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An Assessment of Fossil Energy Materials Research Needs

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Sponsored by:
U.S. Department of Energy
Fossil Energy
Advanced Research and Technology
Development Materials Program

Prepared for:
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
Managed by:
Martin Marietta Energy Systems, Inc.
for the
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AN ASSESSMENT OF FOSSIL ENERGY MATERIALS RESEARCH NEEDS

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ABSTRACT

An assessment was conducted to identify the needs and opportunities in materials research directed at applying new developments in materials science and engineering to fossil energy technologies. The assessment was conducted through literature review and discussions with knowledgeable industrial, academic and governmental personnel. Topics worthy of research which will provide significant benefits to fossil technologies include the following: austenitic alloys, iron aluminides, ceramic filter materials, ceramic membranes, solid electrolytes, catalyst supports, protective coatings, erosion/abrasion/wear research, corrosion mechanism research, intelligent materials processing, diamond films, nanocomposites, superplastic forming of ceramics, surface active dual function materials and ceramic matrix components.

EXECUTIVE SUMMARY

The development of new materials, improved understanding of material behavior and advances in materials processing offer opportunities to improve the performance and durability of fossil fuel conversion and combustion systems. These opportunities however are accompanied by the need to conduct research which addresses the unique conditions and requirements of fossil systems. The purpose of this study was to identify those materials developments which have potential positive impacts on fossil systems and the research required to bring those opportunities to fruition.

A survey of new findings in the field of materials science and engineering was conducted through review of pertinent literature and discussion with individuals at DOE and other Government laboratories, academia and industry active in the field. Concurrent discussions were conducted with individuals involved in the research and development of advanced fossil systems to identify the role new materials would play in enhancing system performance an the possibility of unique new functions.

It was noted that in terms of system performance, higher temperature operation provides improved thermal efficiency but, as significantly, consideration was warranted for those materials applications which offered improvements in process chemistry control as for example through catalysts or separation materials such as filters and membranes. These latter applications provide benefits through fuel and environmental consideration. Attention was directed at primarily coal liquification, coal gasification and combustion and fuel cell applications. Extraction and heat engine utilization of fossil derived fuels were recognized but did not constitute the focus of the study.

Although structural materials have traditionally constituted the major interest in the fossil program, it is recognized that functional medalist (those materials which are not load bearing but perform a unique function by virtue of their intrinsic properties) are of increasing importance, as in solid oxide fuel cells, and consideration was given to identification of materials with dual capabilities, such as reactive filters.

Consideration was also given to identification of mechanisms of transfer from the program to industrial users. Significant examples of utilization of results from the program lie in the development of modified 9 Cr-1 Mo steel for fossil boilers, the development of iron aluminides for automotive related systems, refractory design principles adapted for steel making and other industrial processes from coal gasification applications, and the development of tough ceramic particulate filters via chemical vapor infiltration fabrication. It is concluded that early vapor infiltration fabrication. It is concluded that early industrial participation in the research program on materials which offer potential for application in current or near term company product lines offers the best change of adoption by industry.

An assessment of the benefits of several materials research and development topics to fossil systems was determined as well as the barriers to implementation. The following research topics were identified as holding major potential for contributions by the Program:

Austenitic Alloys - Research conducted on the Program has provided the capability for advances in research on condition specific behavior would be

most effectively conducted in conjunction with industry.

Aluminides - Iron aluminides offer potential for several fossil applications. Research which addresses the scale-up, processing and environmental effects on performance in specific applications is warranted.

Ceramic Filter Materials - Research on the fabrication and evaluation of ceramic filters in warranted due to the potential benefits in terms of emissions reductions and process control, particularly for hot gas clean up systems associated with combined cycle systems. Specific issues which should be considered in the selection of research projects are the selection of durable filters at reasonable costs and the effect of environmental degradation on these high surface to volume ratio materials.

Ceramic Membranes - The use of ceramic material to provide high temperature separation of gases or liquid species has potential in terms of both process selectivity as well as hot gas cleanup. The improved thermodynamic stability which ceramics exhibit relative to metals offers promise for the development of components not currently available. The large surface to volume ratios of these materials which have been used at relatively low temperatures necessitates evaluation in fossil related environments to determine degree of reactivity and the nature of products of reaction between these materials and fossil environments which may contain alkali and sulfur species. Current membranes are generally fabricated of aluminum oxide and the development of silicon nitride or silicon carbide membranes is foreseen as an area of productive research to achieve desired strength and durability.

Solid Oxide Electrolytes - Solid oxide fuel cells, process specie sensors and gas separation devices which rely on the conduction of ionic species offer potential for use in power generation, process control and unique processing. Research underway to better understand the role of material chemistry and processing on properties and performance is required to allow reduced product cost and the ability to reliably predict performance. Close cooperation with commercial firms developing these technologies is recommended.

Catalyst Supports - Catalyst support research in progress has the potential to improve the selectivity of liquefaction, gasification and clean-up-process. Catalyst systems have the potential to greatly improve the economics of these fossil processes and close-coupling with catalyst development research is necessary.

Coatings - Coatings offer the ability to improve the durability and extend the operating limits of existing materials of construction where limitations due to high temperature corrosion or wear and erosion limit performance. Opportunities exist in development of coating-substrate system design for both metallic and ceramic coatings on metallic substrates and ceramic coatings fir ceramic substrates. Technique for application and repair of coatings in-situ, particularly for large components offers opportunities for cost reduction.

Erosion/Abrasion/Wear - Erosion, abrasion and wear remain primary concerns for all coat related systems. Improved understanding of the mechanisms of these modes of deterioration, particularly the role of microstructure with controlled orientation, offers potential for improvements in system durability. Improved understanding of the combined role of corrosion and erosion is desirable.

Corrosion-Corrosion remains a principal cause for deterioration in many fossil systems. Improved understanding of the nature of the corrosion process for both alloys and ceramic materials is required to allow the development and application of materials tailored for fossil applications.

This study, sponsored by the Department of Energy (DOE) Office of Fossil Energy (FE), Advanced Research and Technology Development (AR&TD) Materials Program, has as its objective the identification of opportunities for materials research which would take advantage of recent materials science advances holding the potential for significant favorable impacts on fossil plant efficiencies, operating reliability and reductions in capital investment, all of which affect product cost.

The growing concern for environmental issues which have historically accompanied coal usage, along with steadily rising petroleum imports, form a strong undercurrent which will undoubtedly impact coal technologies and accompanying materials requirements.

In addition to identifying opportunities to move recent Materials Science and Engineering (MSE) research into fossil applications, the study addresses the means of transferring the results of fossil materials research to industry.

The AR&TD Materials Program, established in the Energy Research and Development Administration (ERDA) in 1974, has consistently provided both engineering support to operating fossil systems as well as critical data and mechanistic understanding of materials behavior specific to coal related systems. Not least, the AR&TD Materials Program (hereinafter "Program") has taken an active role in the development of new materials for a variety of fossil applications.

The goal of the Program is to develop a materials technology base to meet the generic needs of fossil energy systems through the development of a fundamental understanding of the behavior of materials in those systems, together with exploratory development of new materials and usage concepts which will significantly impact the performance of current and new systems. This research has, to a degree, addressed high risk concepts not suitable for industrial or other fossil sponsorship and has resulted in payoffs in the fossil technologies as well as in non-fossil areas. This latter fact is exemplified by the widespread industrial interest in the iron aluminides developed in the Program.

This research program has been conducted by utilizing the best talents available in industry, academia, and national laboratories and has contributed significantly to the successful development of a strong materials technology base for those processes supported by the DOE. However, funding for the Program has remained level for the past decade. As a consequence, the number of researchers supported has declined as an effect of inflation and the productivity of the program reflects wise project selection and management rather than abundant funding. The reduced number of new projects which can be initiated will limit the impact of the Program in the future. Effective use of available funds has been accomplished by concentrating on the unique materials performance profiles caused by particular compositional features of coal, namely corrosive species such as sulfur and alkalis, and solid erodents such as coal minerals and char, as well as on the development of materials enabling improvements of fossil systems operating in elevated temperature hostile environments.

Much of this advance has been made by leveraging research initially sponsored by the Basic Energy Science (BES), Energy Conversion and Utilization Technology (ECUT, now the Transportation Materials Program) and nuclear programs within the DOE. Linkage with other sponsoring agencies, such as the Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI), has provided both the ability to participate in larger programs than otherwise possible as well as important transfer to the user community. The Program has served as a link between the materials research establishment and the FE line programs by providing input to critical materials issues of concern to those programs, as well as developing a basis upon which other programs can further develop materials for specific applications.

Significant accomplishments credited to Program initiatives include the demonstration of modified 9 Cr-1Mo steels for coal burning utility superheaters, establishment of a major data base and design methodology for gasifier refractories, in-situ materials evaluation in coal conversion pilot plants, the development of a better basic understanding of the mechanisms of corrosion and erosion in liquefaction, gasification and combustion systems, establishment of a broader data base on mechanical properties of pressure vessel steels, and the development of chemical vapor infiltrated ceramic composites with the potential for high temperature heat exchangers and filters. It significant that these accomplishments have occurred despite basically level program funding.

Program focus from 1974 to 1980 was on resolution of specific material issues of critical importance to coal systems in operation or under design, including substantial technical support for process development unit (PDU) and pilot plant programs. Since 1980, the focus has been on the development of a broad, generic scientific base emphasizing the development and understanding of materials synthesis and mechanisms of deterioration, particularly with regard to functional materials, as contrasted to earlier singular work on structural materials. This program redirection is of major consequence because innovative functional materials are viewed as holding high potential for effecting revolutionary progress in fossil technologies. The potential for breakthroughs applies even more to materials systems combining structural and functional capabilities, as for instance reactive ceramic membranes. Pursuit of such radically novel concepts is obviously a high risk venture, carrying with it a commensurate low probability of success. However, this calculated risk must be balanced against the enormous benefits that would accrue if the R&D objectives are achieved.

Changing concepts of the combustion of coal, and new conversion process developments, have prompted this study which attempts to identify the role of new materials understanding and developments that have evolved from the burgeoning field of materials science. Identification of new materials and their potential application to fossil systems can continue the Program role of transitioning materials from general understanding to advantageous use for specific fossil needs. The technologies under consideration in this assessment study involve the direct utilization of coal, and the production and use of coal derived fuels. The primary focus is on coal gasification, coal liquefaction, combustion systems and, hot gas cleanup (HGCU) processes, with consideration of fuel cells and heat engines. This study did not include coal preparation, flue gas scrubbing and magnetohydrodynamic systems (MHD).

METHODOLOGY

The study was conducted by review of current and past fossil programs, review of technical literature and, most importantly, by interviews with cognizant individuals in industry, academia, R&D organizations, and pertinent DOE Fossil Energy Programs.

Personal Contacts and Interviews

A list of the over 100 individuals contacted is provided in Appendix I. They represent about 50 organizations, in industrial firms, universities, R&D organizations, DOE offices, and other government agencies. In addition to these specific contacts, informal discussions were held during professional and technical society encounters with individuals who were believed to be knowledgeable in the area of fossil energy materials problems and derived research needs and opportunities. Appreciation for the input from these contributors is gratefully acknowledged.

For maximum effectiveness in this information gathering process, an effort was made to arrange face-to-face meetings, rather than relying on telephone conversations and exchange of correspondence. In order to structure and optimize such meetings, visits were preceded by a letter clearly outlining the objectives and scope of the meeting.

Generally, industrial personnel were reluctant to identify material research needs, probably due to their companies' competitive position and the lack of a clearly perceived benefit to them by doing so. In fact, it was clearly stated that unless a program to which they could address their proposals for funds were established, their interest was limited to monitoring ongoing research. This attitude is reflective of the current low interest in coal conversion due to low energy prices.

Positive views of the Program were generally presented by application focused engineers in industry responsible for materials selection and utilization, but identification of opportunities for materials development were lacking. Significantly, contacts from industry emphasized that minor improvements in construction and fabrication would have a negligible effect on plant and product cost and advised against programs in this field. Industry did emphasize that new materials systems, almost regardless of improved performance capabilities, must be available at reasonable cost or remain technological novelties.

