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Ceramic Technology for Advanced Heat Engines

Report of the Committee on Ceramic Technology for Advanced Heat Engines

National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council (U.S.)

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ABSTRACT

The goal of the Department of Energy-Oak Ridge National Laboratory program on ceramic technology for advanced heat engines is "to apply the increasing base of fundamental knowledge and research tools to develop new and improved processes for cost-effective ceramic materials with improved reliability and performance characteristics." A committee appointed to review the program assessed the objectives, balance, and priorities. Emerging opportunities were identified, an international exchange agreement was examined, and the mechanisms of technology transfer were investigated. Coordination efforts were studied, and the technical planning for the program was critiqued. The committee believes that many but not all of the most important components of the basic ceramic technology relating to improved performance and reliability are being addressed. Although the committee did not examine individual projects in detail, it feels that the general quality of the technical work is good. The committee is less certain that progress is being made in bringing these components together into a technically successful process for producing final ceramic products with significantly improved reliability and performance. Also, the committee finds little evidence that substantial progress toward cost-effective processing is being made. Indeed, there appears to be no organized attempt to do cost analysis.

PREFACE

In 1983 the U.S. Department of Energy's Office of Transportation Systems (OTS), formerly the Office of Vehicle and Engine Research and Development, initiated a long-range program known as the Ceramic Technology Program for Advanced Heat Engines. The primary purpose of the program, which was jointly developed by DOE and the Oak Ridge National Laboratory (ORNL), is to develop the industrial ceramic technology base required for ceramic engine components. The program, administered by ORNL, has been funded by DOE in parallel with other DOE programs in advanced gas turbines and heavy-duty adiabatic engine components, which are being administered by the National Aeronautics and Space Administration (NASA). A brief description of the management structure and interfaces for the program is given in Appendix A.

In 1985, DOE requested the National Research Council to establish a committee to assess the program. The committee, organized within the National Materials Advisory Board (NMAB), was charged to (1) review the program and make an assessment of its objectives, milestones, balance, and priorities and the progress being made in these areas; (2) identify emerging opportunities in the program; (3) examine existing international agreements; and (4) critique the interrelationships between the participating organizations (industry, government, and universities) with respect to technical planning, coordination of efforts, and technology transfer.

In conducting this study the committee visited several contractors, and additional meetings were held between individual members of the committee and other contractors.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Numerous studies have shown the feasibility of using ceramic materials in high-temperature heat engines. However, these same studies have also shown that the industrial technology base in the United States is not yet adequate to provide reliable and cost-effective ceramics and ceramic components for these engines. The high-performance, high-temperature ceramic materials now entering, and those planned for, commercial use in engines and other structural applications require a level of fundamental understanding and processing beyond that used in producing conventional ceramics.

This situation led the Department of Energy's Office of Transportation Systems (OTS), formerly the Office of Vehicle and Engine Research, to initiate a Ceramic Technology Program for Advanced Heat Engines. The primary goal of the program is to develop an industrial technology base to provide reliable and cost-effective high-temperature ceramic components. The program is funded in parallel with other DOE-OTS programs aimed at developing ceramic-based heat engines. Although it is meant to provide support for the engine programs, the ceramic program is designed to develop generic technologies and is not intended to be tied to a specific engine design or component.

The program is administered by Oak Ridge National Laboratory (ORNL). In 1982, ORNL published the Ceramic Technology for Advanced Heat Engines Program Plan. The plan was developed after extensive interviews with industry, academia, and other government laboratories, and it identified three principle areas in need of development: materials and processing, design methodology, and data bases and life prediction. These three areas form the basis of a work breakdown structure that was developed to coordinate complementary ceramic programs being funded by other DOE offices, NASA, and other government agencies.

In 1985, at the request of OTS, the National Materials Advisory Board of the National Research Council convened a Committee on Ceramics Technology for Advanced Heat Engines to assess the program's management, direction, content, and coordination with other programs and with industry. The committee met with engine designers, ceramic suppliers, other program contractors, and DOE and ORNL administrators. The result of those interviews and the committee's assessment are summarized here.

There was a general consensus among those interviewed that, although there has been much progress in ceramic technology, many of the problems identified 5 years ago still inhibit the use of ceramics in heat engines. The need for an effective ceramics technology development program remains critical.

The original program plan estimated a 5-year budget of $140 million. Although actual appropriations have fallen short of this target, the program's annual appropriations have grown from $2.4 million in FY 1983 to $12.5 million in FY 1987. The program supports roughly 30 to 40 projects that last from 1 to 3 years and range in size from tens of thousands to hundreds of thousands of dollars. (In FY 1987, three projects topped $1 million.) To ensure that the program's output finds its way into the industrial technology base, the original program plan called for 60 percent of the project support to be spent in industry, 30 percent in government laboratories, and 10 percent in universities. ORNL has been able to meet this distribution in the past 2 years.

A majority of the effort has been devoted to materials and processing, which has received approximately 60 percent of the funds. Data bases and life prediction has received approximately 30 percent, with the balance going toward projects in design methodology. In materials and processing, the program has concentrated on prototype development of improved powder production processes for silicon nitride and silicon carbide, the development of ceramic-ceramic composites, thermal barrier coatings, and ceramic-metal joining. Projects in design methodology have focused on advanced statistics and ceramic behavior at dynamic interfaces. In data bases and life prediction, the program has concentrated on developing a tensile testing capability and some preliminary studies on long-term behavior, such as static fatigue and environmental effects. Individual research tasks are conceptualized by ORNL researchers, who then write RFPs, review proposals, and monitor projects (subcontracts) with industry, universities, and other government laboratories.

The committee feels that the original work breakdown structure provides a good guide for structuring the program. Although it did not examine the individual technical projects in detail, the committee also feels that the general quality of the technical work is good. However, the committee feels that there are too many small contracts awarded across the spectrum of tasks outlined in the work breakdown structure. It is not clear that progress is being made in integrating these divergent projects in a way that will result in technically successful processes for producing final ceramic products with significantly improved reliability and performance. There is an apparent lack of specific prioritized goals, an articulated strategy by which to achieve them, and a set of milestones that act as decision nodes for the program as a whole. Without these the committee feels the program represents a collection of small, technically interesting projects that will only make incremental contributions to the technology base.

The committee recommends that priorities be set and funded at higher levels to ensure that a critical-size group of contractors, under the leadership of a principal investigator, can be focused on a particular goal. This should not preclude the awarding of small, individual-investigator types of projects. However, these must contribute to the more focused goals. The committee also recommends that an annual report evaluate the progress being made against the goals that have been set in each priority area, and that topical workshops in each area be held.

The committee identified a number of emerging opportunities for the program to consider. These include studies specifically aimed at modeling green state processing and scaling behavior, microstructural modeling of fracture behavior, the development of a cost-effective strategy for NDE, and an ongoing engineering cost analysis to monitor the technologies' progress toward cost-effectiveness.

In reviewing the International Exchange Agreement, the committee felt that DOE should critically assess the cost-effectiveness of the agreement as it is now implemented. It is recommended that ASTM and NBS be included in that program.

The committee also recommends that DOE make a stronger effort to coordinate the ceramic technology program and the engine programs. Effective interaction between these programs is imperative to the eventual use of ceramics in heat engines.

In addition, the committee felt that a major push was needed in generating tensile and time-dependent data bases and life prediction models and that more emphasis should be given to composite materials and ceramic-ceramic joining.

CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the major conclusions and recommendations of the committee. Additional material to support and substantiate these conclusions and recommendations is contained in subsequent chapters of the report. The successful and efficient execution of the Ceramic Technology Program for Advanced Heat Engines is vitally important, and it is in this spirit that the committee's conclusions and recommendations are put forth.

CONCLUSION 1

The committee recognizes the need for and importance of a program specifically aimed at developing the technology base in structural ceramics. Furthermore, the committee feels that the original program plan (drawn up after 2 years of extensive interviews with industry, universities, government laboratories, not-for-profit laboratories, etc.), to the extent that it has identified the principal technological areas inhibiting development, provides a valid framework for such a program.

Recommendation

The committee recommends that the program continue to receive support. This does not mean that there should be no changes made in the original program. The basic plan is good, but as time passes, funding levels change, and the research results can and will change the direction of the efforts.

CONCLUSION 2

The management structure set up between DOE, ORNL, and NASA requires both managerial and technical coordination. While there is management coordination between DOE, NASA, and ORNL, a review of the programs shows that the technical coordination is not effective. For all practical purposes the research efforts of each program are unrelated and uncoordinated with one another. If the new DOE Advanced Turbine Technologies Applications Project (ATTAP) is to be successful, it must be better integrated with the ceramic technology programs.

Recommendation

The committee recommends that DOE supply stronger leadership to bring the DOE-NASA engine programs and the DOE-ORNL ceramics program into much closer coordination at the technical level. A failure to do so will result in neither of these programs reaching its objectives.

CONCLUSION 3

Although the original plan provides a general framework for the program and has stated objectives in each of the three major work tasks, these objectives are too broad to provide effective direction and assessment of the overall program. Because of this, the accomplishments of the program are as a whole not sufficiently clear as compared to the accomplishments attained in the individually funded projects. There appears to be a lack of coherence in reporting the technical output. The existing report structure provides only a compilation of individual project reports, and the Contractors Coordination Meeting presents these again in abbreviated form.

Recommendation

An analysis of the overall progress of the program, in terms of its principal goals, should be prepared annually. This analysis should then be used to evaluate and integrate the accomplishments of the individually funded projects.

CONCLUSION 4

Since the program was initiated, much has been learned about the potential applications of ceramics to heat engines, but it is not clear that DOE has recognized this new information in the formulation of current projects.

Recommendation

In light of the evolving knowledge of advanced engine systems, re-evaluation of plans and priorities needs to follow the annual analyses proposed in Conclusion 3. For example, new programs should be introduced in ceramic composites, and older programs that are no longer pertinent to heat engines, such as the ZrO_2 studies, should be phased out.

CONCLUSION 5

There are too many problems that are being addressed with too few resources. Consequently, there are many small contracts spread among many contractors without any apparent coherence or convergence in technical output.

Recommendation

Priorities should be set and funded at a higher level so that a critical-size group of contractors can be assembled in a particular area. Responsibility should be assigned within the group in the form of a single technical coordinator or a technical coordinating committee to monitor and direct the progress of the group.

CONCLUSION 6

There is an inordinate time lag in initiating a contract in the program. Months are spent in initiating requests for proposals, issuing them, reviewing them, negotiating cost-sharing, and working out patent and priority rights.

Recommendation

The contract and awarding procedures should be reviewed and changed with a view to reducing the present 1- to 2-year delay from initiating an RFP to the granting of a contract. DOE should develop procedures to take care of problems related to intellectual property that appear to be the principal delay in making contract awards.

CONCLUSION 7

For a program whose stated principal objective is to support advanced heat engines, the lack of effort in establishing a reliable data base for life prediction is startling. Long-term, high-temperature creep, rupture, and fatigue data in combustion environments are almost completely lacking. The existing data base is largely founded on bend bars and is not adequate for use in the design of ceramic components.

Recommendation

Studies on slow crack growth, tensile creep, stress rupture, and cyclic fatigue at high temperatures should be emphasized, using materials that are apt to be utilized in high-temperature ceramic engines to develop an interim data base. The complete data base needed for engine design is not being suggested here; instead it is the establishment of a set of base-line properties from which improvements can be judged.

CONCLUSION 8

The announced aim of the ceramic technology program is to increase reliability and reduce costs. There is no cost information to be found in any of the documentation examined by the committee or in the discussions held with contractors. Engine manufacturers know the cost/performance trade-off that they are willing to adopt, but it is not clear whether ceramic components or ceramic-based engines can ever compete with their conventional counterparts.

Recommendation

An engineering cost analysis should be initiated, including a realistic assessment of the potential markets, to set program goals in cost reduction. If, as stated in the program plan, costs are a factor, a knowledge of current and projected costs should not be ignored.

CONCLUSION 9

The cost-effectiveness of the International Exchange Agreement, in the opinion of the committee, is questionable.

Recommendation

The International Exchange Agreement should be given a low priority. The efforts of round-robin bend bar testing should be discontinued. Both ASTM and NBS should be included in the U.S. effort. Most importantly, Japan should be included in the Agreement.

CONCLUSION 10

The concept of technology transfer mechanisms as enumerated by ORNL for this program is flawed. Coordination meetings, issuing of reports, contractor's meetings, preparing displays, and participating in international meetings, all of which were identified by ORNL as methods for transferring technology, are in fact public relations, management tools, or the dissemination of information.

Recommendation

The stated policy established by DOE and given in the section of this report under the heading "Technology Transfer" should be followed.

CONCLUSION 11

Difficulties persist in extending the life of key load-bearing components using monolithic ceramic materials. There was general agreement among engine developers that the probability of having to rely on tougher ceramic composite materials is high.

Recommendation

More emphasis should be placed on the development, processing, and characterization of cost-effective ceramic composites to encourage their use in the engine programs.

BACKGROUND

Ceramics research and development in the United States has grown significantly in the past 10 years, with strong industrial interest and many optimistic forecasts for future commercial growth in ceramics use.[1,9,10] Some of this optimism is based on studies dating back to 1971 and earlier.[12,13] These have shown the feasibility of using ceramic materials in high-temperature heat engines. However, these same studies have also shown that the industrial technology base in the United States is not yet adequate to provide reliable and cost-effective ceramics for heat engines. In other words, studies that show that ceramics can be used in certain structural applications do not ensure their use in these applications. Ceramics must also be capable of demonstrating that they at least have the equivalent life and reliability as, and preferably a lower cost than, the materials they are replacing.

There are several driving forces that push the development of the use of ceramics as high-temperature structural materials for heat engines. The first of these is based on the laws of thermodynamics, which specify in their simplest form that the higher the operating temperature is, the greater the thermal efficiency of the system. There are problems with the bottoming part of the cycles, such as recuperation, regeneration, and other types of heat recovery systems, but this is the principal reason engines operate at as high a temperature as possible, commensurate with the properties of the materials used to construct the engines.

In designing engines, as one moves up the temperature scale, because of corrosion and oxidation one moves from simple iron-based alloys to iron-chromium alloys to iron-chromium-nickel alloys to nickel-based alloys to the superalloys. All of these alloys, which involve nickel, chromium, cobalt, molybdenum, tungsten, columbium, et al., are much more costly than iron, and most of them are classified as strategic metals—i.e., metals that are essential for the defense of the United States but that are generally unavailable in significant quantities in this country. Because of supply-and-demand factors, most of these metals are costly. When alloyed and fabricated, the costs of finished components can range from tens to hundred of dollars per pound. This is because the very property that makes them so desirable, their high-temperature strength, makes their fabrication into engine components extremely difficult.

Ceramics such as oxides, carbides, borides, and nitrides, all show considerably higher melting points than the refractory alloys, and they could in theory be substituted for the strategic metals. The raw materials Al_2O_3, SiO_2, MgO, carbon, and nitrogen and the counterparts to metallic alloy systems--silicates, sialons, mixed carbides, carbonitrides, etc.--are with some exceptions, nonstrategic and, depending on market demands, can be more cost-effective than metals.

Ceramics, almost without exception, exhibit brittle behavior--i.e., they show little or no plastic behavior and fail at stresses considerably below their theoretical fracture strength. Engine designers, as a group, have had little or no experience in using these types of materials except in specialized applications such as gaskets, sparkplugs, and seals, none of which are highly stressed or subjected to very high temperatures.

These various factors led the Defense Advanced Research Projects Agency in 1971 to fund what has become known as the DARPA Gas-Turbine Program but whose actual title was the DARPA Brittle Materials Design Program. The objectives of the program were to (1) develop an engine system that would operate at a temperature level higher than any using metallic materials; (2) force designers to learn how to incorporate brittle materials into engine designs; and (3) reduce dependency on strategic materials.

