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Advanced Materials Development Program
Ceramic Technology for Advanced Heat Engines
Program Plan

1983 - 1993

Office of Transportation Materials
Office of Transportation Technologies
Conservation and Renewable Energy
U.S. Department of Energy

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CONTENTS

1.0	SUMMARY AND INTRODUCTION.....	1
1.1	HISTORY OF CERAMIC COMPONENT DEVELOPMENT.....	1
2.0	SUMMARY OF INITIAL PROGRAM PLAN.....	2
2.1	INDUSTRY PARTICIPATION.....	2
2.2	ORGANIZATION.....	2
2.3	INDUSTRY-NEEDS ASSESSMENT.....	4
2.4	COORDINATION WITH OTHER STRUCTURAL CERAMICS PROGRAMS..	4
2.5	PROJECT SCOPE.....	4
2.6	HIGH TEMPERATURE MATERIALS LABORATORY.....	5
3.0	BACKGROUND.....	6
3.1	AUTOMOTIVE PROPULSION OVERVIEW.....	6
3.2	MATERIALS TECHNOLOGY OVERVIEW.....	6
3.3	ECONOMIC AND ENERGY-SAVINGS PAYOFF.....	8
3.4	INDUSTRY NEEDS ASSESSMENT.....	8
3.4.1	Site Visits.....	8
3.4.2	Workshops.....	9
3.4.3	Topical Assessment Documents.....	12
3.4.4	Major Assessments.....	13
3.5	FOREIGN COMPETITION.....	16
3.5.1	Japanese Programs.....	16
3.5.2	West German Programs.....	17
3.5.3	Other European Countries.....	18
3.6	THE FEDERAL ROLE.....	19
3.6.1	National Materials Policy.....	19
3.6.2	Industry Perspective.....	20
4.0	TECHNICAL PLAN.....	22
4.1	IMPLEMENTATION STRATEGY.....	22
4.2	TECHNICAL APPROACH.....	22
4.3	RECOMMENDATIONS FOR FUTURE WORK.....	34
4.3.1	Cost Effective Ceramics for Near-Term Applications in Heat Engines.....	34
4.3.2	Materials for Alternate Fuel Engines.....	35
5.0	MANAGEMENT PLAN.....	35
5.1	MANAGEMENT PLAN DOCUMENT.....	35
5.2	PROGRAM ADVISORY AND CONSULTATIVE GROUPS.....	37
6.0	RESOURCE PLAN.....	39
7.0	PROCUREMENT PLAN.....	43
7.1	PROCUREMENT PROCEDURES.....	43
7.2	ASSIGNMENT OF PATENT RIGHTS.....	45
8.0	REFERENCES.....	46

1. SUMMARY AND INTRODUCTION

The original plan for the Ceramic Technology for Advanced Heat Engines Project (CTAHE) of the Advanced Materials Development Program (ref. 1) was developed jointly by industry, academia, and the U.S. Government, represented by the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DoD). The plan was developed in several stages following an assessment which determined the critical technology base needs, the potential economic value of structural ceramics, the extent of ongoing and planned R&D programs, and the estimated funding required. The plan was prepared by Oak Ridge National Laboratory (ORNL) for the DOE Office of Vehicle and Engine R&D, now the Office of Transportation Systems (OTS) in Conservation and Renewable Energy. The program goal is to develop an industrial technology base capable of providing reliable and cost-effective structural ceramics for application in advanced heat engines.

Significant technical advances have been made since the program was initiated in 1983. In addition, the High Temperature Materials Laboratory (HTML) which serves as a focal point for high temperature ceramics research in the program was completed in 1987. The HTML is officially designated as a Department of Energy User Facility to provide the industrial research community access to special research equipment for determination of structure-property relationships for materials.

This document is essentially an update of the 1983 plan and describes progress to date as well as industry technology needs which remain to be developed, and a multiyear technical and resource plan for the years 1989 through the estimated completion of development in 1993.

1.1 HISTORY OF CERAMIC COMPONENT DEVELOPMENT

Ceramics have been actively investigated as materials for advanced heat engines since about 1970. The interest in ceramics for automotive engines has resulted from concern over exhaust emissions, a need for higher performance and more reliable engines, and a concern for higher fuel efficiency, greater fuel tolerance, and

adaptability to alternate fuels to reduce petroleum imports.

The transportation sector's almost total dependence on petroleum contributes heavily to the resulting U.S. need for imported oil. This in turn creates a major adverse impact on the nation's economy through a negative balance of payments and results in an already demonstrated vulnerability to petroleum supply disruptions.

The energy-saving potential of ceramics in automotive propulsion systems is based, first, on higher operating temperatures and, second, on reduced friction, weight, and inertia stemming from the mechanical and physical properties of ceramics.

A schematic diagram showing the early history of ceramic engine programs in the United States, West Germany, and Japan is shown in Fig. 1. Harmon and Beardsley (ref. 2) reviewed the history of these engine programs, which began with the DoD Advanced Research Projects Agency (ARPA)-Ford-Westinghouse Gas Turbine Program, and continues today with active Department of Energy and Department of Defense programs.

Although these engine and component development and testing programs include component fabrication development activities by ceramic manufacturing companies, there is no focus on basic materials research and development activities. In order to address this critical issue, the Department of Energy initiated the Ceramic Technology for Advanced Heat Engines Project in FY 1983 to provide the necessary parallel base technology materials program.

Fig. 1. Selected highlights and related events in ceramic materials development. Source: R. A. Harmon and C. W. Beardsley, "Ceramics Heat Up," Mechanical Engineering, pp. 22-43 (May 1984). AGT = Advanced Gas Turbine; ARPA = Advanced Research Projects Agency; CAPE = Corporate Average Fuel Economy; CATE = Ceramic Applications in Turbine Engines; DDA = Detroit Diesel Allison Division of General Motors; DFVLR = German Aerospace Research Establishment; ERDA = Energy Research and Development Administration; NPT = Noel Penny Turbine Limited; OPEC = Organization of Petroleum Exporting Countries; TACOM = Army Tank Automotive Command.

2. SUMMARY OF INITIAL PROGRAM PLAN

The purpose of the Ceramic Technology for Advanced Heat Engines (CTAHE) Project is the development of an industrial technology base capable of providing reliable and cost-effective high temperature ceramic components for application in advanced heat engines. There is a deliberate emphasis on "industrial" in the purpose statement. The project is intended to support the U.S. ceramic and engine industries by providing the needed ceramic materials technology.

The important distinction between the CTAHE Project and the component development tasks in the DOE Automotive Technology Development engine programs should be emphasized. The heat engine programs have goals of component development and proof-of-concept. The CTAHE Project is aimed at developing generic basic ceramic technology and does not involve specific engine designs and components. The materials research and development efforts in the CTAHE Project are focused on the needs and general requirements of the advanced gas turbine and low heat rejection diesel engines.

The CTAHE Project supports the DOE Office of Transportation Systems' heat engine programs, Advanced Turbine Technology Applications

(ATTAP) and Heavy Duty Transport (HDT) by providing the basic technology required for development of reliable and cost-effective ceramic components. The heat engine programs provide the iterative component design, fabrication, and test development logic as illustrated in Fig. 2.

2.1 INDUSTRY PARTICIPATION

The CTAHE Project is a unique technology transfer program in that the objective is the establishment of a technology base within industry. A principal method of technology transfer in this project is the inclusion of industry in both the planning and the execution of the research and development. The approximate funding split among industrial laboratories, government laboratories, and universities is shown in Fig. 3. Approximately 60% of the program R&D funds are presently used for research carried out by industrial laboratories. In addition, industry cost shares an average of 25% and as high as 60% of the R&D cost.