However, a more constructive dialogue was found within the materials research and development community when presented with the opportunity to identify promising materials research topics. This response is due to the recognition that the Program has supported materials research as well as the general vitality of the field which has been recognized as critical to national technological and economic well being. It is significant to note that members of the materials research community often focused on manufacturing, particularly with regard to synthesis and processing of ceramic materials, when asked to identify important materials research needs. This opinion is reflected in the recent MIT study (Dertouzos, et al) and the NRC assessment on materials science and engineering for the 1990's which cite manufacturing as a national weakness, and urge that emphasis be placed on synthesis of new materials and on processing technology relevant to manufacturing.

Discussions with FE personnel, both at headquarters and in the field, were particularly useful in determining broad perceived needs. The close interaction of FE personnel with contractors not only provides a valuable experience base, but consolidates the linkage between MSE and the marketplace.

Literature Review

The broad range of literature and reports reviewed as background for this assessment study are itemized in Appendix II. These key documents were studied to gain familiarity with the content and plans of present fossil programs, and to establish a context for materials research opportunities. Appendix II contains a partial list of documents assembled and reviewed by the authors, which supplemented documents furnished by the sponsor. Only major documents (e.g., conference proceedings, books, complete reports, and key technical papers.) are listed in Appendix II. Appendix II also compiles prior assessments of materials constraints and related R&D needs and opportunities to address these constraints. Although these assessments provided an interesting historical perspective, many were found to be fragmentary and/or obsolete. This is an indication of the rapid evolution of materials systems and process technologies, and lends added support for conducting the present study.

Materials science and engineering has undergone dramatic developments in the recent past. This has been spurred by the significant emphasis placed on advanced materials for structural and more importantly for functional applications. Major government funded programs in the DOE such as the development of structure silicon based ceramics and the Department of Defense (DOD) sponsored composite programs have been accompanied by strides in functional materials such as high temperature superconductors. The following sections itemize many of these major areas which are applicable to fossil systems.

Intelligent Processing

Intelligent processing of all classes of materials, wherein sensors detecting a material condition during the consolidation stage have been integrated with process controls and process models to provide real time process parameter variations which determine final properties, is under active development. This technique has been applied to the rolling of steel and aluminum. Fabrication of ceramic components, utilizing intelligent processing, has been under limited development and the lack of adequate sensors has hindered progress.

The motivation for intelligent processing lies in the desire to reduce final product cost through reduced rejection of substandard materials, as well as through maintenance of product consistency. For ceramics, in particular, sensors to detect the presence of flaws has met with limited success as noted by the development of nuclear magnetic resonance (NMR) imaging, ultrasonics and a variety of laser based interrogation techniques. The use of these techniques at ceramic sintering temperatures has not been proven, yet this specific application is key to intelligent processing of ceramics. Process models for ceramics have not been developed in a comprehensive fashion although a large body of knowledge relating processing parameters to final microstructure and properties is available. This lack of development appears to be due to the variability of starting powders both in terms of size distribution and chemistry; the latter factor is of particular concern at very low levels of impurity and sintering aids. Unlike metallic systems, understanding is developed for specific ceramic powder systems, a result of the fact that starting materials for ceramic bodies consist of powders where manipulation of physical and chemical features is limited. Hence, techniques of fabrication are usually developed for specific systems. The Program has addressed the modelling aspect of intelligent processing as it pertains to Chemical Vapor Infiltration (CVI) through a project at the Georgia Institute of Technology Research Institute. This research is a good example of the focused approach necessary to utilize funds effectively.

Aluminides

Nickel based aluminides with superior high temperature strength and excellent oxidation resistance have been developed to the point of industrial licensing for commercial applications. Concurrently, iron based alumindes developed in the Program with good but somewhat lower high temperature strength and better resistance to sulfidation attack have shown potential for use in fossil systems. For instance, iron aluminides may find application for high temperature metallic components in hot gas cleanup systems. Iron aluminide directed R&D in the Program also addresses this material's good corrosion resistance in aqueous environments. Aqueous corrosion is of limited importance in most fossil energy systems but insight into hydrogen effects may be gained through this research. Considerable work remains to be done, and is underway in the Program, to improve ductile properties for use in stressed components, and to facilitate fabrication and welding.

<u>Diamond Films</u>

Diamond films produced from gaseous precursors onto a variety of substrates are under extensive study, particularly with regard to understanding of the deposition and nucleation mechanisms. Benefits for structural applications lie in the extreme hardness of diamond which gives it outstanding wear and abrasion resistance. Diamond's high thermal conductivity has encouraged its development as an electronic substrate where circuit density is limited by heat dissipation. Limited commercial application has occurred, most notably in the electronics field and in the coating of ceramic cutting tools, but high substrate temperatures required have prevented deposition on most metallic materials.

Significant opportunities lie in the application of diamond films to structural components, such as coal slurry fuel injectors, by the development of interlayer designs capable of moving this new class of materials from the basic research state to industrial usage. Oxidation of diamond is of concern above 650°C, (Johnson, et al) making this material suitable for use in a variety of slurry handling components which operate at lower temperatures.

<u>Ceramic Superplastic Forming</u>

Superplastic forming of ceramics offers opportunities for net shape forming and property manipulation beyond that available with conventional ceramic processing. Superplastic deformation is generally understood to be the ability to sustain permanent deformations of 100% or more without cracking. This phenomena has been observed in several ceramic materials with nanometer ($1nm=10^{-6}$ mm) size range grains. Superplastic deformation opens the possibility to forge ceramics, much as metals are, to final size. Subsequent heat treatment allows grain growth and the control of high temperature properties.

In a similar vein, nanometer range silicon nitride powders have been shown to be amendable to compaction to high green densities at high pressure and low temperature and subsequently to sinter to full density without sintering aids at temperature well below that required for conventional processes. Particular advantages are expected in terms of high temperature strength due to the absence of glass grain boundary phases which accompany the use of sintering aids. Potential applications are for wear and erosion resistant slurry pumps and injectors and high temperature structural members for heat exchangers and turbines.

<u>Solid State Electrolytes</u>

Solid state electrolytes, generally based on ZrO_2, have been under extensive development for use in solid oxide fuel cells. Progress in this area has encompassed both powder synthesis methodology as well as basic understanding of the physics and chemistry of these complex oxides in an effort to both improve fabricability and electronic performance. Indications are that the best prospects for contributions by the Program in the realm of solid state electrolyte development lie in the area of solid oxide fuel cells (SOFC), the current primary thrust of this Program. Other important fossil energy related applications such as sensors and gas separation devices, catalytic promoters, photonic conductors, and chemical synthesis devices have been identified.

The bulk of the research sponsored by FE has been in the private sector and focused on the development of fuel cells of a variety of designs. Significant developments at Pacific Northwest Laboratories (PNL) under the Program have resulted in new methods of synthesis and understanding of $ZrO_2(HfO_2)$-Re_xOy-MO_x system for electrode applications and $La(M^1)(Cr, M^{II}) O_3$ for interconnections.

Opportunities is this field have been identified by the Program in the Program Implementation Plan for 1990-94 (ORNL/TM- 111231, March 1990). Basic materials limitations are encountered due to the wide range of oxygen partial pressures over which the interconnect must function as well as the long term (over 10,000 hours) operation, including chemical and thermal upsets, that thin, often weak adjacent materials of different thermal conductivities must survive. A variety of techniques for manufacture of fuel cells has been developed but basic concerns of cost, mechanical durability, and long term stability remain to be resolved.

Ceramic Matrix Composites

Ceramic matrix composites with improved toughness, under intense development for the last 10 years, have resulted in the commercialization of whisker toughened alumina cutting tools. Extensive research (including work in this Program) is underway to develop continuous fiber reinforced ceramic matrix systems for applications such as filters and heat exchangers. Processes ranging from chemical vapor infiltration to traditional powder infiltration of fiber preforms are under development. Significantly, progress has been made in understanding the role and behavior of the critical interface between matrix and fibers to provide controlled toughening.

Novel Processing

Processing of ceramics by novel modification of traditional techniques, is driven by the desire to provide improved properties by reduction of flaws formed during processing. Notable among the developments are gel casting, sol gel synthesis, pressure casting, and improvements in slip casting and injection molding. One of the more novel techniques being commercialized is the Dimox process (Lanxide Corporation) employing controlled melt-oxidation. Processing of materials through nonconventional methods has been addressed in many programs. Hot Isostatic Pressing (HIPing), a novelty a decade ago, is now routinely used to heal casting defects as well as to reduce the flaw population in ceramics, particularly for rolling element bearings.

More recently microwave sintering has been pursued as a means of consolidating ceramic materials. This technique allows uniform heating throughout a green body during sintering, avoiding thermal gradients normally incurred in conventional furnace firing. Reduced sintering temperatures and times have been demonstrated. Microwave baking for binder and water removal is now used commercially for whiteware production. Although much remains to be done in terms of understanding the mechanism of the process and adapting it for practical applications, obvious opportunities for microstructural control are present. Microwave sintering is currently supported by the AR&TD Program as well as by the Transportation Materials Programs (TMP) in DOE.

Nanocomposites/Microengineered Materials

Nanomaterials, those metals and ceramics with a grain size of less than 100 nanometers are viewed as having potential major impacts in many applications. This fine grained material may provide improved strength, toughness and corrosion resistance. Perhaps more significantly, the concept of controlling structure and chemistry on such a fine scale has potential utility for functional applications such as fuel cell components.

These materials are generally formed from nanometer size powders produced by gas phase synthesis, reactive evaporation or precipitation from solution. Powder processing consists of consolidation via pressing and sintering. Although powder synthesis has been demonstrated for several ceramic and metal compositions, large quantities are not generally available (particularly for ceramics) and research has been focused on processing gram quantities.

The ability to manipulate the composition of a structure, even through the placement of species on the surface of powders, allows the well controlled development of microstructure with selective ionic and electronic transport properties. These materials, more specifically identified as nanocomposites, are the subject of active research at several universities and government laboratories.

MSE APPLICATION TO FOSSIL TECHNOLOGIES

The application of new materials science and engineering research results to fossil technologies offers the opportunity to continue to provide both new materials understanding as well as materials development. To determine the relevance of these new research areas to fossil technologies, both the projected benefits to those technologies as well as the barriers to their application require identification. These are addressed in the following discussions.

It becomes clear that most of the new MSE fields identified are applicable to a variety of fossil technologies but that they also have significant barriers to overcome. Also reflected in these discussions are areas where work is judged to have low payoff or warrant consideration of a different focus. Opportunities for meaningful research targeted at these objectives are detailed below.

The AR&TD Materials Program has identified several thrust topics of value to emerging fossil technologies. Those subjects were determined by assessments and discussions between FE headquarters and field personnel, and represent a view of those fields of research which address the materials needs of fossil technology as well as being appropriate topics for program support. This study, although cognizant of those topics, endeavored to identify additional topics that have not been pursued. This section includes discussion of both sets for sake of completeness and draws from prior FE documentation to summarize those already identified.

Coal Liquefaction

The major impact of MSE on coal liquefaction lies in improved catalysts, which are considered to offer the best opportunity to significantly narrow the present-day 2:1 cost advantages of crude oil over coal derived liquids via direct liquefaction. Improvements in structural materials, by comparison, are far less likely to have an appreciable effect on the overall economics of coal liquefaction. The reason is that the corrosion/erosion problems encountered in the second generation processes have been effectively addressed in the large Solvent Refined Coal (SRC), Hydrocarbon Research Inc., (HRI) and Exxon Doner Solvent (EDS) pilot plants and in supplemental laboratory programs. There is of course room for improvements, notably with respect to long-term durability of materials and coatings for components in aggressive slurry services, viz. pressure letdown valves and slurry pumps.

The new generation, two-stage catalytic liquefaction processes operate at lower severity than the second generation processes mentioned earlier. Since lower severity operation proceeds at lower pressure/temperature conditions, it directly decreases the demands on construction materials. This also holds for coal/oil co-processing schemes, particularly with respect to lesser anticipated erosion due to lower solids concentrations in slurry streams. Co-processing is also likely to prove less corrosive than liquefaction, owing to the lower chlorine content in oils compared to coal. New corrosion problems may however crop up with use of novel liquefaction catalysts containing aggressive species, such as metal/iodine co-catalysts which have been shown to be highly effective in hydroconversion of carbonaceous matter.