The DARPA program met most of its objectives. An all-ceramic engine (combustor, regenerator, ducts, stators, and rotors) was designed, built, and operated at 1930°F to 2500°F for over 200 hours. The large (30-MW) gas turbine static rig tests, with ceramic components, operated at 2200°F to 2500°F. The iterative design concept, now used by all ceramic engine designers, was developed and verified. Test beds and test methods were developed. Materials and materials processing, while constantly changing in the lifetime of the program, as they are today, although not optimal, demonstrated the feasibility of the use of ceramics in heat engines.[12,13] It should be noted that these were essentially all short-time tests of feasibility and were not concerned with long-term reliability issues.

Cummins Engine Company initiated in-house efforts on the adiabatic diesel engine in 1973 and TACOM initiated its adiabatic diesel program in 1975 to support the development of uncooled diesel and turbine engines for military applications.[11] DOE has also initiated an adiabatic program in its ongoing Heavy Duty Engine (HDE) program.

In 1976 DOE and NASA funded the Ceramic Application Turbine Engines (CATE) project to evaluate ceramic stators and rotary heat exchangers in a truck engine operating at a turbine inlet temperature of 1900°F. It was installed in a truck and operated for 90 hours and 1600 km of rough-road proving ground. This demonstrated that ceramics could withstand the stresses encountered in the vehicular environment.[14]

In 1979 DOE funded two advanced gas turbine (AGT) programs—one by Allison Engine Division of General Motors Corporation and the second by a team of Garrett Turbine Engine Company and the Ford Motor Company. These engines were to demonstrate high-efficiency automotive gas turbines, capable of using alternate fuels, meet EPA emission requirements, and be competitive in cost (both initial and lifetime), performance, and safety to comparable internal combustion engines.

The AGT program ended in 1986 without demonstrating it goals. However, a follow-on program, called the Advanced Turbine Technologies Application Program (ATTAP) has been authorized for FY 1987. It is a 5-year program and aimed at continuing the progress that was made by the AGT programs.

These programs were designed to accomplish particular objectives such as brittle materials design, engine performance, or demonstrations of proof-of-concept. They were not meant to be materials research and development programs, although they all contained significant elements of ceramic technology.

In 1982 the Ceramic Technology for Advanced Heat Engines Program was developed by Oak Ridge National Laboratories at the request of DOE.[2] Its primary goal was to develop an industrial technology base to provide reliable and cost-effective high-temperature ceramic components for use in advanced heat engines. The program was designed to develop generic ceramic technology and was not tied to a specific engine design or component. The stated objective of the program was that it was to be an industrial technology transfer program; to ensure that transfer occurs, industry was included in the planning and execution of the research and development. The bulk of the program funds were targeted to research and development to be carried out in industry. Sixty percent of the effort was to come from industry, 30 percent from government, and 10 percent from universities.

An industry-needs assessment was made by ORNL to develop a program plan, and in this assessment increased reliability was identified as the principal technology need to advance the use of ceramics. Reliability was in turn related to materials and materials processing, improvements in design methodology, and the development of data bases and criteria for life prediction (see Figure 1). A joint ORNL-NASA work breakdown structure was developed to coordinate complimentary tasks funded by DOE, NASA, and other government agencies and industry. The structure is shown in Figure 2.

OVERALL OBJECTIVES, PRIORITIES, MILESTONES, BALANCE, AND PROGRESS

The management of the Ceramics Technology for Advanced Heat Engines Program has put in place a clearly defined mechanism by which to define and monitor individual research projects' objectives, priorities, and milestones. However, the committee had a difficult time in finding any similar mechanism by which the program monitors itself and its progress. The ORNL/TM-8896 document does state in general terms the goal of the program, the areas of research that are to support this goal, and the

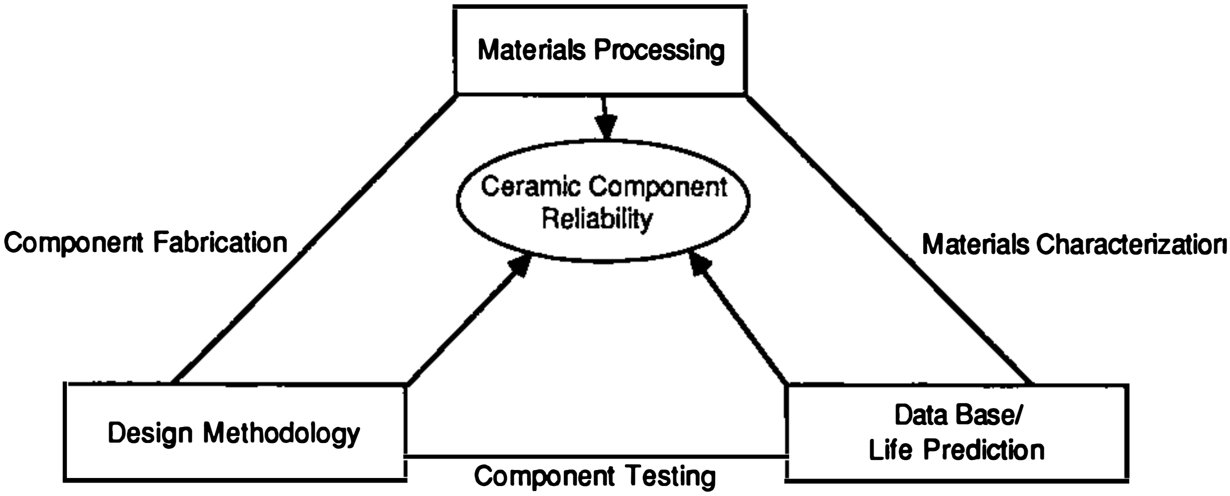


Figure 1. Relationship of major work elements to ceramic component reliability.[2]

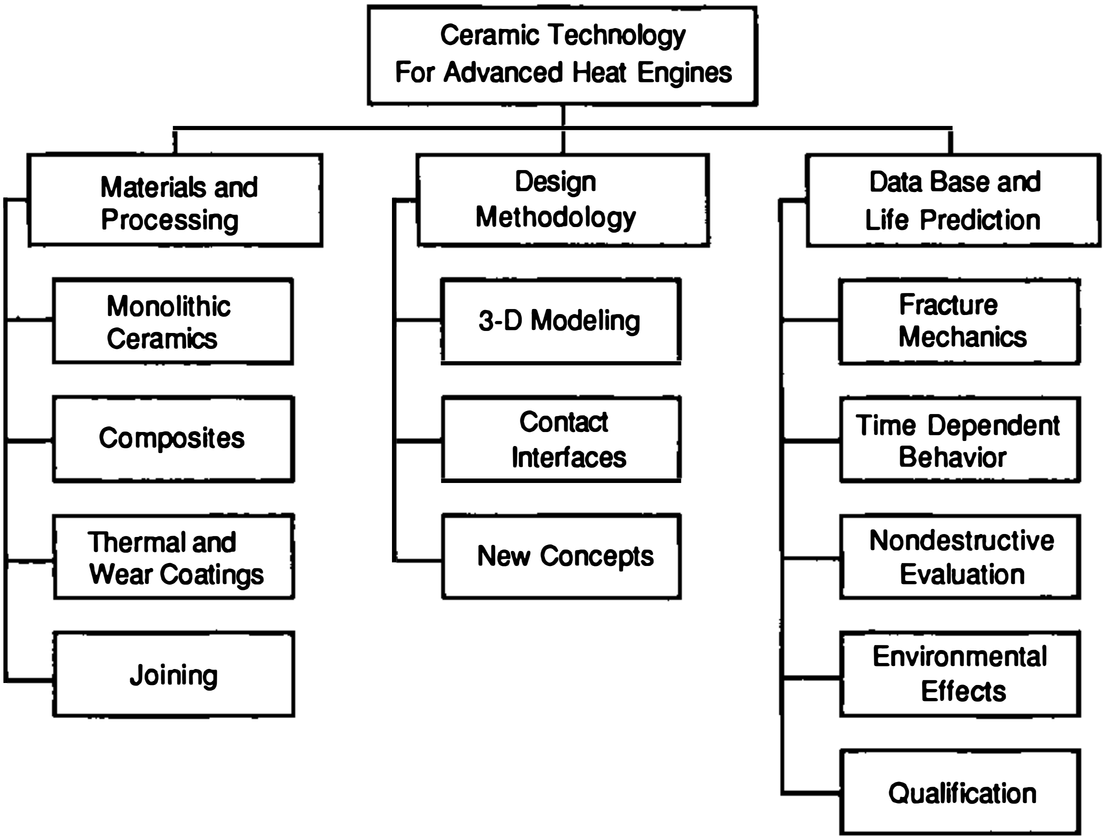


Figure 2. Joint Department of Energy-NASA work breakdown structure for research tasks.[2]

general objectives of each of those research areas. Therefore, the committee's approach was to examine the individual objectives and milestones for each research area and assess how they contributed to the overall objective of the program, and to review the various projects and results in order to determine the program's priorities, strategy, and progress in achieving its goal.

The preceding approach, however, was not easy to follow. The broadly defined research areas overlap with those in other offices within DOE (e.g. the Office of Basic Energy Sciences, Energy Conservation & Utilization Technologies (ECUT), and the Advanced Research and Technology Development Program (ARTDP) within the Office of Fossil Energy). They also overlap with efforts being conducted in other agencies, such as the Department of Defense (DOD), the National Aeronautics and Space Adminsistration (NASA), and the Department of Commerce, and others. Consequently, certain individual segments of the program plan are considered to be the responsiblity of other offices or agencies. Furthermore, within the Ceramics Technology Program alone, over 60 individual projects have been funded over the last 4 years, and some of those were sub-contracted out further. Although there are many meetings between the various program managers aimed at coordinating their individual agendas and efforts, it has been difficult to track the actual technical effort and achievement that is being made.

RESEARCH AREAS

As pointed out earlier, the primary goal of the Ceramic Technology Program for Advanced Heat Engines is to develop an industrial technology base to provide reliable and cost-effective high-temperature ceramic components for use in advanced vehicular heat engines. To attain this goal, a detailed research plan was developed to describe the needs, objectives, and approaches to be employed in achieving the desired reliability.[2] It was determined that the three principal research areas to be pursued were (1) materials and processing, (2) design methodology, and (3) data base and life prediction.

Figures 3, 4, and 5 show the overall schematics for the Ceramic Technology Research Program.

Materials and Processing

The objective of the materials and processing research element is to yield materials with uniform structures and properties required of advanced engine components. Monolithic ceramics of the following types were to be examined: nonoxides (SiC, Si_3N_4 and sialons), oxides (ZrO_2 and AL_2O_3), and silicates—lithium aluminosilicate (LAS), aluminum silicate (AS), and magnesium aluminosilicate (MAS). In each of these the major research tasks to be addressed are powder synthesis and characterization, processing and characterization of the green-state ceramics, densification of green-state ceramics, characterization of dense ceramics, and mechanical and physical properties of dense ceramics.

Also included in this element are composite materials, thermal and wear coatings, and joining (Figure 3).

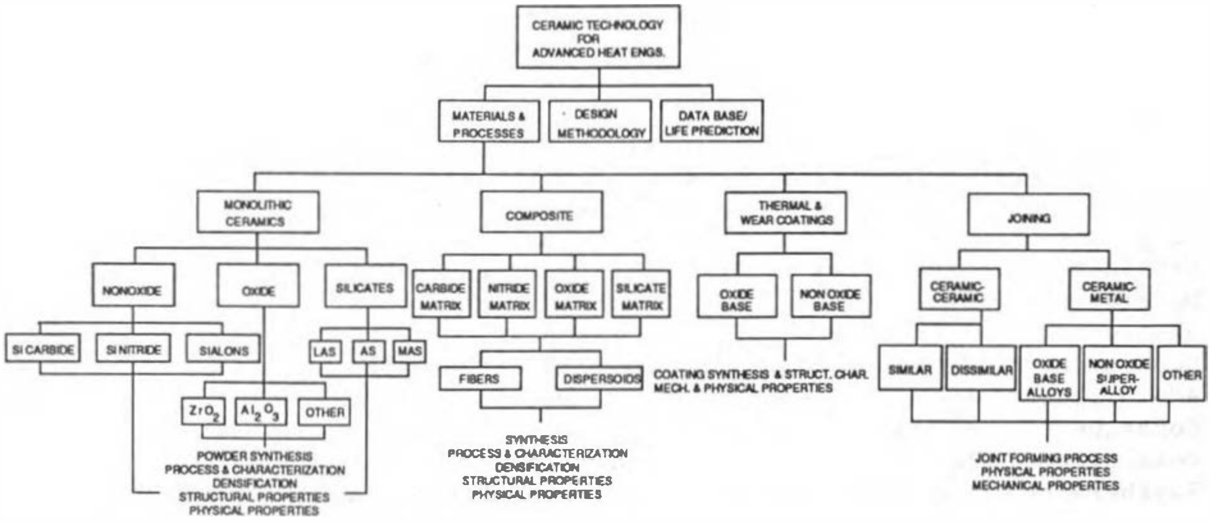


Figure 3. Materials and processing work tasks.[2]

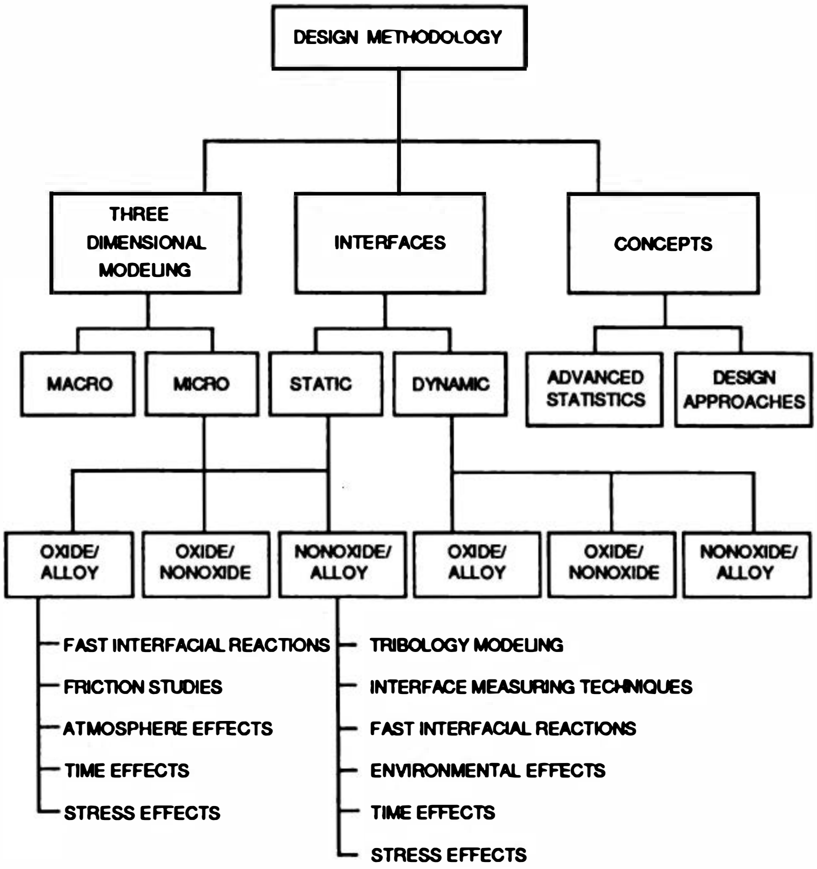


Figure 4. Design methodology work tasks.[2]

Design Methodology

The design methodology program element includes three major subelements: three-dimensional modeling, contact interfaces, and new concepts.

Three dimensional modeling includes the macroscopic approach of finite element modeling and the microscopic approach, which attempts to use finite element analytic methods on a scale of the microstructure of these materials.

The contact interface modeling is organized into two sections: static interfaces and dynamic interfaces. Topics such as static and dynamic friction, wear, and abrasion are examined as a function of time and temperature.

The "new concepts" subelement is organized into two sections: advanced statistical representations of brittle solids and advanced brittle material design methodologies (Figure 4).

Data Base and Life Prediction

The data base and life prediction program element is organized into the following five subelements: structural qualifications, environmental effects, time-dependent behavior, fracture mechanics, and non-destructive evaluation. Each of these five subelements is then broken down into the individual studies shown in Figure 5.

