1000 h	800 °F, 4000 psig Argon	24.3 ± 2.0 (S) 23.5 ± 2.8 (N)	79.5 (5)	97.2 (5)	24.7 (5)	13.9 (5)	74.9 (4)	149.1 (5)
Stress exposed for 168 h	900 °F, 4000 psig Argon	19.1 ± 1.3	77.1 (10)	94.3 (10)	23.6 (10)	13.9 (10)	74.6 (10)	145.0 (10)
Exposed for 168 h in coal slurry	500 °F, 2000 psig Hydrogen	--	79.8 (10)	95.5 (10)	24.3 (10)	14.2 (10)	75.0 (9)	144.0 (9)
Exposed for 168 h in coal slurry	900 °F, 2000 psig Hydrogen	--	78.7 (9)	95.6 (9)	23.2 (9)	13.6 (10)	74.6 (9)	143.7 (10)
Exposed for 168 h in coal slurry	500 °F, 4000 psig Hydrogen	--	79.4 (10)	95.3 (10)	24.6 (10)	14.6 (10)	74.8 (10)	147.5 (10)
Exposed for 168 h in coal slurry	800 °F, 4000 psig Hydrogen	--	77.2 (8)	94.3 (10)	24.5 (10)	14.9 (10)	74.6 (10)	147.1 (10)
Exposed for 856 h in coal slurry	800 °F, 4000 psig Hydrogen	--	78.6 (4)	96.1 (4)	24.2 (4)	14.3 (4)	75.2 (4)	146.5 (4)
Stress exposed for 168 h in coal slurry	500 °F, 2000 psig Hydrogen	24.0 ± 1 (S) 24.4 ± 0.3 (N)	77.9 (9)	94.1 (10)	22.6 (9)	13.5 (9)	74.9 (10)	146.8 (5)
Stress exposed for 168 h in coal slurry	800 °F, 2000 psig Hydrogen	22.5 ± 1.7 (S) 23.1 ± 1.1 (N)	76.1 (8)	91.5 (10)	22.9 (10)	14.0 (10)	75.7 (10)	143.4 (10)
Stress exposed for 168 h in coal slurry	500 °F, 4000 psig Hydrogen	27.2 ± 0.5 (S) 24.0 ± 1 (N)	79.6 (10)	95.3 (10)	24.3 (10)	13.8 (10)	75.5 (10)	147.1 (7)
Stress exposed for 168 h in coal slurry	800 °F, 4000 psig Hydrogen	22.7 ± 1	77.7 (10)	93.8 (10)	23.4 (10)	13.9 (10)	75.8 (10)	--
Stress exposed for 856 h in coal slurry	800 °F, 4000 psig Hydrogen	24.7 ± 1.6 (S) 24.8 ± 1.5 (N)	78.3 (4)	94.6 (4)	23.8 (4)	14.1 (4)	76.4 (3)	144.0 (4)

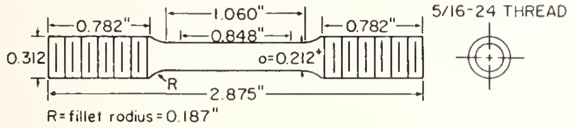
[a] Coal slurry is 35 vol% of -100 mesh Kentucky bituminous and 65% solvent. The solvent is centrifuged Synthoil product from Pittsburgh Energy Technology Center run FB-61 using the same Kentucky bituminous. Solvent analysis (wt%): oils 64.4, asphaltenes 32.3, organic benzene insolubles 3.3. Samples were immersed in the slurry inside a 304 SS can which was placed inside the hydrogen pressure vessel. Hydrogen pressure was controlled to ±100 psig during the run.

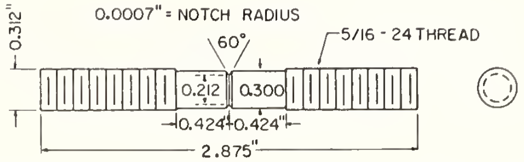
[b] ASTM Specification Verification Tests were done on standard specimens cut from both longitudinal and transverse sections of the plate using a Baldwin-Southwark tensile test machine under ambient conditions at a constant strain rate of 0.01 min^{-1}. Specimens for base data tests and all subsequent tests were prepared from longitudinal sections of the plate. Smooth-bar and notched-bar cylindrical specimens were tensile tested at 72 °F (except for two tests at 500 and 900 °F) on a TT-C Instron tensile machine at constant crosshead speed of 0.05 in/min. (See next page for dimensions of specimens.)

(Table Continued)

EFFECT OF TEMPERATURE, PRESSURE, AND H_2-COAL SLURRY[a] ON ROOM TEMPERATURE TENSILE PROPERTIES[b] OF 2-1/4 Cr-1 Mo STEEL[c][47]

Footnotes Continued





After exposure in coal slurry, remaining slurry was dissolved off specimens with 50/50 acetone-toluene. Threaded portions were cleaned with a wire wheel and samples tested with the surface film intact on the gauge section. All data were calculated from stress-strain curves since these values at the point of fracture were within 1% of the values obtained using fiducial marks. Cross-sections and reduction in area were obtained by averaging measurements across three diameters. Data are statistical averages based on data certified by the "Q" test at the 90% confidence level.

[c]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled. Wilson Rockwell Hardness tester used to test hardness of 12 longitudinal and 20 transverse samples. Average of all measurements is Rockwell C = 15 ± 2. [Note that the minimum value of the Rockwell C scale is 20.]

[d]Samples were stressed during exposure in stainless steel loading rings. The rings were loaded in compression at ambient temperature in a compression cage in a TT-C Instron tensile test machine. The rings were calibrated using thermal expansion and creep data determined from relaxation data. Where one value is given for the stress it applies to both smooth and notched specimens; (S) labels the stress on the smooth specimen, and (N) labels the value for the notched specimen.

[e]The number in parentheses following each value indicates the number of samples averaged.

[f]Note that this and all tests following were performed on longitudinal specimens. See footnote b.

[g]Note that these are the only tests at elevated temperature. See footnote b.

EFFECT OF HYDROGEN, TEMPERATURE, PRESSURE, AND APPLIED STRESS ON THE ROOM TEMPERATURE TENSILE PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEEL[b][47,50]

Type of Exposure[a]	Applied Stress (ksi)	Gas	Exposure Temperature °F	Pressure psig	Time hr	Notched Tensile Strength ksi	Reduction in Area %
Simple	--	Argon	900	4000	168	146.6	26.0
Stress exposure	20.4-17.8[c]	Argon	900	4000	168	145.0	24.0
Simple	--	H_2	900	4000	350	153.0	20.6
Stress exposure	26.8-21.6	H_2	900	4000	350	149.5	20.7
Prestrained	--	H_2	900	4000	350	150.0	17.8
Simple	--	H_2	900	4000	1000	151.8	20.8
Stress exposure	26.1-19.2	H_2	900	4000	1000	150.9	17.4
Prestrained	--	H_2	900	4000	1000	151.0	16.9
Simple	--	H_2	950	2000	350	149.0	21.8
Stress exposure	24.3-19.8	H_2	950	2000	350	148.7	23.0
Prestrained	--	H_2	950	2000	350	148.1	17.1
Simple	--	H_2	950	4000	100	145.9	24.3
Stress exposure	24.6-20.7	H_2	950	4000	100	147.2	25.0
Prestrained	--	H_2	950	4000	100	146.5	19.9
Stress exposure	24.0-20.1	Argon	950	4000	350	149.7	24.2
Simple	--	H_2	950	4000	350	150.2	22.6
Stress exposure	24.3-18.1	H_2	950	4000	350	149.7	23.0
Prestrained	--	H_2	950	4000	350	149.6	20.5
Simple	--	H_2	975	2000	350	147.7	24.1
Stress exposure	25.1-19.8	H_2	975	2000	350	147.6	23.9
Prestrained	--	H_2	975	2000	350	147.9	20.1
Simple	--	H_2	1000	750	350	150.9	20.8
Stress exposure	27.0-20.5	H_2	1000	750	350	152.3	19.6
Prestrained	--	H_2	1000	750	350	148.9	18.5

(Table Continued)

EFFECT OF HYDROGEN, TEMPERATURE, PRESSURE, AND APPLIED STRESS ON THE ROOM TEMPERATURE TENSILE PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEEL[b][47,50], Continued

Type of Exposure[a]	Applied Stress (ksi)	Gas	Exposure Temperature °F	Pressure psig	Time hr	Notched Tensile Strength ksi	Reduction in Area %
Simple	--	H_2	1000	1300	350	149.6	24.5
Stress exposure	26.3-20.2	H_2	1000	1300	350	147.9	23.1
Prestrained	--	H_2	1000	1300	350	149.0	24.6
Simple	--	H_2	1000	2100	350	148.3	22.2
Stress exposure	26.3-20.2	H_2	1000	2100	350	150.6	21.4
Prestrained	--	H_2	1000	2100	350	148.5	20.1
Simple	--	Argon	1000	4000	250	148.2	26.1
Stress exposure	26.4-20.1	Argon	1000	4000	250	149.4	25.3
Prestrained	--	Argon	1000	4000	14	149.8	23.7
Simple	--	H_2	1000	4000	250	148.6	25.3
Stress exposure	26.4-19.4	H_2	1000	4000	250	147.3	20.4
Prestrained	--	H_2	1000	4000	250	145.4	17.7
Simple	--	H_2	1000	4000	500	148.0	21.0
Stress exposure	31.2-19.7	H_2	1000	4000	500	128.0	11.0
Simple	--	H_2	1050	750	350	148.0	22.8
Stress exposure	24.9-20.3	H_2	1050	750	350	147.0	21.2
Prestrained	--	H_2	1050	750	350	145.7	21.3
Simple	--	H_2	1100	750	350	134.6	25.4
Stress exposure	25.1-18.9	H_2	1100	750	350	140.8	23.6
Prestrained	--	H_2	1100	750	350	133.4	22.1
Simple[d]	--	H_2	1000	4000	168	79.5, 96.0[d]	74.2
Simple[d]	--	H_2	1000	4000	500	78.5, 95.0[d]	75.4
Stress exposure[d]	30.2-17.8	H_2	1000	4000	500	76.5, 93.0[d]	74.2

[a]Notch-bar cylindrical specimens were prepared from longitudinal sections of the plate. See Sections B.3.1.88 and B.3.1.89 for descriptions of the specimens and the testing and stress exposure means. The specimens labelled as prestrained above were prestrained in air at room temperature (ε_p = 0.92%).

(Table Continued)

EFFECT OF HYDROGEN, TEMPERATURE, PRESSURE, AND APPLIED STRESS ON THE ROOM TEMPERATURE TENSILE PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEEL[b][47,50], Continued

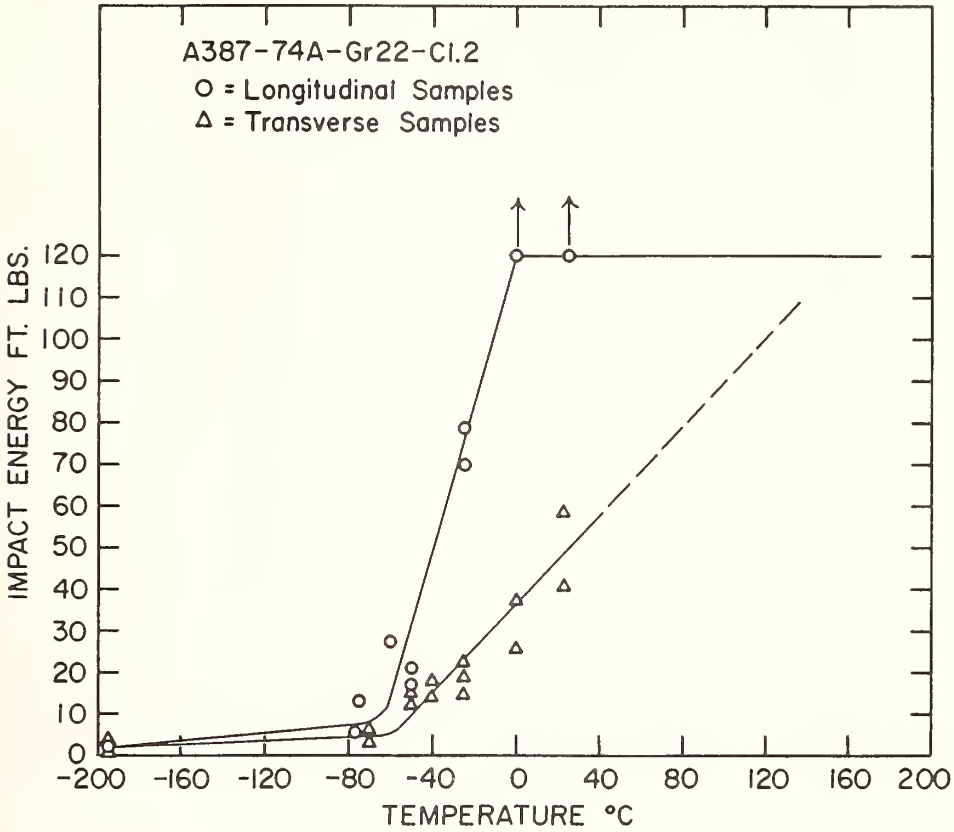
Prestrained specimens were not stress exposed.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled.

[c]Range indicates the stress at the beginning and at the end of the test.

[d]These specimens were smooth-bar cylindrical specimens (see sections B.3.1.88 and B.3.1.89 for descriptions). The values appearing in the Notched Tensile Strength column are 0.2% Offset Yield Strength and Ultimate Tensile Strength.

CHARPY V-NOTCH DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b][47]



Longitudinal Samples (Notch Radius, 0.24 mm; Notch Angle, 45°)

Test Temperature (°C)	Impact Energy (ft-lbs)	Area at Base of Notch (in^2)
25	>120	--
-78.5	5.5	0.122
-195.8	--	0.121
0	>120	0.122
0	>120	0.124
-25	78.5	0.123
-25	70	0.125
-50	21	0.124
-50	17	0.122
-75	18	0.122
-60	27	0.122
-195.8	2	0.125

(Data Continued)

CHARPY V-NOTCH DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b][47], Continued

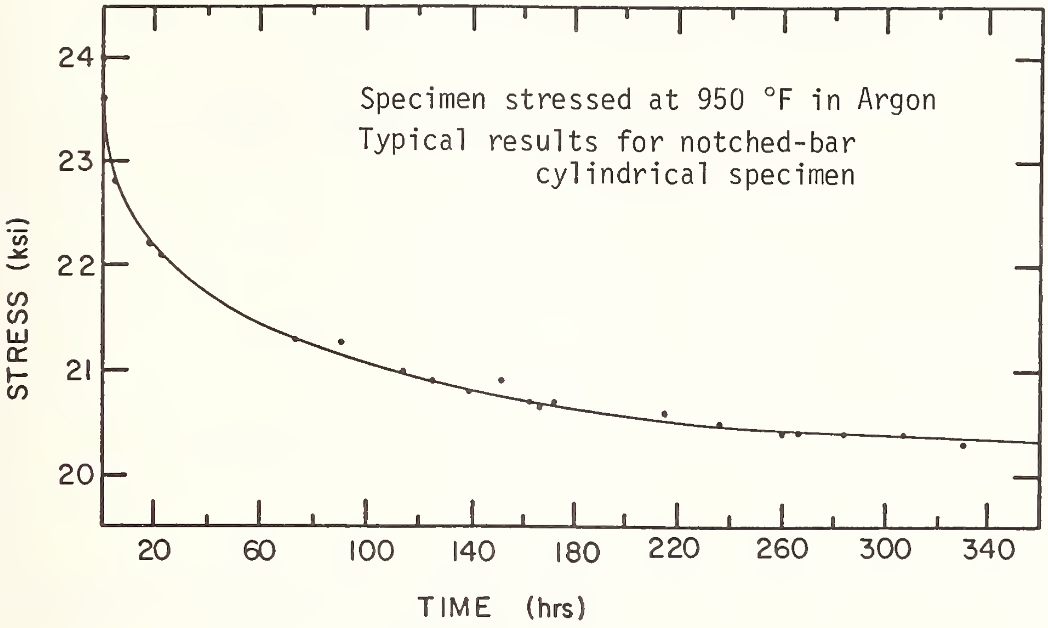
Transverse Samples (Notch Radius, 0.16 mm; Notch Angle, 45°)

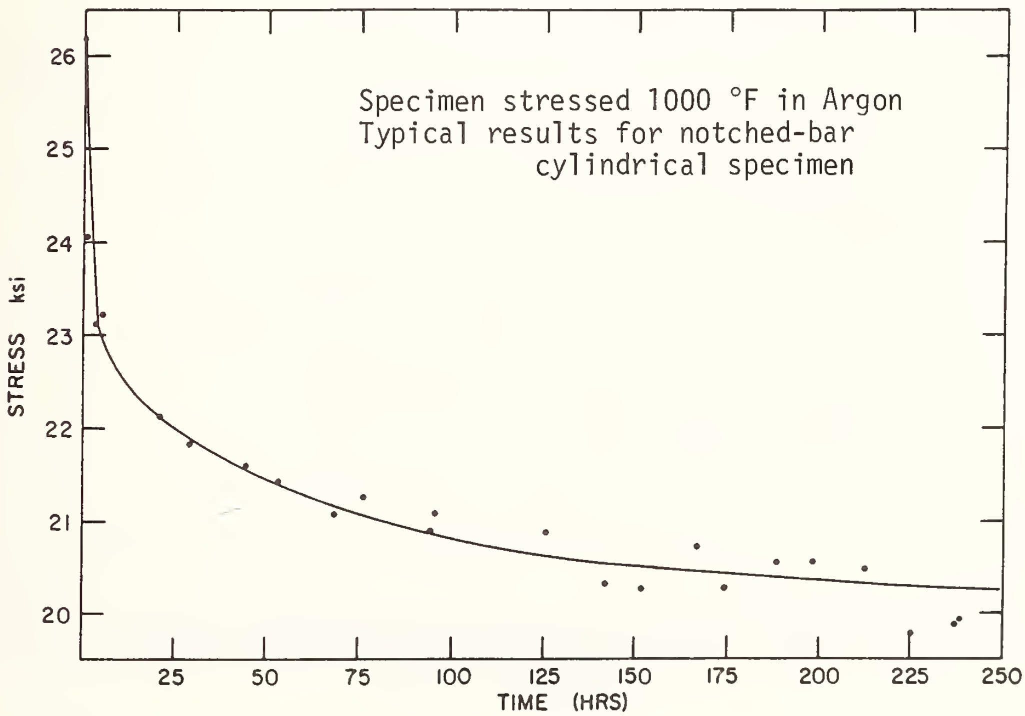
Test Temperature (°C)	Impact Energy (ft-lbs)	Area at Base of Notch (in^2)
23	58.5	0.125
23	42	0.123
0	26.5	0.124
0	37	0.123
-25	22.5	0.121
-25	14	0.124
-25	18.5	0.125
-40	14	0.122
-40	18.5	0.122
-50	11.5	0.124
-50	20	0.123
-70	3	0.125
-70	6	0.123
-195.8	1.5	0.125
-195.8	2	0.124

[a]Charpy V-Notch samples were machined from both longitudinal and transverse sections of plate with the notch milled parallel to the plate surface for both types of samples. Samples were 10 x 10 x 55 mm, notch depth 2 mm.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled. Wilson Rockwell Hardness tester used to test hardness of 12 longitudinal and 20 transverse samples. Average of all measurements is Rockwell C = 15 ± 2. [Note that the minimum value of the Rockwell C scale is 20.]

STRESS RELAXATION DUE TO CREEP OF 2-1/4 Cr-1 Mo STEEL[a] SPECIMENS[b] UNDER COMPRESSION LOAD[c][47]





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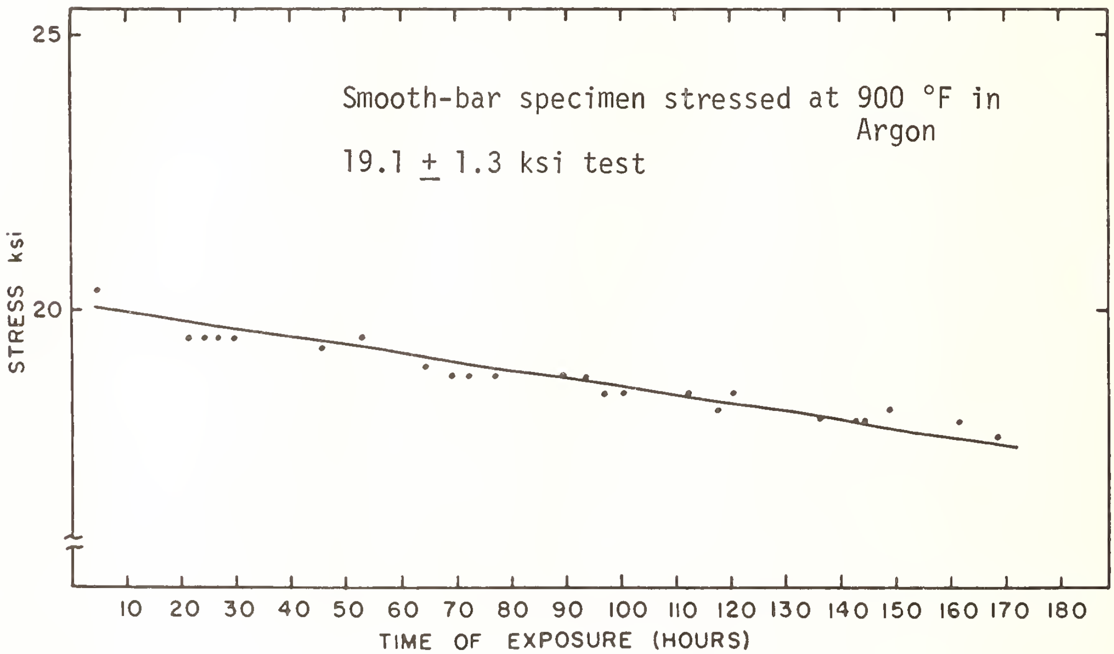
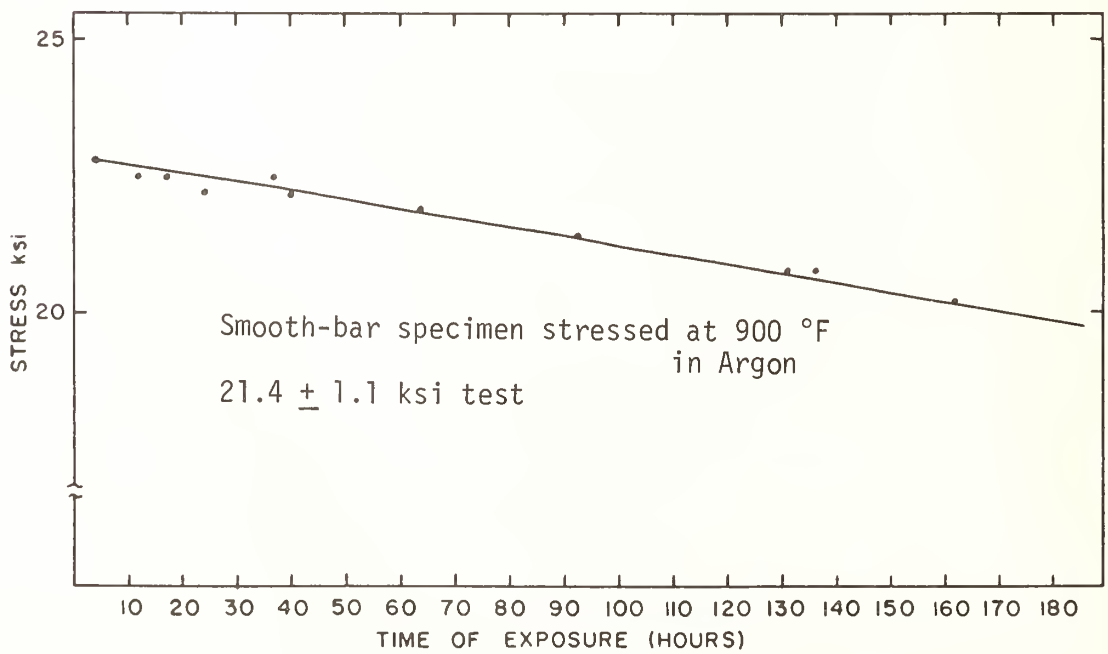
STRESS RELAXATION DUE TO CREEP OF 2-1/4 Cr-1 Mo STEEL[a] SPECIMENS[b] UNDER COMPRESSION LOAD[c][47], Continued





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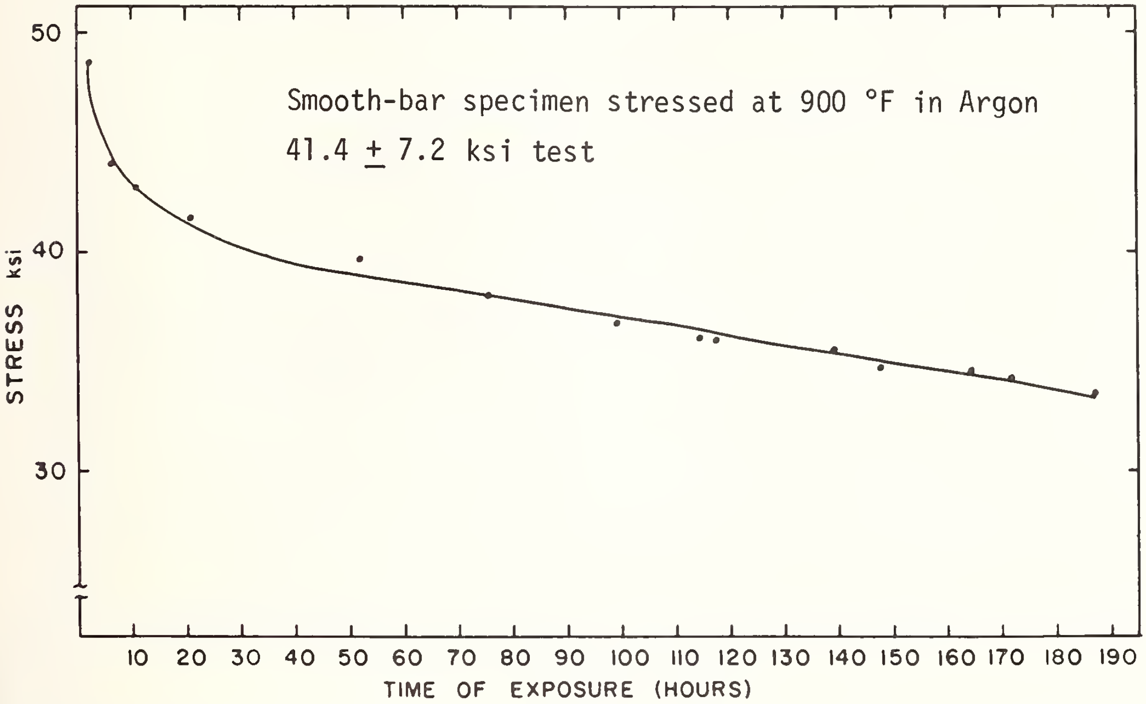
STRESS RELAXATION DUE TO CREEP OF 2-1/4 Cr-1 Mo STEEL[a] SPECIMENS[b] UNDER COMPRESSION LOAD[c][47], Continued



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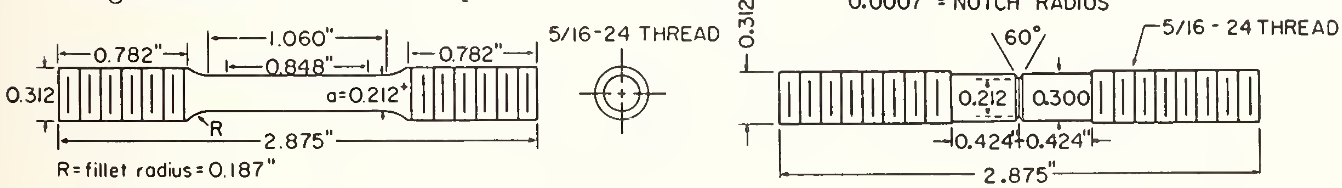
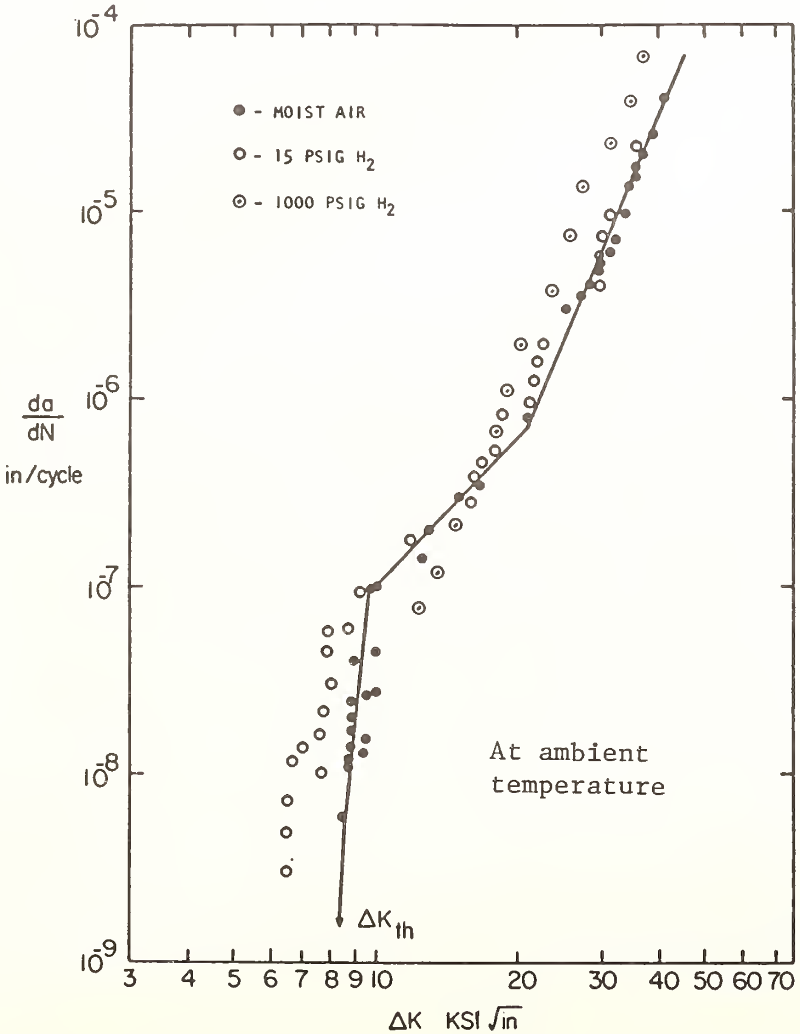
[a]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, then tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled.

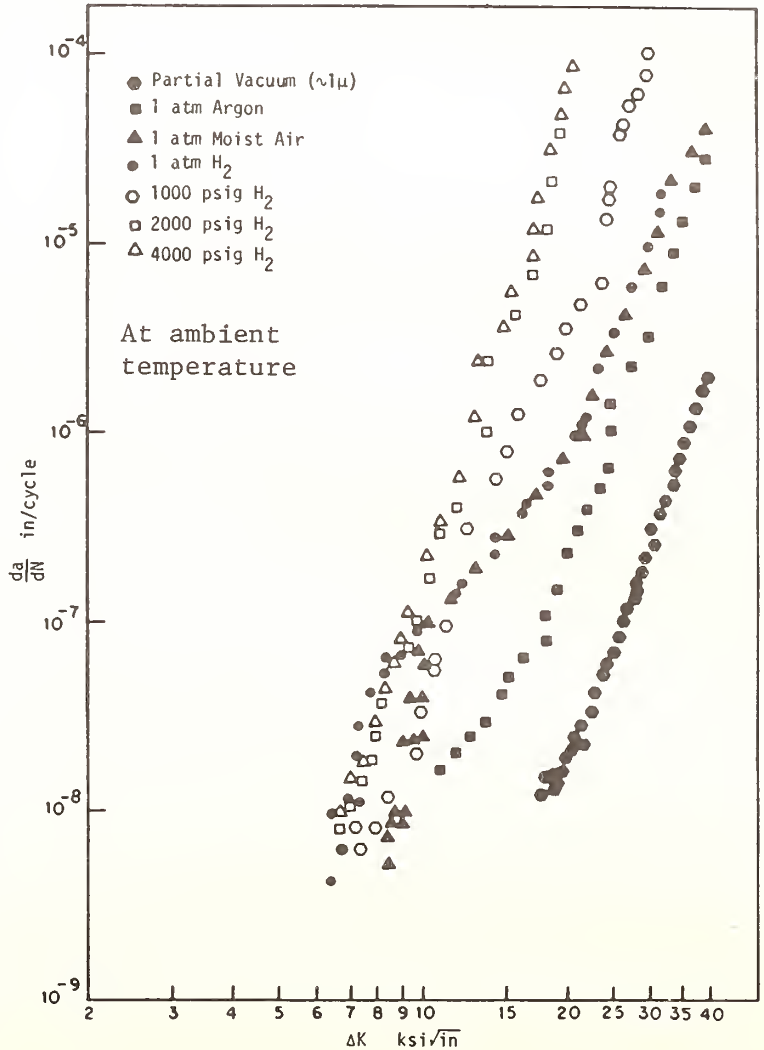
[b]Notched- and smooth-bar cylindrical tensile specimens were prepared from longitudinal sections of plate.



[c]Specimens were ring loaded in compression at ambient temperature in a compression cage in a TT-C Instron Tensile Test machine. The ring-specimen composite was heated in a specially designed quartz thermal expansion rig. Creep was measured in three ways: 1. by change in fiducial marks on gauge sections of specimens using a toolmaker's microscope; 2. by micrometer measurement of ring-specimen composite before and after test exposure; 3. by capacitance gauge transducer in the quartz dilatometer rig. The stress was calculated from the measurements.

FATIGUE CRACK GROWTH RATES[a] OF 2-1/4 Cr-1 Mo STEEL[b] AT VARIOUS HYDROGEN PRESSURES[47,50]





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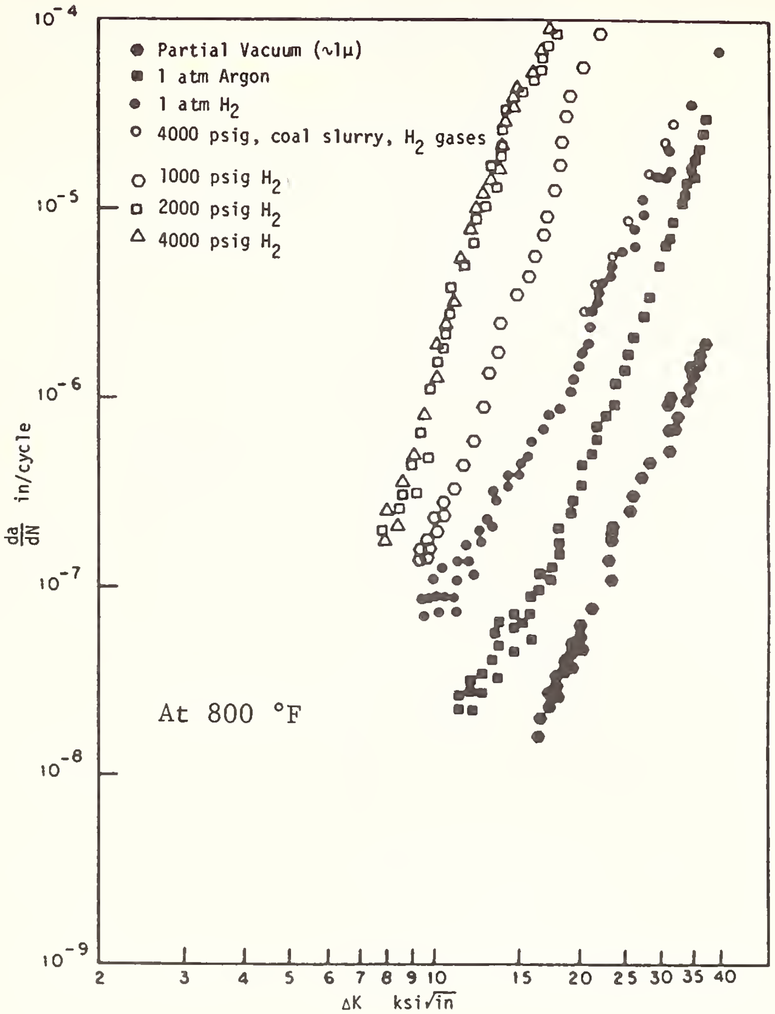
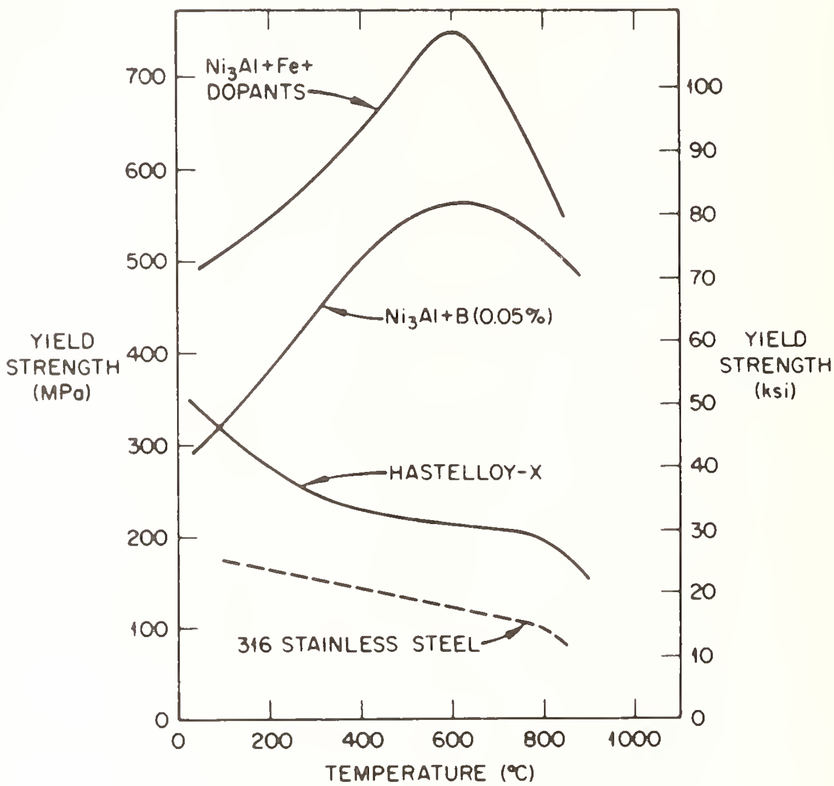
FATIGUE CRACK GROWTH RATES[a] OF 2-1/4 Cr-1 Mo STEEL[b] AT VARIOUS HYDROGEN PRESSURES[47,50], Continued



[a]Fatigue crack growth rates (da/dN) are given as a function of the stress intensity factor range (ΔK). Both scales are logarithmic. Compact tension specimens were prepared (ASTM Specification E-399, L-T type specimen). Surface of the specimens were mechanically polished to 600 grit. They were precracked in load control. The frequency was 20 Hz, with sinusoidal loading in a tension-tension mode with minimum load controlled at 10% of maximum. ASTM E-399 fatigue precracking procedure was followed. The crack growth in the dynamically loaded compact specimens was monitored by an electropotential measurement system designed to eliminate thermal potentials and other transients. The tests in coal slurry used the stroke amplitude of the fatigue cycle calibrated against the electropotential drop measurement to monitor the crack growth. The coal slurry gases caused noise and stable measurement was otherwise not possible. The slurry consisted of 35 vol % of -100 mesh Kentucky bituminous and 65% solvent. The solvent is centrifuged Synthoil product from Pittsburgh Energy Technology Center run FB-61 using the same Kentucky coal. Solvent analysis (wt %): oils 64.4, asphaltenes 32.3, organic benzene insolubles 3.3. Where moist air is specified it refers to ∿30 % relative humidity.

[b]A387-74A, Grade 22, Class 2. Heat treatment: normalized, 1650-1700 °F, held 1 hour per inch minimum and air cooled, tempered at 1350 °F, held 3/4 hour per inch minimum and air cooled.

YIELD STRENGTH[a] VERSUS TEMPERATURE FOR COMMERCIAL[b] AND EXPERIMENTAL[c] ALLOYS[51]



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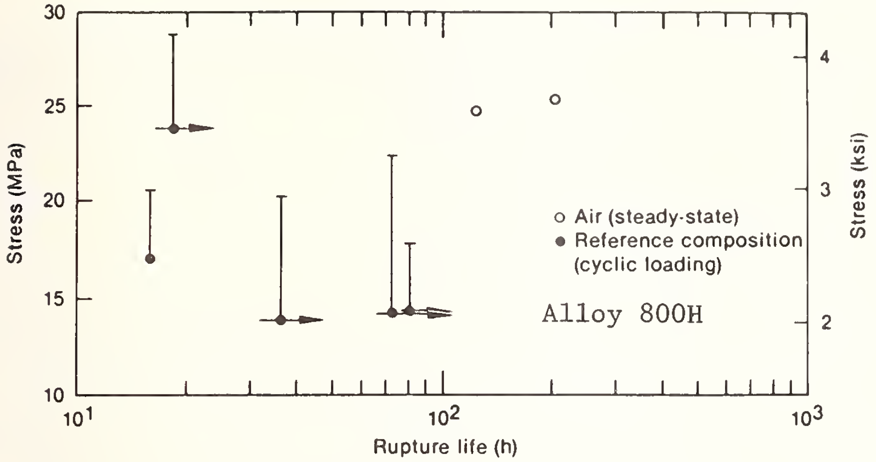
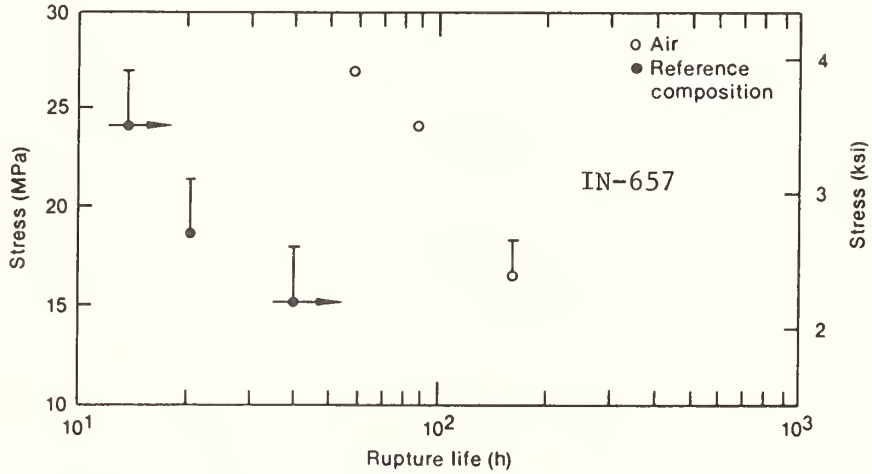
[a]Tensile testing was done at a crosshead speed of 2.5 mm/min.

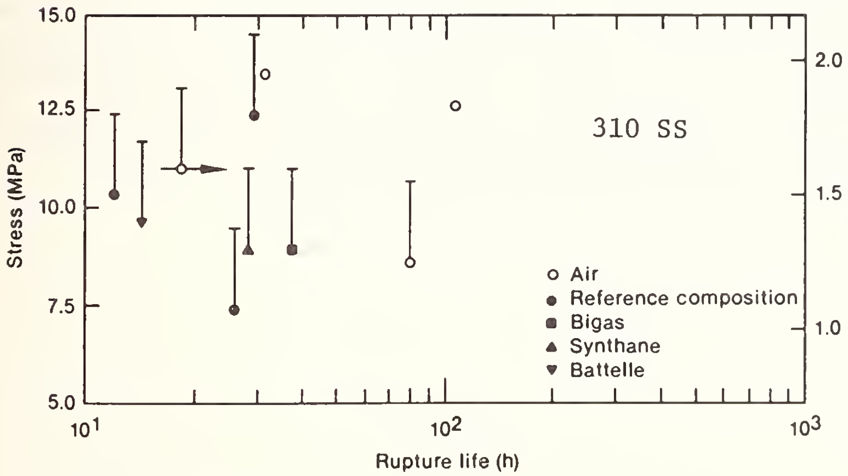
[b]316 stainless steel and Hastelloy X.

[c]A boron-doped (0.05%) nickel aluminide and a nickel aluminide with iron plus dopants (in wt %: 10.7 Fe-10.1 Al-1.0 Mn-0.5 Ti-0.05 B-balance Ni). The latter alloy ingot was fabricated into 0.8 mm-thick sheets by repeated cold rolling and heat treatment at 1000 °C. Cold work was initially about 15% reduction in thickness and gradually increased to 50% between each intermediate annealing. Tensile specimens were blanked from the sheets and recrystallized for 30 minutes at 1000 °C.

BIAXIAL STRESS VERSUS RUPTURE LIFE[a] FOR FOUR ALLOYS[b] IN AIR AND IN VARIOUS COAL GASIFICATION ATMOSPHERES[c][54]

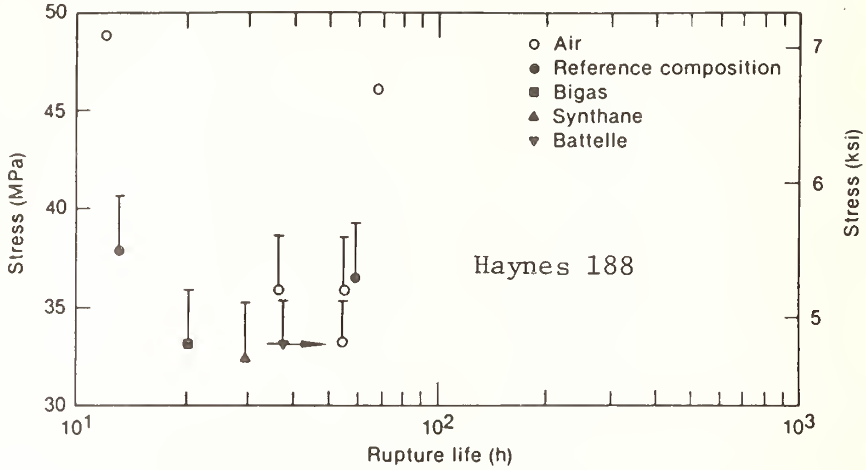






(Data Continued)

BIAXIAL STRESS VERSUS RUPTURE LIFE[a] FOR FOUR ALLOYS[b] IN AIR AND IN VARIOUS COAL GASIFICATION ATMOSPHERES[c][54], Continued



[a]Tubular specimens, approximately 1 cm in diameter by 11 cm long with the outside diameter of the central 7 cm portion reduced to form a gauge section, were pressurized to measure 100- and 500-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 rupture was measured by sensing a significant drop in specimen argon pressure. Biaxial stress is plotted against rupture life. Arrows indicate minimum rupture life, flags indicate the magnitude of stress variations introduced by pressure fluctuations. See Section B.3.1.25 for earlier work on this project, and also Section B.3.1.26.

[b]See Section B.3.1.25, footnotes f, g, i, j, and l for alloy information.

[c]Air tests were at 1 atmosphere except for those with flags which indicate 1000 psi tests. All other gas tests were run at 1000 psi. The temperature was 1800 °F. Cyclic loading refers to pressure fluctuations caused by the venting and replenishing of gases to maintain the proper gas compositions. All of the gas atmospheres provided cyclic loading. Input test gas compositions in vol %: Reference composition = MPC CGA, 24H , 18CO, 12CO , 5CH , 40H O, 1NH , 0.5H S; Bigas, $15H_2$, 12CO, $13CO_2$, $7CH_4$, $52H_2O$, $1.06NH_3$, $0.53H_2S$; Synthane, $18H_2$, 10CO, $18CO_2$, $16CH_4$, $37H_2O$, $0.6NH_3$, $0.3H_2S$; Battelle, $48H_2$, 26CO, $5CO_2$, $6CH_4$, $14H_2O$, $0.6NH_3$, $0.3H_2S$.

EFFECT OF CYCLIC LOADING IN AIR ON THE STRESS RUPTURE LIFE[a] OF INCOLOY 800H[b][54]

Type of Test[a]	Base Stress, MPa	Cyclic Stress, MPa	Lifetime, h
Pressurized tube	17.2	2.8[c]	236
Axial	32.4	0	41.4
Axial	32.4	0	38.9
Axial	29.6	2.8[c]	41.8

[a]See Sections B.3.1.26 and B.3.1.95 for testing of pressurized tube specimens. Cyclic loading caused by pressure fluctuations. Uniaxial specimens were prepared from the same plate as the tube specimen. Uniaxial specimens were heated in air and stressed in load control mode with an hydraulic test machine. Two specimens had a constant stress applied, a third had a cyclic stress imposed on the base stress. No difference in creep rates was noted between constant- and cyclic-loaded specimens.

[b]See Section B.3.1.25 for alloy specifications.

[c]Superimposed loading stress was cycled every 90 seconds. The stress showed a more rapid initial decrease, from 2.8 to 2.1 MPa, during the first ten seconds, and then a fairly linear decrease during the rest of the cycle.

BIAXIAL STRESS RUPTURE DATA[a] FOR FOUR ALLOYS[b] IN A SIMULATED LOW-BTU ATMOSPHERE[c][54]

Alloy[b]	Hoop Stress, MPa	Lifetime, h
Incoloy 800H		
Specimen 1	62.0	91
Specimen 2	48.2	58
310 SS	27.6	270
Inconel 657		
Specimen 1	110.2	39
Specimen 2	48.2	283[d]
Haynes 188	110.2	369

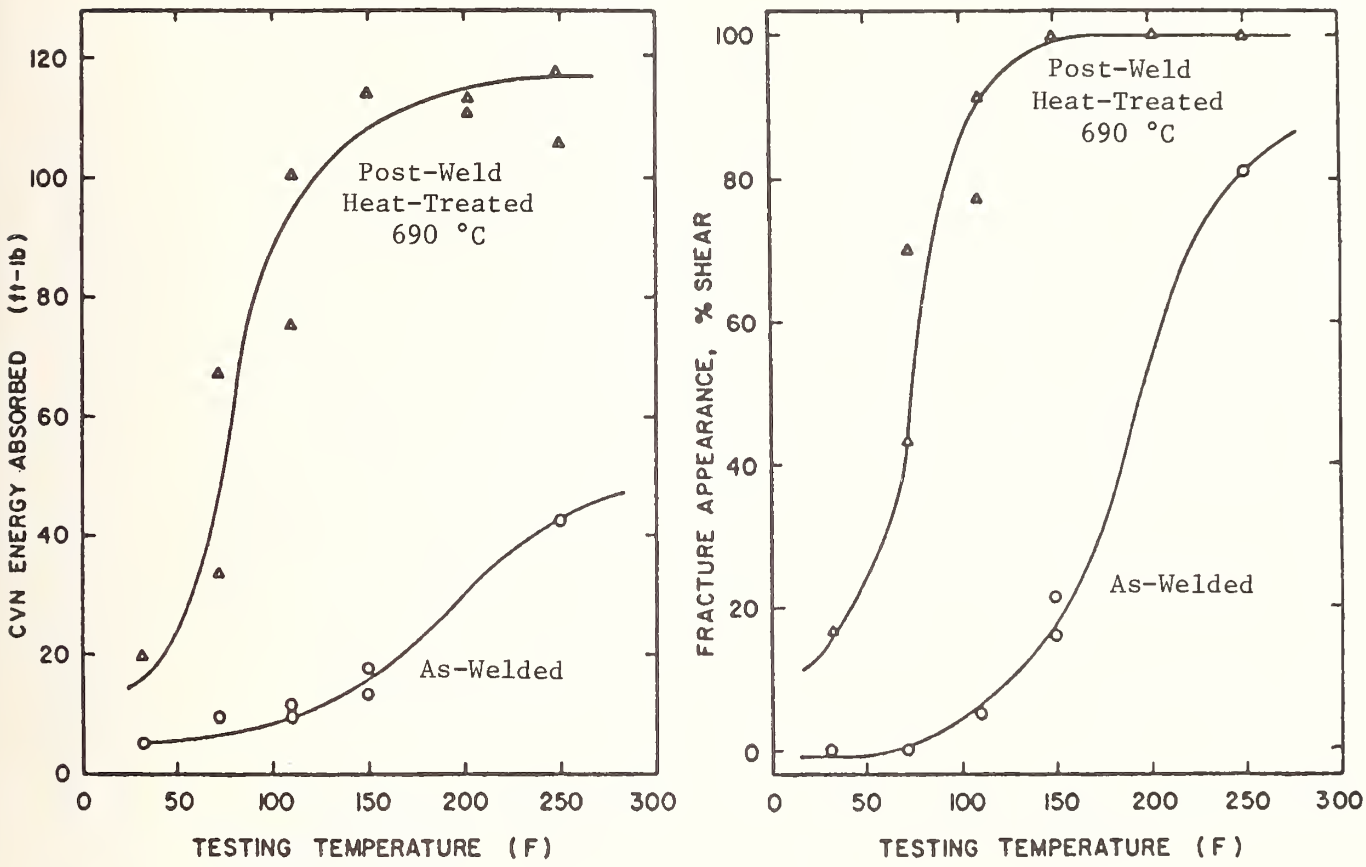
[a]See Sections B.3.1.25, B.3.1.26, and B.3.1.95 for biaxial stress rupture testing.

[b]See Section B.3.1.25 for alloy specifications.

[c]Atmosphere consists of Argon-H_2-H_2O-H_2S. Test temperature 879 °C. $P_{O_2} = 1 \times 10^{-19}$ atm and $P_{S_2} = 1.3 \times 10^{-7}$ atm.

[d]A leak developed at a closure weld at the end of the specimen.

EFFECT OF POST-WELD HEAT TREATMENT[a] ON CHARPY V-NOTCH TOUGHNESS[b]
OF ELECTROSLAG WELDMENTS OF 2-1/4 Cr-1 Mo STEEL[c][55]

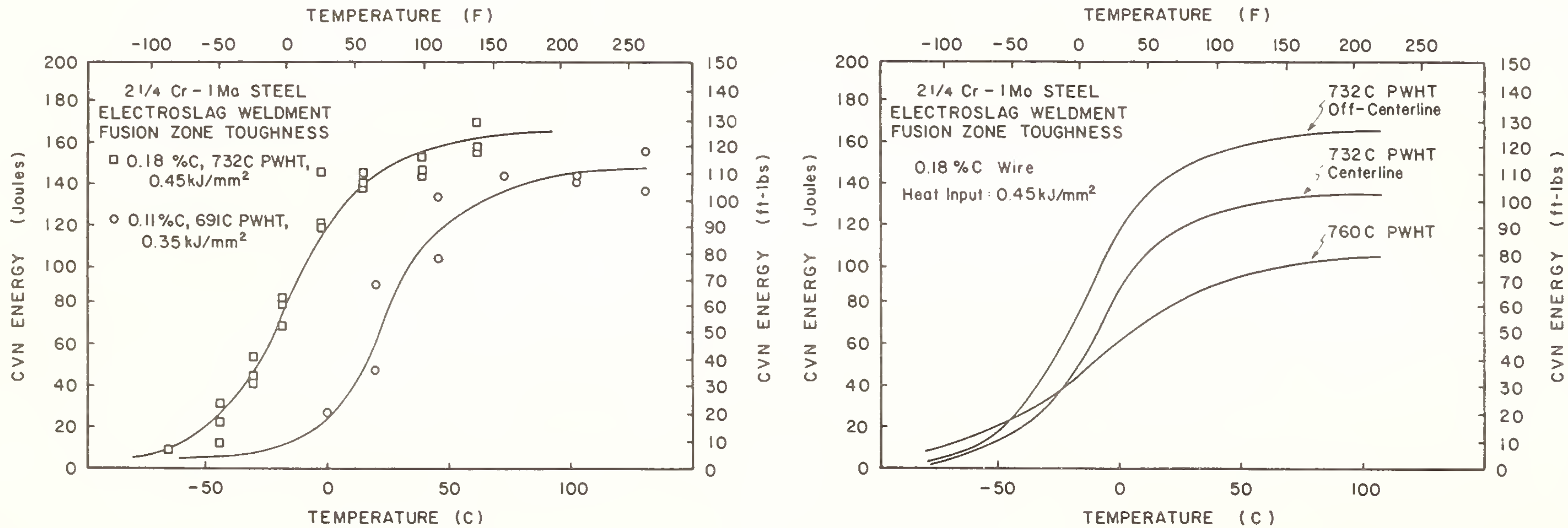


[a]Stress-relief heat treated at 690 °C. Treatment refines and distributes carbides homogeneously within the bainitic microstructure.

[b]CVN = Charpy V-Notch.

[c]4-inch (102-mm) thick.

EFFECT OF POST-WELD HEAT TREATMENT TEMPERATURE[a] ON FUSION ZONE TOUGHNESS[b] OF 2-1/4 Cr-1 Mo STEEL[c] ELECTROSLAG WELDMENTS[d][55]



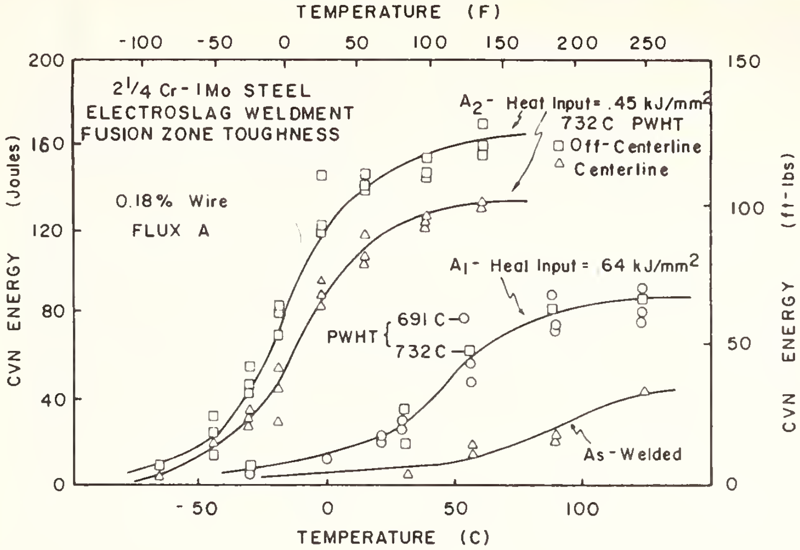
[a]The effect of three post-weld heat treatment (PWHT) temperatures is shown, 691 °C, 732 °C, and 760 °C. Metallographic examination showed that the section treated at 732 °C shows fine bainite structure, the section treated at 760 °C shows major fractions to be a polygonal ferrite.

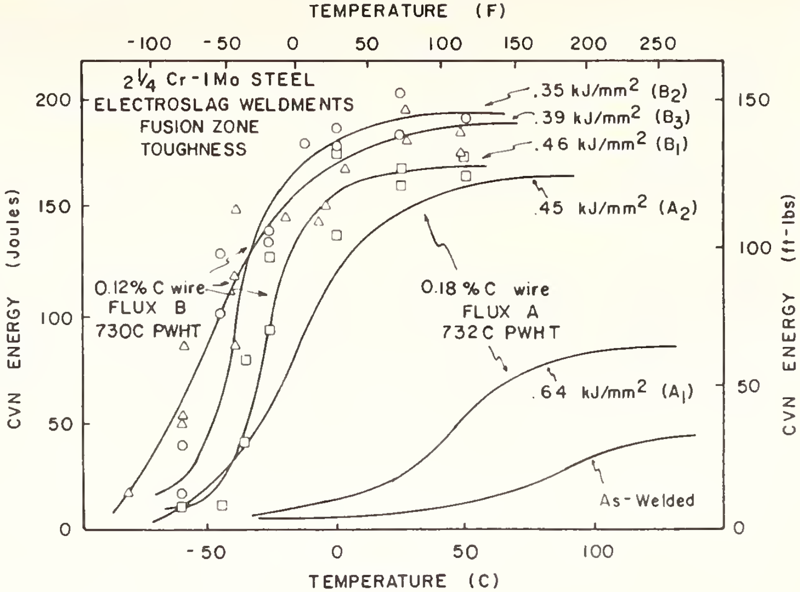
[b]Toughness as measured by Charpy V-Notch (CVN) impact energy.

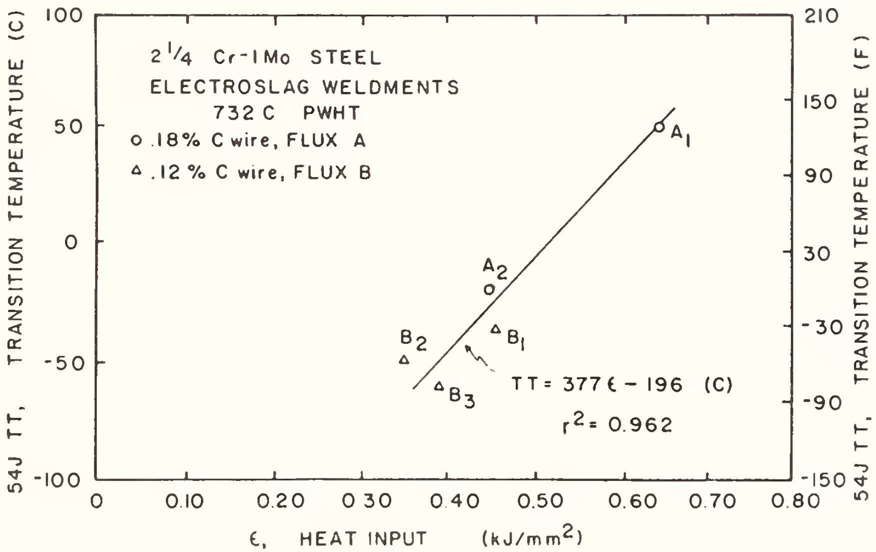
[c]4-inch (102-mm) thick plate.

[d]Flux used is a commercial manganese silicate-based one containing ∿32 wt % transition oxides. Wire with 0.11 % and 0.18 % carbon was used.

EFFECT OF FLUX CHEMISTRY[a], HEAT INPUT DURING WELDING AND POST-WELD HEAT TREATMENT[b] ON FUSION ZONE TOUGHNESS[c] OF ELECTROSLAG WELDS OF 2-1/4 Cr-1 Mo STEEL[d] [55]

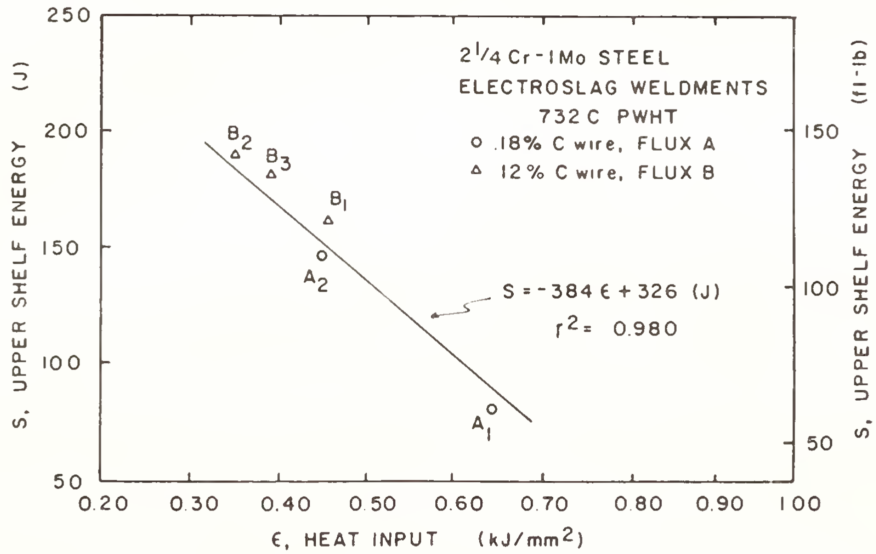






(Data Continued)

EFFECT OF FLUX CHEMISTRY[a], HEAT INPUT DURING WELDING AND POST-WELD HEAT TREATMENT[b] ON FUSION ZONE TOUGHNESS[c] OF ELECTROSLAG WELDS OF 2-1/4 Cr-1 Mo STEEL[d][55], Continued



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[a]Flux A is a commercial manganese silicate-based one containing ∿32 wt % transition oxides. The wire used had a 0.18% carbon content. Flux B is an oxide-based one (Linde 124), with composition (wt%) 32 SiO_2, 7 MnO, 22 CaO, 7 MgO, 15 Al_2O_3, 1 TiO_2, 1 FeO, 12 CaF_2 (9 % transition oxides). The wire used a 0.11% carbon content. Subscripts on flux letters, A_1, A_2, etc. refer to different welds with the same flux.