2.2 ORGANIZATION

Figure 4 is a simplified schematic representation of the program management. The Assistant Secretary, Conservation and Renewable Energy, maintains overall responsibility for all program management and policy. The Assistant Secretary exercises control through the Deputy

CERAMIC TECHNOLOGY PROJECT

HEAT ENGINE PROGRAMS

Fig. 2. Approach to reliable components for advanced heat engines.

DISTRIBUTION OF R&D FUNDS

Fig. 3. Approximate distribution of funds.

Assistant Secretary for Conservation and the Office of Transportation Systems. Direct management responsibility is exercised by the Advanced Materials Development Program Manager under the Heat Engine Propulsion Division. The technical management of the project is delegated to the project office at the Oak Ridge National Laboratory. (ORNL is owned by DOE, but staffed and managed by Martin Marietta Energy Systems, Inc., under contract to DOE.) The program is actually carried out by numerous industrial laboratories, government laboratories, and universities. The project tasks are funded and managed as subcontracts from ORNL.

Fig. 4. Organization and management.

2.3 INDUSTRY-NEEDS ASSESSMENT

An industry-needs assessment was conducted to obtain the information required to develop a program plan consistent with industry requirements. The assessment was focused on critical technology needs for ceramics in advanced gas turbines and low heat rejection diesel engines. The relationship of ceramic technology to other engine concepts and other applications such as rail, domestic marine, military vehicles, stationary engines, and cogeneration systems was also considered.

The strategy for this assessment was (1) to determine the critical technology needs for ceramics in advanced heat engine applications, (2) to identify the potential technology areas requiring government funding, and (3) to review the current programs and plans of other federal agencies for ceramic technology in order to avoid unnecessary duplication. The approach was to review the status of current heat engine ceramic programs thoroughly and to obtain direct input from site visits and other contacts with major engine manufacturers, ceramic manufacturers, industrial laboratories, government laboratories, and universities.

The assessment concluded that the major technology development needed is a substantial increase in the reliability of current materials and an investigation of new materials and processes having the potential for higher reliability. The product of the industry-needs assessment was the Program Plan for the CTAHE Project.

2.4 COORDINATION WITH OTHER STRUCTURAL CERAMIC PROGRAMS

In order to realize maximum benefit of government funding for structural ceramics development, the CTAHE Project has been closely coordinated with other government programs to avoid undesirable duplication of effort. The National Aeronautics and Space Administration Ceramic Technology Program for Aerospace Applications was planned jointly with the present DOE program. These two efforts have been continuously reviewed in joint DOE-NASA meetings. Ceramic programs throughout DOE have been coordinated through the Energy Materials Coordinating Committee (EMaCC) and through formal and informal programmatic meetings of the project offices. An informal

interface with the Department of Defense agencies and laboratories that fund and manage ceramic research has been maintained through periodic reviews and planning meetings and participation on DoD steering committees. An annual meeting of all government agencies supporting structural ceramics work has been held for review and planning purposes. Federal structural ceramics programs were also coordinated through a subcommittee of the OSTP Committee on Materials (COMAT).

2.5 PROJECT SCOPE

The work breakdown structure for the project is shown in Fig. 5. The three principal areas of research in the project are (1) materials and processing, (2) design methodology, and (3) data base and life prediction. All three research areas are extremely important to a balanced program. Advances in materials processing technology are necessary for the development of improved materials with fewer and smaller flaws, more uniform microstructures, and improved and more consistent mechanical properties. Advances in design methodology are required if ceramic component design, with its requirements of statistical representation of strengths, is to become a reality. Mechanical evaluation and life prediction are required to characterize existing and new ceramics and to develop procedures for life prediction in engine environments.

The objective of the materials and processing research is to develop processing methods that can yield materials with the uniform microstructures and high-temperature mechanical and corrosion-resistance properties required of advanced engine components. Near-net shape processing techniques are required to minimize costly machining of these very hard materials. Principal research areas include powder synthesis and characterization; processing, characterization, and densification of green-state ceramics; application and characterization of thermal barrier and wear-resistant coatings on appropriate substrates including metals and ceramics; development and characterization of new toughened ceramics, including transformation-toughened materials and ceramic-ceramic composites; and development of processes for joining ceramics to metal and ceramic parts.

Research in design methodology is oriented to development of the tools (models, computer codes) necessary for establishing realistic engine

Fig. 5. Joint Department of Energy-National Aeronautics and Space Administration work breakdown structure for research tasks.

component life prediction technology. The research includes studies of static and dynamic friction and wear of ceramic heat engine materials (monoliths, composites, and coatings) in environments of stress, temperature, and atmosphere representative of advanced engines. The development of advanced statistical representations of material strength is necessary for determination of the confidence intervals around predictions of service life from a specific body of data.

Research efforts in the data base and life prediction area are focused on developing testing procedures; mechanical property data including high-temperature, time-dependent, and atmosphere-dependent data; nondestructive evaluation (NDE) procedures and data; and development, demonstration, and documentation of component life prediction methodology.

2.6 HIGH TEMPERATURE MATERIALS LABORATORY

The High Temperature Materials Laboratory (HTML) is a new research facility at the Oak Ridge National Laboratory, Oak Ridge, Tennessee. It is designed to address the high-temperature materials problems that limit the efficiency and reliability of advanced energy conversion systems and thereby assist U. S. industry in meeting the current challenge of foreign competition in this area.

Sponsored by the DOE Office of Transportation Systems under the Assistant Secretary for Conservation and Renewable Energy, the HTML serves as the focal point for a multidisciplinary staff investigating new materials, both ceramics and alloys, having potential for high-temperature structural applications.

Another major function of the HTML is its role as a user facility. It contains a collection of the special research equipment needed to characterize materials in terms of microstructure and microchemistry as well as physical and mechanical properties. These instruments are being made available to industrial and university researchers to provide them with the opportunity of bringing to bear the most modern techniques and equipment on their material problems.

The 6000-m² research facility contains 49 laboratories and enough offices to accommodate a permanent staff of about 65, plus 15 to 20 users and other visitors. The four User Centers occupy more than one-third of the laboratory space in the building.

The HTML is a separate program from the Ceramic Technology Project. However, the participants in the CTAHE Project are encouraged to become users of the HTML, and a significant synergism exists between the two programs.

3. BACKGROUND

3.1 AUTOMOTIVE PROPULSION OVERVIEW

In spite of substantial improvements in fuel efficiency in automobiles, trucks, and aircraft since 1973, the amount of petroleum used each day by the transportation sector in the United States is more than one million barrels higher than in 1973. The transportation use of petroleum continues to rise (in spite of impressive gains in new vehicle fuel economy) because the demand for travel continues to grow. In 1988, the transportation sector used about 10 million barrels of oil per day, 63% of the U. S. oil consumption (Fig. 6). This amounted to 24% more oil than the United States produced. Automobiles and light and heavy trucks accounted for about 82% of the oil consumed by the transportation sector. U.S. production of oil is on the decline, and it has been projected that imported oil will grow by three to five million barrels per day over the current level by 1995. This would put the percentage use of imported oil at 50 to 57%. The transportation sector is the major user of petroleum and, therefore, the major cause of U.S. trade deficits. In 1988, about \$38 billion or 34% of the foreign trade deficit (\$120 billion) resulted from the cost of imported oil. Since 1985, a second and even larger contribution of transportation to the deficit is the cost of imported vehicles. As shown in Fig. 7, the cost of imported vehicles ranged between \$55 billion and \$70 billion for each year in the period from 1985 to 1988,

Fig. 6. Petroleum usage by sector in the U.S. Transportation accounts for 63% of the total petroleum usage and exceeds the total U.S. production.

therefore accounting for approximately 35-50% of the trade deficit (ref. 3).