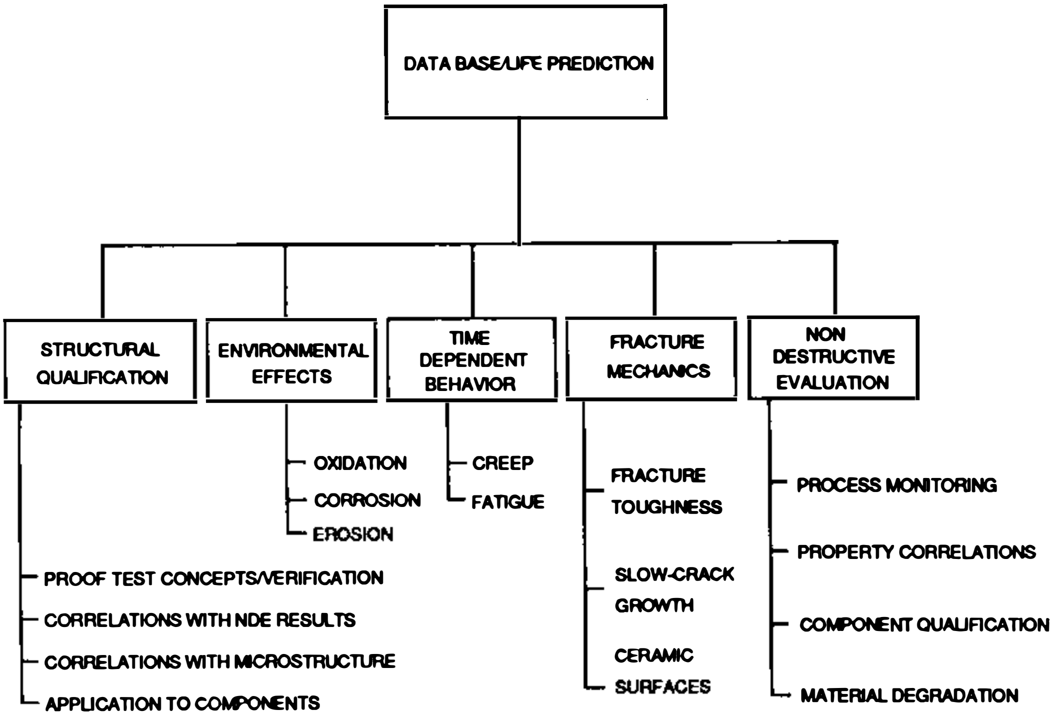


Figure 5. Data base and life prediction work tasks.[2]

DISCUSSION

OBJECTIVES

As summarized earlier, a program objective was stated by DOE for each of the three major categories of the program plan.[2] These objectives are worthwhile in themselves but are so broad that they provide little basis for program direction and assessment. What is needed is further development within each objective of a strategy leading to priorities. For example, within the materials and processing category a large list of ceramics is mentioned for study. Also, a list of five areas of research ranging from the initial stages of materials synthesis, through processing, to properties is called for study. Two problems are apparent: First, one category, ceramic composites, for example, may deserve higher priority than some of the other ceramics. Second, different aspects of the processing and property study sequence mentioned in the plan may be more critical for different ceramics.

PRIORITIES

In some respects the present program can be characterized as a matrix of materials versus areas of study. It appears that priorities have developed de facto by a sequence of individual decisions regarding need and opportunity for work in each matrix element. While this process has much merit resulting from decisions by experts in specific areas, it can lead to a lack of overall effectiveness unless balanced by an overall purpose. What is lacking is a sense of an overall strategy in choosing the individual work elements.

MILESTONES

There are two difficulties with the present milestones in the ceramic technology program. First, corresponding to the lack of an explicitly stated strategy and associated priorities, milestones relating to achieving successive stages in the overall program plan are not evident. To illustrate, there are separate projects relating to powder synthesis, to processing, and to property measurement for silicon nitride. There appear to be no stated milestones that relate to the use of the new powder in processing and property studies and to feedback to the powder synthesis effort. The milestones stated by DOE primarily relate to activities within specific work elements.

The second difficulty concerns the nature of the existing project milestones. These milestones have primarily an administrative character and are concerned with completion of the successive stages of each contract. What is not as strongly developed is a design of milestones in terms of programmatic decision points.

TECHNICAL CONTENT

The critique of the technical content follows the three major research areas: materials and processes, materials design methodology, and data base and life prediction. The committee decided that it was beyond its charter to review individual contractors and projects. However, the committee did receive information on specific projects by interviewing selected contractors, attending the annual contractors' meeting, and receiving the program's semiannual progress reports. Based on this information, the committee judged that, in general, individual projects were of high quality. It is the aim of this critique to analyze which areas of importance are under-funded and should be reassessed in the light of the following discussion. Hence, this critique contains a series of emerging opportunities.

Materials and Processes

Materials and processes have long been key areas in the development of ceramics for high-performance applications.[3,4] Rightly so, they are given high priority in the ORNL program, with more than half of the available funding (65 percent).

In interviews with engine and component manufacturers, however, there was general agreement that difficulties persist in achieving any reasonable life in key load-bearing components (especially the turbine rotors) using monolithic materials. Problems remain in reducing and controlling flaw populations in the fabrication of complex shapes. In addition, there are still no life-prediction models that would allow designers to take into account slow crack growth initiating from both inherent processing flaws or from service-generated flaws. Given these difficulties the committee feels that more flaw tolerant materials may have to be introduced in key components before the engine programs can achieve their near-term endurance goal of 3500 hours. The committee recommends that the program's effort in ceramic composites and toughened ceramics should be strengthened to provide the technology base needed to fabricate and test cost-effective composite or toughened components within the engine programs.

The materials and processes projects appear to be materials-specific and rely on proprietary technology of the industries involved. However, there are numerous areas that can be generically studied to better fulfill the objectives of the program plan.

The program recognized the importance of studies of "green-state processing." Many researchers believe that the process of preparing powder suspension, forming shapes, and drying or burnout is where precursor defects are introduced that lead to the final defects limiting reliability. The program directly addresses powder preparation and sintering. By implication, some of the projects necessarily include the post-powder-synthesis and pre-sintering state of processing, but there are two serious limitations. First, there is no direct charge to investigate and report on this area. This is an area that is critical to success with structural ceramics and is an area of science and technology that should not be left open or ignored. Second, ceramic component manufacturers regard the processing of specific components as proprietary. The company who can successfully develop its processes to reduce problematic flaw size or eliminate the formation of anamolous flaws holds a distinct advantage over competing manufacturers. Any effort at studying green state processing in general must take the proprietary nature of the work into account.

The overall program would benefit from a project with the specific objective of attempting to model theoretically the whole sequence of suspension, forming, and drying or burnout. This modeling need not be a highly theoretical process. More likely it would be a model made of coupled segments, most of which would at present have to be based on empirical experience.

In the case of the fundamentals of scaling behavior in ceramic processing, there is some overlap with the preceding problem, but it also has distinct features. Mass and heat flow will be different in bodies of different size during the drying or burnout stage and the sintering stage of processing. The scaling behavior has cost implications as well as implications for the limits of what ceramic processing may be able to achieve in making large parts or parts with sections of greatly differing thickness. Again, this problem is implicit in some of the projects, but study and reporting on scaling behavior is nowhere called out as a specific objective. Here, too, progress as incidental work on other projects is just the sort of thing that will most likely be kept proprietary.

There is an important opportunity here for a combined program of theoretical and experimental work. The stated objectives should include exploring scaling behavior in the drying-through-sintering stage and using the results in a predictive mode to assess the conditions (such as time required), the limitations (such as inherent sintering inhomogeneity due to temperature lag in the interior of thick pieces), the probable limitations on reliability resulting from large pieces, and the additional costs for large pieces resulting from trying to minimize these problems by drying or firing schedules.

The committee also recommends that the joining program be strengthened. Of the four projects listed in this area, three involve ceramic-metal joints. The only one on ceramic-ceramic joining apparently is in the stage of "complete request for proposals for ceramic-ceramic joining." Ceramic-ceramic joining may be as important as ceramic-metal joining if difficulties with making large, complex, and reliable monolithic parts persist. Also, this project should be specified in such a way that there will be some emphasis on the fundamentals of joining and a requirement to report rather than keep the key technology proprietary.

Design Methodologies

This program has emphasized the materials aspects of design methodology, such as contact stresses, wear and friction, and advanced statistics.

A study of the fundamentals of the statistics of fracture, which includes asking whether Weibull statistics is the appropriate kind, is very important for ceramic technology.

There is an opportunity that does not appear to be addressed in this program: the attempt to reason from physical models of microstructure and associated defects to an appropriate form of statistics of fracture. For example, fiber-reinforced ceramics should have a different form of relationship between flaw size and stress to extend the flaw than the classical law from linear elastic fracture mechanics. This phenomenon should change the shape of the curve relating fracture probability to stress. Other phenomena that are undoubtedly important to the failure process of ceramics and that might lead to a different form of fracture statistics include the R-curve behavior of polycrystalline ceramics and the whole process of high-temperature failure.

In the light of doubts about the applicability of Weibull statistics to some of the real and important modes of failure, and in view of the critical role Weibull statistics currently play in probabilistic design and the great expense of obtaining data for a Weibull analysis, it seems important to strengthen these studies.

A further concern relates to scaling from laboratory tests to component tests. As was noted at the Allison Division of General Motors, rotors that had been mechanically tested demonstrated a different flaw population than bend bars that were used to establish the Weibull statistics for life prediction.[2] The bend bar data base in this instance was useless in life prediction for the rotors. This may in part be due to multiaxial stresses, which do not manifest themselves in bend tests. Alternatively, extrapolation to larger and more complex volumes may not be appropriate. Advanced statistics models should incorporate both scaling and multiaxial stress effects.

Data Base and Life Prediction

Obviously a valid design methodology relies on an adequate data base and verified life-prediction schemes. Therefore, the third major technical area emphasizes the data base and life prediction aspect.

The research on mechanical behavior of ceramics in the past 10 to 15 years has emphasized the reliability of the materials under short-term loads. This emphasis was necessary to assure a reasonable probability of survival under start-up stresses. However, the time-dependent failure processes must now be addressed to assure an economically feasible lifetime in service.

Environmentally assisted crack growth at and near room temperature has received sufficient attention so that lifetime prediction for glasses and some crystalline oxides can be accomplished with some confidence. The current program is heavily weighted toward similar studies in the zirconia family and other oxides that are unlikely to see high-temperature structural application. In view of the consensus of engine manufacturers that time-dependent, high-temperature properties of candidate engine materials are virtually nonexistent, the current emphasis of the program should be re-evaluated.

There is virtually no data base concerning the creep-rupture or cyclic fatigue behavior at elevated temperatures that would be suitable for the most tentative design exercises. Moreover, the understanding of the failure processes and the basic materials characteristics that control these failure processes is very primitive. The research community has focused much of its energy on mechanical response such as strength and toughness in short-term fracture studies with the justification that the material must survive the initial stress conditions before one can become concerned with the long-term reliability. In many cases adequate, or at least interesting, materials are commercially available for engine components, and the major questions become those of long-term reliability and behavior under sustained and cyclic stresses at elevated temperatures.

Therefore, the ceramic technology program should contain (it currently does not!) a major effort on creep, stress-rupture, and cyclic fatigue behavior of candidate structural ceramics and composites at elevated temperatures with two objectives: (1) to develop an interim design data base for existing materials being commercialized; and (2) to develop a fundamental understanding of the failure processes and the materials characteristics that control these processes.

Test methodology will be an important element in this program, but university and national laboratory groups have developed techniques that are suitable. These fledgling efforts should be bolstered and closely coupled to the needs of the engine manufacturers (materials, stresses, temperatures, etc.).

The influence of combustion environments or contaminants must be included in these programs, since the candidate nonoxide ceramics are often unstable or only "kinetically stable" in these ambients.

Nondestructive evaluation of green and sintered ceramics has long been recognized to be an important problem, and much money and effort has been expended. In view of this, the committee recommends that the NDE program be critically reviewed, particularly since methods to detect the small flaws responsible for failure in high-strength ceramics have not been found. Various NDE techniques do detect larger flaws that also sometimes occur and lead to much lower strength ceramics. One can imagine two rationales:

- Improved NDE will allow one to detect the very fine flaws (50 micrometers or less in largest dimension, with much smaller crack thicknesses). If this is the rationale, what are the new ideas that offer hope that this can ever be done in materials of complex structure with many designed-in inhomogeneities, which will tend to make detection of the critical flaws more difficult? Simply putting more effort on this problem may be akin to trying to cure cancer by spending money without an idea. If a major effort is being made on microfocus x-ray or ultrasonics, for example, in the hope of being able to detect the very fine critical flaws, one would like to have a rational argument that basic physical laws allow this possibility.

- Even if the very fine flaws limiting strength cannot be detected, reliable NDE procedures to detect the larger flaws would be useful as part of a screening procedure. One could, for example, perhaps hope to find larger flaws in green ceramics and recycle the defective parts back into the processing sequence before sintering. If this is the rationale for the NDE program, a technical and economic analysis of the value of success of the NDE program could be made. One could assign parameters such as the cost of NDE inspection, minimum strength that passing the NDE inspection could ensure, cost of a proof test on a finished part, assumed statistical distribution of strengths from processing, and minimum probability of nonfailure that is tolerable in the testing as functions of x and y. One could thus arrive at cost figures and effectiveness of different testing strategies for ensuring low failure probability.

In the absence of such an analysis, it is not clear that NDE on structural ceramics will pay for itself. Of course, the above simple ideas only hint at the sophistication which a proper analysis should have. The real goal is to improve processing, not just to reject parts. A good analysis should address how NDE technically and economically can rationally be expected to do this.

Technical Program Management

The committee acknowledges that the original program plan was quite comprehensive in identifying the multitude of technical areas requiring development. It is clear, however, that, given the current funding levels, the program cannot support fundamental science, process development, and pilot manufacturing for all materials to be used in three different engines. The committee could not find any evidence of an overall strategy by which the limited resources are effectively directed to make significant progress in a given area. It does not appear that the technical priorities have been clearly defined. Consequently, there are many small groups working across the spectrum of technical tasks without any apparent coherence or convergence of output. An accounting of individual projects, from FY 83 to FY 87, is given in Appendix B.

The committee recommends that priorities be clearly defined and funded at higher levels. This not only would allow a "critical mass" of contractors to be assembled but also would offer more stable funding for a particular area. This should not preclude small, individual-investigator projects, but it implies that such projects should be a part of a more focused effort. Furthermore, it is recommended that responsibility be assigned within the group, in the form of a single technical coordinator or a technical coordinating committee, to monitor the group's effort and to produce an annual unified report of technical accomplishments and progress.

It may also be of great value to schedule topical workshops in each of the priority areas.

TECHNOLOGY TRANSFER

The basic question that this committee was requested to address regarding technology transfer was "How are the mechanisms for the transfer of technology (and assimilation) being used?"

In its assessment of the situation underlying a response to the request, the committee has determined that the approach employed by DOE to developing and transferring ceramic technology is, in principle, sound. The policy established by DOE defined technology transfer as follows:

> The transformation of R&D into processes, products, and services that can be applied to state and local government and private-sector needs. The R&D laboratory technology transfer program emphasizes personal interaction between the technical staff of the R&D laboratory technology and representatives of the public and private sectors. The R&D laboratory technology transfer program includes the following activities:
>
> 1. Assessment of R&D projects for applicability to the needs of the private sector and state and local governments.
> 2. Application and/or adaptation of research or technology into processes, products, and service for use by the private sector and state and local governments.
> 3. Technical assistance to the private sector and state and local governments in adapting federally developed technology for use.
> 4. Cooperation with technology transfer brokers to move technology from the laboratories to the private sector and state and local governments.
> 5. Licensing of DOE-owned patented technology for commercial use.