Coal Gasification

The major impact of MSE on surface coal gasification is believed to be through development of reliable and durable systems and devices for chemical and physical hot gas clean-up (HGCU) enabling the simplified integrated gasification combined cycle (IGCC) concept advocated by the Morgantown Energy Technology Center (METC). This concept is widely acknowledged as offering a better prospect for coal gasification commercialization in the near-term energy scenario than production of syngas or fuel gas. Coal gasification will also play a prominent role in the hybrid pyrolysis/PFBC combined cycle systems under development. These hybrid systems will of course also be dependent on reliable materials for HGCU equipment.

Since the main deterrent to greater acceptance of coal gasification in the commercial sector rests on unattractive economics, the FE Surface Gasification Line Program has targeted cost reduction as a major strategic objective. Such savings are to be realized not only through simplifications in processing schemes, equipment and designs, but also through reduced materials and manufacturing costs. However, the premise that cost reduction of equipment through incrementally improved materials systems or manufacturing techniques can make a significant impact, must be tempered. The long term costly development and testing effort required for new alloys and innovative manufacturing/construction techniques to provide incremental improvements over available materials should be initiated only after due consideration and a substantial commitment of funds.

Process simplification offers considerably better prospects for substantive cost reduction because it may totally eliminate entire sub-systems, thus enabling increased thermodynamic efficiency and the need for fewer equipment items. The central idea of the process simplification concept is matching pressures and temperatures of the gasifier effluent (with little or no quench) to those of the gas cleanup and power generation equipment. Complete heat integration will in most instances require raising the temperature capabilities of materials and components in these systems above presently achievable limits. This importantly affects the HGCU systems, gas turbine fuel control devices, and ultimately the gas turbine itself. Of these considerations, development of new, not incrementally improved, materials able to survive in corrosive/erosive environments at temperatures above present limits should be considered a key overall objective.

As a final comment, it should be recognized that not everyone in industry shares the METC strong advocacy of the simplified IGCC concept embodying hot gas cleanup. The potential concern is that hot chemisorption and physical filtration systems are unreliable and that breakdowns could quickly lead to major damage of downstream gas turbines or fuel cells and resultant costly and lengthy outages. While it is agreed that the present status of hot gas cleanup systems is inadequate as regards industrial acceptance criteria, this does not detract from the soundness of the simplified IGCC concept per se. Recognizing the present day critical shortcomings, FE's hot gas cleanup program is appropriate and specifically aimed at improving performance characteristics and long-term reliability of both chemical and physical HGCU systems.

Combustion Systems

Fluid bed combustion of coal generally entails considerably milder exposure conditions than coal gasification, and consequently presents fewer materials problems and needs. Atmospheric Fluidized Bed Combustion (AFBC) in particular is rapidly progressing to the stage of being a competitive commercial coal-based combustion technology. Its even greater acceptance is hampered by metal wastage of in-bed components by erosion or erosion-corrosion, a remaining materials problem that continues to occur in AFBC installations, though to a lesser extent in circulating beds compared to bubbling bed systems. These wastage problems are being addressed empirically by a combination of more resistant materials (coatings and cladding), better mechanical design features, and improved fluid dynamics. Similar erosion/corrosion considerations apply to combustors in Pressurized Fluidized Bed Combustion (PFBC) but are overshadowed by the far greater erosion/corrosion concerns with expander turbines employed. More challenging problems are encountered in second generation coal PFBC systems incorporating separate pyrolysis (mild gasification) and combustion stages. Such hybrid systems are being demonstrated in PFBC combined cycle plants in the Clean Coal Technology Demonstration Program. The materials constraints and needs broadly resemble those in IGCC, insofar that a reliable hot gas cleanup system is a critical need to safeguard the gas turbine from erosion/corrosion. This poses a far greater concern in second than in first generation PFBC because of the former's much higher turbine inlet temperatures. Maximizing this temperature would allow higher net plant efficiency, which even now approaches 50% in designs combining hybrid PFBC concepts with advanced steam cycles.

Hot Gas Cleanup (HGCU)

As emphasized in the sections on coal gasification and combustion systems, reliable HGCU capability is a crucial need for commercializing IGCC and PFBC power generation. Currently, neither physical nor chemical gas cleanup systems have come close to demonstrating the degree of reliability and ruggedness demanded by industrial users, let alone public utilities. Moreover, neither is operational in the upper temperature regions where these systems would ideally operate for maximum efficiency.

Physical HGCU

Two most promising methods for physical HGCU are the use of barrier filters made of either porous ceramic composites or ceramic fabrics. Among the rigid barrier filters two concepts under development are ceramic candle and ceramic crossflow (CXF) filters. The latter appears more advantageous, particularly for full-size plants. However, obstacles need to be overcome in developing CXF filters for commercial acceptance. Most importantly, long-term mechanical integrity needs to be demonstrated to withstand the high thermal-mechanical stresses and degradation modes imposed by cyclic operation. Long-term chemical resistance to alkalis and other detrimental elements in coal derived gas streams also requires verification. Major effort to address these issues is planned as part of test installations sponsored by the FE Line Programs and the CCT Program.

In designing CXF filters, there is an inherent trade-off between strength and filtering effectiveness. For the latter, a thin, highly porous structure is desirable which makes it vulnerable to mechanical failures, notably web collapse. Thermal and pressure cycling imposes heavy demands on the frail filter structure, and is responsible for cracking and delamination failures. Another development goal for CXF filters is raising their temperature limit beyond the presently attained 870°C level. Maximum target limits are about

930°C for PFBC, 980°C for IGCC and molten carbonate fuel cells, and as high as 1230°C for direct coal fired turbines.

Similar to rigid filters, ceramic bag filters are also limited by a number of degradation modes due to chemical, physical, mechanical and thermal effects, though not thermal shock. Specific failure modes result from fiber loss and embrittlement, pinholing, and seam breakage. As with CXF filters, there are at present constraining temperature limits. Even at relatively mild temperature conditions of 815°C encountered in PFBC testing, unacceptable failure rates were experienced. Obviously, considerable development effort lies ahead before ceramic bag filters will come anywhere near the dependable performance of conventional fabric bag filters in industrial use.

A critical issue for both types of filters is the thermochemical stablity of ceramic materials in high temperature corrosive environments. Corrosive reactions can both weaken the filters as well as block filtration and increase pressure drops.

Chemical HGCU

Chemical hot gas cleanup of corrosive constituents from raw coal gas is no less important than particulate removal for viable coal gasification, FBC, and fuel cell power generation systems. While alkali control is critical for preventing gas turbine hot corrosion, sulfur removal is a more universal need. The most effective method under development appears to be external chemisorption by means of mixed-metal oxide sorbents, specifically zinc ferrite ($ZnFeO_2$). The key performance parameter needing improvement is durability of the ($ZnFeO_2$), i.e. its ability to retain efficient sulfur absorbing capacity and mechanical properties under repeated cycling between sulfiding and regeneration conditions.

Aside from inadequate ruggedness and long-term serviceability, there are some inherent negative aspects of ($ZnFeO_2$). One serious detriment is its temperature limit of around 650°C, imposed by the thermochemistry of the sulfur absorption reaction. This is several hundred degrees below the desirable temperature levels for optimum heat integration for maximizing power generation efficiency. Another unfavorable characteristic is the risk of producing sulfates during regeneration, which leads to an unwanted release of SO_2 during the subsequent sulfiding operation.

Other mixed-metal oxide sulfur sorbents are described as superior to $ZnFeO_2$ as regards SO_2 formation and the ability to function effectively at higher temperatures. Zinc titanate, for example, which can operate up to about 760°C and is a more efficient sulfur getter. Others are inexpensive iron oxide base sorbents under development by the Japanese, which generate elemental sulfur rather than SO_2.

Coal/Waste Co-processing

Ever-tightening environmental regulations governing land and ocean dumping give strong impetus to the disposal of refuse and sewage sludge by thermal destruction. This applies particularly to populated regions where available landfill area is rapidly declining, and where the supplemental means of power generation offers added economic incentive. Although incineration continues to be the dominating technology, increasing interest has been building in coal/waste co-disposal options, all of which pose new corrosion challenges.

Three such technologies under development or commercial demonstration are briefly described below.

<u>Co-gasification of coal and sewage sludge</u> is being actively developed by Texaco. Successful test studies have been conducted in their Montebello pilot plant to produce a clean synthesis gas from a 3:1 coal-to-sludge ratio.

<u>Co-combustion of coal and municipal refuse derived fuel (RDF)</u> has been experimented with in the U.S. since the 1960's, but has been largely abandoned because of excessive fouling and other problems. However, several utilities are still practicing this technique on a consistent basis. Demonstrations include a variety of furnace designs, and have utilized RDF fractions from 10-50%. One advantage of such a co-disposal scheme is stabilization of combustion and heat release.

<u>Co-combustion of coal and industrial wastes</u>. There is increasing interest in the U.S. and abroad in co-disposal technologies employing coal and various industrial wastes ranging from biomass to hazardous chemical waste streams. For instance, Tennessee Eastman for over 15 years has been co-firing coal with a broad slate of chemical wastes at their Kingsport, TN plant, utilizing a variety of boiler designs. Recent focus is on co-firing coal and diverse waste streams in circulating FBC boilers, as has been widely practiced in Scandinavian co-generation facilities employing woodwastes.

Compared to coal combustion, coal/waste co-firing potentially increases corrosion, slagging and fouling, which are often inter-related phenomena. These problems need to be systematically addressed and counteracted to permit these technologies to gain wider acceptance by utilities and industrial users. An area of justified concern is the high chloride content of many waste streams. In that regard, it needs to be emphasized that the role of chlorine is not yet clearly understood in refuse incineration, nor for that matter in coal combustion. Uncertainties and controversy also exist with respect to the purported ability of sulfides to suppress high temperature chloride corrosion, as was serendipitously discovered by Battelle. If borne out by further research and testing, the co-firing of high sulfur coals and high chloride refuse would present a favorable waste disposal option.

Another matter of concern, specific to coal/sewage sludge co-gasification is the high ash content of the sludge. It typically runs about 40% which is far higher than normally present in U.S. coals. Consequently, the coal/sludge mixture may result in increased erosion damage relative to coal alone.

There are evidently a number of unresolved corrosion issues in coal/waste co-disposal that merit systematic study. On the basis of the growing waste disposal crisis, and the reasonable assumption that coal could play a significant part in these developmental waste disposal technologies, the Program might consider research on the type of interactions and synergism described above.

<u>Catalyst Supports</u>

Tailored catalyst support structures enabling atomistic dispersion of active sites unquestionably hold great potential for achieving greatly improved catalyst reactivity and selectivity, and thus represent an excellent means for improved catalysis. While no one interviewed took issue with this general assessment, discussions held with representatives of industry and academia brought out a number of questions and concerns, relating not only to technical matters but importantly also to the manner in which this catalyst/catatlyst support research is presently organized.

The central uncertainty revolves around the unproven ability of these novel catalyst support structures to live up to expectations for the intended application. Major concerns are long-term stability, regeneration characteristics, and resistance to poisoning effects. Furthermore, it was pointed out by several catalyst experts that the effort required for realistic testing needed to verify performance would be very difficult and costly. Other opinions expressed were that catalyst preparation via ion exchange is by no means a novel technique, and that it may actually be less appropriate for coal liquefaction than for other processes.

While these comments reflect serious concerns, they would not by themselves be a deterrent for pursuing this catalyst support development. In fact, it could be argued that the goal of the program was specifically to overcome and negate such concerns. Success would constitute a real breakthrough with commensurate high payoff.

Advanced Austenitic Alloys

This comprehensive project in the Program is nearing completion, with aims to have sufficient experimental data to induce industry to continue on toward final development and commercial exploitation. Discussion with industry representatives reveal a surprisingly low level of interest in these developmental high strength alloys for advanced steam cycle superheaters and reheaters. One probable reason is the lack of interest by U.S. utilities in building supercritical plants, notwithstanding the fact that 170 supercritical units have been in operation in domestic plants, most of them for many years. Another reason may be the commercial availability of several high strength steam cycle alloys from Japanese manufacturers, obviating the incentive for developing similar alloys and/or pioneering their industrial use. Interest from the emerging FBC industry appears to be similarly low. Their lukewarm attitude is most likely related to the restricted role of superheaters and reheaters in FBC power generation.