[b]Post-weld heat treatment (PWHT) was at 691 °C, 730 °C, or 732 °C.

[c]Toughness as measured by Charpy V-Notch (CVN) impact energy; transition temperature and upper shelf energy plots are for 54J (40 ft-lb).

[d]4-inch (102-mm) thick plate.

CHARPY V-NOTCH TOUGHNESS OF DEVELOPMENTAL 9 Cr-1 Mo STEEL[56]

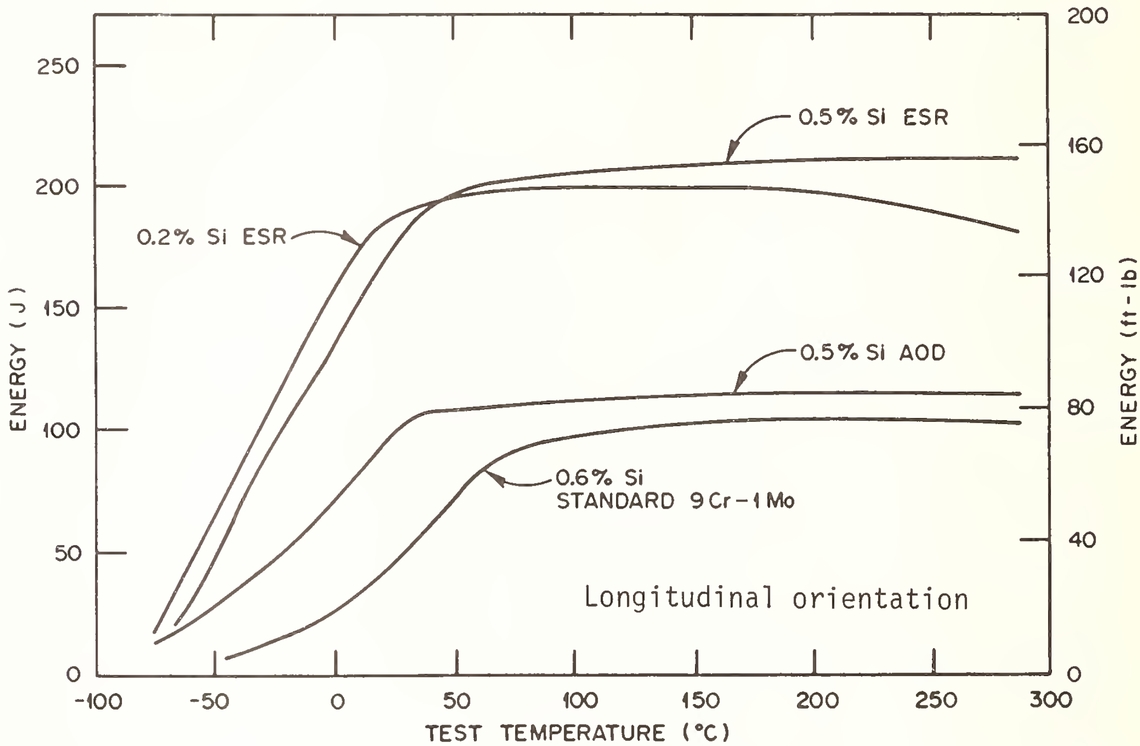
Specimen[b]	Specimen Orientation	Temperature, °C (°F): Charpy V-Notch 68 J (50 ft-lb)	0.89 mm (35 mil) Lateral Expansion	50% Shear	100% Ductile Fracture[a]	Upper-Shelf Energy J (ft-lb)
ESCO heat, low C, N, high Cr	Longitudinal	27 (80)	21 (70)	32 (90)	71 (160)	180 (132)
	Transverse	16 (60)	10 (50)	13 (55)	∿38 (100)	231 (170)
ESCO heat, low Nb	Longitudinal	4 (40)	2 (35)	18 (65)	46 (115)	158 (116)
	Transverse	-1 (30)	-1 (30)	7 (45)	27 (80)	201 (148)
ESCO heat, low C, N, high Cr	Longitudinal	21 (70)	18 (65)	32 (90)	99 (210)	>234 (>172)
	Transverse	27 (80)	18 (65)	24 (75)	49 (120)	>325 (>240)
Quaker heat, low N, high S[c]	Longitudinal	10 (50)	-4 (25)	10 (50)	27 (80)	102 (75)
	Transverse	-48 (-55)	-51 (-60)	-32 (-25)	∿-12 (10)	204 (150)

[a] Estimated temperature at which 100 % ductile fracture was first obtained; ∿ indicates an extrapolated value.

[b] Compositions not given, only deviations from intended composition indicated. All heats by argon-oxygen-decarburization process. Specified range for modified steel (wt %): Cr 8-9, Mo 0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-0.25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001.

[c] Directionality caused by MnS stringers.

CHARPY IMPACT DATA FOR TWO COMMERCIAL HEATS[a] OF MODIFIED 9 Cr-1 Mo STEEL[b][56]



Alloy/Melt[a]	Si wt %	Temperature, °C: Charpy V-Notch 68 J (50 ft-lb)	Temperature, °C: 0.89 mm (35 mil) Lateral Expansion	Upper Shelf Energy J (ft-lb)
Heat 2, ESR	0.2	-50	-37	197 (145)
Heat 1, ESR	0.5	-40	-32	210 (155)
Heat 1, AOD	0.5	2	2	115 (85)
Standard alloy, electric furnace	0.6	46	43	102 (75)

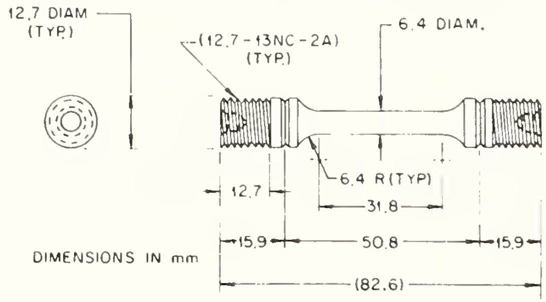
[a] Two 14 Mg (15 ton) heats were melted by Cartech. Ingots were hot-rolled to plate, Charpy impact data obtained and compared with data for standard 9 Cr-1 Mo steel. ESR = electroslag remelt process, AOD = argon-oxygen-decarburization melt process.

[b] Specified composition ranges for modified alloy (wt %): Cr 8-9, Mo 0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-0.25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001. [Standard ranges for 9 Cr-1 Mo steel: Cr 8.0-10.0, Mo 0.90-1.20, C 0.15-0.20, Mn 0.30-0.65, P 0.03-0.05, S 0.03-0.06, Si 0.25-1.00.]

TENSILE TEST DATA[a] FOR A MODIFIED 9 Cr-1 Mo STEEL[b][56]

Temperature °C	Temperature °F	Modulus GPa	0.2% Offset Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, % Uniform	Elongation, % Total[c]	Reduction in Area, %
Transverse Specimens							
ambient		211	539	666	6.20	23.62	69.46
38	100	216	535	653	5.94	23.11	69.34
93	200	213	517	627	5.17	22.25	72.11
149	300	201	504	610	4.91	22.33	71.71
204	400	217	494	598	4.42	21.24	70.45
260	500	205	484	579	4.23	20.84	71.54
316	600	204	475	569	4.24	19.82	68.13
371	700	196	469	553	3.67	16.93	68.31
427	800	188	441	517	3.67	23.12	72.27
482	900	162	418	459	2.23	26.75	79.21
538	1000	153	370	399	1.26	34.91	84.22
593	1100	112	278	306	0.97	38.15	90.69
649	1200	90	178	217	1.92	49.20	92.27
704	1300	71	116	148	2.49	46.28	91.49
Longitudinal Specimens							
ambient		218	528	655	6.37	24.83	68.79
593	1100	89	277	305	0.97	41.09	90.25

[a]Tensile tests were run on a 44 kN Instron universal testing machine at constant crosshead speeds. The nominal strain of 0.004/min. was held constant. Yield strength was obtained from the extensometer chart, the ultimate tensile strength from the load-deflection chart. Tensile specimens were machined from the 16 mm plate, see diagram.



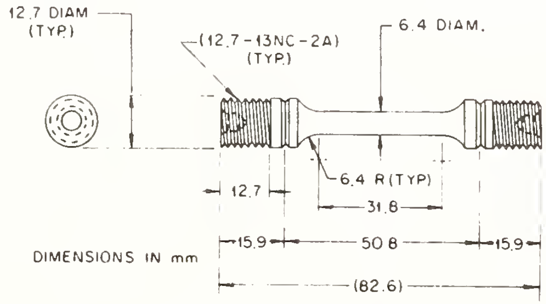
[b]Ingot produced by argon-oxygen-decarburization melt process. Ingot hot-rolled to 16 mm plate, normalized 1038 °C, held 1 hour, air-cooled, then tempered to 760 °C, held 1 hour, air-cooled. Composition of plate (wt %): 8.83Cr, 0.94Mo, 0.10C, 0.43Mn, 0.36Si, 0.12Ni, 0.208V, 0.058Nb, 0.023Co, 0.09Cu, 0.01Ti, 0.01W, 0.01P, 0.016S, 0.011N, balance Fe. Ingot from Quaker.

[c]In 25.4 mm.

TENSILE TEST DATA[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b] WELDMENT[c][56]

Temperature °C	0.2% Offset Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, %[d]		Reduction in Area, %
			Uniform	Total	
ambient	451	609	5.94	19.15	65.45
593	184	205	2.37	34.04	92.31
649	103	132	3.40	53.73	94.06

[a]Tensile tests were run on a 44 kN Instron universal testing machine at constant crosshead speeds. The nominal strain of 0.004/min. was held constant. Yield strength was obtained from the extensometer chart, the ultimate tensile strength from the load-deflection chart. Tensile specimens were machined from the weldments, see diagram.

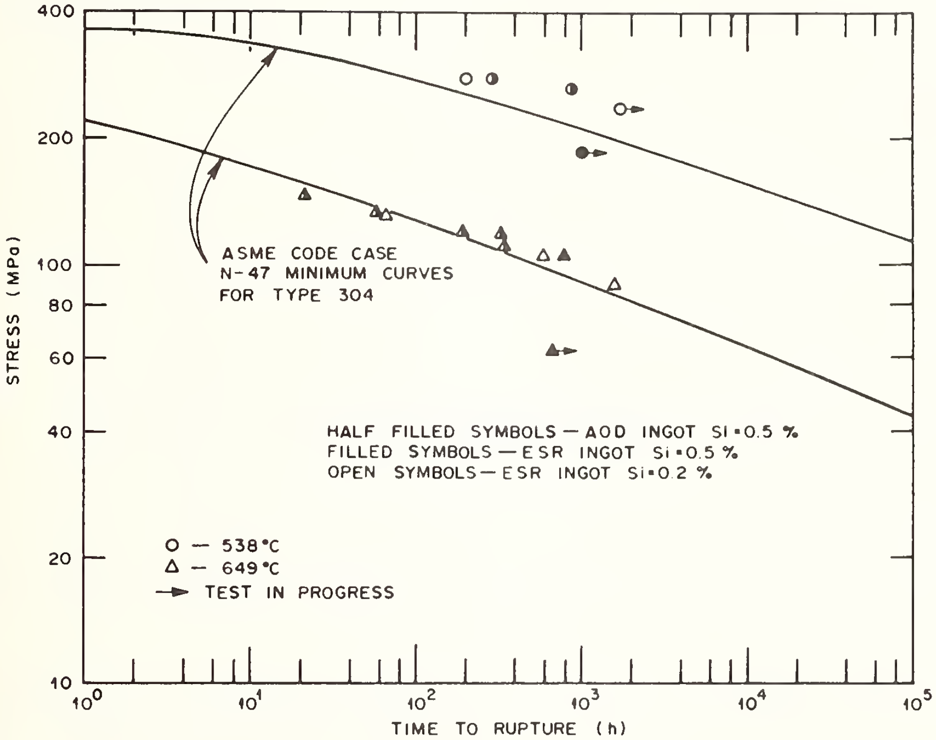


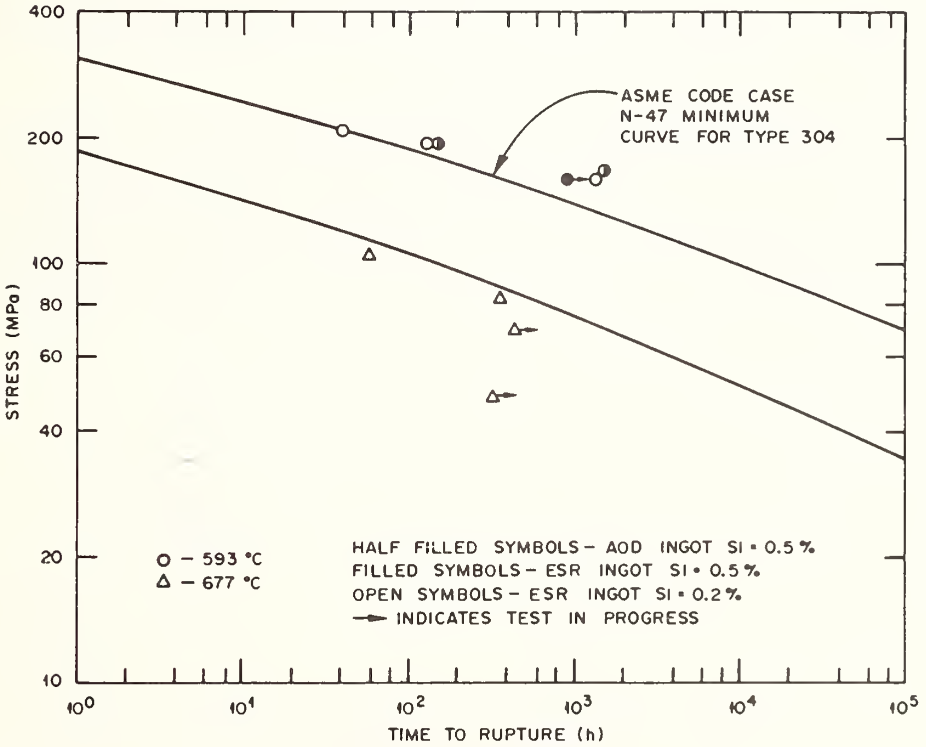
[b]Ingot produced by argon-oxygen-decarburization melt process. Ingot hot-rolled to 16 mm plate, normalized 1038 °C, held 1 hour, air-cooled, then tempered to 760 °C, held 1 hour, air-cooled. Composition of plate (wt %): 8.83 Cr, 0.94 Mo, 0.10 C, 0.43 Mn, 0.36 Si, 0.12 Ni, 0.208 V, 0.058 Nb, 0.023 Co, 0.09 Cu, 0.01 Ti, 0.01 W, 0.01 P, 0.016 S, 0.011 N, balance Fe. Ingot from Quaker.

[c]Plate was welded using unmodified 9 Cr-1 Mo steel filler (contains no Nb or V). After gas tungsten-arc welding the weld was post-weld heat treated at 788 °C for 1 hour.

[d]In 25.4 mm.

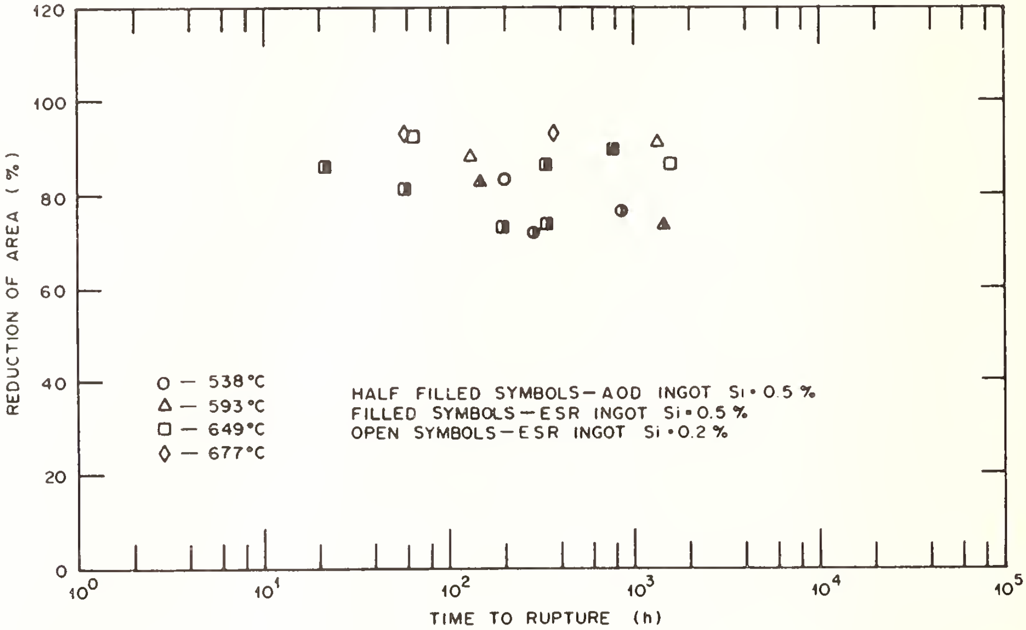
CREEP-RUPTURE DATA FOR TWO COMMERCIAL HEATS[a] OF MODIFIED 9 Cr-1 Mo STEEL[b][56]





(Data Continued)

CREEP-RUPTURE DATA FOR TWO COMMERCIAL HEATS[a] OF MODIFIED 9 Cr-1 Mo STEEL[b][56], Continued



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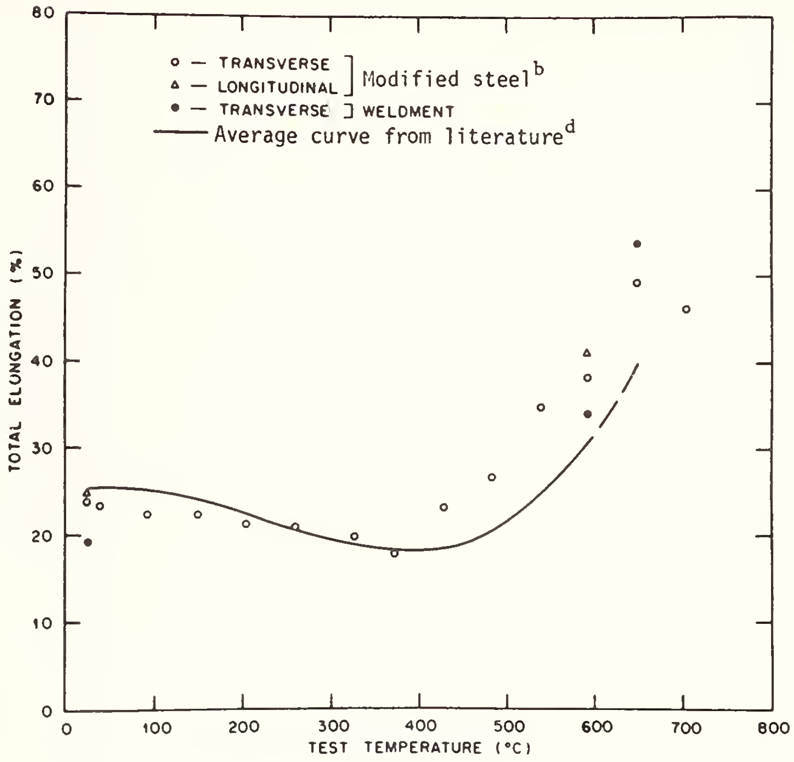
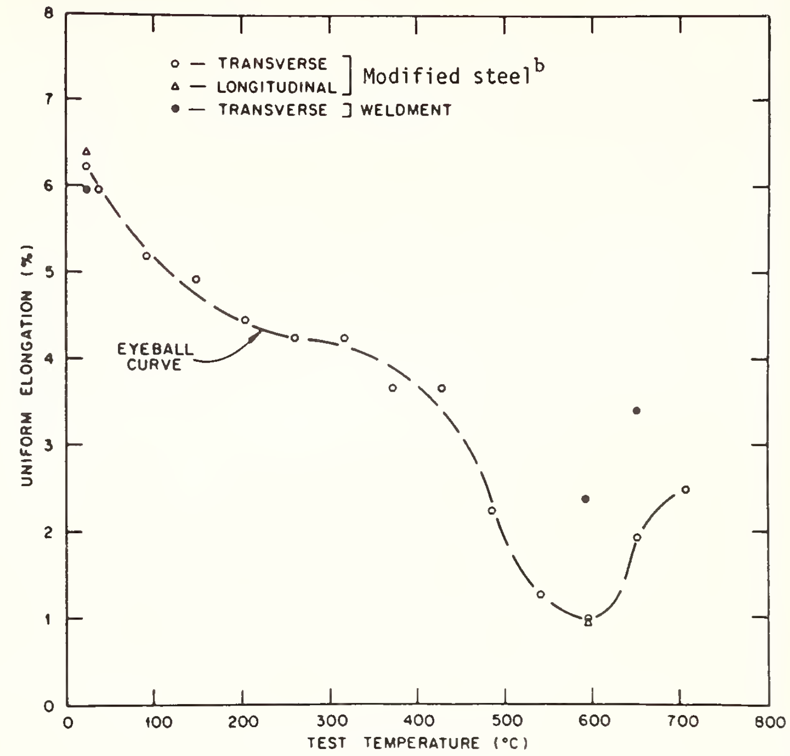
[a]Two 14 Mg (15 ton) heats were melted by Cartech. Ingots were hot-rolled to plate, specimens prepared and creep-rupture data obtained. Heat 1 ingots above are those identified by Si = 0.5 %, heat 2 by Si = 0.2 %. ESR = electroslag remelt process, AOD = argon-oxygen-decarburization melt process.

[b]Specified composition ranges for modified alloy (wt %): Cr 8-9, Mo 0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-0.25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001. [Standard ranges for 9 Cr-1 Mo steel: Cr 8.0-10.0, Mo 0.90-1.20, C 0.15-0.20, Mn 0.30-0.65, P 0.03-0.05, S 0.03-0.06, Si 0.25-1.00.]

TENSILE PROPERTIES[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b] AND WELDMENT[c][56]





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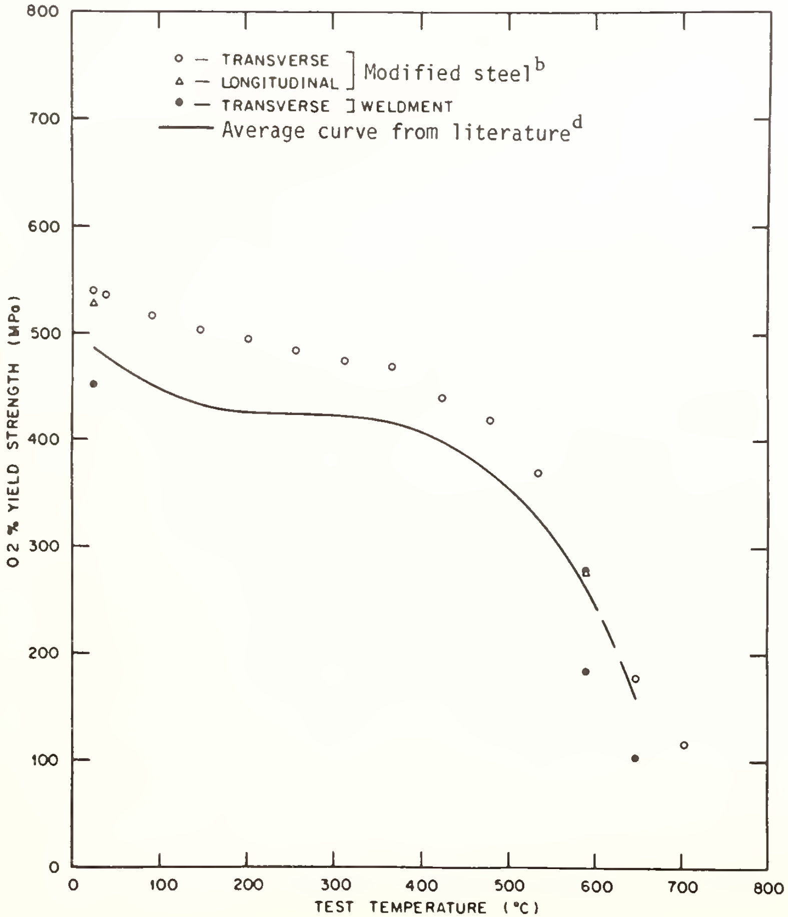
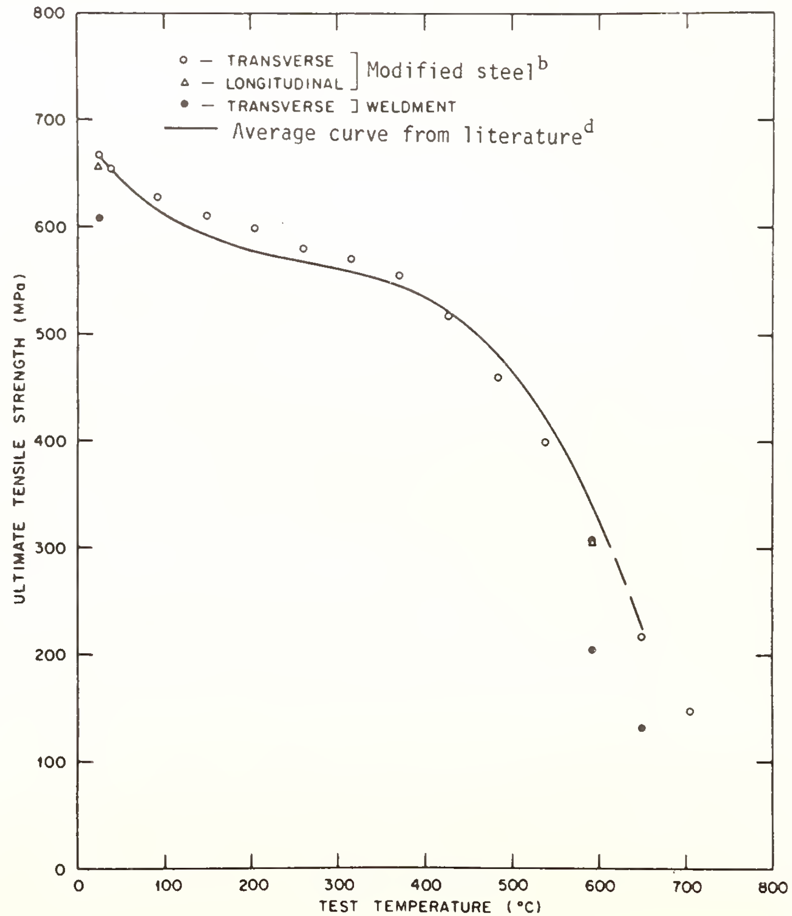
TENSILE PROPERTIES[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b] AND WELDMENT[c][56], Continued





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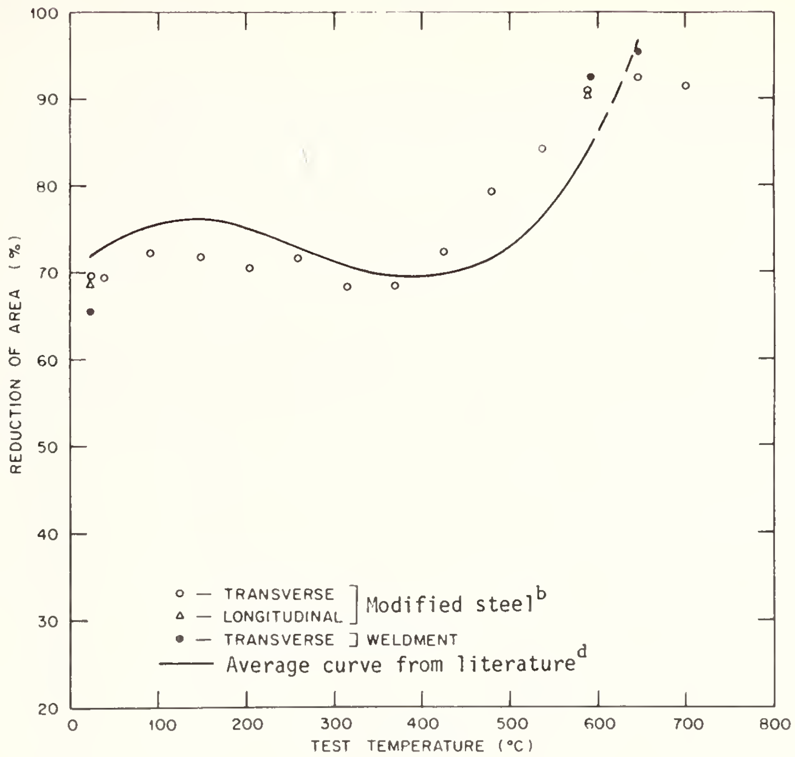
TENSILE PROPERTIES[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b] AND WELDMENT[c][56], Continued



[a]See B.3.1.103 and B.3.1.104 for the data on which these curves are based.

[b]Ingot produced by argon-oxygen-decarburization process. Ingot hot-rolled to 16 mm plate, normalized 1038 °C, held 1 hour, air-cooled, then tempered to 760 °C, held 1 hour, air-cooled. Composition of plate (wt %): 8.83 Cr, 0.94 Mo, 0.10 C, 0.43 Mn, 0.36 Si, 0.12 Ni, 0.208 V, 0.058 Nb, 0.023 Co, 0.09 Cu, 0.01 Ti, 0.01 W, 0.01 P, 0.016 S, 0.011 N, balance Fe. Ingot from Quaker.

[c]Plate was welded using unmodified 9 Cr-1 Mo steel filler wire (contains no Nb or V). After gas tungsten-arc welding the weld was post-weld heat treated at 788 °C for 1 hour.

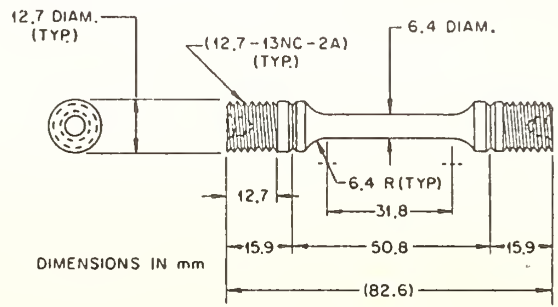
[d]Literature data for standard 9 Cr-1 Mo from the United Kingdom. [Standard ranges for 9 Cr-1 Mo steel: Cr 8.0-10.0, Mo 0.90-1.20, C 0.15-0.20, Mn 0.30-0.65, P 0.03-0.05, S 0.03-0.06, Si 0.25-1.00.]

CREEP DATA[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b][56]

Temperature °C	Stress MPa	Strain, % Primary	Strain, % Secondary	Strain, % Rupture	Time, hours Primary	Time, hours Secondary	Time, hours Rupture	Reduction in Area, %	Stable Creep Strain, %
538	317	0.00	3.25	26.99	0.0	6.15	9.2	77.20	4.83
538	262	0.50	4.00	29.33	4.0	90.0	149.9	82.97	6.03
538	248	1.125	4.00	35.03	21.25	117.5	209.5	84.87	6.285
538	234	1.50	4.25	27.07	85.0	450.0	802.2	80.40	6.22
649	131	0.75	4.75	32.68	1.0	25.25	44.1	43.82	c
649	131	0.85	4.50	35.17	1.25	24.5	42.0	88.69	6.72
649	117	1.00	3.375	38.85	5.00	56.0	116.3	88.70	5.31
649	103	0.75	2.75	32.77	12.50	175.0	356.3	86.50	4.36
649	97	0.625	2.25	27.37	15.0	305.0	630.7	86.50	3.63
649	83	0.500	2.00	29.10	40.0	610.0	1301.4	87.89	1.79
649	69						>2540.0		d
704	69	0.25	2.00	45.95	1.0	42.0	104.4	94.99	1.89

[a]Transverse specimens were machined from 16 mm plate and tested on an Instron universal testing machine at constant crosshead speed. Strains were measured by extensometers, crosshead displacement versus load was graphed simultaneously and monitored continuously to rupture. See diagram for specimen specifications and Section B.3.1.108 for plotted data.

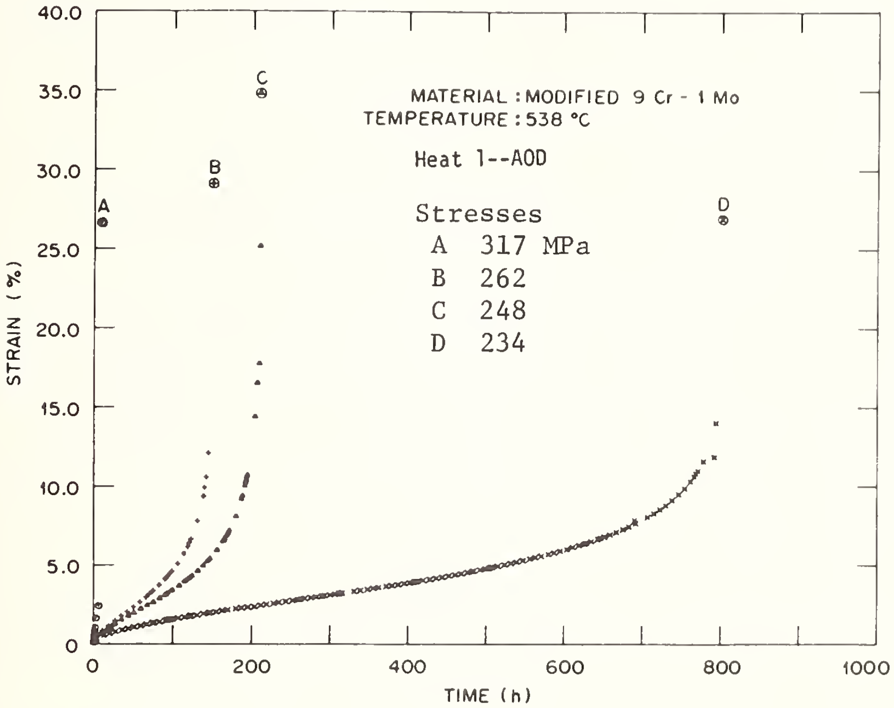
[b]Ingot produced by argon-oxygen-decarburization process. Ingot hot-rolled to plate, normalized 1038 °C, held 1 hour, air-cooled, then tempered to 760 °C, held 1 hour, air-cooled. Composition of plate (wt %): 8.83Cr, 0.94Mo, 0.10C, 0.43Mn, 0.36Si, 0.12Ni, 0.208V, 0.058Nb, 0.023Co, 0.09Cu, 0.01Ti, 0.01W, 0.01P, 0.016S, 0.011N, balance Fe. Ingot from Quaker.

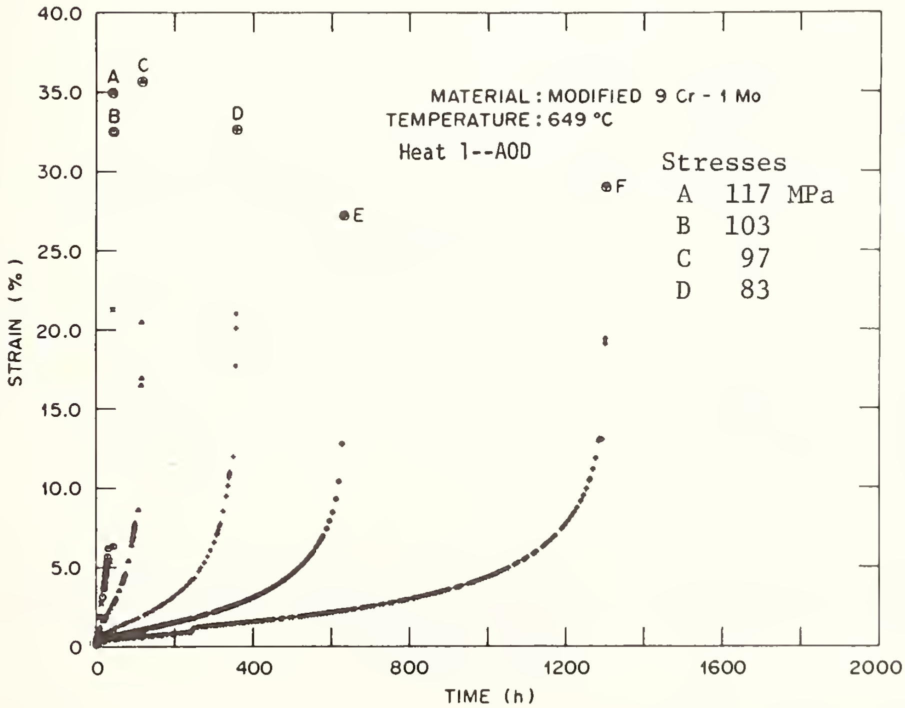


[c]Test discontinued.

[d]Test in progress.

CREEP AND STRESS-RUPTURE DATA[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b][56]





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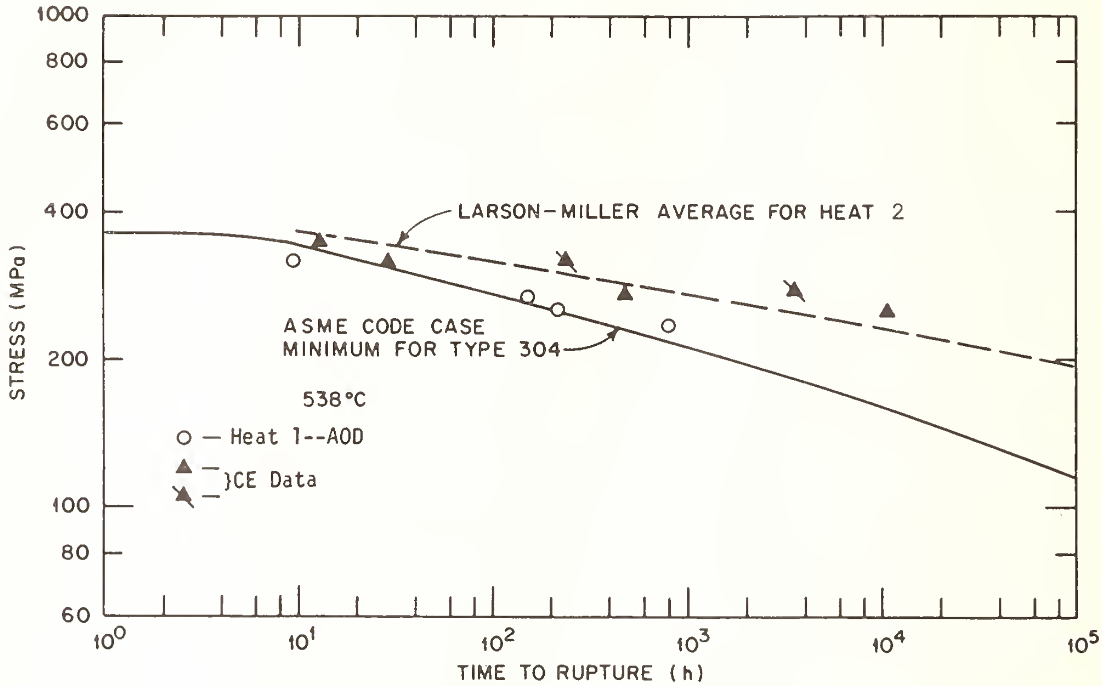
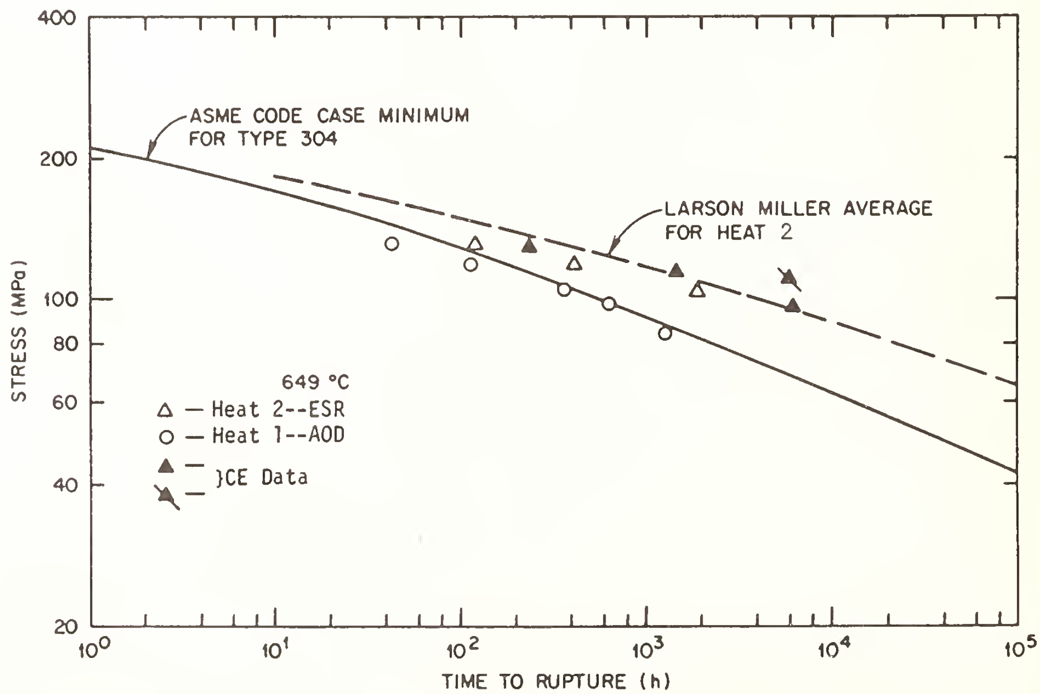
CREEP AND STRESS-RUPTURE DATA[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b][56], Continued





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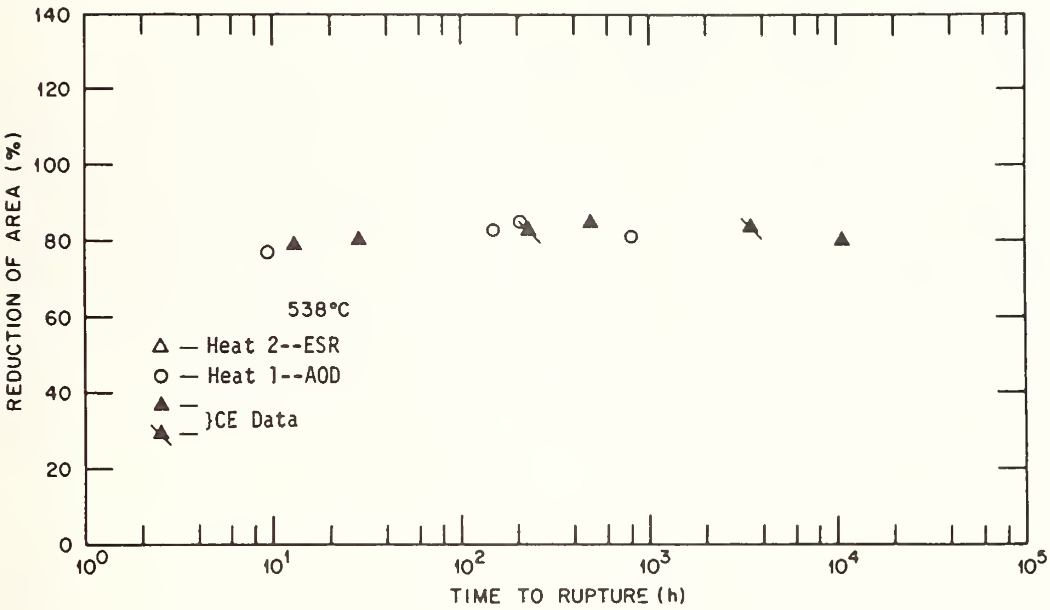
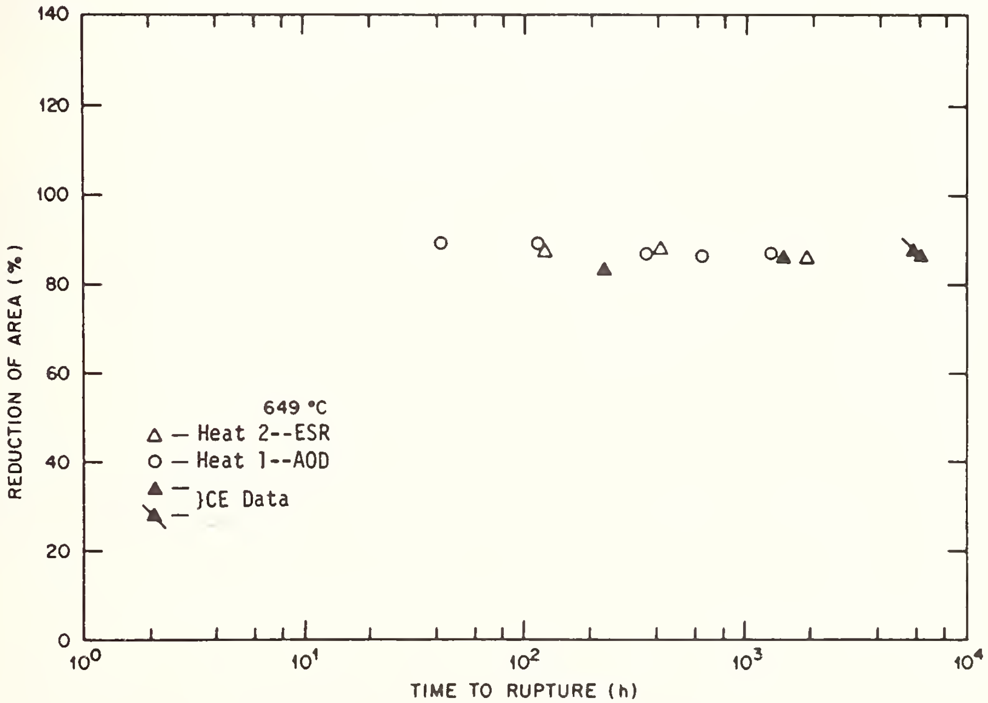
CREEP AND STRESS-RUPTURE DATA[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b][56],

Continued





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(Data Continued)

CREEP AND STRESS-RUPTURE DATA[a] FOR MODIFIED 9 Cr-1 Mo STEEL[b][56], Continued

Footnotes

[a]See B.3.1.107 for tabulated creep data for Heat 1 material.

[b]Heat 1: argon-oxygen-decarburization process (AOD) by Quaker. Heat 2: electroslag remelt process (ESR) by Cartech. Ingots were hot-rolled to plate, normalized 1038 °C, held 1 hour, air-cooled, then tempered to 760 °C, held 1 hour, air-cooled. Specified composition ranges for modified alloy (wt %): Cr 8-9, Mo 0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-0.25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001. Data points designated "CE Data" determined by Combustion Engineering.

TENSILE PROPERTIES[a] OF HOT-EXTRUDED TUBES OF MODIFIED 9 Cr-1 Mo STEEL[b][56]

Temperature °C	Modulus GPa	0.2% Offset Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, % Uniform	Elongation, % Total	Reduction in Area, %
Heat 1, 0.2% Si, AOD[b], front						
25	218	511	665	8.75	29.15	73.93
204	205	472	611	6.78	23.90	75.53
427	199	431	543	7.05	25.92	77.10
649	107	187	222	2.24	50.60	93.42
Heat 1, 0.2% Si, AOD, tail						
25	211	532	681	7.65	25.85	72.65
204	202	492	624	5.70	23.60	74.52
427	257	445	559	5.90	23.95	76.82
649	96	190	228	2.14	54.85	92.65
Heat 1, 0.2% Si, ESR-AOD, front						
25	223	521	673	7.96	30.00	73.55
204	215	480	610	6.15	20.52	75.08
427	157	449	555	6.05	23.47	74.22
649	99	201	231	1.80	47.80	94.14
Heat 1, 0.2% Si, ESR-AOD, tail						
25	223	541	692	7.58	27.10	72.73
204	206	498	624	5.38	21.00	76.01
427	200	446	558	5.65	23.70	75.36
649	120	187	229	1.96	46.10	94.33
Heat 2, 0.5% Si, ESR-AOD, front						
25	216	486	628	7.72	27.15	75.99
204	189	445	559	5.05	25.83	78.28
427	185	411	504	5.47	24.40	76.75
649	106	187	221	1.52	44.70	93.13
Heat 2, 0.5% Si, ESR-AOD, tail						
25	216	515	649	7.21	22.68	75.40
204	208	471	589	5.08	23.95	76.49
427	167	462	523	5.02	25.06	76.49
649	102	198	229	1.86	44.38	93.37

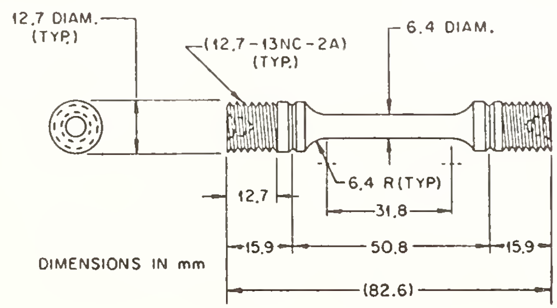
(Table Continued)

TENSILE PROPERTIES[a] OF HOT-EXTRUDED TUBES OF MODIFIED 9 Cr-1 Mo STEEL[b][56], Continued

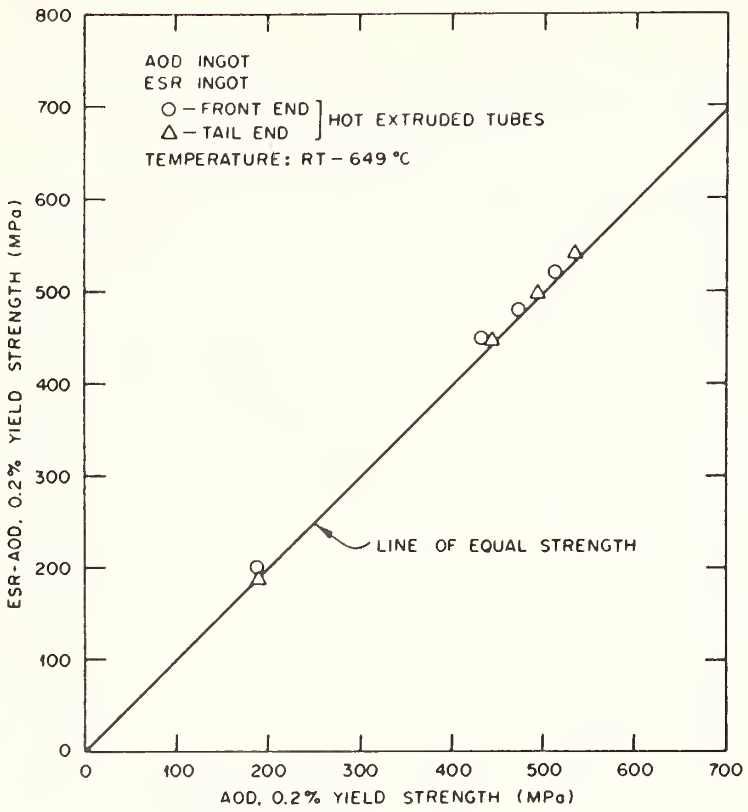
Footnotes

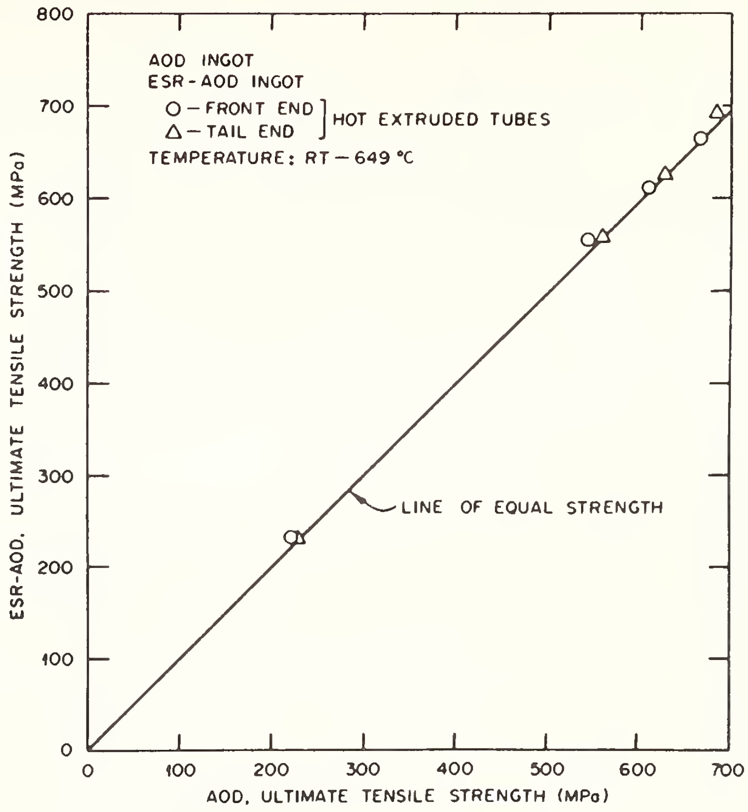
[a]Tensile tests were run on a 44 kN Instron universal testing machine at constant crosshead speed. The nominal strain rate of 0.004/min. was held constant. Yield strength was obtained from the extensometer chart, the ultimate tensile strength from the load-deflection chart. Tensile specimens (see diagram) were machined from the 15 mm wall tubing in the axial direction from both front and tail ends of the tubes.

[b]Two heats were melted by Cartech. Heat 1 had a Si content of 0.2% and ingots were prepared by both argon-oxygen-decarburization process (AOD) and by AOD followed by electroslag remelt process (ESR-AOD) Heat 2 had a 0.5% Si content and ingots were prepard by electroslag remelt following argon-oxygen-decarburization (ESR-AOD). The hot-extruded tube lengths were normalized at 1038 °C, held one hour, air-cooled, then tempered at 760 °C for 1 hour, air-cooled. The specified ranges for the modified steel are (wt %): Cr 8-9, Mo 0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001.



EFFECT OF MELT PROCESS[a] ON MECHANICAL PROPERTIES[b] OF MODIFIED 9 Cr-1 Mo STEEL[c] [56]





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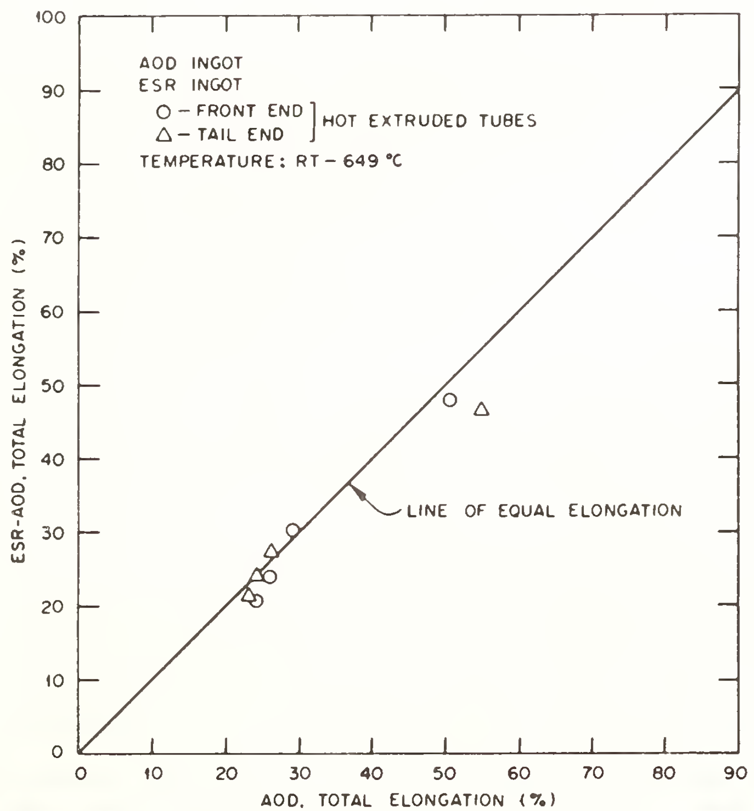
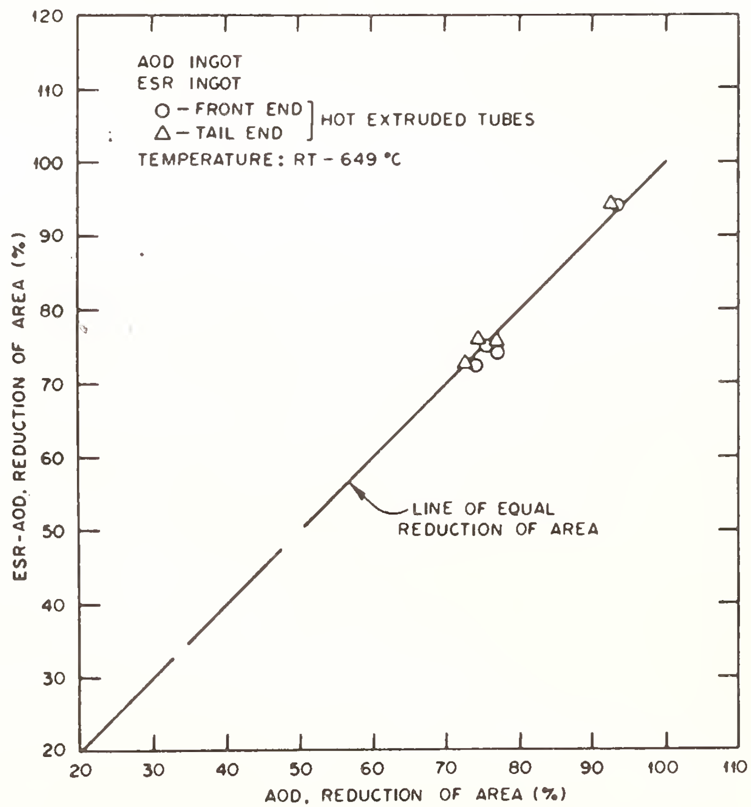
EFFECT OF MELT PROCESS[a] ON MECHANICAL PROPERTIES[b] OF MODIFIED 9 Cr-1 Mo STEEL[c][56],Continued





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[a] AOD = argon-oxygen-decarburization melt process, ESR-AOD = electroslag remelt following argon-oxygen-decarburization.

[b] See Section B.3.1.109 for the tabulated data plotted here for alloy from Heat 1, 0.2% Si content.

[c] See Section B.3.1.109 for details of the modified alloy.

COMPARISON OF HARDNESS, TOUGHNESS, AND WEAR FOR CAST AND FORGED EXPERIMENTAL STEELS[a][41]

Alloy[a]	Hardness[b] R_c	Charpy Impact Toughness[b] ft-lb	3-Body Wear Ratio[b,c]
Base+1 Al+1 Si+0.4 V			
Cast	54.5	2.5	0.51
Forged	55	17	0.56
AISI 4340+1.5 Al+1.5 Si			
Cast	49	9.3	0.50
Forged	51	20	0.45

[a] Base alloy composition: 0.36 C, 0.5 Mn, 1.0 Cr, 3.0 Ni, 2.0 Mo, balance Fe.

[b] All values for cast materials are for equiaxed zone.

[c] Three-body wear was determined using a specimen disc 3.75 inches in diameter, 0.25 in thick, with a central hole 5/16 inches in diameter. After heat treatment the surfaces of the disc were ground (to 0.11 in thickness) to remove the decarburized layer. The apparatus contained an acrylic tube (containing 120 grit SiC and fitting into a horizontal beam and plunger with weights) sitting on the disc specimen which rotates beneath it. The conditions provided an effective load of 2.5±0.3 kg applied to the specimen. Wear was analyzed by plotting the weight loss against the number of cycles, least squares fitting of a straight line, and reporting the slope as wear per 100 cycles.

$$\text{Volume Wear Rate} = \frac{\text{Weight Loss}}{\text{Density x Distance x Load}}$$

$$\text{Wear Ratio} = \frac{\text{Wear Rate of Specimen}}{\text{Wear Rate of Standard}}$$

1020 steel was used as the standard. Two specimens were used for each test.

EFFECT OF ALLOY CARBIDE PRECIPITATION IN AN EXPERIMENTAL SECONDARY HARDENING STEEL[a][41]

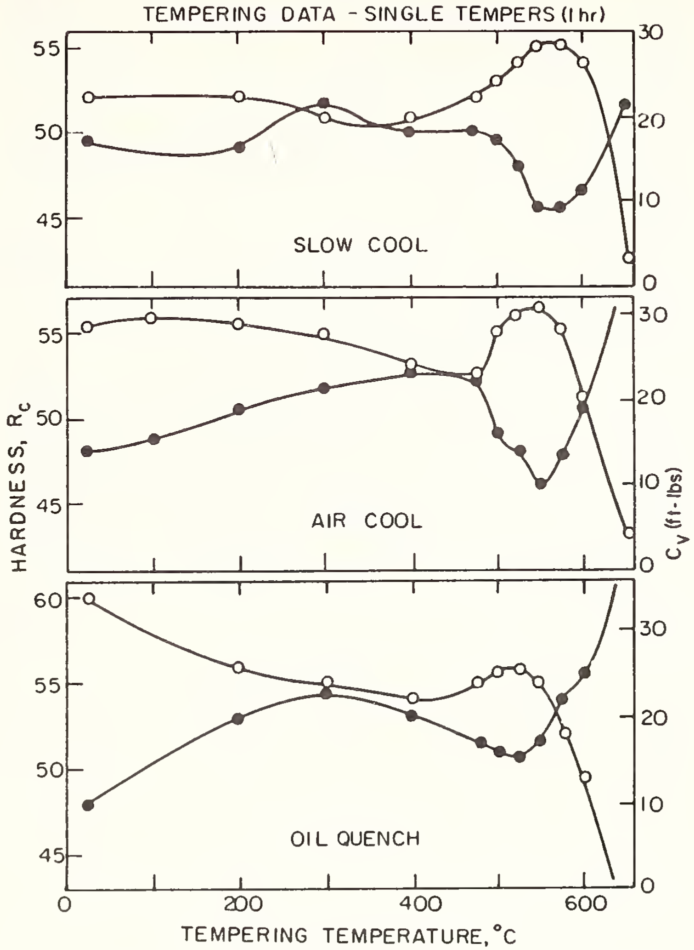
	No Alloy Carbides	Alloy Carbides
Heat Treatment	1050 °C austenitized 200 °C tempered	1050 °C austenitized 550 °C tempered
Hardness, R_c	56.9	54.2
Impact Toughness, ft-lb	17	36.5
Tensile Strength, ksi	306.0	274.3
Yield Strength, ksi	213.8	223.3
% Elongation	10	12
2-Body Wear Ratio[b]	0.6105	0.5563
3-Body Wear Ratio[c]	0.456	0.409

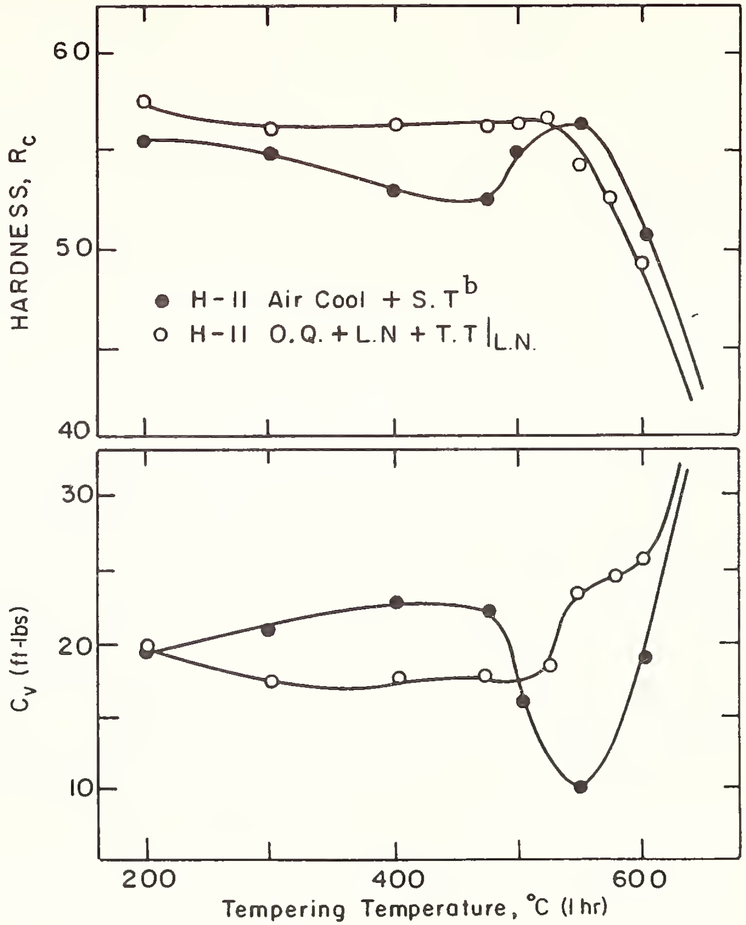
[a]Composition of the experimental steel (wt%): 0.39 C, 1.92 Mo, 3.87 Cr, 0.49 W, 0.45 V, 0.5 Mn, balance Fe.