The Under Secretary of Energy is responsible for establishing policy and overall guidance for the R&D laboratory technology transfer program, with support provided by the Director of Energy Research (ER). In this supporting role, the Director is charged to provide guidance regarding incorporation of the technology transfer program functions into the existing institutional planning process for multiprogram laboratories such as the Oak Ridge National Laboratory (ORNL).

A requirement established in the order is the submission of an annual 5-year R&D laboratory technology transfer program plan for approval by the Director of ER in the case of ORNL. By implication, this establishes the requirements for a 5-year technology transfer plan for ORNL's Ceramic Technology for Advanced Heat Engines Program.

The foregoing statement applies mainly for transferring technology out of the lab and into the private sector. An alternative strategy being employed by ORNL is to fund technology development within industry, thereby eliminating the need for transfer. ORNL places projects in industry by RFP or, in some cases, by funding unsolicited proposals and sole-source contracting. DOE patent rights are waived for small businesses and nonprofit organizations, in accordance with Public Law 96-517. Furthermore, patent waivers are granted to larger firms if they, in turn, waive subcontractor costs and cost-share at least 20 percent. All patent waivers are upheld as long as the patenting firm makes available relevant technology through licensing agreements. Although these mechanisms are well established, negotiations between DOE and the contractor take a very long time—often between 1 and 2 years from the time an RFP is issued to granting of a contract.

The strategy of achieving technology transfer by directly funding technology development within industry is sound in principle. However, the division of work among the various institutions—industry, universities, and government labs—needs careful analysis. Work of a generic nature (e.g., statistical design) needs to be fully disseminated and may be more properly funded in a public institution rather than in private industry. Patentable technology that can be made available for licensing may be more properly funded in private industry. However, in an area such as processing, many companies prefer to keep their expertise proprietary, thereby inhibiting the exchange of information. This proprietary nature of some of the work conducted by the industrial sector puts the burden on ORNL program managers not to fund projects with broad generic implications in industrial labs.

Effective transfer of technology with government funding occurs through interaction among university, laboratory, and industrial personnel, timely publication of information, and appropriate licensing agreements. This program attempts to stimulate interaction by spreading funds among these three sectors.

It should, however, be noted that the simple involvement of industrial laboratories may not be sufficient for producing interlaboratory technology transfer. This is particularly the case if related contracts are placed at various institutions whose only contact is through the usual open meetings, open literature, or through somewhat sketchy annual reports. An intimate, ongoing interaction between all parties concerned with a specific set of related subcontracts should be strongly stimulated.

The committee therefore recommends the following:

- Integration of closely related contract efforts under a single technical coordinator—e.g., the principal investigator for the chief contract in such a program subgroup—with the requirement to produce an annual unified report of technical progress and accomplishments.

- Continued and expanded dialogue between the engine developers and domestic ceramic suppliers to define further the ceramic materials requirements and to have rapid feedback on materials performance.

- Exchange of personnel between ORNL, ceramic suppliers, and universities, which should be encouraged by specifying it as a contract performance task.

INTERNATIONAL AGREEMENTS

The committee feels strongly that the International Exchange Agreement phase of the ceramic technology program should be critically examined on a cost-benefit basis. The modulus of rupture testing program should be reconsidered in light of its limited ability to provide a usable design data base. Some of the other programs planned have more value but only on a long-term basis. The ASTM and NBS should, if the program is continued, be included as participants. The Japanese are not included in the program despite the fact that they are a dominant force in ceramic technology.

There are in existence good relationships between the various foreign countries that are active in structural ceramic research and development, particularly Japan, the real leader in this area. There is a relatively free exchange of information, cross-licensing agreements, joint ventures, visiting scientists and engineering personnel exchanges, technical society exchanges, etc., between all concerned groups. It would seem that formalizing this information flow by way of an international agreement is somewhat superfluous at the present stage of development of ceramic technology.

A statement of the International Exchange Agreement is given in Appendix C.

FOREIGN COMPETITION

Many studies have confirmed that high-performance ceramics are essential materials for electronic, optical, and structural applications.[7,8] Monolithic ceramics, composites, and ceramic films and coatings will find an ever-increasing market in the future. These same studies also generally agree that the United States has been a leader in the basic science studies that underlie the use of ceramics in engineering applications.

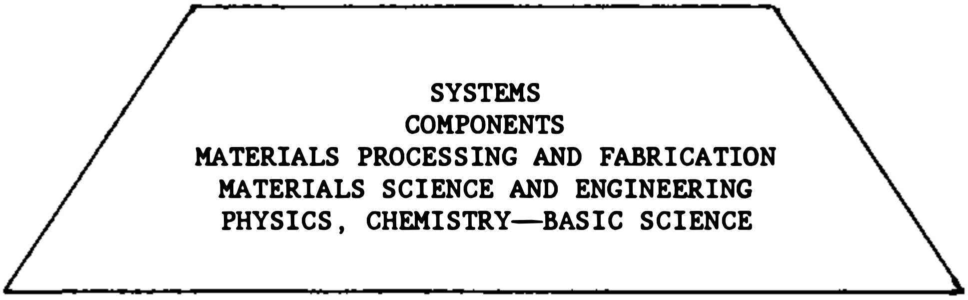
Where the United States appears to lag is in transferring the basic science to engineering practice, although the nation is not completely inept in this. One can point to automotive applications such as spark plugs, catalytic converters, pump seals, ceramic machine tools, ceramic heat exchangers, semiconductor packaging, coatings, thin film, optical fibers, etc. In all of these there is a market, the products are reliable, and they are cost-effective.

There is a sense that, since the United States has had a leadership position in basic research, then it would follow that it should have a leadership in engineering applications. This is not necessarily true. Economics plays as important a role as does the basic science. Studies showing that ceramics can be used in certain applications do not ensure their use in those applications. They must demonstrate that they have the equivalent life and reliability of the materials they are replacing. In addition, they must compete at an equivalent or preferably lower cost.

While plans are being made to increase basic science, train more people, develop university-industry relationships, establish interdisciplinary centers and centers of excellence, etc., these measures do not address the central problem, which is the transfer of basic science to engineering practice. This is not just a U.S. problem. The same condition exists in Western Europe and Eastern Europe (including Russia).

The Japanese seem to have recognized this problem and to have taken steps to remedy it. There are numerous examples of how they vertically integrate basic science, engineering science, product development, and system development to a market pursuit.

The 1986 report of the Japan Fine Ceramics Association[16] details the modus operandi used by the Japanese for their development of advanced ceramics technology. Although their technique is not directly applicable to the United States, there are some facets of it that merit consideration for study and implementation. Among these is the concept of vertical integration, which is based on the following pyramidal structure:



The ultimate payoff is in systems, but, to achieve this, all the elements must be closely integrated. Many Japanese companies perform all of these functions in-house as do some of the larger U.S. companies. In areas where this is not the case, as is currently the situation with ceramics and heat engines in both Japan and the United States, vertical integration of these elements must be achieved externally. In Japan, the Ministry of International Trade and Industry organizes the vertical integration. The United States tends to compartmentalize these elements and fund them separately. DOE's AGT and Heavy-Duty Engine Programs support systems and component development and some materials development. The DOE-ORNL Ceramic Technology for Advanced Heat Engines Program supports materials and to some extent process development and generic materials science and engineering. Separate programs in DOE, DOD, and NSF support basic sciences and generic materials science and engineering. Although there is some overlap and continuous coordination to avoid duplication, integration from top to bottom is not as evident.

An area that appears to be falling through the cracks is component fabrication and testing—i.e., the transition from laboratory test bars to engineering practice. To meet engine test schedules, the engine programs have gone to Japan for some critical components, namely turbine rotors. Although U.S. suppliers are now achieving comparable materials properties in test specimens, they have had problems achieving these

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properties in finished components. Any effort at developing ceramic materials and processes must follow through with fabrication and testing.

It is well understood that achieving a desirable microstructure in complex shapes is much more difficult than achieving it in test specimens. The committee recognizes that the DOE-ORNL program does not want to supply components to the engine programs. Similarly, the engine programs are under time and resource constraints to test engine components and meet engine test schedules. Some kind of complex shape fabrication and testing, tied in perhaps with the scaling studies recommended earlier, independent of the engine programs, could provide critical and timely feedback.

COORDINATION OF EFFORTS

The interrelationships between participating funding agencies is handled by many (too many?) meetings of program managers. This procedure is useful in keeping the managers aware of activities in specific contracts and should result in complementary programs. However, despite these meetings, it is not apparent to the committee that the technical efforts are coordinated with a mutually reinforcing overall strategy. In particular, the successful integration of the DOE-NASA engine program and the DOE-ORNL ceramics program into an effective whole is not apparent.

The committee is especially concerned about the exchange of technical information among program participants. The Contractors Coordinating Meeting emphasizes managerial overviews but provides relatively little opportunity for technical interchange.

There are bimonthly NASA-DOE engine project management meetings as well as site visits to contractors and contractor visits to ORNL. Reports are exchanged, and RFPs are coordinated. Similar arrangements exist for interactions with the Departments of Defense and Commerce. DOE internally has several coordinating committees to follow the various activities of the ceramic efforts of the different offices. Many of these appear to be similar to the Contractors Coordinating Meeting in that the management aspects of the efforts are emphasized rather than the technical efforts.

It could be that the major emphasis of the program—to get industry involved—has produced this lack of free exchange of technical information. There are proprietary rights and patent rights that tend to inhibit such an exchange. Whatever the cause, it is the opinion of the committee that the DOE-ORNL ceramic technology program is overcoordinated at the managerial level. Efforts should be made to get a wider dissemination of the technical efforts and a greater exchange of information at the working levels such as is obtained in NSF and DOD contracts.

There is no doubt that there is management coordination of the DOE-NASA and DOE-ORNL programs, but not at the technical level. They appear to be independent programs, with no real technical exchange between the groups. If the projected ATTAP is to be successful, this situation must be corrected.

ENGINE PROGRAMS

While its charter was to review and report primarily on the long-range Ceramic Technology for Advanced Heat Engines Program, the committee also had the opportunity to review other programs funded by DOE-OTS through DOE-NASA contracts. These were the AGT 100 program at Allison Engine Company in Indianapolis, the AGT 101 program at the Garrett-AiResearch Company in Phoenix, and the Heavy Duty Engine (Adiabatic Diesel) Program at the Cummins Engine Company in Columbus, Indiana. These are much larger and more mature programs than the ceramic technology program. For instance, the AGT 100 Project at Allison was to finish its fifth and final year in December 1986, having been funded over that period to the extent of $35 million. The AGT 101 Program at Garrett-AiResearch, funded at approximately the same level, will be completed in 1987. The Adiabatic Diesel Program is being funded at a lower level.

The rationale for having the committee review and receive briefings from these contractors was to acquaint the committee with the ceramic problems encountered in these feasibility programs and to enable it to envision what future ceramic studies should be planned in the ceramic technology program. In this context, the highlights of the committee's findings are summarized in the following pages. In addition, in Appendixes D and E are included two committee position papers relative to materials requirements for current and future heat engines. These position papers were written by individual committee members but represent the consensus of the entire committee.

Cummins

Cummins Engine Company's main product is heavy-duty diesel engines and their associated accessories. Most of its government-sponsored efforts have been through the U.S. Army Tank Automotive Command in developing "adiabatic" diesels for truck and tank applications. The company has also worked with ORNL on the characterization of chrome oxide coatings, nickel-aluminides, partially stabilized zirconia (PSZ), and aluminum titanate.

The basic motivation for the "adiabatic" diesel is to increase the power density of the engine by eliminating the cooling system and running the engine at a higher temperature. To do this requires new insulating and new metallic materials. Results include high oil consumption and greater particulate emissions, although the fuel tolerance of the engine—i.e., the ability to burn lower Btu fuels—is improved.
The use of insulation alone does not have much of an effect on fuel economy, the basic motivation in commercial applications, since the heat saved via insulation is lost to the exhaust, unless a bottoming cycle is employed. In fact, there is a reverse transfer of heat from the hotter combustion zone surfaces to the intake gases, and this lowers the volumetric efficiencies.

Cummins, in its studies on insulating surfaces, has worked on the piston cap, cylinder head, valves, and cylinder walls; heat loss through the cylinder walls is not an important heat sink as compared to these other surfaces in the engine.

Monolithic PSZ has been used as a candidate insulating material since its expansion coefficient is compatible with cast iron, to which it must be attached. The current PSZ materials, however, lose their strength, and their metastable structure degrades at the temperatures and times of operation of the diesel engine. As an alternative to PSZ, Cummins has an ongoing effort for applying and characterizing thick thermal coatings.

Cummins engineers pointed out to the committee that the "adiabatic" engine will result in operating temperatures above the limit of current lubrication systems. To develop new lubricants is a major undertaking and will require studies on the tribological behavior of ceramic materials. In their opinion, liquid lubricants will be required for the foreseeable future in any "adiabatic" diesel engine.

Allison

The Allison Engine Division of the General Motors Corporation produces turbines for small aircraft, ground transportation, and power generation. In the advanced gas turbine program Allison is responsible for the development of the AGT-100 two-shafted regenerated turbine rated at 100 horsepower. The design objectives, relative to a comparable internal combustion engine, are (1) lifetime (3500 hours) and reliability, (2) competitive cost (initial and lifetime), (3) performance (acceleration), and (4) safety.

To achieve these goals Allison set out to develop and verify design techniques for ceramic components. At the same time ceramic materials and component fabrication techniques were developed. Since 1979 Allison has subcontracted over $10 million to various ceramic companies for the materials and process development. These companies include Sohio (Carborundum), GTE, Corning, Norton, and Coors. They have also purchased components from Kyocera and NGK. To date Kyocera has produced the materials that are best from a strength and process control basis. The major parts that have been fabricated are the gasifier rotor, power rotor, turbine scroll, combustor, and regenerator.

In design methodology two- and three-dimensional finite element methods are used, and the designs for components are to specified reliability based on Weibull fast fracture strength data. It has been found that the Weibull data are best determined from test bars sectioned from finished components rather than from test bars made for test purposes.

Although components have been rig-tested and engine-tested to verify the design methodology, a more extensive design data base is needed, since the materials being used are still in development and undergoing changes in chemistry and processing. Time-dependent data such as creep and stress-rupture have yet to be incorporated into the design methodology. Composites will undoubtedly come into use, and their behavior and properties need to be incorporated into the design methodology.

The most difficult ceramic component is the gasifier rotor, which rotates at 86,000 rpm at a temperature of 2350°F. The strength has been set at 65 ksi with a Weibull modulus of $m = 12$ for rotor materials. Sinterable Si_3N_4 and SiC are the candidate materials. Carborundum is providing injection-molded SiC rotors. GTE is supplying injection-molded Si_3N_4 rotors; Kyocera is providing slip-cast Si_3N_4. Only Kyocera had delivered a rotor that had been qualified for engine testing at the time of the interview.

Garrett

Garrett is part of the Allied/Signal Corporation and, with the Ford Motor Company, has been working since 1979 on a single-shaft regenerated-gas turbine designated as the AGT 101. Garrett's major products consist of small turbines for aircraft propulsion, rotorcraft, cruise missiles, and auxiliary power units (APUs). In the DOE-NASA program for the AGT 101, Garrett subcontracts their material and processing development to Ford, AiResearch Casting, ACC (a Garrett division), Corning, and Sohio (Carborundum); parts are also obtained from Kyocera and NGK-Locke.

The objectives of the Garrett program are similar to the Allison program. The two programs are competitive in the sense that they have the same objectives but are approached with two different designs.

Garrett reported the following:

- Design methodology for fast fracture requires development on the effects of surface area, the effects of volume, and the effects of multi-axial stresses.
- Thermal shock and limited durability under thermal cycling have been demonstrated for both SiC and Si_3N_4.
- The room-temperature and high-temperature strengths of both compounds have been improved (SiC through processing and Si_3N_4 through a combination of chemistry and processing).
- The control of pressure and temperature during processing has been improved.
- The forming capability, in both thick and thin sections, has been improved (primarily in Japan).
- The material supplies base has expanded, primarily from Japanese and German sources.