Corrosion and Erosion Research

Fundamental investigations of the phenomenology of corrosion and erosion processes has historically been an important component of the Program since its inception. With the advent of novel ceramics and ceramic composites, research studies on elucidating degradation mechanisms and developing control measures have assumed even greater importance. There are several specific areas, some old and some new, where research effort appears to be warranted.

High temperature corrosion studies which focus on the role of corrodent species particular to fossil systems have been a premier portion of the Program. Continuation of studies to improve the understanding of corrosive processes which constrain commercialization of advanced coal-based technologies is critical. The increased emphasis on the application of ceramic components such as filters, membranes, coatings and structural elements such as heat exchangers warrants a focus on these materials. The current state of understanding of corrosion mechanisms of silicon carbide and silicon nitride in fossil environments is considerably less developed than for metallic systems but suggests that coatings for these materials may be desirable. Improved understanding of the thermochemistry and thermal-mechanical behavior of these ceramic systems is required to define their use limits and to facilitate protective coating development. The accurate control of pore size for both filters and membranes will necessarily depend on the rate and limit of corrosion product formation. A comprehensive program which addresses these materials and provides guidelines for application and limits of operating envelopes for ceramics of interest in fossil energy systems is recommended.

Virtually all coal conversion/utilization technologies, involve erosion and/or erosion-corrosion of metals by abrasive coal, char or ash particles, many at high temperatures and in corrosive environments. It is therefore evident that fundamental studies in the area merit unflagging support. A case in point is the remaining controversy and uncertainties regarding interactions and synergism of corrosive and erosive wear in fluid bed systems, notably the complexities of competing processes of scale destruction/re-formation that ultimately control wastage rates.

The practical ramifications of a better grasp of FBC erosion are highlighted by the continuing, unpredictable tube wastage problems at Grimethorpe, which have a direct bearing on industry confidence in PFBC. Accelerated wear of materials is also a serious recurring problem in circulating FBC, as discussed in the referenced EPRI workshop on CFB materials issues. An unexpected problem encountered in these units is severe abrasive wear of boiler waterwall tubing immediately above the termination of the refractory lining.

The deleterious effect on mechanical properties resulting from elevated temperature exposures in corrosive environments presents a formidable barrier to the commercialization of coal conversion/utilization technologies. This applies both to strength properties, notably creep rupture, as well as to ductile properties, which may suffer drastic impairment due to embrittlement phenomena. Growing concern about damage to mechanical properties of structural materials resulting from environmental interactions has given rise to considerable activities in Europe and Japan (e.g., programs at the Joint Research Center, Petten and KFA - Julich) but limited interest in the U.S..

There are obvious opportunities for research in this area. Such work should focus on mechanistic studies, not on data gathering as was the case in an earlier DOE/GRI co-sponsored program at the Southwest Research Institute (Mechanical Properties of Materials in Coal Gasification Environments- GRI-87/0153).

In contrast to the vast number of high temperature erosion studies and tests, virtually nothing has been done in the area of 3-body abrasion at elevated temperatures. This is a serious gap because abrasive wear in high temperature applications, often in combination with corrosion, is assuming ever increasing practical significance in modern industrial processes, including coal conversion and utilization technologies. Most specifically, direct-fired gas turbines and diesel engines are prone to abrasion damage. However, coal gasification, HGCU and fluid bed combustion systems are also affected. This applies particularly to fully heat-integrated combined cycle plants envisioned by METC, which will require valving and other critical equipment items subject to high temperature abrasion.

Phenomenological understanding and predictive capabilities in the area of high temperature abrasion are in a state of infancy. The state of understanding is even less developed for reactive environments where corrosion synergism comes into play. Such abrasion-corrosion is considerably more difficult to model and test than erosion-corrosion, because of the complexity of contact force interactions between wear surfaces and entrapped abradant particles. The complicating factor introduced by the contact force parameter and the difficulty of controlling it experimentally, is no doubt responsible for the dearth of research and test programs in this area.

Coatings

Development of improved protective coatings for fossil energy applications has been a long-standing element in the Program, and continues to be an important objective. It can in fact be argued that the need is growing with the trend toward ever higher temperatures and lower quality fuels. Protective coatings represent a cost-effective avenue for tailoring very different alloy substrate and surface properties. Such optimization assures special importance in high sulfur environments, where many materials possessing excellent high temperature strength (e.g. nickel alloys and nickel aluminides) are particularly vulnerable to corrosion, and unsuitable for most fossil energy applications without protective coatings or cladding.

Considerable evolutionary progress is being made with conventional coatings systems applied by a variety of techniques. These include plasma (air and low pressure) and inert gas arc wire spray systems for depositing overlay coatings, as well as pack cementation diffusion bonded coatings. Progress in spray applied systems, enabled mainly by improvements in powder quality, robotics, and application hardware, is exemplified by Union Carbides' Super D-Gun detonation coatings, and the so-called High Velocity Oxy-Fuel (HVOF) hypersonically applied coatings. Other coating types benefitting from evolutionary advances are the two systems in the Program, i.e., pack cementation dual-metal (Cr-Al and Cr-Si) diffusion coatings and electro-spark deposition (ESD).

Steady progress is similarly being made in cladding systems, largely through refinements and improvements in materials and application techniques. Included are plasma transfer arc (PTA) overlays, and composites produced by various techniques such as co-extrusion, co-casting, hot isostatic pressing (HIPing) and highly automated weld overlaying.

Most of the high quality coating systems have serious practical shortcomings with respect to fossil energy applications, in terms of one or several of the following limitations: coating/substrate incompatibility, size and geometry of component to be coated, insufficient coating thickness, need for line-of-sight application, unsuitability for field application, slow deposition rate, excessive cost, and difficulty of repair. These limitations severely constrain the use of the majority of coatings for commercial coal conversion/utilization applications, many of which entail protection of equipment that is not only large and complex, but additionally has extensive vulnerable areas that are inaccessible, such as tube bores. This is considered a serious limitation of conventional coating systems, creating the incentive to explore and develop radically new concepts.
Research in these areas may offer the Program an opportunity to score major advances in the coating field. One interesting development involves a CVD silica coating employing alkoxysilanes, which dissociate on hot metal surfaces

and deposit a thin but impervious layer of SiO_2. Though not reportedly demonstrated, this technique lends itself in principle to in-situ coating of installed piping circuits by means of a circulating hot gas stream containing organosilicon compounds (a similar surface modification flow through technique employing nitric acid is utilized for passivating titanium equipment and connecting piping).

The technique for vapor deposition of SiO_2 coatings was developed at Harwell Laboratory (England) in the early 1980's, specifically for protecting stainless steel fuel cans used in UK Advanced Gas Cooled Reactors. Work on these coatings has continued and has been broadened under the auspices of two European programs (CREST and EURAM). Capabilities have progressed to the stage where vapor deposited SiO_2 coatings have proved to be remarkably effective in protecting 2 1/4Cr-1Mo steel, Incoloy 800, and IN 738LC in high temperature sulfidizing environments. Current development activities are additionally focusing on an alternative technique for depositing SiO_2 coatings, that involves laser consolidation. In this method, powdered silica blown onto a substrate is fused to produce thick, diffusion resistant deposits.

Another highly intriguing development centers on self-repairing ceramic coatings. Representing an extension of plasma cermet coating technology, these coatings use multi-layer structures consisting of a metallic bond layer, an intermediate chromium deposit, and a ceramic oxide top coat. Due to synergistic interaction of the three layers, the originally porous structure is sealed by spontaneous formation of Cr_2O_3 to form a well bonded, dense, and thermal shock resistant barrier to corrosion. This self-sealing action in environments oxidizing to Cr induces a "self-ceramizing" effect in the coating structure. It has not been determined whether any additional R&D of this intriguing coating concept has been carried out by Perugini and others.

Still another opportunity area where development work is needed is ceramic coatings for ceramic substrates. Although generally viewed as "inert", recent research on SiC and Si_3N_4 for heat exchanger applications has shown these materials to be susceptible to corrosive deterioration in the presence of halides and alkali sulfate deposits. Limited experimental data indicate that oxide coatings applied to these materials can significantly improve corrosion resistance. These oxides, generally applied by plasmas, have a potential weakness in that long term thermochemical compatibility is unproved. Also thermal expansion mismatches may cause spallation during thermal cycling.

Ceramic Membranes

Ceramic membranes, identified as a Program thrust, offer the potential to separate individual species from process streams at ambient or elevated temperatures. Ceramic membranes generally consist of a thin layer of material containing Angstrom diameter pores which is applied to a thick substrate containing much larger pores (micron to millimeter in diameter). The current Program sponsored activity in this field is based on heretofore classified technology developed at the Oak Ridge K-25 site. Interest in inorganic, i.e., ceramic, membranes is increasing but current usage is limited. The ability to operate at elevated temperatures and to provide chemical stability superior to organic or metallic membranes is the basis for much of the interest. Aluminum oxide is the material of greatest current interest. However, it should be noted that operation at temperatures of most interest to fossil technologies (e.g., above 500°C) may jeopardize maintenance of pore size due to both creep and formation of corrosion products on the alumina. The opportunity awaits for the Program to utilize basic processing science and mechanistic understanding to transition the technology to fossil applications. Major challenges still confront the commercialization of ceramic membranes. However, it is expected that this field will greatly expand in the near future. It should be noted that the temperature limitations of alumina may be surpassed by the use of silicon carbide and silicon nitride as membrane materials, a research topic with potential high payoff which has been identified but has not been initiated.

Solid State Electrolytes

Solid state electrolytes for use in SOFC have been identified as a Program thrust area with major potential payoffs for fossil energy. Technology developments in the field of gas (oxygen and hydrogen) separation, electrochemical synthesis, HGCU (ahead of SOFC and following other coal utilization processes) and gas detection, measurement and control can be expected to accompany electrolyte development.

The Program has identified a variety of specific materials research needs, noted below, which are tested comprehensively in the PNL program:

- New materials systems
- Materials synthesis.
- Processing and fabrication.
- Electrochemistry research.

An overall goal of cost effective manufacture and use should continue to be directed to these research needs.

Intelligent Processing

Intelligent processing, the control of a material during processing through on-line sensing of material properties and accompanying real time process parameters variation, offers the potential to improve the reproducibility of both ceramics and alloys used in virtually all fossil plant systems. An intelligent processing system consists of the following elements: (1) a process model which relates processing parameters to material microstructure and properties; (2) a means of sensing important material parameters such as density, chemistry, flaw distribution, texture, and grain size or other microstructural features; and (3) a process control system which is linked to both the process sensor and process model, and implements process changes such as rolling speed or sintering temperature or environment. Much of the materials research conducted in the past focused on the microstructure-property-processing relationship and hence contributes to the development of process models. Less thoroughly addressed is the development and demonstration of on-line materials sensors.

The development of ultrasonic and x-ray based sensors for determination of texture during rolling of steel and aluminum has been demonstrated in operating plants. Sensing techniques for processing of alloy forgings, pipe and plate of components for use in fossil systems can probably be adapted from those already developed. The primary impact of this adaptation would be reduced cost, with the added prospect that such improvements in alloy technology may find widespread adoption in many industrial systems.

Sensors for ceramic processing have not been as extensively investigated and, due to the more stringent requirements for structural ceramic components, greater sensitivity for interrogation is required. Specifically, to control the presence of flaws at the tens of micrometer range, the ability to detect them in parts up to 8-10 mm thick must be developed. Similarly development effort needs to be directed at detection of chemistry variations in starting powders of Si_3N_4 or SiC on the order of parts per hundred or thousand that are nominally in the 1 micrometer size, or the detection of agglomerates of these powders in the 10 micrometer range. Both of these capabilities are of importance but are of significant difficulty, particularly in real time.

The opportunity to significantly impact the use of ceramics for structural applications in fossil systems by intelligent processing is available. To date other programs have not addressed the topic comprehensively. Obviously, structural elements such as heat exchanger tubes could benefit from developments in this field, as could filters and SOFC elements. The Program is in a unique position to provide a significant materials technology base that can impact both reliability and cost of ceramic components, although it should be recognized that entry into this field necessitates a major funding commitment.