The DOE Automotive Technology Development Program is focused on the development of advanced heat engine propulsion systems with the capability for significant improvements in fuel economy, multifuel utilization, and improved emission characteristics. All of these advanced engines operate at high combustion temperatures, and require the development of new materials and components capable of long life under severe high temperature environments. Ceramic materials and components have the potential to meet these requirements using low-cost mass manufacturing techniques. The development of ceramic components is therefore an integral part of the advanced engine programs.

There are also potential benefits from use of ceramic components in contemporary engines. Ceramic parts have densities less than their metallic counterparts and provide faster engine response due to lower inertia and, in addition, wear is reduced because of the lower resulting forces. Increasing the reliability of ceramic parts while holding down their cost is of primary importance.

3.2 MATERIALS TECHNOLOGY OVERVIEW

Materials potentially capable of achieving higher engine operating temperatures in advanced heat engines include the following:

- advanced metal alloys (made by powder metallurgy, single-crystal, and rapid solidification rate technologies),
- carbon and carbon composites, and
- structural ceramics (monolithics, composites, and coatings).

Of these, the first two are being developed by either industry or the military. Advanced structural ceramics differ from conventional ceramic consumer goods in that they are made from extremely pure, microscopic powders that are consolidated at high temperatures to yield a dense, durable structure. Compared with metals, ceramics have superior wear resistance, high temperature strength, and chemical stability; they also have lower thermal conductivity, thermal expansion, and lower toughness (i.e., they are brittle). This brittleness causes catastrophic failure when applied stress is sufficient to propagate cracks that originate at microscopic flaws in the

material. Unpredictable failure caused by poor control over flaw populations remains a major handicap to the use of structural ceramics in load-bearing applications.

The most satisfactory approach to improving the toughness of ceramics is to design the microstructure of the material to resist propagation of cracks. Ceramic matrix composites which contain dispersed ceramic particulates, whiskers, or continuous fibers are an especially promising technology for toughening ceramics. Silicon carbide is the most common whisker material. Currently, whisker-reinforced ceramic matrix composites are fabricated by uniaxial hot pressing, which substantially limits size and shape capabilities and requires expensive diamond grinding to produce the final part. Fabrication of ceramic matrix composites reinforced with continuous fiber is presently of a prototype nature and is very expensive. However, relatively inexpensive advanced polymer matrix composites which typically contain a large percentage of high performance continuous fibers are used, primarily in the aerospace industry.

Transformation toughening also has great potential for increasing the use of ceramics in wear-resistance applications. Crack propagation is inhibited by one or more of several mechanisms due to transformation of particles of a metastable phase, including: absorption of crack energy, application of compressive stress to the crack due

to an increase in volume, and crack retardation interaction at the particle-matrix interface. The key ceramic material is zirconia which undergoes a phase transformation from the tetragonal to the monoclinic crystal form while cooling through a temperature of about 1150°C. Polycrystalline partially stabilized zirconia (PSZ) exhibits strengths of 500-1500 MPa and fracture toughness of about 12-16 MPa m^{1/2} at room temperature. PSZ can also provide strengths of up to 700 MPa at 1500°C (ref. 6).

The operation of machinery in hostile environments often results in component degradation which can be traced to deleterious processes occurring in the surface region of the material. To reduce or eliminate such effects, ceramic coatings have been developed to protect or lubricate a variety of substrate materials including metals, ceramics, and cermets. The application of a thin ceramic coating to a metal substrate yields a component with the surface properties of a ceramic combined with the high toughness of metal in the bulk. Titanium nitride, titanium carbide, and alumina are currently being used to extend the useful life of tungsten carbide or high-speed steel cutting tools by a factor of 2 to 5. Ceramic coatings are also finding wide application in turbojet and gas turbine engines for thermal corrosion and erosion protection of turbine blades and vanes.

Fig. 7 Cost of imports: oil and vehicles, 1975 to 1988.

Metal matrix composites (MMC) usually consist of a low-density metal such as aluminum reinforced with particulates or fibers of a ceramic material such as alumina or silicon carbide or graphite. Although metal matrix composites have significantly greater stiffness and strength, these properties are obtained at the cost of lower ductility and toughness. Currently, metal matrix composites remain primarily materials of military interest in the United States, because only the Department of Defense's high-performance specifications have justified the high costs of these materials. Costs could be substantially reduced if net-shape processes currently used with metals, such as casting or powder technology, can be successfully adapted to metal matrix composites. The most significant commercial application of MMCs to date is a squeeze-cast aluminum diesel engine piston locally reinforced with alumina ceramic fibers which is produced for Toyota by Art Metal. Art Metal produces about 300,000 pistons per year (ref. 6). Although no data on production costs for these pistons are available, this development is significant because it suggests that MMC components can be reliably mass-produced to be competitive in a very cost-sensitive application.

3.3 ECONOMIC AND ENERGY- SAVINGS PAYOFF

An economic study for DOE in the early 1980s by Argonne National Laboratory (ref. 7) revealed that the use of advanced ceramic materials in automobiles, trucks, and other vehicles could substantially increase U.S. economic growth. By 1986, the rapidly advancing state of ceramic technology required a detailed review of the timing and rate of development of ceramic engine materials. Argonne was asked to update and refine its earlier study so that both government and industry could make better decisions on developing ceramic engine technology based on accurate projections of market development and timing.

For this second study (ref. 8), Argonne asked ceramic experts around the world for their judgments on the future of ceramics in engines. Questionnaires were mailed to a select group of experts in Europe, Japan, and the U.S. Each questionnaire asked for views on current and future market size, benefits of using the technology, possible barriers to its use, and the state of international competitiveness in engine ceramics. The United States Advanced

Ceramic Association helped Argonne prepare the questionnaires and gather the data. Several important points were revealed by the study:

- Some 164 million ceramic engine parts will be needed in the U.S. in 2000; this number grows to 558 million by 2010.
- The value of these parts (in 1986 dollars) will expand from more than \$1 billion in 2000 to more than \$3.6 billion in 2010.
- No matter which country ultimately dominates the market for ceramic engine components, the economic impact to the U.S. will be significant. U.S. gross national product (GNP) could expand by \$11 billion in the year 2000 if U.S. manufacturers lead, or decline by \$26 billion if foreign producers lead.
- Japan is seen as the leader in ceramic engine technology both now and five years from now; Japan's share of the world market by 2000 is expected to be 40%, compared to 25% for the U.S. (Fig. 8).
- The Department of Energy's research and development program for advanced ceramics has cut Japan's lead in half, although Japan still is more than two years ahead of the U.S.
- Annual savings in petroleum due to use of ceramic engine technology will be more than 11.3 million barrels by 2000, worth \$675 million; this expands to 65.9 million barrels and \$5.5 billion by 2010 (Fig. 9).

3.4 INDUSTRY NEEDS ASSESSMENT

3.4.1 Site Visits

The original ceramic technology assessment was done by numerous meetings held at industrial, university, and government laboratories, ORNL, and at DOE. Following those meetings, held over a period of a year, the draft Program Plan was sent to a number of people for comment.

We have continued that assessment, which has really been continuous since 1983. In particular, when we are planning a major new activity, we solicit input from program participants and other interested researchers. We have kept detailed records since 1986 of trips we have made to other sites and trips made by others to DOE and ORNL for the purpose of commenting on the program. The organizations that have contributed to, or commented on, the technical plan for the

Fig. 8. World market share in 2000, as predicted by responding experts (dot is median; bar shows interquartile range, that is, the range that half the respondents thought was possible).