[b]For description of 2-body wear testing see B.2.1.40.

[c]For description of 3-body wear testing see B.2.1.60.

HARDNESS AND CHARPY V-NOTCH ENERGY OF A COMMERCIAL SECONDARY HARDENING STEEL[a] AS FUNCTIONS OF TEMPERING TEMPERATURES[41]





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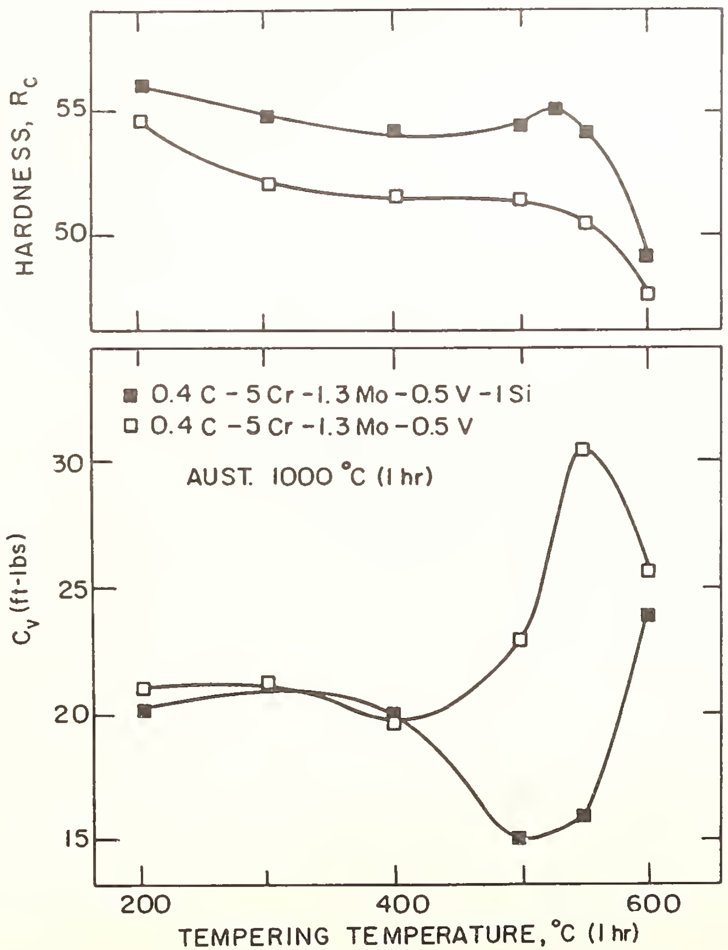
HARDNESS AND CHARPY V-NOTCH ENERGY OF A COMMERCIAL SECONDARY HARDENING STEEL[a] AS FUNCTIONS OF TEMPERING TEMPERATURES[41], Continued



[a]Steel is H-11, nominal composition 0.4 C, 5.0 Cr, 1.3 Mo, 0.5 V, 1.0 Si, balance Fe. Normal heat treatment--hold at 815 °C for 1 hour per inch of thickness, austenitize at 1010 °C for fifteen minutes per inch of thickness, then air cool to ambient temperature.

[b]Different treatments: normal air cool with standard temper (S.T.) of 1 hour; second treatment is to first oil quench (O.Q.), refrigerate in liquid nitrogen (L.N.), and then temper three times (T.T) with refrigeration treatments between each temper.

WELDABILITY TESTING[a] OF CHROMIUM-MOLYBDENUM STEELS[57]

Electrode[a]	Standard[b] 9 Cr-1 Mo weld metal	HAZ[f]	Modified[c] 9 Cr-1 Mo weld metal	HAZ[f]	HT9[d] 12Cr-1Mo-V-0.2C weld metal	HAZ[f]	2-1/4 Cr-1 Mo[e] weld metal	HAZ[f]
Standard, E 6010	C[g]	NC[h]	C	NC	C	NC	C	C[i]
Stronger, E 8010	C	NC	C	NC	C	NC	C	NC
Humidity-exposed, E 505-18	NC	NC	NC	NC	NC	NC	NC	NC
GTA-5% H_2	NC	NC	NC	NC	NC	NC	NC	NC
GTA-10% H_2	NC	NC	NC	NC	NC	NC	NC	NC

[a]Standard test for underbead cracking uses a E 6010 electrode, 3.2 mm diameter, current 100 A, 24-26 V, travel speed 254 mm/min, energy input 590 J/mm to deposit a weld bead at any required test temperature. The temperature for all the above tests was 0 °C (32 °F). After welding the specimen is held at 15.5 °C (60 °F) for 24 h, the tempered 595 °C (1100 °F) for 1 h. The weld is sectioned longitudinally and examined by magnetic particle and metallographic techniques. Besides the higher strength electrode, E 8010, welds were also prepared with electrodes which had been exposed to 90% humidity for 24 h (E 505-18). Hydrogen was added to the shielding gas to prepare gas tungsten arc (GTA) welds with welding parameters, 250 A, 9 V, travel speed 127 mm/min, using a 3.2 mm diameter thoriated tungsten electrode.

[b][Standard ranges for 9 Cr-1 Mo steel (wt%): Cr 8.0-10.0, Mo 0.90-1.20, C 0.15-0.20, Mn 0.30-0.65, P 0.03-0.05, S 0.03-0.06, Si 0.25-1.00.]

[c]Specified composition ranges for modified steel (wt%): Cr 8-9. Mo 0.85-1.05, C 0.08-0.12, Mn 0.30-0.50, P 0.02 max, S 0.01 max, Si 0.25-0.45, Ni 0.2 max, V 0.18-0.25, Nb 0.06-0.10, Ti 0.01 max, Cu 0.2 max, Al 0.04 max, B residual, W <0.01, Zr <0.01, N 0.03-0.07, O <0.02, Sb <0.001. This steel is the Cartech heat specified as Heat 2 in Sections B.3.1.102 and 105 and as Heat 1 in B.3.1.109.

[d]Composition given (wt %): Cr 11.65, Mo 1.02, V 0.29, C 0.20, Mn 0.61, P 0.016, S 0.007, Si 0.26, Ni 0.54, Nb/Ta 0.01, Ti <0.01, Co 0.09, Cu 0.03, Al 0.009, B 0.001, W 0.61, As 0.004, Sn 0.001, Zr 0.002, N 0.041, O 0.013.

[e]Composition given (wt %): Cr 2.15, Mo 1.09, C 0.13, Mn 0.45, P 0.013, S 0.021, Si 0.23, Ni 0.20, V 0.01, Co, 0.05, Cu 0.13, others not given.

[f]HAZ = heat affected zone.

[g]Cracks observed.

[h]No cracks observed.

[i]Few intergranular cracks.

STRESS RELIEF CRACKING EVALUATION[a] OF WELDED STANDARD[b] AND MODIFIED 9 Cr-1 Mo STEEL[c][57]

Alloy[b,c]	Thermal History	Stress MPa	Stress ksi	Time to Rupture, min	Ductility[d] RA, %
Standard	Normalized and tempered; heated at 111 °C/s to 732 °C; held to rupture	152	22.0	1.5	78
Standard		104	15.0	11	85
Modified		148	21.4	10.5	87
Standard	2kJ/mm thermal cycle to peak of 1260 °C; cooled; heated at 111 °C/s to 732 °C; held to rupture	83	12.0	57.17	78
Standard		104	15.0	10	82
Standard		98	14.2	7.5	81
Standard		124	18.0	4.3	85
Standard		140	20.2	1.5	86
Modified		141	20.4	48	56
Modified		166	24.0	46.9	40
Modified		187	27.0	21	38
Modified		218	31.6	13	35
Modified		207	30.0	8.9	39
Modified		247	35.7	8	35
Modified		228	33.0	7.75	42
Modified		269	39.0	5.9	39
Modified		294	42.5	2.9	49

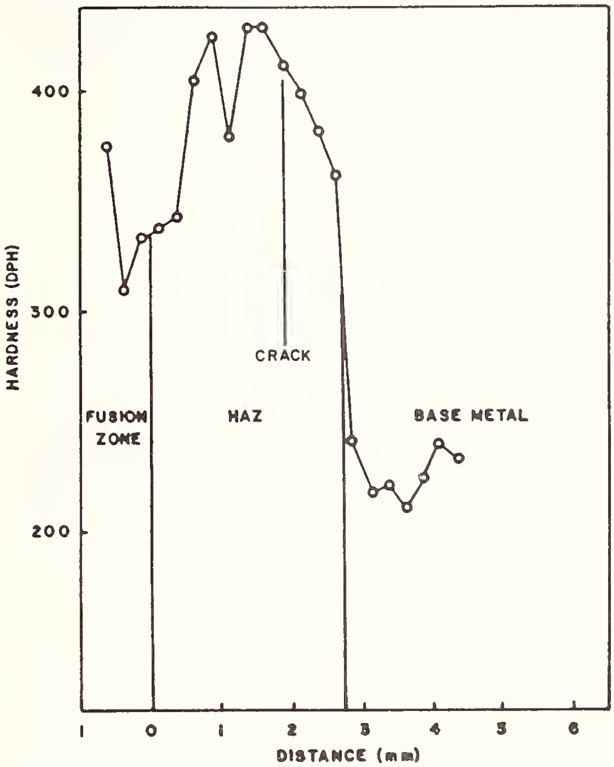
[a]Tests were done on a high-speed resistance heating control integral with high-strain tensile capability (Gleeble apparatus). Stress relief cracking in a weld heat-affected zone (HAZ) occurs during post weld heat treatment (PWHT) when the HAZ creep ductility is too low to absorb post-welding strain. Cracking evaluation was made by imposing thermal cycles producing a microstructrue like that of the coarse-grained HAZ. Short-time rupture stress range was established by testing original normalized (1038 °C) and tempered (760 °C) alloy. Weld heating was simulated by a thermal cycle representing 2kJ/mm (50kJ/in.) in 1 inch of plate, peak temperature 1260 °C (2300 °F). Uncycled and thermal-cycled specimens were stressed, heated to 732 °C (normal PWHT temperature), and held at load and temperature until rupture.

[b]Composition (wt%): 9.12 Cr, 0.96 Mo, 0.065 C, 0.41 Mn, 0.025 P, 0.004 S, 0.44 Si.

[c]Composition (wt%): 8.61 Cr, 0.89 Mo, 0.081 C, 0.37 Mn, 0.010 P, 0.003 S, 0.11 Si, 0.09 Ni, 0.209 V, 0.072 Nb/Ta, 0.004 Ti, 0.10 Co, 0.04 Cu, 0.007 Al, 0.055 N, <0.01 W, B, As, Sn, Zr, all <0.001.

[d]Ductility as measured by reduction in area (RA).

MICROHARDNESS SURVEY[a] OF HAZ[b] AND FUSION ZONE OF A SULFIDE STRESS CRACKED[c] MODIFIED 9 Cr-1 Mo STEEL[d] WELD[e][57]



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[a]Diamond pyramid hardness (DPH) was measured across the weld.

[b]HAZ = heat-affected zone.

[c]See Section B.1.1.156 for a description of the preparation of specimens and the stress-corrosion testing.

[d]Argon-oxygen-decarburization melt process. Composition (wt%): 8.46 Cr, 1.02 Mn, 0.083 C, 0.46 Mn, 0.010 P, 0.004 S, 0.41 Si, 0.09 Ni, 0.198 V, 0.072 Nb/Ta, 0.005 Ti, 0.055 Co, 0.03 Cu, 0.002 Al, 0.05 W, 0.051 N, B, As, Sn, Zr, all <0.001.

[e]The weld specimen is the Number 12 specimen in Section B.1.1.156.

HARDNESS OF STANDARD[a] AND MODIFIED 9 Cr-1 Mo STEEL WELDS[b][57]

	Diamond Pyramid Hardness		
Welded Alloy	Base Metal[c]	Heat-Affected Zone[d]	Fusion Zone[e]
Standard[a]	209	407	376
ESR Modified alloy 1[f]	221	460	436
ESR Modified alloy 2[g]	232	434	406
ESR Modified alloy 2, 300 °C preheat	234	416	414

[a]Standard composition (wt %): 9.12 Cr, 0.96 Mo, 0.065 C, 0.41 Mn, 0.025 P, 0.004 S, 0.44 Si.

[b]Welds were deposited on 3-mm thick coupons at 80-100 A, 10 V, at a speed of 127 mm/min., using a 1.58-mm diameter 2% thoriated tungsten electrode. The shielding gas was 5% hydrogen-95% argon. These gas tungsten arc welds are the same ones used for the hydrogen sensitivity tests reported in B.1.1.154.

[c]Average reading for base metal.

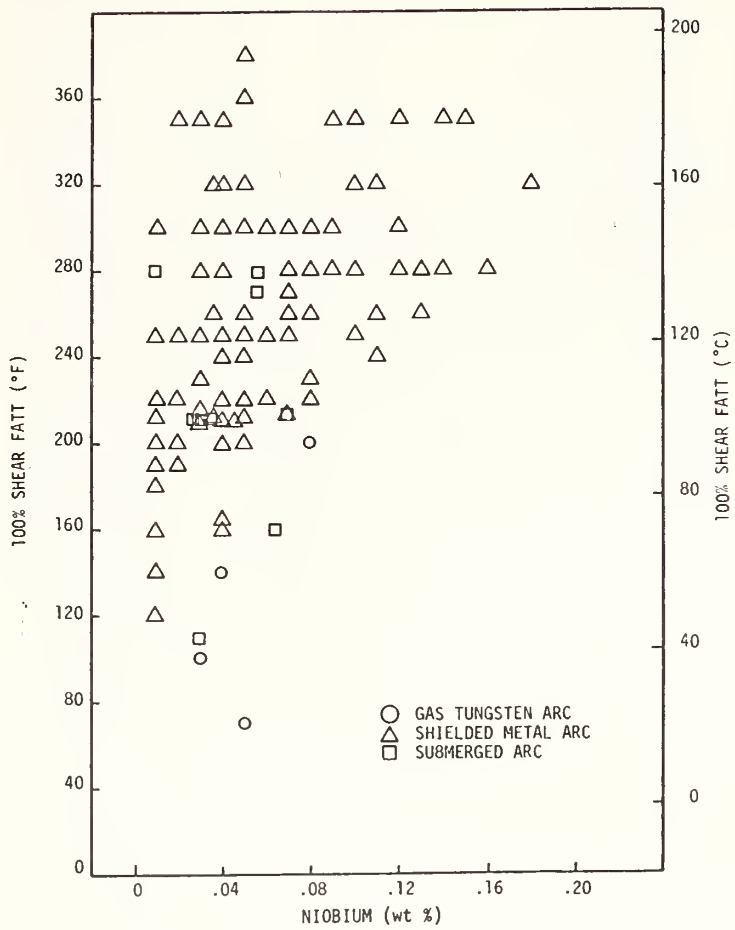
[d]Maximum hardness value.

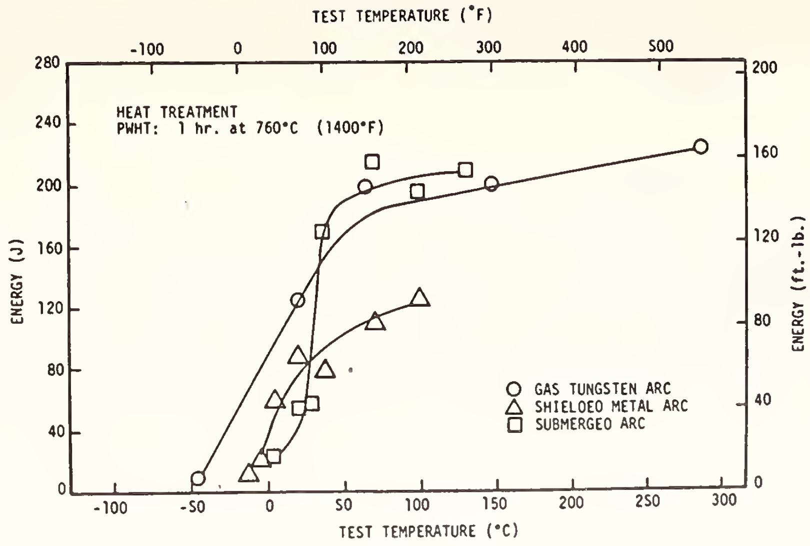
[e]Average reading for fusion zone.

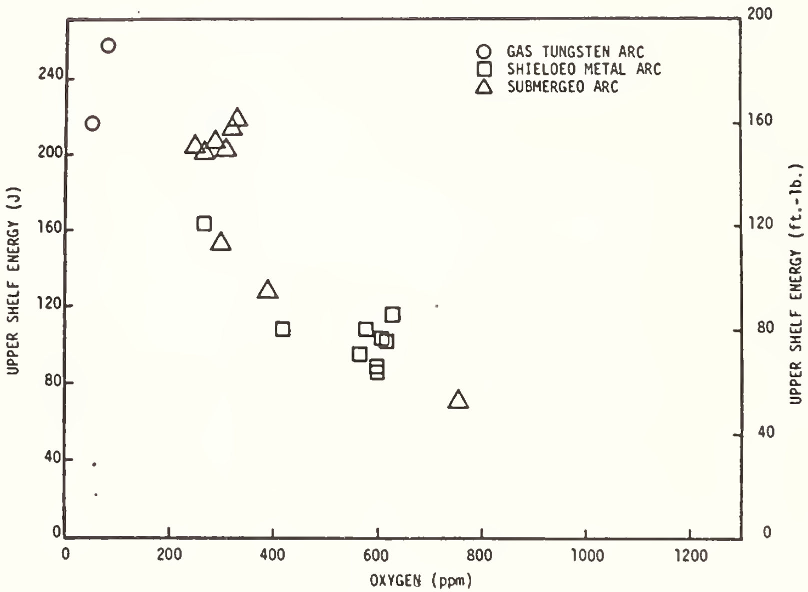
[f]ESR = electroslag remelt process, following argon-oxygen-decarburization. Composition (wt %): 8.61 Cr, 0.89 Mo, 0.081 C, 0.37 Mn, 0.010 P, 0.003 S, 0.11 Si, 0.09 Ni, 0.209 V, 0.072 Nb/Ta, 0.004 Ti, 0.10 Co, 0.04 Cu, 0.007 Al, 0.055 N, <0.01 W, B, As, Sn, Zr, all <0.001.

[g]ESR = electroslag remelt process, following argon-oxygen-decarburization. Composition (wt %): 8.57 Cr, 1.02 Mo, 0.084 C, 0.46 Mn, 0.010 P, 0.003 S, 0.40 Si, 0.09 Ni, 0.198 V, 0.073 Nb/Ta, 0.005 Ti, 0.055 Co, 0.04 Cu, 0.014 Al, 0.05 W, 0.053 N, B, As, Sn, Zr, all <0.001.

TOUGHNESS[a] OF VARIOUS MODIFIED 9 Cr-1 Mo STEEL WELDS[b][58]







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TOUGHNESS[a] OF VARIOUS MODIFIED 9 Cr-1 Mo STEEL WELDS[b][58], Continued

Weld[c]	Post Weld Heat & Time		Hardness[d] Rockwell B	Transition Temp. °F 50 ft-lb	100% Shear FATT	Upper Shelf Energy, ft-lb
SMA-1	1400 °F	1 hour	95.4	130	212	91
SMA-2	1400	1	101.4	150	212	80
SMA-3	1400	1	94.5	60	212	92
SMA-4	1400	1	91.0	40	212	102
SMA-5	1400	1	101.4	212	320	121
SMA-6	1400	1	97.2	180	280	68
SA-1	1400	1	101.5	130	212	165
SA-2	1400	1	96.8	40	280	150
SA-3	1400	1	99.6	140	280	113
SA-4	1400	2	95.9	140	270	149
SA-5	1450	1	94.9	90	160	150
SA-6	1400	2	95.6	60	212	150
SA-7	1400	2	96.0	90	212	95
SA-8	1400	2	96.6	95	212	153
SA-9	1400	2	96.0	90	212	151
SA-10	1400	6	93.6	55	212	150

[a] CVN = Charpy v-notch. FATT = fracture appearance transition temperature.

[b] Submerged arc welds used core wire of mild steel, and a commercial low oxygen potential, very high basicity flux (Oerlikon OP76), with modified 9 Cr-1 Mo steel filler wire. Compositions of examples of the various welds follow in wt %: gas tungsten arc, 8.37 Cr, 1.03 Mo, 0.10 C, 0.46 Mn, 0.014 P, 0.005 S, 0.43 Si, 0.09 Ni, 0.199 V, 0.076 Nb, 0.002 Ti, 0.056 Co, 0.04 Cu, 0.013 Al, 0.05 W, 0.002 Sn, 0.052 N, 0.005 O, B, As, Zr, all <0.001; submerged arc, 9.15 Cr, 0.85 Mo, 0.076 C, 0.49 Mn, 0.009 P, 0.009 S, 0.32 Si, 0.09 Ni, 0.23 V, 0.062 Nb, 0.004 Ti, 0.023 Co, 0.03 Cu, 0.007 Al, 0.01 W, 0.002 As, 0.002 Zr, 0.037 N, 0.032 O, both B and Sn <0.001; shielded metal arc, 8.73 Cr, 1.02 Mo, 0.065 C, 0.94 Mn, 0.003 P, 0.018 S, 0.24 Si, 0.02 Ni, 0.14 V, 0.036 Nb, 0.007 Ti, 0.013 Co, 0.03 Cu, 0.12 W, 0.001 Sn, 0.034 N, 0.085 O, Al, B, As, Zr, all <0.001.

[c] SMA = shielded metal arc, SA = submerged arc.

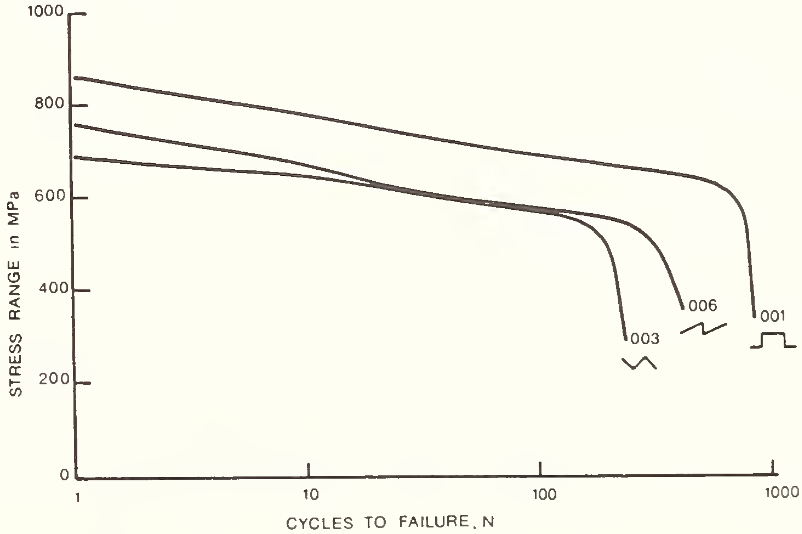
[d] Average values.

FATIGUE TESTING[a] OF A COMMERCIAL 2-1/4 Cr-1 Mo STEEL[b][59]

Test Number	Temperature	Cycles to Failure N_f	
1	565 °C	900	Equal hold times in tension and compression
2	482	1206	Sawtooth, slow-slow ramps
3	565	226	Sawtooth, slow tension ramp-fast compression ramp
4	565	154	Sawtooth, slow tension ramp-fast compression ramp (buckled)
5	565	396	Sawtooth, slow tension ramp-fast compression ramp
6	565	392	Sawtooth, slow-slow ramps
7	565	868	Sawtooth, slow tension ramp-fast compression ramp
8	565	(1.8×10^4 s)	Constant strain rate tensile test
9	565	326	Equal hold times in tension and compression

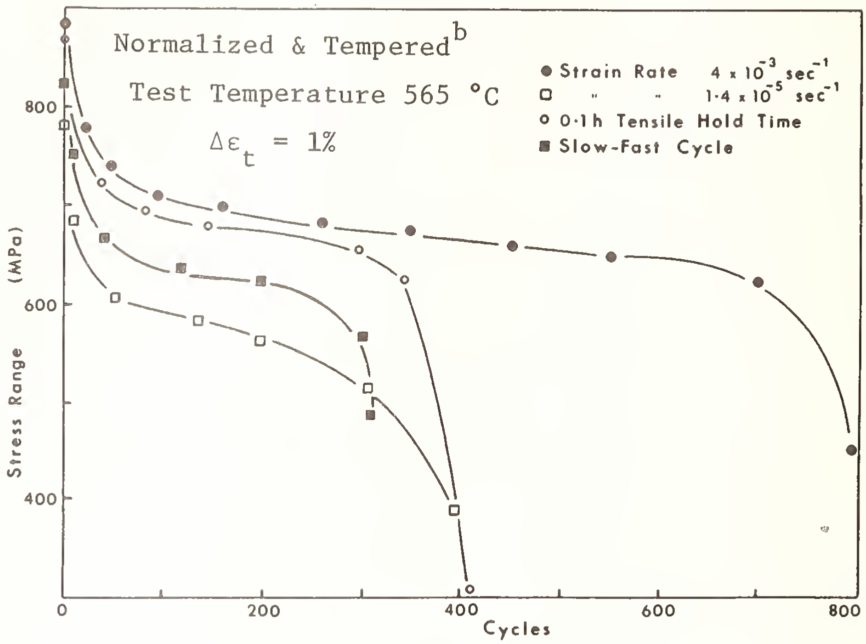
[a]Fatigue tests were performed under strain control for a variety of waveforms on an MTS machine. Strain range was 1 %, hold time 6 minutes.

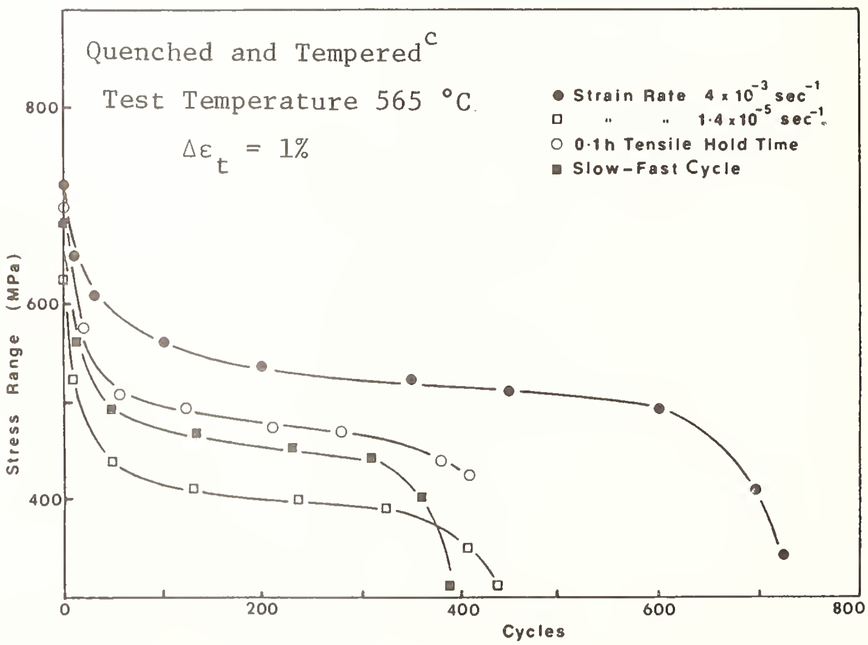
Uniformity of shape of curves of stress range variation against time implies some insensitivity to waveform.



[b]SA-387, Grade 22 Class 2 (Luken's heat A6660). Normalized and tempered (bainitic microstructure). Heat treated in the form of 150 mm plate for 12 hours at 900 °C, air cooled to 690 °C, held isothermally for 12 hours and air cooled to ambient temperature.

FATIGUE TESTS[a] FOR A STANDARD 2-1/4 Cr-1 Mo STEEL[b] AND A MODIFIED STEEL[c][59]





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FATIGUE TESTS[a] FOR A STANDARD 2-1/4 Cr-1 Mo STEEL[b] AND A MODIFIED STEEL[c][59], Continued

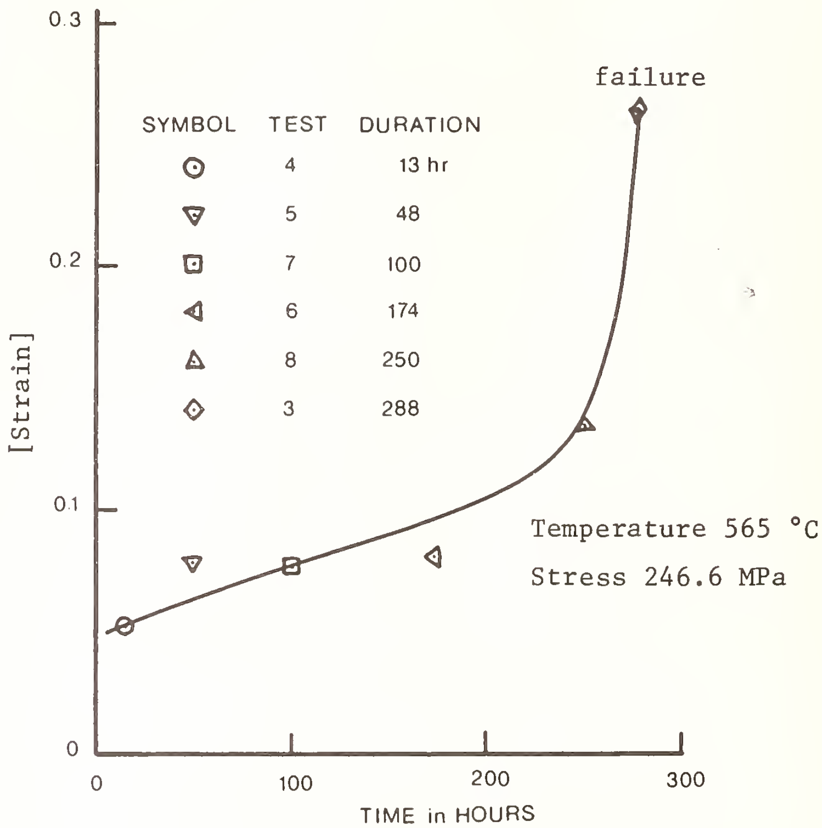
Footnotes

[a]Strain-controlled fatigue tests were conducted on a MTS machine at 565 °C and 1 % total strain range for a variety of waveforms. Stress range is plotted as a function of cycles for each of 4 waveforms involving fully reversed cyclic loading.

[b]SA-387, Grade 22 Class 2 (Luken's heat A6660). Normalized and tempered (bainitic microstructure). Heat treated in the form of 150 mm plate for 12 hours at 900 °C, air cooled to 690 °C, held isothermally for 12 hours and air cooled to ambient temperature.

[c]Forged Kawasaki steel, quenched and tempered V-Ti-B modified alloy of low residual element content in 400 mm plate.

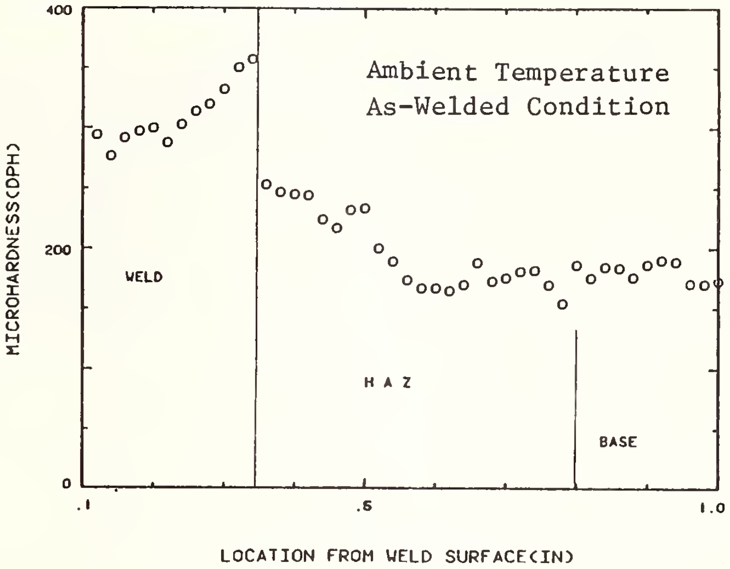
INTERRUPTED CREEP TESTS[a] OF COMMERCIAL 2-1/4 Cr-1 Mo STEEL[b][59]

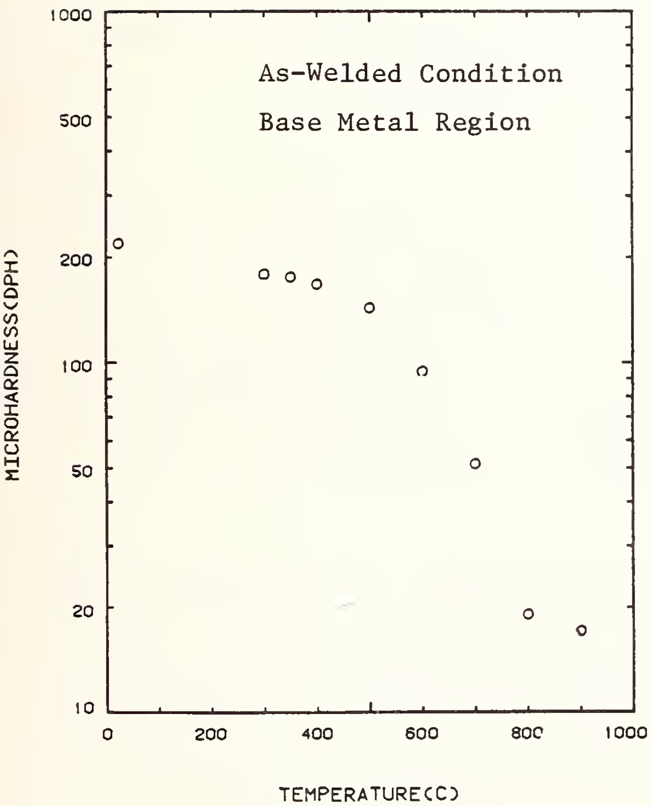


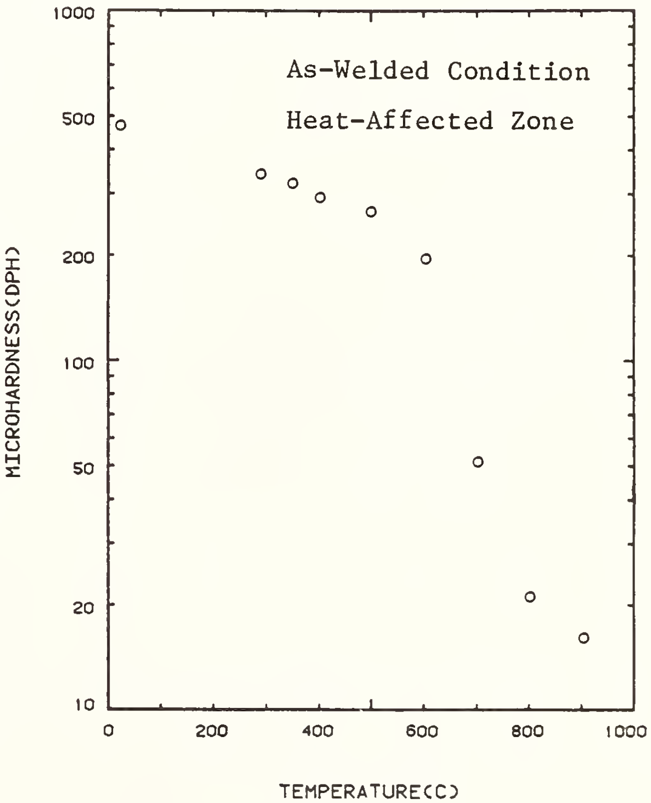
[a]Creep tests under constant load of 246.5 MPa were conducted at 565 °C and interrupted at various times ranging from 10 % up to full life. [The ordinate of the above plot was not labelled in the original report.]

[b]SA-387, Grade 22 Class 2 (Luken's heat A6660). Normalized and tempered, bainitic microstructure. Heat treated in the form of 150 mm plate for 12 hours at 900 °C, air cooled to 690 °C, held isothermally for 12 hours and air cooled to ambient temperatures.

MICROHARDNESS[a] OF 309 SS WELD-CLADDED 2-1/4 Cr-1 Mo STEEL[b][60]

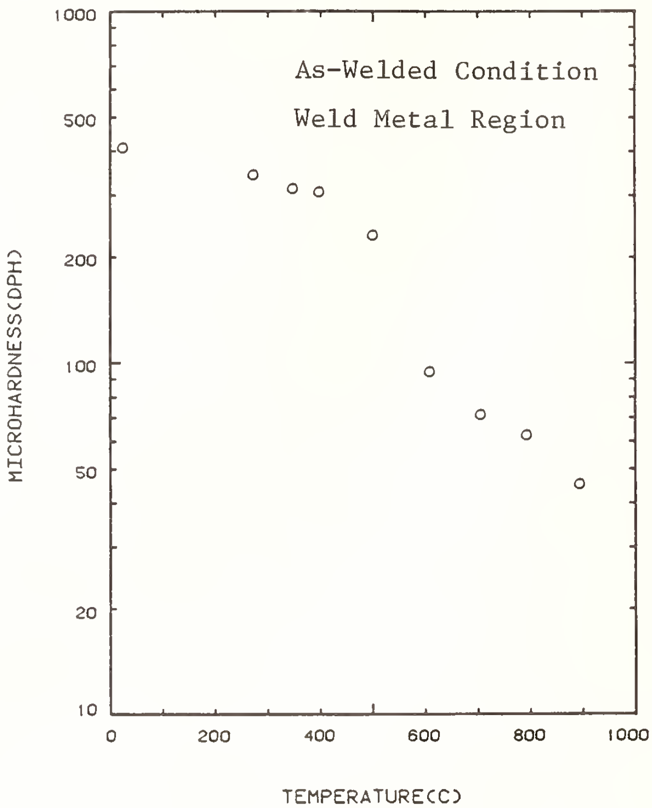






(Data Continued)

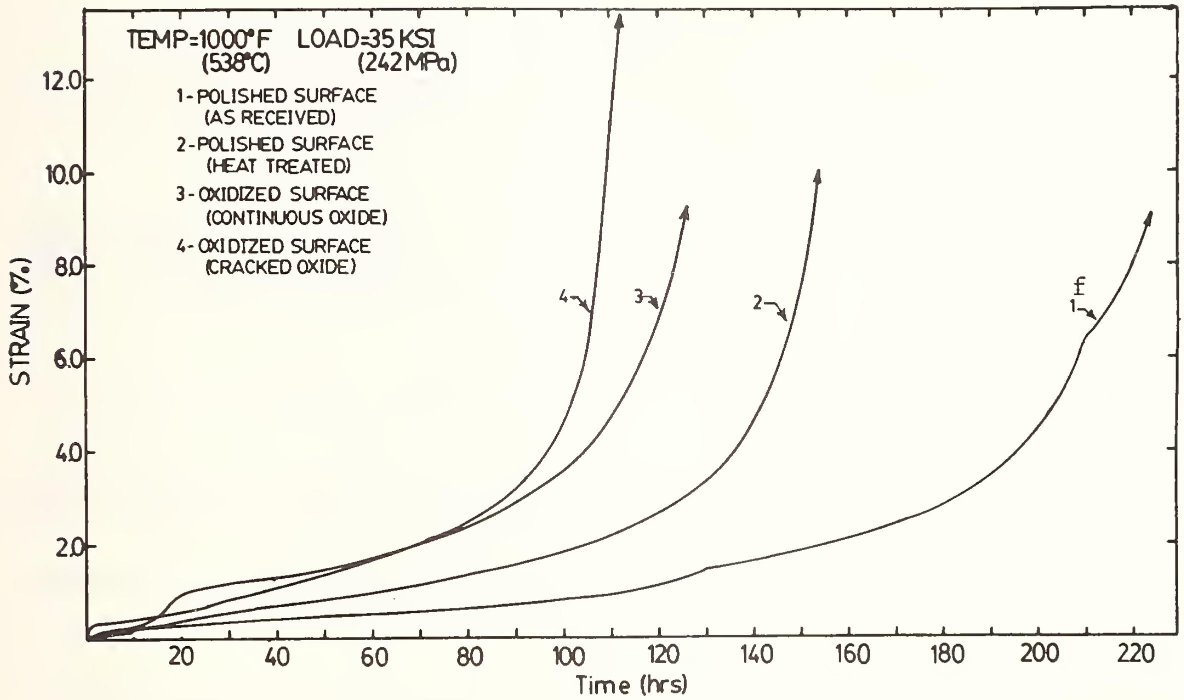
MICROHARDNESS[a] OF 309 SS WELD-CLADDED 2-1/4 Cr-1 Mo STEEL[b][60], Continued



[a]Diamond pyramid hardness (DPH) measured with a Wilson Tukon-Model MO microhardness tester with a 136 ° diamond pyramid indenter and a 500 g load at ambient temperature. A 10 g load was used for measurement across the small transition zone (∿20 μm wide). High-temperature testing was done in a specially designed apparatus which was first flushed with high-purity argon, evacuated to 2.5 x 10^{-5} torr and then maintained at 5 psi positive pressure of argon. The Vickers-type indenter was made of sapphire. Load was 500 g for a constant load duration of 30 s. Indents, spaced about 0.020 inches apart, were measured at 20X magnification.

[b]Base material is 2-1/4 Cr-1 Mo steel (SA-387, Grade 22 Class 2), heated to 1700-1800 °F, held 0.5 hour per inch thickness, water quenched, tempered at 1225 °F, held 0.5 hour per inch thickness and water quenched. Composition (wt%): 2.33 Cr, 1.06 Mo, 0.13 C, 0.43 Mn, 0.010 P, 0.003 S, 0.24 Si, 0.03 Ni, 0.08 Cu, balance Fe. Cladding weld overlay was made by strip submerged arc welding using AWS E309 austenitic stainless steel filler metal. Composition (wt%): 23-25 Cr, 0.5 Mo, 1.0-0.65 Mn, 0.03 P, 0.03 S, 0.30-0.65 Si, 12-14 Ni, 0.5 Cu, balance Fe. Base metal was 2 inches thick, flux was Sandvik-34WF, preheat temperature 200 °F, three passes were made at 500 A, 36-38 V, travel speed 6 in/min.

EFFECT OF VARIOUS PRETREATMENTS[a] ON CREEP BEHAVIOR[b] OF 2-1/4 Cr-1 Mo STEEL[c] [63]



Tests Carried to Rupture

Test No.	Pretreatment[d]	Surface Condition	Time to Failure	Strain to Failure[e]	Reduction in Area, %
1	None	polished, as received	Stopped 242 h	-	-
2	60 h, 538 °C, in vacuo	polished	157	31	87
3	60 h, 538 °C, in air	oxidized (continuous oxide surface)	141.5	29	85
4	60 h, 538 °C, then 0.2 % prestrain	oxidized (cracked oxide surface)	113.5	25	84
5[f]	0.2 % prestrain	polished	Stopped 88.5	-	-

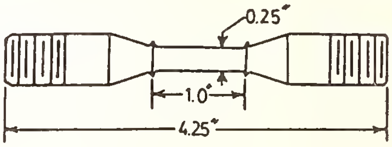
(Data Continued)

EFFECT OF VARIOUS PRETREATMENTS[a] ON CREEP BEHAVIOR[b] OF 2-1/4 Cr-1 Mo STEEL[c][63]

Footnotes

[a]Specimens were subjected to various pretreatments before the creep testing. The numbers on the curves of the strain-time plot correspond to the test numbers in the table in which the pretreatments are described.

[b]See diagram for creep specimen geometry. Specimens were polished after machining. The specimens were provided with knife edges to seat an extensometer. Strains were measured by means of a linear variable differential transducer. The tests took place in a resistance furnace at 538 °C (1000 °F) and at a tensile stress of 242 MPa (35 ksi).



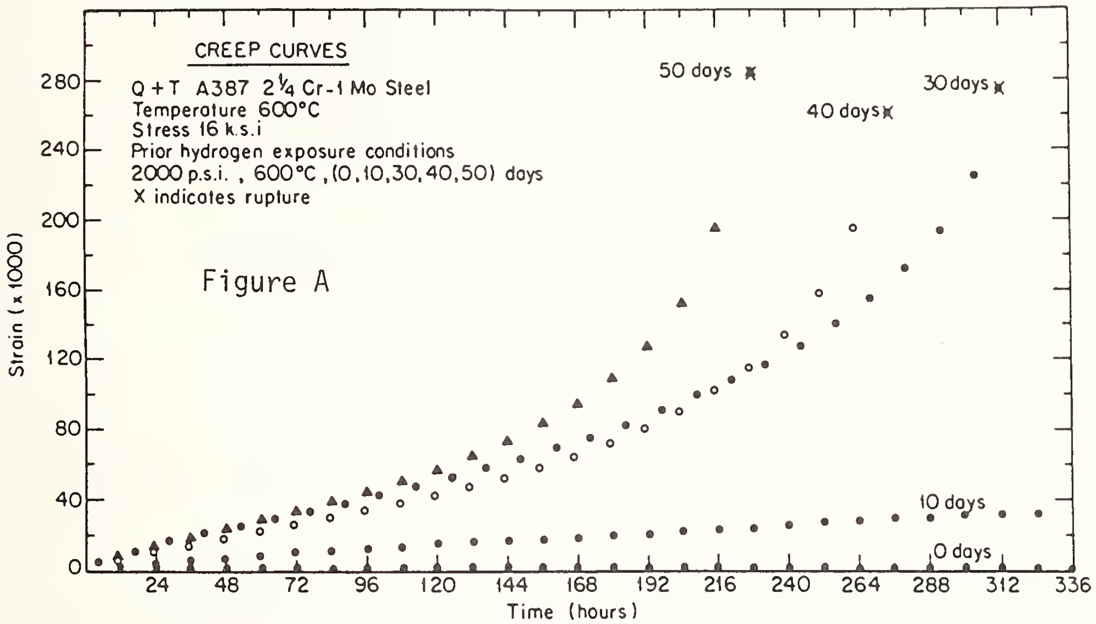
[c]Steel was supplied by Climax-Molybdenum as 5-8 inch rod. Heat treatment: 955 °C for 1 hour, air cooled, 730 °C for 2 hours, and air cooled. Specimens were polished after machining.

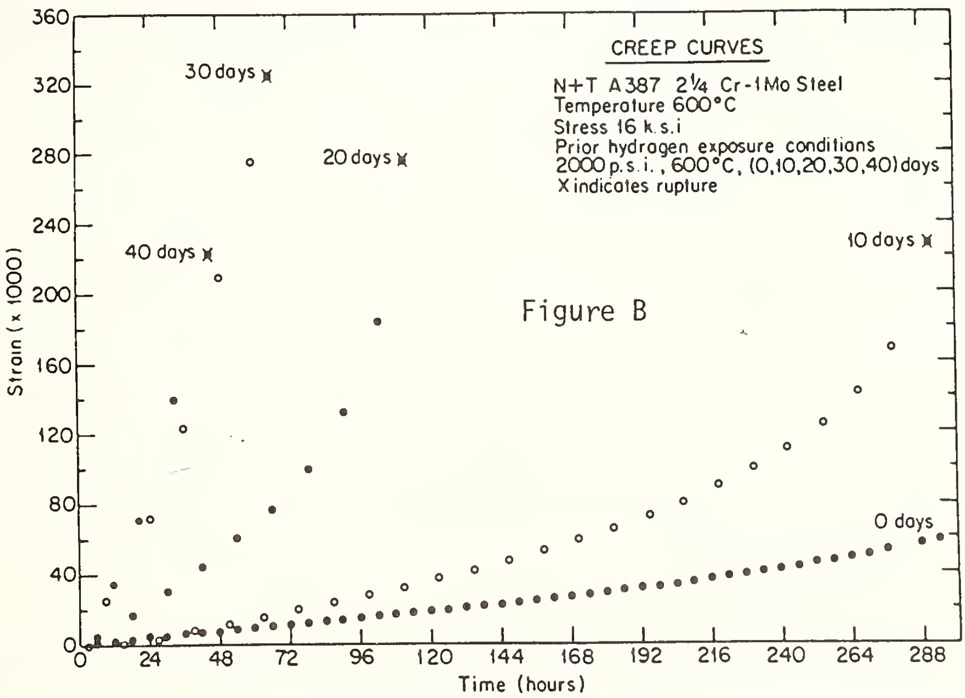
[d]As-received material, machined and polished, was subjected to the pretreatments listed before creep testing.

[e]1 inch gauge length.

[f]Curve for creep data of test 5 was so close to the curve for creep data of test 1 that those results were omitted from the plot for clarity.

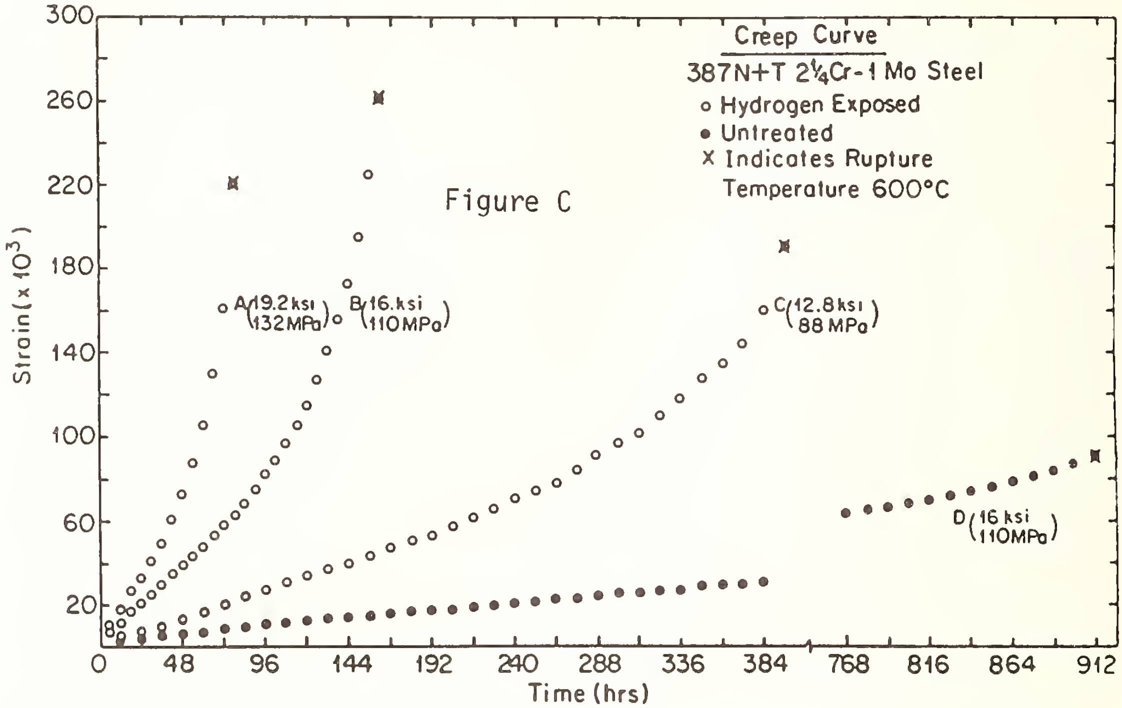
CREEP AND STRESS RUPTURE DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN[c][61,62]

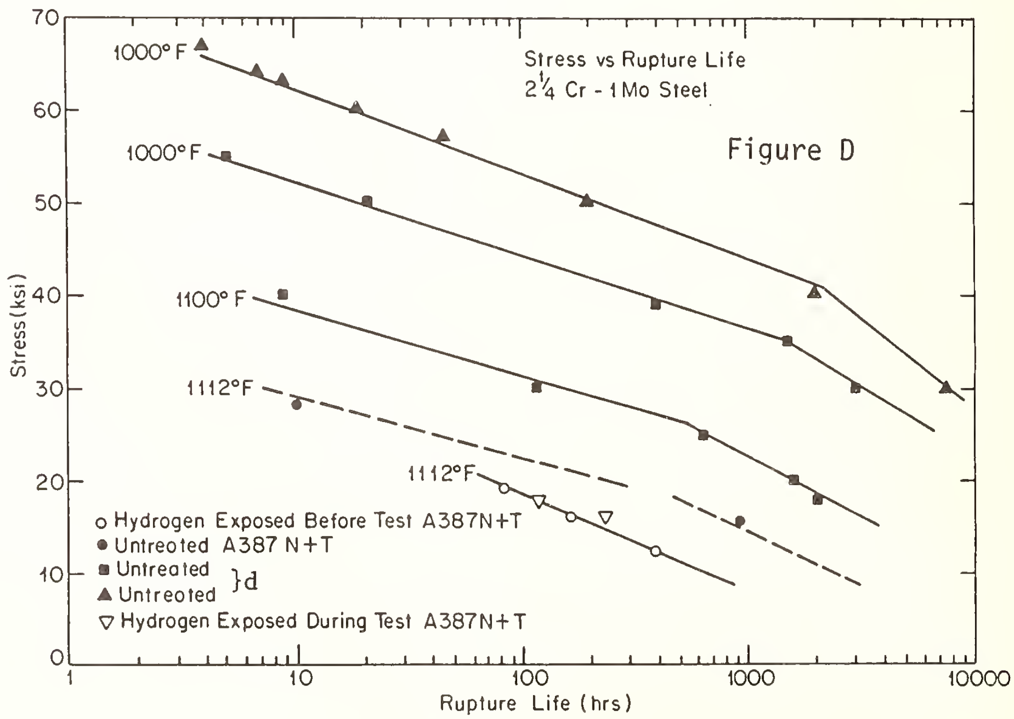




(Data Continued)

CREEP AND STRESS RUPTURE DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN[c][61,62], Continued





(Data Continued)

CREEP AND STRESS RUPTURE DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b] EXPOSED TO HYDROGEN[c][61,62], Continued

Footnotes

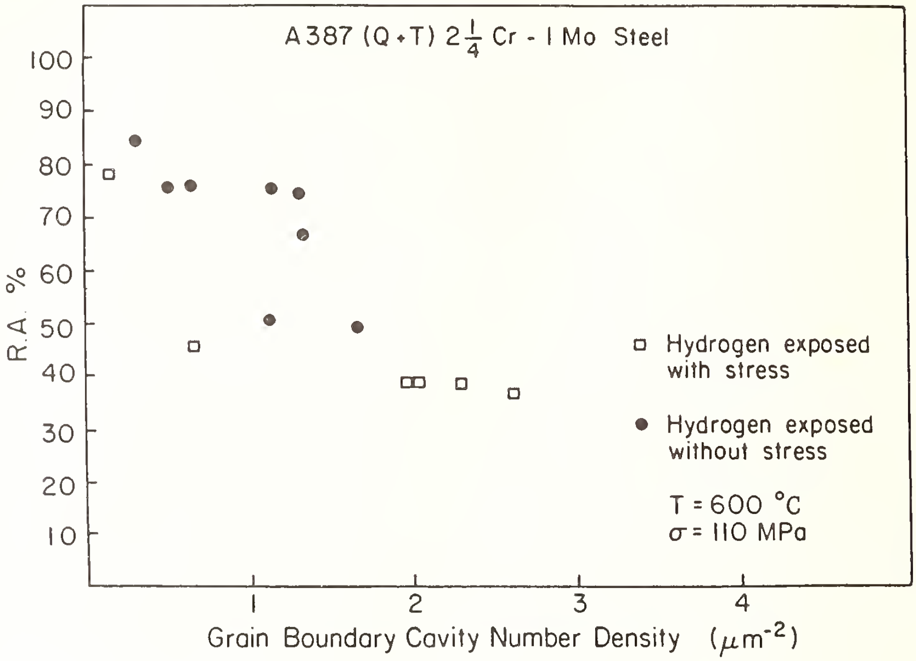
[a]Figure A shows creep to rupture data at 16 ksi stress for quenched and tempered steel and Figure B data for normalized and tempered steel. Both steels had been subjected to prior hydrogen exposure for varying time periods. Figure C shows creep data for normalized and tempered steel tested at three different stress levels. The steel had been hydrogen-exposed for 20 days at 13.8 MPa (2000 psi) at 600 °C (1112 °F) before testing. All tests were made at 600 °C (1112 °F). Figure D compares stress-rupture data for the tests in Figure C with literature data for steel unexposed to hydrogen. Data are also included for steel exposed to hydrogen during testing (13.8 MPa at 600 °C).

[b]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Specimens were taken from the surface of 12-inch thick plate. Heat treatments: quenched and tempered plate was austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched; normalized and tempered plate was austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. The Q + T material had a bainite microstructure (no proeutectoid ferrite) and the N + T material showed a bainite and proeutectoid ferrite microstructure.

[c]Specimens were loaded in autoclaves (fitted with a creep stand) which were first evacuated to 10^{-3} torr, brought to 600 °C in a split furnace and loaded with hydrogen to the prescribed pressure, 13.8 MPa (2000 psi). Round tension specimens, 19 mm gauge length, 1.8 mm gauge diameter, were used.

[d]Literature data.

REDUCTION IN AREA[a] FOR HYDROGEN EXPOSED[b] QUENCHED AND TEMPERED 2-1/4 Cr-1 Mo STEEL[c] [61,62]

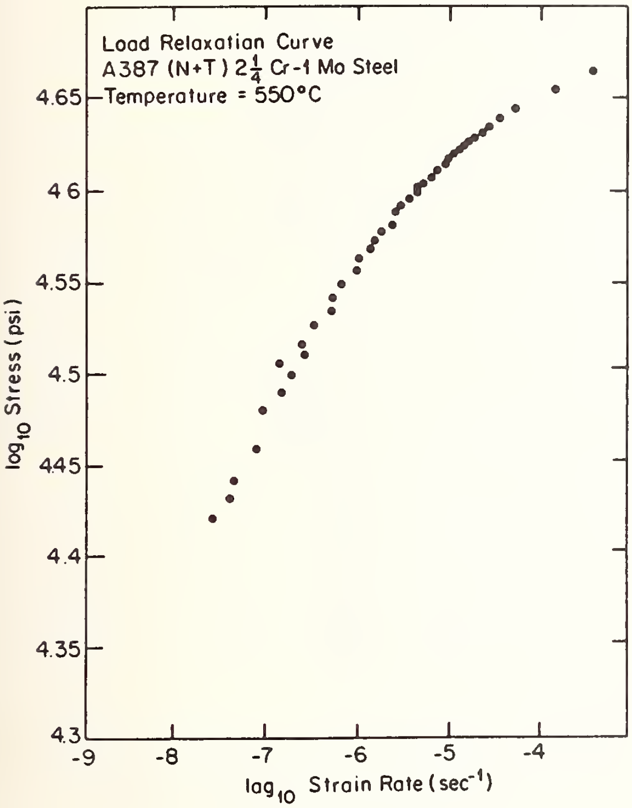


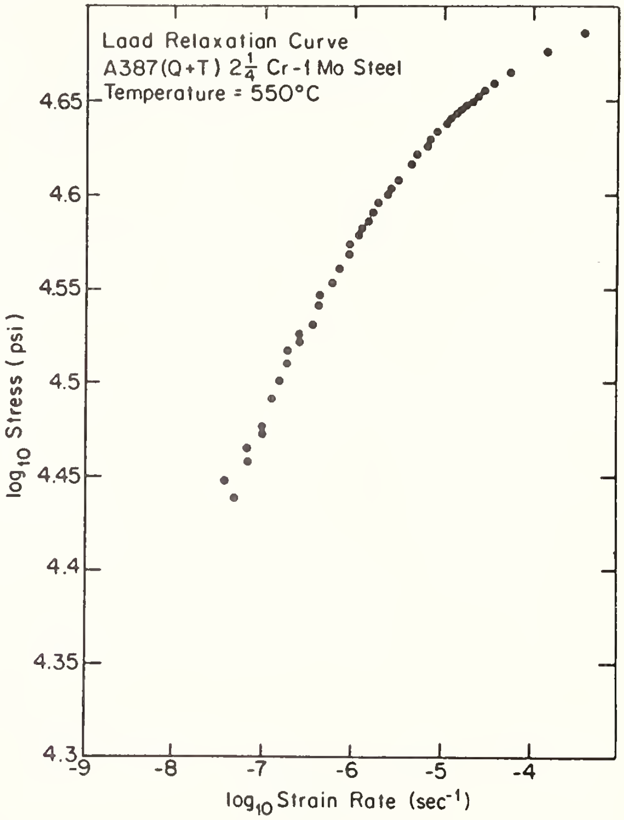
[a]Reduction in area versus grain boundary cavity density is plotted for specimens subjected to hydrogen exposure with and without applied stress. The specimens ruptured in creep growth treatment (110 MPa at 600 °C) following hydrogen exposure. See Sections B.1.1.178 through B.1.1.182 for grain boundary cavity density data versus hydrogen exposure time. Since the specimen size was small, 19 mm gauge length and 1.8 mm gauge diameter, decarburization may also have been a factor in the loss of ductility as well as the increased bubble density. These reduction in area values may not apply to thicker specimens.

[b]Specimens were loaded in autoclaves (fitted with creep stands) which were first evacuated to 10^{-3} torr, brought to the prescribed temperature in a split furnace and loaded with hydrogen to the prescribed pressure.

[c]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Specimens were taken from the surface of 12-inch thick plate. Heat treatment: austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched. The microstructure was bainitic with no proeutectoid ferrite.

EFFECT OF HEAT TREATMENT[a] ON LOAD RELAXATION OF 2-1/4 Cr-1 Mo STEEL[b][61,62]

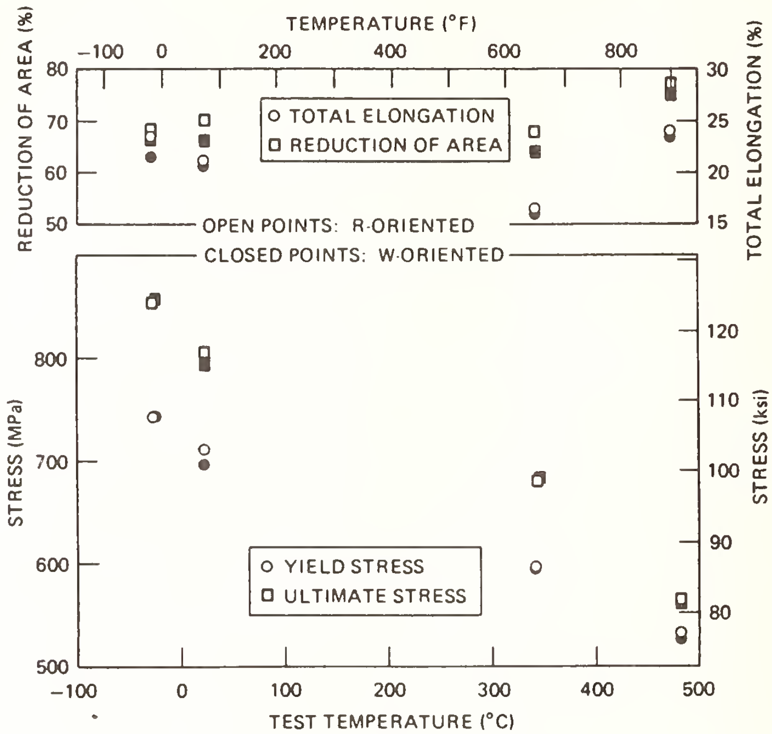




[a]N + T = normalized and tempered, austenitized at 1675 °F for 12 hours, air cooled, tempered at 1275 °F for 12 hours, and air cooled. Microstructure was bainitic with proeutectoid ferrite. Q + T = quenched and tempered, austenitized at 1675 °F for 12 hours, water quenched, tempered at 1275 °F for 8 hours, and water quenched. Microstructure was bainitic only.

[b]A387 Grade 22 steel. Analysis (wt %): 0.13 C, 0.52 Mn, 0.10 P, 0.10 S, 0.23 Si, 0.18 Ni, 2.23 Cr, 0.95 Mo, 0.021 Al, balance Fe. Specimens were taken from the surface of 12-inch thick plate. Round tension specimens, 19 mm gauge length, 1.8 mm gauge diameter, were used.