Specifically, the development of sensing techniques to detect material condition during processing are required. Currently, rejection rates of 50% are typical for ceramic high technology applications, and are not uncommon for well developed products such as spark plug insulators. A program to focus on the critical parameters which control the properties of fuel cell electrodes that is adaptable to production systems would serve to further the implementation of SOFC. Techniques to access powder chemistry and size distribution in real time would improve product quality, as would techniques to control quality during tape casting. Similar concepts could be applied to the Chemical Vapor Infiltration process now under development in the Program.

Diamond Films

Diamond films formed on substrates from gaseous precursors (generally a methane plus a few percent hydrogen mixture) offer the ability to develop hard erosion resistant interfaces for use in abrasive environments. Research on this topic has been primarily funded by the Office of Naval Research, with a primary focus on understanding the deposition phenomena and for applications such as sensor windows and electronic substrates. Public funding for diamond coating of structural components has been limited and industry has directed its attention to the development of coatings for tungsten carbide or silicon nitride cutting tools.

Particular benefits can be foreseen in applications requiring exceptional abrasion resistance, such as slurry valves and pumps in liquefaction or gasification systems. Diamond film coatings also appear to hold promise in coal slurry combustion systems, e.g., diesel injection nozzles. This demanding application has encouraged the use of diamond compact, an effective but expensive solution to the wear problem.

Several barriers to use of diamond films require resolution, principally the high substrate deposition temperature (1100°C) required. At this temperature metallic substrates soften, and to date deposition has been generally limited to silicon, ceramic or cermet substrates (Si_3N_4, SiO_2, WC, SiC). Research to either reduce deposition temperatures or to develop processes for diamond deposition on an intermediate layer (e.g., Si) which could be bonded to conventional alloys at a lower temperature, would offer the widespread usage of this new class of materials. The high hardness of diamond films would encourage the use of this material on mating surfaces which are prone to high wear, such as piston rings in coal slurry fueled diesel engines. However, these films typically have rough surfaces which wear the materials with which they are in contact. Research is required to develop methods of smoothing diamond films. Lastly, the limits of use in terms of temperature, contact loading and reaction with fossil related species requires definition.

Fossil sponsored research in this field could well benefit from fundamental efforts sponsored by other agencies and clearly, opportunities are available to utilize the unique properties of diamond films for fossil applications.

Superplastic Forming of Ceramics

Conventional techniques for fabricating ceramic bodies to full density generally rely on solid state diffusion to bond micron sized particles together, usually with the addition of a sintering aid. This process, which entails the burnout or evaporation of binders and surfactants together with sintering for long times, is accompanied by significant shrinkage and often grain growth. The use of sintering aids often also is accompanied by the formation of glassy grain boundary phases which are strength limiting at high temperature. The development of nanometersize powders has allowed the fabrication of ceramics which have extremely fine grains and fine grain material has been shown to have the ability to undergo superplastic deformation (e.g., deformation greater than 100%) without cracking. Similarly, it has been demonstrated that these nanopowders can be compacted at high pressure and relatively low temperatures to nearly full density. This ability to compact to high density has been further shown for silicon nitride to allow sintering to fuel density and fine grain size without sintering aids. Subsequent heat treatment is expected to allow controlled grain growth and improved high temperature strength. These features offer the potential to form nanopowders and nanograined bodies to net shape by high temperature processing, much as alloy shapes are made by forming and extrusion.

This fabrication has to date been the subject of research at Japanese and American universities and research laboratories on a small scale. Extension to larger bodies remains to be demonstrated but the opportunity is present to develop a new method of processing to net shape and the achievement of improved properties, property control and property consistency. Applications to fossil technologies would lie in those components where improved high temperature strength and wear or erosion resistance would provide higher efficiency due to higher operating temperatures and better durability due to the great hardness of ceramics. Economic benefits resulting from reduced machining costs are also possible if components can be made to net shape. Component elements of interest would include heat exchanger tubes and headers; cross flow filters and heat exchangers; heat engine components such as injectors, valves, piston rings, valve train elements and connecting rods; and filters.

Development to the point of component demonstration will require a commitment to both basic research, such as powder rheology at high pressure, and applied research, such as scale-up.

Ceramic Matrix Composites

The fabrication of ceramic matrix composites has been pursued in both the DOE Fossil AR&TD Materials and Conservation Programs. A major program in continuous fiber composites is underway under Air Force sponsorship, as well as the DOE Office of Industrial Programs. The motivation for these programs has been the capability of these materials to fail "gracefully" rather than catastrophically. A variety of techniques to fabricate these materials have been investigated. The most exotic one is chemical vapor infiltration to form SiC/SiC composites. This process, based on chemical vapor deposition, consists of infiltrating a SiC fiber perform with a reactive gas which deposits SiC in the preform interstices. The simplest is conventional powder slurry infiltration of fiber preforms to create a shape subsequently sintered to final density. A promising technique developed under GRI sponsorship is the forming on a mandrel of tape cast layers which include fibers or whiskers. This method offers a cost effective means for producing ceramic composite tube forms.

Significant advantages to be realized by the use of ceramic composites can be identified in gasification or combustion systems where high temperature heat exchangers can greatly improve process efficiency. This, in fact, has been the target application of current Program efforts in this area. The production of rigid ceramic filters of ceramic composite materials also offers benefits, as identified in other sections of this report. Imaginative applications such as SOFC electrodes can also be envisioned which would enable the fabrication of more rugged devices which could withstand thermal shock without catastrophic failure.
Implicit in these applications is the drive for producing composites which offer substantial improvements in terms of ruggedness, but at a reasonable cost. To this end, significant effort must be directed toward simple processing schemes such as pressureless sintering of large sizes. Significant difficulties are expected in controlling shrinkage and residual stress in continuous fiber ceramics, which can limit operating stresses. Little research has been undertaken to develop process models which address this critical problem which must be overcome to facilitate commercialization.

Nanocomposites

The consideration of controlling material to be processed at the nearly atomic (nanoscale) level is a recent concept in Materials Science. By a variety of techniques such as chemical precipitation, sputtering, chemical vapor deposition and electroplating, solid bodies having specific predetermined nanostructures can be built up from controlled precursor materials prepared for subsequent consolidation. Control at this level allows properties to be precisely tailored for final applications. Work is progressing at Cornell University's National Nanofabrication Facility where a variety of techniques have been utilized to fabricate microcomposites and research is underway at Argonne National Laboratory and other government laboratories.

Although traditional processing has been successful in creating nanostructures through the thermodynamic manipulation of metals to form precipitates, limits set by thermochemistry restricted the extent of manipulation possible. Development of heterogenous structures controlled at the nanometer level has been pioneered by the electronics industry, where thin film deposition by technique such as Molecular Beam Epitaxy (MBE) provided the structures required for precise control of electronic properties.

Adaptation of this concept to produce improved structural materials of value to fossil technologies could result in the development of tougher ceramics which contain discrete, dispersed second phases, and ceramic coatings with excellent wear resistance which contain a lubricating phase such as graphite in a hard ceramic matrix with improved wear resistance. Functional materials applications could also be greatly benefitted, as for example, the fabrication of improved devices such as SOFC electrodes, catalytic combustors, and gas enrichment or separation membranes which rely on controlled ionic or electronic mobility or surface reactive chemistry. In short, nanophase concepts and techniques hold promise for enabling dramatic advances in engineered materials that could have a major favorable impact on virtually all fossil technologies. Little specific research on materials of this type focused on fossil energy systems is underway, opening an opportunity for the Program to pioneer developments in this area.

Surface Active Materials

Many of the nonstructural functions of materials utilized in fossil systems rely upon the unique chemical behavior of surfaces. Examples include catalysts and catalytic combustors for use in liquefaction, gasification (particularly gas cleanup) and combustion systems.

The opportunity to utilize surface active properties in conjunction with other functions of a component opens the possibility to develop components with dual functions. An intriguing realization of this concept would be membranes or filters which, in addition to their function as barriers, could simultaneously react a specie to a more desirable form, thereby either transforming it into a more desirable product after separation, or increasing the efficiency of separation. The potential to reduce process steps, and hence a number of unit operations, provides value to this concept in terms of reductions in plant cost and complexity. Although conceptually feasible, the principle has not been demonstrated. Work in the area of surface engineering and science to control the synthesis and manufacture of these materials is required and advocated.

Appendix III summarizes the potential benefits and scientific barriers to implementation of several of these new materials science concepts, with specific regard to fossil technologies.

RELATED PROGRAMS

A comprehensive summary of the totality of materials research programs sponsored by government agencies has not been compiled since 1976. This summary of related programs is not presented as complete, but does include the major programs which include elements that are complementary to Program interests. Those applied programs which address FE applications are primarily supported by the FE line programs, EPRI programs and, to a lesser extent, GRI programs.

Significantly, these programs address, for the most part, the resolution of immediate operational problems, such as erosion in fluidized bed combustors, or development of materials for specific applications. At the other extreme are fundamental investigations intended to provide understanding of the nature and behavior of materials. This latter research is primarily sponsored by the Basic Energy Sciences program in the DOE Office of Energy Research, the National Science Foundation, Office of Naval Research, Army Research Office and Air Force Office of Scientific Research. Transition programs, such as the AR&TD Materials Program which attempt to utilize the basic programs in the resolution of operating problems include the Conservation Transportation Materials Program and selected portions of the DARPA program.

It is worth noting that with the exception of the DOE Energy Materials Coordinating Committee (EMACC) and the Interagency Coordinating Committee on Structural Ceramics, little comprehensive exchange of programmatic data occurs.

The extent of materials research sponsored in the FE line programs has been estimated. In brief, the estimate showed that approximately $20M of clearly identified materials research was sponsored by line programs in 1989. It is worth noting that most of that research was directed toward the resolution of specific operational or durability issues such as selection of materials for FBC heat transfer tubes. The most substantial materials development efforts are those associated with the development of SOFC materials, where this effort is strongly integrated with the applications orientation of the FE line programs. Notably, relatively little research to advance the understanding of materials behavior is sponsored. Also largely absent from the line programs is work directed at processing of materials for fossil applications which can have a major impact on economics.

The DOE Basic energy Sciences program is sponsoring approximately $140M in 1990 for research on the fundamental aspects of materials. It is a tenet of this program that sponsored research should not address specific applications such as, for example, sulfidation in gasification systems. Therefore, relating specific projects to fossil technologies is tenuous. However, there is a general relationship between BES research areas to fossil technologies or to the thrust areas identified as worthwhile to the Program. Research sponsored by the BES program has in some cases provided the fundamental basis that has allowed the development of an understanding of fossil specific materials phenomena. Mechanisms of sulfidation in fossil environments is a case in point where knowledge of thermochemistry and diffusion mechanisms has furthered understanding of the fossil case and in turn provided guidelines for the development of alloys. Similarly, BES sponsored research on the micromechanics of creep in alumina (chosen as a model material) will have value in assessing the behavior of alumina membranes.

Aside from the BES program, R&D efforts are underway that both complement and support Program efforts. Three such programs sponsored by the Office of Conservation and Renewable Energy are heat exchanger development (Office of Industrial Programs) ceramic component design and processing and, coatings (Transportation Materials) Program) and development of aluminides and materials by design (Advanced Industrial Materials Program).

In the field of ceramics, the most significant programs bearing on the Program thrusts are those sponsored by NASA and the Air Force on ceramic matrix composites (CMC). Both of these agencies have selected CMC as the most likely means of providing increased engine temperatures at acceptable reliability for advanced aerospace applications such as the National Aerospace Plane (NASP). It is worth noting that CVI fabrication of SiC/SiC CMC originally funded by the Program has been selected for funding by the Air Force as part of their program.