Despite these improvements, still further progress is required if cost, reliability, and durability problems are to be solved.

There are three stages in the engine development program at Garrett. The first is a 1600°F engine test to test the aerodynamic design based on ceramics; second is a 2100°F test, all ceramic but for the metal rotor; and third is a 2500°F test, all-ceramic hot section. The 1600°F tests have been completed. A 100-hour test was successfully run on a 2100°F engine. This test was run at steady-state cruise conditions and showed no indication of performance or ceramic degradation. Leakage is still a problem, but improvements have been demonstrated with monolithic ceramic static seal development. One 2500°F engine test with an all-ceramic hot section has been run for 3.5 hours, but it was terminated because of a regenerator roller failure. The engine had accumulated 10 starts and had operated at a rotor speed of 75,000 rpm. The goal of this part of the program is a temperature of 2500°F at 100,000 rpm. Six to eight all-ceramic engine tests were scheduled for 1986.

Engine Program Problems

All engine program personnel at Cummins, Allison, and Garrett responded freely and forthrightly to the questions submitted by the committee prior to its visits (Appendix F). At the actual meetings, considerable time was spent in discussing the questions, clarifying certain points, and introducing additional points.

In view of the limited knowledge of design technology for ceramics, the current designs for the AGT 100 and AGT 101 engines and the designs used by Cummins in their TACOM and other component efforts are outstanding. This needs to be emphasized at this point because the discussion that follows essentially points up deficiencies uncovered in the several years of experience in ceramic materials design and utilization.

There was a surprising unanimity in the answers submitted by the engine companies, which enabled the committee to combine the answers received into the following summaries.

At the start of the AGT and HDE programs the critical problem areas were specific fuel consumptions and alternate fuels; emissions and particulate levels to meet EPA goals; component processing, costs, reliability, and performance; material characterization; defect identification; and development of a design strategy and methodology.

At the present time the list has changed somewhat to include the following critical problem areas: component reliability, cost, and performance; improved materials; reliable quality supply of parts; interface and seal problems; and long-time high-temperature design data base.

All the engine companies were of the opinion that there has been no significant transfer from the ceramic technology program to their programs. This is not unexpected, since the ceramic program lags the engine programs by 3 to 5 years, and their projects are structured to address generic problems, not the specific problems of the engine companies.

The engine companies recognize that there are problems in the design area in regard to the adequacy of the Weibull analyses that are used. They utilize them, but from their engineering experience they modify them to match that experience. The ceramic technology program has an effort in this area, but it is too early to expect it to have any influence on the current engine programs.

In the materials and processing areas the engine companies were almost unanimous in their belief that materials property improvements have not been achieved. In materials processing, yields of components are unacceptable for transfer to developmental production.

All the engine companies have been able to show improved NDE capability, but there is still a need to characterize the flaws detected in regard to size, shape, and orientation with their subsequent behavior in service. The area of defect interpretation for brittle materials is not understood. No NDE in-process methods have been identified.

The data base to permit high-temperature design and analyses is quite inadequate. Methods to predict the effects of multiaxial stress, creep, slow crack growth, and cyclic fatigue and the influence of component size are not available. Without accurate methods for predicting these effects, conservative designs are the result.

Components "never" achieve the strength levels achieved in MOR test bars. In components, the strength levels vary with the microstructure throughout the component, and the correlation of this information with the basic property data is not fully understood.

All the engine companies are of the opinion that the use of structural ceramics in heat engines will be evolutionary. Stationary components with low structural property requirements will be developed first, then the rotating components will be developed later in the cycle.

These comments were offered by all the engine companies. The following additional comments were offered but were not as universally accepted as true by all the companies:

- Adequate sintered Si_3N_4 is not available for static components at 2500°F.

- U.S. suppliers have been unable to consistently fabricate engine rotors.

- The toughness of reaction-bonded silicon nitride (RBSN) and silicon carbide (SiC) is not adequate for some static components.

- In processing and fabrication, U.S. suppliers do not have consistent control of their products to ensure reliability.

- ORNL is credited with making a significant effort in disseminating information on structural ceramics between government and industrial groups, but engine companies do not seem to be in these information channels.

- There is a belief that the structural ceramics program should be refocused to address current engine needs.

- The large number of small contracts funded by ORNL makes it too difficult for the engine companies to develop and maintain close working relationships with these contractors.

- The contractors' general meetings are of limited usefulness for real technical information exchange. Limited attendance has been suggested to try to improve this exchange.

- There was a criticism of the ceramic technology program in that no engine evaluation of components is included in their studies. It is felt that such verification is necessary to obtain the use of the technology in industry.

CERAMIC PROGRAMS

The committee reviewed the programs at GTE and Norton-TRW, and a subcommittee reviewed the programs of Sohio. These are three of the principal powder producers, powder processors, and ceramic part manufacturers in the United States.

GTE

GTE has extensive programs in ceramic materials that are centered primarily in the Diversified Products Division, which includes the GTE Laboratories and Electrical Products Group.

In structural ceramic materials, the primary GTE emphasis is on Si_3N_4. GTE has programs in powder R&D and manufacturing, materials development, shape fabrication, ceramic-to-metal joining, and NDE.

In structural ceramics, GTE is very much aware that the principal research need is to improve component reliability. To develop highly reliable and cost-effective Si_3N_4, GTE emphasizes the following research topics: processing (prevent flaw formation); toughening (reduce flaw sensitivity); NDE (eliminate flawed parts); and proof testing (eliminate flawed structures).

The GTE efforts are concentrated on sintered silicon nitride utilizing sintering aids selected to optimize specific alloy properties. The company has gained improved strengths and reliability from internal programs on green microstructure control through improved processing as well as NDE analysis. It is the feeling that several fabrication processes, including slip casting and injection molding, can markedly reduce the flaws in both green and consolidated microstructures. Ultimately, the resultant properties are improved, as is reliability.

In making precision shapes, GTE has fabricated small complex-cross-section components such as vanes and blades by injection molding. GTE Labs entered the AGT program to supply turbine rotors to Allison. Initially, internal cracking related to burnout in these large-cross-section components developed. After an in-house study, the problem was solved with a proprietary process. Currently GTE is again participating in the AGT program and will supply rotors to Allison.

For silicon nitride matrix composites, an in-house effort has resulted in the commercialization of a wear-resistant particulate composite. GTE has an ORNL program to study the toughening mechanisms and micromechanics of both particulate- and whisker-reinforced composites. They are a Si_3N_4 matrix with SiC and TiC particles or whiskers. Improved fracture toughness and strength were obtained with Si_3N_4-SiC whisker composites; shape-making research is under way.

GTE has a ceramic joining program to establish design concepts and criteria for reliable joints in high-temperature, high-stress and corrosive environments.

Norton-TRW

Norton's Engineering Materials Group deals with industrial ceramics, chemical process products, high-performance plastics, and high-performance ceramics (HPC). It is the HPC group whose function is to develop new businesses, build them to commercial status, and transfer them to operating units, create new Norton entities, or form joint ventures. The group's material capabilities are in SiC, B_4C, Si_3N_4, AlN, Al_2O_3, and ZrO_2. The materials are formed by casting, injection molding, cold pressing, extrusion, sintering, HIP, hot pressing, and diamond machining.

Norton-TRW is building a business to develop markets and cost-effective manufacturing for ceramic components for hydrocarbon engines. The strategy is to understand market needs, then focus R&D to satisfy the customers' requirements. The group is looking to ceramic applications in valve train components, piston caps, rings, inserts, exhaust system insulation, and turbocharger rotors.

To accomplish this the company plans to increase component performance by maintaining laboratory properties in the component, minimizing variability through quality control, eliminating grinding by using near-net shape, and decreasing HIP by moving to sinterable materials. Efforts in powder R&D and manufacturing are aimed at developing both monoliths and composites, shape fabrication by injection molding, slip casting, die pressing, and isopressing. Studies are in process on ceramic-to-metal joining and in NDE.

Norton strategy is to continue to develop materials capabilities and to concentrate on processes and their effect on reliability and cost. The company also felt that a manufacturing technology type of program would be premature at this time since materials and processes have not yet reached commercial feasibility.

Sohio

A committee member visited the Standard Oil Engineered Materials Company, which had been sent a copy of the questions asked of other materials companies (Appendix F). A summary of the discussion with Sohio follows.

At the start of the AGT programs the problem areas were the inability to produce test bar results in components; improvements needed in baseline properties; unattainability of economical fabrication of complex shapes; need for development of NDE methods; and inability of industry to supply materials and components.

At the present time many of these same items are still problem areas: baseline material improvements; design and fabrication costs; NDE and engine evaluation of components; and demonstration of low-cost, high-volume production of components.

Progress has been made in design, materials, processing, fabrication, and testing, but still further progress is required. Some of the key areas of "progress" are as follows:

- Engine components have been produced with strengths approaching 80 percent of the results achieved with MOR test bars. This compares to 50 percent or less a number of years ago.

- Engine components are routinely produced and provided to the engine builders for testing and evaluation. The number of hours of testing in actual or simulated engine operating conditions is very significant. This leads directly to improvements in the design and fabrication of subsequent components.

- New or improved monolithic and composite materials have been developed.

- The direct interaction between ceramic suppliers and engine designers as a result of the current programs has likely improved the effectiveness of the technical work performed.

Like the other ceramic companies, Sohio sees a billion-dollar structural ceramic market, but not until the year 2000 or beyond. More immediate applications will be in retrofitting existing engines.

Summary of Ceramic Programs

Like the engine companies, the ceramic groups' comments were all similar and in some cases were the same comments as those of the engine companies.

All felt that it is too early to judge the technology transfer program of ORNL. To date most of the transfer has been in the reverse direction—from industry to the program. The ceramic companies felt that the AGT program did not allow enough time or money for materials and processing development.

There is general approval of the ORNL program plan, but the companies pointed out several deficiencies, such as the slow and costly RFP process; the lack of effectiveness of the contractors' coordination meeting; minimal university input; and lack of a long-time, high-temperature data base on creep, rupture, and cyclic fatigue.

BUDGET ANALYSIS

The original program plan[2] was for a 5-year period and required on the order of 200 person-years per year of support. An average cost of $120,000 per person-year was projected for labor, overhead, and materials costs. When cost escalation and program management were added to these costs, it appeared that $140 million would be required over a 5-year period. Estimates were made of research programs funded by DOE, DOD, NASA, NSF, and industry, and the estimated funding for the ceramic technology program was made; the figures are shown in Table 1.

TABLE 1 Funding for Ceramic Technology Program

Fiscal Year	Estimated Funding ($ Million)	Actual Appropriation ($ Million)
1983	2.7	2.42
1984	4.6	4.85
1985	6.3	5.67
1986	10.6	8.08
1987	14.9	12.5
1988	16.9	....
1989	10.5	....

The point was made by ORNL that actual appropriations have not kept pace with the estimated funding. The effect of this is to move the program from a 5-year completion period to an 8- to 10-year period. This is of course true if one insists on holding to the plan as originally scoped but there is no reason that this has to be done. The committee has recommended that the initial plan be re-examined and rescoped on an annual basis.

ORNL gave an excellent analysis of the intricacies of government funding of research. It was pointed out that in FY 1985 the value of the funded R&D projects was $9.2 million, but the actual funding was $5.7 million. This kind of discrepancy occurs because the actual budget is for 1 year at a time but ORNL must make multiyear commitments. An example quoted was the funding of a Sohio project on SiC powder, where funds were appropriated over a 4-year period. ORNL noted that a 2-year project may involve 4 years of financial transactions and a commitment of funds from 3 or 4 budget years. At any one time a significant amount of money is tied up in pending subcontracts, while at the same time there is a significant mortgaging of the following year's funds. ORNL cannot change funding levels of existing projects each time the budget goes up or down according to the actions of the various congressional committees.

Complete budget information was given to the committee. In ORNL's accounting, program management and technology transfer, which are all

TABLE 2 Distribution of Research Funds (Thousands of Dollars)

	FY 83		FY 84		FY 85		FY 86		FY 87	
Sector	**Amount**	**Percent**	**Amount**	**Percent**	**Amount**	**Percent**	**Amount**	**Percent**	**Amount**	**Percent**
Industry	1439	60	1622	33	1717	31	3529	43	580	61
University	193	8	585	12	703	12	958	12	1540	12
Government	783	32	2643	55	3252	57	3801	45	3382	27
Total	2415	100	4850	100	5672	100	8088	100	12502	100

government-funded activities, were separated out from the R&D activities. The committee folded these back into the government funding category, as shown in Table 2.

Figure 6 shows the distribution of funds among these three groups. These data show that only in FY 1983 and FY 1987 did the distribution of funds approach the 60-30-10 percent distribution that was one of the goals of the program. In view of the difficulties in balancing the funds received on an annual basis over several years, the distributions are understandable.

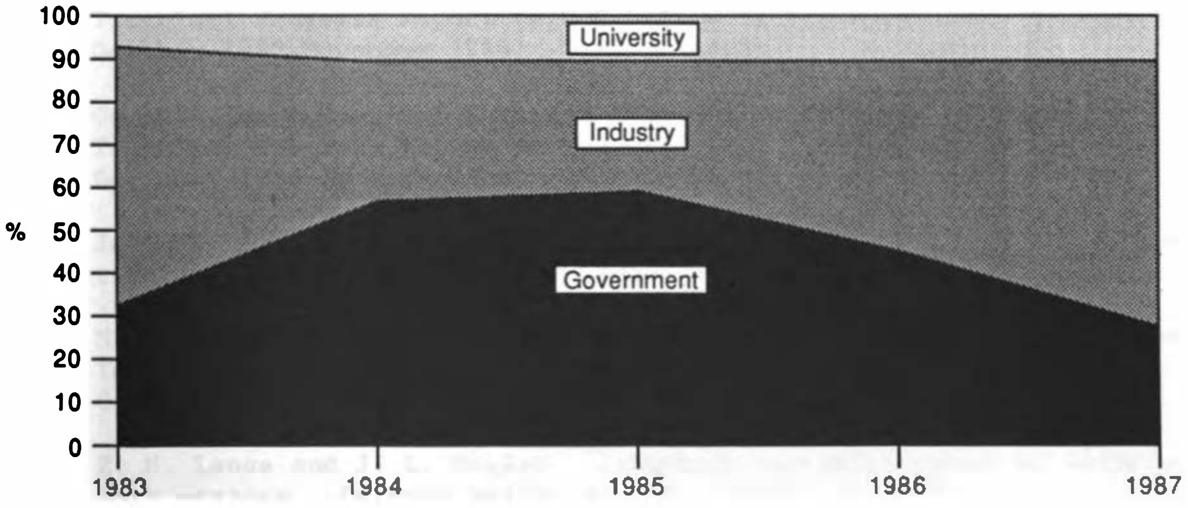

Figure 6. Percentage distribution of project funds.

For just the R&D component of the budget (total minus project management minus technology transfer), Table 3 was generated. From this it can be seen that the materials and processing component of the program has taken 65 percent of the funds; data base and life prediction took 29 percent, and design methodology 7 percent. It is difficult to determine what the optimal distribution of funds between these program elements should be, but the decreasing effort in design methodology appears to be too low, in view of the fact that design should be moving from short-time reliability into long-time reliability and the same methodology will not necessarily be applicable to both areas.