TENSILE PROPERTIES[a] OF Ni-Cr-Mo LOW ALLOY STEEL THICK PLATE[b][35]



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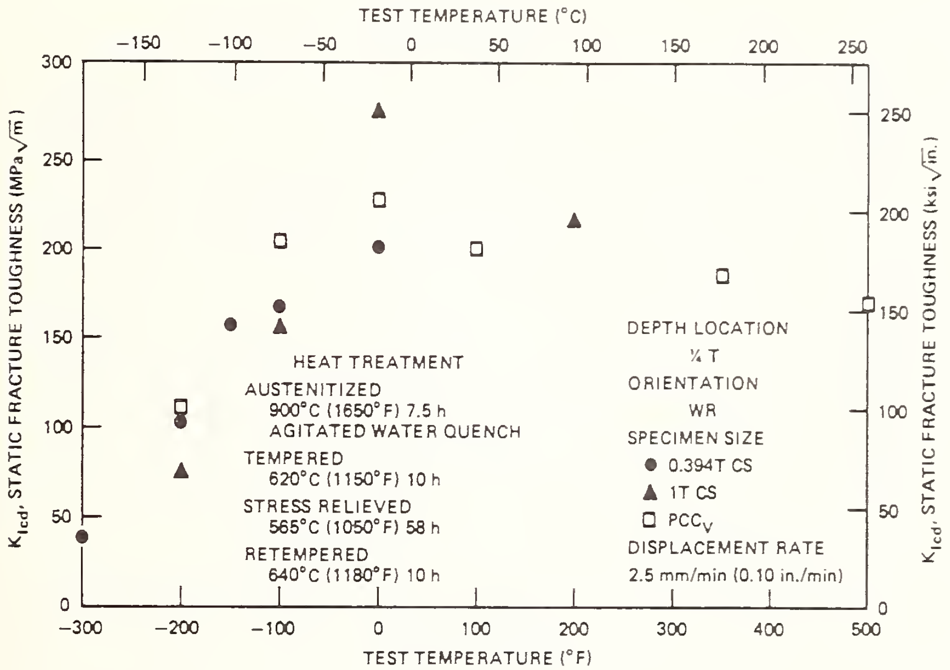
[a]See Section B.3.1.45 for these data in tabular form.

[b]A543 Class 1 steel; 248 mm (9 3/4 in.) thick plate; specimens were removed from the 1/4-thickness depth.

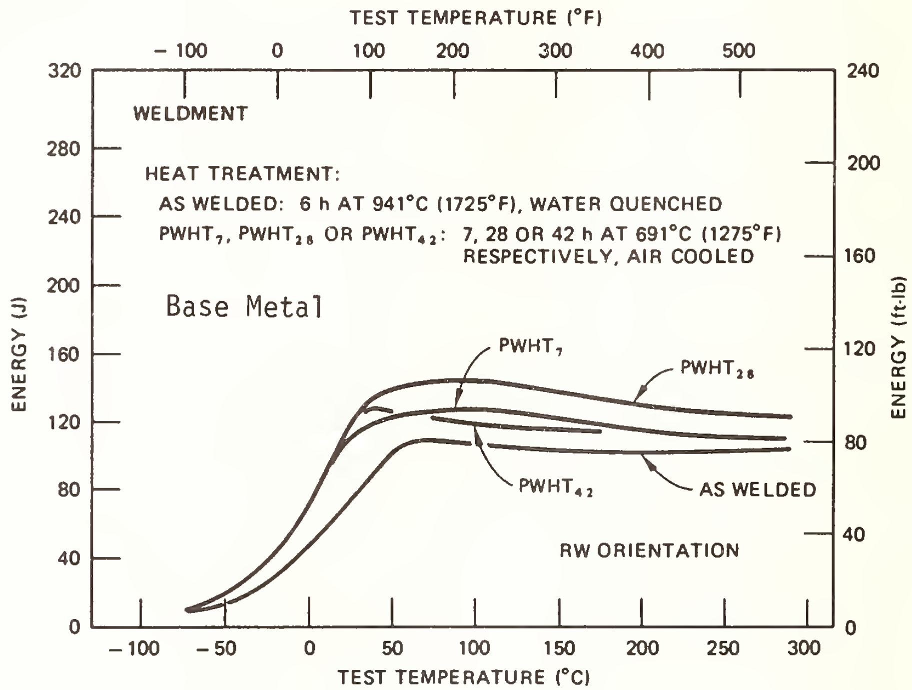
VARIATION OF STATIC FRACTURE TOUGHNESS[a] WITH TEMPERATURE FOR Ni-Cr-Mo LOW ALLOY STEEL THICK PLATE[b] [35]

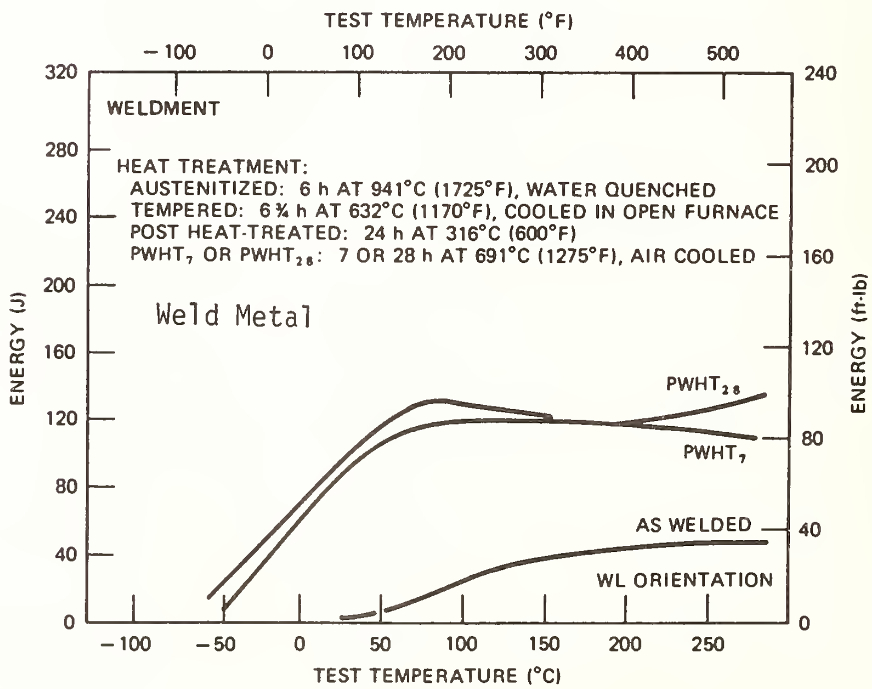


[a] See Section B.3.1.42 for data plotted here for 1/4-thickness location. CS = compact specimen, PCC_V = precracked Charpy v-notch data.

[b] A543 Class 1 steel; 248 mm (9 3/4 in.) thick plate.

EFFECT OF POST WELD HEAT TREATMENT[a] ON CHARPY V-NOTCH IMPACT PROPERTIES OF A SUBMERGED ARC WELD[b] IN THICK 2-1/4 Cr-1 Mo STEEL PLATE[c][35]





(Data Continued)

EFFECT OF POST WELD HEAT TREATMENT[a] ON CHARPY V-NOTCH IMPACT PROPERTIES OF A SUBMERGED ARC WELD[b] IN THICK 2-1/4 Cr-1 Mo STEEL PLATE[c][35], Continued

Condition[a]	Temperature, °C (°F): 68-J(50 ft-lb) Transition Temperature	0.89 mm(35 mil) Lateral Expansion	50% Shear	100% Shear	Upper-Shelf Energy at 149°C(300°F): J	ft-lb
BASE PLATE[d]						
As welded	22 (70)	27 (80)	24 (75)	66 (150)	102	75
PWHT, 7 h	- 1 (30)	4 (40)	18 (65)	32 (90)	122	90
PWHT, 28 h	- 1 (30)	- 7 (20)	18 (65)	27 (80)	140	103
PWHT, 42 h	- 1 (30)	- 1 (30)	10 (50)	38 (100)	117	86
WELD METAL[e]						
As welded	77 (170)[f]	96 (205)[f]	129 (265)	177 (350)	48	34
PWHT, 7 h	7 (45)	10 (50)	13 (55)	66 (150)	121	89
PWHT, 28 h	2 (35)	2 (35)	2 (35)	82 (180)	122	90

[a]Metallurgical condition as follows. As welded denotes austenitization at 941 °C (1725 °F) for 6 hours, water quenching, tempering at 632 °C (1170 °F) for 6.75 hours, cooling in an open furnace. Finished weldment was post weld hydrogen treated (referred to in fugure as post heat treated) at 316 °C (600 °F) for 25 hours. PWHT denotes postweld heat treatment for 7, 28, or 42 hours at 691 °C (1275 °F).

[b]Weldment fabricated by Chicago Bridge and Iron Company.

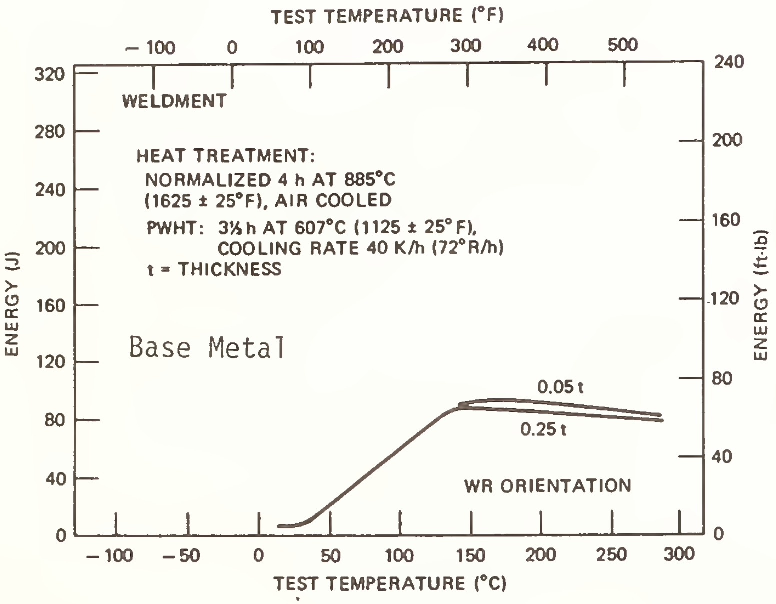
[c]A387 Grade 22 Class 2 steel; 286 mm (11 1/4 in.) plate supplied by Lukens.

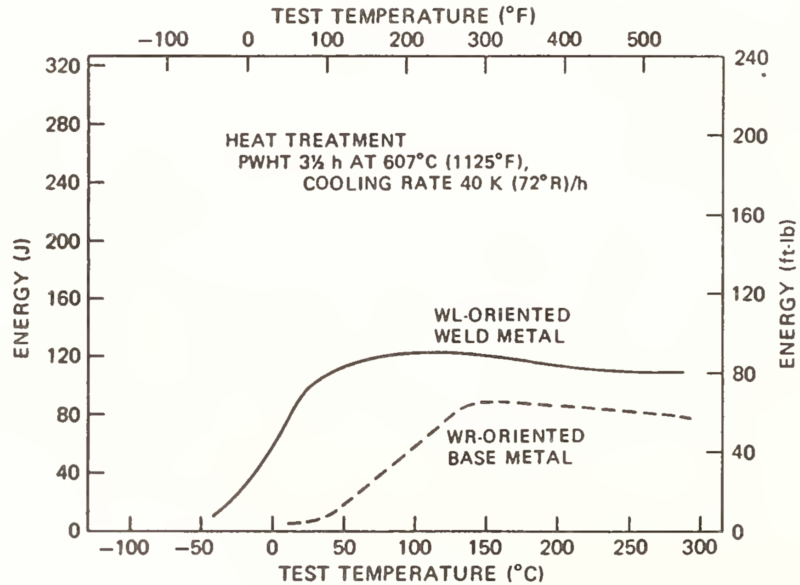
[d]RW orientation, specimen axis parallel to major rolling direction (R) and fracture perpendicular to R.

[e]WL orientation, specimen axis perpendicular to welding direction (L) and fracture parallel to L.

[f]14-J (10 ft-lb) transition temperature; 0.25 mm (10 mil) lateral expansion. Material in this condition did not achieve 68-J energy level.

CHARPY V-NOTCH DATA FOR WELDMENT[a] IN LOW ALLOY STEEL THICK PLATE[b][35,74]





	Specimen Depth[c]	Temperature, °C (°F): 41-J (30 ft-lb) Transition Temperature	Temperature, °C (°F): 0.89 mm (35 mil) Lateral Expansion	Upper-Shelf Energy at 204 °C (400 °F): J	Upper-Shelf Energy at 204 °C (400 °F): ft-lb
Base Metal	0.05t	79 (175)	85 (185)	91	67
Base Metal	0.25t	77 (170)	91 (195)	86	63
Weld Metal	d	-12 (10)	- 7 (20)	114	84

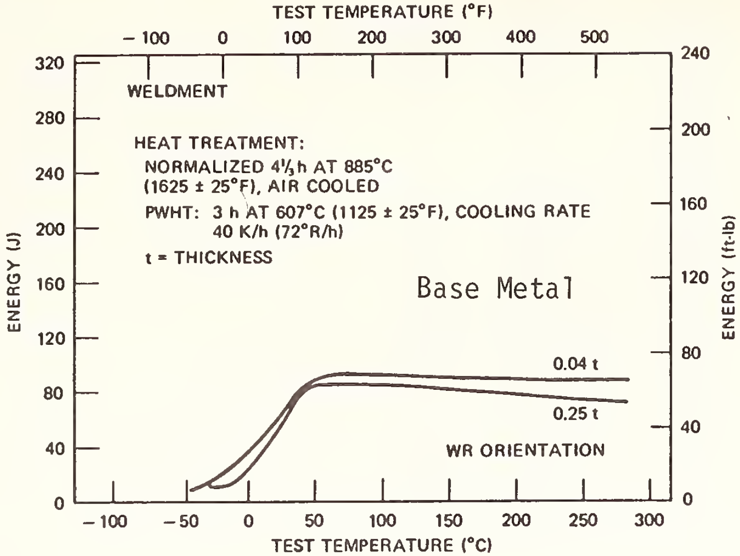
[a] Submerged arc weldment by Chicago Bridge and Iron Company.

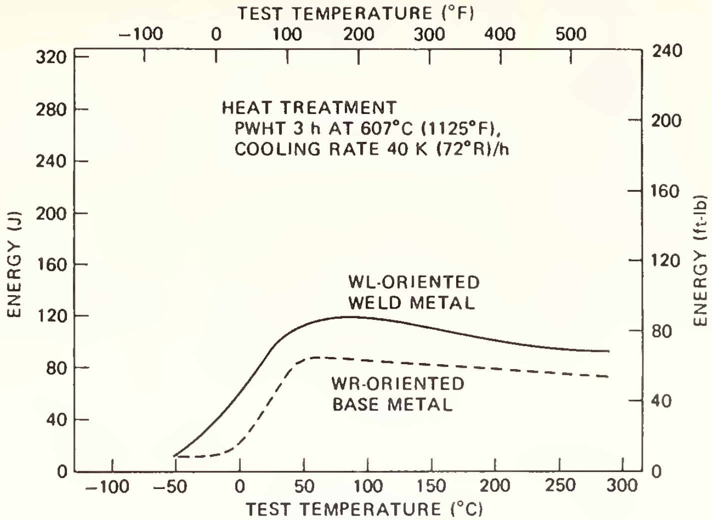
[b] SA204 Grade B steel (C-1/2 Mo) supplied by Bethlehem Steel Company; 152 mm (6 in.) thick plate. See figures for heat treatment. Orientation: WR = specimen axis transverse to major rolling direction (R) and fracture parallel to R; WL = specimen axis perpendicular to welding direction (L) and fracture parallel to L.

[c] t = plate thickness.

[d] Specimens distributed along centerline of weld.

CHARPY V-NOTCH DATA FOR WELDMENT[a] IN CARBON STEEL THICK PLATE[b][35,74]





	Specimen Depth[c]	Temperature, °C (°F) 41-J (30 ft-lb) Transition Temperature	Temperature, °C (°F) 0.89 mm (35 mil) Lateral Expansion	Upper-Shelf Energy at 204 °C (400 °F) J	Upper-Shelf Energy at 204 °C (400 °F) ft-lb
Base Metal	0.04t	7 (45)	18 (65)	90	66
Base Metal	0.25t	16 (60)	24 (75)	79	58
Weld Metal	d	-15 (5)	- 1 (30)	100	74

[a] Submerged arc weldment by Chicago Bridge and Iron Company.

[b] SA516 Grade 70 steel supplied by U.S. Steel; 156 mm (6 1/8 in.) thick plate. See figures for heat treatment. Orientation: WR = specimen axis transverse to major rolling direction (R) and fracture parallel to R; WL = specimen axis perpendicular to welding direction (L) and fracture parallel to L.

[c] t = plate thickness.

[d] Specimens distributed along centerline of weld.

TENSILE PROPERTIES[a] OF BASE AND WELD METAL FROM WELDMENT[b] IN LOW ALLOY STEEL THICK PLATE[c] [35,74]

Test Temperature °C (°F)	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)	Ductility, % Total Elongation[d] L/D = 7	L/D = 4	Reduction in Area
		BASE METAL			
-73 (-100)	373(54.1)	573(83.2)	24.8	30.4	51
-18 (0)	306(44.4)	532(77.2)	23.2	28.7	54
27 (80)	278(40.4)	501(72.7)	27.0[e]	29.0	53
93 (200)	278(40.3)	504(73.2)	15.6	18.8	50
177 (350)	287(41.6)	608(88.3)	11.6	13.9	40
260 (500)	260(37.8)	619(89.8)	16.5	20.1	37
343 (650)	260(37.8)	544(79.0)	19.9	26.0	50
		WELD METAL			
-73 (-100)	542(78.6)	646(93.8)	20.1	26.4	65
-18 (0)	493(71.6)	607(88.1)	16.4	21.8	62
21 (70)	482(70.0)	584(84.8)	16.1	21.6	65
93 (200)	473(68.6)	575(83.4)	14.6	19.8	64
177 (350)	452(65.6)	562(81.6)	11.7	16.7	64
260 (500)	450(65.3)	586(85.0)	12.3	17.0	63
343 (650)	428(62.1)	587(85.2)	16.3	21.5	66

[a] Average of two specimens; W-oriented (specimen axis transverse to rolling direction); 0.016/minute strain rate. Specimens from 1/4-thickness location.

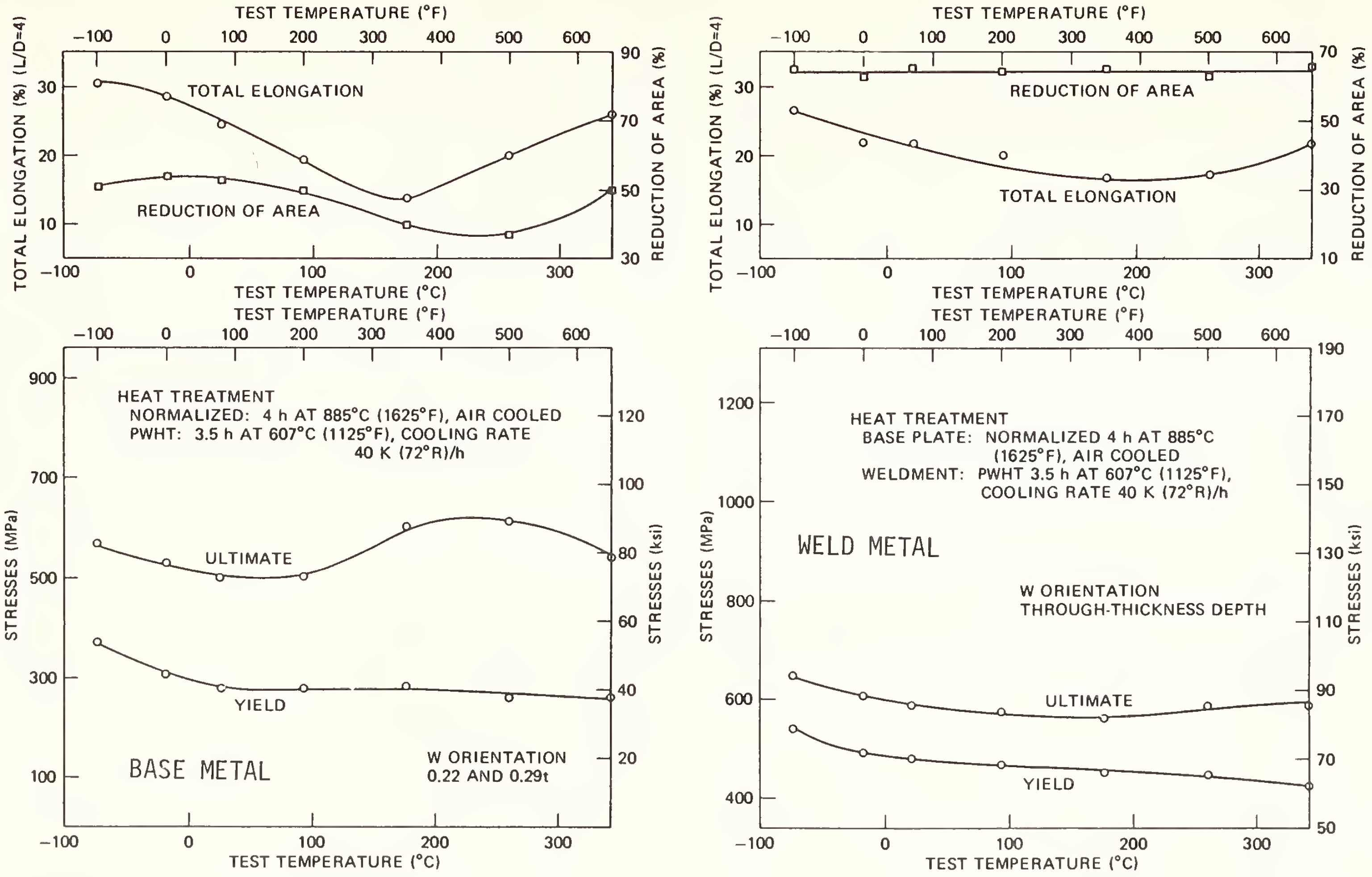
[b] Submerged arc weldment by Chicago Bridge and Iron Company.

[c] SA204 Grade B steel supplied by Bethlehem Steel Company; 152 mm (6 in.) plate. Heat treatment: austenitized at 885 °C (1625 °F) for 4 hours, air cooled, postweld heat treatment (PWHT) at 607 °C (1125 °F) for 3.5 hours, cooled 40 K/h (72 °R/h).

[d] L/D = gauge length/gauge diameter; L/D = 4 was calculated from L/D = 5 or 7.

[e] L/D = 5; rest of data L/D = 7.

TENSILE PROPERTIES[a] VERSUS TEMPERATURE OF BASE AND WELD METAL FROM WELDMENT IN LOW ALLOY STEEL THICK PLATE[35,74]



[a]See Section B.3.1.132 for the data plotted here.

TENSILE PROPERTIES[a] OF BASE AND WELD METAL FROM WELDMENT[b] IN CARBON STEEL THICK PLATE[c] [35,74]

Test Temperature °C (°F)	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)	Ductility, % Total Elongation[d] L/D = 7	Ductility, % Total Elongation[d] L/D = 4	Ductility, % Reduction in Area
BASE METAL					
-73 (-100)	409(59.3)	587(85.2)	26.2	29.2	52
-18 (0)	327(47.4)	537(77.9)	25.4	30.9	56
27 (80)	288(41.8)	508(73.8)	27.9[e]	30.4	54
93 (200)	284(41.2)	481(69.8)	22.5	27.5	55
177 (350)	242(35.0)	466(67.6)	22.4	27.3	61
260 (500)	207(30.1)	501(72.7)	22.7	27.8	54
343 (650)	208(30.2)	494(71.7)	25.1	32.8	61
WELD METAL					
-73 (-100)	550(79.9)	657(95.4)	19.2	24.5	64
-18 (0)	528(76.6)	630(91.4)	16.5	22.0	62
21 (70)	520(75.4)	627(90.9)	15.7	21.2	62
93 (200)	470(68.1)	584(84.6)	13.8	19.0	64
177 (350)	409(59.4)	562(81.6)	7.5	9.1	34
260 (500)	392(56.9)	587(85.2)	12.4	15.4	49
343 (650)	413(60.0)	586(85.0)	13.4	17.6	55

[a] Average of two specimens; W-oriented (specimen axis transverse to rolling direction; 0.016/minute strain rate. Specimens at 1/4-thickness location.

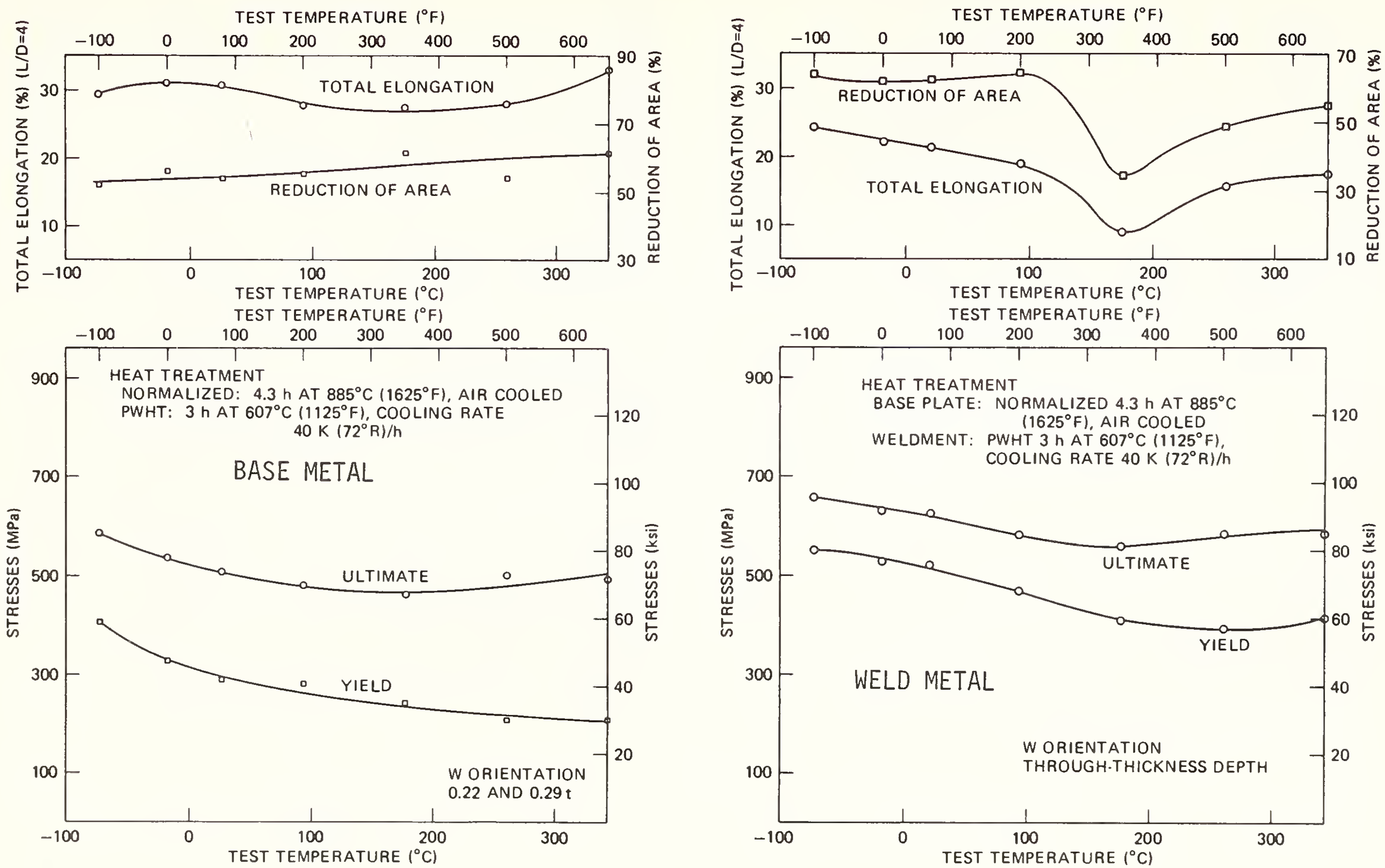
[b] Submerged arc weldment by Chicago Bridge and Iron Company.

[c] SA516 Grade 70 steel supplied by U.S. Steel; 156 mm (6 1/8 in.) thick plate. Heat treatment: Austenitized at 885 °C (1625 °F) for 4.3 hours, air cooled, postweld heat treatment (PWHT) at 607 °C (1125 °F) for 3 hours, cooled 40 K/h (70 °R/h).

[d] L/D = gauge length/guage diameter; L/D = 4 was calculated from L/D = 5 or 7.

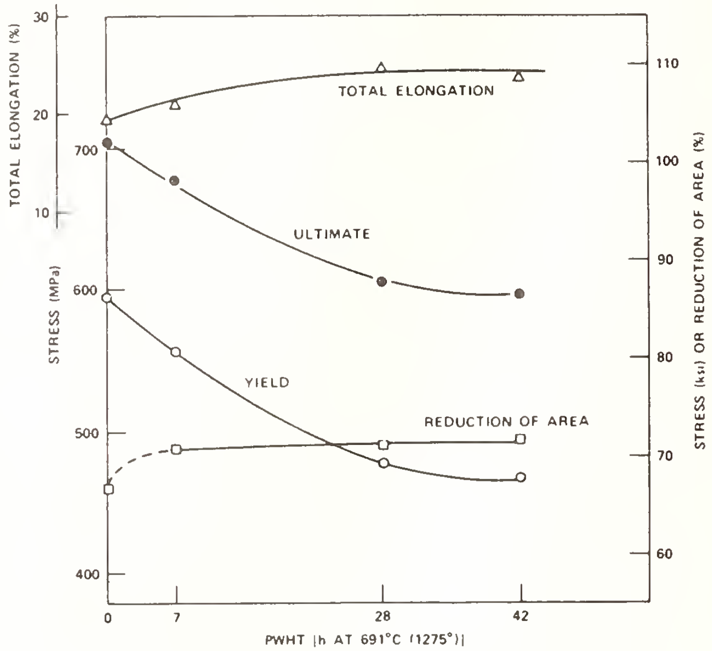
[e] L/D = 5; rest of data L/D = 7.

TENSILE PROPERTIES[a] VERSUS TEMPERATURE OF BASE AND WELD METAL FROM WELDMENT IN CARBON STEEL THICK PLATE[35,74]



[a] See Section B.3.1.134 for the data plotted here.

EFFECT OF POST WELD HEAT TREATMENT[a] ON THE TENSILE PROPERTIES[b] OF 2-1/4 Cr-1 Mo BASE STEEL[c] OF WELDMENT[d] [35,74]



Post Weld Heat Treatment[a] hours	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)	Ductility, %		
			Total Elongation[e] L/D = 7	L/D = 4	Reduction in Area
0	595(86.2)	707(102.)	13.4	19.2	67
7	558(80.8)	678(98.2)	14.7	20.9	71
28	476(69.2)	606(87.8)	17.3	24.4	71
42	467(67.8)	596(86.5)	16.8	23.8	72

[a] Postweld heat treatment (PWHT): 7, 28, or 42 hours at 691 °C (1275 °F), and air cooled.

[b] Average of two specimens; R-oriented (R = rolling directions); 0.016/minute strain rate; tests at 21 °C.

[c] SA387 Grade 22 Class 2 steel; 286 mm (11 1/4 in.) plate, supplied by Lukens.

[d] Submerged arc weld fabricated by Chicago Bridge and Iron Company.

[e] L/D = ratio of gauge length to gauge diameter. Values in the L/D = 4 column were calculated from L/D = 7 data.

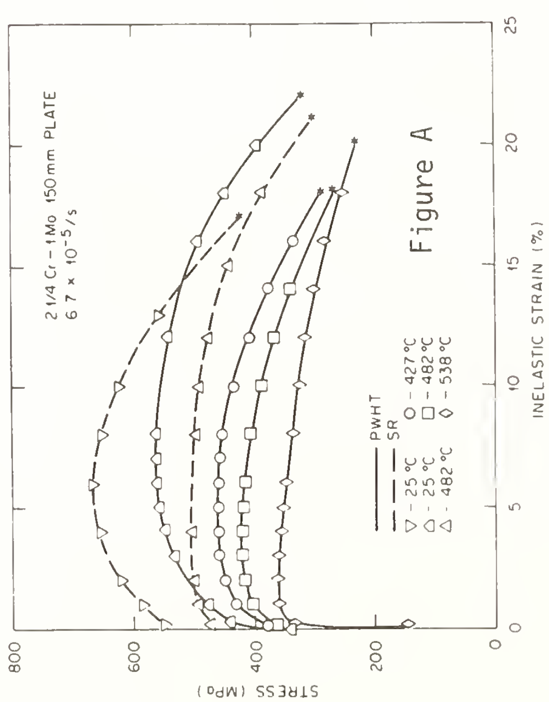
CREEP FATIGUE TESTS[a] OF 2-1/4 Cr-1 Mo STEEL[b][75]

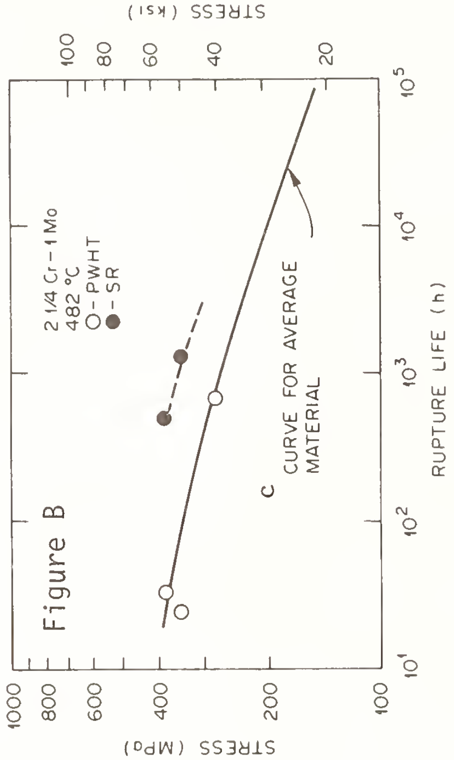
Sample	Total Strain Range, %	Hold Time hours	Stress Range MPa	Stress Range ksi	Cycles to Failure
1	2.0	None	724	105.	645
2	1.0	None	648	94.	2,465
3	0.6	None	552	80.	24,554
4	0.45	None	504	73.1	56,366
5	0.35	None	476	69.0	500,145
6	2.0	0.01 compression	709	102.8	581
7	2.0	0.1 compression	723	104.8	483
8	2.0	0.1 tension	748	108.5	324

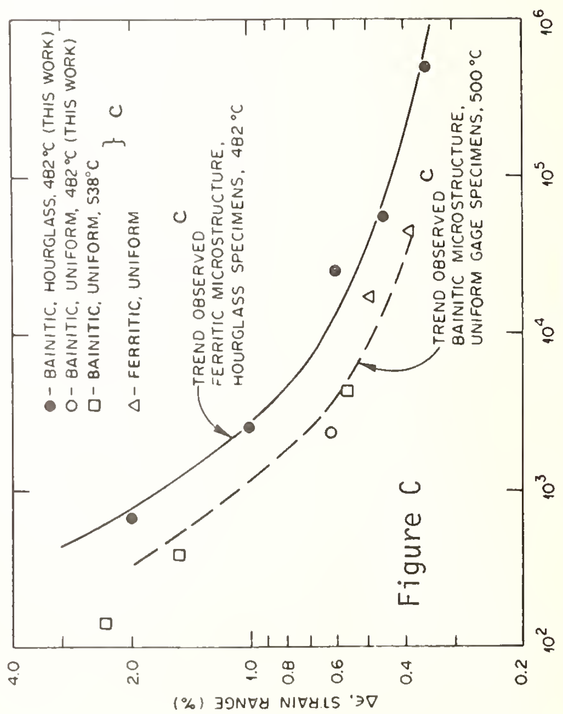
[a] Continuous cycling fatigue testing at 482 °C. [Data were labelled exploratory by original authors.]

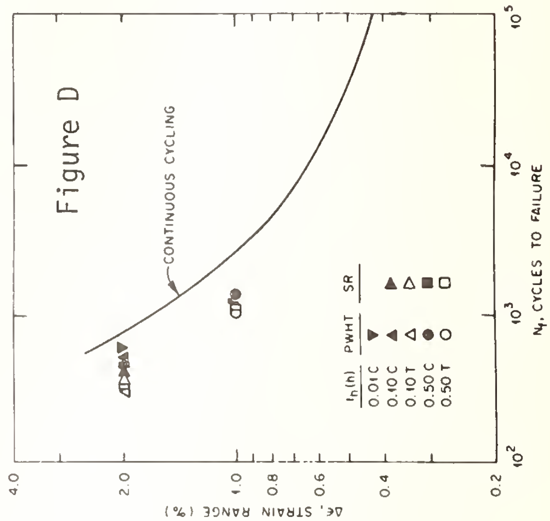
[b] SA387 Grade 22 Class 2. Specimens machined from 150 mm plate. Normalized and tempered. Simulated postweld heat treatment at 690 °C for 28 hours.

STRESS-STRAIN, CREEP RUPTURE, FATIGUE, AND CREEP-FATIGUE DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b][75]



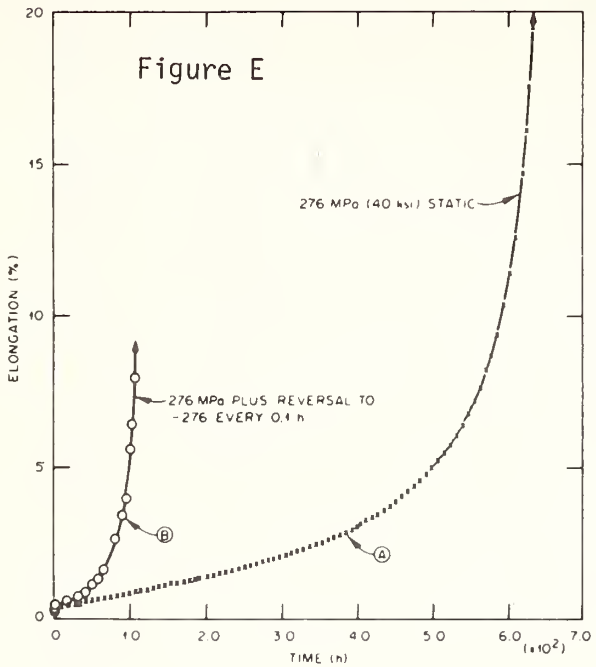






(Data Continued)

STRESS-STRAIN, CREEP RUPTURE, FATIGUE, AND CREEP-FATIGUE DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b][75], Continued



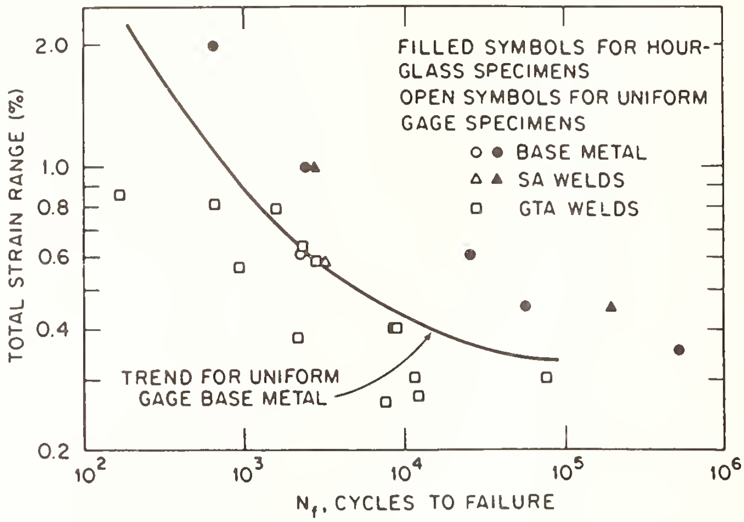
Footnotes

[a]Data for two material conditions shown: stress-relieved (SR) at 662 °C for 6 hours, and simulated post weld heat treated (PWHT) at 690 °C for 28 hours.
- Figure A shows stress-strain data for several temperatures.
- Figure B shows creep rupture data. Symbols are experimental points and the line is from literature data.
- Figure C is continuous cycling fatigue data (log strain range versus log cyclic life) for both uniform and hourglass specimens in post weld heat treated (PWHT) condition. Data from the literature are added. The solid curve represents data for specimens tested at 1 to 4 x 10^{-3}/s. The dashed curve is for data taken at a strain rate of 10^{-3}/s.
- Figure D shows the effect of hold time on strain fatigue behavior. T = tension, C = compression.
- Figure E shows the effect of stress reversals on creep-rupture behavior. Curve A is for an accelerated test at 276 MPa at 482 °C (time to 1% strain = ∿120 hours, time to failure = ∿630 hours). Curve B is for tests in which a reversed stress (-276 MPa) was introduced every 0.1 hour.

[b]SA387 Grade 22 Class 2; 150 mm plate.

[c]Literature data.

FATIGUE DATA[a] FOR WELDMENTS[b] IN 2-1/4 Cr-1 Mo STEEL[c][75]



[a]Continuous cycling fatigue tests at 482 °C on uniform gauge specimens 6.3 mm diameter and 19 mm reduced section [no information given for hourglass specimens]. Variation in data apparently due to strength differences between base metal, weld metal, and heat-affected zone. Specimens included varying amounts of the three.

[b]SA = specimens machined from 300 mm (12 in.) thick submerged arc weldment. GTA = specimens machined from hot wire narrow groove gas tungsten arc weld in 200 mm (8 in.) plate. Specimens were machined from eight thickness levels and two lateral locations relative to the vertical centerline of the weld. Specimens included varying amounts of weld, relative amount of the weld metal in the gauge length varying from 50 to 100%. After machining samples were post weld heat treated at 690 °C for 20 hours.

[c]SA387 Grade 22 Class 2; 150 mm plate.

EFFECT OF COOLING RATE, TEMPERING, AND POST WELD HEAT TREATMENT ON CHARPY IMPACT DATA FOR 2-1/4 Cr-1 Mo STEELS[a] WITH DIFFERENT CARBON CONTENT[b][35]

Metallurgical Condition[c]	Quench Rate after Austenitization K/s	°R/s	Temperature, °C (°F) 54-J(40 ft-lb) Transition Temperature	0.89 mm(35 mil) Lateral Expansion	Upper-Shelf Energy at 149°C(300°F) J	ft-lb
			0.14% Carbon[b]			
Q	0.2	0.3	57 (135)[d]	88 (190)[d]	56	41
Q, T	0.2	0.3	16 (60)	16 (60)	78	57
Q, T, $PWHT_{24}$	0.2	0.3	2 (35)	- 1 (30)	114	84
Q, T, $PWHT_{48}$	0.2	0.3	- 4 (25)	- 4 (25)	109	80[e]
Q	0.3	0.6	32 (90)[d]	79 (175)[d]	57	42
Q, T	0.3	0.6	13 (55)	32 (90)	78	57
Q, T, $PWHT_{24}$	0.3	0.6	- 7 (20)	- 7 (20)	114	84
Q, T, $PWHT_{48}$	0.3	0.6	-12 (10)	-18 (0)	107	79
			0.12% Carbon[b]			
Q	0.2	0.3	35 (95)[d]	66 (150)[d]	34	25
Q, T	0.2	0.3	- 9 (15)	-15 (5)	71	52
Q, T, $PWHT_{24}$	0.2	0.3	2 (35)	4 (40)	88	65
Q, T, $PWHT_{48}$	0.2	0.3	4 (40)	- 1 (30)	98	72
Q	0.3	0.6	49 (120)[d]	66 (150)[d]	34	25
Q, T	0.3	0.6	29 (85)	-15 (5)	67	49
Q, T, $PWHT_{24}$	0.3	0.6	4 (40)	4 (40)	91	67
Q, T, $PWHT_{48}$	0.3	0.6	- 4 (25)	- 1 (30)	92	68

[a]SA387 Grade 22 steel, supplied by Lukens. Austenitized 30 minutes at 927 °C.

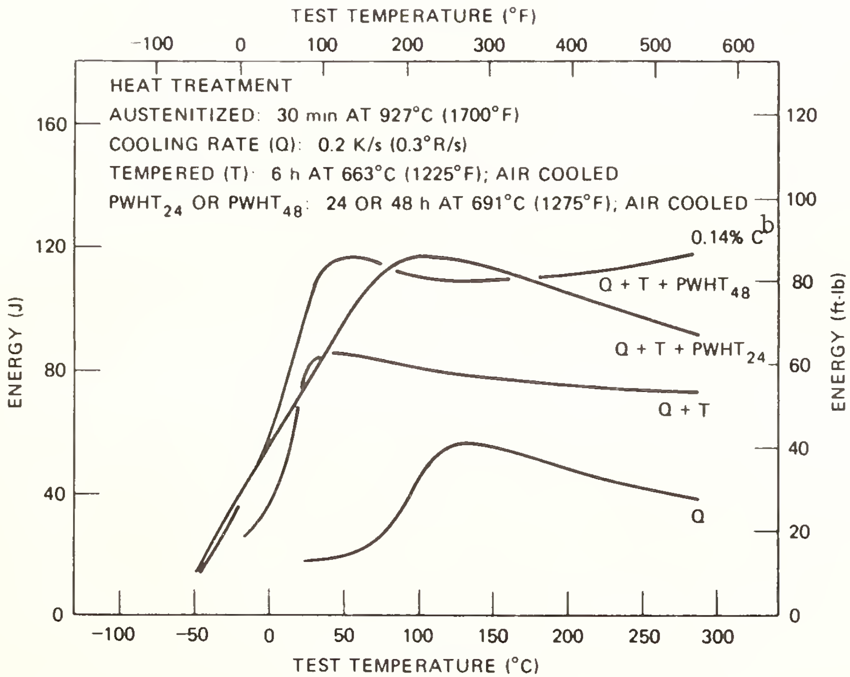
[b]Two different heats were supplied with the same amounts of other constituents but one heat contained 0.14% carbon, the other 0.12% carbon.

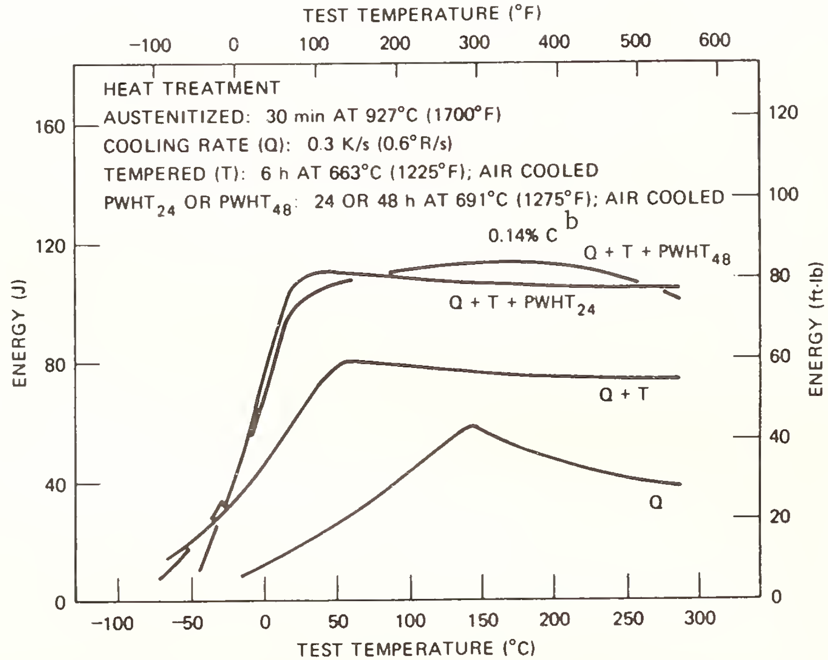
[c]After austenitization materials were given varied heat treatments. A device called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific depth locations in thick steel plates that have been annealed or quenched by subjecting the specimens to a preselected thermal 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. Treatments were in air on 127 mm long and 13mm square bars. Q denotes quench rate simulated by DATA TRAK; T denotes tempered at 663 °C (1225 °F) for 6 hours, followed by air cooling; PWHT denotes post weld heat treatment for 24 or 48 hours at 691 °C (1275 °F), followed by air cooling. Cooling rates represent those of 1/4 thickness depth of 406 mm (16 in.) and 305 mm (12 in.) thick plate water quenched.

[d]20-J (15 ft-lb) transition temperature; 0.38 mm (15 mil) lateral expansion.

[e]All upper-shelf energies except the $PWHT_{48}$ decreased after the 149 °C comparison temperature.

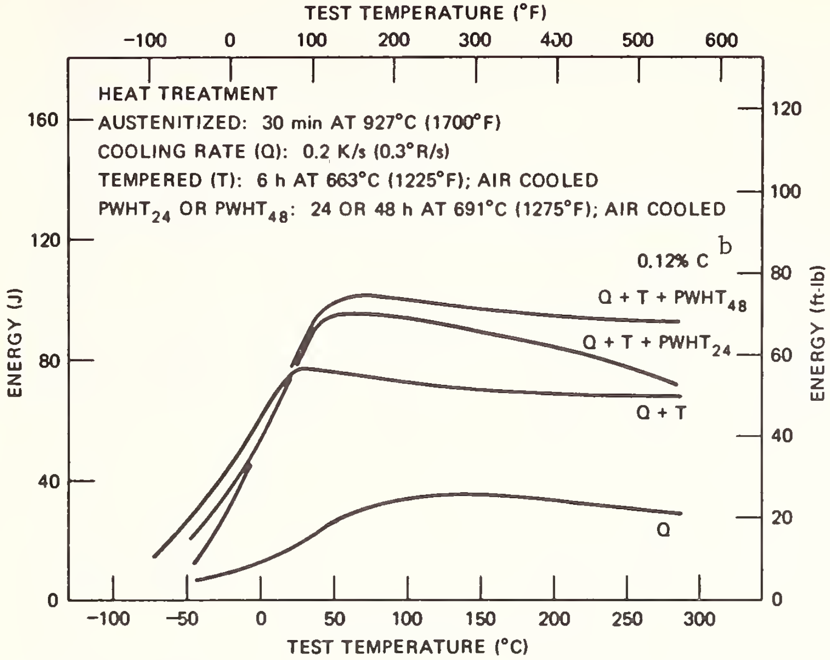
CHARPY V-NOTCH DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b] AFTER VARIOUS PROCESSING HEAT TREATMENTS[c][35]

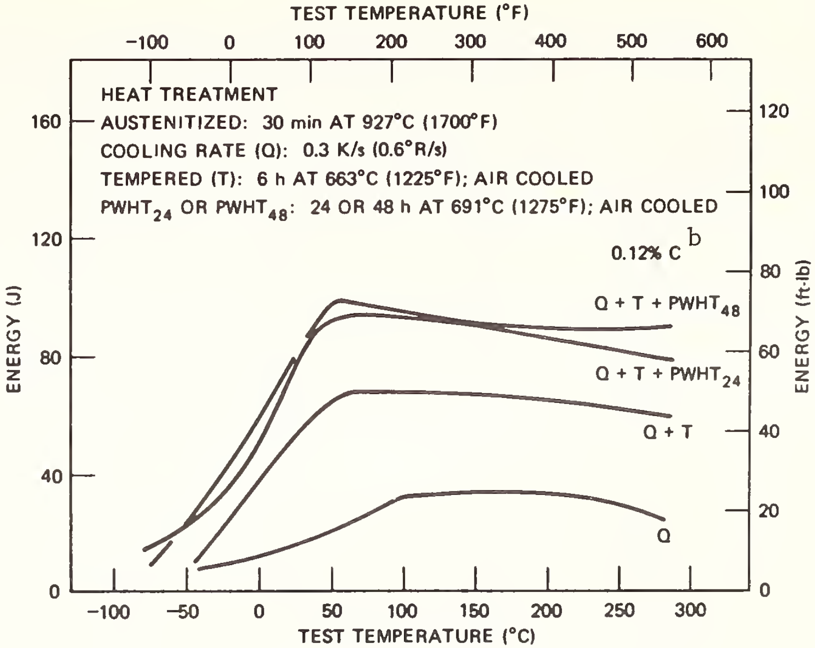




(Data Continued)

CHARPY V-NOTCH DATA[a] FOR 2-1/4 Cr-1 Mo STEEL[b] AFTER VARIOUS PROCESSING HEAT TREATMENTS[c][35], Continued





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[a] See Section B.3.1.140 for data plotted here.

[b] SA387 Grade 22 steel supplied by Lukens. Two different heats were supplied with the same amounts of other constituents but one heat contained 0.14% carbon, the other 0.12% carbon.

[c] See B.3.1.140 for details of heat treatment.

EFFECT OF COOLING RATE, TEMPERING, AND POST WELD HEAT TREATMENT ON TENSILE PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEELS[b] WITH DIFFERENT CARBON CONTENT[c] [35]

Metallurgical Condition[d]	Quench Rate[e] K/s	Quench Rate[e] °R/s	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)	Ductility, % Total Elongation[f] L/D = 7	Ductility, % Total Elongation[f] L/D = 4	Ductility, % Reduction in Area	Rockwell Hardness
0.14% Carbon[c]								
Q	0.2	0.3	778(113.)	1062(154.)	11.0	14.5	45	27.7[g]
Q, T	0.2	0.3	578(83.9)	705(102.)	14.1	19.8	67	96.1
Q, T, $PWHT_{24}$	0.2	0.3	436(63.2)	582(84.4)	18.1	24.5	69	88.3
Q, T, $PWHT_{48}$	0.2	0.3	385(55.8)	537(77.8)	21.6	28.6	70	85.6
Q	0.3	0.6	816(118.)	1097(159.)	11.9	16.6	53	33.6[g]
Q, T	0.3	0.6	616(89.4)	742(108.)	15.1	21.3	66	97.0
Q, T, $PWHT_{24}$	0.3	0.6	441(63.9)	577(83.6)	19.0	26.0	72	88.0
Q, T, $PWHT_{48}$	0.3	0.6	408(59.2)	556(80.6)	23.6	31.5	72	85.8
0.12% Carbon[c]								
Q	0.2	0.3	641(93.0)	882(128.)	11.4	14.2	36	21.0[g]
Q, T	0.2	0.3	440(63.7)	606(87.9)	17.1	23.0	61	88.3
Q, T, $PWHT_{24}$	0.2	0.3	375(54.3)	525(76.1)	21.3	27.6	58	83.7
Q, T, $PWHT_{48}$	0.2	0.3	369(53.5)	518(75.1)	21.1	27.7	66	80.9
Q	0.3	0.6	737(107.)	995(145.)	10.3	13.8	46	30.0[g]
Q, T	0.3	0.6	554(80.4)	669(97.0)	13.8	18.8	60	92.7
Q, T, $PWHT_{24}$	0.3	0.6	423(61.3)	556(80.6)	19.6	26.5	67	85.6
Q, T, $PWHT_{48}$	0.3	0.6	389(56.4)	523(75.9)	22.2	29.4	68	83.4

[a] Average of two specimens.

[b] SA387 Grade 22 steel supplied by Lukens. Austenitized 30 minutes at 927 °C.

[c] Two different heats were supplied with the same amounts of other constituents but one heat contained 0.14% carbon, the other 0.12% carbon.

[d] After austenitization materials were given varied heat treatments. 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 the specimens to a preselected thermal cycle. Tungsten filament quartz lamps are the heat source; cooling is by gas flowing directly

(Data Continued)

EFFECT OF COOLING RATE, TEMPERING, AND POST WELD HEAT TREATMENT ON TENSILE PROPERTIES[a] OF 2-1/4 Cr-1 Mo STEELS[b] WITH DIFFERENT CARBON CONTENT[c][35], Continued

Footnotes continued

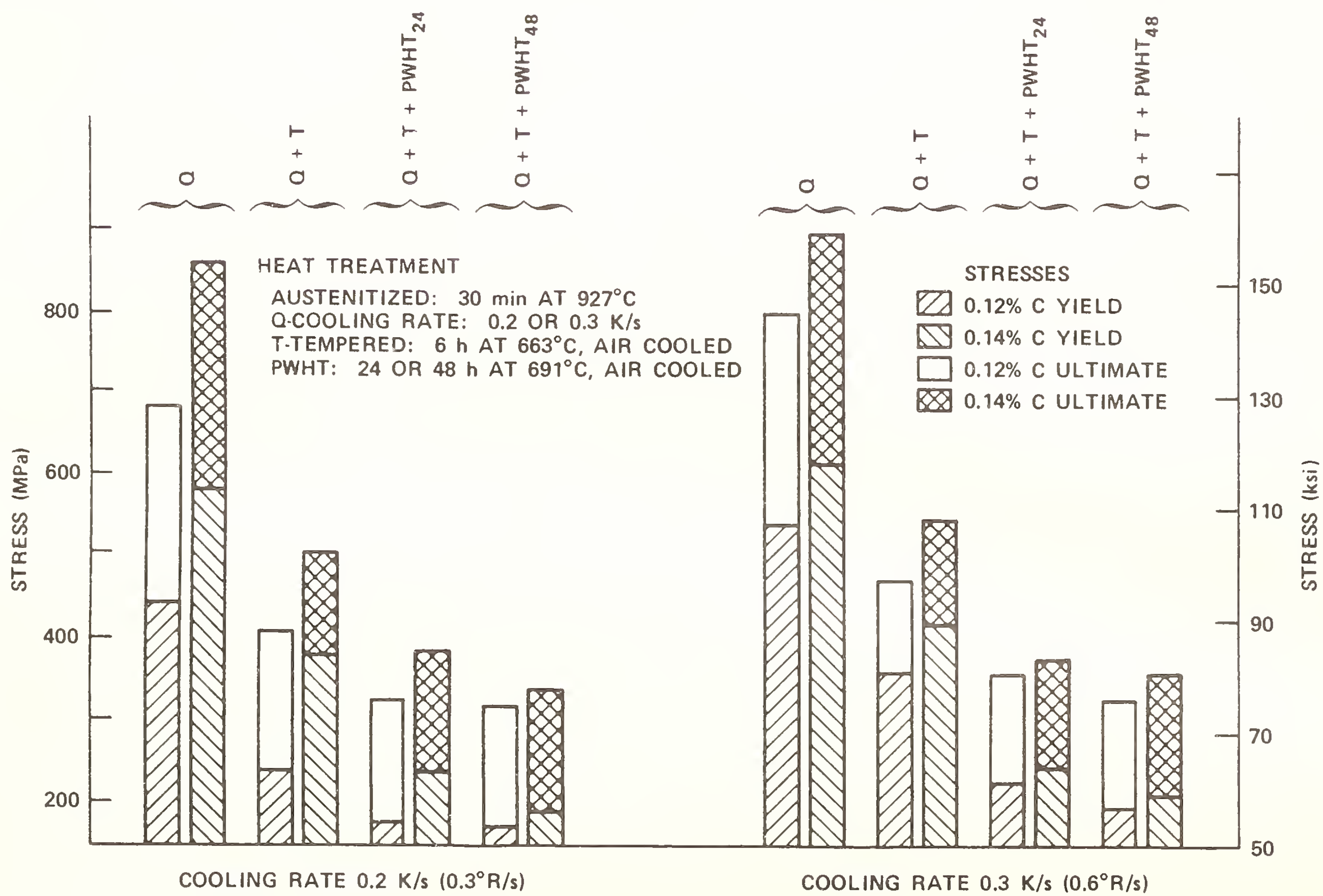
on the specimen while addition radiant "make-up heat" maintains the desired cooling rate. Treatments were in air on 127 mm long and 13 mm square bars. Q denotes quench rate simulated by DATA TRAK; T denotes tempered at 663 °C (1225 °F) for 6 hours, followed by air cooling; PWHT denotes post weld heat treatment for 24 or 48 hours at 691 °C (1275 °F), followed by air cooling. Cooling rates represent those of 1/4 thickness depth of 406 mm (16 in.) and 305 mm (12 in.) thick plate water quenched.

[e]After austenitization.

[f]L/D = ratio of gauge length to gauge diameter. The values in the L/D = 4 column were calculated from the L/D = 7 data; strain rate is 0.016/minute.

[g]Rockwell "C" scale; rest of values are on Rockwell "B" scale.

TENSILE PROPERTIES[a] FOR 2-1/4 Cr-1 Mo STEEL[b] AFTER VARIOUS PROCESSING HEAT TREATMENTS[c][35]



[a]See Section B.3.1.142 for data plotted here.

[b]SA387 Grade 22 steel supplied by Lukens. Two different heats were supplied with the same amounts of other constituents but one heat contained 0.14% carbon, the other 0.12% carbon.

[c]See Section B.3.1.142 for details of heat treatment.

COMPARISON OF WELD METAL AND BASE METAL TEST DATA[a] FOR A 2-1/4 Cr-1 Mo STEEL[b] WELDMENT[c] [75]

Properties	Weld Metal	Base Metal
Yield Strength, 0.2% offset, MPa	373	365
Ultimate Tensile Strength, MPa	433	419
Rupture Life at 276 MPa, hours	658	639
Fatigue Life at 1% Δe, cycles	2,596	2,465
Fatigue Life at 0.45% Δe, cycles	184,844	56,366
Uniform Gauge Fatigue Life, cycles	3,150	2,260

[a] Tests at 482 °C.

[b] SA387 Grade 22 steel supplied by Lukens; 300 mm plate.

[c] Submerged arc weldment by Chicago Bridge and Iron Company. Material was tested after a 20 hour post weld heat treatment at 692 °C (1275 °F).

EFFECT OF COOLING RATE AND HEAT TREATMENT ON THE TENSILE PROPERTIES[a] OF MODIFIED 2-1/4 Cr-1 Mo STEELS[b][35,74]

Metallurgical Condition[c]	Quench Rate[d] K/s	Quench Rate[d] °R/s	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)	Ductility, % Total Elongation[e] L/D = 7	Ductility, % Total Elongation[e] L/D = 4	Ductility, % Reduction in Area
Vacuum-Carbon-Deoxidized Heat #1[b]							
Q	0.3	0.6	816(118.)	1077(156.)	12.4	18.0	61
Q, T	0.3	0.6	570(82.6)	684(99.2)	16.0	23.2	77
Q, T, $PWHT_{28}$	0.3	0.6	446(64.8)	576(83.4)	18.2	25.8	76
Q	3.	5.	922(134.)	1137(164.)	11.3	17.2	63
Q, T	3.	5.	585(84.8)	699(102.)	16.4	24.1	77
Q, T, $PWHT_{28}$	3.	5.	466(67.7)	586(84.8)	19.6	27.8	78
Vacuum-Carbon-Deoxidized Heat #2[b]							
Q	0.3	0.6	836(122.)	1060(158.)	12.6	18.2	61
Q, T	0.3	0.6	627(91.0)	722(104.)	13.6	20.2	74
Q, T, $PWHT_{28}$	0.3	0.6	477(69.2)	594(86.1)	17.0	24.6	78
Q	3.	5.	942(137.)	1148(166.)	11.4	17.0	65
Q, T	3.	5.	649(94.2)	742(108.)	14.5	21.4	75
Q, T, $PWHT_{28}$	3.	5.	466(67.7)	589(85.4)	18.4	26.4	78
Silicon-Killed Heat #1[b]							
Q	0.3	0.6	807(117.)	1108(161.)	12.1	17.3	59
Q, T	0.3	0.6	599(86.9)	724(105.)	14.9	21.4	76
Q, T, $PWHT_{28}$	0.3	0.6	462(67.0)	600(87.0)	19.0	26.8	75
Q	3.	5.	942(136.)	1164(169.)	12.5	18.6	62
Q, T	3.	5.	616(89.4)	732(106.)	16.4	23.8	77
Q, T, $PWHT_{28}$	3.	5.	478(69.3)	603(87.5)	17.6	24.8	77
Silicon-Killed Heat #2[b]							
Q	0.3	0.6	828(120.)	1092(158.)	13.3	19.0	60
Q, T	0.3	0.6	628(91.1)	739(108.)	15.2	22.1	73
Q, T, $PWHT_{28}$	0.3	0.6	472(68.4)	601(87.2)	18.5	26.0	76
Q	3.	5.	934(136.)	1150(167.)	11.4	16.9	63
Q, T	3.	5.	660(95.7)	761(110.)	14.7	21.6	76
Q, T, $PWHT_{28}$	3.	5.	478(69.4)	610(88.4)	19.0	26.8	77
Silicon-Aluminum-Killed Heat #1[b]							
Q	0.3	0.6	842(122.)	1093(158.)	12.2	17.7	61
Q, T	0.3	0.6	562(81.6)	693(100.)	15.9	22.8	76
Q, T, $PWHT_{28}$	0.3	0.6	442(64.1)	598(86.6)	20.0	27.9	76
Q	3.	5.	942(136.)	1176(170.)	11.5	17.2	64
Q, T	3.	5.	594(86.2)	712(104.)	14.6	21.3	77
Q, T, $PWHT_{28}$	3.	5.	452(65.4)	596(86.4)	20.3	27.8	76

(Table Continued)

EFFECT OF COOLING RATE AND HEAT TREATMENT ON THE TENSILE PROPERTIES[a] OF MODIFIED 2-1/4 Cr-1 Mo STEELS[b][35,74], Continued

Metallurgical Condition[c]	Quench Rate[d] K/s	°R/s	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)	Ductility, %: Total Elongation[e] L/D = 7	L/D = 4	Reduction in Area
Silicon-Aluminum-Killed Heat #2[b]							
Q	0.3	0.6	822(119.)	1098(159.)	12.6	18.0	60
Q, T	0.3	0.6	562(81.4)	694(100.)	16.1	23.2	76
Q, T, PWHT	0.3	0.6	460(66.6)	612(88.7)	20.0	28.0	77
Q	3.	5.	925(134.)	1163(169.)	10.4	15.4	60
Q, T	3.	5.	598(86.7)	715(104.)	15.4	22.4	77
Q, T, PWHT	3.	5.	458(66.4)	602(87.3)	20.4	28.2	77

[a]Average of two specimens; W-orientation (specimen axis transverse to the rolling direction).