The other major program which impacts the Program's ceramics effort is the GRI sponsored research on materials for ceramic heat exchangers. This effort, although not intended to address fossil applications, does provide a major technology base for the use of ceramic tube heat exchangers. Worth noting is the emphasis placed on development of cost effective processing and proof of concept; the latter achieved through the design, construction, and monitoring of demonstration units at industrial sites where development costs have been shared by GRI and the host facility. Applications have included the recovery of waste heat from aluminum remelters and glass furnaces. Laboratory research has been conducted at the NIST, Pennsylvania State University, University of Illinois, Solar Turbines, Coors, and Columbia Gas. The significant difference between these efforts and the fossil applications of interest (hot gas coolers) lies in the effect of the fossil specific corrosive environment on long term properties. In fact, the same applies to the CRE, NASA, and DOD programs, none of which concern themselves with chemical degradation caused by prolonged exposures in aggressive environments.

EPRI has long supported research on materials for fossil systems including gasification, liquefaction, FBC and fuel cells. Currently, EPRI activities include development and demonstrations of alloy steels and coatings for gas coolers, based on experience at the Cool Water IGCC plant, as well as comprehensive research and test programs on the corrosion/erosion wastage of alloys in FBC systems.

Research on diamond films has largely been sponsored by the Office of Naval Research whose primary interest lies in the use of this material for electronic applications, and abrasion resistant windows for a variety of wavelengths where erosion damage increases optical loss. To that end a significant portion of the research has been devoted to understanding deposition and adherence mechanisms.
The primary benefits of diamond films to fossil technologies lies in their abrasion resistance; however, significant research programs on this material for protecting equipment components are unknown. The only work holding some relevance to fossil energy is the industrially sponsored development of diamond coated cutting tools.

Intelligent processing of materials has been most notably addressed by the NIST initiatives in this field. Funding of the order of $3M per year has been directed to development of process models and sensors for a variety of materials including alloys, polymers and most recently ceramics. The program is structured to provide the ability to control processing of materials of interest to industry. Prior to implementation of the program, workshops were held with industry to determine their needs and to gain their support. Significant industrial cooperation is a characteristic of the program.

TECHNOLOGY TRANSFER

The transfer of results from the Program to industrial application is an important objective of the program. The degree to which research results are utilized by industry depends both on industry's awareness of the work and the utility of the work to industry's needs. In this latter regard, the more closely research addresses specific industry problems, the more likely it is that the research will be limited in scope.

Unfortunately, industry increasingly views research as what is more appropriately called applied research, i.e., work directed at correcting existent problems rather than at developing a broader phenomenological understanding. Another point to be made is that many in industry view as most valuable only such information or technology which they individually control to the exclusion of competitors. In fact, knowledge which is available to everyone often is of limited value to anyone. This explains the often encountered reluctance to participate in collaborative R&D programs, and the difficulty in attracting strong industrial commitment to support or even use publicly sponsored research. The writers believe that this negative situation prevails particularly in the field of materials development.

Several mechanisms to overcome this reluctance have been developed, e.g., (1) licensing of patentable technology to companies whereby they obtain exclusive use, (2) conduct of research by industry where the publication of critical data is delayed to provide an advantageous incentive to that company to utilize the data on an exclusive basis, (3) conduct of research by a company where a specific product is under development and the use of the data has corollary benefits, and (4) industrial staff sited at government laboratories engaged on projects of interest to both the company and the laboratory.

DOD and NASA programs which focus on the development of a specific product inherently provide linkage between research and application. The broader transfer of this science or technology to the commercial market is enhanced when a company active in these agencies' research programs also manufactures products which can utilize the research results.

The fundamental precept of technology transfer is that the recipient is motivated to acquire the technology and/or science base to either increase profits in existing markets or to enter new markets. Transfer from government programs may occur at any time in a research project from inception to completion. However, it is difficult to effect this transfer after the fact, i.e., to establish the necessary linkage between in-hand research findings and industrial organizations interested in and capable of exploiting these findings commercially. This requires shrewd analysis of what is useful to industry, as well as a strong effort to find interested recipients. To this end, DOE laboratories have established technology transfer offices which attempt to interest industry in program results, with a focus on National Laboratory projects. The most concrete measure of sucess is the industrial purchase of a license to utilize laboratory developed technology. ORNL has been particularly successful in this regard. To implement technology transfer from the initiation of a project, early participation of industry is vital to determine the type and extent of required data and demonstrations. Good examples are the DOE Superconductivity Pilot Centers which, by bringing together teams of companies early in a program, stand to gain industrial commitment. This process was utilized in early Program sponsored research on corrosion in gasification systems, and was also recently utilized in the refractory design consortium (The Thermomechanical Model Software Development Center at the Tennessee Center for Research and Development) organized under the auspices of the Program.

Moving industry to employ data and techniques after development by the government is more difficult to accomplish though seemingly more appropriate in many instances. In this regard, non-Fossil applications are often apparent and of interest to industry. It is noted that significant progress has resulted from the efforts of the National Laboratories to seek out companies which can utilize technology developed at government expense. Similarly, the implementation of Cooperative Research and Development Agreements (CDRAs) provides a venue for industry to work with government laboratories on specific research projects. A key feature of this mechanism is the clear identification of intellectual property rights, making it attractive to industry.

One useful technique for enhancing transfer of scientific information of widespread interest is the linkage of specific program areas with technical societies having a similar interest in that technology area through information exchange seminars. For example, NACE and/or ASM together with the Program could sponsor joint technical conferences, seminars, or workshops describing program results and industrial needs and experience.

RECOMMENDATIONS

Assessment of the changing fossil technologies, i.e., coal conversion and combustion, together with identification of new developments lead the writers to endorse the thrust topics identified by the AR&TD Materials Program, with the caveats noted, together with several new topics which are perceived as having a major potential for improvements in fossil systems.

Austenitic Alloys - This research has provided advances in the capability to produce superheater materials with superior properties. Basic processing and property data has been gathered. Further work would be most effectively conducted through cooperative R&D with industry.

Aluminides - Iron alumindes offer potential for a variety of fossil applications. Although processing and properties have been explored more work is needed to achieve further improvements. Also a comprehensive investigation of environmental effects which emphasize selective potential applications, such as FBC, should be undertaken.

Ceramic Filters - Increased R&D efforts on ceramic filter materials is strongly justified by increasing concerns for environmental quality which can be addressed by emission control, as well as high temperature capability and accompanying efficiency improvement, notably via combined cycle systems employing HGCU. Consideration of cost is required and may be addressed through the development of processes other than CVI, and which are focused on process control to maintain required material durability and reliability. Significant attention should be given to environmental effects which can strongly impact these high surface-to-volume ratio components.

Ceramic Membranes - The application of ceramic membranes offers benefits similar to those cited for ceramic filters. Additional benefits may be gained through application to gas and liquid separation in process technologies. The requirement for long-term microstructural and dimensional stability, and mechanical durability at elevated temperatures necessitate a consideration of material compositions beyond the currently available alumina properties. Environmental deterioration and thermal cycling data for the use of membranes in selected fossil applications is required.

Solid Electrolytes -	Major advantages in SOFC, sensors and gas separation may be realized through this program. However, efforts on mechanical properties, cost effective manufacturing, and close integration with a few firms pursing the SOFC technology should be increased.
Catalyst Supports -	The innovative catalyst support research has indicated benefits in term of selectivity and activity. Because catalyst systems have a major impact on liquefaction process efficiency, close coupling between the development research on catalyst supports and the catalyst itself (sponsored by the Liquefaction Program) would be advantageous.
Coatings -	Coatings offer opportunities to improve the durability and operability of existent systems. To capitalize on this field, emphasis on design of both metallic and ceramic coatings and substrates as a system should be considered, as well as the development of techniques for in-situ coating and coating repair of large components. Also, novel coating concepts should be explored, notably those involving ceramic coatings for both metallic and ceramic substrates.
Erosion/Abrasion/Wear	Erosion, abrasion and wear continue to be primary modes of failure of coal systems. Although basic work has advanced our understanding of mechanisms, the opportunities now exist to explore the development of directionally controlled microstructure to improve performance. Also, improved understanding is needed for corrosion interactions with wear processes, and the effect of corrosion on mechanical properties at elevated temperatures.
Corrosion -	Corrosion limits the durability of ceramic components such as filters and membranes required for reliable application of these devices. Corrosion mechanisms and chemical interaction need further elucidation. Data on chemical attack and property degradation in fossil environments are quite limited, making this a critical element for component development.

Intelligent Processing-	Intelligent Processing to effectively reduce cost, improve reproducibility and allow flexible manufacturing is in its infancy. Continued process modelling research is required, but significant efforts should be directed toward development of real time material parameter sensors and process controls.
Diamond Films -	Diamond Films offer the potential to dramatically reduce erosion and wear in many fossil system components, increasing operability at temperatures below 650°C and ultimately reducing product cost. Significant funding by DOD has established strong fundamental understanding of the mechanisms of deposition, but the application of these materials to practical substrate materials, such as steel or superalloys, is undeveloped.
Nanocomposites -	The ability to tailor microstructure at the near atomic level has been developed for electronic structures and currently is under evaluation for magnetic materials. This concept could be applied to the development of improved structural alloys, ceramics, ceramic electrodes and electrolytes, ceramic membranes and a variety of self lubricating coatings for fossil equipment.
Ceramic Superplastic Forming -	High quality ceramic components such as bearings and turbine hardware are currently fabricated by slipcasting or injection molding followed by Hot Isostatic Pressing and final machining. Superplastic forming of nanometer powders offers the potential to form high quality components to near net shape in one step. Significant impacts on costs would be realized through development of this technology.
Surface Active Materials -	The ability to perform dual functions in a component provides the opportunity to reduce capital costs through consolidation of components. Significant benefits can accrue by integrating catalytic functions with filtration or separation to selectively remove and convert gaseous components from a process stream. Basic understanding of the separate functions is available, but research is required to integrate these functions in the processing or fabrication of materials and components as well as demonstration of effectiveness and durability.

Ceramic Matrix Composites - Ceramic Matrix Composites offer the potential for high temperature operation with improved toughness. Other government programs in this area should be leveraged by the Program in terms of lower cost fabrication technique (particularly for continuous fiber reinforcement) and research focused on fossil-specific applications (e.g., gasification or fuel cells) with attendant fossil-specific environmental effects.

APPENDIX I

Personal Contacts and Interviews

Companies	Contacts
Acurex	J. Sawyer
Amoco	S. Ibarra
APS - Materials	D. Harris
Babcock & Wilcox	W. Long, L. Paul
Ceramem	J. Evans
Cerbec	J. Hanoosh
Combustion Engineering	A. Plumley
Dow Chemical	T. Doty
Exxon	E. Effron, J. Feather, M. Gorbaty, G. Melin, M. Humphries
Foster-Wheeler	K. Ahluwalia, J. Blough, G. Carli, A. Robertson, W. Wolowodiuk
HRI	A. Comolli, J. Duddy, J. MacArthur, G. Wilson, J. Zievers
John Deere	N. Weil
M. W. Kellogg	J. Campbell, P. Cherish
Lummus Crest	D. Cooperberg, A. Gupta, G. Wagner, J. Zwicky
Mobil	D. Whitehurst
Norton	P. Bell, J. Panzarino
Pratt & Whitney	R. Hecht, D. Novak, R. Roark
Stone & Webster	T. Williams
Hobart/TAFA	M. Thorpe
Tennessee Eastman	L. Long, G. Whittaker
Westinghouse	T. Lippert, M. Alvin

Universities	Contacts
Ohio State University	R. Rapp
University of Delaware	A. Mills
University of Manchester, England (Institute of Science and Technology)	W. Stott, H. Wood
State University New York	H. Hermann
University of Wisconsin	M. Anderson

R&D Organizations (Private Sector)	Contacts
CEGB (Brit.)	B. Meadowcroft
Battelle Columbus	V. Sethi, I. Wright
EPRI	W. Bakker, J. Stringer
GRI	V. Hill, M. Klein, S. Friedman, M. Lukaszwicz, K. Woodcock
Harwell (Brit.)	M. Bennett
Petten Establishment (Neth.)	J. Norton, M. Van deVoorde
Southwest Research Institute	F. Lyle, V. Swaminassen

Miscellaneous	
Kentucky Energy Cabinet Laboratory	B. Davis
Materials Properties Council	M. Prager
SFA Pacific	D. Simbeck

Department of Energy	Contacts
ANL	K. Natesan, W. Ellingson
CRE	J. Fairbanks, S. Richlen
FE	L. Miller, P. Scott
HEDL	R. Johnson
LBL	H. Heinemann, A. Levy
METC	J. Halow, J. Holcombe, L. Hemenway
ORNL King,	Z. Egan, D. Fain, R. Judkins, R. V. Sikka, R. Swindeman, J. Weir
PETC	J. Hickerson
PNL	L. Bates
WHC	R. Johnson
SNL	J. Doughty
U.S. Government (Non-DOE)	
DOD	A. Katz, F. Warzoulis, G. Quinn
NASA Lewis	S. Levine
NIST	E. Fuller, L. Ives, S. Malghan A. Pechenik, M. Peterson, G. Piermarini, J. Ritter S. Wiederhorn, T. Yolken

APPENDIX II

Selected Literature Reviewed

ASSESSMENTS

Michael L. Dertouzos, Richard K. Lester, Robert M. Solow and the MIT Commision on Industrial Productivity, Made in America: Regaining the Productive Edge; the MIT Press, 1989.