Fig. 9. Predicted U.S. energy savings from use of ceramic components.

program are shown in Table 1. Figure 10 shows the number of contacts per year, divided into industry, university, and government organizations. Some organizations have, of course, participated in numerous meetings. We intend to continue this type of assessment for the life of the program.

3.4.2 Workshops

Workshops were held in 1983 and 1984 on transformation-toughened ceramics for engine applications (ref. 9). The joint DOE/NASA/DoD workshops were held for the purpose of assessing the status of toughened oxide research in the U.S., to provide contractor reviews to the three government agencies, and to provide a forum for the exchange of ideas and opinions about this class of materials. The participants were the three government agencies, their contractors, and domestic ceramic companies. The purpose was an exchange of research results among the participants, communication between users and manufacturers of toughened ceramics and the government agencies, and coordination of the government programs. The consensus of the meetings was that toughened oxides will likely have an important role in heat engines in the future, but numerous technical problems must be overcome. The exchange of ideas and information which occurred during the workshops was considered an important step toward the needed solutions.

Automotive Technology Development Contractors' Coordination Meeting (CCM) workshops were held in 1985 and 1987 to update plans for DOE's (1) CTAHE Project, (2) Advanced Turbine Technology Applications Program (ATTAP), and (3) Heavy Duty Transport Project. The workshops also provided an opportunity for information exchange between ceramic companies and engine manufacturers concerning

Table 1. Organizations providing input to continuing ceramic technology assessment

Industry

Alcoa
 Allied-Signal
 Allison Gas Turbine Div., General Motors
 American Matrix
 AVCO
 Babcock and Wilcox
 Carborundum Company
 Caterpillar
 Ceramic Process Systems
 Champion Spark Plug
 Coors Ceramic Company
 Corning Glass Company
 Cummins
 Detroit Diesel Allison
 Dow Chemical
 Dow Corning
 Dupont
 Ford
 Garrett Auxiliary Power Division
 Garrett Ceramic Components Division
 General Electric
 Greenleaf Corporation

 GTE Laboratories
 J. M. Huber Corporation
 Keramont Corporation
 Molycorp
 Nichols Research Center
 Norton
 PCK Technology
 Radiation Sciences
 Research Triangle Institute
 Ricardo-ITI
 Rocketdyne Div., American Rockwell
 Solar Turbine
 Technology Research Institute
 Thermal Electron
 Vapor Technologies
 Vista Chemical
 Westinghouse

Universities

Univ. of Dayton
 Univ. of Delaware
 Georgia Institute of Technology
 So. Ill. Univ. at Carbondale
 Johns Hopkins Univ.
 Univ. of Massachusetts
 Univ. of Michigan
 Univ. of Missouri
 NC A&T State Univ.
 Penn State Univ.
 Rutgers Univ.
 Univ. of Tennessee
 Univ. of Washington

Government Labs

Argonne National Lab
 Army Materials Technology Lab
 Army Research Office
 Battelle Columbus Labs
 Los Alamos National Lab
 Nat'l Aeronautics & Space
 Admin.
 Nat'l Institute of Standards
 and Technology
 Nat'l Materials Advisory Board

Fig. 10. Site visits (visits to ORNL by others and visits by Project personnel to other sites) that have contributed to continuing ceramic technology assessment.

requirements for ceramic components in low heat rejection diesel engines and for the AGT100/AGT101 advanced gas turbines. Bringing engine designers and parts fabricators together was a response to the observation that communication between these two groups is often poor. Information exchange is essential since arriving at a final product is an iterative process. Typically, this sequence requires the assumption of properties (or dimensions), detailed stress analysis, and comparison of assumed or calculated material properties with those of existing materials. An understanding of and accounting for the effect of the testing procedure used on measured properties of ceramic parts is essential to successful engine design.

A surprising diversity of opinion concerning critical component materials property requirements arose among designers of the low heat rejection engine at the 1985 workshop. A lack of well-defined target characteristics was the apparent cause due to several competitive design concepts and confirmed the need for DOE to develop a realistic standard low heat rejection engine design and to encourage more productive and interactive dialogue between engine designers and ceramic manufacturers.

Panelists agreed that work on solid lubricants for engines should be confined to very basic laboratory studies and engine development using liquid lubricants should be continued. However, at the time of the workshops, there was a poor match between perceived material requirements and

known material properties. There was insufficient information on high-temperature strength, chemical stability, effect of combustion products, fracture toughness, and cyclic fatigue. Continuing work on each of these items was seen as particularly important. In addition, the probability of survival of key ceramic parts must be increased from the then estimated value of 0.86 to a survival rate of 0.9999 to 0.999999.

The panelists more readily arrived at agreement on a projected plan for the Advanced Turbine Technology Applications Program. A scenario was selected in which existing calculations of mechanical stresses and temperature profiles were to be used to determine the required ceramic properties. This was followed by the measurement of performance of leading candidate ceramics in engine tests, then by selection and economic analyses, evaluating the manufacturability of the selected ceramic parts, completing measurement of their properties, and assessing the reproducibility of these properties. The above scenario can be repeated as required to refine the selection process.

Actions in the CTAHE Project as a result of the 1985 workshop were as follows:

- Increased emphasis on use of high-temperature liquid lubricants in sliding friction and wear studies.
- Compilation of mechanical properties data to be followed by regular updates.
- Continuation of the program as a liaison between engine and ceramic companies

in defining material property requirements.

The 1987 workshop dealt only with ceramic components for advanced diesel engines. As with the 1985 workshop the object was to foster an exchange of information and ideas between ceramic companies and engine manufacturers and to clarify the status of materials technology with respect to perceived requirements for viable ceramic components.

Major problems facing the diesel engine manufacturer were given as: emission control, fuel economy, durability/reliability, and alternative fuel utilization. Ceramics were said to have potential roles as thermal barriers, light-weight moving parts, and in wear/friction components. However, ceramics would be used only if cost effective.

As in the 1985 workshop, engine designers again emphasized the continuing need for physical properties over a range of temperatures for use in conducting accurate life-prediction analyses. Life-prediction and fast-fracture aspects of the design methods are largely based on probabilistic analysis incorporating Weibull theory. Thus, property data from large numbers of samples are needed for the statistical approach. Concern was expressed about extrapolating the current data range to the reliability required in mass production (0.9999 to 0.999999). There was a stated need for experience with design models and ceramic components. Ceramic and engine companies agreed that the design, fabrication, and testing (to failure) of a large number of simple components will complete the process of developing fast-fracture and life-prediction models. Experience would be gained in design, fabrication, and large-scale production. Concurrently, the Weibull modulus would increase due to process improvements resulting from large-scale production.

Engine designers made numerous recommendations on the types of data or materials tests that would be useful in their design efforts including the following: stress-rupture measurements and high-cycle fatigue testing for life-prediction analysis, subcritical-crack growth data, information on surface characteristics as related to failure, erosion and corrosion effects in the operating engine environment and their effects on property measurements, and tensile strength data or, in its absence, carefully documented four-point fracture measurements. Accelerated test results are suspect since new failure modes may be introduced.

Although specific values were not set, important characteristics were identified, including: cost (should be reduced an order of magnitude from the present), Weibull modulus of 25 or higher, improved toughness to reduce reliance on nondestructive examination, low thermal conductivity, process to near net shape, thermal expansion compatible with metal parts, and easy and inexpensive attachment to metals.