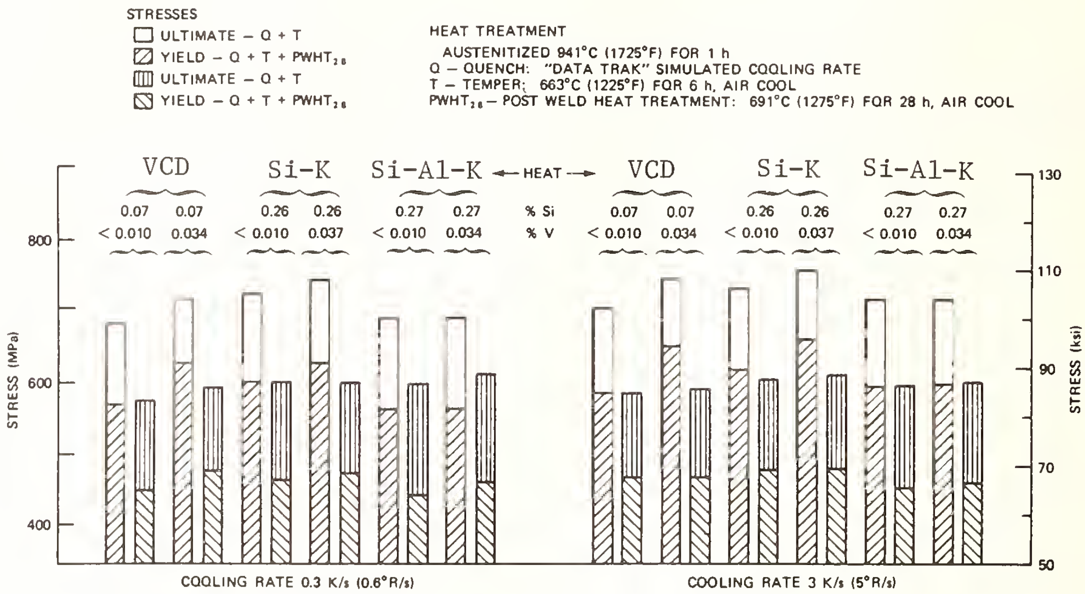
[b]Modified steels by U.S. Steel; plates fabricated from vacuum induction melted heats by three processes. Analyses (wt%):
Vacuum-carbon-deoxidized heat #1--0.16 C, 0.46 Mn, 2.27 Cr, 0.52 Ni, 0.99 Mo, 0.07 Si, <0.010 V, balance Fe.
Vacuum-carbon-deoxidized heat #2--assumed same as heat #1 except 0.034 V.
Silicon-killed heat #1--0.16 C, 0.45 Mn, 2.23 Cr, 0.50 Ni, 0.99 Mo, 0.26 Si, <0.010 V, balance Fe.
Silicon-killed heat #2--assumed same as heat #1 except 0.034 V.
Silicon-aluminum-killed heat #1--0.16 C, 0.46 Mn, 2.18 Cr, 0.51 Ni, 0.99 Mo, 0.27 Si, <0.010 V, balance Fe.
Silicon-aluminum-killed heat #2--assumed same as heat #1 except 0.034 V.

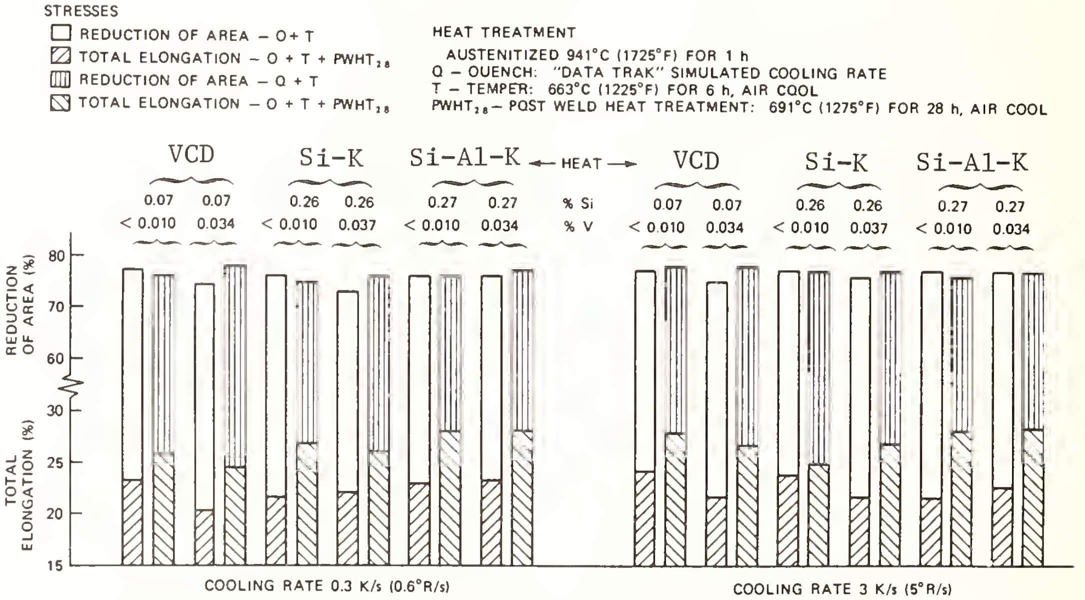
[c]Materials were austenitized at 940 °C (1725 °F) for 1 hour. After austenitization materials were given varied heat treatments. A device called DATA TRAK was used to obtain specimens whose thermal exposure simulates that of specific depth locations in thick steel plates that have been annealed or quenched by subjecting the specimens 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. Treatments were in air on 127 mm long by 13 mm square bars. Q denotes the quench rate simulated by DATA TRAK. Rate of 3 K/s simulates the thermal cycle at the near surface of water quenched 254 to 305 mm thick plate after austenitization. Rate of 0.3 K/s simulates the 1/4 thickness depth condition in 305 mm plate for the same treatment. T denotes temper at 663 °C (1225 °F) for 6 hours followed by air cooling; PWHT denotes post weld heat treatment at 691 °C (1275 °F) for 28 hours, followed by air cooling.

[d]After austenitization.

[e]L/D = ratio of gauge length to gauge diameter. The values in the L/D = 4 column were calculated from L/D = 7 data; strain rate, 0.016/minute.

TENSILE PROPERTIES[a] FOR MODIFIED 2-1/4 Cr-1 Mo STEELS[b] AFTER VARIOUS PROCESSING HEAT TREATMENTS[c] [35,74]





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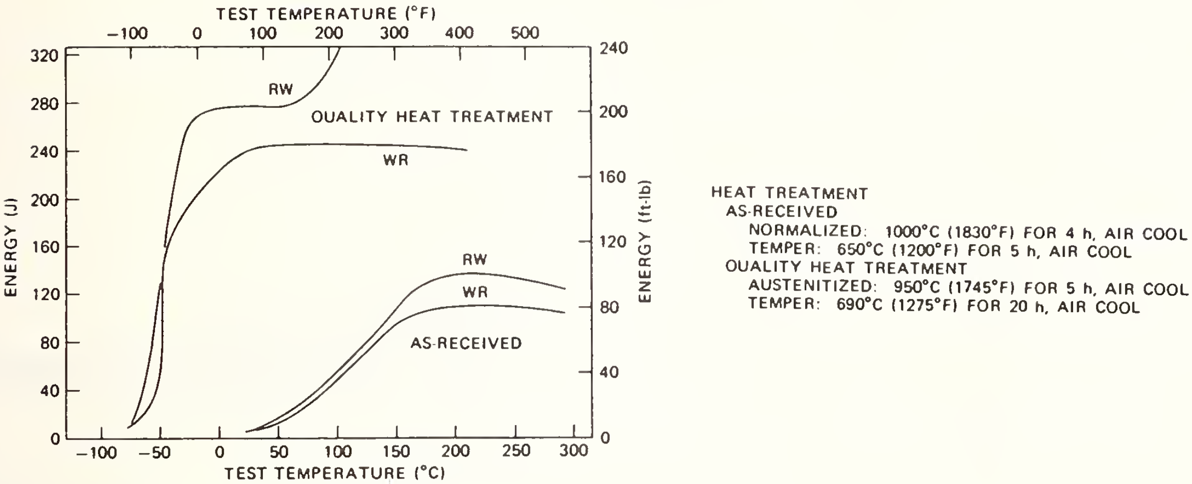
[a] See Section B.3.1.145 for data plotted here.

[b] See Section B.3.1.145 for compositions of various heats. VCD = vacuum-carbon-deoxidized, Si-K = silicon-killed, Si-Al-K = silicon-aluminum-killed.

[c] See Section B.3.1.145 for details of heat treatments.

CHARPY V-NOTCH DATA FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[a] AFTER "QUALITY" HEAT TREATMENT[b][35,74]



	Temperature, °C (°F)				Upper-Shelf Energy	
Orientation[c]	68-J(50 ft-lb) Transition Temperature	0.89 mm(35 mil) Lateral Expansion	50% Shear	100% Shear	J	ft-lb
As-Received[a]						
RW	113 (235)	127 (260)	129 (265)	182 (360)	136	100
WR	121 (250)	129 (265)	121 (250)	182 (360)	109	80
"Quality" Heat Treated[b]						
RW	-57 (-70)	-54 (-65)	-37 (-35)	-23 (-10)	272	200[d]
WR	-46 (-50)	-46 (-50)	-46 (-50)	10 (50)	245	180

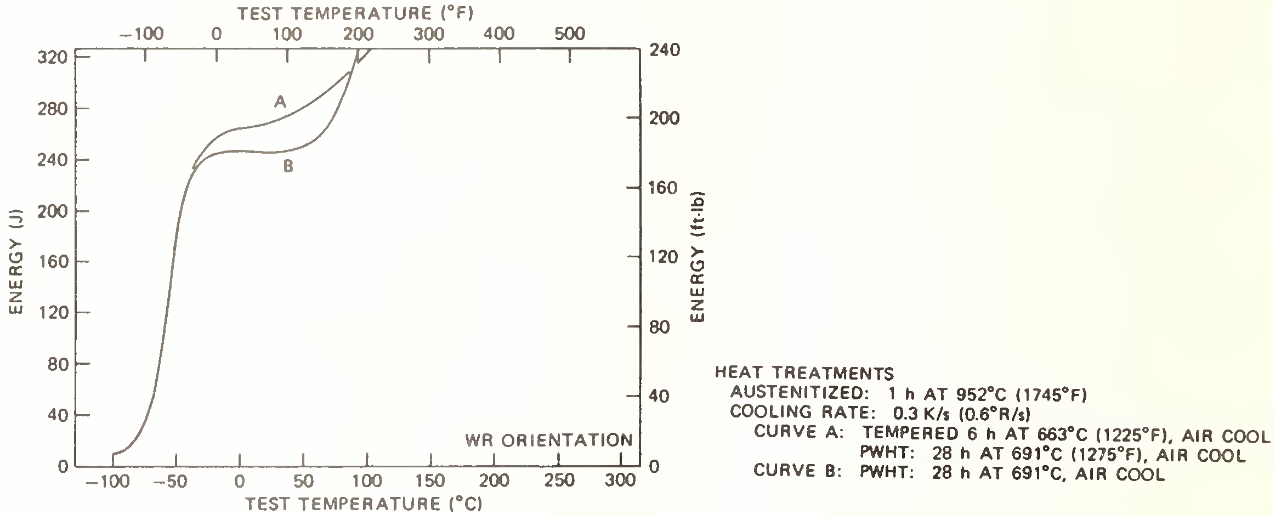
[a]V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Ingots were hot-forged to 29 mm (1 1/8 in.) thick plates. Heat treatment: normalized for 4 hours at 1000 °C (1830 °F), air cooled, tempered for 5 hours at 650 °C (1200 °F), and air cooled.

[b]"Quality" treatment: austenitized for 5 hours at 950 °C (1745 °F), air cooled, tempered for 20 hours at 690 °C (1275 °F), and air cooled.

[c]RW = specimen axis parallel to rolling direction, fracture perpendicular to R; WR = specimen axis transverse to rolling direction, fracture parallel to R.

[d]Exceeded machine capacity (326 J) between 93 and 149 °C (200 and 300 °F).

CHARPY V-NOTCH DATA[a] FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b] AFTER PROCESSING HEAT TREATMENTS[c][35,74]



Heat Treatment[c]	Temperature, °C (°F): 68-J(50 ft-lb) Transition Temperature	0.89 mm(35 mil) Lateral Expansion	50% Shear	100% Shear	Upper-Shelf Energy at 10 °C(50 °F): J	ft-lb
Q, T, PWHT	-65 (-85)	-68 (-90)	-57 (-70)	-37 (-35)	265	195[d]
Q, PWHT	-65 (-85)	-68 (-90)	-51 (-60)	-29 (-20)	245	180[d]

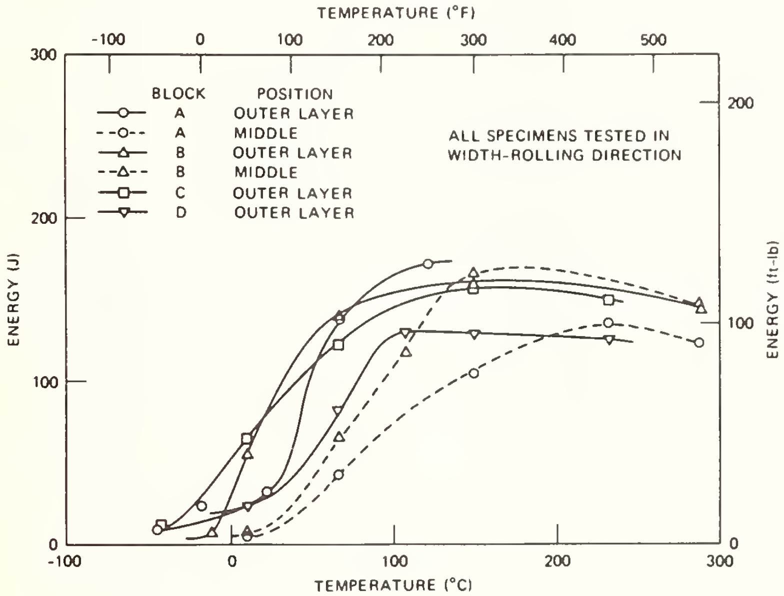
[a]Specimen orientation, WR, specimen axis transverse to rolling direction, fracture parallel to rolling direction.

[b]V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Ingots were hot-forged to 29 mm (1 1/8 in.) thick plates. Normalized for 4 hours at 1000 °C (1830 °F), air cooled, tempered for 5 hours at 650 °C (1200 °F), and air cooled.

[c]Materials were austenitized at 952 °C for 1 hour. After austenitization materials were given varied heat treatments. A device called DATA TRAK was used (see footnote c, Section B.3.1.145 for description of device). Q denotes the 0.3 K/s (0.6 °R/s) quench rate simulated by DATA TRAK; T denotes temper at 663 °C (1225 °F) for 6 hours, followed by air cooling; PWHT denotes a post weld heat treatment at 691 °C (1275 °F) for 28 hours, followed by air cooling. The cooling rate simulates the quench rate for 1/4 thickness in 254 to 305 mm thick plate.

[d]Exceeded machine capacity (326 J) near 93 °C (200 °F).

CHARPY V-NOTCH DATA FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[a]
FORGED TO DIFFERENT THICKNESS REDUCTIONS[b][76,77]



[a]V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. As received heat treatment: normalized at 1020 °C for 15 hours, air cooled, tempered at 700 °C for 10 hours, and furnace cooled; austenitized at 950 °C for 7 hours, water quenched, tempered at 650 °C for 15 hours, and air cooled.

[b]The above data are for 4 blocks from the same ingot which were forged to 4 different reductions in thickness.

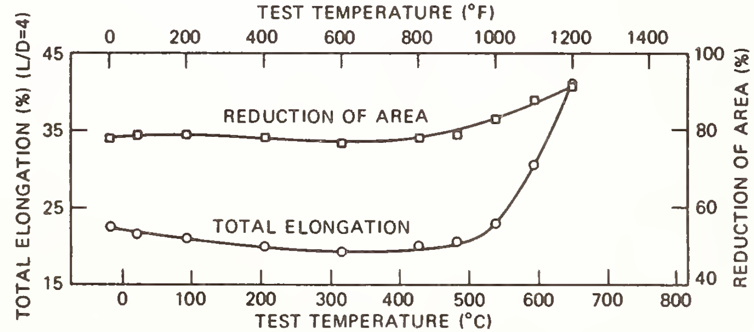
Block A--reduced to ∿50% thickness by forging (final thickness 525 mm)
Block B--reduced to ∿59% thickness by forging (final thickness 425 mm)
Block C--reduced to ∿68% thickness by forging (final thickness 332 mm)
Block D--reduced to ∿78% thickness by forging (final thickness 235 mm)

Blocks A and B were also sectioned at the midthickness position. Samples were taken then from the surfaces of all four blocks and from the mid-thickness position of Blocks A and B.

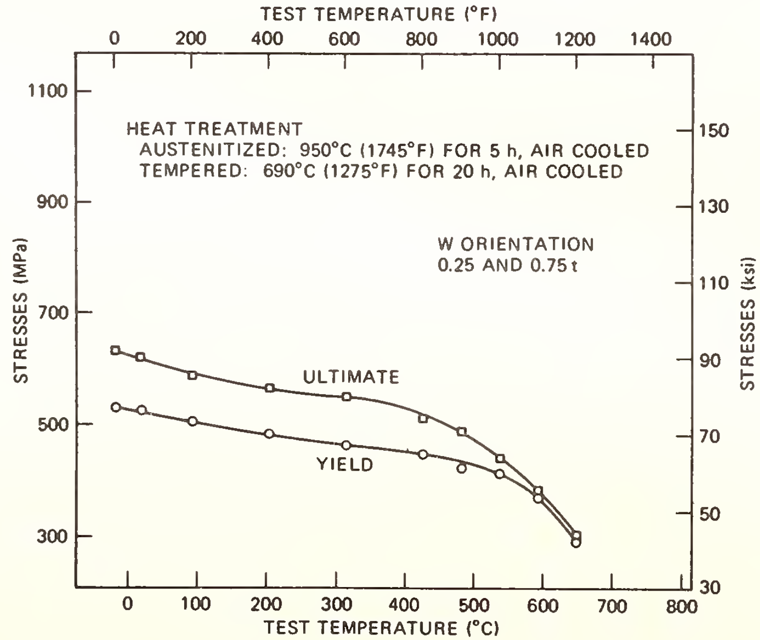
TENSILE PROPERTIES[a] OF V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b] AFTER VARIOUS HEAT TREATMENTS[35,74]

Tensile Properties after "Quality" Heat Treatment[c]

Test Temperature °C	Test Temperature °F	Ductility, % Total Elongation[d] L/D = 7	Total Elongation[d] L/D = 4	Reduction in Area
-18	0	15.5	22.5	78
21	70	14.8	21.7	79
93	200	14.2	21.0	79
204	400	13.1	19.9	78
316	600	12.5	19.1	77
427	800	13.0	20.1	78
482	900	13.4	21.1	79
538	1000	13.9	22.8	83
593	1100	17.8	30.6	88
649	1200	23.8	41.2	91



Test Temperature °C	Test Temperature °F	0.2% Offset Yield Strength MPa(ksi)	Ultimate Tensile Strength MPa(ksi)
-18	0	529(76.8)	631(91.6)
21	70	525(76.2)	624(90.6)
93	200	506(73.5)	590(85.6)
204	400	484(70.2)	566(82.2)
316	600	464(67.3)	553(80.2)
427	800	449(65.2)	513(74.5)
482	900	422(61.1)	490(71.1)
538	1000	413(60.0)	442(64.1)
593	1100	370(53.7)	384(55.7)
649	1200	291(42.2)	304(44.1)



(Data Continued)

TENSILE PROPERTIES[a] OF V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b] AFTER VARIOUS HEAT TREATMENTS[35,74], Continued

Tensile Properties after Processing Treatments[e]

Heat Treatment[e]	Yield Strength[f] MPa	Yield Strength[f] ksi	Ultimate Tensile Strength MPa	Ultimate Tensile Strength ksi	Total Elongation[d], % L/D = 7	Total Elongation[d], % L/D = 4	Reduction in Area, %
Q, T, PWHT	507	73.5	608	88.2	16.4	24.3	78
Q, PWHT	518	75.2	618	89.7	16.2	24.1	78

[a] Average of two specimens; 0.016/minute strain rate; W-orientation (specimen axis transverse to the rolling direction).

[b] V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Ingots were hot-forged to 29 mm (1 1/8 in.) thick plates. Normalized for 4 hours at 1000 °C (1830 °F), air cooled, tempered for 5 hours at 650 °C (1200 °F), and air cooled.

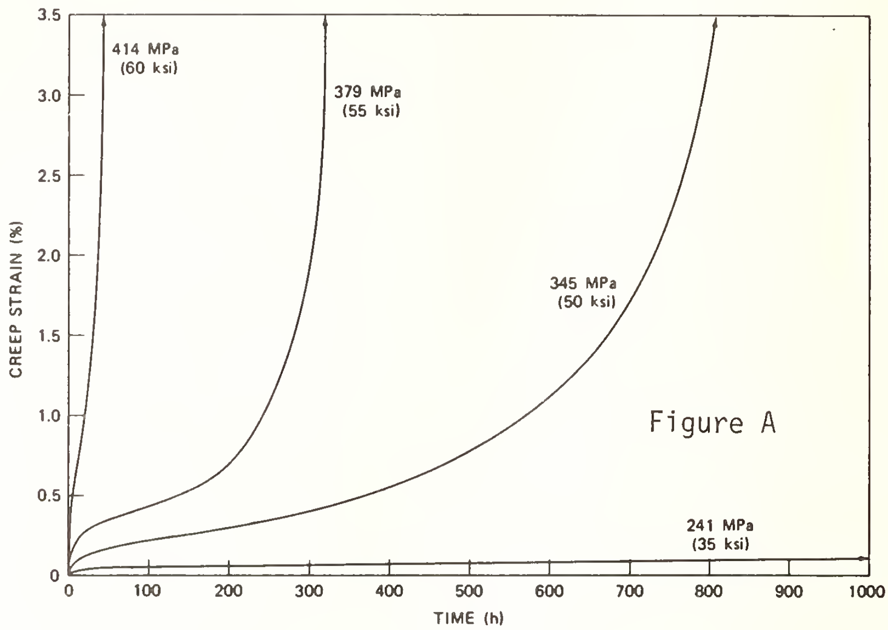
[c] "Quality" heat treatment: austenitization at 950 °C (1745 °F) for 5 hours, air cooling, tempering at 690 °C (1275 °F) for 20 hours, followed by air cooling.

[d] L/D = gauge length/gauge diameter, L/D = 4 was calculated from L/D = 7.

[e] Materials were austenitized at 952 °C for 1 hour. After austenitization materials were given various heat treatments. A device called DATA TRAK was used (see footnote c, Section B.3.1.145 for description of device). Q denotes 0.3 K/s (0.6 °R/s) quench rate simulated by DATA TRAK; T denotes temper at 663 °C (1225 °F) for 6 hours, followed by air cooling; PWHT denotes a post wel heat treatment at 691 °C (1275 °F) for 28 hours, followed by air cooling. The cooling rate simulated is that of the 1/4 thickness depth in 254 to 305 mm (10-12 in.) thick plate when water quenched.

[f] 0.2% Offset yield strength.

CREEP DATA FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[a][35,74,76,77]



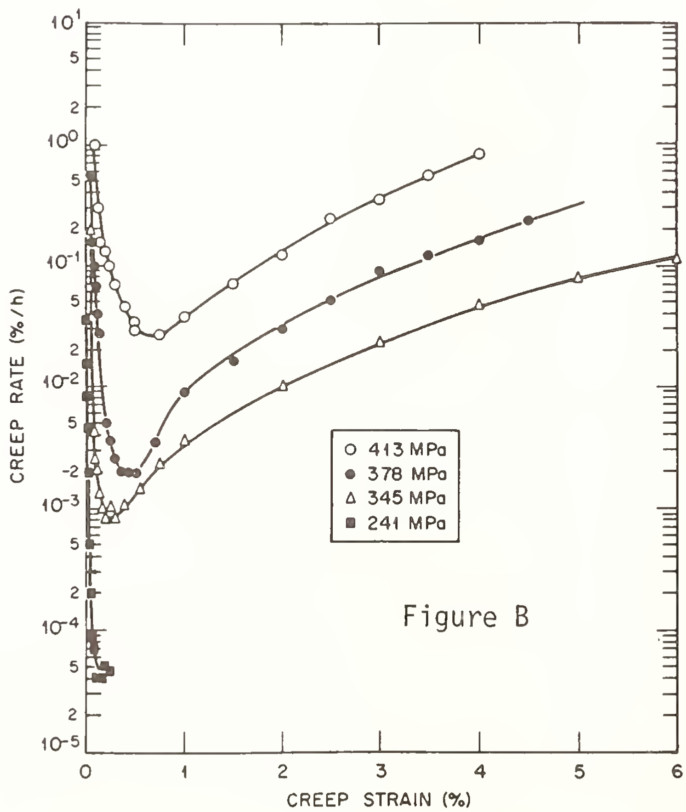
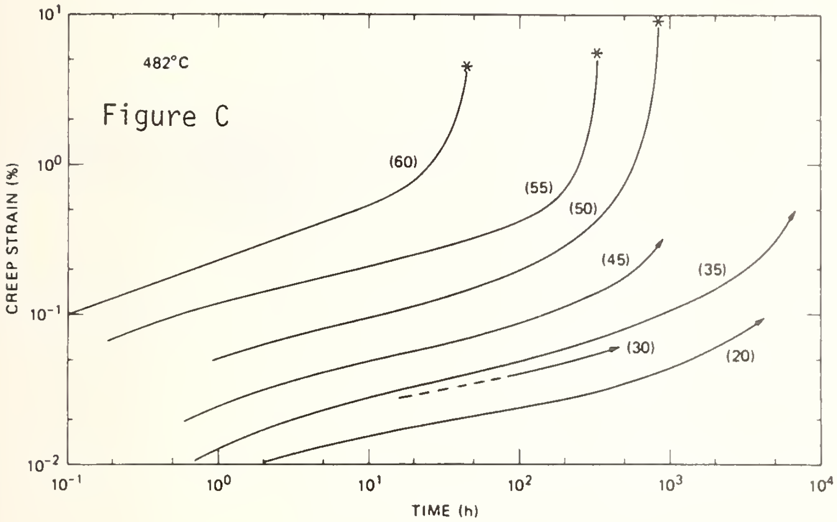


Figure A - Creep strain versus time for 4 stress levels at 482 °C

Figure B - Creep rate versus creep strain for 4 stress levels at 482 °C

(Data Continued)

CREEP DATA FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[a][35,74,76,77], Continued

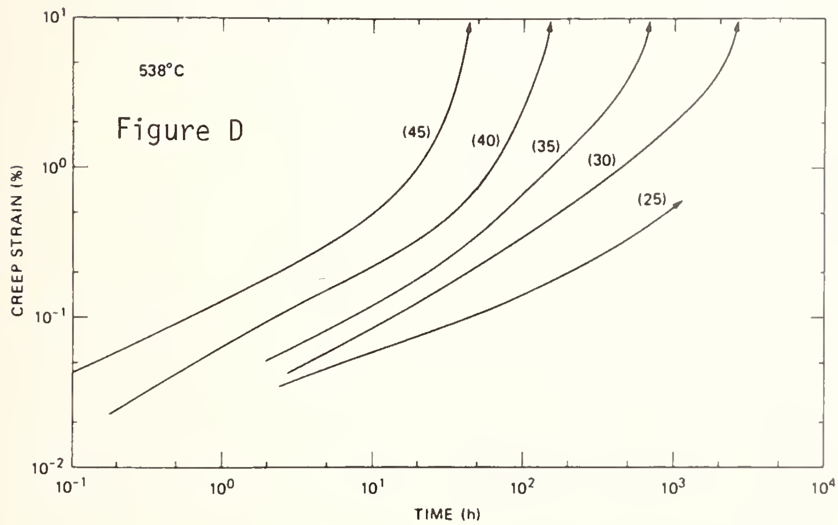


For comparison with Figures A and B--

ksi	MPa
60	413.7
55	379.3
50	344.8
45	310.3
40	275.9
35	241.4
30	206.9
25	172.4
20	137.9

Figure C - Log creep strain versus log time for 7 stress levels (labelled in ksi) at 482 °C (* indicates rupture).

Figure D - Log creep strain versus log time for 5 stress levels (labelled in ksi) at 538 °C.



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(Data Continued)

CREEP DATA FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[a][35,74,76,77], Continued

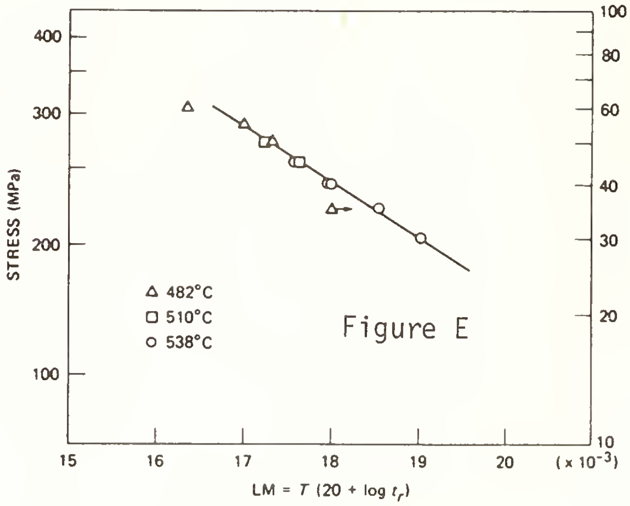

Figure E - Log stress versus Larson-Miller parameter

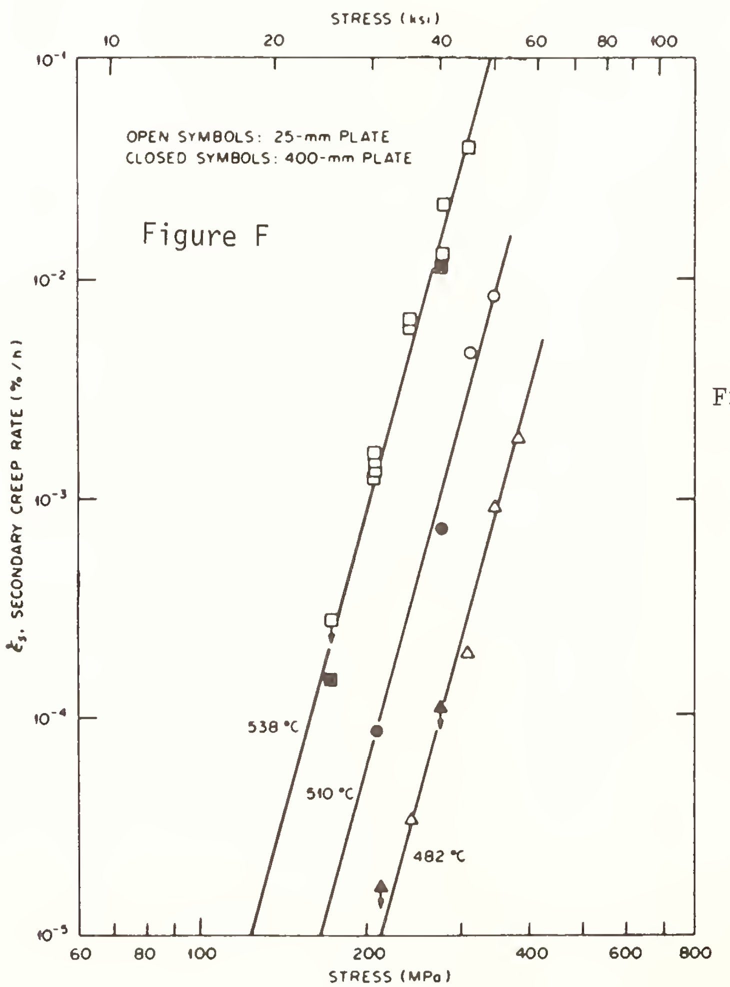

Figure F - Secondary creep rate versus stress from tests at 3 temperatures

(Data Continued)

CREEP DATA FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[a][35,74,76,77], Continued

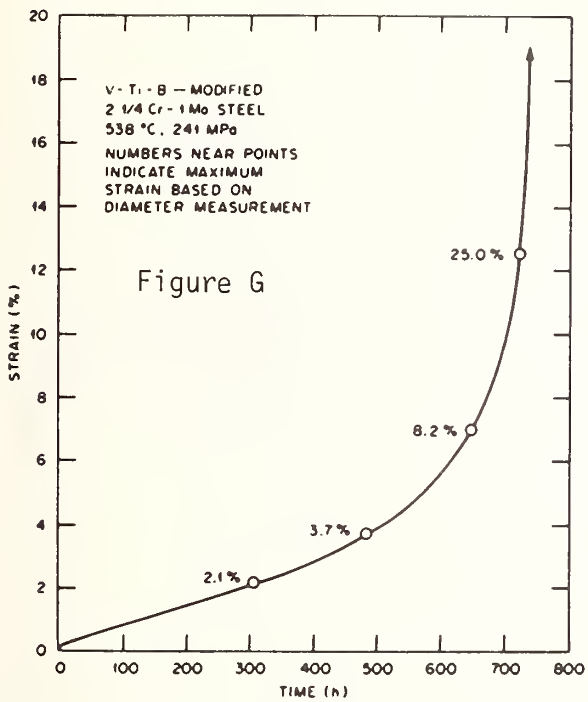

Figure G - Strain versus time for creep test interrupted periodically for measurement of the diametric strain.

Dimensions were measured in the secondary and tertiary creep stages.

Axial strain

Up to 4%	--strains uniformly distributed in gauge length
At 7%	--some necking
At 12%	--maximum diametric strain was 25%

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[a]V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Bainitic microstructure.

METALLURGICAL DAMAGE[a] OF V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b] UNDER STRESS[76,77]

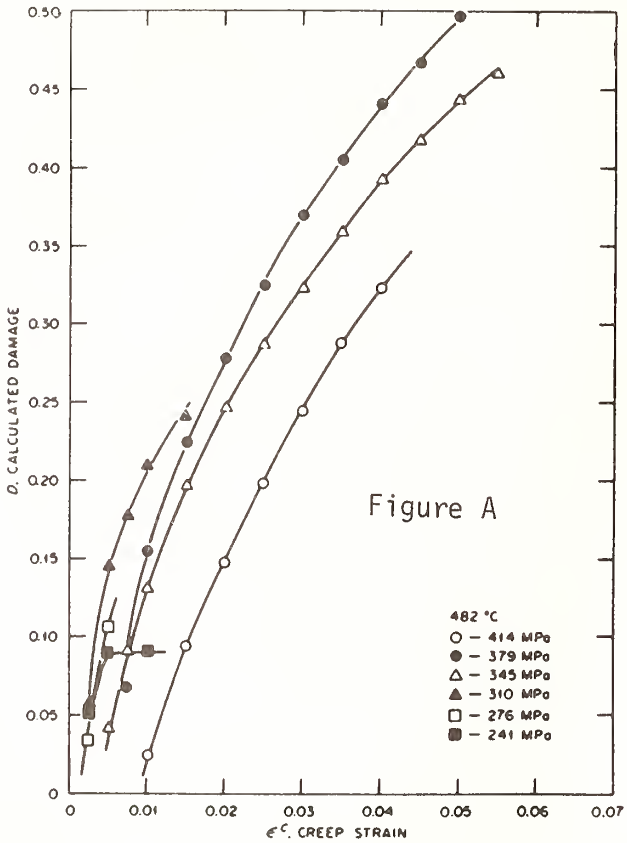

Figure A - The calculated Damage Factor versus the creep strain for tests at 482 °C.

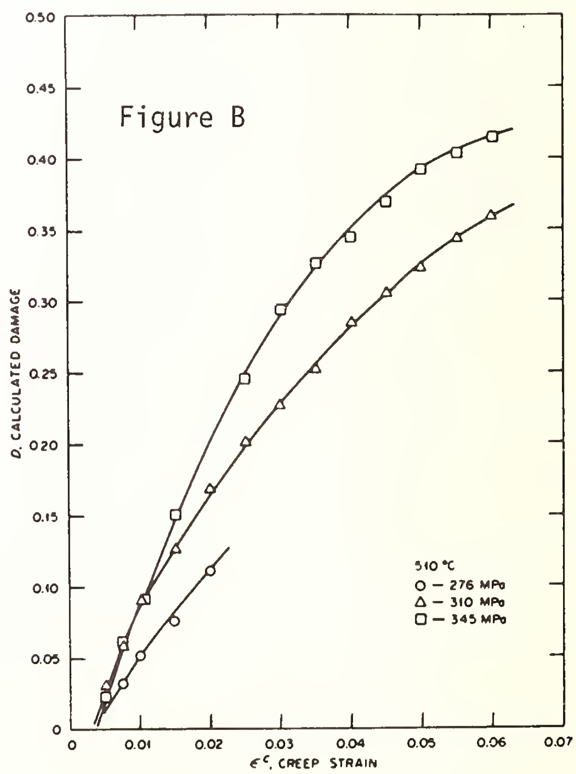

Figure B - The calculated Damage Factor versus creep strain at 510 °C.

(Data Continued)

METALLURGICAL DAMAGE[a] OF V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b] UNDER STRESS[76,77], Continued

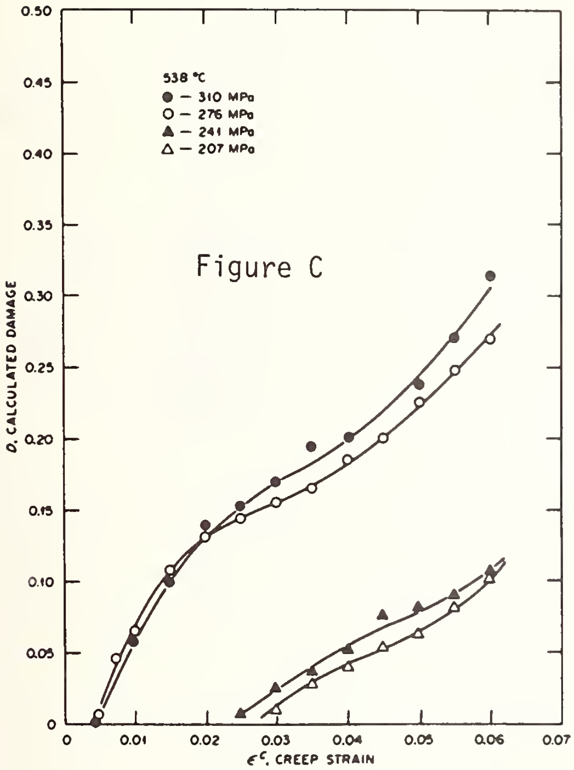

Figure C - The calculated Damage Factor versus creep strain at 538 °C.

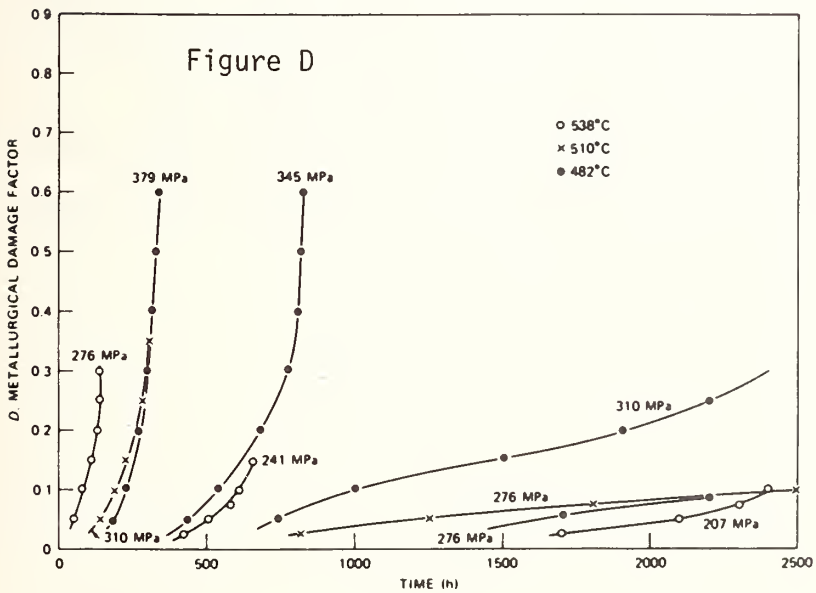

Figure D - Damage Factor versus time for constant stress creep tests at several temperatures.

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(Data Continued)

METALLURGICAL DAMAGE[a] OF V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b] UNDER STRESS[76,77], Continued

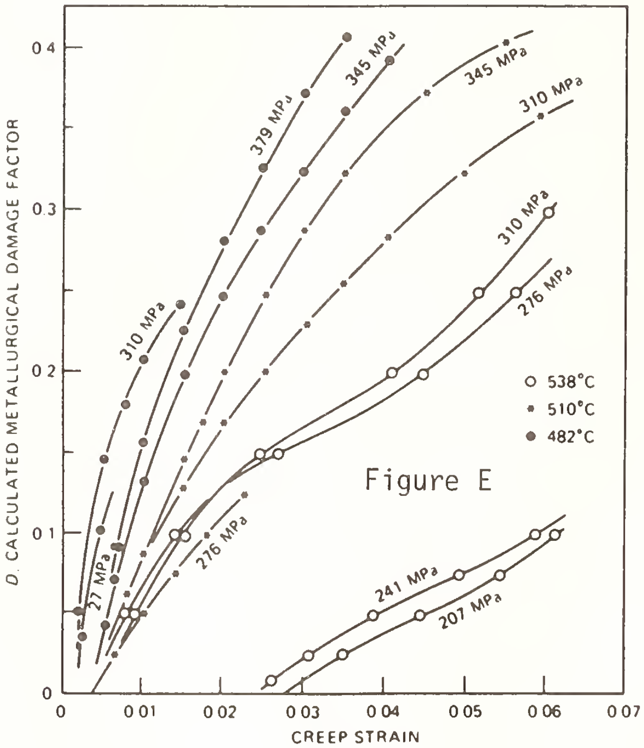

Figure E - Damage Factor versus creep strain for constant stress creep tests at several temperatures.

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[a] Metallurgical Damage Factor, D, includes such damage features as strain-accelerated softening of the metallurgical structure, possible microvoid formation, particle coarsening, etc. It can be calculated from creep data using the instantaneous values of creep rate and creep strain, minimum creep rate, and the stress sensitivity of the creep rate.

[b] V-Ti-B modified steel, vacuum-induction-melted, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Bainitic microstructure.

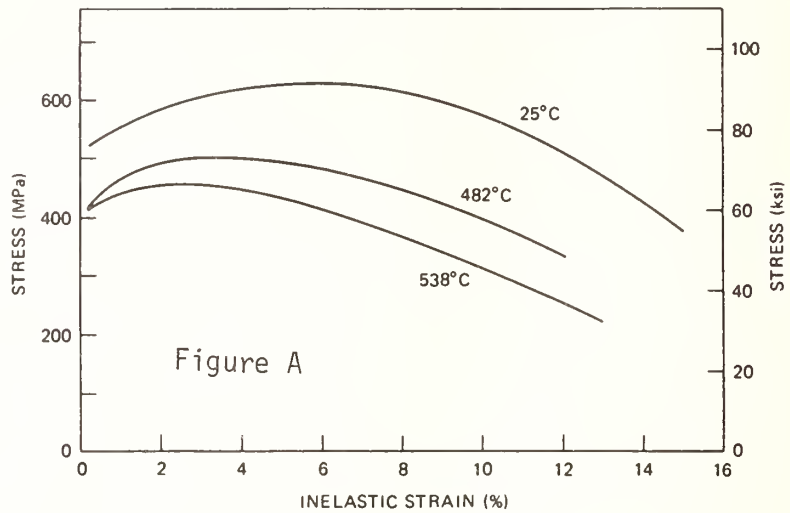
EFFECT OF STRESS OR TEMPERATURE CHANGE DURING CREEP TESTING ON METALLURGICAL DAMAGE FACTORS[a] FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b][76,77]

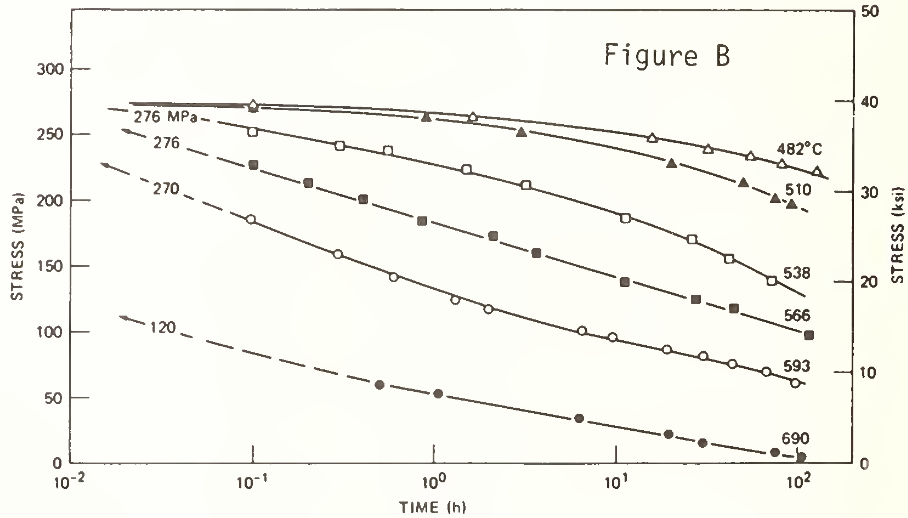
	Before Change				After Change		
Specimen	Temperature °C	Stress MPa	D	Strain %	Temperature °C	Stress MPa	D
1	482	276	0.08	0.5	482	310	0.25
2	482	241	0.09	1.0	482	276	
3	538	276	0.04	2.0	538	310	0.13
4	538	207	0.0	2.0	538	241	0.02
5	538	172	0.0	1.0	538	241	0.07
6	538	241	0.0	0.5	538	276	0.015
7	510	207	0.0	0.3	538	207	0.0

[a]Metallurgical Damage Factor, D, includes such damage features as strain-accelerated softening of the metallurgical structure, possible microvoid formation, particle coarsening, etc. It can be calculated from creep data using the instantaneous values of creep rate and creep strain, minimum creep rate, and the stress sensitivity of the creep rate. D values above were calculated just before and after the stress or temperature change.

[b]V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Bainitic microstructure.

RELAXATION DATA[a] FOR V-Ti-B MODIFIED 2-1/4 Cr-1 Mo STEEL[b][76,77]





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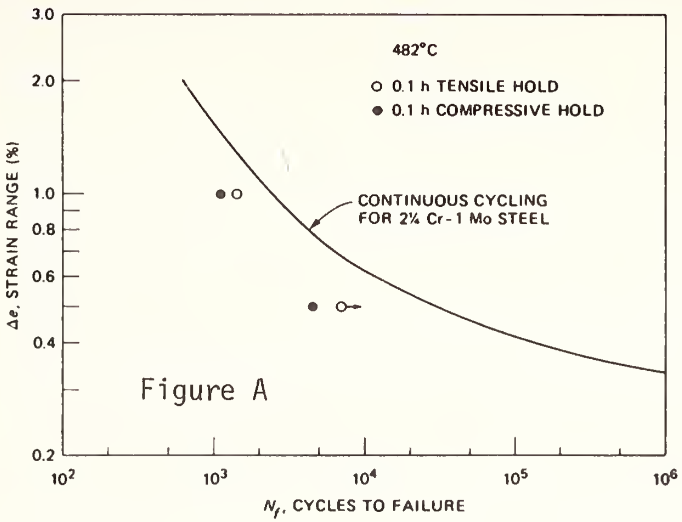
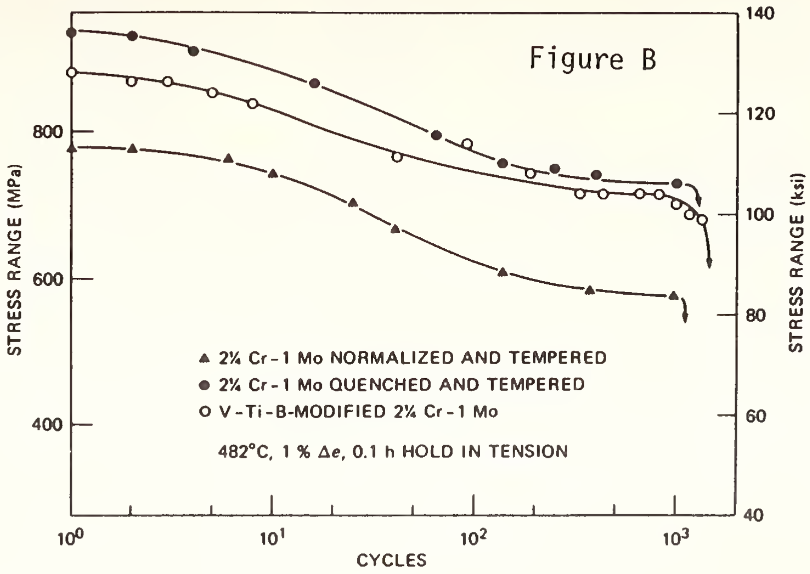
[a]Figure A shows stress versus inelastic strain at several temperatures. Figure B shows relaxation curves from 482 °C to 690 °C. Tests were performed on the same specimen, starting at 482 °C and moving to higher temperatures after each 100-hour relaxation period. Starting stresses are indicated on the figure.

[b]V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Bainitic microstructure.

CREEP-FATIGUE DATA[a] FOR 2-1/4 Cr-1 Mo AND V-Ti-B MODIFIED[b] STEELS[76,77]





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[a] Figure A shows fatigue data at 482 °C for V-Ti-B modified steel (symbols representing experimental points) and for bainitic 2-1/4 Cr-1 Mo steel (smooth curve).
Figure B shows cyclic softening at 482 °C for 1% cyclic strain level testing for two heat treatments of 2-1/4 Cr-1 Mo steel and for the V-Ti-B modified steel.

[b] V-Ti-B modified steel, vacuum-induction-melted experimental heats, supplied by Japan Steel Works. Analysis (wt %): 0.12 C, 0.50 Mn, 2.28 Cr, 0.10 Ni, 0.99 Mo, 0.02 Si, 0.25 V, 0.021 Ti, 0.0022 B, balance Fe. Bainitic microstructure.

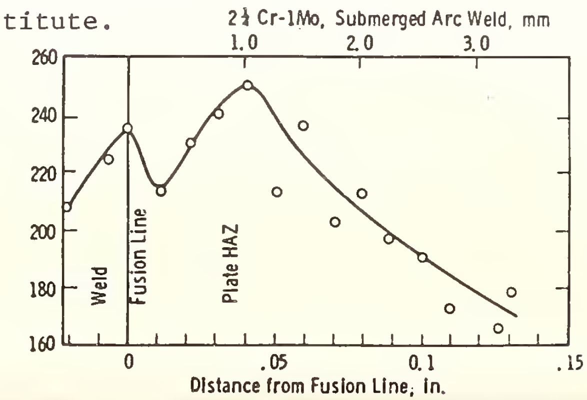
COMPARISON OF HEAT AFFECTED ZONE PEAK HARDNESS WITH BASE METAL HARDNESS FOR SEVERAL Cr-Mo STEEL WELDMENTS[78,79]

Weldment[a]/ Heat Treatment	Peak Value-Heat Affected Zone: Measured 500 g Knoop Hardness[b]	Peak Value-Heat Affected Zone: Rockwell Hardness[c]	Peak Value-Heat Affected Zone: Ultimate Tensile Strength[c]	Base Metal: Measured 500 g Knoop Hardness[b]	Base Metal: Rockwell Hardness[c]	Base Metal: Ultimate Tensile Strength[c]
2-1/4 Cr-1 Mo Submerged arc weld/ 1100 °F for 8 h, 1200 °F for 15 h, 1275 °F for 7 h, cool 50 °F/h	[222]	[95]	[101]	[150]	[79]	[71]
2-1/4 Cr-1 Mo Submerged arc weld/ 1 hour/inch at 1175 °F (635 °C)	293	(>100)	127 ksi	276	99	120 ksi
*2-1/4 Cr-1 Mo Submerged arc weld/ 24 hours at 1274 °F (690 °C), furnace cool	250[227]	98[96]	108[103]	177[160]	84[82]	78[75]
2-1/4 Cr-1 Mo Shielded metal arc weld/24 hours at 1274 °F (690 °C), furnace cool	230[214]	96[94]	103[100]	170[190]	82[90]	75[89]
3 Cr-1 Mo Submerged arc weld/ 24 hours at 1274 °F (690 °C), furnace cool	223	94	100	200	90	89
3 Cr-1 Mo Shielded metal arc weld/ 24 hours at 1274 °F (690 °C), furnace cool	225	95	101	200	90	89

[a]Six commercially produced weldments from the American Petroleum Institute.

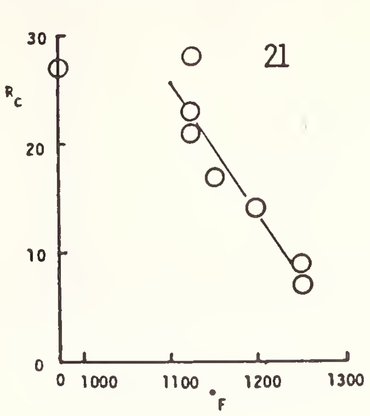
[b]Specimens were polished and macroetched in 2% nital to reveal the weld interface and heat affected zone. Tukon microhardness testing machine was used to measure the Knoop hardness. The adjacent figure is a profile for the Knoop measurements of the weld preceded by * above. Values in square brackets [] were obtained by diamond pyramid hardness testing.

[c]Not measured, equivalent values. Rockwell scale is B.