TABLE 3 R&D Budget (Thousands of Dollars)

	FY 83		FY 84		FY 85		FY 86		FY 87	
Program Element	Amount	Percent	Amount	Percent	Amount	Percent	Amount	Percent	Amount	Percent
Design methodology	199	9.3	591	15.3	415	9.4	376	5.6	300	2.7
Data base and life prediction	293	13.7	1215	31.4	1410	31.9	2009	30.1	3250	28.7
Materials and processing	1644	77.0	2061	53.3	2592	58.7	4287	64.3	7745	68.5
Total	2136		3867		4417		6672		11295	

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Appendix A

ORGANIZATIONAL AND MANAGEMENT INTERFACES FOR THE CERAMICS TECHNOLOGY FOR ADVANCED HEAT ENGINES PROJECT

In FY 1983 the Department of Energy Office of Transportation Systems (OTS), under the Deputy Secretary for Conservation and Renewable Energy, established the Advanced Materials Development Program (Figure A-1). The purpose of the program is to develop the industrial technology base in advanced ceramic materials in support of the advanced heat engine programs within the Office. OTS has assigned the technical project management responsibility to Oak Ridge National Laboratory (ORNL), with the DOE Oak Ridge Operations (ORO) office serving as the principal field office. OTS, among its other project responsibilities, establishes the program's goals, objectives, policies, schedules, budget, and financial constraints. ORO ensures that the activities are carried out in accordance with agreed-upon plans, schedules, and costs. Technical support and oversight is provided by ORNL as directed. Within ORNL the program is called the Ceramics Technology for Advanced Heat Engines Project, hereafter called the Ceramics Technology Project (Figure A-2).

ORNL functions as a matrix organization with the operating divisions conducting R&D and providing personnel for program offices, which may coordinate activities across several divisions. The Metals and Ceramics Division is the lead division and provides the ORNL Project Manager, personnel for in-house research, and contract monitors. The Ceramics Technology Project Manager reports to ORO through the Conservation Technology Program Manager. The organizational interfaces within ORNL are shown in Figure A-3.

Financial control is maintained directly by the Ceramics Technology Project Manager. Research and development activities are conducted either by subcontractors or performed in-house. ORNL contract monitors conceptualize tasks, write RFPs, review proposals, monitor progress, and report directly to the Project Manager. In-house activities are managed within ORNL's High-Temperature Materials Program. The manager of that program is responsible to the Ceramics Technology Project Manager for identification of relevant in-house projects. The level of in-house effort is negotiated with OTS.

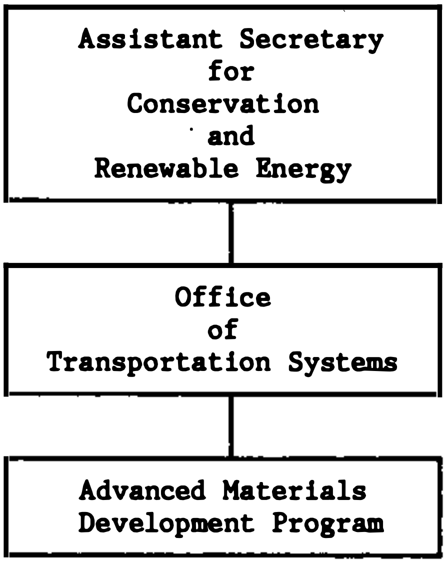

Figure A-1. Location of Advanced Materials Program within DOE.

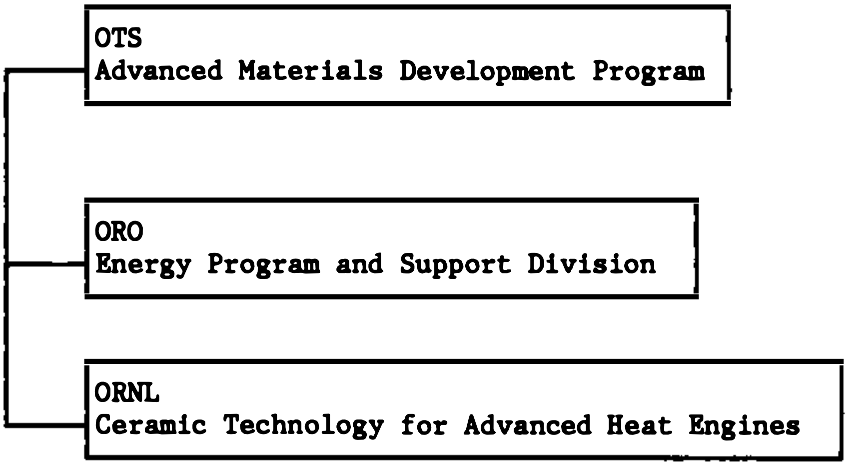

Figure A-2. DOE/ORO/ORNL program and technical interfaces.

For subcontracting matters, a Martin Marietta Energy Systems Subcontract Administrator (Martin Marietta operates ORNL for DOE) interfaces with a counterpart in the subcontractor's organization.

In addition to the interfaces described previously, ORO and ORNL technically interface with a number of other organizations where research and development of interest to the project is being performed. Explicitly, ORO and ORNL are to interact with the OTS engine programs, which are being technically managed by NASA, as well as NASA's own ceramic and advanced engine programs.

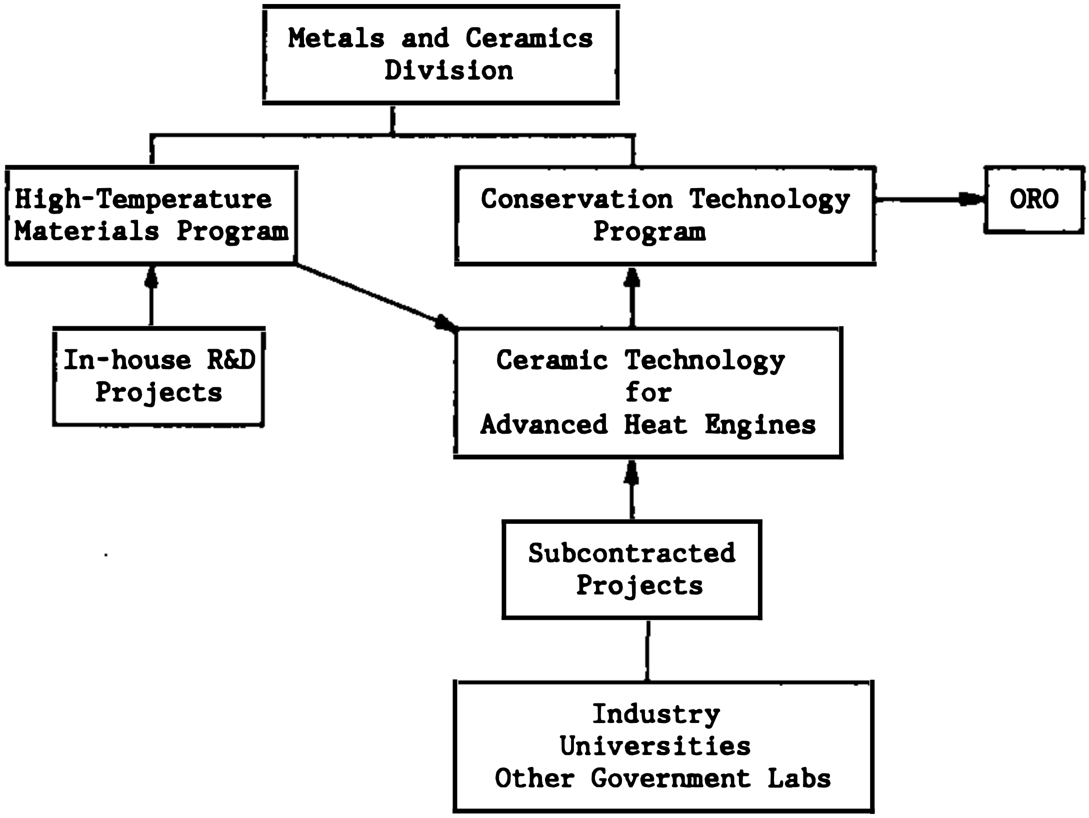

Figure A-3. Project interfaces within ORNL.

Appendix B

ITEMIZED BUDGET: FY 1983-FY 1987

CERAMIC TECHNOLOGY PROJECT

PROJECT MANAGEMENT

WBS	TITLE	FY-83	FY-84	FY-85	FY-86	FY-87
1	DOE SUPPT CONTRACTS (GOVT)	128	10	0	100	0
111	PROG MGT ORNL (GOVT)	25	370	385	450	550
112	RSC MR (TAX)	126	73	85	90	125
113	HTML PREOP MGT ORNL (GOVT)	0	0	160	0	0
200	AMTL MGT (GOVT)	0	50	0	0	0
TOTALS		279	503	630	640	675

CERAMIC TECHNOLOGY PROJECT

TECHNOLOGY TRANSFER

WBS	TITLE	FY-83	FY-84	FY-85	FY-86	FY-87
4112	TECH ASSES & PLAN ORNL (GOVT)	0	30	30	30	30
4113	ANM MIC SUPPT (GOVT)	0	60	120	50	50
4114	IEA AGREEMENT AMMRC (GOVT)	0	90	0	0	0
4115	SPECIMENS IEA ORNL (GOVT)	0	150	100	200	50
4116	STD PWD NBS (GOVT)	0	0	110	133	132
4117	TECH SUPPT CNTRCTS ORNL (GOVT)	0	100	250	250	250
4118	PROG DISPLAY ORNL (GOVT)	0	50	15	20	20
TOTALS		0	480	625	683	532

Source: Data supplied by Ceramic Technology Project Management.

CERAMIC TECHNOLOGY PROJECT

INDUSTRY R&D PROJECTS

WBS	TITLE	FY-83	FY-84	FY-85	FY-86	FY-87
1112	SIC POWDER SOHIO (IND)	150	100	110	106	0
1115	SIC WHISKERS (IND)	0	0	0	150	225
1122	SINTERING FURNACE GEO (IND)	0	80	80	70	70
1123	SI3N4 POWDER FORD (IND)	150	100	110	139	0
1131	POWDER SCALE UP (IND)	0	0	0	50	1660
1141	PROCESSING MONOLITHICS (IND)	340	156	0	0	1000
1221	WHISK TOUGH SI3N4 SC AIR (IND)	130	0	35	337	0
1222	TRANS TOUGH SI3N4 RYDNE (IND)	110	130	40	220	0
1223	WHISK TOUGH SI3N4 IM GTE (IND)	0	165	0	335	0
1224	COMPOSITE DEV (IND)	0	0	0	100	250
1225	ADV COMPOSITES (IND)	0	0	0	0	2000
1232	SYN PROC TT CERAM NORTON (IND)	120	75	100	366	0
1237	LAYERED COMP CERAMATEC (IND)	0	0	150	85	0
1241	SIC WHISK-MULLITE GEYFSC (IND)	120	0	130	180	0
1312	ADV COATING AGT (IND)	0	0	100	150	150
1313	CR203 COAT EVAL CUMMINS (IND)	120	100	0	0	0
1331	WEAR RESIST COATING (IND)	0	0	200	150	175
1341	COATING SCALE UP (IND)	0	0	0	0	0
1412	M-C JOINT AGT (IND)	0	0	105	200	200
1413	M-C JOINT DIESEL (IND)	0	0	100	100	150
1421	C-C JOINT AGT (IND)	0	0	100	200	150
2211	HI T COAT GTEC (IND)	77	111	146	11	0
2221	DYN INTERFACE BCL (IND)	122	125	110	189	150
2222	WEAR BEHAVIOR (IND)	0	0	0	0	0
2313	ADV STATISTICS GE LAB (IND)	0	200	101	116	100
3113	TRANSLUCENSE EFFECTS ITI (IND)	0	50	0	0	0
3221	EXP LIFE TEST FORD (IND)	0	230	0	0	0
3222	LIFE PREDICTION (IND)	0	0	0	75	600
3513	CHAR DEV (IND)	0	0	0	200	700
TOTALS		1439	1622	1717	3529	7580

Source: Data supplied by Ceramic Technology Project Management.

CERAMIC TECHNOLOGY PROJECT

UNIVERSITY R&D PROJECTS

WBS	TITLE	FY-83	FY-84	FY-85	FY-86	FY-87
1113	POWDER CHAR MIT (UNIV)	30	30	30	0	0
1132	POWDER SCALE UP (UNIV)	0	0	0	50	300
1234	TT AL2O3 MICH (UNIV)	0	70	160	160	160
1242	LOW EXP CERAMIC VPI (UNIV)	0	0	0	150	150
2212	COAT ADHER TEST UT (UNIV)	0	0	18	0	0
3223	LIFE PREDICTION (UNIV)	0	0	0	0	340
3312	STATIC FATIGUE U ILL (UNIV)	0	0	120	120	120
3314	ENV EFFECTS U DAYTON (UNIV)	102	125	125	163	150
3411	FRACT TOUGH U WASH (UNIV)	61	60	150	115	120
3412	HI TEMP TENSILE NCA&T (UNIV)	0	300	100	200	200
3516	NDE/CHAR (UNIV)	0	0	0	0	0
TOTALS		193	585	703	958	1540

Source: Data supplied by Ceramic Technology Project Management.

CERAMIC TECHNOLOGY PROJECT

GOVERNMENT LAB R&D PROJECTS

WBS	TITLE	FY-83	FY-84	FY-85	FY-86	FY-87
1	DOE SUPPT CONTRACTS (GOVT)	128	10	0	100	0
1111	SIC POWDER ORNL (GOVT)	60	60	0	0	0
1114	SIC WHISKERS LANL (GOVT)	0	60	0	0	0
1121	SINTERING SI3N4 AMTL (GOVT)	0	70	70	70	70
1211	DISP TOUGH SIC ORNL (GOVT)	70	70	77	0	0
1231	OXIDE MAT COMP ORNL (GOVT)	0	200	345	355	355
1233	SOL GEL OXIDE PWD ORNL (GOVT)	90	105	100	100	100
1235	INJ MOLD COMP ORNL (GOVT)	0	100	200	277	300
1311	CVD COATING ORNL (GOVT)	154	200	0	0	0
1411	M-C BRAZING ORNL (GOVT)	0	190	250	280	280
2311	DESIGN ALLOW CODE AMTL (GOVT)	0	130	0	0	0
2312	ADV STATISTICS ORNL (GOVT)	0	25	40	60	50
3111	FAILURE ANALYSIS NBS (GOVT)	0	0	100	0	0
3112	PHY PROPERTIES ORNL (GOVT)	0	0	0	120	60
3211	CHAR TT CERAM AMTL (GOVT)	0	70	80	100	100
3212	TIME-TEMP PROP AMTL (GOVT)	0	100	85	0	0
3213	FRACT BEHAVIOR ORNL (GOVT)	130	230	190	166	200
3214	CYL FATIGUE ORNL (GOVT)	0	0	90	280	280
3224	LIFE PRED METH ORNL (GOVT)	0	0	0	50	0
3413	STD TENSILE TEST NBS (GOVT)	0	0	90	90	100
3511	NDE DEV ORNL (GOVT)	0	0	70	150	150
3512	NDE ASSESMENT ORNL (GOVT)	0	0	80	50	0
3514	MATL CHAR AMTL (GOVT)	0	0	130	130	130
3515	C TOMOGRAPHY ANL (GOVT)	0	50	0	0	0
TOTALS		504	1660	1997	2278	2175

Source: Data supplied by Ceramic Technology Project Management.

Appendix C

INTERNATIONAL EXCHANGE AGREEMENT

International Energy Agency

ANNEX II

Co-operative Programme on Ceramics for Advanced Engines and Other Conservation Applications

The United States of America, the Federal Republic of Germany, and Sweden recently reached an agreement to cooperatively undertake a four-year research program in high-temperature structural ceramics. This will be the second effort under an International Energy Agency's *Implementing Agreement for a Programme of Research and Development on High Temperature Materials for Automotive Engines*, with Sweden joining the original two participants in this new initiative. The U.S. Department of Energy (DOE) is the operating agent for the Agreement, with program management provided by the Heat Engine Propulsion Division of the Office of Transportation Systems (OTS). The DOE Oak Ridge National Laboratory has overall technical program management responsibility for coordinating the activity in the United States. The responsible organization in the Federal Republic of Germany is the Kernforschungsanlage Jülich GmbH (KFA-PLR) and within Sweden is the Swedish National Board for Technical Development (STU).