Materials Science and Engineering for the 1990's: Maintaining Competitiveness in the Age of Materials, National Research Council, National Academy Press, 1989.

Materials Problems and Research Opportunities in Coal Conversion, Volumes I and II, Proceedings of a Workshop Sponsored by the National Science Foundation and the Office of Coal Research; R. W. Stachle, editor, April 1984.

Interaction, Cooperation and Competition in Materials Science and Engineering, National Institute of Standards and Technology, NIST Report, NIST IR 89-4041, June 1989.

Technologies for Producing Electricity in the Twenty-First Century, EPRI Sponsored Conference, San Francisco, CA, October 3-November 2, 1989.

Energy Materials Coordinating Committee Report, Fiscal Year 1989, Department of Energy, Report No. DOE/ER-0388, September 1988.

Fossil Energy Material Needs Assessment, Department of Energy; Report No. ORNL/TM 7232, July 1980.

G. Sorell, M. J. Humphries, E. Bullock and M. Vande Voorde, "Materials Technology Constraints and Needs in Fossil Fuel Conversion and Upgrading Processes", International Metals Reviews, Vol 31, Nol 5. P. 218-242, 1986.

Assessment of Materials Needs for Advanced Steam Cycle Coal Fired Plants, Department of Energy, Report No. ORNL/TM 9735, August 1985.

Assessment of Materials Technology for Gasification and Reaction Pressure Vessels and Piping for Second Generation Commercial Coal Conversion Systems, Department of Energy, Report No. ORNL-6238, August 1978.

Coal Liquefaction - A Research Needs Assessment Technical Background U.S. Department of Energy Report, DOE/ER-0400, Vol. II, February 1989.

Coal Liquefication: Direct Applications and Synthesis of Chemical and Fuels - A Research Needs Assessment, DOE/ER-0326, June 1987.

Assessment of Research Needs for Advanced Fuel Cells, U.S. Department of Energy, Report DOE/ER/30060-T2, November 1986.

FOSSIL PROCESSES

A Techno-Economic Assessment of the Mobile Two-Step Slurry Fischer-Tropsch/ZSM-5 Process, November 1984, Sponsor: Sandia National Laboratory Contract No.: 58-0336.

Coprocessing Studies, Pittsburgh Energy Technology Center, U.S. Department of Energy, presented at DOE Direct Liquefaction Contractor's Review Meeting, Pittsburgh, PA, October 22, 1986.

High Quality Transportation Fuels from Synthesis Gas and Methanol, Pittsburgh Energy Technology Center, U.S. Department of Energy, 1986.

Energy Technology XIII "Energy in Transition", Proceeding of the Thirteenth Energy Technology Conference, March 17-19, 1986.

Coal Gasification: Direct Applications and Synthesis of Chemicals and Fuels, U.S. Department of Energy, Office of Energy Research, Office of Program Analysis, June 1987.

System Design Study to Reduce Capital and Operating Cost of a Moving Distributor, AFB Advanced Concept - Comparison with an Oil-Fired Boiler, December 1985, U.S. Department of Energy, Morgantown Energy Technology Center.

System Design Study to Reduce Capital and Operating Costs and Bench-Scale Testing of a Circulating Bed AFB Advanced Concept, U.S. Department of Energy, Morgantown Energy Technology Center, April 1987.

Use of Solid Collector for Control of Emissions in Advanced Coal Conversion Processes, U.S. Department of Energy, Morgantown Energy Technology Center, December 1986.

Fludized-Bed Combustion Development, Volume's I, II, III, IV. U.S. Development of Energy, Morgantown Energy Technology Center, May 1986.

Pressurized Fluidized-Bed Combustion Technology Status Report, U.S. Department of Energy, Morgantown Energy Technology Center, October 1984.

Fludized Bed Combustion: Analysis of Technology Economics and Markets, SFA Pacific, Inc., October 1987.

1988 Seminar on Fluidized-Bed Combustion Technology for Utility Applications, Volume I: Atmospheric Fluidized-Bed Combustion, May 3-5, 1988 and Volume 2: Pressurized Fluidzed-Bed Combustion.

Proceedings of the Fifth Annual Contractor's Meeting on Contaminant Control in Coal-Derived Gas Streams, U.S. Department of Energy, Morgantown Energy Technology Center, May 1985.

Physical Gas Stream Cleanup, Technology State Report, U.S. Department of Energy, Morgantown Energy Technology Center, April 1986.

Gas Stream Cleanup, Technology State Report, U.S. Department of Energy, Morgantown Energy Technology Center, October 1987.

Gas Stream Cleanup Papers from DOE/MTEC - Sponsored Contractors Review Meetings in 1987, U.S. Department of Energy, Morgantown Energy Technology Center, October, 1987.

Performance Evaluation of a Ceramic Fabric Bag Filter on a Bench-Scale Coal Gasifier, Final Report, U.S. Department of Energy, Morgantown Energy Technology Center, October 1986.

Feasibility of a Phosphoric Acid Fuel Cell Basic Technology Program, U.S. Department of Energy, Morgantown Energy Technology Center, February 1987.

Anode Development for Solid Oxide Fuel Cells, Final Technical Report for the Period September 30, 1985 - December 31, 1986, U.S. Department of Energy, Morgantown Energy Technology Center.

Study of the Effects of Soot, Particulate, and Other Contaminates on Molten Carbonate Fuel Cells Fueled by Coal Gas, Topical Report, September 1984 - August 1985, U.S. Department of Energy, Morgantown Energy Technology Center.

High Temperature Coal Gas Chloride Cleanup for Molten Carbonate Fuel Cell Applications, Topical Technical Report for the Period September 1984 - June 1985, U.S. Department of Energy, Morgantown Energy Technology Center.

Internal Reforming Development for Solid Oxide Fuel Cells, Final Report, U.S. Department of Energy, Morgantown Energy Technology Center, U.S. Department of Energy, Morgantown Energy Technology Center, February 1987.

Energy Technology XIV "Changing Times for Energy Industries", Proceeding of the Fourteenth Energy Technology Conference, April 14-15, 1987.

Proceedings of the Second Annual Heat Engines Contractors Meeting, U.S. Department of Energy, Morgantown Energy Technology Center, May 1985.

Coal-Fueled Heat Engines, Technology Status Report, U.S. Department of Energy, Morgantown Energy Technology Center, October 1985.

Systems Studies and Combustion Research for Coal-Fueled Heat Engines, Technology Status Report, U.S. Department of Energy, Morgantown Energy Technology Center, August 1985.

Clean Coal Technology and the Current Status of the U.S. Clean Coal Technology Demonstration Program 15th Technology Conference, U.S. Department of Energy, Office of Fossil Energy, Office of Coal Technology, February 17, 1988.

Proceedings of Sixth Annual Coal-Fueled Heat Engines and Gas Steam Cleanup

Systems Contractors Review Meeting, DOD/METC-89/6101, March 1989.

Proceedings of Ninth Annual Liquefication and Gas Stream Cleanup Systems Contractors Review Meeting, 2 Volumes, DOE/METC-89/6107, June 1989.

Proceedings of Eighth Annual Gasification and Gas Stream Cleanup Systems Contractors Review Meeting, 2 Volumes, DOE/METC-88/6092, May 1988.

Eighth Annual EPRI Conference on Coal Liquefaction, EPRI GS-6485, August 1989.

Proceedings of the Third Annual Oil Shale, Tar Sand, and Mild Gasification Contractors Review Meeting, DOE/METC-88-6098, December 1988.

Liquid Transportation Fuels for Natural Gas, Coal,Oil Shale and Tar Sands; Economics and Technology SFA Pacific, Inc., May 8, 1989.

Membrane Technology and Application: An Assessment, EGG-2282, U.S. DOE Report DE 84009000, February 1984.

Proceedings of First Annual Heat Engines Contractors Meeting, DOE/METC/84-31, November 1984.

Office of Coal Technology Fiscal Year 1989 Program Summary Department of Energy, Report No. DOE/FE-0127, April 1989.

Clean Coal Technology Demonstration Program, Annual Report to Congress, Department of Energy, Report No. DOE/FE-0125, February 1989.

MATERIALS

Materials Performance in Coal Gasification Pilot Plants, R. Judkins and R. Bradley, Oak Ridge National Laboratory, Report No. DE 88001417 October 15, 1987.

Analysis of Metal Wastage in Coal-Fired Fluidized-Bed Combustors, Final Report, March 1986, U.S. Department of Energy, Morgantown Energy Technology Center

"Assessment of the Causes of Failure of Ceramic Filters for Hot-Gas Cleanup in Fossil Energy Systems and Determination of Materials Research and Development Needs," Acurex Corporation, ORNL/Sub/86-57964/01 (in press).

The Effects of Halides on the Performance of Coal Gas-Fueled Molten Carbonate Fuel Cells, Topical Report, U.S. Department of Energy, Morgantown Energy Technology Center, December 1986.

Nickel Transport in Molten Carbonate Fuel Cell Electrolytes, Final Report, U.S. Department of Energy, Morgantown Energy Technology Center, November 1986.

Corrosion Resistant Materials in MCFC Environment, Final Report for the Period 1984-September 1986, U.S. Department of Energy, Morgantown Energy Technology Center.

Ceramic Technology for Advanced Heat Engines, "Report of the Committee on Ceramic Technology for Advanced Heat Engines", National Materials Advisory

Board, National Academy Press, NMAB-43.

Office of Coal Technology Fiscal Year 1988 Program Plan, March 1988, U. S. Department of Energy, DOE/FE-0102, March 1988.

Fossil Energy Materials Program Conference Proceedings, Oak Ridge, May 1987. DOE Report ORNL/FMP-87/4 August 1987.

Proceedings Seminar on Applications for and Designing High Temperature Materials for Natural Gas Usage, Chicago, GRI Report CAM-8903, April 1989.

Hydrous Metal Oxide-Supported Catalysts: Part I. Preparation Chemistry and Physical and Chemical Properties, DOE Report SAND 89-2399, UC-108, February 1990.

Hydrous Metal Oxide-Supported Catalysts: Part II. Calalytic Properties and Applications, SAND 89-2400, UC-108, February 1990.

Euro-Ceramics, Volume 1, Processing of Ceramics, Elsevier Applied Science.

CRSC/EPRI First International Conference on Chlorine in Coal (Preprints), Chicago, IL, October 1989.

Engineering Foundation Conference on Fireside Problems While Incinerating Municipal and Industrial Waste (Preprints), Palm Coast, FL, October 1989.

Corrosion Resistant Materials for Coal Conversion Systems, Applied Science Publishers Ltd., 1983.

High Temperature Materials Corrosion in Coal Liquefaction Atmospheres, Elsevier Applied Science Publishers 1984.

Structural Integrity of Vessels for Coal Conversion Systems, U.S. Department of Energy, Report ORNL/TM-6969, September 1979.

Alloy Development and Mechanical Properties of Nickel Aluminide (Ni_3Al) Alloys, U.S. Department of Energy Report, ORNL-6483, August 1988.

Proceedings First Conference on Advanced Materials for Alternative Fuel Capable of Directly Fired Heat Engines, DOE/EPRI Conference 79074.9, December 1979.

Thermal/Chemical Degradation of Ceramic Cross-Flow Filter Materials, Technical Report-Phase I, Westinghouse, November 1989.