On-going R&D in the OTS-sponsored CTAHE Project is directed at providing missing parts of the data base (such as cyclic fatigue and time-dependence and environmental effects). A data base (ref. 10) of ceramic properties is now operational.

An important industrial development which will substantially reduce the problem of communication between ceramic fabricators and engine component manufacturers is the formation of teams, such as Norton/TRW, Eaton/GTE, and Ford/Ceradyne.

Attendees departed the workshop with a better understanding of the needs of their counterparts and, from the perspective of the workshop organizers, communications between the diesel engine manufacturers and ceramic companies were definitely improved.

3.4.3 Topical Assessment Documents

Three assessment documents have been prepared since 1984. The contents and recommendations are presented below.

Ceramic Coatings for Heat Engine Materials - Status and Future Needs (ref. 11). Coating deposition processes including plasma spraying, electron beam evaporation, sputtering, chemical vapor deposition, sol-gel, ion, and laser techniques were evaluated and compared. Although zirconia thermal barrier coatings were emphasized, coatings for wear and erosion resistance, lubrication, chemical protection, seals, and interfaces were also addressed. Methods for assessing coating adherence and defects were reviewed. It was concluded that the potential for use of ceramic coatings will expand in the future, permitting higher performance, more reliable heat engines. The cutting tool industry is a prime example of how the desirable properties of coatings are currently being utilized. One major problem which limits much wider industrial use of coatings is their frequent poor adherence. In addition, lower temperature processes should be developed so that less refractory substrates can be coated.

Needs Assessment for Nondestructive Testing and Materials Characterization for Improved Reliability in Structural Ceramics for Heat Engines (ref. 12). Raw materials, green state bodies, and sintered ceramics were considered. The overall approach taken to improve the reliability of structural ceramics requires key inspections throughout the fabrication flowsheet, including raw materials, green state, and dense parts. The applications of nondestructive inspection and characterization techniques to ceramic powders and other raw materials, green ceramics, and sintered ceramics were discussed and the current state of inspection technology was reviewed for all identified attributes and stages of a generalized flowsheet for advanced structural ceramics. As an integral part of the development of new technology, correlations should be established between the nondestructive characterization and service performance or performance-related properties, and the reliability of the characterization technique must be established. Although it may be impractical to apply the recommended examinations to 100% of the production quantities of large-volume items, the application of proven methods and techniques on a sampling basis can ensure the control of the fabrication process. The NDE must be associated closely with design and stress analysis to enhance relevant accept/reject criteria and improve performance prediction capabilities. The following items constituted the primary recommendation for development of material characterization and NDE technology for making significant improvements in reliability of structural ceramics:

- Standard reference powders should be developed for powder characterization.
- Significant attention should be given to development of ultrasonic instrumentation and techniques for determination of volumetric and surface properties of green and dense ceramics.
- Advanced X-ray techniques to detect and characterize density variations, flaws, inclusions, and other internal discontinuities should be developed.
- An extensive, carefully controlled processing improvement program with one or more simple product lines should be conducted to establish relationships between analytical and process-related characterization techniques and quality of components produced.
- The use of magnetic resonance

inspection (MRI) for characterizing green ceramics for binder distribution should be further studied.

Several other areas including the development and publication of guidelines for writing meaningful specifications for ceramic raw materials, and investigating basic problems in materials characterization were recommended for developmental consideration pending availability of resources.

An Assessment of the State of the Art in Predicting the Failure of Ceramics (ref. 13). As a consequence of the potential economy associated with the increasing use of structural ceramics, a great deal of research has been funded in an effort to develop sound, widely applicable models on which a comprehensive design methodology can be based. This report was an attempt to define the boundary between what is known and what is only suspected in predicting failure in structural ceramics. Two types of failure were considered: fracture governed by initiation of unstable crack propagation (fast fracture), and fracture which occurs after an acceptably long service life and which is governed by fatigue mechanisms. It was determined that the greatest weakness in existing design strategies for brittle fracture is in the narrow range of conditions for which the strategies are adequate. To improve the design methodology, the models must be improved. Specifically recommended improvements were (1) develop models of cracks with realistic geometry under arbitrary stress states; (2) identify and model the most important relationships between fracture processes and microstructural features; (3) assess the technology available for acquiring statistical data on microstructure and flaw populations, and establish the volume of data necessary for verification of statistical models; and (4) establish a computer-based fracture simulation that can incorporate a wide variety of mechanical and statistical models and crack geometries, as well as arbitrary stress states.

3.4.4 Major Assessments

In response to a joint request from the House Committee on Science and Technology and the Senate Committee on Commerce, Science, and Transportation to analyze the military and commercial opportunities presented by new structural materials technologies and outline the Federal research and development priorities consistent with those opportunities, the Office of Technology Assessment (OTA) prepared a

technical memorandum in September 1986 (ref. 14). A hierarchy of R&D priorities was included and is summarized below:

Very Important

Processing Science. There is a great need for generic research to support the development of practical manufacturing technologies within industry. A partial listing of topics includes:

- Development of near-net-shape processes;
- Development of pure, reproducible feed materials;
- Development of practical in-process inspection devices and techniques;
- Iterative development of new equipment such as hot isostatic presses (HIPs) and multistage processes such as a sinter-HIP, with emphasis on scaling up to commercial size;
- Development of an understanding of the relationship of coating process variables and final properties of ceramic coatings.

Environmental Behavior. An understanding of the long-term behavior of candidate ceramics in the anticipated environment is a prerequisite to development of higher-temperature, corrosion-resistant materials.

- For heat-engine applications, the general requirement is to understand the mechanical and chemical behavior of advanced ceramics in environments of air, carbon monoxide, and carbon dioxide at 1000°C to 1400°C (1800°F to 2600°F).
- In ceramic wear parts, it is necessary to understand the interrelationships of wear, erosion, and toughness in the presence of lubricating fluids.
- Heat exchangers generally fail by slow corrosion at high temperatures; therefore, an understanding of the chemical processes is necessary. Corrosion-resistant coatings may become important.

Reliability. Because reliability is essential for the successful application of ceramics, cost-effective, nondestructive examination (NDE) methods are required. The NDE method must distinguish between critical and harmless flaws. Design models which can make this distinction are also needed.

Interface in Ceramic Matrix Composites (CMCs). Little is known about the interface between ceramic fibers and the matrices of CMCs. Modification of the surface chemistry of ceramic fibers and their matrix could yield remarkable improvements in ceramic performance and reliability.

Important

Joining of Ceramics. Joining of parts is essential to building larger assemblies. Techniques for joining ceramics to ceramics and to conventional materials are needed. A key to joining is an understanding of the surface properties of the two materials and of their interface.

Tribology of Ceramics. Conventional lubricants are unsuitable for the high temperature environment of advanced heat engines. Solid lubricants or modifications of component surfaces to produce self-lubrication are possibilities, but further research is clearly needed.

Failure Mechanisms in CMCs. CMCs offer the best solution to the problem of catastrophic failure of ceramics. Fundamental understanding of the failure mechanisms in CMCs would provide guidance for development of new, tougher ceramics.

A review of the R&D topics contained in the CTAHE program showed that each of the recommendations made by OTA, relating to advanced ceramics, has been or is being implemented.

A second assessment, entitled Advanced Materials by Design, was recently completed by the Office of Technology Assessment (ref. 15). The subject assessment responded to a joint request by the House Committee on Science, Space, and Technology and the Senate Committee on Commerce, Science, and Transportation to analyze the military and commercial opportunities presented by new structural materials technologies and to outline the federal policy objectives that are consistent with those opportunities.