The completed first effort under the Agreement (Annex I) emphasized ceramic component development for gas turbines. The new activity (Annex II) focuses on generic R&D in high-temperature structural ceramics for advanced engines and other conservation applications, with a major objective being the evolution of standardized mechanical testing and characterization methods for these new materials. Substantial participation by industry is a key part of the planned work, since the production and international marketing of reliable ceramic powders and sintered ceramic materials will require proven characterization methods, test procedures, and property standards for use by both manufacturers and users of these advanced materials. Industry and government laboratory researchers from each country have worked closely together to define the technical scope of work, and industry participants in each country are cost sharing their portion of the research.

Three major tasks are being conducted in Annex II to achieve the program objectives. The first task includes characterization of ceramic powders. Physical and chemical properties of five selected powders will be analyzed by participants in each of the three countries. The analyses will include particle size distribution, particle morphology, elemental content, crystalline/noncrystalline phases, and other physical properties. This task is oriented to the evolution of standardized ceramic powder characterization. The powders have been obtained from major suppliers: silicon nitride from GTE in the United States, silicon nitride and silicon carbide from H.C. Starck in Germany, silicon from KemaNord in Sweden, and zirconia from Toyo Soda in Japan. The U.S. National Bureau of Standards (NBS) is responsible for riffling, packaging, and distributing the powder samples to all of the international participants for characterization. The U.S. Army Materials Technology Laboratory is responsible for coordination of these characterization activities in the United States, and for statistical analyses of results from this task. The Technische Universität Berlin and The Swedish Institute for Silicate Research are responsible in Germany and Sweden, respectively, for coordinating the research in this task.

The second task includes characterization of dense ceramics in the form of flexure bar specimens. The flexure bars will be supplied by industrial participants from each country: silicon nitride from GTE in the United States, hot isostatically pressed silicon carbide from Elektroschmelzwerk Kempten in Germany, and hot isostatically pressed silicon nitride from ASEA-CERAMA AB in Sweden. Each country will perform nondestructive evaluation on its flexure bar specimens before they are provided to industrial and government laboratory participants for analyses. Analyses will include grain boundary phases and morphology, crystallinity/noncrystallinity of the major phases, grain size distribution, elemental content, density, and residual stress. This task is focused toward the development of standardized chemical and structural characterization techniques for structural ceramics. The GTE Laboratories Inc., Universität Karlsruhe (Institut für Zuverlässigkeit und Schadenskunde im Maschinenbau), and The Swedish Institute for Silicate Research are responsible in the United States, Germany, and Sweden, respectively, for coordinating the research in this task.

The third task initially includes measurement of the fracture strength in four-point flexure at room temperature of three structural ceramics, one from each country, with all investigators using the same specimen and fixture dimensions as well as stressing rate. The same ceramic materials studied in the second task are studied in this task in order to correlate the structural, chemical, and mechanical properties. The data will be analyzed to determine the Weibull parameters using both least-squares linear regression and maximum likelihood statistical methods. Computer software has been prepared for use by participants in all three nations for entering and analyzing the fracture strength data for the three structural ceramics. The flexure bars analyzed in this task are from the same production lots as used in the ceramic characterization task. In addition to flexure strength measurements and fracture statistics analyses, fractography will be performed on low, medium, and high strength specimens to determine the nature of the critical flaws which reduce the reliability of the ceramic materials. The DOE Oak Ridge National Laboratory is responsible for coordination of these activities and integration of the test data. The Universität Karlsruhe (Institut für Zuverlässigkeit und Schadenskunde im Maschinenbau), and ASEA-CERAMA AB are responsible in Germany and Sweden, respectively, for coordinating the research in this task.

The United States participants include A.C. Spark Plug Division of the General Motors Corp., Alcoa, Allison Gas Turbine Operations of General Motors, Corning Glass Works, Elkem Metals Co., Ford Motor Co., Garrett Turbine Engine Co., GTE Laboratories, Inc., NASA Lewis Research Center, National Bureau of Standards, Norton Co., Oak Ridge National Laboratory, Standard Oil Engineered Materials Co., and the U.S. Army Materials Technology Laboratory

The German participants include Bayer AG, Robert Bosch GmbH, Cremer Forschungsinstitut, Daimler-Benz AG, Degussa AG, Dynamit Nobel, Elektroschmelzwerk Kempten GmbH, Feldmühle AG, Fraunhofer-Institut für Werkstoffmechanik, Fraunhofer-Institut für zerstörungsfreie Prüfverfahren, H.C. Starck Berlin, Hoeschst CeramTec AG, Hutschenreuther, ISD-Ingenieurkeramik GmbH, KFA-Jülich GmbH, Lonza Werke GmbH, M.A.N. Technologie GmbH, Sigri Elektrographit GmbH, Technische Universität Berlin, Universität Karlsruhe (Institut für Zuverlässigkeit und Schadenskunde im Maschinenbau), and Universität Karlsruhe (Institut für Werkstoffkunde II).

Swedish participants include Sandvik Hard Materials AB, ASEA-CERAMA AB, KemaNord Industrikemi AB, The Swedish Institute for Silicate Research, and United Turbine AB.

Source: International Energy Agency.

Appendix D

CERAMICS FOR RECIPROCATING INTERNAL COMBUSTION ENGINES

C. D. Wood

The case for the use of ceramics in reciprocating engines rests on three characteristics: high-temperature resistance, low thermal conductivity, and corrosion resistance.

The low thermal conductivity of some ceramics leads to the concept of an "adiabatic" engine, or more properly, an engine with a low rate of heat rejection. A reduced rate of heat rejection leads inevitably to high material temperatures, which further reinforces the consideration of ceramics for this concept. The main benefit of this concept is the elimination (or reduction in size) of the engine cooling system. Direct gains in thermal efficiency are small. Indirect gains in power and thermal efficiency may be realized for heavy-duty engines by adding machinery to the engine machinery that can extract heat energy from the exhaust gases, since exhaust gas temperatures are higher in low-heat-rejection engines. The cost-effectiveness of this strategy has not been clearly shown to be superior to other, more conventional, strategies.

However, low-heat-rejection engines face a difficulty that is independent of the properties of the engine materials. Known lubricating oils to provide the lubricating film between piston and cylinder have upper temperature limitations far below the projected temperatures of the pistons and cylinders in low-heat-rejection engines. The limiting factor for the design of such engines is therefore the lubricant rather than the ceramic material.

Ceramic materials have better potential for reciprocating engines in applications where high-temperature lubrication is not required. These applications take advantage of the high-temperature resistance of ceramics (e.g., engine valves, precombustion chambers, glow plugs), the lower density of ceramics (e.g., turbocharger turbine rotors, valve gear) or the corrosion resistance of ceramics (e.g., piston crowns and exhaust valves in engines burning heavy fuel oil). In general, larger engines have a better benefit potential than smaller ones because of their more stringent operating conditions.

For ceramics to be widely used in reciprocating engines, the most important requirement is that the ceramic material have properties that are predictable, particularly with respect to fatigue life.

COOLING

Since the use of ceramics in the reciprocating engine is often associated with insulating the engine combustion chamber, it is worthwhile to briefly consider the engine cooling process. Current engines are cooled by circulating a fluid, either air or a water-based liquid, around the engine cylinder and cylinder head. In addition, lubricating oil cools the underside of the piston crown. The heat in the cooling media is eventually transferred to the ambient air by means of heat exchangers. The cooling system is designed so that the cylinder wall, to which the lubricating oil film is attached, does not exceed a temperature of about 250°F. Most engine components are currently made from conventional materials such as cast iron or aluminum, except for high-temperature components (e.g., valves, precombustion chambers), which are made from high-temperature alloy steels.

If the engine cooling is disrupted, the engine quickly fails because of the loss of the lubricating film between the cylinder and the piston rings. The loss of this film is caused by lubricant evaporation and reduced viscosity. The failure is characterized by metal-to-metal contact between rings and cylinder, scuffing of these surfaces, and finally engine seizure.

Cooling is therefore required in conventional engines primarily to preserve the lubricating oil film between cylinder and piston ring. If this problem could be eliminated, engines would be routinely designed without cooling systems, because they are bulky, heavy, require power to drive fans and pumps, and are always a source of maintenance problems. The primary barrier to the removal of the cooling system is the lubricating oil film problem. Without a solution to the lubricating oil film problem, it is unlikely that cooling systems will be totally eliminated; furthermore, the development of suitable ceramic materials does not solve this problem.

Another incentive for designing an "adiabatic" engine that has been projected is an increase in engine efficiency. However, unlike the Brayton-cycle gas turbine engine, the efficiency of the reciprocating Otto-cycle engine does not increase with increasing temperature of the working fluid. Blocking the heat flux to the coolant by using insulative engine materials raises the temperature of the gases in the combustion chamber but has little effect on the thermal efficiency. However, the temperature of the exhaust gas is raised by this measure, and this increases the availability of the hot exhaust gases. To produce a thermal efficiency increase in the engine system as a whole, energy can be extracted from the higher temperature exhaust gases by an exhaust turbine or a Rankine "bottoming cycle." This strategy is most effective when the engine is running at high loads. At low engine loads, the strategy may be relatively ineffective, or may even result in a net power loss, because of the unavoidable inefficiencies of the exhaust gas turbine or Rankine cycle.

Another consequence of operating an engine at high temperatures is that the fuel-air ignition process is altered. In a spark-ignition engine where the fuel-air mixture is introduced on the intake stroke, the mixture is heated by the hot combustion chamber walls and may prematurely ignite on the compression stroke, or the last part of the mixture to burn after a normal start of combustion by the spark plug may detonate, causing engine "knock." Both of these phenomena must be avoided because they always produce noisy combustion and frequently catastrophic engine failure. Thus, spark-ignition engines using homogeneous fuel-air mixtures do not appear to be promising candidates for removal of the cooling system. On the other hand, combustion processes using nonhomogeneous fuel-air mixtures, where the fuel is injected into the combustion chamber late during the compression stroke, may benefit from an increase in gas temperature. In such engines ignition is spontaneous because of the heating of the fuel-air mixture by compression, and an increase in temperature reduces the ignition delay time and allows the use of fuel that is more difficult to ignite spontaneously—i.e., fuel having a lower cetane number. For these reasons, attention has been focused on diesel engines for investigation of the effects of removal of the cooling system.

It should be noted, however, that the increase of combustion chamber wall temperature is not the only and perhaps not even the best way to increase the fuel tolerance of diesel engines, as there are a number of other methods that have been developed to do this.

LARGE VERSUS SMALL ENGINES

Reciprocating diesel engines are used for a very wide range of applications, and consequently there are a similar wide range of engine designs. Application type and engine design features vary generally as the bore size of the engine.

Engine bore diameter varies from about 2 inches to 40 inches. Engines with larger bore diameters are used in applications that require a long life and a high load factor (load factor is the average percent of maximum load experienced by the engine). These engines have a relatively high cost per horsepower because of the lower production volumes and the greater weight of metal per horsepower. The fuel consumption of these engines is important to the user because of the large quantity of fuel consumed and the high percentage of operating costs this fuel represents. Larger engines are able to burn low-quality fuels because engine speeds are low, thus giving more time for combustion to be completed, and because it is economically feasible to include fuel treatment devices in the engine system. As a result, these engines are subjected to increased wear and corrosion, because the low-quality fuels contain relatively large quantities of sulfur, vanadium, ash, water, and other undesirable materials. The designers of large engines are concerned very much with thermal stresses, which increase with an increase in engine dimensions. On the other hand, inertial stresses are less.

In contrast, smaller engines tend to be designed for lower load factors and for higher quality fuel. Inertial stresses are of more concern than thermal stresses. Engines are produced in larger quantities, and therefore the cost per horsepower is less. Attaining a high efficiency is somewhat less important than in the larger engines.

ENGINE FAILURES

Structural failures in engines are almost always due to fatigue. Two types of fatigue stresses are recognized. One source is the increase and decrease of cylinder pressure each cycle. The engine is also subjected to "low-cycle fatigue stresses." One such cycle occurs each time the engine is started from a cold condition, warmed up, then shut down.

All engines eventually fail because of wear-out. Wear is particularly critical at the interface between piston ring and cylinder and at exhaust valve seats and valve inserts. Wear is a progressive type of failure. Piston ring wear leads to gas leakage past the ring from the combustion chamber to the oil sump. This leakage burns and scours away the lubricant film between ring and liner and thereby accelerates the wear rate. In addition, the combustion gases cause degradation of the oil in the oil sump, which detrimentally affects the lubrication of the piston rings and cylinder as well as other bearing surfaces in the engine. Fuel that contains sulfur, vanadium, ash, and water causes both corrosive and abrasive wear. Therefore, a viable approach to ceramics applications in reciprocating engines takes advantage of both the high-temperature and corrosion-resistant characteristics of ceramic materials. These applications are turbocharger turbine rotors, valves, precombustion chambers, glow plugs, and piston crowns; they all have the common feature that their success does not depend on maintaining a high-temperature lubricant film and thus does not depend on the development of new lubricants.

The primary requirement for engine materials is predictability. This is obviously true both for materials used in production engines and for developmental work and prototype engine design. Engine structural failures often are catastrophic and result in significant program delays and cost increases. Ambitious prototype developments should not be undertaken without assurance that the properties of available materials can be measured and predicted. It is probably more important to develop repeatable material process procedures and material properties data than it is to refine and improve material properties by changes in material composition. Without the former, the latter will have poor acceptance as a candidate material.

Note that cast iron is a material widely used in reciprocating engines for blocks, cylinder heads, crankshafts, and other engine components. In some respects, cast iron has relatively poor structural properties, but these are counterbalanced by good casting properties and good machinability. Consequently, engine designs have been tailored to minimize the effects of the poor qualities of cast iron while taking advantage of the good qualities. This is possible because the material properties of cast iron are highly predictable. A similar case needs to be made for the use of ceramic materials.

CONCLUSION

Applications that do not require the development of new lubricants have the best possibility for near-term success. The use of ceramics in applications requiring high-temperature lubricant films is less likely to achieve commercial utilization. The controlling factor in the latter application is not the ceramic materials properties but the development of new methods for lubrication or new lubricants. Emphasis should therefore be placed on the development of ceramics for corrosion-resistant and temperature-resistant applications.

While all diesel engines could conceivably benefit both economically and from a performance viewpoint from the application of ceramics, large engines would seem to have the strongest need for these materials. This is because large engines currently experience corrosion problems due to low-grade fuels, cooling and thermal stresses are major design considerations, internal stresses are lower than in small engines, engine life is a more critical economic factor, and the engines operate at a higher load factor.

Appendix E

MATERIALS REQUIREMENTS FOR TURBINE ENGINE PROGRAMS

T. Vasilos

A gas turbine is a form of heat engine for producing work with the aid of heated gases. It is an attempt to achieve the advantages of internal combustion engines without the complications associated with reciprocating motion. Its principle of operation is to direct a continuous stream of hot gases against the blading of a turbine rotor. In current engines, air is first compressed in a compressor before being directed into combustion chambers. In these, fuel is mixed with a portion of the air and burned. The emerging gases are directed through nozzles and against the blading of the turbine rotor, furnishing power to drive the compressor with enough left over for purposes of propulsion or other uses. The result is a smooth-running machine incorporating the advantages of internal combustion without the disadvantages of reciprocating pistons.

The progress of the gas turbine engine has been closely related to the development of materials capable of withstanding the engine's environment at high operating temperature. Since the early days of the engine, new metal alloys have been developed that have allowed a gradual increase in operating temperatures. Today's nickel-chromium superalloys are in use without cooling at turbine inlet gas temperature of 1800 to 1900°F. With air cooling, large turbine engines (thousands of horsepower) can operate with combustion temperatures of 2800°F; however, small turbine engines (less than 1000 horsepower) suitable for ground vehicle propulsion, etc., cannot be efficiently cooled, and the incentive is to further increase turbine inlet temperature—e.g., to 2500°F—to improve specific air and fuel consumptions. The use of ceramics in such gas turbine engines may well be necessary for increasing turbine inlet temperature. Advantages over reciprocating engines would include smooth, vibrationless operation, flat torque versus speed characteristics, light weight, small space requirements, lack of need for a cooling system, and the possibility of burning cheaper fuel than gasoline.