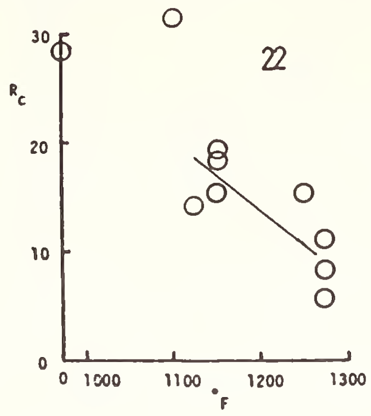


HARDNESS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b] FOR Cr-Mo STEELS[c][79]

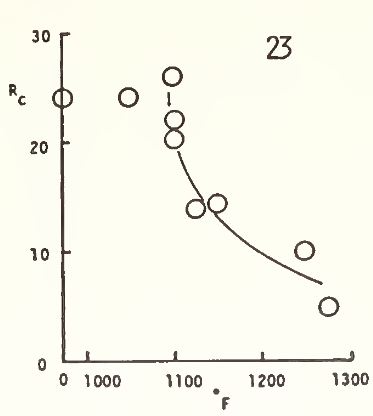
2.25 Cr-0.95 Mo-0.11 Mn-0.46 Si-0.13 C-0.016 P



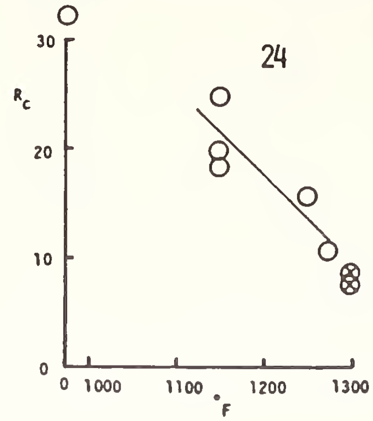
2.13 Cr-0.93 Mo-1.15 Mn-0.46 Si-0.13 C-0.015 P



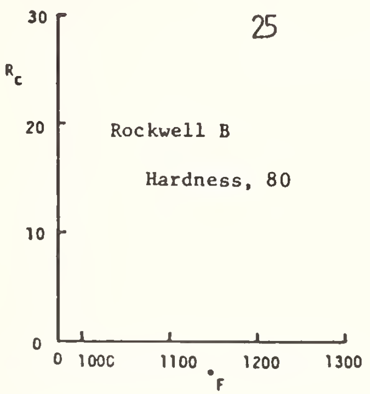
2.25 Cr-0.96 Mo-0.61 Mn-0.06 Si-0.12 C-0.016 P



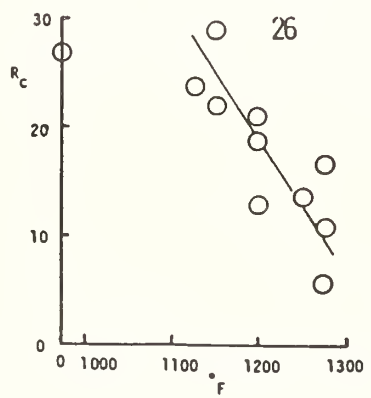
2.24 Cr-0.93 Mo-0.61 Mn-0.89 Si-0.12 C-0.022 P



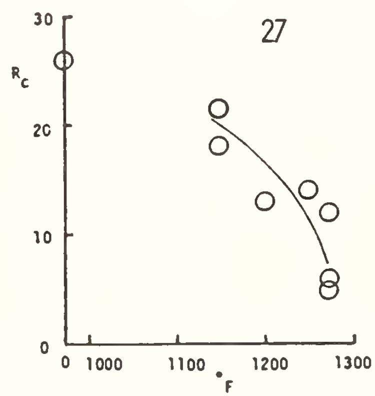
2.23 Cr-0.90 Mo-0.57 Mn-0.43 Si-0.024 C-0.014 P



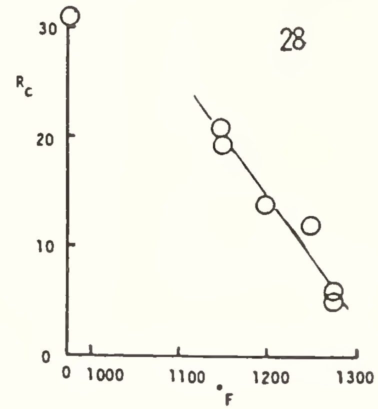
2.20 Cr-0.92 Mo-0.61 Mn-0.47 Si-0.22 C-0.014 P



2.15 Cr-0.92 Mo-0.57 Mn-0.47 Si-0.12 C-0.002 P



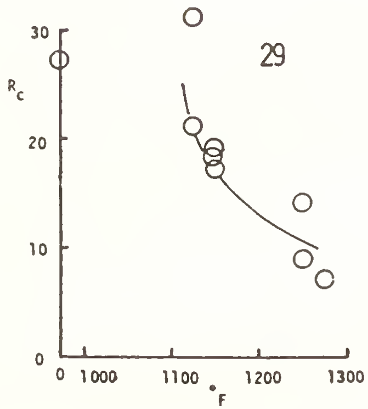
2.20 Cr-0.94 Mo-0.61 Mn-0.44 Si-0.12 C-0.028 P



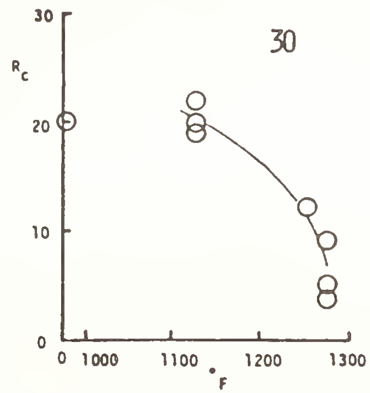
(Data Continued)

HARDNESS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b] FOR Cr-Mo STEELS[c][79], Continued

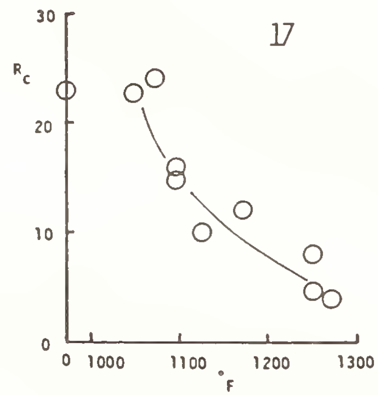
2.08 Cr-0.94 Mo-0.64 Mn-0.45 Si-0.12 C-0.14 P



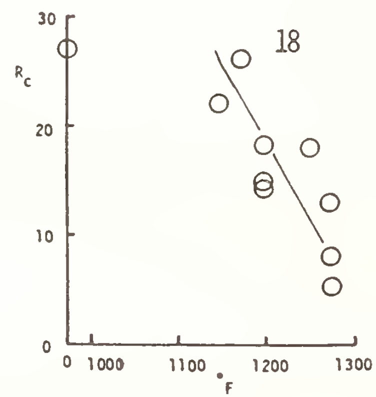
2.14 Cr-0.91 Mo-0.58 Mn-0.45 Si-0.12 C-0.014 P



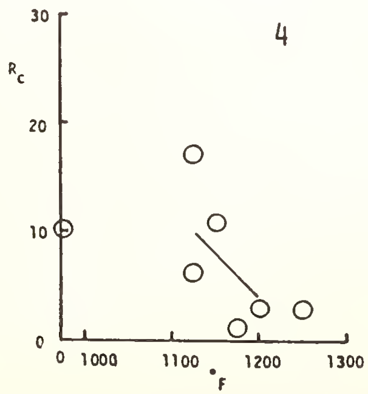
2.19 Cr-0.32 Mo-0.61 Mn-0.45 Si-0.13 C-0.014 P



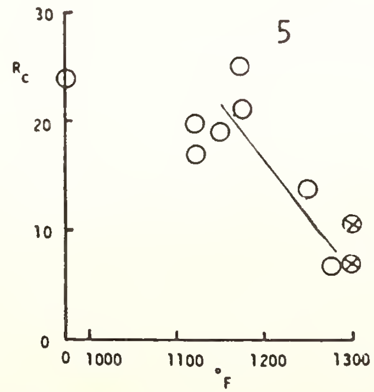
2.22 Cr-1.63 Mo-0.63 Mn-0.45 Si-0.13 C-0.018 P



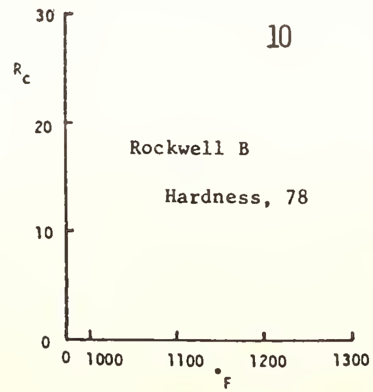
1.53 Cr-0.63 Mo-0.37 Mn-0.26 Si-0.071 C-0.009 P



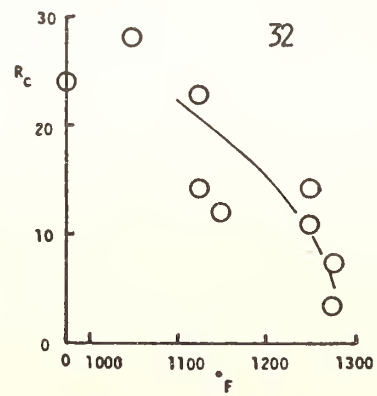
1.55 Cr-0.62 Mo-0.87 Mn-0.64 Si-0.17 C-0.020 P



1.49 Cr-0.61 Mo-0.35 Mn-0.62 Si-0.07 C-0.020 P



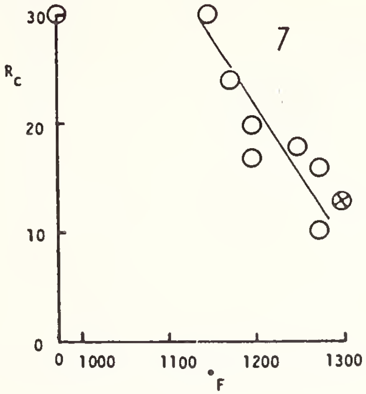
1.45 Cr-0.62 Mo-0.86 Mn-0.27 Si-0.16 C-0.009 P



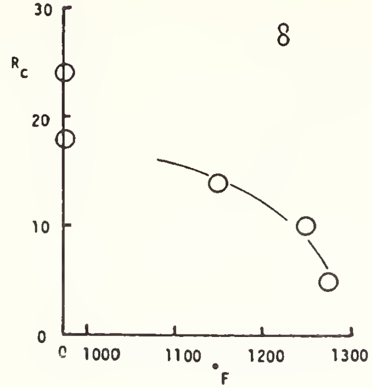
(Data Continued)

HARDNESS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b] FOR Cr-Mo STEELS[c][79], Continued

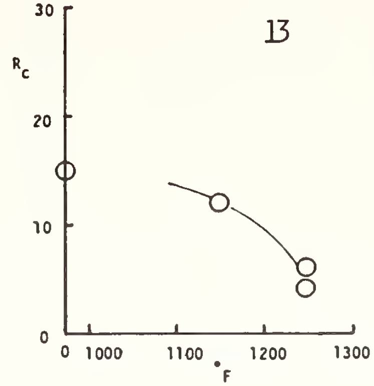
1.47 Cr-1.25 Mo-0.39 Mn-0.65 Si-0.17 C-0.011 P



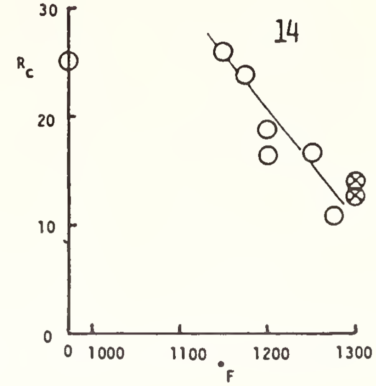
1.46 Cr-1.29 Mo-0.86 Mn-0.24 Si-0.069 C-0.020 P



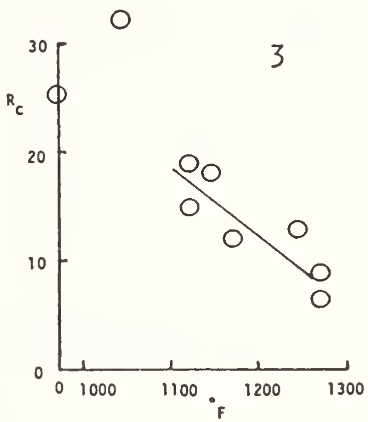
1.50 Cr-1.27 Mo-0.86 Mn-0.65 Si-0.065 C-0.010 P



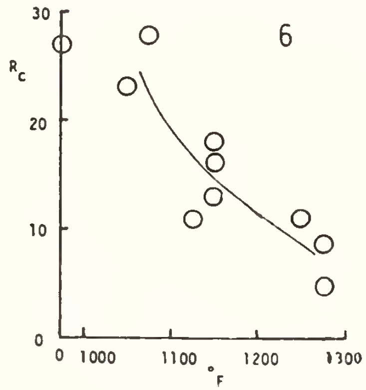
1.46 Cr-1.25 Mo-0.36 Mn-0.26 Si-0.17 C-0.021 P



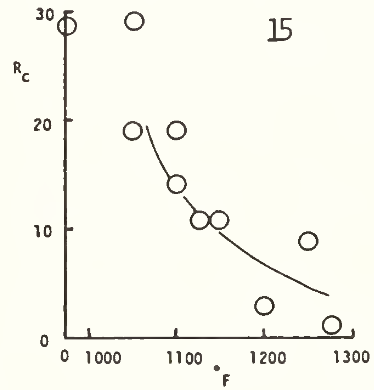
2.73 Cr-0.62 Mo-0.33 Mn-0.26 Si-0.17 C-0.022 P



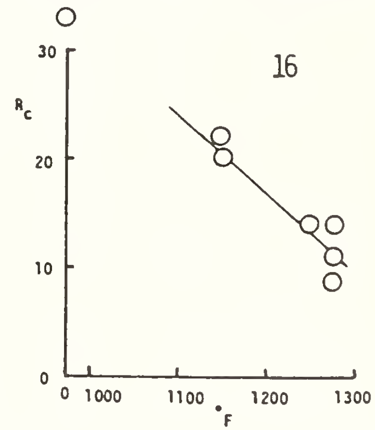
2.84 Cr-0.61 Mo-0.82 Mn-0.66 Si-0.075 C-0.007 P



2.78 Cr-0.63 Mo-0.91 Mn-0.28 Si-0.072 C- 0.021 P



2.11 Cr-0.62 Mo-0.35 Mn-0.64 Si-0.18 C- 0.009 P

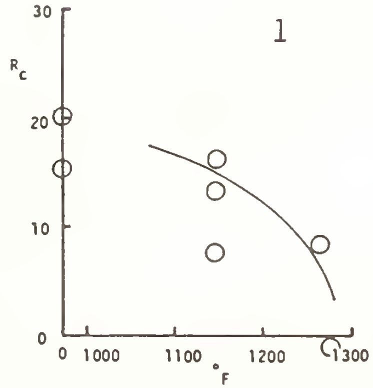


- -

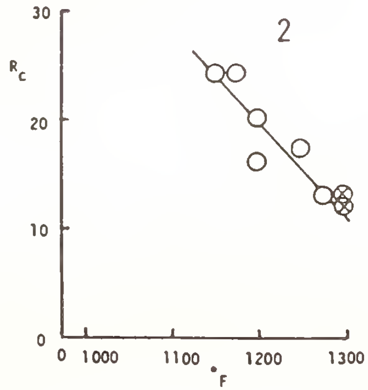
(Data Continued)

HARDNESS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b] FOR Cr-Mo STEELS[c][79], Continued

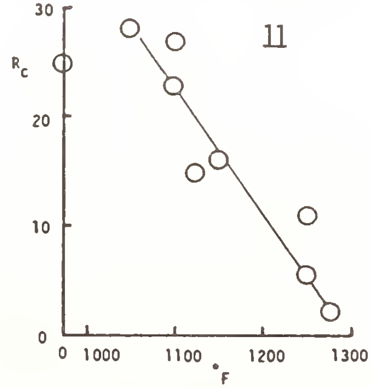
2.72 Cr-1.30 Mo-0.33 Mn-0.65 Si-0.071 C-0.020 P



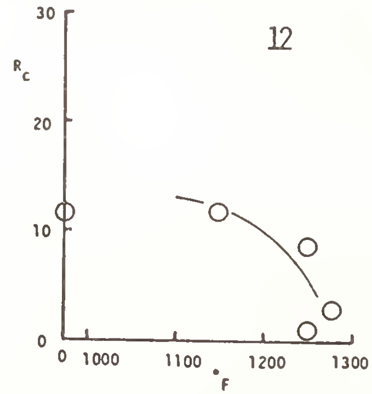
2.78 Cr-1.27 Mo-0.85 Mn-0.24 Si-0.17 C-0.009 P



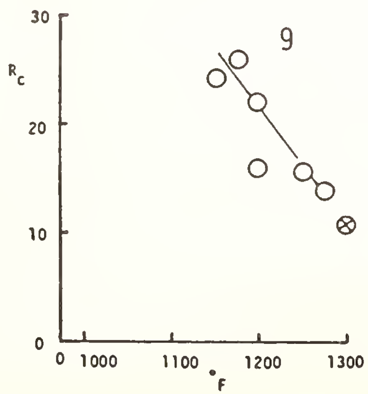
2.69 Cr-1.29 Mo-0.33 Mn-0.25 Si-0.07 C-0.010 P



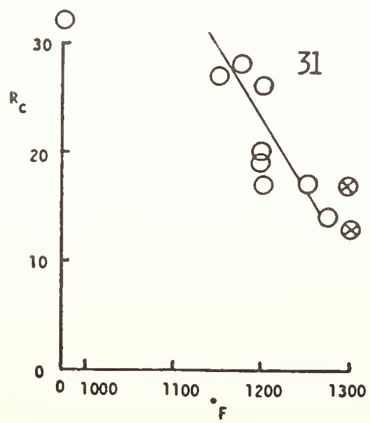
2.71 Cr-1.32 Mo-0.35 Mn-0.65 Si-0.068 C-0.023 P



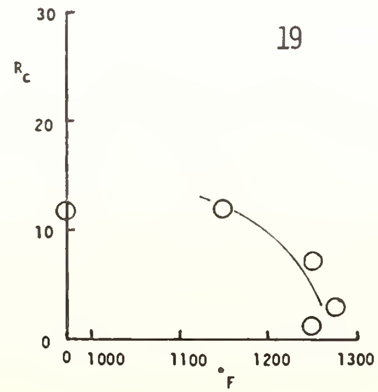
2.74 Cr-1.25 Mo-0.85 Mn-0.62 Si-0.17 C-0.019 P



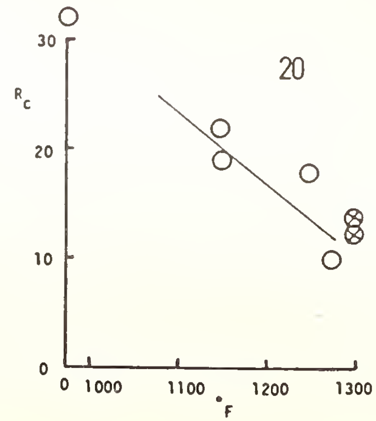
2.77 Cr-1.22 Mo-0.88 Mn-0.65 Si-0.17 C-0.018 P



0.78 Cr-0.95 Mo-0.62 Mn-0.44 Si-0.12 C-0.016 P



3.48 Cr-0.95 Mo-0.61 Mn-0.44 Si-0.12 C-0.014 P



(Data Continued)

HARDNESS[a] AS A FUNCTION OF TEMPERING TEMPERATURE[b] FOR Cr-Mo STEELS[c] [79], Continued

Footnotes

[a]Rockwell hardness; in the lower Rockwell C range both Rockwell B and C readings were taken in order to plot the tempering curves on the C measurement scale. [Note the Rockwell C scale minimum value is 20.] Specimens were cubes subjected to varied tempering treatments, see footnote b. Hardness measurements were made on central sections of the cubes which were ground wet to a 32 finish. Hardness Rockwell C data are plotted versus tempering temperature. Each point plotted is the average of five readings on each sample. Untempered hardness is given in each figure at zero on the temperature scale. Data with a X in the symbols are for samples tempered at 1275 °F for 6 hours and are offset for comparison.

[b]The initial heat treatment for the steels are intended to produce a bainitic structure: Austenitization at 1700 °F (927 °C) for 2 hours, air cooling to 1600 °F (870 °C) for about 100 seconds, oil quenching for 45-50 seconds to 1100 °F (600 °C), transfer to furnace at 800 °F (426 °C) and hold at 800 °F for 2 hours after samples reach furnace temperature, followed by air cooling. The treatment produced a composition dependent structure of bainite or bainite with ferrite.
One inch cube coupons of each steel were tempered for 2 hours at temperatures from 1050 °F to 1275 °F. A few samples were also tempered at 1275 °F for 6 hours.

[c]Actual compositions (wt %) are given above each figure. They are grouped by Cr-Mo contents. The sample numbers on each figure correspond to the sample numbers in Section B.3.1.158.

TEMPERING TREATMENTS[a] AND HARDNESSES[b] FOR Cr-Mo STEELS[c][79]

Sample	Temperature °F	Time h	Rockwell Hardness	Temperature °F	Time h	Rockwell Hardness
1	1150	2	C 13	untempered		C 20 (B 99)
2	1275	6	C 12	1200	2	C 20 (B 98)
3	1275	2	C 12	1125	2	C 29
				1125	4	C 19
4	1175	2	C 1	1125	2	C 6 (B 90)
5	1175	4	C 11	1125	2	C 20 (B 98)
6	1275	2	C 8	1100	2	C 18
7	1275	2	C 16	1200	2	C 21
8	1275	2	C 4	untempered		C 23 (B 101)
9	1275	6	C 11	1200	2	C 22
10	untempered		B 81	higher strength not possible		
11	1250	2	C 6	1100	2	C 27 (B 103)
				1100	4	C 23
12	1250	2	C 1	higher strength not possible		
13	1250	2	C 4	higher strength not possible		
14	1275	6	C 13	2300	2	C 19
15	1250	2	C 3	1100	2	C 19
16	1275	4	C 10	1150	2	C 22
17	1250	2	C 4	1100	2	C 15
18	1275	4	C 8	1200	2	C 19
19	1250	2	C 1	higher strength not possible		
20	1275	6	C 12	1150	2	C 21
21	1250	2	C 9	1125	2	C 28
				1125	4	C 23
22	1275	4	C 5	1150	2	C 18
23	1275	2	C 5	1100	4	C 22
24	1275	6	C 9	1150	4	C 19
25	untempered		B 79	higher strength not possible		
26	1275	4	C 11	1200	2	C 19
27	1275	4	C 5	1150	2	C 21
28	1275	2	C 8	1150	2	C 21
29	1275	2	C 7	1150	2	C 17
30	1275	4	C 4	1125	4	C 22
31	1275	6	C 13	1200	4	C 20
32	1275	2	C 7	1100	2	C 22

[a]Initial heat treatments producing a composition dependent structure of bainite or bainite with ferrite: austenitization at 1700 °F for 2 hours, air cooling to 1600 °F for ∿100 seconds, oil quenching for 45-50 seconds to 1100 °F, transfer to furnace at 800 °F and hold for 2 hours after samples reach furnace temperature, followed by air cooling. One inch cubes of each steel were tempered at the above temperatures for the given times.

[b]See Section B.3.1.157, footnote a, for measurement of Rockwell Hardness

[c]See Section B.3.1.157 for the compositions of the samples. Sample numbers above correspond to the sample numbers of each of the figures of B.3.1.157.

CHARPY IMPACT DATA FOR SEVERAL Cr-Mo STEEL WELDMENTS[a][78,79]

Weldment[a]/ Heat Treatment	Specimen Location[b]	Fracture Appearance Transition Temperature °F	40 ft-lb Transition Temperature °F	Ambient Temperature Impact Energy ft-lb
2-1/4 Cr-1 Mo Submerged arc weld/ 1100 °F for 8 h, 1200 °F for 15 h, 1275 °F for 7 h, cool 50 °F/h	plate	150	130	10
	HAZ	30	0	70
2-1/4 Cr-1 Mo Submerged arc weld/ 24 hours at 1274 °F, furnace cool	plate	30	5	100
	HAZ	0	-5	85
2-1/4 Cr-1 Mo Shielded metal arc weld/24 hours at 1274 °F, furnace cool	plate	10	5	100
	HAZ	-30	-75	100
2-1/4 Cr-1 Mo Shielded metal arc weld/24 hours at 1274 °F, furnace cool; then temper embrittled at 875 °F for 1000 h	plate	30	0	90
	HAZ	10	-40	95

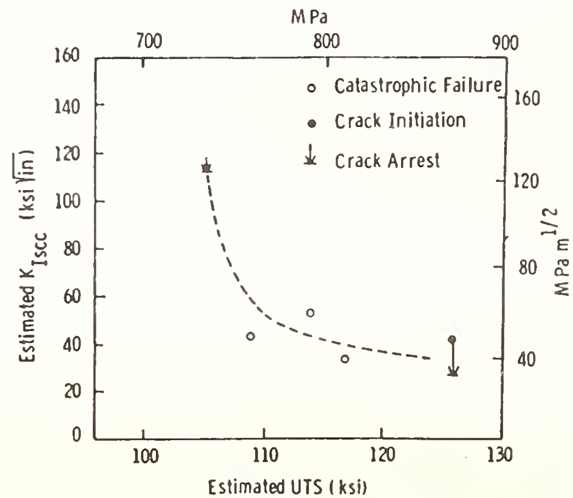
[a]Commercially produced weldments from the American Petroleum Institute.

[b]HAZ = heat affected zone.

CRACK GROWTH TESTING[a] OF 2-1/4 Cr-1 Mo STEEL[b] IN H_2S[c] [78,79]

Specimen	Tempering Temperature °F	Time h	Rockwell Hardness	Ultimate Tensile Strength[d] ksi	Estimated K_{Iscc} ksi$\sqrt{in}$	Comments
1	untempered		C 27	126	28	Slow crack growth from 42 ksi$\sqrt{in}$ in 54 h
2	1100	4	C 22	117	34	Catastrophic fracture; specimen completely failed
3	1100	6	B 99	114	52	No failure after 17 h at 50 ksi$\sqrt{in}$; catastrophic at 52
4	1100	12	B 97.5	109	42	Catastrophic failure
5	1100	16	B 97	106	113	Very small crack growth (0.05 in) in 28 h

[a] 2T compact specimens were used with 0.25 in (6×10^{-3} m) deep side grooves incorporated to minimize the effect of plane stress. The incubation time was minimized by cyclic loading in the environment at 0.5 to 1 Hz. Once the crack was propagating the load was raised to slightly over the maximum cyclic load and specimens were held in constant displacement (simulated bolt load test). Specimens were monitored for load drop indicating crack growth. When load no longer decreases, the crack has arrested. K_{Iscc} was estimated by the compliance method from the point at which the crack was arrested. The adjacent figure shows the threshold stress intensity for crack growth versus the ultimate tensile strength.

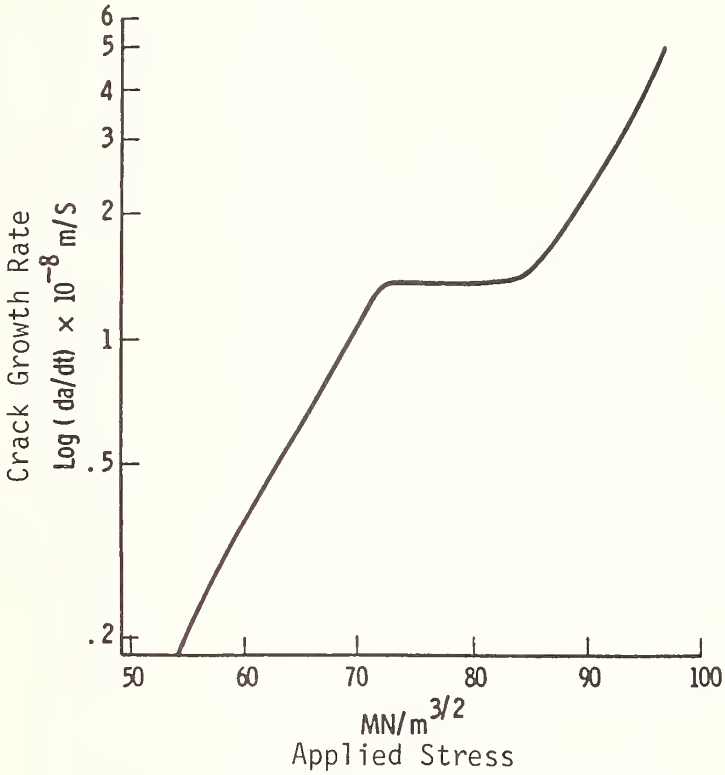


[b] Composition (wt %): 2.28 Cr, 1.00 Mo, 0.103 C, 0.41 Mn, 0.21 Si, 0.15 Ni, 0.15 Cu, 0.007 P, 0.015 Sn, 0.003 Sb, 0.010 As, 0.006 O, 0.007 N, 0.016 S, balance Fe. Heat treatments: 3 h at 1750 °F, water quench, 4.5 h at 1225 °F, air cool, 15 h at 1100 °F, 30 h at 1275 °F, 16 h at 1275 °F (last 3 heats to simulate post weld heat treatment; to form bainite, 900 °F for 15 h, 1700 °F for 3 h, repeated water dip quench to 900 °F (not <700 °F), 900 °F for 1 h, air cool.

[c] Commercial high-purity H_2S at 50 psig (446 kPa).

[d] Estimated from Rockwell hardness.

CRACK GROWTH RATE[a] FOR 2-1/4 Cr-1 Mo STEEL[b] IN H_2S + H_2O[c][78,79]

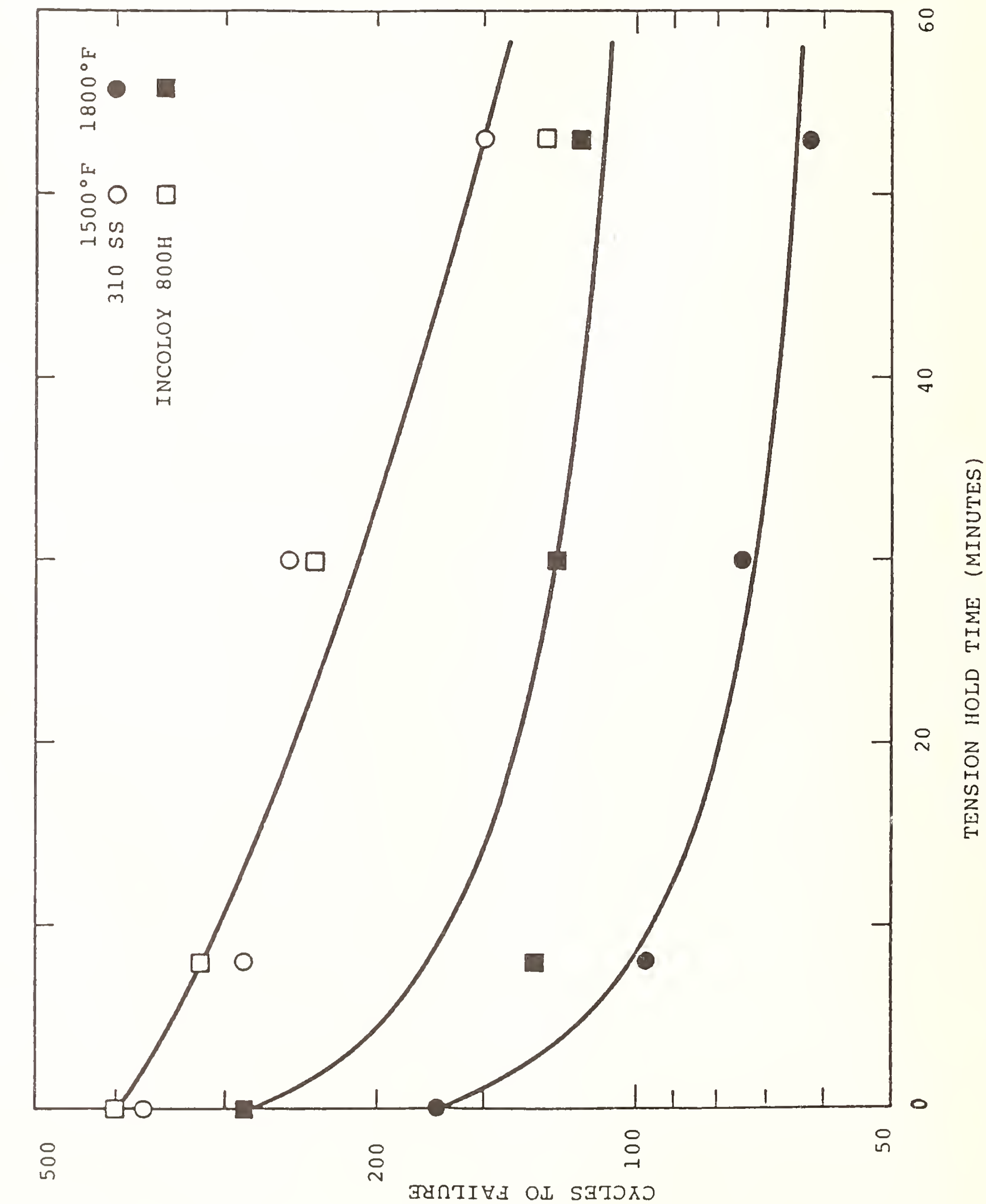


[a]Conventional 2T compact specimens were used with 0.125 in (3.1×10^{-3} m) deep side grooves incorporated to minimize the effect of plane stress. The incubation time was minimized by cyclic loading in H_2S at 1 Hz to induce an unoxidized sharp crack. Once the crack was propagating the load was raised to slightly over the maximum cyclic load (88 ksi$\sqrt{in}$, 97 MPa$\sqrt{m}$) and specimens were held in constant displacement (simulated bolt load test). Specimens were monitored for load drop indicating crack growth. When the load no longer decreased (at 26 days) the crack was arrested. The crack had grown 0.8 in (2×10^{-3} m). By measuring the compliance of the specimen crack growth can be assessed. K_{arrest} = 49 ksi$\sqrt{in}$ (54 MPa$\sqrt{m}$).

[b]Composition (wt %): 2.23 Cr, 0.97 Mo, 0.126 C, 0.45 Mn, 0.39 Si, 0.16 Ni, 0.10 Cu.

[c]Commercial high-purity H_2S, 50 psig 446 kPa) saturated with water at 25 °C.

EFFECT OF TENSION HOLD TIME[a] ON THE CYCLIC LIVES OF TWO ALLOYS[10]



[a] See Section B.3.1.16 for the low-cycle fatigue data plotted here for 310 SS and Incoloy 800H.

LOW-CYCLE FATIGUE TESTING FOR TWO ALLOYS[10]

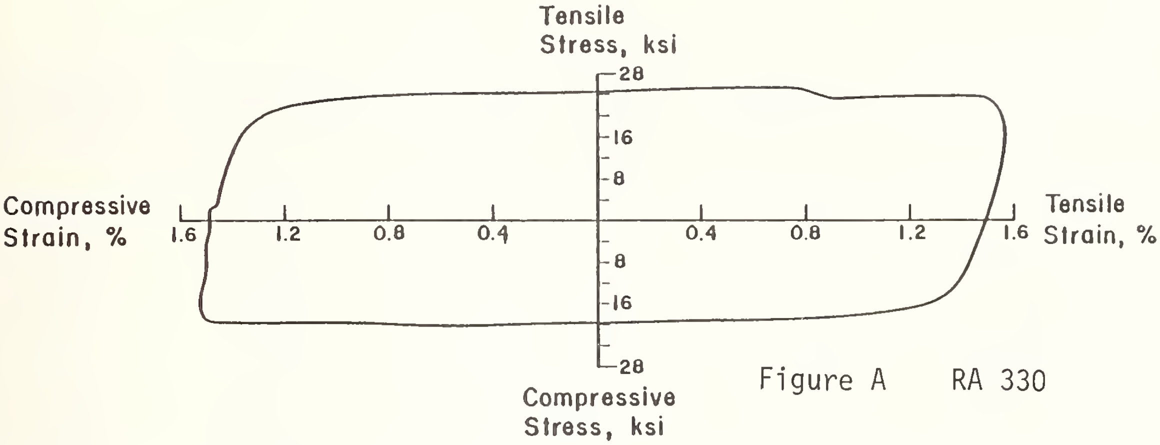


Figure A RA 330

Figure A shows a typical hysteresis loop for low-cycle fatigue testing in an environment of 67 atm argon/1 atm air (total 68 atm, 1000 psi) at 1500 °F between total strain limits of ±1.5%. Hold time was 10 minutes at both strain limits. The RA 330 fractured after 67 cycles.

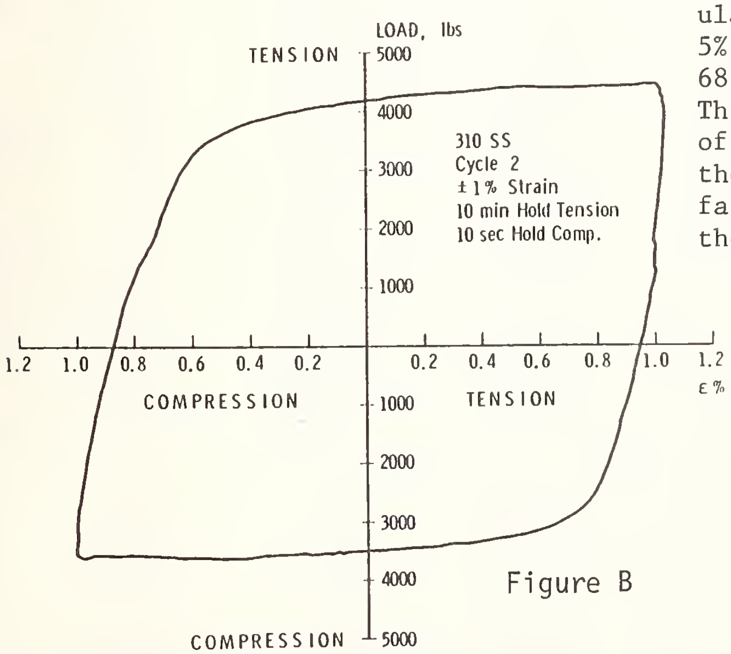


Figure B

Figure B shows the second cycle hysteresis loop for testing in a coal gasification atmosphere (simulated, 12% CO_2, 18% CO, 24% H_2, 5% CH_4, 0.5% H_2S, balance H_2O) at 68 atm (1000 psi) and 1500 °F. This second cycle loop is typical of the first 60 cycles after which the loads dropped rapidly and failure occurred at cycle 66 for the 310 SS.

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON THE STRESS-RUPTURE[b] OF SEVERAL ALLOYS[c] [10]

Heat[c]	Test Gas[a]	Temperature °F	Tensile Stress ksi	Hours to Failure	Elongation[d] %	Reduction in Area %	Minimum[e] Creep Rate %/h
INCOLOY 800H							
1	CGA	1200	23.0	37.1	44.0	53.4	
3	CGA, CF	1500	6.0	400.5	14.0	23.0	0.0164
2	CGA	1500	5.8	629.0	22.4	22.4	
2	CGA	1500	5.8	1624.2	28.6	42.5	
3	CGA, CF	1500	5.6	192.1	24.5	57.1	0.0282
3	CGA, CF	1500	5.5	176.2	18.4	14.5	0.0254
3	CGA, CF	1500	5.3	1758.4	20.0[f]	18.1	0.0081
2	CGA	1500	5.0	2855.6	30.3	24.4	
2	CGA	1500	4.7	4087.6	24.8	23.4	
3	CGA, CF	1500	4.7	4438.6	4.6[f]	8.9	0.0003
2	CGA	1500	4.6	7120.[g]	2.4[g]	2.0[g]	
2	CGA, CF	1500	4.5	2042.8	38.4	18.5	0.0049
3	CGA, CF	1500	4.3	3293.1	13.4[f]	49.4	0.0035
310 STAINLESS STEEL							
2	CGA	1500	3.7	721.2	80.4	50.0	
2	CGA	1500	3.6	397.6	46.7	45.7	
3	CGA, CF[h]	1500	3.5	1070.5	32.8	47.8	0.0062
2	CGA	1500	3.3	603.8	50.8	49.2	
1	CGA, CF	1500	3.2	1375.8	44.7[f]	32.10	0.0117
2	CGA	1500	3.0	1370.4	51.7	48.3	
2	CGA	1500	3.0	1120.1	64.4	49.2	
1	CGA	1500	3.0	64.3	41.5	37.3	
1	CGA, CF	1500	3.0	805.3	38.5[f]	32.6	0.0084
3	CGA, CF	1500	3.0	3253.8	42.8[f]	45.7	0.0081
2	CGA	1500	2.9	1615.9	55.7	48.3	
1	CGA, CF	1500	2.8	1267.8	47.8[f]	32.0	0.0099
3	CGA, CF	1500	2.8	1541.9	34.4[f]	34.1	0.0104[i]
3	CGA, CF	1500	2.7	1093.9	28.1[f]	29.9	0.0075
2	CGA, CF	1500	2.5	1734.4	45.9	38.4[j]	0.0127[j]
3	CGA, CF	1500	2.4	2366.2	38.6[f]	36.4	0.0071
2	CGA	1500	2.0	2956.[g]	35.1[g]	17.0[g]	
3	CGA, CF	1500	1.8	4286.6	28.2[f]	33.0	0.0020
HAYNES 188							
1	CGA	1500	20.0	34.8	57.4	59.8	
1	CGA	1500	13.0	946.0	31.3	33.0	
1	Argon-air	1500	13.0	565.8	24.3	57.5	
1	Argon-air	1800	3.5	31.8	83.3	40.4	
1	CGA	1800	3.0	201.8	63.2	63.8	
1	Argon-air	1800	3.0	268.0	66.0	64.8	

(Table Continued)

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON THE STRESS-RUPTURE[b] OF SEVERAL ALLOYS[c][10], Continued

Heat[c]	Test Gas[a]	Temperature °F	Tensile Stress ksi	Hours to Failure	Elongation[d] %	Reduction in Area %	Minimum[e] Creep Rate %/h
			RA 333				
1	CGA	1500	9.0	348.8	45.1	55.4	
2	CGA	1500	8.8	276.6	21.2	18.1	
1	Argon-air	1500	8.0	372.3	49.2	70.2	
3	CGA	1500	6.4	1349.4	53.6	55.7	
2	CGA	1500	6.3	872.6	18.5	17.7	
3	CGA	1500	6.3	2220.3	26.0	33.8	
3	CGA, CF	1500	6.0	2187.0	12.8	22.4	0.0020
3	CGA, CF	1500	6.0	1004.3	24.3	52.0	0.0121
3	CGA, CF	1500	6.0	1363.2	20.8	50.1	0.0082
1	CGA, CF	1500	6.0	629.1	27.1[f]	49.8	0.0268
1	CGA, CF	1500	5.7	733.2	45.9[f]	51.2	0.0099
3	CGA, R	1500	5.7	4902.4	27.1[f]	40.9	
1	CGA, CF	1500	5.5	600.3	31.4[f]	57.6	0.0054
2	CGA	1500	5.4	1146.2	14.4	16.7	
1	CGA, CF	1500	5.4	2206.0	24.4[f]	31.4	0.0026
3	CGA, R	1500	5.4	4971.4	31.7[f]	54.9	
3	CGA, CF	1500	5.4	3723.6	37.2[f]	37.3	0.0031
1	CGA, CF	1500	5.2	1063.2	26.6[f]	51.7	0.0029
3	CGA, CF	1500	5.2	2178.8	35.9[f]	47.2[f]	0.0019
3	CGA	1500	5.0	5049.2	11.2	37.3	
2	CGA	1500	4.9	4356.6	18.2	17.0	
2	CGA	1500	4.9	1224.[g]	15.3[g]	11.9[g]	
2	CGA	1500	4.5	1754.[g]	8.7[g]	6.2[g]	
3	CGA, CF	1500	4.4	6016.6	23.4[f]	33.4	0.0029[k]
2	CGA, CF	1500	4.3	4200.3	10.6[f]	15.6	0.0013
			INCONEL 657				
1	CGA	1200	22.0	1839.1	4.7	3.9	
1	CGA	1500	10.0	29.3	12.6	36.4	
1	CGA	1500	6.5	726.8	10.5	8.9	
1	CGA	1500	6.0	155.4	6.0	16.7	
1	CGA	1800	2.0	51.6	9.5	14.9	
			HK-40				
1	CGA	1500	4.0	1318.0	4.4	4.3	
			STELLITE 6B				
1	CGA	1500	13.0	2016.1	4.0	3.1	

[a]CGA = coal gasification atmosphere. Gas supply system to the autoclaves, in which the testing took place, produces the CGA mixture by sparging a bottled

(Table Continued)

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON THE STRESS-RUPTURE[b] OF SEVERAL ALLOYS[c][10], Continued

Footnotes continued

gas mixture of CO_2, CO, H_2, CH_4, and H_2S through water at 450 °F and 1000 psi. Gas components, except water, are constantly replenished by the pre-mixed gas. The composition (12% CO_2, 18% CO, 24% H_2, 5% CH_4, and 0.5% H_2S, balance H_2O) of the CGA is more stable than in earlier testing. See Section B.3.1.14 for these same alloys tested in air and in CGA. Note that in this table (B.3.1.164) there is no ammonia in the CGA as there was in tests reported in B.3.1.14. All tests above were run at pressure of 68 atm (1000 psi). After equilibration of the system as to temperature and pressure under argon, the argon was replaced by CGA. When the argon valve was closed and the CGA inlet valve opened, the CGA outlet valve was opened five times for 2-3 seconds each time. The specimen was then soaked in the CGA for 24 hours before testing. During "static" testing (designated by CGA in the table) the outlet valve was opened approximately 2 seconds once each hour. CGA, CF refers to tests in a continuously-flowing ($\sim$0.5 ft^3/h or 14.2 l/h) atmosphere during testing. For tests designated CGA, R, the atmosphere was "refreshed" by manually replacing the gas once an hour. The test gas designated argon-air consisted of 67 atm argon-1 atm air.

[b]Compare Section B.3.1.14 for earlier testing of these same alloys. The heats used in the B.3.1.14 tests are the same as those designated by heat 1 in this table.

[c]Three different heats of the various alloys were tested, heat number 1 in this table being the heat in testing reported in Section B.3.1.14.

[d]Elongation based on crosshead displacement except for tests otherwise indicated.

[e]From extensometer readings.

[f]Elongation based on post-test measurements.

[g]Run terminated before failure.

[h]Continuous flow of CGA only during the first 311 hours of the test.

[i]Valid creep-rate data during first 528 hours; erratic data thereafter, not plotted.

[j]Erratic extension data, creep rate estimated on basis of total extension, not plotted. [Another table with the same stress-rupture data gives a value of 22.0% for the Reduction in Area.]

[k]Erratic extension data, minimum creep rate estimated on basis of total extension less 0.199 inch extension recorded during last 168 hours, not plotted.

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON THE STRESS-RUPTURE[b] OF SEVERAL WELDMENTS[c] [10]

Heat[c]	Test Gas[a]	Temperature °F	Tensile Stress ksi	Hours to Failure	Elongation[d] %	Reduction in Area %	FL[e]
WELDED INCOLOY 800H							
1	CGA	1200	20.0	439.1	18.2	37.9	B
1	Argon-air	1500	9.0	28.4	18.8	56.0	B
1	Argon-air	1500	8.5	138.3	6.2	15.9	W
1	CGA	1500	7.6	352.5		0.78	HAZ
1	CGA	1500	6.5	307.2		1.9	W
1	Argon-air	1500	6.5	1057.2	2.8	5.5	W
1	Argon-air	1500	6.5	382.5	3.9	2.0	W
1	CGA	1500	5.5	536.8	1.8	0	HAZ
1	CGA	1800	2.5	312.2	8.4	16.4	W
1	CGA	1800	2.5	251.0		2.3	HAZ & W
1	CGA	1800	2.0	194.8		5.9	HAZ
1	CGA	1800	1.5	549.8	0.4	6.2	W
WELDED INCOLOY 800H ALUMINIZED							
1	CGA	1200	13.0	338.0		30.5	HAZ
1	CGA	1500	7.6	48.5		6.1	HAZ
1	CGA	1500	17.5	1022.		16.5	W & HAZ
WELDED 310 SS							
1	CGA	1200	10.0	793.3	5.0	2.4	W
1	CGA	1500	8.3	17.0	17.0	13.7	W
1	CGA	1500	4.0	133.8	9.2	4.7	W
1	CGA	1500	2.5	119.8	7.2	6.2	W
1	CGA	1500	2.5	498.0	2.9	0	W
1	CGA	1800	0.6	384.2	28.9	20.6	W
1	CGA	1800	0.5	633.7		35.8	W
WELDED RA 333							
1	CGA	1200	24.0	345.3	52.6	64.6	B
1	CGA	1200	20.0	137.0	17.6	20.6	W
1	CGA	1200	20.0	679.7			
1	CGA	1200	18.0	1205.		2.3	W
1	CGA	1500	9.0	27.6	53.0	82.7	B
1	CGA	1500	9.0	119.3	12.0	5.9	W
1	CGA	1500	6.0	674.2	16.7	12.7	W
1	CGA	1500	5.5	962.3	9.2	9.3	W
1	CGA	1800	1.5	36.8	49.2	72.5	B
1	CGA	1800	1.3	82.4		6.7	W
1	CGA	1800	0.9	188.6		66.8	W & B
1	CGA	1800	0.8	54.3	38.8	28.9	B

(Table Continued)

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON THE STRESS-RUPTURE[b] OF SEVERAL WELDMENTS[c][10], Continued

Heat[c]	Test Gas[a]	Temperature °F	Tensile Stress ksi	Hours to Failure	Elongation[d] %	Reduction in Area %	FL[e]
WELDED HAYNES 188							
1	CGA	1200	44.0	384.		5.4	W & HAZ
1	CGA	1200	22.0	441.0	8.7	3.1	W
1	CGA	1200	20.0	679.7	15.9	17.0	W
1	CGA	1500	20.0	185.2	25.9	24.1	W
1	CGA	1500	17.0	488.0	27.2	43.8	B
1	CGA	1500	15.0	580.2	32.7	41.3	B
1	CGA	1500	15.0	718.4	31.6	42.5	B
1	CGA	1500	15.0	504.0	23.0	40.4	B
1	CGA	1500	15.0	121.7	31.4	46.5	B
1	CGA	1500	14.0	202.5	22.8	46.7	B
1	CGA	1500	13.0	407.6	37.8	55.9	B
1	CGA	1800	3.5	283.		60.4	B
1	CGA	1800	3.5	133.0	42.4	64.0	B
1	CGA	1800	3.0	109.5	56.5	70.1	B
1	CGA	1800	2.5	340.9	42.4	65.8	B
WELDED INCONEL 657							
1	CGA	1200	35.0	142.3		1.9	W
1	CGA	1200	21.0	2322.6	3.3	3.9	B
1	CGA	1500	6.0	2229.5	4.9	0.8	W
1	CGA	1800	1.9	56.8	13.9	47.9	W
1	CGA	1800	1.5	21.3	14.4	42.4	B

[a]CGA = coal gasification atmosphere. Gas supply system to the autoclaves, in which the testing took place, produces the CGA mixture by sparging a bottled gas mixture of CO_2, CO, H_2, CH_4, and H_2S through water at 450 °F and 1000 psi. Gas components except water are constantly replenished by pre-mixed gas. The composition (12% CO_2, 18% CO, 24% H_2, 5% CH_4, and 0.5% H_2S, balance H_2O) of the CGA is more stable than in earlier tests. See Section B.3.1.13 for these same weldments tested in CGA. Note that in this table (B.3.1.165) there is no ammonia in the CGA as there was in the tests reported in B.3.1.13. All tests above were run at a pressure of 68 atm (1000 psi). After equilibration of the system as to temperature and pressure under argon, the argon was replaced by CGA. When the argon valve was closed and the CGA inlet valve opened, the CGA outlet valve was opened five times for 2-3 seconds each time. The specimen was then soaked in the CGA for 24 hours before testing. During "static" testing (designated by CGA above) the outlet valve was opened approximately 2 seconds once each hour. The test gas designated argon-air consisted of 67 atm argon-1 atm air.

(Table Continued)

EFFECT OF COAL GASIFICATION ATMOSPHERE[a] ON THE STRESS-RUPTURE[b] OF SEVERAL WELDMENTS[c][10], Continued

Footnotes continued

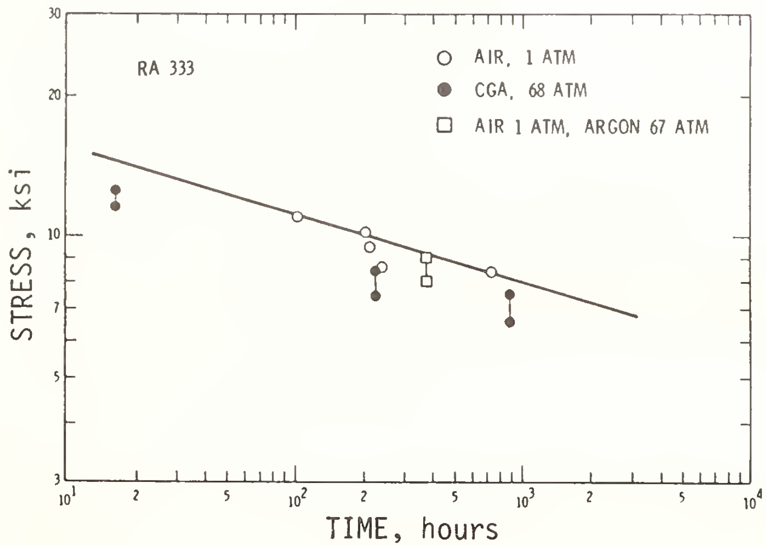
[b]Compare Section B.3.1.13 for earlier testing of these same weldments. The heat designated as 1 above is the same heat as the heat of the weldments included in B.3.1.13. [Heat number was included to aid in comparisons with Section B.3.1.164.]

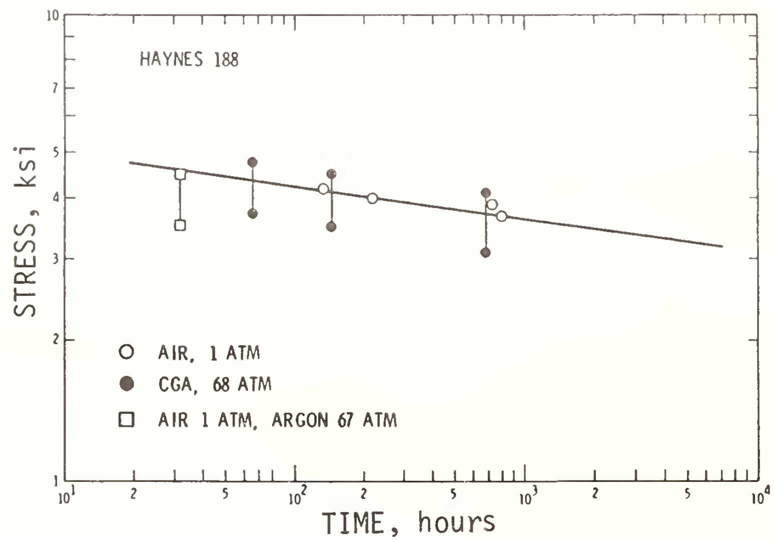
[c]The same heats of the various weldments correspond to the heats used for the weldments reported in B.3.1.13.

[d]Elongation based on crosshead displacement.

[e]FL = failure location, W = weld metal, B = base metal, HAZ = heat affected zone.

COMPARISON OF APPLIED STRESS[a] AND EFFECTIVE STRESS[b] FOR HIGH-PRESSURE TESTING[c] OF TWO ALLOYS[10]





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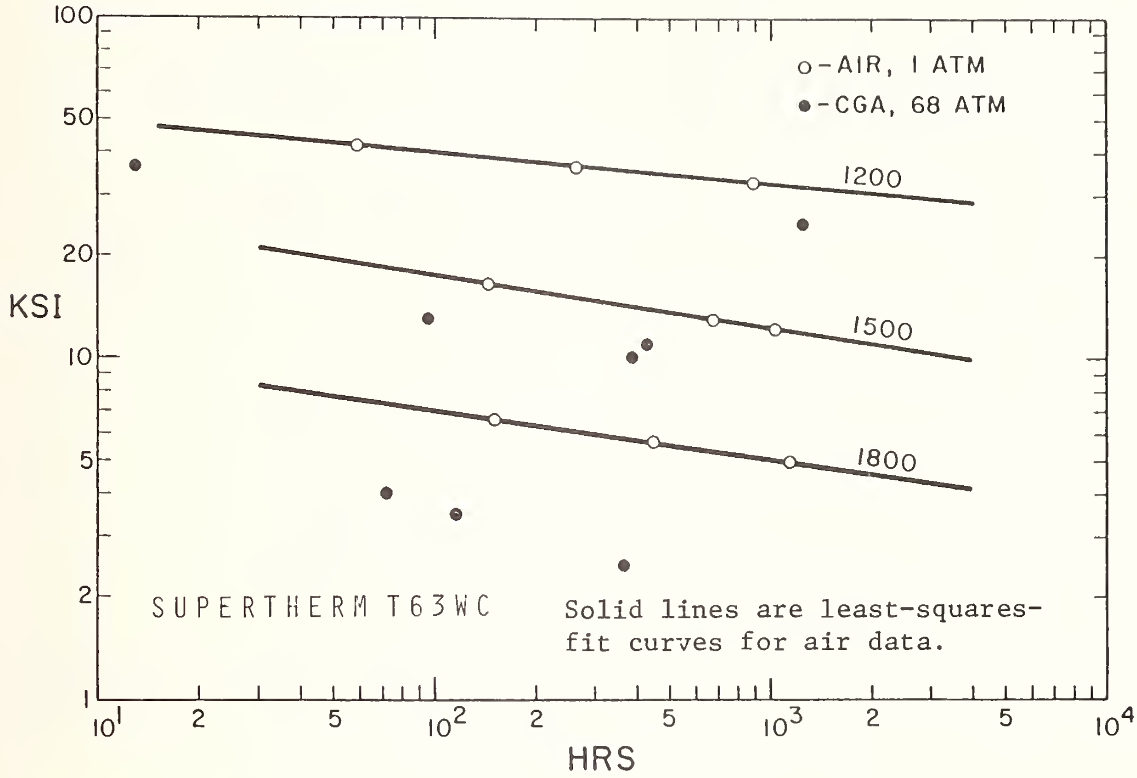
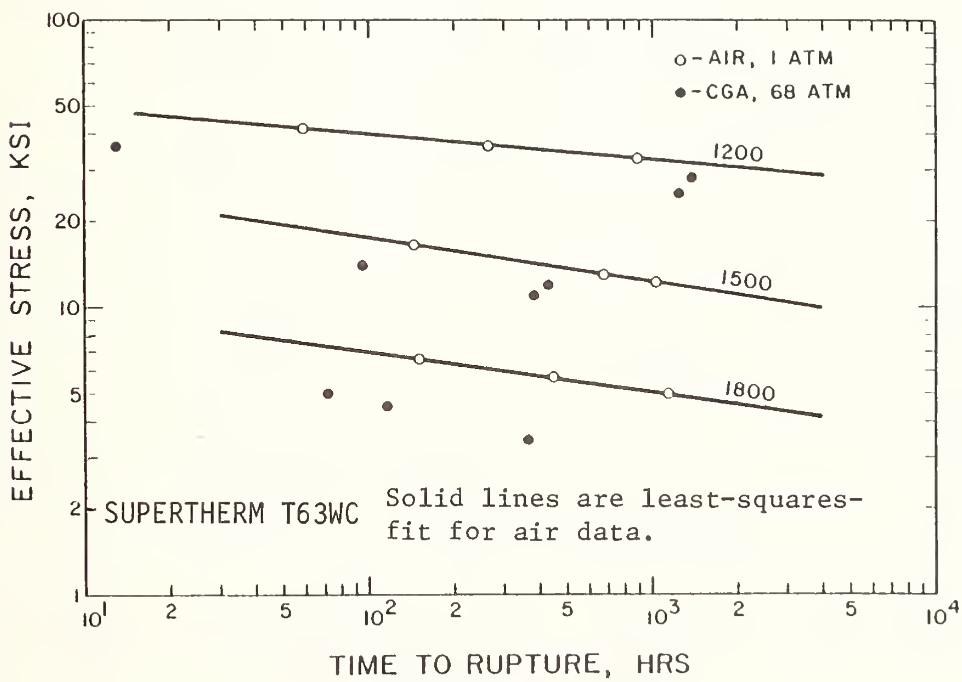
[a] Applied axial tensile stress, plotted as the lower points for the high-pressure data in the stress-rupture plot.

[b] Sum of the axial stress and the pressure (assuming that necking behavior and ductility are the same in high- and ambient-pressure tests), plotted as the upper points for the high-pressure data.

[c] Testing and conditions are the same as that given in B.3.1.14 and B.3.1.164.

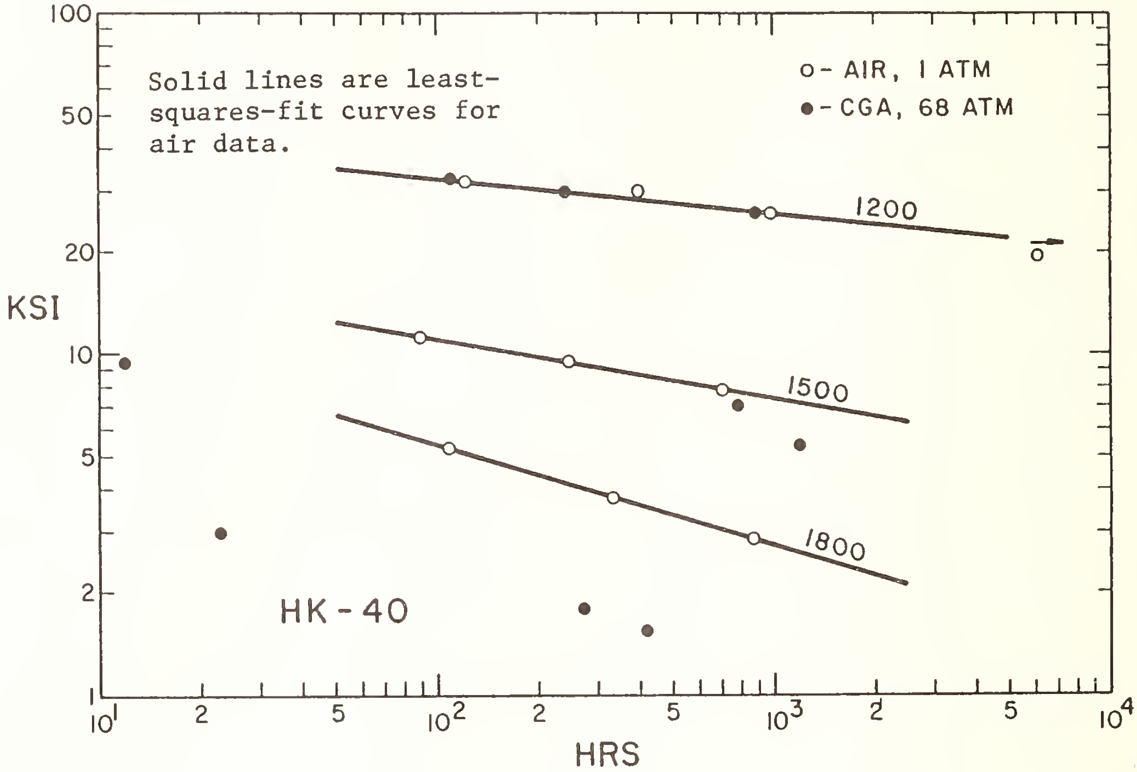
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10]

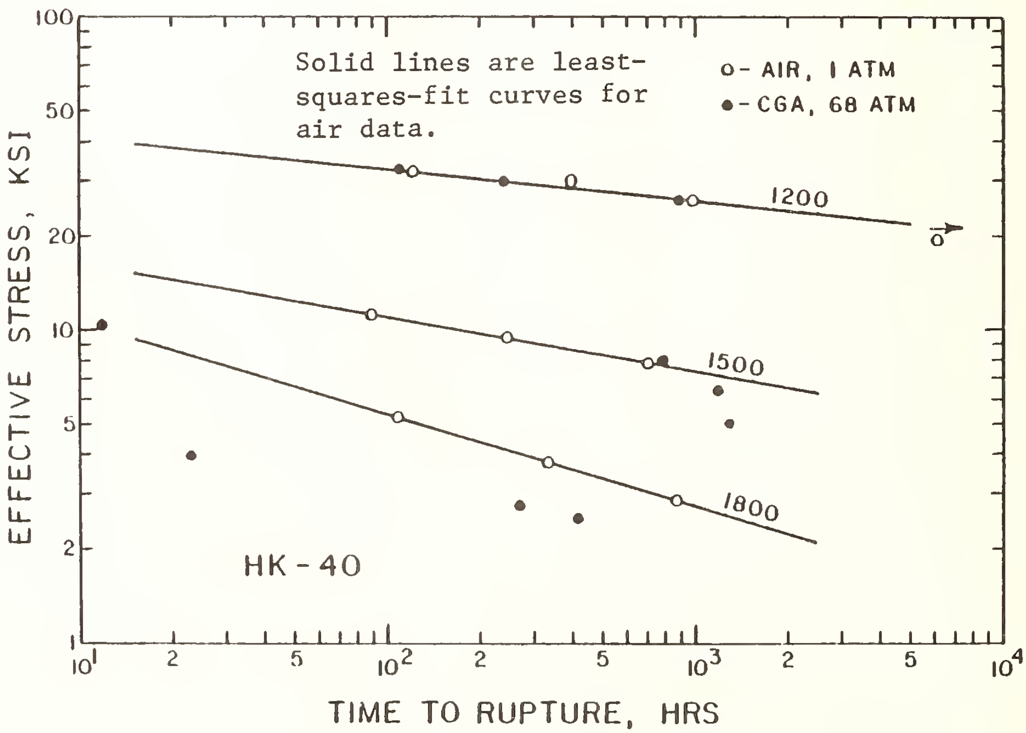




(Data Continued)

STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued





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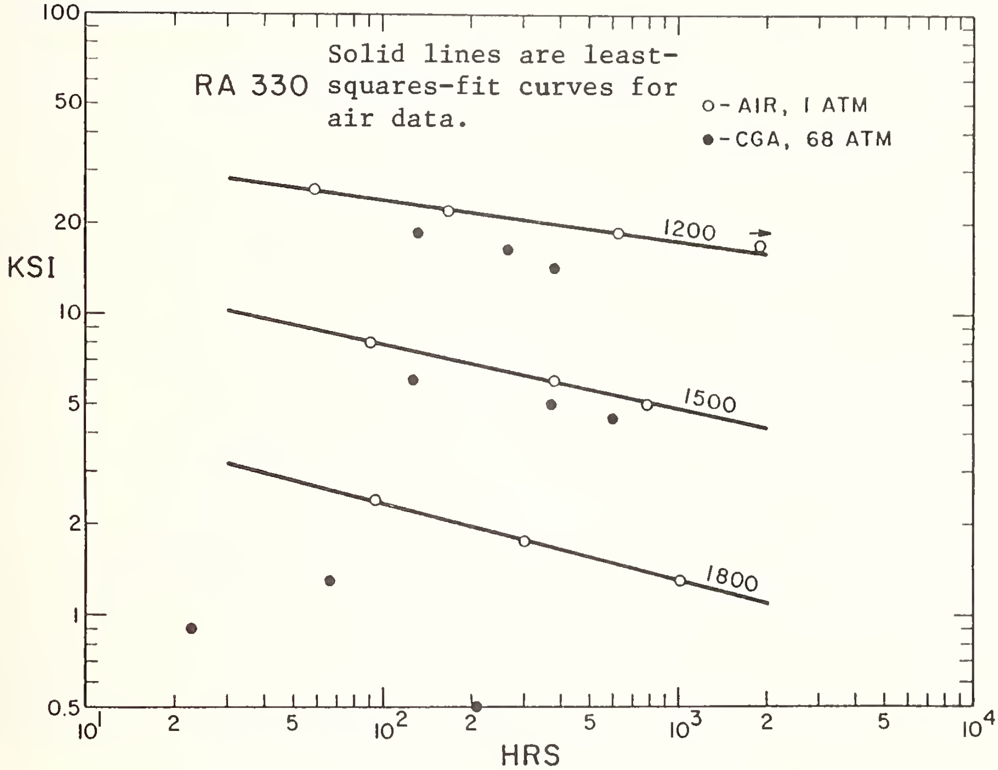
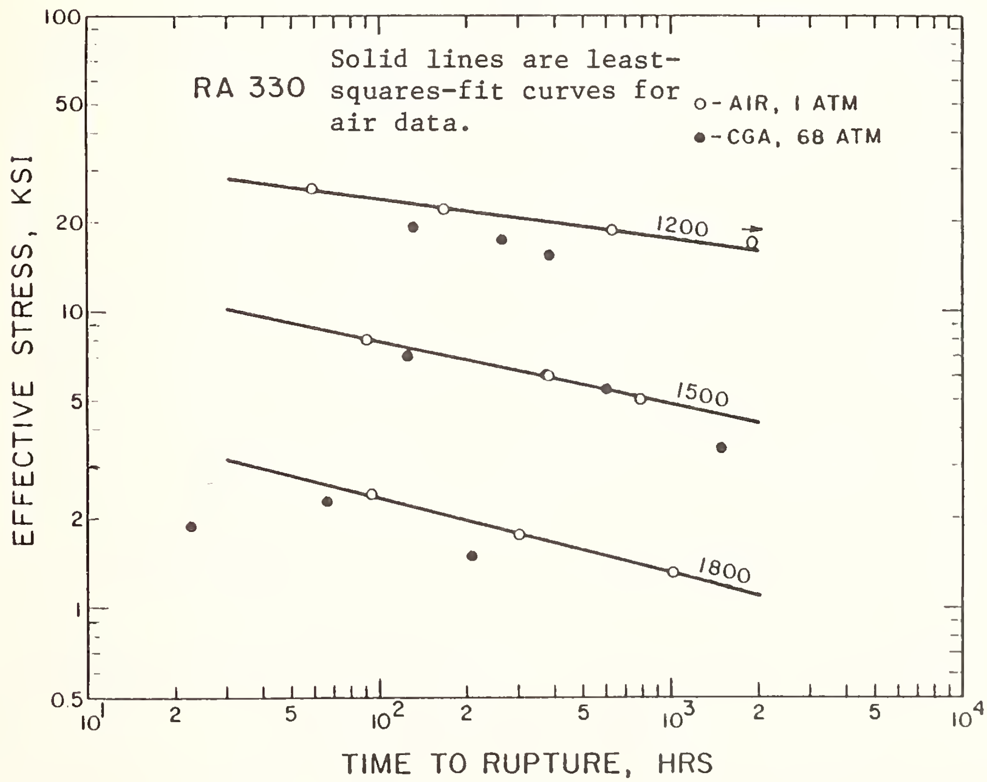
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued





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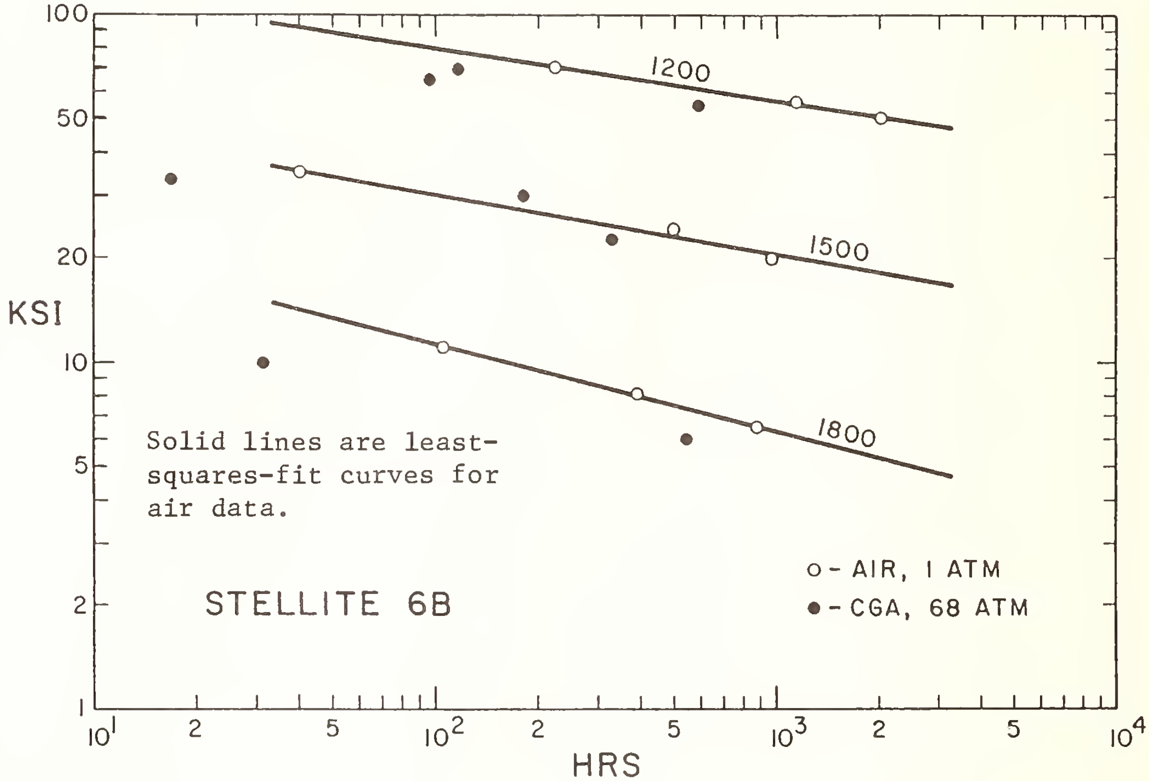
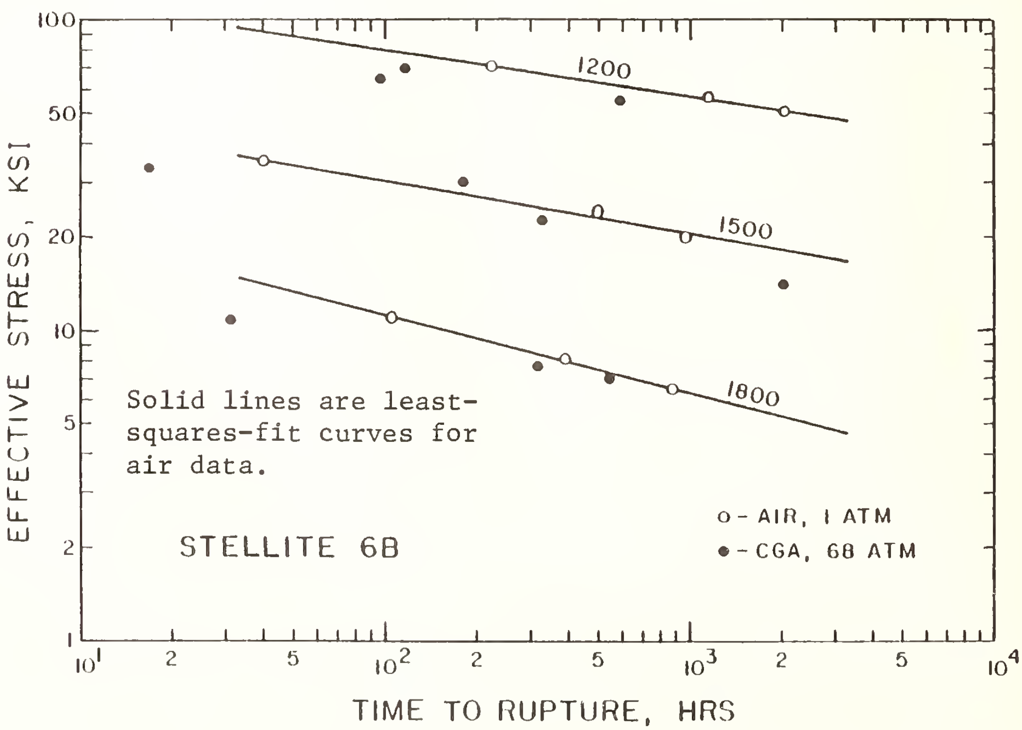
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued





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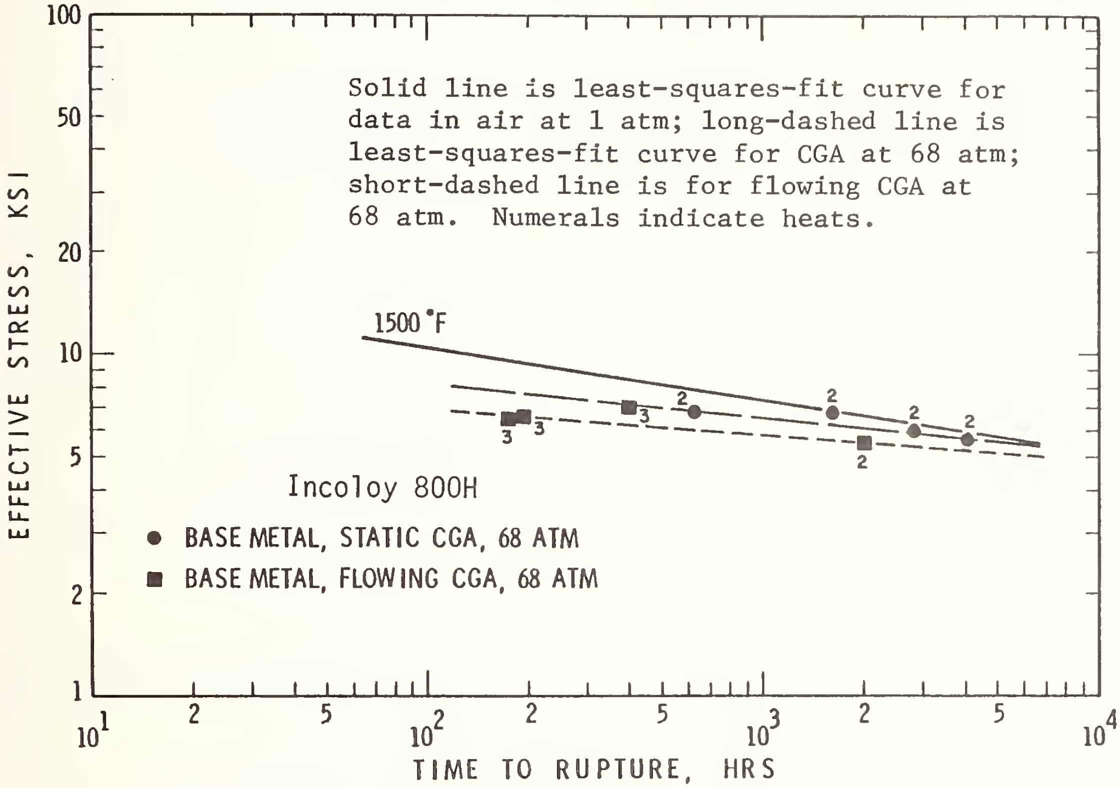
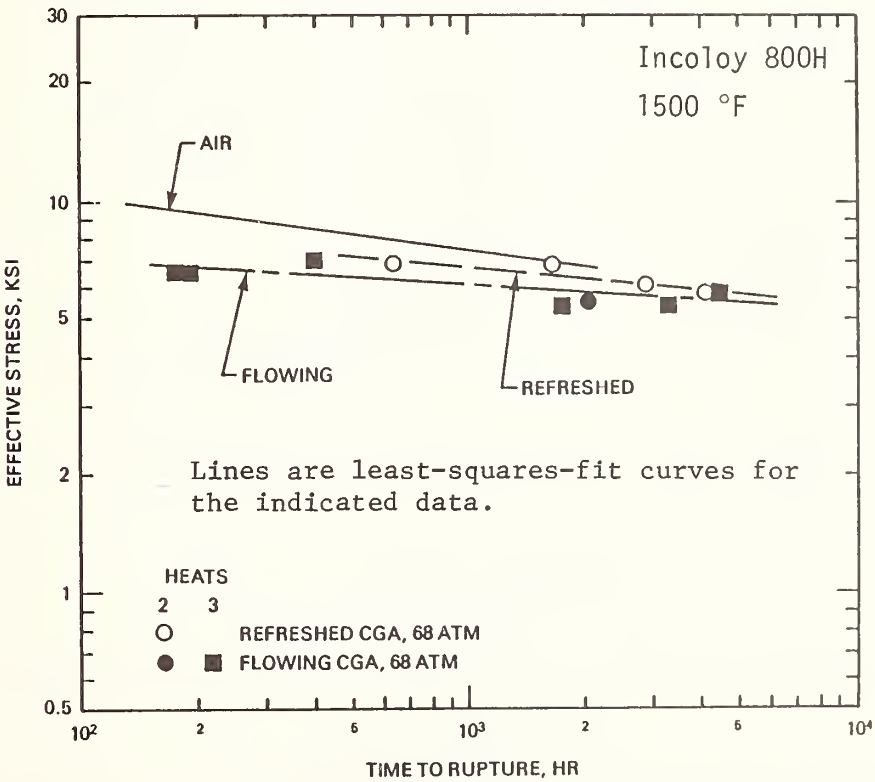
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued





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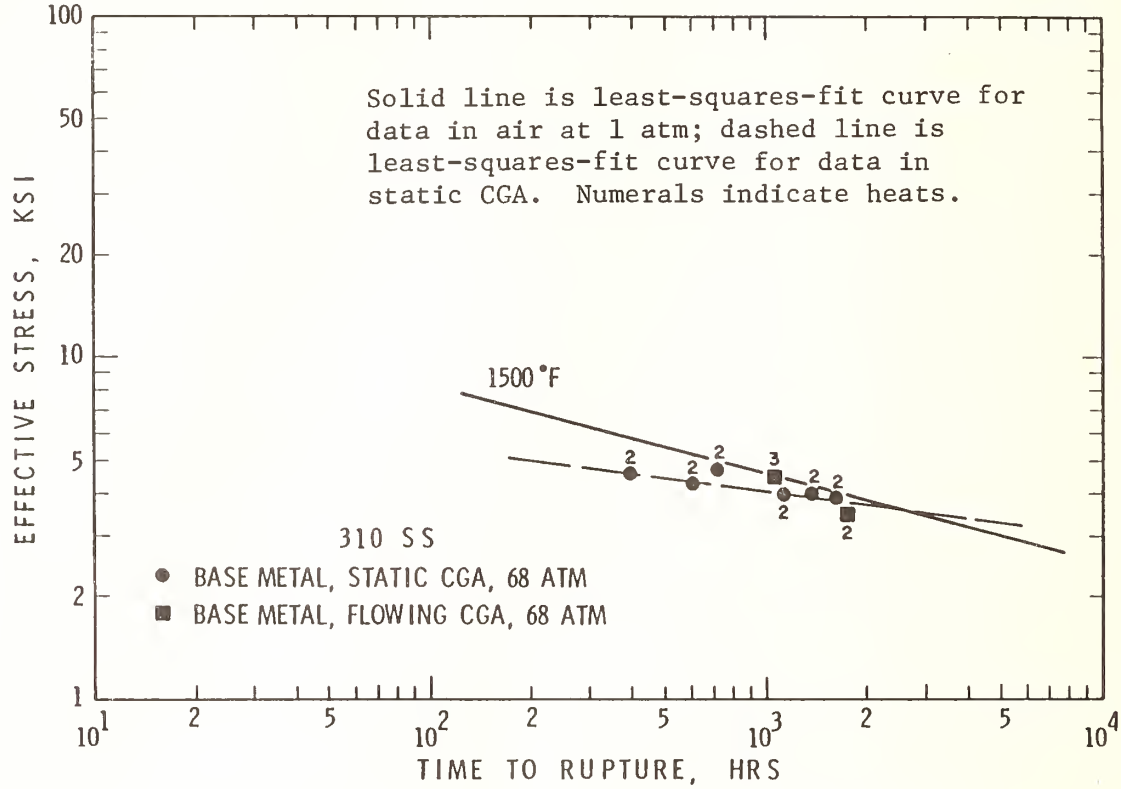
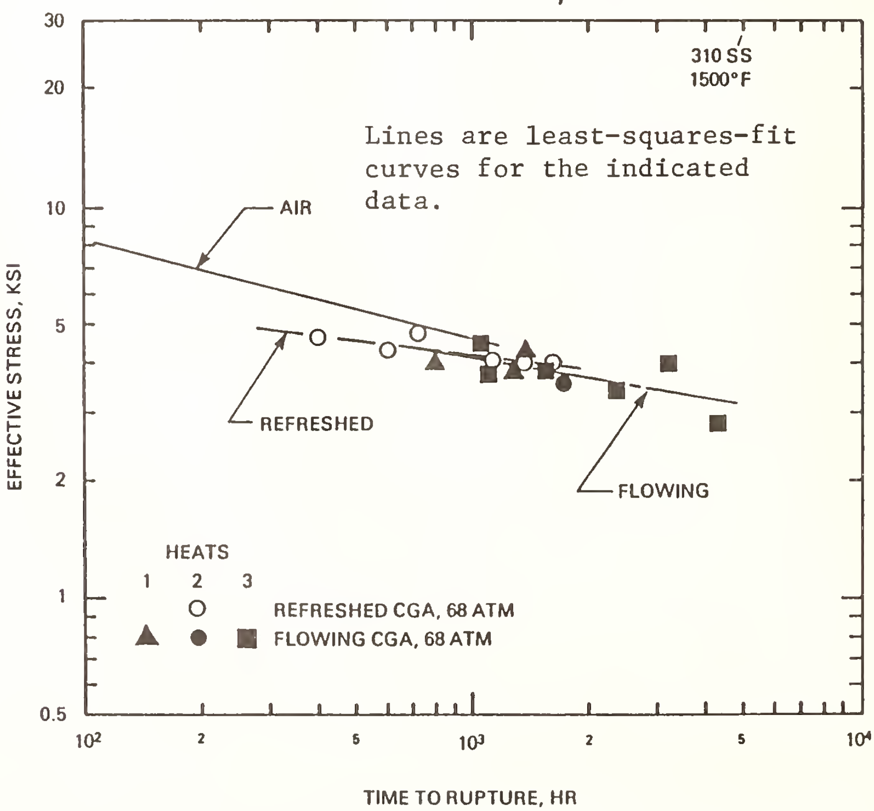
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued





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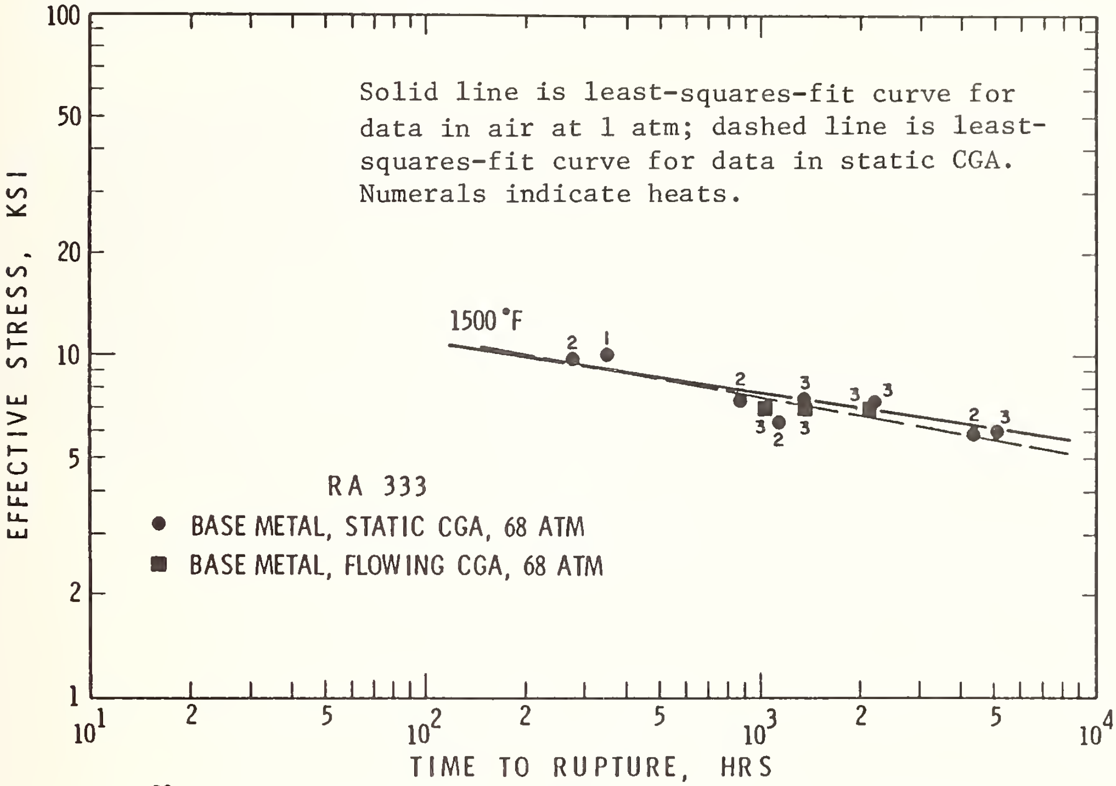
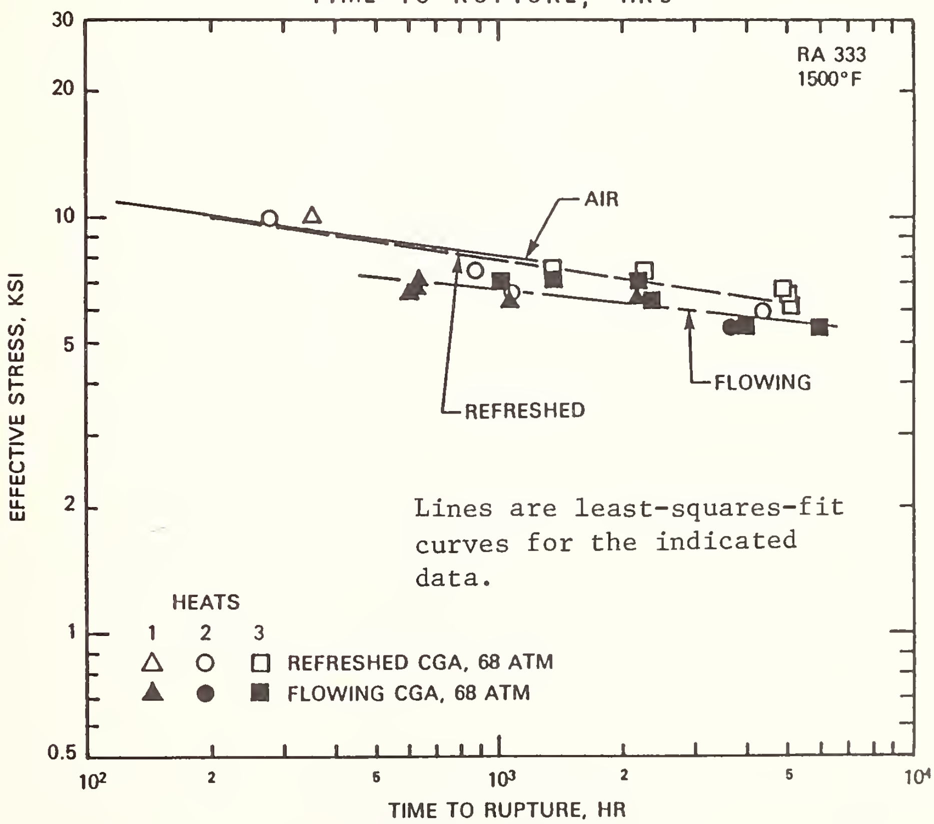
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued





(Data Continued)

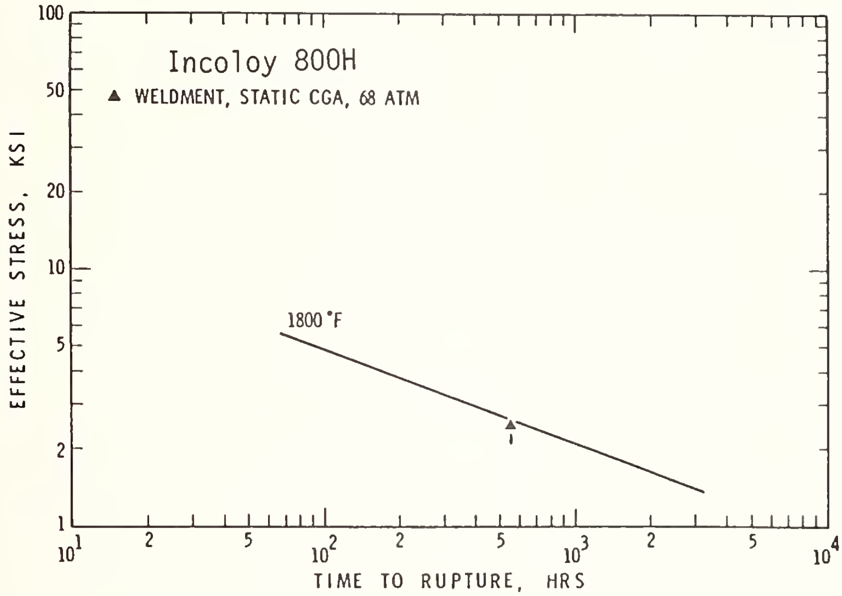
STRESS-RUPTURE DATA[a] FOR VARIOUS ALLOYS IN CGA[b][10], Continued

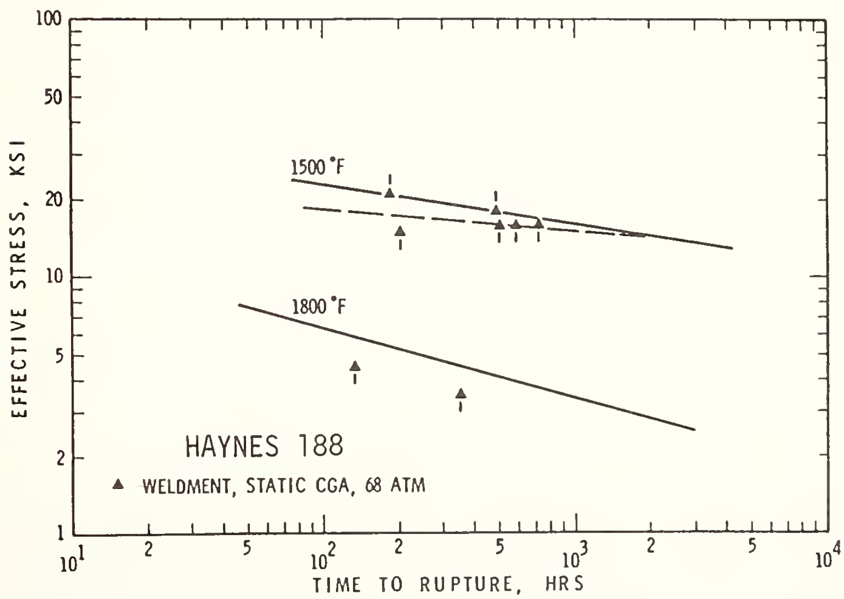
Footnotes

[a]Applied axial stress or effective stress in ksi is plotted against the time to rupture in hours. See Sections B.3.1.14 and B.3.1.164 for the data plotted here and for definitions of the test atmospheres. Arrow over test points indicate tests terminated prior to rupture. Figures bearing an ordinate label of ksi only are for axial stress only. The effective stress is the sum of applied axial stress and environmental pressure (see Section B.3.1.166). There is overlap in the data. Both stress plots are included where they were available because the applied axial stress is that given in Sections B.3.1.14 and B.3.1.164 but the effective stress plots in general contain more data points. Differences in the data are most noticeable for the lower stress tests.

[b]CGA = coal gasification atmosphere.

STRESS-RUPTURE DATA[a] FOR SEVERAL WELDMENTS[b] IN CGA[c][10]





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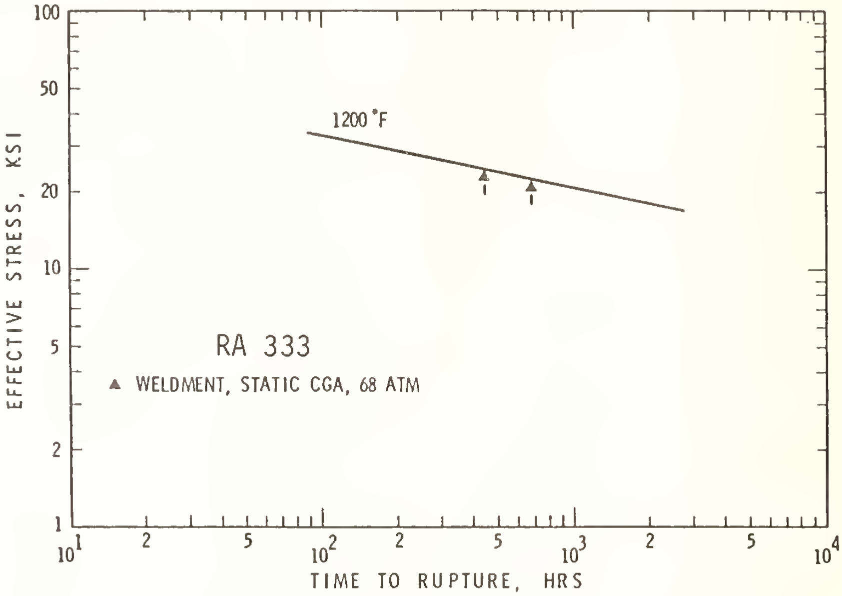
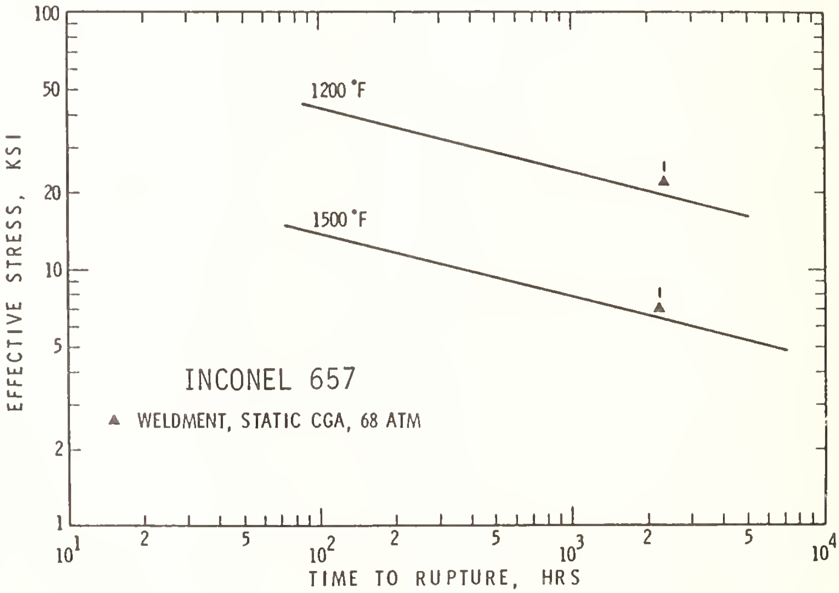
STRESS-RUPTURE DATA[a] FOR SEVERAL WELDMENTS[b] IN CGA[c][10], Continued





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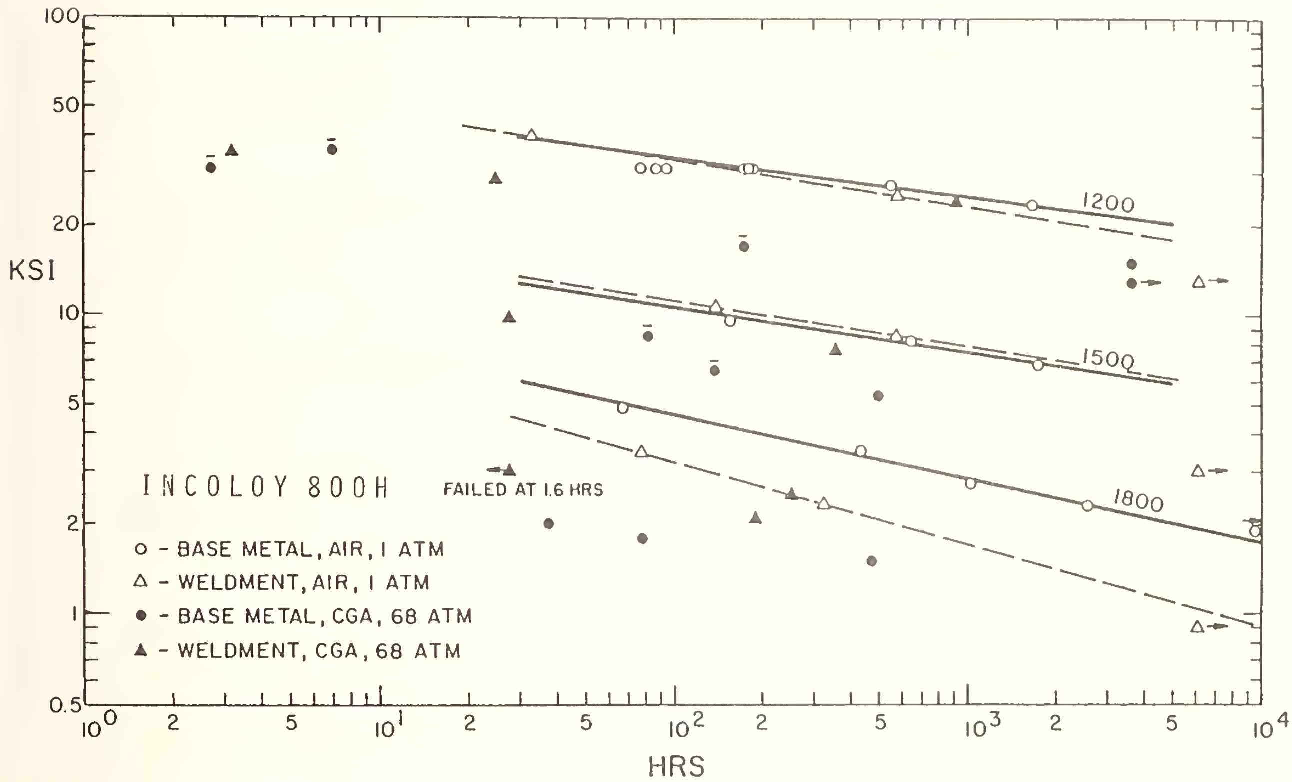
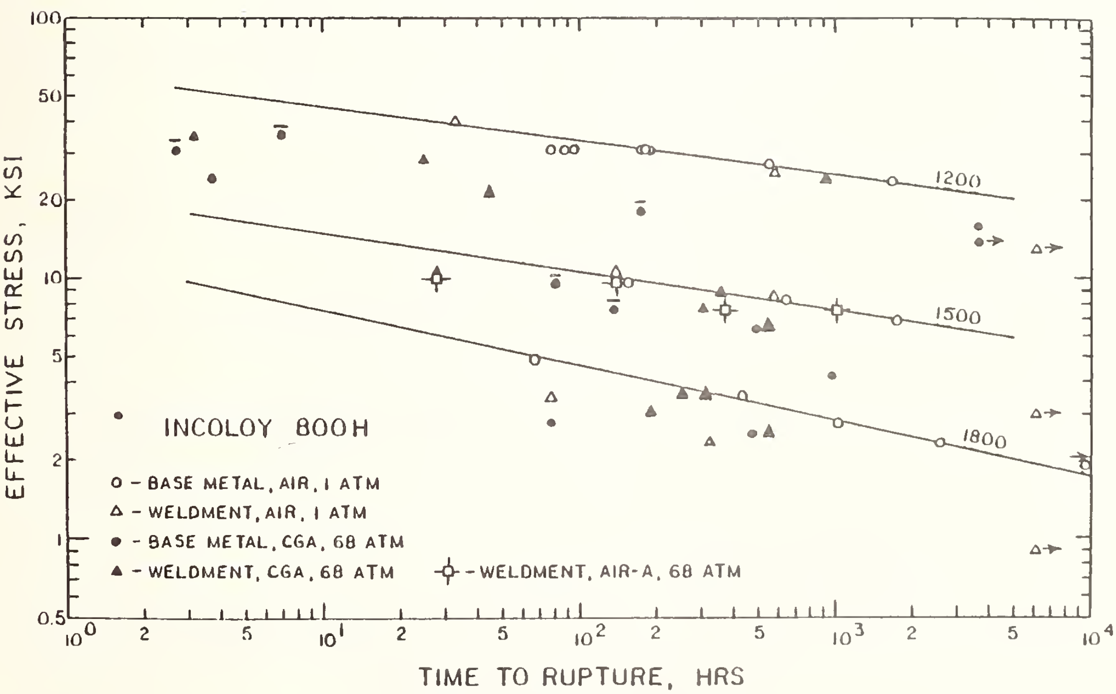
[a]Stress-rupture data from Section B.3.1.165. The effective stress (see Section B.3.1.166) is plotted here as opposed to the applied stress values given in B.3.1.165. The solid lines are least-squares-fit curves for data in air at 1 atm. The dashed line is the least-squares-fit curve for the coal gasification atmosphere data at 1500 °F.

[b]The numerals on the data points indicate heat numbers (all weldment data are for specimens made from heat 1 material.

[c]CGA = coal gasification atmosphere.

STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10]





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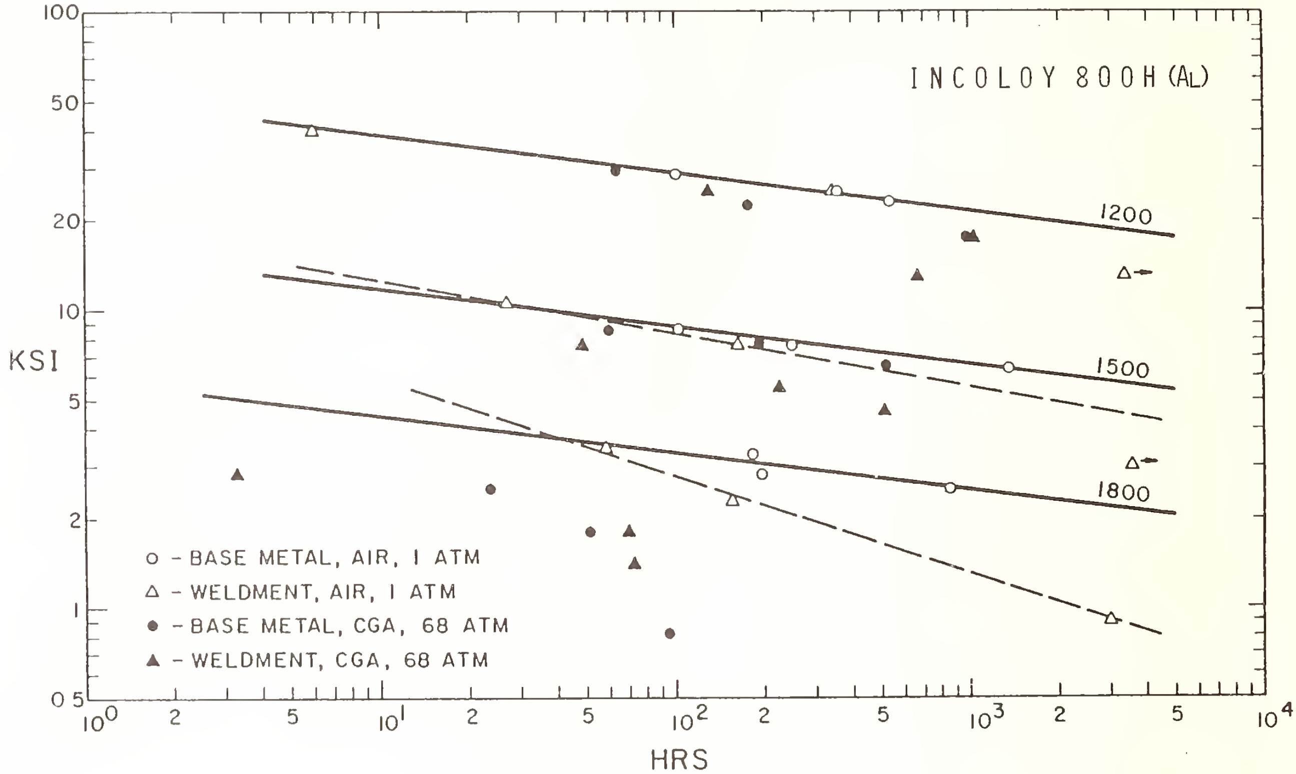
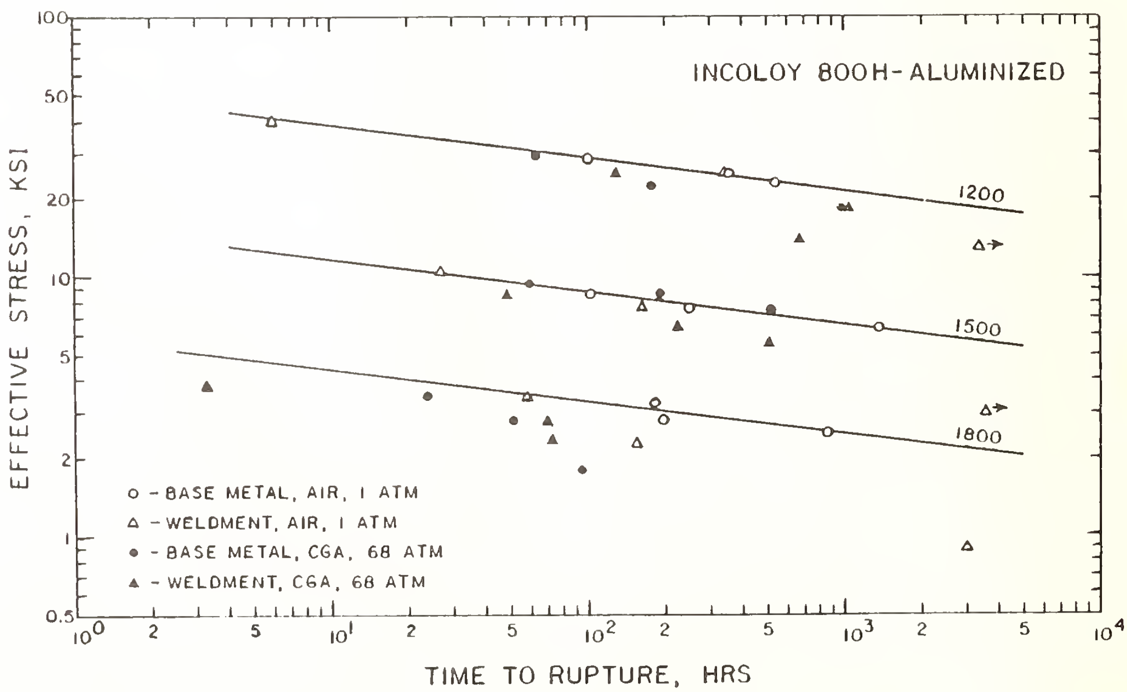
STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10], Continued





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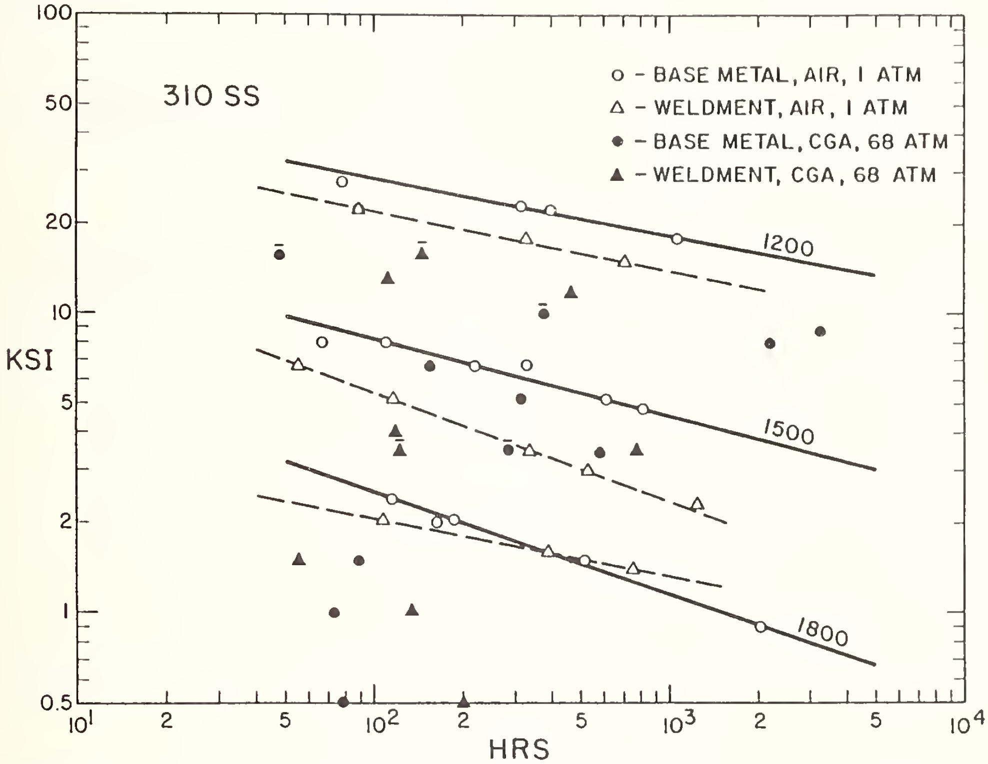
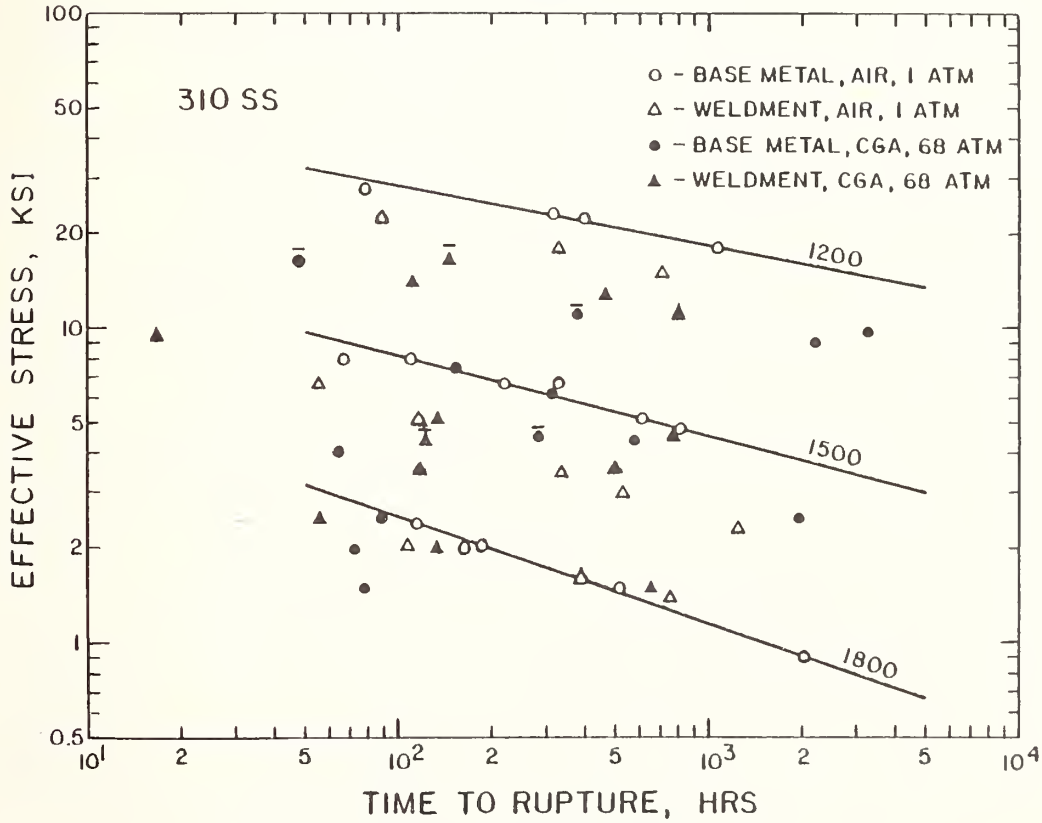
STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10], Continued





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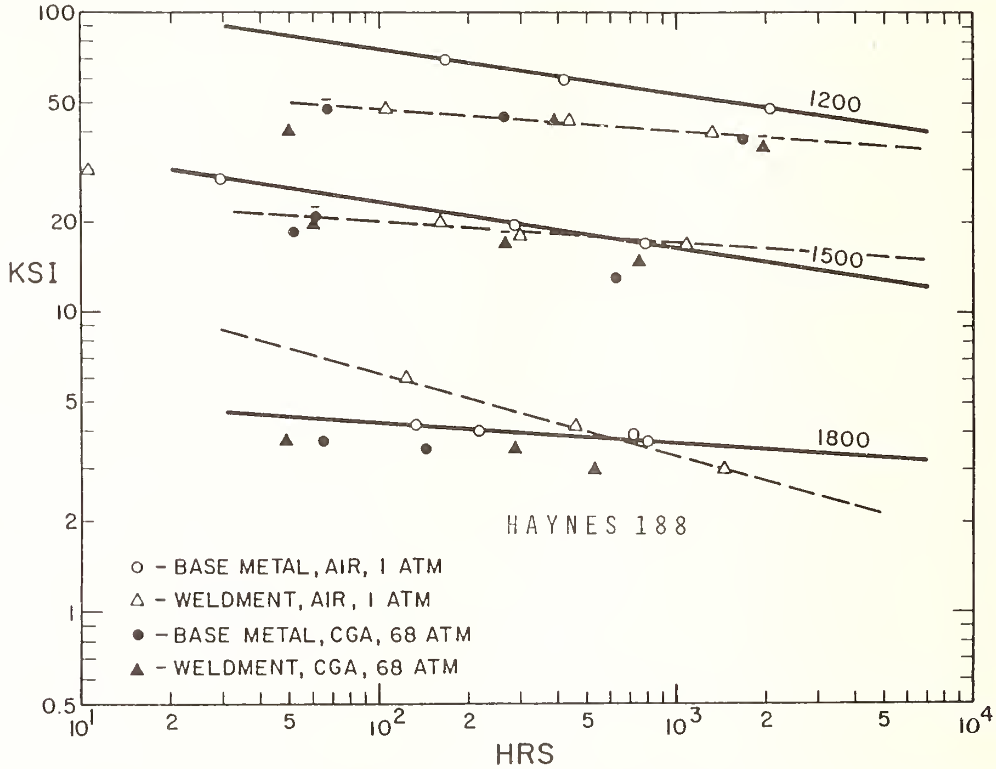
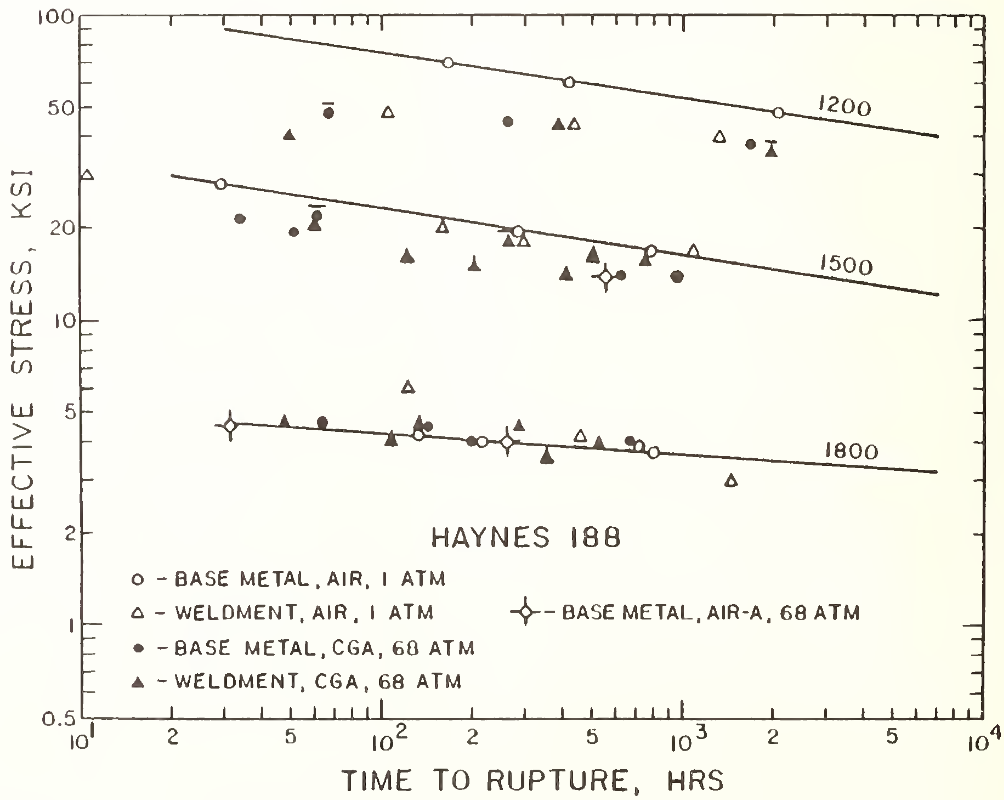
STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10], Continued





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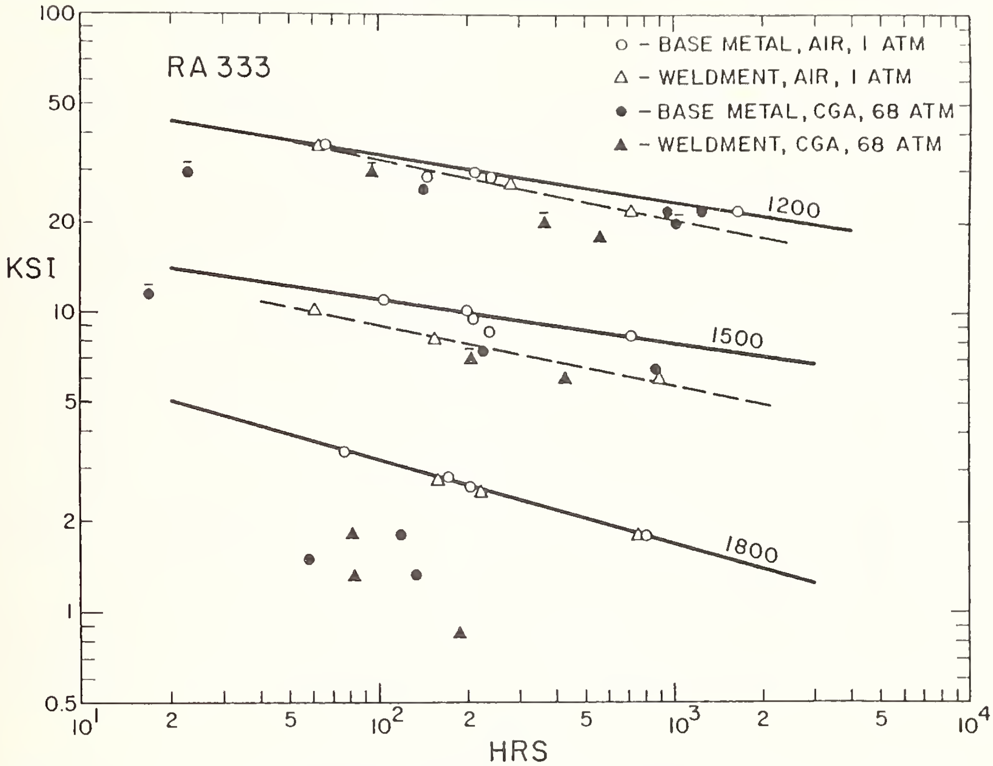
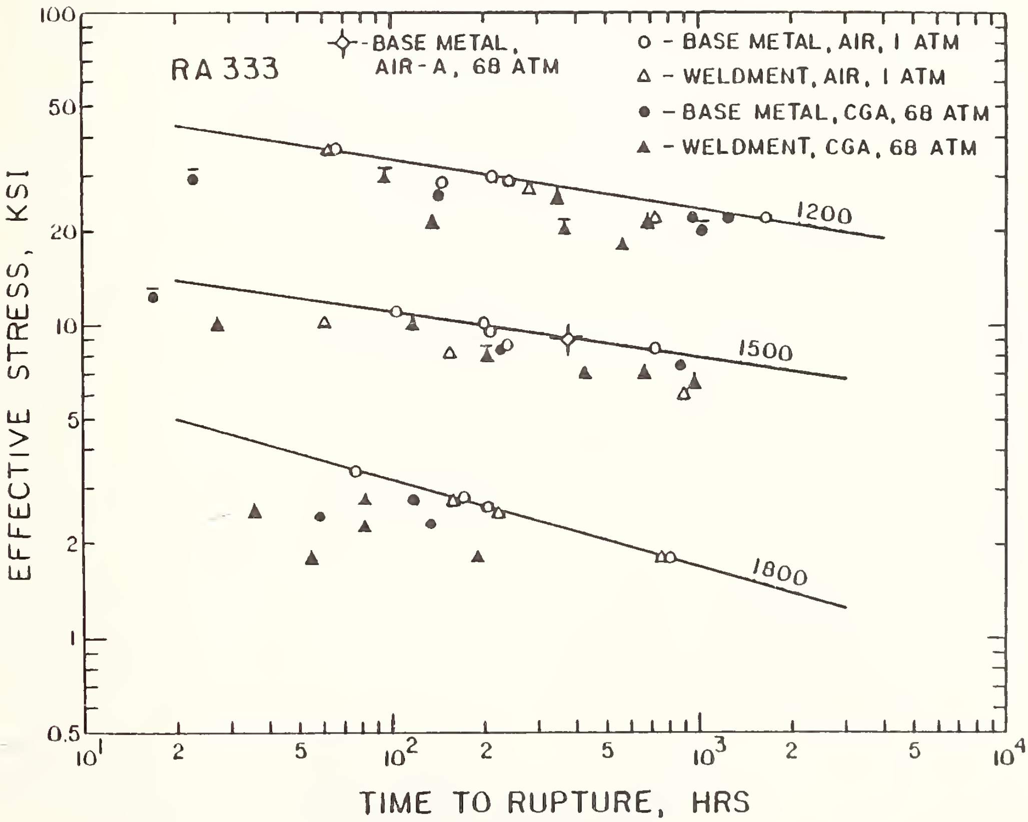
STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10], Continued





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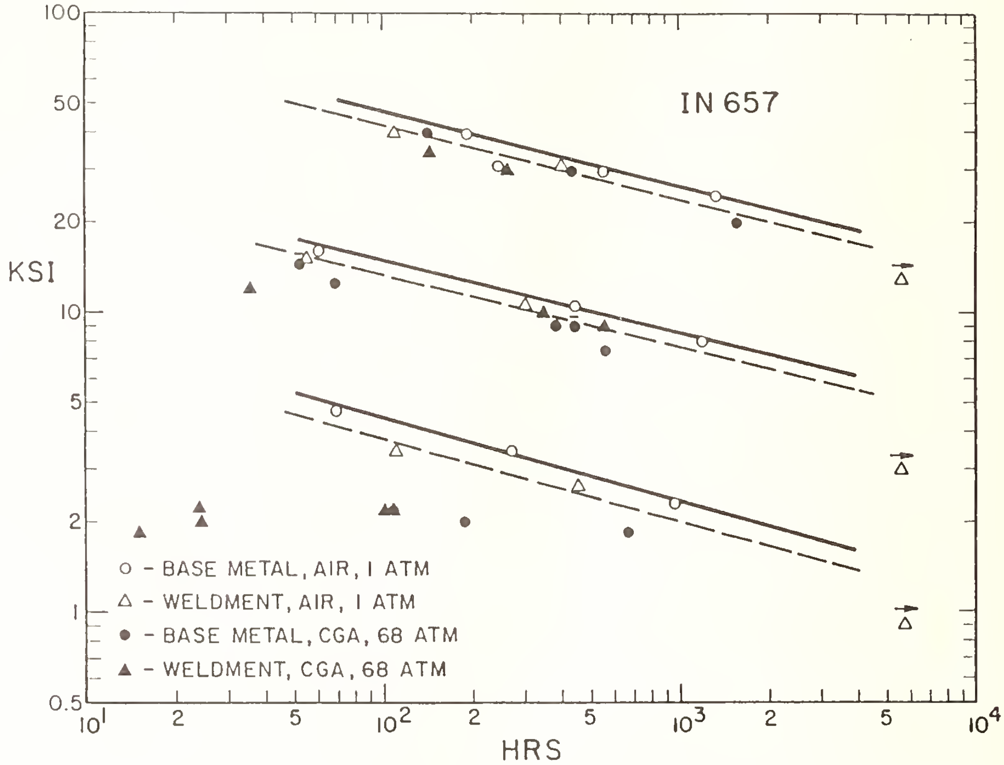
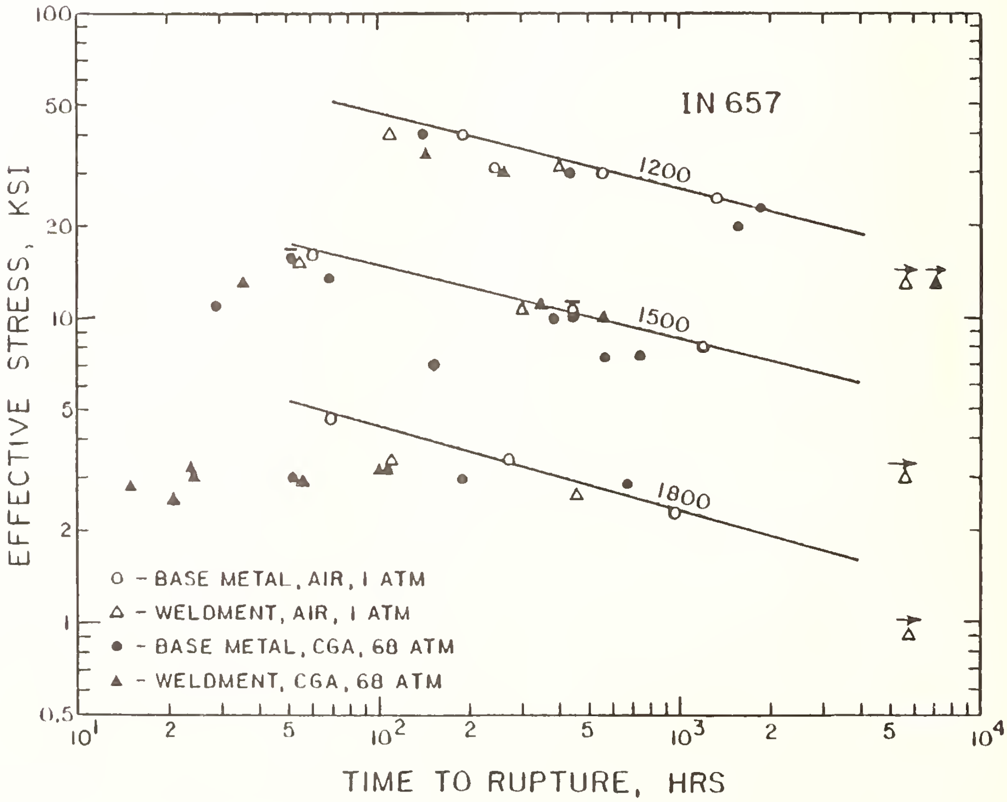
STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10], Continued





(Data Continued)

STRESS-RUPTURE DATA[a] FOR ALLOYS AND WELDMENTS EXPOSED TO CGA[b][10], Continued

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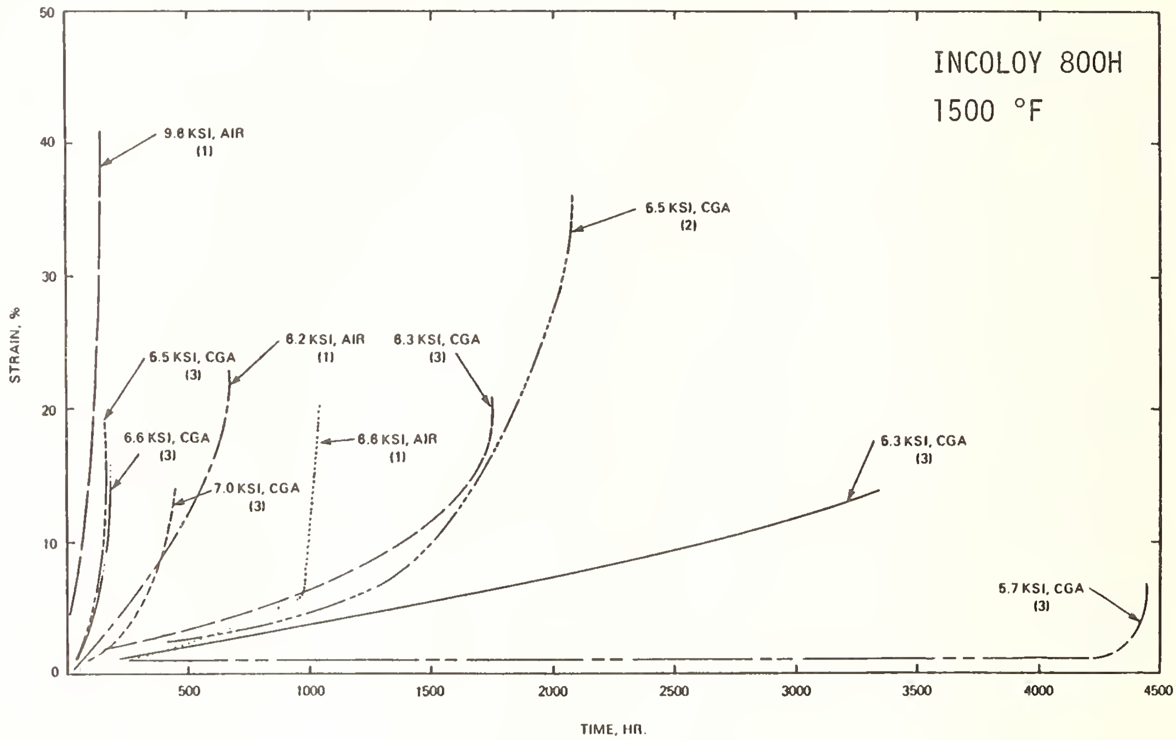
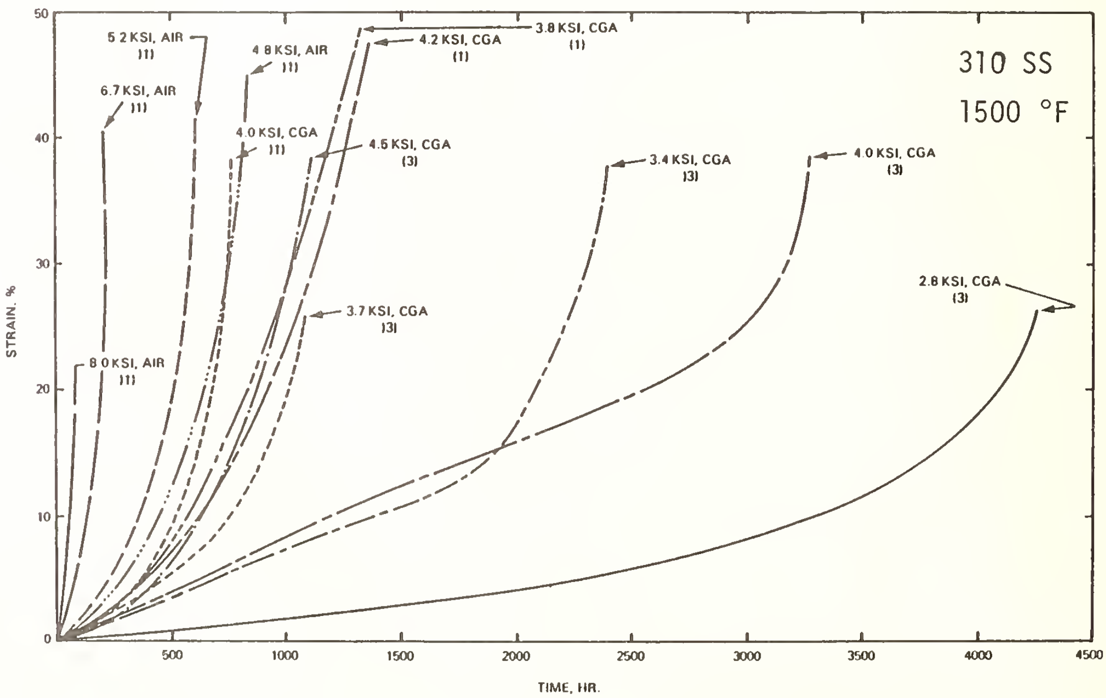
[a]See Sections B.3.1.13, B.3.1.14, B.3.1.164, and B.3.1.165 for data plotted here for those alloys indicated as "Heat 1", that is, all alloys and weldments of B.3.1.13 and B.3.1.14 and those designated as number 1 in B.3.1.164 and B.3.1.165. The solid lines are least-squares-fit curves for base metals in air; dashed lines are least-squares-fit curves for weldment data in air. Straight lines over experimental points indicate tests at 1253 °F or 1583 °F instead of 1200 and 1500 °F. Arrows indicate tests which were terminated prior to rupture. Plots of applied stress (labelled only ksi) and effective stress are included because both plots do not contain all of the same data points. The tables in the four sections specified above list the applied axial stress. Since the effective stress (see Section B.3.1.166) is the sum of the applied axial stress and the environmental pressure the differences between the pairs of plots for the same alloy occur only for the high-pressure data (68 atm, 1000 psi) and are most noticeable for the low applied stress data.

[b]CGA = coal gasification atmosphere. See the sections mentioned above in footnote a for the atmospheres and conditions.