This report by the OTA reviews the evolution of advanced materials over recent years and projects both their technological and economic impact in the future. Ceramics and ceramic composites are included along with other materials. The high-temperature strength, high stiffness, and light weight of ceramics can be used to obtain higher fuel efficiencies, lower assembly costs, and longer service life for many manufactured products. The favorable properties

of ceramics are compromised, however, by their characteristic brittleness, which makes ceramic parts susceptible to breakage because of relatively small surface or internal flaws.

The OTA concludes that advanced materials technology in the United States is evolving, but cost-effective commercial use remains to be demonstrated for most materials. Potential end users in the United States have adopted a "wait and see" attitude, pending the solution of remaining technical and economic problems. However, through well coordinated government-industry efforts, several countries, notably Japan, have initiated more aggressive programs to commercialize their evolving technologies.

Potential U.S. commercial end users believe that major use of advanced materials will not be profitable within the next five years, which is the typical planning horizon of most firms. Hence, there is little commercial "market pull" on advanced materials technologies in the U.S.

In contrast to the limited market-pull orientation of firms in the U.S., end users in competing industrial countries, especially Japan, are pursuing a "technological push" approach, in which near-term profits are sacrificed in favor of gaining the production experience necessary to secure a share of large future markets. U.S. companies should not expect to be able to step in and produce competitive advanced materials products after the manufacturing problems have been solved by others.

A competitive assessment of the U.S. advanced ceramic industry was carried out by the Industry Analysis Division/Trade Information and Analysis in the U.S. Department of Commerce (DOC) and published in March 1984 (ref. 16). Their recommendations were as follows:

"If the U.S. Government were to act now to strengthen the competitive position of the U.S. advanced engineering ceramics industry, there are a number of options that might be considered.

Those options designed to push ahead U.S. advanced engineering ceramics technology, including the removal of barriers to such progress, can be seen below.

- Increasing the amount of Federal Research and Development expenditures related to advanced engineering ceramics.
- Increasing the amount of Federal R&D aimed at military and space applications of advanced engineering ceramics and improving the technology transfer

function to commercial applications.

- Increasing Federal incentives directed toward increasing private industry R&D on advanced engineering ceramics.
- Allowing antitrust exemptions for cooperative industrial R&D to develop major advanced engineering ceramic applications and promote the Research and Development Limited Partnership (RDLP) concept for this purpose.
- Improving U.S. capacity to obtain and disseminate foreign scientific and technical information (STI).
- Increasing educational opportunities and incentives for product design and manufacturing of advanced engineering ceramics.

In addition to pushing technology, there are options the Federal Government might consider to help create or increase the market for advanced engineering ceramics. Such measures would presumably provide more incentives for U.S. private industry to invest in these product and process development activities.

- Increase Federal procurement of advanced engineering ceramics for military, space, and other applications.
- Use Federal regulatory policy to increase the market for advanced engineering ceramics.
- Provide Federal risk or liability insurance for advanced engineering ceramics producers and/or users in case of catastrophic failure.
- Revise the Standard Industrial Classification codes to isolate advanced ceramics inputs and products. This would facilitate assessing developments in the industry.
- Encourage the various standards setting associations to develop, in concert with the National Institute of Standards and Technology, preliminary reliability standards for advanced ceramics. As more knowledge is available from ongoing research programs, the standards should be revised accordingly."

An assessment of the R&D needs for ceramic tribology was recently completed by the National Materials Advisory Board (NMAB) (ref. 17). A brief summary of their findings is as follows:

"To summarize, then, the critical need to solve difficult tribological problems, particularly for

ceramic components, is at the heart of such technological challenges as designing the next generation of high-performance gas turbines as well as advanced military and space systems. However, the science and technology base available is not adequate for the development of advanced mechanical systems operating at extreme temperatures. If ceramic tribo-elements are to be successfully employed in meeting such challenges, research needs to be undertaken on theoretical modeling, performance and structure relationships, surface modification, lubricants, and the effects of various chemical, mechanical, and thermal environments on tribological performance. The allocation of national resources is clearly called for to build the infrastructure needed for a multidisciplinary approach to the science and technology of tribology."

3.5 FOREIGN COMPETITION

3.5.1 Japanese Programs (ref. 18)

Japan has formulated a national program in which the resources of government, industry, and academia are integrated to develop and market fine ceramics for next generation industries. This program is one of several directed at development of new inorganic materials. The agency responsible for establishing an industrial base and promoting technological development is the Ministry of International Trade and Industry (MITI).

The program is designed to develop fine ceramics having high strength, high corrosion resistance, and resistance to wear. The research ranges from preparation and control of raw materials to forming, sintering, and bonding. Also included is the development of design criteria which takes into account the brittle character of ceramics. Taking part in the turbine research and development are six national laboratories and institutes and 15 private corporations. Industrial property rights evolving from this research will be jointly owned by government and the private sector.

The Japan Fine Ceramic Association (JFCA) and the Japan Fine Ceramic Center (JFCC) provide facilities for preparation of raw materials, fabrication, product evaluation, and application technology. In addition to large industrial companies, participation of small and medium-sized businesses is encouraged through support systems which include technical training and guidance. International exchange is accomplished through invitations to foreign researchers and the

holding of international forums and workshops.

To assure consistency in measurements, the JFCA was given responsibility for commissioning of "Survey and Research on the Standardization of Fine Ceramics" which requires development of standardized methods for measuring physical, mechanical, and chemical (oxidation, corrosion) properties of fine ceramics. MITI also contracted the "Survey and Research on a Fine Ceramics Data Base System" to the JFCC. The data base is to respond to the needs of both domestic and overseas users.

Japan has also promoted international cooperation in technological development through the Versailles Project on Advanced Materials and Standards (VAMAS) and with bilateral agreements with several countries on industrial, scientific, and technology exchanges.

Two new ceramic gas turbine programs were initiated in 1988. MITI began a program for the development of a 300 kW ceramic gas turbine for cogeneration use. The program, funded at ¥16 billion (\$119.4 million at 134 ¥/\$) is scheduled for completion in 1996. Goals for the 300 kW program include a thermal efficiency greater than 42% and a turbine inlet temperature of 1350°C, which is very close to the 1370°C goal for the U.S. ATTAP Program.

A 100 kW automotive ceramic gas turbine engine is to be developed in the same time frame, 1988-1996. The budget for that program is expected to be ¥10 billion (\$74.6 million at 134 ¥/\$). A preliminary study is being conducted in the first two years, 1988 and 1989; the R&D activities will follow the study. The goals of the program include 40-45% efficiency, realized at a turbine inlet temperature of 1350-1400°C; multifuel utilization, and low atmospheric emissions. Both of these ceramic gas turbine programs include extensive material development activities.

The MITI budget for fine ceramics is shown in Table 2. The technology development programs are the fine ceramics research project (R&D of basic technologies for future industries or their "Jisedai") and the gas turbine component development project (Moonlight Project). Until recently this was the only funding information available and was compared to the U.S.-government funded programs. The funding level of the industry equipment and loan program was not known. Government-targeted technology areas are included in the program, and the loans are to be paid back for commercially successful

Table 2. Japanese government-funded ceramics R&D

	<u>MITI budget for new materials</u> [\$ millions (134 yen/\$)]	
	<u>1987</u>	<u>1988</u>
Planning and surveys	0.3	1.0
Technology development programs	23.0	29.0
Private sector capital investment and loan service	187.0	196.0
Total MITI budget	210.3	226.0

projects. Besides MITI, ceramics research is also funded by the Ministry of Education (university research), Ministry of Transportation (diesel engines), and the Science and Technology Agency of Japan (aerospace research).