A simplified schematic of the flow path of a regenerative-type vehicular gas turbine engine (after Ford Motor Company) is shown in Figure E-1. Air is introduced through an intake silencer and a filter into a radial compressor and then is compressed and ducted through one side of each of two rotary regenerators. The hot compressed air is then supplied to a combustion chamber where fuel is added and combustion takes place. The hot gas discharging from the combustor is then directed into the turbine stage by a turbine inlet structure, in this case shown as a nose cone. The gas then passes through the turbine stages, which comprise two turbine stators, each having stationary airfoil blades that direct the gas onto each corresponding turbine rotor. In passing through the turbine, the gas expands and generates work to drive the compressor and supply useful power. The expanded turbine exhaust gas is then ducted through the hot side of each of the two regenerators, which, to conserve fuel, transfers much of the exhaust heat back into the compressed air.

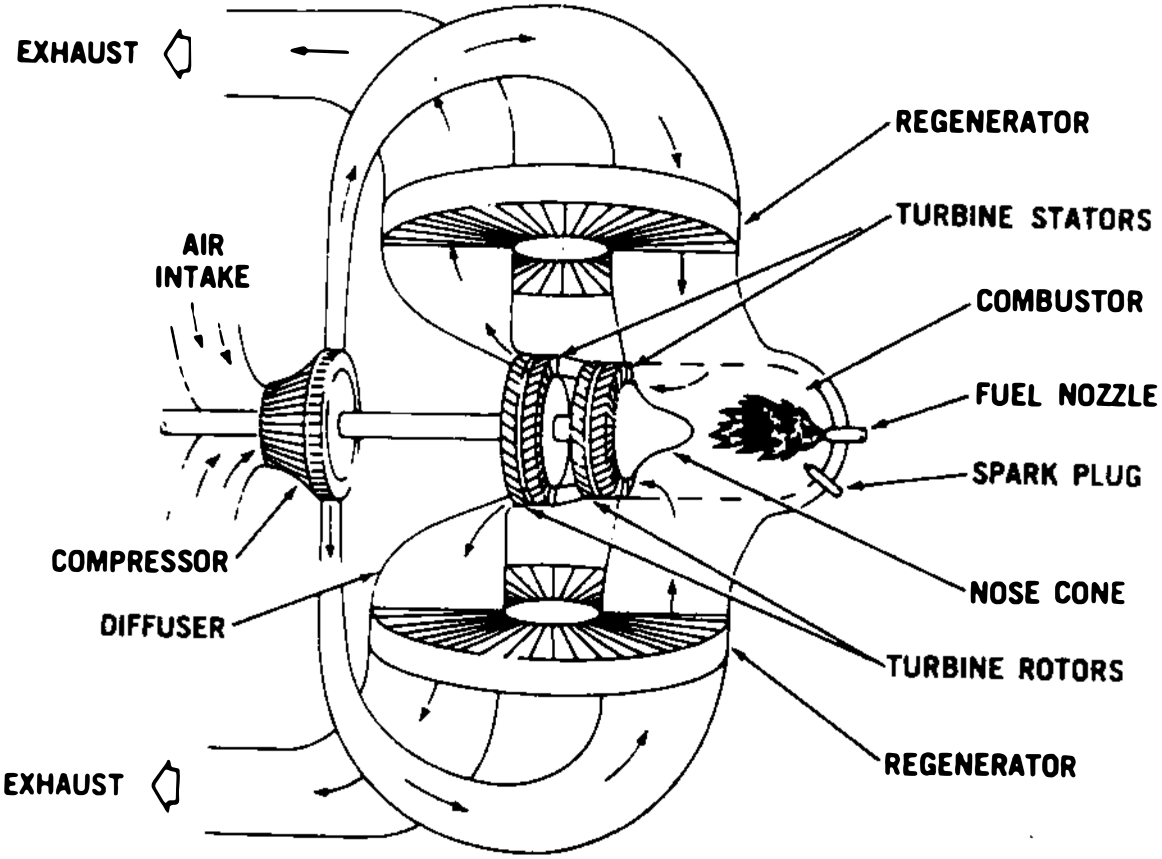

Figure E-1. Regeneration-type vehicular gas turbine engine.

The parts that are subject to the peak cycle temperature are the combustor, the turbine inlet nose cone, the turbine stators, and the turbine rotors. These are areas where ceramics could be exploited and have the greatest impact on improving engine efficiency.

The goal for future uncooled small turbine engines employing ceramics in the hot flow paths is to achieve improvements in specific fuel consumption of 20 percent or more. The engine should exhibit reliability and life comparable to existing powertrains and ultimately be competitive in initial and life-cycle costs.

MATERIAL REQUIREMENTS

To achieve significant levels of improvement in specific fuel consumption, it is anticipated that materials in the hot flow paths will have to perform satisfactorily at temperatures up to 2500°F in a complex thermomechanical environment, superimposed with corrosive gas chemistry and perhaps erosive particulates. Further, the selected materials will have to be cost-effective for such engine applications.

FABRICATION

The fabrication of near-net-shape turbine engine components will be a requirement to achieve cost-effectiveness. This means that the material fabricator will have to furnish materials with specific properties, in complex shapes, on a reproducible basis, with minimal post-grinding processing.

MATERIALS DURABILITY

A 2500°F material capability is required to achieve the small turbine engine performance goals. This must first be demonstrated reproducibly on a technology basis prior to being scaled into component hardware.

Turbine engine hot flow path components endure demanding service conditions. Static components such as combustors or nozzles must survive, on a long-term basis, a severe thermal cycle fatigue environment coupled with a corrosive gas chemistry. Changing surface chemistry and structure on long-term exposure and its impact on component thermal stress resistance need to be addressed.

Turbine engine rotors in particular have the most severe duty cycle. Stress rupture and creep are superimposed on thermal stress in this case. Mechanical stress levels may exceed 100,000 psi in the hub region at operating temperature. The requirement for high strength and durability over an extended time period on as complex a shape as a rotor component is difficult to achieve.

Some level of fracture toughness may also be required as a material property to delay or avoid catastrophic component failure.

SEALS AND INTERFACES

The static seal leakage problem must be solved before ceramic gas turbine engines can realize their anticipated performance efficiencies. The interface wear problem of materials in moving contact at high temperatures needs consideration and solution.

PROOF TESTING AND NDE

Satisfactory techniques for inspecting and qualifying material in component form must be developed so that acceptance criteria can be established that are simpler than actual engine testing. It must be realized, however, that, during engine development, testing of full-size components is absolutely necessary.

Appendix F

QUESTIONS TO ENGINE AND CERAMIC COMPANIES

To assist the committee on its visits to the various contractors, a list of questions was forwarded prior to the visit to give the contractors an opportunity to focus their presentation to the committee. The questions to the engine contractors were different in some degree from those sent to ceramic companies. Both sets of questions are given here.

ENGINE MANUFACTURERS

1. What were the critical problem areas when the AGT and diesel programs were initiated?
2. What are the critical problem areas now after several years of effort?
3. Are the problems in design? materials? processing? fabrication? testing?
4. What is the extent and value of transfer from the ceramic technology program to the engine program?
5. To what extent is the engine program locked into existing technology?
6. What is your prognosis of the future market for structural ceramics in advanced heat engines?
7. To what extent is there a fruitful exchange of information between the various government and industrial groups funding or carrying out work in structural ceramics?
8. What are the deficiencies in existing programs on structural ceramics and how should they be addressed and corrected?

CERAMIC MANUFACTURERS

1. What were the critical problems associated with supplying components and developing the ceramic technology when you began participating in the AGT program?

2. What are the critical problems now?

3. Specifically, what still needs to be done in

    Materials properties?
    Controlling and improving microstructures?
    Forming complex shapes?
    Both in-process and final NDE?
    Production capacity?

4. To what extent and value has the ceramic technology program helped to develop or transfer technology in these areas? To what extent does this program contribute in other areas of interest to your company?

5. Do you perceive a lag in U.S. progress in these areas relative to foreign competitors and, if so, what can DOE do to help close that gap?

6. Is there fruitful exchange of information and coordination between the various government, industrial, and university sectors?

7. What are the deficiencies in the existing program and how should they be addressed?

8. What is your prognosis of the future market for structural ceramics in advanced heat engines?

Appendix G

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

MAURICE J. SINNOTT received B.S., M.S., and Sc.D. degrees in metallurgical engineering from the University of Michigan. He worked as a plant metallurgist at Great Lakes Steel Corporation and as a development engineer at Goodyear Aircraft Corporation before joining the University of Michigan faculty, where he is professor of chemical and metallurgical engineering and associate dean of engineering. He is a member of the American Society of Metals, the American Institute of Mining, Metallurgical and Petroleum Engineers, and the British Institute of Metals. His research interests are in metal physics, grain boundary phenomena, x-ray analysis, and nucleation and growth.

LUTGARD C. DEJONGHE received his undergraduate education at the Higher Technical Institute in Antwerp, Belgium, his M.A.S. degree in metallurgy from the University of Delaware, and a Ph.D. degree in materials science from the University of California, Berkeley. He worked as a research fellow at Harvard University and as an assistant professor of the Materials Science and Engineering Department at Cornell University. Currently he is a staff senior scientist in the Materials and Chemical Sciences Division of Lawrence Berkeley Laboratory and a professor-in-residence at the Materials Science and Mineral Engineering Department of the University of California, Berkeley. He is a fellow of the American Ceramic Society and a member of the National Institute of Ceramic Engineers. He received the Electrochemical Society's Richard M. Fulrath Award in 1985. His research interests include ceramic fabrication science and advanced electrochemical storage systems.

ROBERT J. EAGAN received M.S. and Ph.D. degrees from the University of Illinois in ceramic engineering. He is currently manager of the Chemistry and Ceramics Department of the Sandia National Laboratories. He is a fellow of the American Ceramic Society and a member of the National Institute of Ceramic Engineers. His research interests are in development and characterization of new glass and glass ceramic materials and glass ceramic-to-metal seal technology.

KATHERINE T. FABER received her M.S. degree in ceramic science from Pennsylvania State University and a Ph.D. in materials science from the University of California, Berkeley. Her professional experience includes work with the Inorganic Materials Division, Lawrence Livermore Laboratory; Alpha Silicon Carbide Division of the Carborundum Company; and associate professor of ceramic engineering at Ohio State University. She is a member of the American Ceramic Society, Ceramic Educational Council of the American Ceramic Society, Keramos, Sigma Xi, and the Society of Women Engineers. She is a recipient of the Presidential Young Investigator Award and the IBM Faculty Development Award.

WILLIAM R. MARTIN received a B.S. degree from the University of Cincinnati in metallurgical engineering. His professional experience includes work as a metallurgist with Oak Ridge National Laboratories and in materials processing with Union Carbide's Nuclear Division. He is currently manager of Cabot Electronic Ceramics, Inc. He is a Fellow of the American Society of Metals and a member of Sigma Xi and the American Society for Testing and Materials and a recipient of ASM's Application Engineering Award. His research interests are materials processing, powder metallurgy, mechanical properties, and electronic ceramics.

MAURICE E. SHANK received his Sc.D. degree in mechanical engineering at Carnegie-Mellon University and his Sc.D. degree in metallurgy at Massachusetts Institute of Technology, where he also served as associate professor of mechanical engineering. He is currently vice president of Pratt & Whitney of China, Inc. Until 1985 he was director of Engineering-Technical, at Pratt & Whitney Engineering Division, United Technologies. In that position, he was responsible for advancing state-of-the-art technology and component development for aerodynamic components, materials, structural analysis, fuel systems and controls, and advanced engine programs. He is a member of the National Academy of Engineering, a fellow of the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, the Metallurgical Society of AIME, and the American Society for Metals, and a member of the Society of Automotive Engineers.

RICHARD E. TRESSLER received a B.S. degree in ceramic technology from Pennsylvania State University, his M.S. degree in ceramics from Massachusetts Institute of Technology, and a Ph.D. in ceramic science from Pennsylvania State University. His professional experience includes materials research at Tem-Pres Research, Inc., the Air Force Materials Laboratory, and the University of Essex, England. He is currently director of the Center for Advanced Materials, Pennsylvania State University. He is a member of the American Ceramic Society, Metallurgical Society of AIME, Electrochemical Society, Sigma Xi, and Keramos. His research interests include fabrication and mechanical behavior of structural ceramic and composite materials, fracture and strengthening mechanisms, and integrated circuit processing and properties.

DONALD R. UHLMANN received a B.S. degree from Yale University in physics and a Ph.D. degree from Harvard University in applied physics. He was Cabot Professor of Materials at Massachusetts Institute of Technology before joining the University of Arizona's Department of Materials Science and Engineering, where he is department head. He is a fellow of the American Ceramic Society and the British Society of Glass Technology and a member of the American Physical Society, American Institute of Mining, Metallurgy, and Petroleum Engineers, Society of Photo-Optical Instrumentation Engineers, and Ceramic Education Council. His research interests include the structure and properties of glasses, ceramic matrix composites, the structure and properties of polymers, and electro-optic materials.

THOMAS VASILOS earned his B.S. degree at Brooklyn College and his D.Sc. degree in ceramics at Massachusetts Institute of Technology. He was associated with Ford Motor Company and Corning Glass Works before joining Avco Systems-Textron, where he is principal scientist. He is active in the American Ceramic Society and has served on earlier National Materials Advisory Board committees. His research interests include the thermal and mechanical properties of ceramics, crystal growing, ferroelectric ceramics and crystals, ceramic coatings, plastic-ceramic composites, and composite formulation and properties.

JOHN B. WACHTMAN received his B.S. and M.S. degrees from Carnegie Institute of Technology and a Ph.D. degree from the University of Maryland, all in physics. He joined the National Bureau of Standards, where he became the director of the Center of Materials Science. In 1983 he was appointed director of the Center for Ceramic Research at Rutgers University. He is a member of the National Academy of Engineering. His professional affiliations include the American Ceramic Society (past president), National Institute of Ceramic Engineers, Federation of Materials Societies (past president), and American Society for Testing and Materials. His research interests include mechanical properties of materials and effective utilization of inorganic materials.

DAVID WIRTH received B.S., M.S., and Ph.D. degrees from the University of Illinois. His professional experience includes work at Los Alamos Scientific Laboratory and inorganic materials research and development at W. R. Grace Company. He is currently vice president of technical operation, Coors Porcelain Company, Inc. His research interests are materials engineering and corporate administration.

CHARLES D. WOOD received a B.S. degree from Rice University and M.S. degree from Southern Methodist University in mechanical engineering. He worked at Ling-Temco-Vought, Inc., before joining Southwest Research Institute, where he is vice president, Engine and Vehicle Research Division. He is a member of the Society of Automotive Engineers. His research interests are engine design and development; development of off-highway equipment; fuel-air explosive devices for earth moving, rock ripping, hard-facing deposition, and ship propulsion; undersea seismic shock generation, dredging, and pumping; minefield clearance; and marine icebreaking.

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14.

15. Supplementary Notes

16. Abstracts The goal of the Department of Energy-Oak Ridge National Laboratory program on ceramic technology for advanced heat engines is "to apply the increasing base of fundamental knowledge and research tools to develop new and improved processes for cost-effective ceramic materials with improved reliability and performance characteristics." A committee appointed to review the program assessed the objectives, balance, and priorities. Emerging opportunities were identified, an international exchange agreement was examined, and the mechanisms of technology transfer were investigated. Coordination efforts were studied, and the technical planning for the program was critiqued. The committee believes that many but not all of the most important components of the basic ceramic technology relating to improved performance and reliability are being addressed. Although the committee did not examine individual projects in detail, it feels that the general quality of the technical work is good. The committee is less certain that progress is being made in bringing these components together into a technically successful process for producing final ceramic products with significantly improved reliability and performance. Also, the committee finds little evidence that substantial progress toward cost-effective processing is being made. Indeed, there appears to be no organized attempt to do cost analysis.

17. Key Words and Document Analysis. 17a. Descriptors

Advanced heat engines
Ceramic composites
Ceramic reliability
Ceramic research
Ceramic technology
Monolithic ceramics

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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