"Assessment of the Causes of Failure of Ceramic Filters for Hot Gas Cleanup in Fossil Energy Systems and Determination of Materials R&D Needs", ORNL/Sub/86-57964/01, Final Report, February 1988.

Alloy Development and Mechanical Properties of Nickel Aluminide (Ni_3Al) Alloys, ORNL-6483, August 1988.

Proceedings First Conference on Advanced Materials for Alternative Fuel Capable Directly Fired Heat Engines, DOE/EPRI Conference 79074.9, December 1979.

Proceedings of First Annual Heat Engines Contractors Meeting, U.S. Department of Energy Report DOE/METC 84-31, November 1984.

"Materials Aspects of World Energy Needs," National Research Council, National Academy Press, Washington, D.C., 1980.

Curtis E. Johnson, Wayne A. Weiman and Daniel C. Harris, Characterization of Diamond Films by Thermogravimetric Analysis and Infrared Spectroscopy, Mat. Res. Bull. Vol 24, 1989, p 1127-1134.

Assessment of Materials Selection and Performance for Direct Coal Liquefaction Plants, Department of Energy, ORNL Report ORNL-6382, October 1987.

Hydrous Metal Oxide - Supported Catalysts: Part 1. Preparation Chemistry and Physical and Chemical Properties, R. G. Dosch, H. P. Stephens, F. V. Stohl, B. C. Bunker, C.H.F. Peda, Sandia Report SAND 89-2399-UC-108, February 1989.

Hydrous Metal Oxide - Supported Catalysts: Part II. Catalytic Properties and Applications, R. G. Dosch, H. P. Stephens, F. R. Stohl, Sandia Report SAND 89-2400.UC-108, February 1989.

Investigation of Joining Techniques for Advanced Austenitic Alloys, C. G. Lundin, C.Y.P. Qiao, Y. Kikushi, C. Shi and T.P.S. Gill, Report ORNL/SUL/88-07585/02, May 1991.

Research Opportunities for Materials with Ultrafine Microstructures, Report of the Committee on Materials with Submicron-Sized Microstructures, National Materials Advisory Board, NMAB-454, National Academy Press, 1989.

Inorganic Composite Materials in Japan: Status and Trends, M. J. Koszak, K. Prause, A. Mortensen, S. Fishman, M. Brarsoum and R. Gottschall, ONR Scientific Monograph ONRFE M7, November, 1989.

Ceramic Technology for Advanced Heat Engines, Report of the Committee on Ceramic Technology for Advanced Heat Engines, National Materials Advisory Board, NMAB-431, National Academy Press, 1987.

Injection Nozzle Materials for a Coal-Fired Diesel, Materials and Components in Fossil Energy Applications, DOE/FE-0085/85, April 1, 1990, p 1-2.

"Porous Ceramics for Gas Filtration", James F. Zievers, Paul Eggerstadt, Elizabeth C. Zievers, Ceramic Bulletin, Vol 70, NO. 1, 1991, p 108-111.

"Sol-gel Processing for Gas Separation Membranes", Lisa C. Klein and Nicoles Gisszpenc, Ceramic Bulletin, Vol 69, No. 11, 1990, pg. 1821-25.

"Ceramic Membranes - Growth Prospects and Opportunities", Keith K. Chan and Arthur M. Brownstein, Ceramic Bulletin, Vol 70, No. 4, 1991, p 703-707.

"Assessment of Porous Ceramic Materials for Hot Gas Filtration Applications", Mary Anne Alvin, Thomas E. Lippart and Jay E. Lane, Ceramic Bulletin, Vol 70, No. 9, 1991, p 1491-1498.

Materials for Large Land Based Gas Turbines, National Research Council Committee on Materials for Large Land Based Turbines, EPRI Report No. AP 4476, March 1986.

Aqueous Corrosion Characteristics and Corrosion-Related Cracking Susceptibilities of Fe_3Al Type Iron Alumindes, R. A. Buchanan and J. G. Kim, ORNL/Sub/88-07684 CT 92/01, April 1991.

Advances in Thermal-Spray Technology, Herbert Herman, Advanced Materials and Processes, April 1990, p 41-45.

"Characterization of Diamond Films by Thermogravimetric Analysis and Infrared Spectroscopy", Curtis E. Johnson, Wayne A. Weiman and Daniel C. Harris, Materials Research Bulletin, Vol 24, 1989, p 1127-1134.

"Ceramics in Fuel Cells", Kevin Kendell, Ceramic Bulletin, Vol 70, No. 7, 1991, p 1159-1160.

"Corrosion Resistant Ceramics for Severe Environments", Laurel M. Sheppard, Ceramic Bulletin, Vol. 70, No. 7, 1991, p 1146-1158.

"Ceramics for Fossil Energy Systems", Materials and Components in Fossil Energy Applications, DOE FE-0088/88 October 1, 1990, p 1-4.

"Ceramic Filters to be Tested at Tidd PFBC", Materials and Components Newletter, DOE/FE-0090-90, February 1, 1991, p 1-2.

"Durability of SiC Materials in Gas and N_2-H_2-CO Heat Treatment Environments", Center for Advanced Materials Newletter, Volume 5, No. 1, 1991, p 1-11.

"Diamond and Diamond-Like Coatings - Conference Survey and Potential", Michael J. Koczak, ONR Scientific Information Bulletin, ESN1B 91-02, p 50-53.

Potential Applications of Structural Ceramic Composites in Gas Turbines, W. P. Parks, Jr., R. R. Ramey, D. C. Rawlines, J. R. Price, M. VanRoode, Final Report prepared by H. Babcock and Wilcox Company, Report ORNL/Sub/88-SA798/01, September 1989.

Intelligent Processing of Materials, A Strategic Plan, Institute for Materials Science and Engineering, National Bureau of Standards, December 1987.

Appraisal of Foreign Capabilities in Ceramic Composites, Prepared for Office of Industrial Progeams, U.S. Department of Energy, RCG/Hagler Bailley, Inc., RH/HBI Ref. Nos. 89-5073 and 89-3090, February 13, 1990.

"A National Forum on the Future of Automatic Materials Processing in U.S. Industry - The Role of Process Models", Artificial Intelligence and Computer Integration Sponsored by Industrial Research Institute and White House Office of
Science and Technology Policy, U.S. Department of Commerce, National Bureau of Standards, NBS IR 87-3544, April 1987.

"Membrane Technology and Applications: An Assessment", Stephen A. Leeper, Daniel H. Stevenson, Peter Y.-C. Shiu, Stephen J. Priebe, Herbert F. Sanche and Penny M. W. Koff, EG&G Idaho, Inc., Idaho Falls, Idaho Report EGG-2282 (DE 84 009000), February 1984.

Using Inorganic Membranes in Separate Gases: R&D Status Review, B. Zane Egan, Oak Ridge National Laboratory, Report ONRL/TM-11345, November 1989.

"Ceramic Thin Films: Fabrication and Applications", M. Sager and K. Sreenivas, Science Vol 247, 2 March 1990, p 1056-1060.

Materials Science Program, Fiscal Year 1988, Department of Energy, Report No. DOE/ER-0389, September 1988.

APPENDIX III

SOLID STATE ELECTROLYTES

TECHNOLOGY BENEFITS/BARRIERS

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
APPLICATIONS	Oxygen production gas clean-up, Hydrogen production, sensors for O_2, H_2S, SOX, NOX, electrochemical reactors	Oxygen production gas clean-up, Hydrogen production, sensors for O_2, H_2S, SOX, NOX, electrochemical reactors	Oxygen production gas clean-up, Hydrogen production, sensors for O_2, H_2S, SOX, NOX		Improved transport properties, cell efficiency, costs
UNCERTAINTIES	Cost, efficiency, durability, long-term stability	Cost, efficiency, durability, long-term stability	Cost, efficiency, durability, long term stability		Cost, long-term performance, durability

APPENDIX III

CERAMIC MATRIX COMPOSITES

TECHNOLOGY BENEFITS/BARRIERS

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
BENEFITS	High temperature corrosion resistant filters, pump components, heat exchangers, valves	High temperature heat exchangers, HGCU barrier filters	High temperature heat exchangers, HGCU, barrier filters	Tough engine components for high temperature wear resistance	Improved durability electrodes
BARRIERS	Cost, reliabilty, design practice, long term thermal-mechanical behavior	Cost, reliability design, long term thermal mechanical behavior	Cost, reliability, design practices	Cost, design guidelines long term properties environmental effects, thermal-mechanical behavior	Demonstration of concept for materia of interest, long t stability, performa

APPENDIX III

NANOCOMPOSITES

TECHNOLOGY BENEFITS/BARRIERS

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
BENEFITS	Self lubricated coatings for controlled wear and friction, slurry components	High temperature components with improved strength, and toughness	Catalytic burners with O_2 enrichment conditions	Self lubricated coatings for controlled wear, friction	Stonger FC elements, improved durability
BARRIERS	Cost, demonstration, scale-up	Cost, demonstration, scale-up	Design, fabrication, reliability	Demonstration, proof-of concept and reliability	Adaptation of conce[illegible] to materials and structures

APPENDIX III

SURFACE ACTIVE MATERIALS

TECHNOLOGY BENEFITS/BARRIERS

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
BENEFITS	Catalysts, gas clean up elements with selective removal	Desulfurization systems	Gas clean-up, catalytic combustors		Gas clean-up, electrodes with combined selectivit and reactivity.
BARRIERS	Data, cost	Efficiency, cost	Efficiency, cost		Efficiency, cost, interface control

APPENDIX III

TECHNOLOGY BENEFITS/BARRIERS

INTELLIGENT PROCESSING

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
BENEFITS	Reduced cost/improved reliability of weldments, tubeforms, valves, piping	Reduced cost/improved reliability of weldments, tubeforms valves, piping, membrane and filter fabrication	Reduced cost/improved reliability of weldments, tubeforms valves, piping, reliable, membrane and filter fabrication	Improved reliability, reduced cost/of coated hardware	Reduced cost/improve reliability of electrodes, inter-connections
BARRIERS	On line sensing of texture, weld cracking	On line sensing of texture, weld cracking, porosity sensing, powder chemistry, morphology process models	On line sensing of texture, weld cracking	Deposition sensing, coating condition, process models	Powder sensing and control, tape castin and extrusion, textu sensing process mode control systems

APPENDIX III

IRON ALUMINIDES

TECHNOLOGY BENEFITS/BARRIERS

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
BENEFITS	Corrosion resistant piping, valves, filters, heat transfer surfaces, costs	Corrosion resistant heat transfer surfaces valves piping membrane and filter fabrication, costs	Corrosion resistant heat transfer surfaces valves, piping, membrane and filter fabrication, costs	High temperature corrosion resistant components, costs	
BARRIERS	Higher temperature capability, moisture embritlement and high ducticity	Higher temperature capability, moisture embritlement and high ducticity	Higher temperature capability, moisture embritlement and high ducticity.	Higher temperature capability, moisture embritlement and high ducticity.	

APPENDIX III

DIAMOND FILMS

TECHNOLOGY BENEFITS/BARRIERS

	Liquefaction	Gasification	Combustion	Heat Engines	Fuel Cells
BENEFITS	Erosion/abrasion reduction in valves pumps, heat transfer surfaces	Erosion/abrasion reduction in valves pumps, heat transfer surfaces	Erosion/abrasion reduction in valves pumps, heat transfer surfaces	Reduced wear of slurry injectors	
BARRIERS	High deposition temperature, adherence, interface control, scale-up	High deposition temperature, adherence, interface control, 650°C oxidation limit	High deposition temperature, adherence, interface control, 650°C oxidation limit	High deposition temperature, adherence engineering development, 650°C oxidation limit	

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An assessment was conducted to identify the needs and opportunities in materials research directed at applying new developments in materials science and engineering to fossil energy technologies. The assessment was conducted through literature review and discussions with knowledgeable industrial, academic and governmental personnel. Topics worthy of research which will provide significant benefits to fossil technologies include the following: austenitic alloys, iron aluminides, ceramic filter materials, ceramic membranes, solid electrolytes, catalyst supports, protective coatings, erosion/abrasion/wear research, corrosion mechanism research, intelligent materials processing, diamond films, nanocomposites, superplastic forming of ceramics, surface active dual function materials and ceramic matrix components.

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