The value of the fine ceramics market in Japan in 1987 was estimated at \$5.3 billion (710 billion yen) and is projected to \$31 billion (4137 billion yen) in 2000. Capacitors in integrated circuits accounted for 80% of the 1987 total. Kamigaito (ref. 19) tabulated the ceramic engine components commercialized in Japan, including the specific automakers and ceramic suppliers involved, along with components that are not yet commercialized (Table 3)

3.5.2 West German Programs (ref. 20)

The German Ministry for Research and Technology (BMFT) has supported research on ceramics for engines since 1974. Like the DOE Advanced Gas Turbine program, their original program was ceramic components for gas turbines. Gas turbine manufacturers (Daimler-Benz, Volkswagen, and MTU), ceramic materials producers, and university laboratories participated in this program, managed by the German Aerospace Research Establishment (DFVLR). Progress was made in component development, that demonstrated the feasibility of using ceramics in engines. However, like the U.S. program, the progress was not sufficient for automotive industry turbine engine production, and a more generic program for engines, turbines, and chemical equipment was planned. During the period of the

DFVLR-managed program (and afterwards), there has been good cooperation and information exchange with DOE through an International Energy Agency Agreement.

Ceramic research is now a part of the BMFT Materials Research Program started in 1985, and managed by a project office established at the Nuclear Research Center Juelich (KFA Juelich). Elements of the ceramic research are: fundamental material and method development, new methods of powder production, method development for prototype components, and joining of ceramics. Funding obligated for ceramics in 1987 is shown in Table 4.

The industry joint projects typically run for 3 years, and industry cost-shares approximately 55 percent, depending on university and institute participation. The industry proposed and accepted joint projects are more on near-term/applied research than are the CTAHE program industry contracts. Other direct research grants are fully funded at universities and institutes such as: University of Karlsruhe, NDT Institute Saarbruecken, Max Planck Institute, and Technical University of Berlin.

One development in the FRG program considered an unqualified success was the "cast-in method" of installing ceramic exhaust ports in aluminum alloy blocks. Ceramic exhaust port liners are in commercial production for Porsche automobiles.

Daimler-Benz AG showed an experimental gas turbine powered Mercedes S-class automobile

TABLE 3 - ENGINE COMPONENTS AND RELATED MAKERS IN JAPAN

SYSTEM	ASSEMBLIES OR COMPONENTS	AUTOMAKERS OR MACHINE MAKERS	CERAMICS OR CHEMICAL MAKERS: SUPPLIER OR MAKERS IN COOPERATION	REMARKS
COMPOUND ENGINE	ADIABATIC COMPOUND ENGINE*	ISUZU MOTORS LTD KOMATSU LTD		Si3N4, Al2O3 ZrO2 COATING
ENGINE	PISTON* PISTON PIN* CYLINDER*	MANY AUTOMAKERS	MANY MAKERS	KYOCERA CONSTRUCTS SMALL DI DIESEL ENGINE, Si3N4 or SiC
	SWIRL CHAMBER**	ISUZU MOTORS LTD** MAZDA MOTORS LTD** TOYOTA MOTOR CO**	KYOCERA CORP** NGK INSUL LTD** NTK SPARK PLUG LTD** INNER PRODUCTION OTHER MAKERS*	UNCHARGED ENGINE, Si3N4** FULL CERAMICS, Si3N4** CHARGED ENG, Si3N4** Si3N4* or SiC*
ENGINE ASSISTING COMPONENTS	TURBOCHARGER**	NISSAN MOTOR CO** OTHER MAKERS* IHI CO LTD*	NTK SPARK PLUG LTD** OTHER MAKERS* NGK INSUL LTD*	Si3N4** Si3N4* or SiC* Si3N4*
	GLOW PLUG**	ISUZU MOTORS LTD	KYOCERA CORP**	Si3N4**
	VALVE*	ISUZU MOTORS LTD*	KYOCERA CORP*	Si3N4*
	CAM*	MANY MAKERS*	OTHER MAKERS*	Si3N4* or SiC*
	TAPPET*	MAZDA MOTORS LTD*		Si3N4*
	ROCKER ARM**	mitsubishi motors corp** OTHER MAKERS*	NGK INSUL LTD** OTHER MAKERS*	Si3N4** Si3N4* or SiC*

(*) Not commercialized yet. (**) Commercialized, Installed in Passenger Car.

at the 1981 Frankfurt Auto Show and is known to be continually testing these vehicles around their R&D center in Stuttgart and on the autobahns. Daimler-Benz, with interests also in diesel and gasoline engines, is a major automotive industry participant in the BMFT/KFA ceramics program.

A new 100 kW ceramic gas turbine program is scheduled to begin in 1990, the AGATA Project. The project will emphasize fuel economy and exhaust emissions. The target turbine inlet temperature is greater than 1350°C. The project is divided into two stages. The first stage, definition and development of components, is scheduled for four years. The second stage, design and fabrication of components and engine

demonstration is scheduled for an additional three years. The funding level for the program is not known.

3.5.3 Other European Countries (ref. 15)

The most recent estimate of government funding for Advanced Ceramics R&D in several additional European countries applies for 1986.

	\$ millions
France	64
United Kingdom	51
Nine Other Countries	21.5

Table 4. Funding in 1987 for ceramics under the German Materials Research Program

Total cost (\$ millions*)	Government cost (\$ millions)	Grants - 1986 (\$ millions)	Average government cost-share (percent)
87.5	44.7	10.7	51.0

*Conversion rate: DM 1.8/\$

Details on the content of these programs are not available although it is reported that France has developed a strong capability in ceramic matrix composites.

The Commission of the European Community (EC) has initiated the Research and Development Programme on Manufacturing Technologies and Advanced Materials (BRITE/EURAM) as part of the formation of the new economic affiliation of western European countries. The BRITE/EURAM program has been approved by the Commission of the EC for the years 1989-1992.

Over the next four years, this new program is scheduled to spend about 500 million Ecu on manufacturing technology and materials research. (An Ecu is a monetary unit, valued at about one U.S. dollar, of the new currency that is planned for use throughout the EC.)

The prime objective of the BRITE/EURAM program is to make European manufacturing industries more competitive in world markets by expanding their industrial manufacturing and materials technology base. Ninety percent of the EC projects will be applied research, and will be 50% cofunded by industry. The remaining 10% of the projects will be fundamental research, and will be wholly funded by the EC.

3.6 THE FEDERAL ROLE

3.6.1 National Materials Policy

Numerous high-level studies on advanced ceramic materials have been completed since 1984. The Interagency Committee on Materials (COMAT), overseen by the White House Office of Science and Technology Policy (OSTP), established a working group to examine federal programs in advanced ceramics; OSTP also sponsored a National Academy of Sciences/Engineering study to identify "research areas of unusual scientific opportunity" for ceramics and ceramic composites. The National Materials Advisory Board of the Academy has conducted several studies, including "Ceramic Technology for Advanced Heat Engines" published in 1987. Both DOE and the National Science Foundation have conducted studies of opportunities and needs in advanced ceramics. At the request of Congress, the Office of Technology Assessment has also conducted several studies.

According to OTA's report published in June 1988, Congress and the current Administration hold conflicting views on policymaking with respect

to advanced materials. In the congressional view, the Federal Government should formulate a high-level national plan for advanced materials research, development, and technology as evidenced by passage of materials-related bills since the Strategic War Materials Act of 1939. In 1970 Congress called upon the executive branch to develop a comprehensive national materials policy covering the entire materials cycle. Congressional concern about the lack of a coherent national materials and minerals policy was reemphasized in 1980 with passage of the National Material and Minerals Policy, Research, and Development Act.