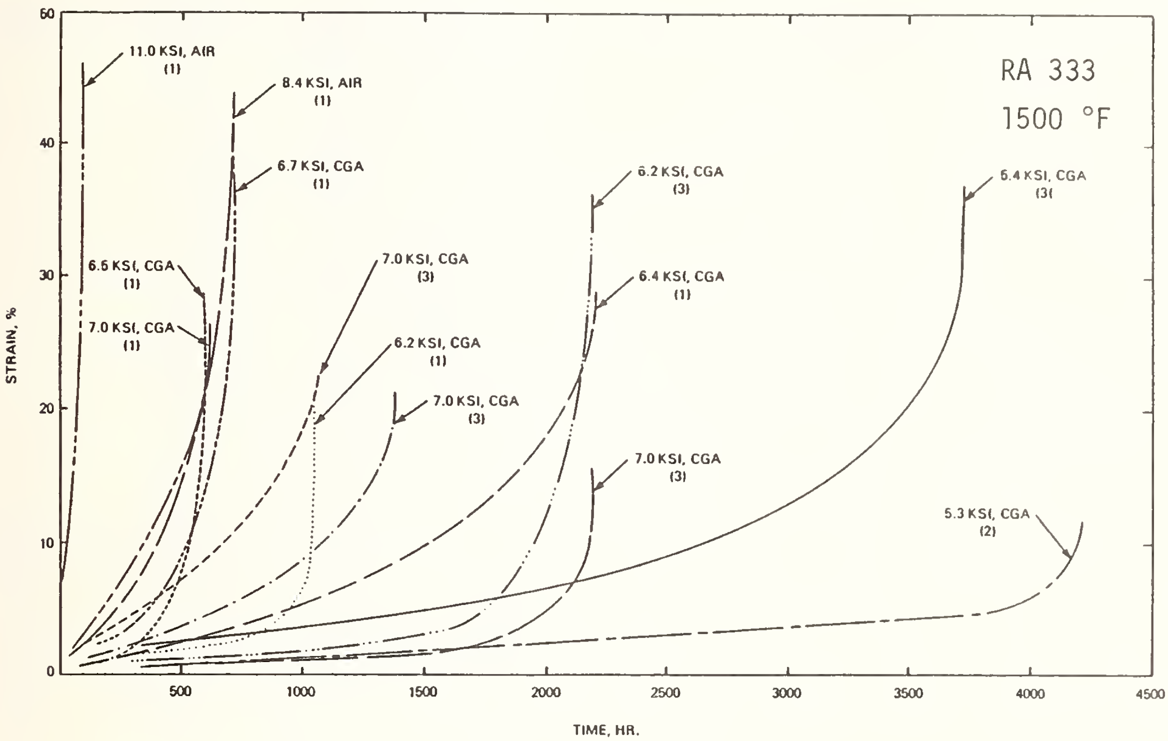
CREEP DATA[a] FOR THREE ALLOYS[b] IN COAL GASIFICATION ATMOSPHERE[c][10]





(Data Continued)

CREEP DATA[a] FOR THREE ALLOYS[b] IN COAL GASIFICATION ATMOSPHERE[c][10], Continued



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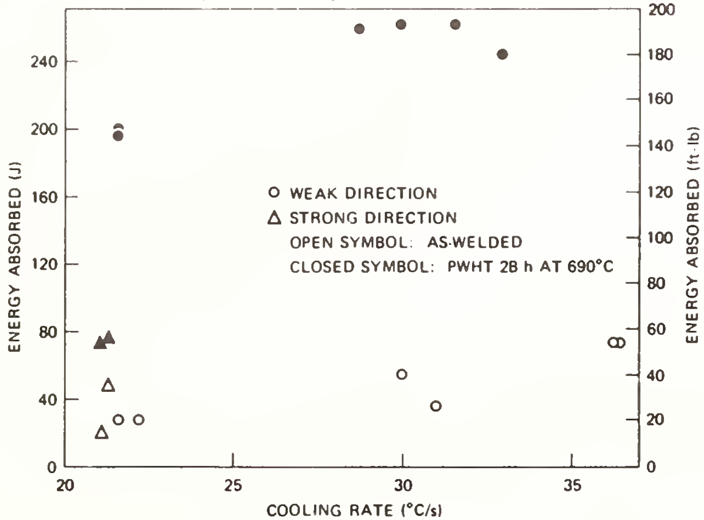
[a]See minimum creep rates listed in Section B.3.1.164 and B.3.1.14 for the creep curves plotted here. Note that the stress values in those sections are applied axial stress only. In the above curves, the stress labels are for effective stress (see Section B.3.1.166), that is, applied stress plus the environmental pressure, 68 atm (1000 psi) for the CGA exposures.

[b]The small numbers in parentheses labelling the curves indicate the heat number of the alloys (3 heats of each alloy were obtained and used in the testing).

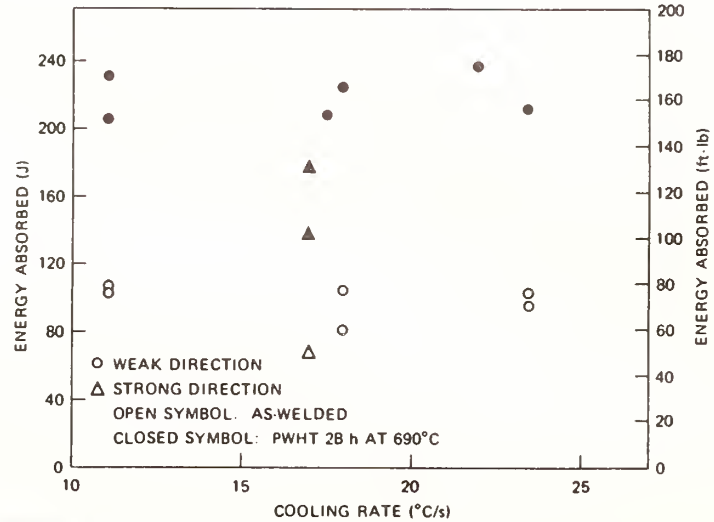
[c]CGA = coal gasification atmosphere. See B.3.1.164. In these tests the gas was flowing continuously at about 0.5 ft^3/hour.

EFFECTS OF COOLING RATE[a] ON CHARPY IMPACT ENERGY[b] OF THICK 2-1/4 Cr-1 Mo STEEL PLATE[c] [82,83]

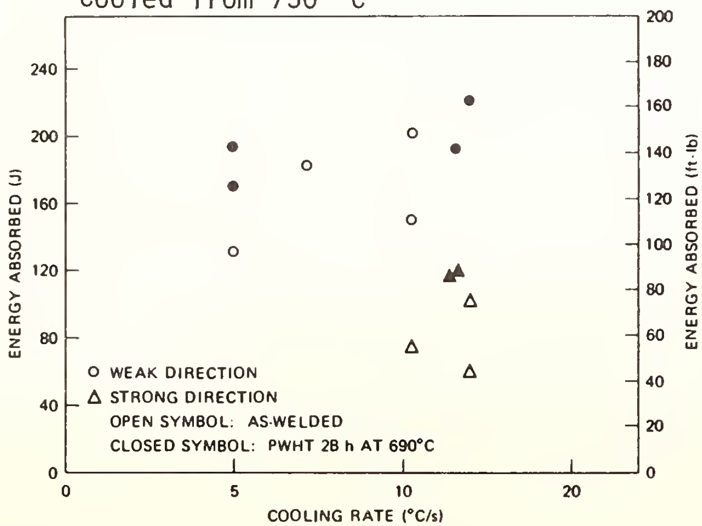
Cooled from 1370 °C



Cooled from 955 °C



Cooled from 730 °C



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[a] Specimens were given simulated weld heat-affected zone thermal cycles in Gleeble testing equipment. Weak direction (test plane parallel to rolling direction) and strong direction (test plane perpendicular to rolling direction) specimens were tested to determine the effect of cooling rate on both as-welded and post weld heat treated (PWHT) material.

[b] V-notch specimens were tested at ambient conditions.

[c] A387 Grade 22 Class 2 steel; this is the same base-metal plate for which Charpy data are given in Section B.3.1.129.

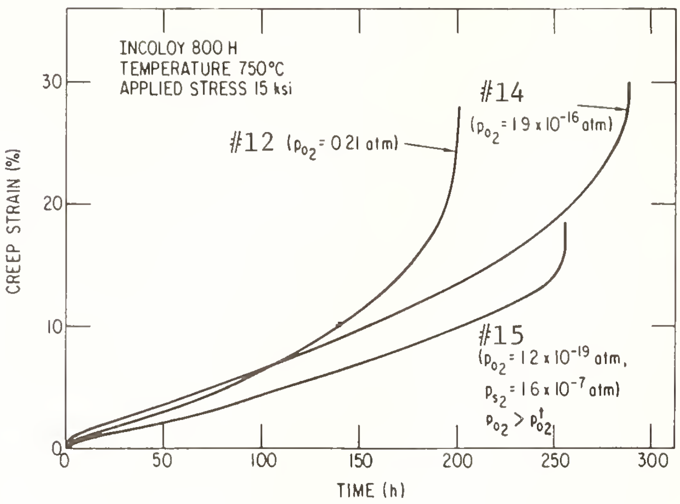
CREEP DATA[a] FOR INCOLOY 800H IN MIXED GAS ENVIRONMENT[30]

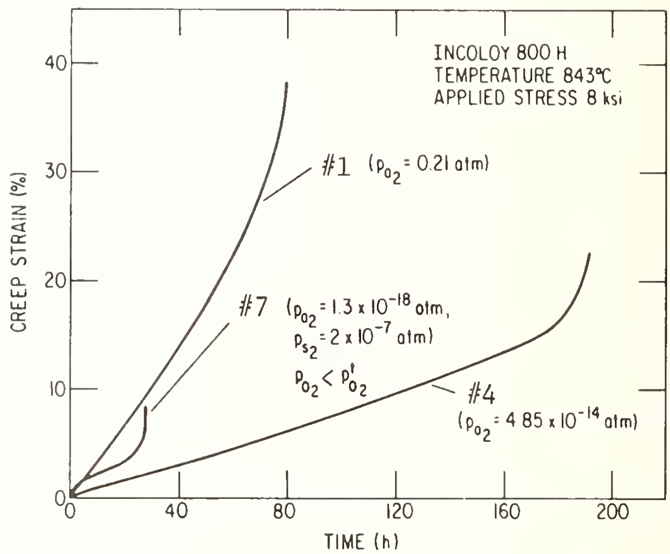
Sample No.	Applied Stress MPa(ksi)	Rupture Time, h	Test Environment	P_{O_2}, atm	P_{S_2}, atm
			TEMPERATURE 843 °C		
1	55.2(8)	79.6	air	0.21	-
2	41.4(6)	638.4			
3	41.4(6)	2697.7	$CO-CO_2$	4.85×10^{-14}	
4[b]	55.2(8)	191.7			
5[b]	41.4(6)	690.3			
6	55.2(8)	24.2	$CO-CO_2-CH_4-H_2-H_2S$	1.3×10^{-18}	$2. \times 10^{-7}$
7	55.2(8)	27.3			
8	41.4(6)	615.3			
9	27.6(4)	2088.7			
			TEMPERATURE 750 °C		
10	68.9(10)	5165.4	air	0.21	-
11	89.6(13)	324.8			
12	103.4(15)	201.8			
13	124.1(18)	75.4			
14	103.4(15)	289.4	$CO-CO_2$	1.9×10^{-16}	-
15	103.4(15)	255.4	$CO-CO_2-H_2-H_2S$	1.2×10^{-19}	1.6×10^{-7}
			TEMPERATURE 927 °C		
16	41.4(6)	16.9	air	0.21	-
17	27.6(4)	310.1			
18	17.2(2.5)	2311.0			
19[b]	27.6(4)	369.8	$CO-CO_2$	3.4×10^{-12}	-
20[b]	27.6(4)	364.0			
21	41.4(6)	6.3	$CO-CO_2-CH_4-H_2-H_2S$	7.7×10^{-17}	8.7×10^{-17}
22	27.6(4)	473.2			
23	17.2(2.5)	1988.0			

[a] Creep specimens fabricated according to ASTM E-139-70. High-temperature environmental chambers were procured and installed in creep machines. Creep strain was measured by a linear-variable-differential transducer attached between fixed and moveable pull rods of the creep assembly. A three-zone resistance-heated furnace was used for the creep tests at elevated temperatures.

[b] Specimens were furnace aged for 160 h in vacuum prior to creep test.

CREEP-STRAIN VERSUS TIME[a] FOR INCOLOY 800H IN MIXED GAS ENVIRONMENTS[30]





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[a]See Section B.3.1.172. The numbers on the curves above refer to the sample numbers in the table of Section B.3.1.172. $P^t_{O_2}$ is the threshold oxygen partial pressure required for formation of a protective oxide on the specimen surface.

HEAT TREATMENT INFLUENCE ON TENSILE PROPERTIES OF C-V-Ni DEVELOPMENTAL STEELS[80]

Alloy[a]	1 hr Aust. Temp. °C	Cooling Rate[b]	Yield ksi	UTS ksi	El. %	RA %
0.1C-0.5V-1.5Ni-0.5Mn-0.025Nb	900	1"	60	74	33	73
	1000	1"	74	95	22	64
	1000	slow	60	77	31	71
0.1C-0.5V-3.0Ni-0.5Mn-0.025Nb	900	1"	76	90	31	70
	1000	1"	113	131	22	60
	900	fast	70	89	30	69
	1000	slow	82	103	29	68
0.15C-0.75V-1.5Ni-0.5Mn	900	1"	61	75	37	78
	1000	1"	93	116	24	64
0.15C-0.75V-3.0Ni-0.5Mn	900	1"	78	94	32	74
	1000	1"	136	153	18	46
	900	fast	85	97	31	72
0.2C-1.0V-1.5Ni-0.5Mn	900	1"	62	80	35	76
	1000	1"	89	106	28	75
	900	fast	64	75	34	75
	1000	slow	73	86	34	75
0.2C-1.0V-3.0Ni-0.5Mn	1000	slow	68	101	30	77
0.2C-1.0V-3.0Ni-0.5Mn-0.5Al	1000	slow	95	110	27	73
	1000	OQ	113	169	20	62
0.2C-1.0V-3.0Ni-0.5Mn-1.0Si	1000	slow	98	112	30	76
0.2C-1.0V-3.0Ni-0.5Mn-1.5Mo	1000	slow	110	146	20	71

[a] Approximate composition of non-ferrous elements given, balance of alloy is Fe.

[b] Slow cooling ∿10-15°/min, 1" cooling rate ∿60°C/min, fast cooling ∿120°C/min, oil quench (OQ) ∿400°C/min.

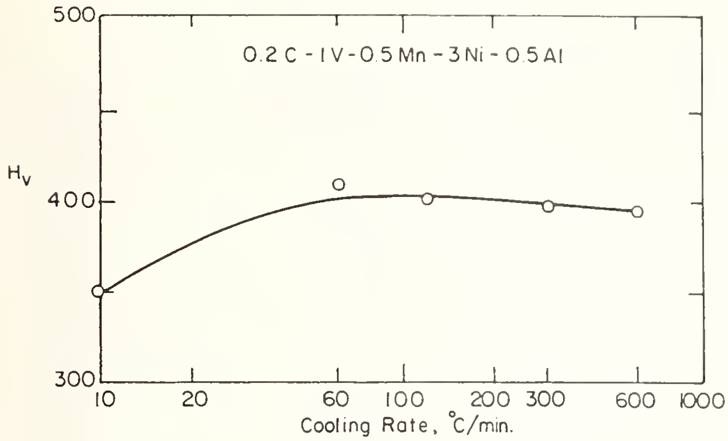
HEAT TREATMENT INFLUENCE ON CHARPY VALUES OF C-V-Ni DEVELOPMENTAL STEELS[80]

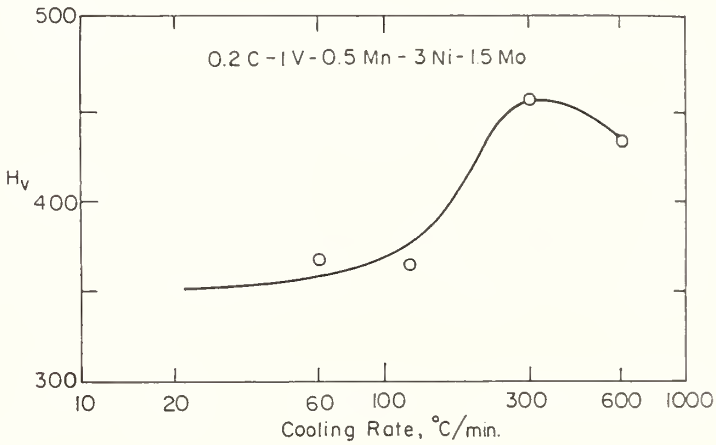
Alloy[a]	Aust. Temp. °C	Cooling Rate[b]	Charpy V-Notch (ft-lb) Room Temp.	Upper Shelf
0.1C-0.5V-1.5Ni-0.5Mn-0.025Nb	900	1"	205	205
	1000	1"	3	135
	1000	slow	10	135
0.1C-0.5V-3.0Ni-0.5Mn-0.025Nb	900	1"	160	165
	1000	1"	3	35
	900	fast	150	180
	1000	slow	7	125
0.15C-0.75V-1.5Ni-0.5Mn	900	1"	225	225
	1000	1"	16	152
0.15C-0.75V-3.0Ni-0.5Mn	900	1"	165	165
	1000	1"	3	25
	900	fast	185	185
0.2C-1.0V-1.5Ni-0.5Mn	900	1"	240	245
	1000	1"	235	245
	900	fast	-	-
	1000	slow	235	240
0.2C-1.0V-3.0Ni-0.5Mn	1000	slow	142	-
0.2C-1.0V-3.0Ni-0.5Mn-0.5Al	1000	slow	131	-
	1000	OQ	47	-
0.2C-1.0V-3.0Ni-0.5Mn-1.0Si	1000	slow	170	-
0.2C-1.0V-3.0Ni-0.5Mn-1.5Mo	1000	slow	47	-

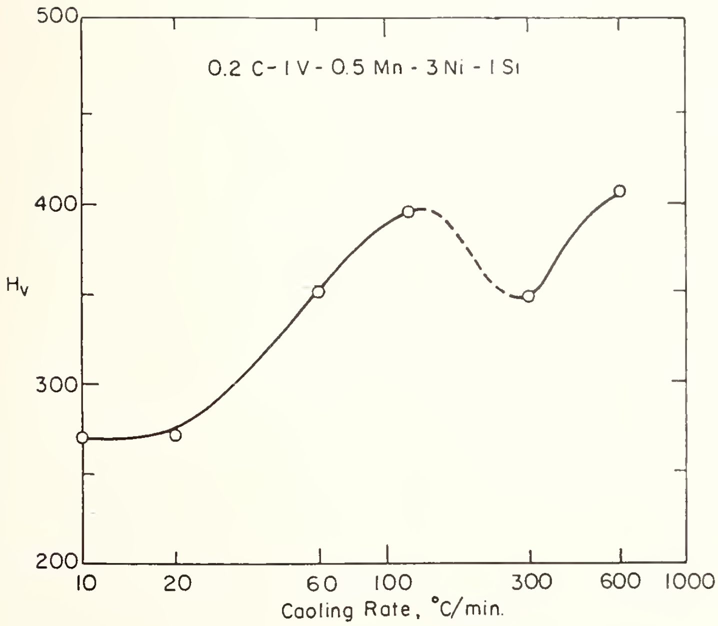
[a]Approximate composition of non-ferrous elements given, balance is Fe.

[b]Slow cooling ∿10-15°C/min, 1" cooling rate ∿60°C/min, fast cooling ∿120°C/min, oil quench (OQ) ∿400°C/min.

VICKERS HARDNESS VERSUS COOLING RATE FOR SOME C-V-Ni DEVELOPMENTAL STEELS[a] [80]







[a] Approximate composition of non-ferrous elements given, balance is Fe. Austenitized at 1000 °C for one hour.

TENSILE PROPERTY DATA FOR 3 Cr-1 Mo-1 Mn-1 Ni[a] STEEL FOR VARIOUS HEAT TREATMENTS[81]

Heat Treatment[b]	0.2% Yield Strength MPa (ksi)	Ultimate Tensile Strength MPa (ksi)	% Elongation	Reduction in Area %
as received	1105 (160.2)	1243 (180.2)	16.7	55.0
OQ	1049 (152.1)	1287 (186.7)	17.2	56.1
OQ, 650°C	642 (93.1)	762 (110.5)	26.7	72.0
OQ, 700°C	494 (71.6)	621 (90.0)	30.3	74.1
OQ, 650°C, SR	432 (62.6)	585 (84.8)	33.0	74.8
OQ, 700°C, SR	435 (63.1)	582 (84.4)	32.0	73.4
SC	1022 (148.2)	1218 (176.6)	19.5	57.5
SC, 650°C	593 (86.0)	745 (108.0)	25.0	73.8
SC, 700°C	500 (72.5)	671 (97.3)	29.0	74.2
SC, 650°C, SR	453 (65.7)	628 (91.1)	31.0	73.0
SC, 700°C, SR	463 (67.2)	639 (92.7)	31.0	73.0

[a]Nominal composition: 0.15C, 3.0Cr, 1.0Mo, 0.5Mn, 1.0Ni, 0.2Si, Bal. Fe.

[b]All samples were austenitized 1 hour at 1000°C, oil quenched (OQ) or slow cooled (SC) at 8°C/min, tempered for 4 hours at indicated temperature. Some samples were, also, stress relieved (SR) by heating 18 hours at 590°C plus 20 hours at 690°C.

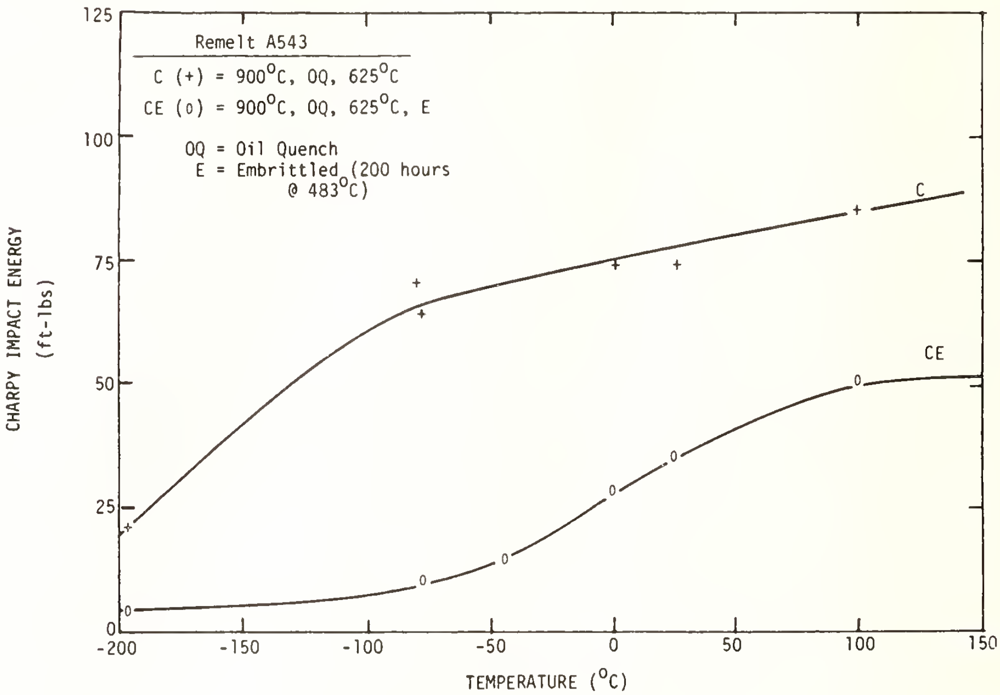
HARDNESS AND CHARPY DATA FOR 3 Cr-1 Mo-1 Mn-1 Ni[a] STEEL FOR VARIOUS HEAT TREATMENTS[81]

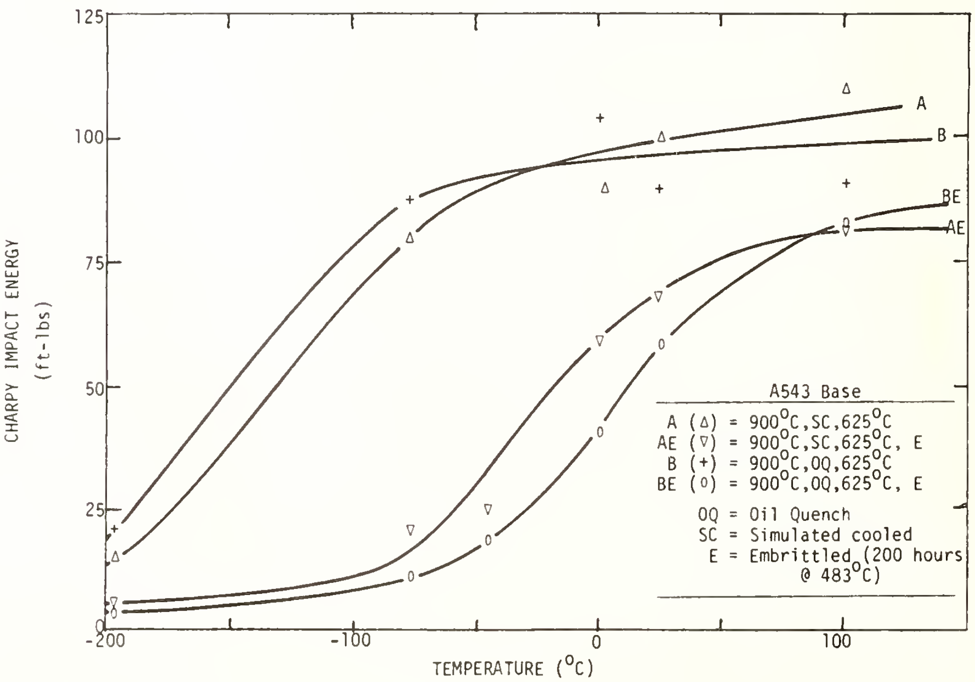
Heat Treatment[b]	Hardness R_C	Hardness R_B	Charpy Transition Temperatures 50 ft-lb °C	Charpy Transition Temperatures 50 Joule °C
as received	39.1		100	44
OQ	40.3			
OQ, 650°C	23.0		-38	-54
OQ, 700°C		93.7	-42	-52
OQ, 650°C, SR			-58	-68
OQ, 700°C, SR			-54	-70
SC	37.4			
SC, 650°C	18.8	98.1	-6	-58
SC, 700°C	12.2	92.7	-74	-92
SC, 650°C, SR	11.5	92.4	-62	-86
SC, 700°C, SR	8.0	88.5		

[a]Nominal composition: 0.15C, 3.0Cr, 1.0Mo, 0.5Mn, 1.0Ni, 0.2Si, Bal. Fe.

[b]All samples were austenitized 1 hour at 1000°C, oil quenched (OQ) or slow cooled (SC) at 8°C/min, tempered for 4 hours at indicated temperature. Some samples were, also, stress relieved (SR) by heating 18 hours at 590°C plus 20 hours at 690°C.

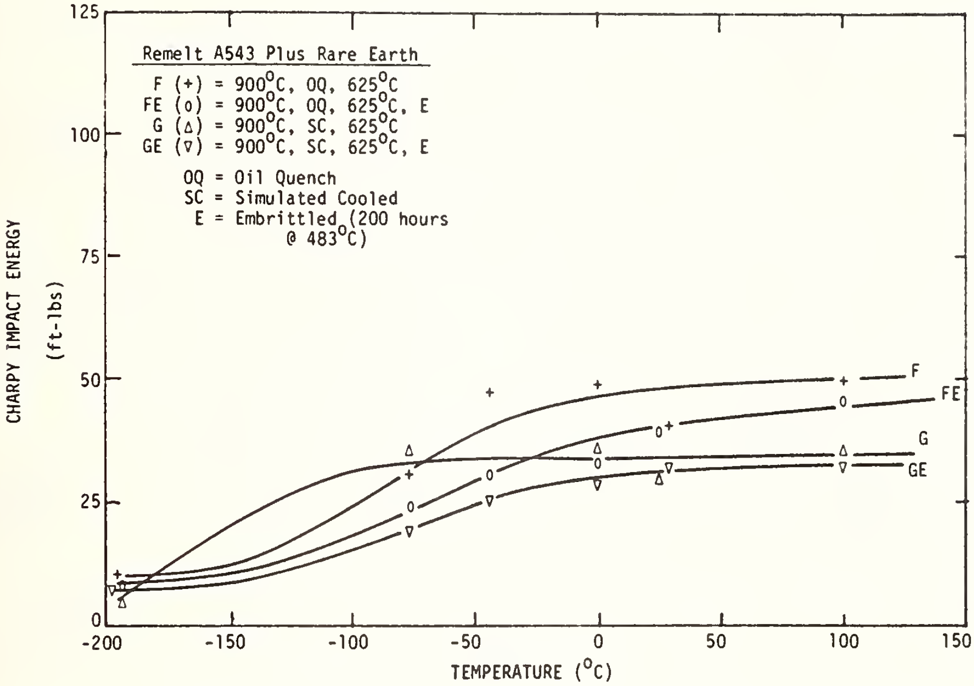
CHARPY IMPACT TESTS OF A543 ALLOY AND MODIFICATIONS[a] SUBJECTED TO ISOTHERMAL EMBRITTLEMENT[b] [81]





(Data Continued)

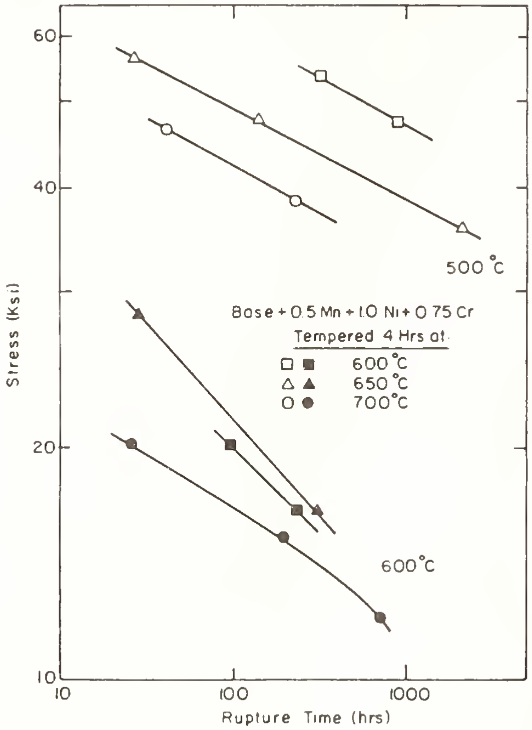
CHARPY IMPACT TESTS OF A543 ALLOY AND MODIFICATIONS[a] SUBJECTED TO ISOTHERMAL EMBRITTLEMENT[b] [81], Continued

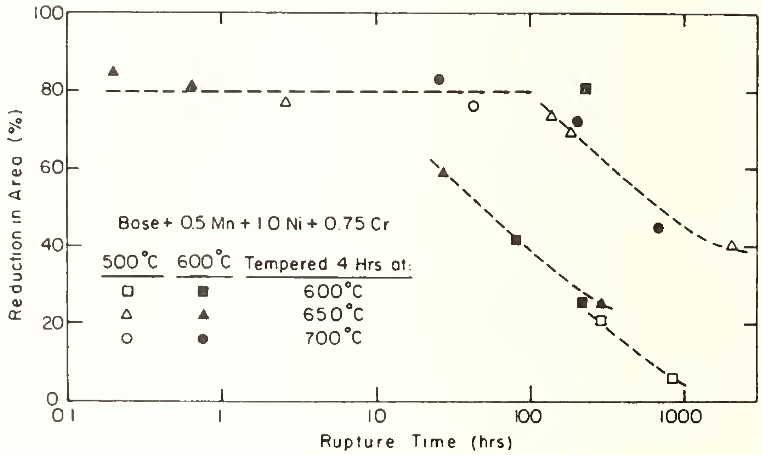


[a]Analyzed compositions (wt %):
A543: 0.23 C, 0.3 Mn, 3.5 Ni, 1.65 Cr, 0.5 Mo, 0.30 Si, 0.02 S, 0.015 P, 0.02 Al, 0.16 Cu, 0.01 V;
Remelted A543: 0.19 C, 0.25 Mn, 3.49 Ni, 1.93 Cr, 0.51 Mo, 0.28 Si, 0.024 S, 0.01 P, 0.08 Al, 0.17 Cu, 0.01 Sn, 0.009 V;
Remelted A543 + Rare Earth: 0.23 C, 0.12 Mn, 3.62 Ni, 1.69 Cr, 0.49 Mo, 0.24 Si, 0.016 S, 0.009 P, 0.15 Al, 0.16 Cu, 0.01 Sn, 0.01 V, 0.03 La, 0.17 Ce.
Both remelted materials had a much higher inclusion content than the base material.

[b]All samples were austenitized at 900 °C (time not specified), either oil quenched (OQ) or simulated cooled (SC) at rates corresponding to 1/4 thickness of a 12 inch thick plate, then tempered 4 hours at 625 °C. Embrittled samples (E) were made by additional isothermal aging for 200 hours at 483 °C.

EFFECT OF TEMPERING TEMPERATURE ON CREEP-RUPTURE BEHAVIOR OF A MODIFIED 2-1/4 Cr-1 Mo STEEL[a][81]





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[a]Base composition (wt %): 0.15 C, 0.42 Mn, 0.91 Mo, 0.10 Ni, 2.18 Cr, 0.30 Si, 0.009 S, 0.015 P, 0.019 Al, 0.08 Cu, balance Fe. Heat treatment: austenitized 1 hour at 1000 °C, simulated cooling equivalent to 1/4 thickness of a 12 inch plate, tempered 4 hours at indicated temperatures followed by a water quench. Test measurements were made at 500 °C (open symbols), and 600 °C (filled symbols).

EFFECT OF HYDROGEN EXPOSURE[a] ON TENSILE PROPERTIES OF VARIOUS STEELS AND MODIFICATIONS[b] [81]

Alloy	Hours Exposed to H_2	0.2% Yield Strength ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction in Area %
Fe-0.15C-0.5Mn (carbon steel)	0	63.66	66.54	14.25	80.98
	0	54.56	64.90	16.38	81.90
	500	18.22	38.36	26.00	63.94
	500	19.56	40.34	24.50	70.41
	1000	21.65	42.51	15.00	42.20
	1000	15.89	34.22	9.13	65.89
Fe-0.15C-0.5Mn-1.9 Cr	0	168.77	176.20	30.30	82.21
	500	53.31	67.01	28.12	86.06
	500	53.09	66.75	29.62	86.70
	1000	50.31	64.69	35.00	87.79
	1000	50.73	64.17	40.75	84.70
Fe-0.15C-0.5Mn-3.5 Mo	0	162.32	172.47	15.50	46.16
	500	97.01	116.71	22.75	75.99
	500	95.21	113.45	23.00	76.40
	1000	96.03	111.27	22.13	78.71
Fe-0.15C-0.5Mn-6.7 W	0	144.89	161.34	19.50	62.83
	0	143.30	159.86	19.30	56.62
	500	126.51	140.23	17.50	57.07
	500	120.41	134.13	15.75	63.36
	1000	104.73	121.16	12.63	37.72
	1000	106.27	123.21	14.00	37.53
2.25Cr-1Mo (base)	0	95.2	107.8	25.8	73.4
	500	87.6	99.6	27.3	75.0
	1000	74.7	87.8	30.2	75.1
Base + 1Mn	0	93.3	106.3	26.7	72.8
	500	90.4	103.9	25.0	67.5
	1000	77.4	90.9	27.8	71.5
Base + 0.5Mn + 0.5Ni	0	95.3	107.1	25.8	71.8
	500	91.7	103.9	26.4	79.9
	1000	82.6	94.9	26.5	68.4
A533B (base)[c]	0	93.1	105.6	25.4	73.3
	500	83.4	98.3	28.5	65.7
	1000	44.3	49.0	3.92	0.0
Base + 1Cr	0	107.8	117.2	25.52	68.02
	500	98.0	108.2	24.15	66.86
	1000	89.4	100.4	16.75	30.58

(Table Continued)

EFFECT OF HYDROGEN EXPOSURE[a] ON TENSILE PROPERTIES OF VARIOUS STEELS AND MODIFICATIONS[b][81], Continued

Alloy	Hours Exposed to H_2	0.2% Yield Strength ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction in Area %
Base + 0.7Mn + 1Cr	0	104.4	117.2	25.42	71.96
	500	100.2	107.9	25.62	69.05
	1000	90.3	102.5	25.15	65.8
Base + 0.7Mn + 1Cr + 1Si	0	131.3	140.8	21.00	64.2
	500	106.3	120.7	23.62	56.7
	1000	91.8	108.7	26.50	66.1

[a]Hydrogen exposure at 550 °C at 1500 psi hydrogen.

[b]All materials initially austenitized, quenched, and tempered at 650 °C for 4 hours.

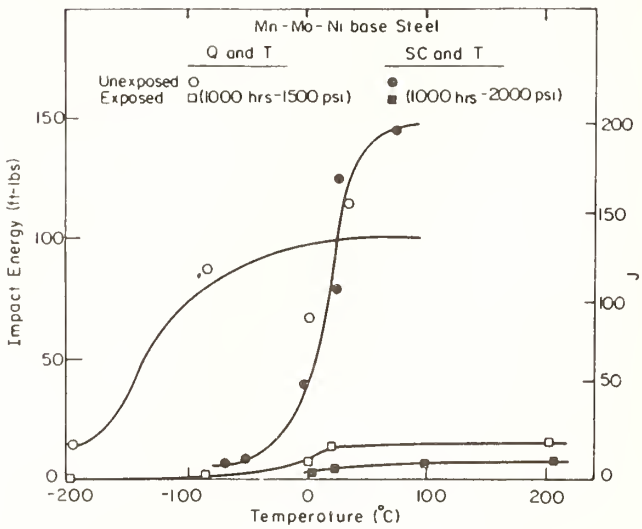
[c]Nominal base composition is 1.3 Mn, 0.5 Mo, 0.5 Ni, 0.2 C, 0.2 Si, balance Fe.

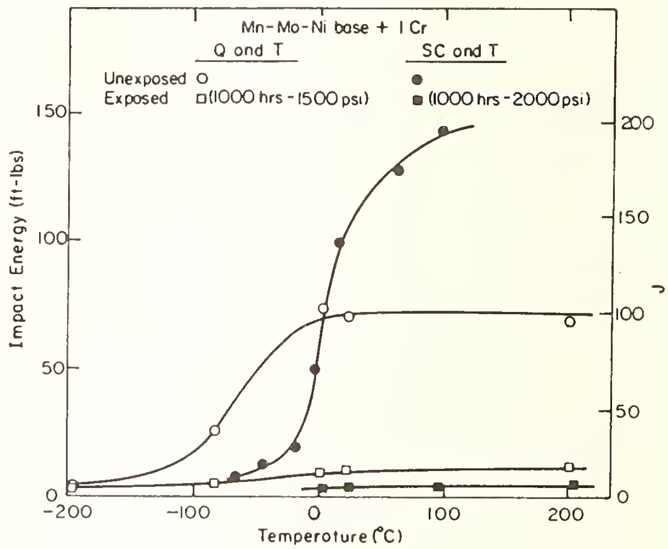
IMPACT PROPERTIES OF HYDROGEN-EXPOSED VERSUS NON-EXPOSED SPECIMENS OF C-V-Ni DEVELOPMENTAL STEELS[80]

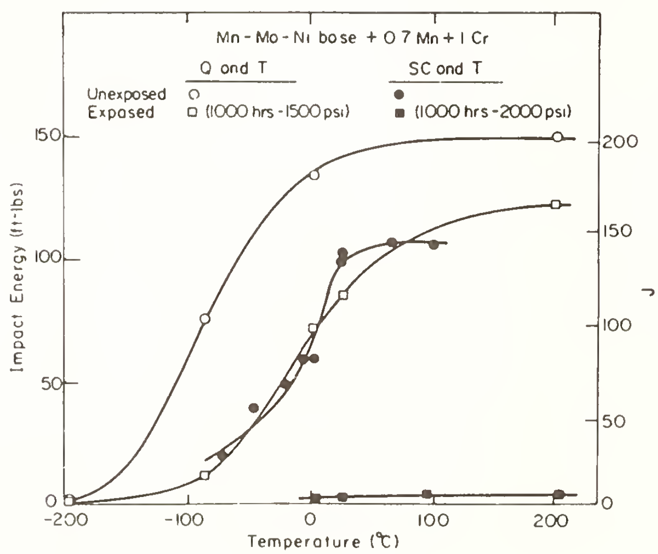
Alloy	Upper Shelf Energy (ft-lbs)	Lower Shelf Energy (ft-lbs)	Transition Temperature
0.2C-1.0V-1.5Ni-0.5Mn, bal Fe			
Hydrogen exposed[a]	240	4	-25°C
Non-exposed	240	4	-38°C
0.2C-1.0V-3.0Ni-0.5Mn, bal Fe			
Hydrogen exposed	20	6	-50°C
Non-exposed	160	6	-
0.2C-1.0V-3.0Ni-0.5Mn-0.5Al, bal Fe (slow cooled)			
Hydrogen exposed	24	-	-
Non-exposed	140	10	-25°C
0.2C-1.0V-3.0Ni-0.5Mn-0.5Al, bal Fe (oil quenched)			
Hydrogen exposed	6	-	-
Non-exposed	100	6	+10°C

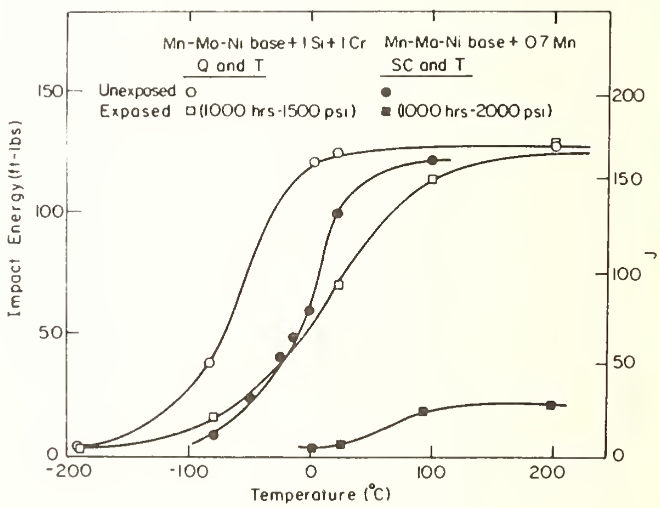
[a]Exposed to 2000 psi hydrogen atmosphere at 550°C for 1000 hours.

EFFECT OF HYDROGEN EXPOSURE[a] ON THE IMPACT PROPERTIES OF MODIFIED Mn-Mo-Ni BASE STEELS[b][81]



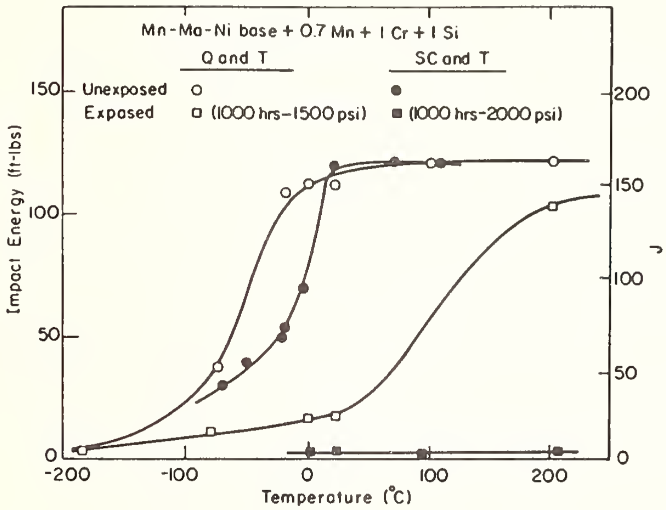






(Data Continued)

EFFECT OF HYDROGEN EXPOSURE[a] ON THE IMPACT PROPERTIES OF MODIFIED Mn-Mo-Ni BASE STEELS[b][81], Continued



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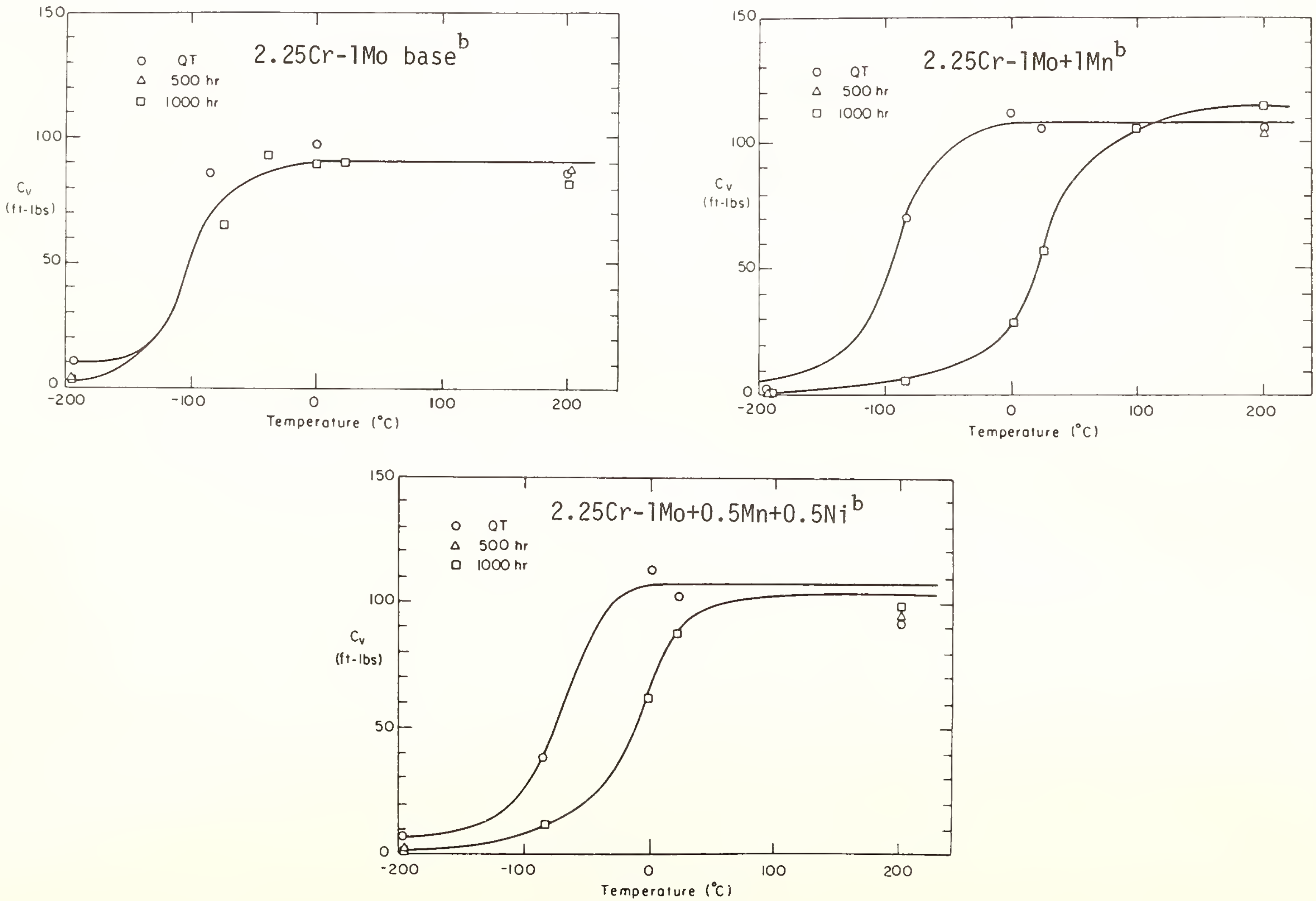
[a] Hydrogen exposure at 550 °C for the times and at the hydrogen pressures given on the figures.

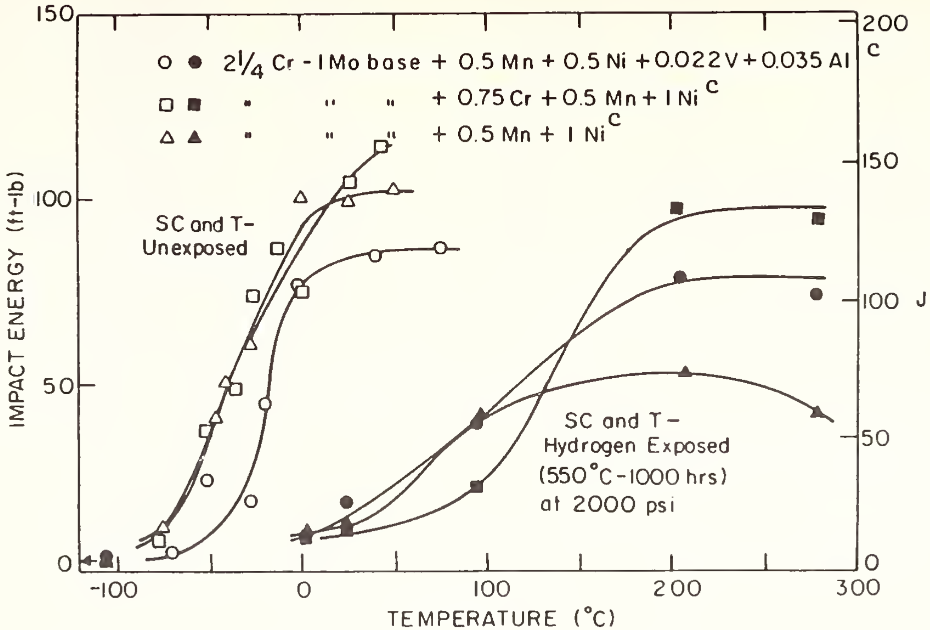
[b] Base composition (wt %): 0.22 C, 1.32 Mn, 0.65 Ni, 0.57 Mo, 0.20 Si, 0.009 P, 0.007 S, 0.036 Al, 0.07 Cu, balance Fe. Heat treatment: austenitized 1 hour at 1000 °C, either quenched (Q) or simulated cooling (SC) equivalent to 1/4 thickness of a 12 inch plate, then tempered 4 hours at 650 °C.

EFFECT OF HYDROGEN EXPOSURE ON THE IMPACT PROPERTIES OF MODIFIED 2-1/4 Cr-1 Mo STEELS[a][81]



(Data Continued)

EFFECT OF HYDROGEN EXPOSURE ON THE IMPACT PROPERTIES OF MODIFIED 2-1/4 Cr-1 Mo STEELS[a] [81], Continued



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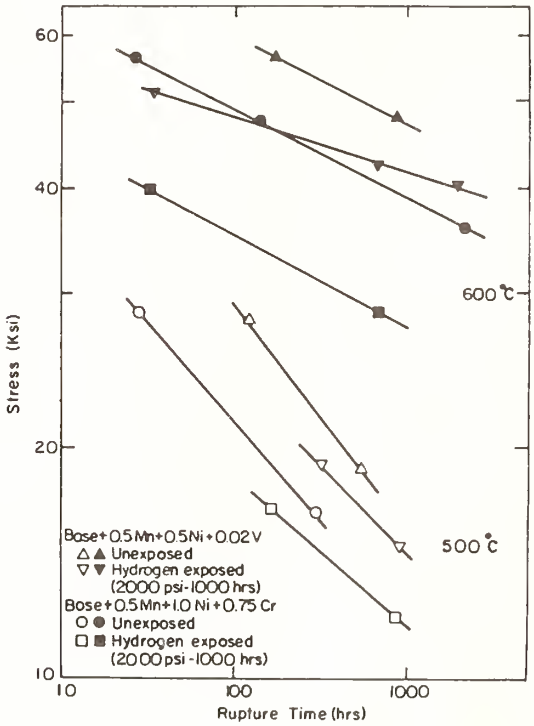
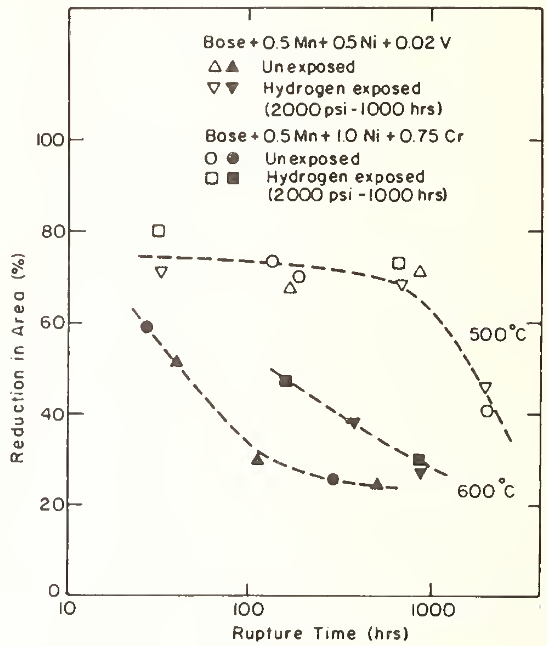
[a]Base composition (wt %): 0.15 C, 0.42 Mn, 0.91 Mo, 0.10 Ni, 2.18 Cr, 0.30 Si, 0.009 S, 0.015 P, 0.019 Al, 0.08 Cu, balance Fe.

[b]Heat treatment: austenitized 1 hour at 1000 °C, quenched, then tempered 4 hours at 650 °C. The exposed specimens in these figures were exposed to 1500 psi hydrogen at 550 °C for 500 and 1000 hours.

[c]Heat treatment: austenitized 1 hour at 1000 °C, simulated cooling (SC) equivalent to a 1/4 thickness of a 12 inch thick plate, tempered 4 hours at 650 °C. The exposed specimens in this figure were exposed to 2000 psi hydrogen at 550 °C for 1000 hours.

EFFECT OF HYDROGEN EXPOSURE[a] ON ELEVATED TEMPERATURE CREEP-RUPTURE BEHAVIOR OF MODIFIED 2-1/4 Cr-1 Mo STEELS[b][81]





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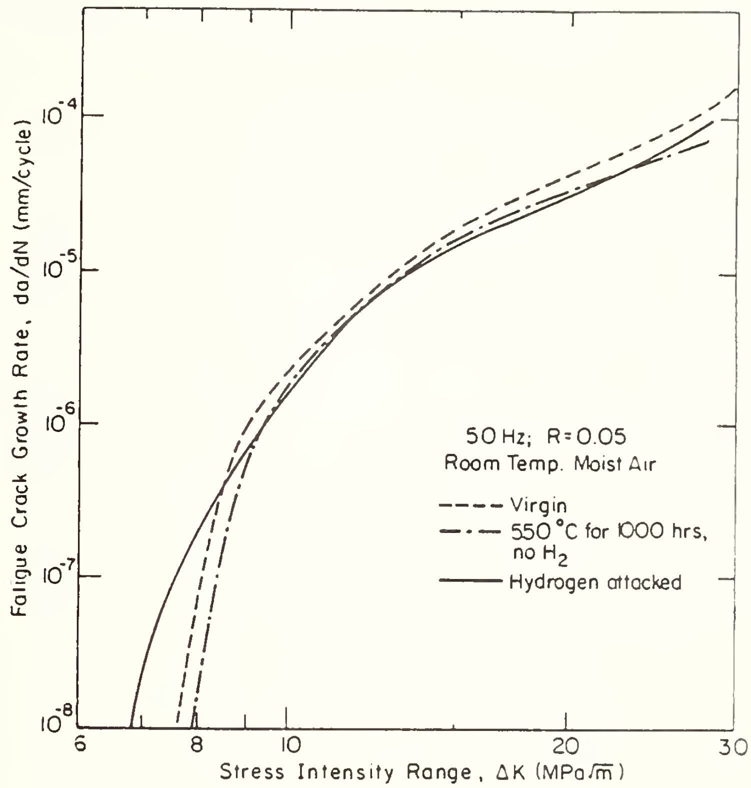
[a]Exposure was at 2000 psi hydrogen and 550 °C for 1000 hours.

[b]2-1/4 Cr-1 Mo base composition (wt %): 0.15 C, 0.42 Mn, 0.91 Mo, 0.10 Ni, 2.18 Cr, 0.30 Si, 0.009 S, 0.015 P, 0.019 Al, 0.08 Cu, balance Fe. Heat treatment: austenitized 1 hour at 1000 °C, simulated cooling equivalent to 1/4 thickness of a 12 inch plate, tempered 4 hours at 650 °C, followed by a water quench. Testing was done at 500 °C (open symbols) and at 600 °C (solid symbols).

EFFECT OF HYDROGEN EXPOSURE[a] ON FATIGUE CRACK GROWTH RATE[b] OF A BAINITIC 2-1/4 Cr-1 Mo STEEL[c][81]



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[a] Specimens consisted of unexposed material,
of material exposed to air at 550 °C for 1000 hours,
of material exposed to 2000 psi hydrogen at 550 °C for 1000 hours.

[b] Testing was done on 12.7 mm thick compact specimens machined in the T-L orientation using a 50 kN Instron electro-servo-hydraulic machine operating under load control. Tests were conducted at ambient temperature in moist (40% relative humidity) air. Data taken at 50 Hz frequency and a 0.05 load ratio.

[c] Composition (wt %): 0.12 C, 0.45 Mn, 0.21 Si, 0.11 Ni, 2.28 Cr, 1.05 Mo, 0.014 P, 0.015 S, 0.12 Cu, balance Fe. Heat treatment: austenitized 5.5 hours at 945 °C, water quenched, tempered 8 hours at 663 °C, stress-relieved at 593 °C (15 hours) plus 649 °C (22 hours) plus 663 °C (18 hours).

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THERMAL EXPANSION DATA[a] FOR THREE ALLOYS[47]

Alloy	Temperature Range °F	Thermal Expansion Coefficient[b] μ in/in/°F
2 1/4Cr-1 Mo (A387)	72 - 500	7.03 ± 0.035
	72 - 800	7.43 ± 0.015
	72 - 900	7.48 ± 0.013
	72 - 1000	7.53 ± 0.02
316 SS	72 - 500	9.54 ± 0.045
	72 - 800	9.87 ± 0.014
	72 - 900	9.93 ± 0.011
	72 - 1000	10.16 ± 0.01
Carpenter 883 (H-13)	72 - 800	7.07 ± 0.02

[a] Measurements were made with a specially designed quartz dilatometer. The rig incorporates a capacitance gauge transducer with a resolution of 4×10^{-7} inches of length change.

[b] Values are the statistical average of five runs each on four different samples, totalling 20 tests.

MELTING RANGE AND DENSITY OF VARIOUS ALLOYS[a][10]

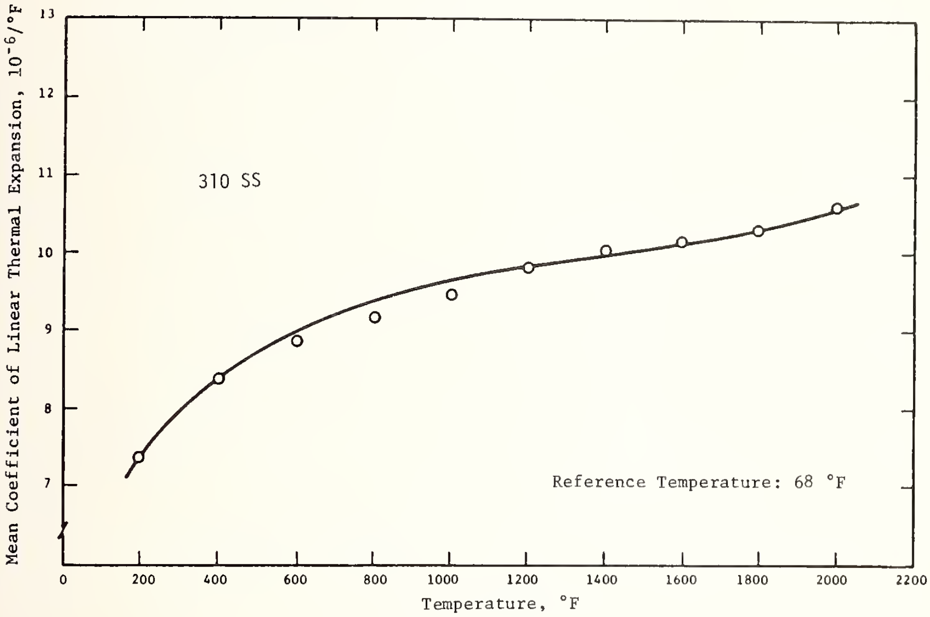
Alloy[a]	Melting Range, °F DTA[b]	Melting Range, °F TTA[c]	Density lb/in^3
Incoloy 800H	2516-2540	---	0.287
310 SS	2529-2557	2529-2561	0.284
RA 333	2383-2451	---	0.294
Haynes 188	2500-2563	2487-2568	0.324
Inconel 657	2367-2399	2336-2403	0.282
HK-40	2361-2532	2370-2536	0.283
Stellite 6B	2336-2392	2331-2521	0.301
Supertherm T63WC	2359-2487	2350-2484	0.299
RA 330	2484-2525	2475-2530	0.287

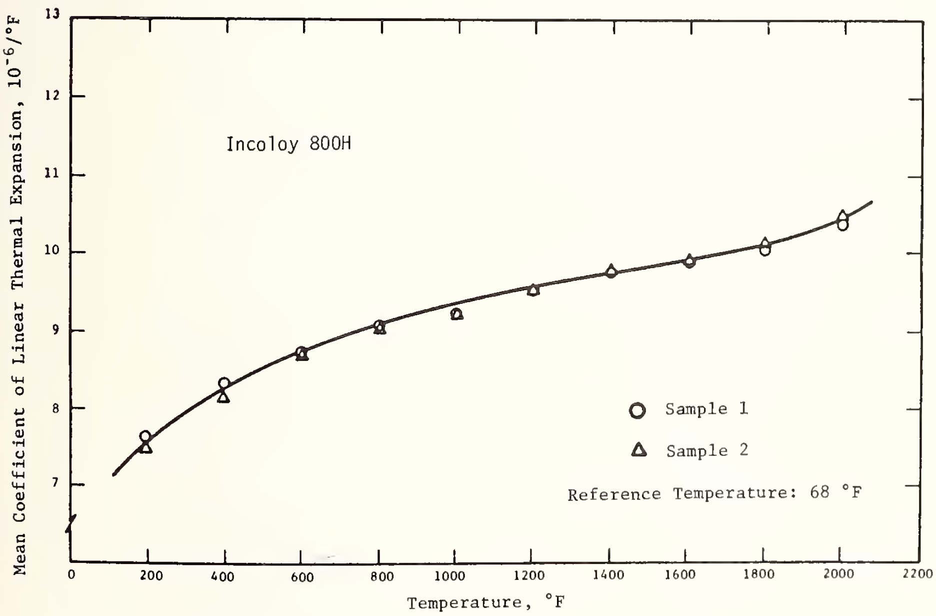
[a]Alloys are those for which tensile, stress-rupture, and other data are given in Sections B.3.1.8, B.3.1.13-16, B.3.1.18-21.

[b]Differential thermal analysis, 10-14 °F/minute.

[c]Time-Temperature analysis, 10-14 °F/minute.

THERMAL EXPANSION FOR TWO ALLOYS[a][10]





[a]Alloys are those for which tensile, stress-rupture, and other data are given in Sections B.3.1.8, B.3.1.13-16, B.3.1.18-21.

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[86] THE PROPERTIES AND PERFORMANCE OF MATERIALS IN THE COAL GASIFICATION ENVIRONMENT, edited by V. Hill and H. L. Black. American Society for Metals, Metals Park, Ohio, 1981, pp. 225-288.

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MATERIALS INDEX

The index is ordered primarily on materials and secondarily on properties. If some property is of primary interest it is assumed that the reader will go to the appropriate A or B sections to locate that information.

The user is assumed to have some knowledge of the broad categories into which various materials are likely to be placed by virtue of their composition, form, or properties. For example, a specialty steel might be found in the Metals and Alloys index under Heat Resistant Alloys, High-Iron Alloys and Superalloys, or High Strength Steels depending on its normal industrial use. In the refractories section it is necessary to know the form (Brick and Shapes, Castable, Cements and Mortars, or Plastics and Ramming Mixes) first and then the composition to locate a material of interest.

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.

D. Index

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1984- 421-997:1

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS SP 642, Suppl. 1	2. Performing Organ. Report No.	3. Publication Date December 1983

4. TITLE AND SUBTITLE

Construction Materials for Coal Conversion
Performance and Properties Data
Supplement 1

5. AUTHOR(S) Helen M. Ondik, Bruce W. Christ, T. Robert Shives, Alvin Perloff, and Betty A. Beck

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered
N/A

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Laramie Energy Technology Center
U. S. Department of Energy
University Station
Laramie, Wyoming 82071

10. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 82-600610

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. 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 expands the information provided in the original NBS SP 642 publication, Construction Materials for Coal Conversion--Performance and Properties Data, which was intended to provide 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 book is organized so that the information is given both with respect to the various component areas of coal gasification or liquefaction plants and with respect to the properties or possible failure mechanisms, e.g. corrosion, erosion, mechanical properties, and physical properties.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

alloys; coal conversion; coal gasification; coal liquefaction; mechanical properties; physical properties

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☒ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES
774

15. Price

USCOMM-DC 6043-P80

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