In July 1984, Congress passed the National Critical Materials Act which mandated a National Critical Materials Council in the White House. The three-member council was expected to serve as a focal point to coordinate and set priorities for the U.S. national materials policy and to define a national Federal advanced materials and research program (ref. 15). Although council members were finally appointed late in 1985, two of the three quickly resigned and the effort has been in limbo ever since. While it is unclear whether the Council can overcome these early obstacles, it remains clear that the U.S. must take aggressive coordinated action to set goals for addressing advanced materials issues (refs. 21 and 22).

Implicit in the congressional view is that national goals and priorities for advanced materials can be identified as readily as those for more traditional materials. According to this view, such goals and priorities should be established above the agency level, and agency spending on materials programs should be made consistent with them.

In the Administration's view, it is not appropriate for the Federal Government to engage in strategic advanced materials planning. Since the different agencies have different missions and different requirements for materials, the determination of R&D priorities is best made at that level. Thus, the United States has long had a decentralized approach to advanced materials policy in sharp contrast to Japan's aggressive coordinated government-industry effort since 1981. On a positive note, meetings among managers of programs involving advanced ceramic materials are held fairly frequently to exchange information about ongoing materials projects. These include COMAT, the Interagency Materials Group hosted by NSF, and the Interagency Coordinating Committee for Structural Ceramics (Bureau of

Mines, National Institute of Standards and Technology, National Science Foundation, NASA, DOE, DoD, and the Gas Research Institute). Such groups also exist within the various agencies, including DOE's Energy Materials Coordinating Committee (EMaCC) which serves primarily to enhance coordination among the Department's materials programs and to further the effective use of materials expertise within the Department. This is accomplished through the exchange of budgetary and planning information among program managers and through technical meetings and workshops involving DOE and major contractors on select topics. In the Administration's view, information exchange between COMAT and other interagency materials committees is deemed adequate to avoid excessive duplication of efforts and waste in Federal materials R&D programs (ref. 15).

In the report OTA summarized the role of the Federal Government in the development of advanced materials through funding of basic research, technology demonstration programs, and military and aerospace procurement of advanced materials and structures (ref. 15). The U.S. Government currently spends about \$167 million on structural ceramics and composites. Counting only basic and applied research, the Department of Defense sponsors about 60% of this total. In the case of the military, the government itself is the customer for materials technology and hardware. Transfer of DoD-funded materials technology to the commercial sector, however, is discouraged by two major factors. First, the high cost of military materials and fabrication processes limits their acceptance in the commercial sector. Second, the government imposes restrictions on the export of these materials and on access to related technical data to deny this technology to U.S. adversaries. The remainder of Federal spending for structural ceramics and composites is non-military in nature and includes most of the work supported by DOE, NASA, NSF, NIST, and the Bureau of Mines. Technology transfer to the private sector is openly sought by these agencies, where appropriate.

OTA's analysis suggested four key Federal policy objectives that could accelerate commercialization of advanced materials technologies which are listed below.

"1. Encourage potential end users to make long-term capital investments in advanced materials.

2. Facilitate government/university/industry

collaboration in R&D for low-cost materials fabrication.

3. Facilitate more effective commercial exploitation of military R&D investments where possible.

4. Build a strong advanced materials technology infrastructure."

3.6.2 Industry Perspective

Formed in 1985, USACA (United States Advanced Ceramics Association) is a national trade association currently representing U.S. companies with an interest in the emerging field of advanced ceramics. The organization is dedicated to promote free market approaches to the advancement and commercialization of advanced ceramic products and, in other ways, better serve the interests of the U.S. advanced ceramics industry. Since 1985, USACA members have testified four times before Congress.

In December 1987, USACA released a study which showed that private research and development expenditures totaled more than \$152 million in 1986. Government contracts awarded for advanced ceramics R&D totaled slightly over \$46 million for the same time period. While these results indicate that advanced ceramics companies are confident about the long-term viability of advanced ceramics, it is also obvious that industry is sharing a substantial portion of the research and development expense in this area (ref. 23).

In February 1986, Johnathan Hinton, chairman of USACA's Government Affairs Committee, testified before the House Science and Technology Committee Subcommittee on Transportation, Aviation, and Materials and strongly urged "Congress not to cut the essential and necessary Federal Government advanced ceramics R&D programs." At that time Hinton was vice president and general manager of the Structural Ceramics Division for Standard Oil Engineered Materials Company, now Carborundum Company. He stated that DOE-sponsored advanced gas turbine and other Federal Government advanced ceramic technology programs have made substantial gains toward their goals and have been successful in initiating increased involvement and investment by industry. He also indicated that "continued U.S. expenditures for R&D for advanced ceramics are a critical factor in helping to ensure that the U.S. continues to be a key player in advanced ceramics development as this industry becomes more

commercialized." Basic research in the fundamental science of ceramics, development of dependable ceramic materials and processes, and development of new systems designed to take advantage of the attributes of ceramics were three key areas identified by Hinton for continued Federal Government advanced ceramics R&D. He further advocated "that the Congress ensure that a mechanism exists in the Executive Branch to identify and coordinate all Federal Government advanced ceramics R&D activity to eliminate any waste or overlap" (ref. 24).

In September 1986, Hinton again testified before the House Science and Technology Committee Subcommittee on Transportation, Aviation, and Materials regarding implementation of the Critical Materials Act of 1984. Hinton was accompanied by John Coppola, also from Carborundum Company, who had recently returned from spending three years in Japan. In his testimony, Hinton stated "It is essential that the President and other key governmental officials be advised of the tremendous potential of advanced ceramics for the United States. The newly-created National Critical Materials Council appears to be an appropriate forum for these endeavors." Hinton also urged the panel to continue its funding of essential advanced ceramic research and development programs as part of its commitment to implementation of the National Critical Materials Act of 1984 (ref. 25).

USACA President William Payne testified before the Senate Commerce Committee in May 1987 in conjunction with the Committee's review of the Technology Competitiveness Act of 1987. Payne mentioned that several commercial markets for advanced ceramics have been developed and that further improvements in strength and hardness could lead to future automotive, aerospace, electronics, and defense applications. He also said that the use of ceramic-based automobile engines could have a major impact on U.S. energy dependence by reducing fuel consumption, and urged that Federal funding to support research and development in advanced ceramic fundamental science and process technology should be continued at current or higher levels. Payne called for a "focused research and development effort directed at overcoming technical barriers to the commercialization of advanced ceramic products." In conclusion, Payne warned that the failure to develop a viable program to attack barriers to the commercialization of advanced ceramic products

would lead, in a short time, to pressure to erect trade barriers against foreign products (ref. 26).

On July 15, 1987, USACA Executive Director Steve Hellem testified before the House Budget Committee's Task Force on Community and Natural Resources regarding "The Federal Budget and Economic Growth Opportunities in Energy Conservation and Research and Development" program. In his testimony Hellem said: "Clearly the Federal government has a role to play in research and development of new technologies, particularly advanced ceramics. The role is to search out and identify emerging technologies, prime the pump on risky, long-term activities, and initiate research and development programs with a central focus on the ultimate commercialization of those products by private industry." He echoed earlier comments made by Payne when he concluded with "...If we do not create and continue to support national research and development programs that are focused on the commercialization, foreign competitors will meet the challenge and, in a few years, the calls for trade barriers to protect us from worldwide competition will be deafening" (ref. 27).

4. TECHNICAL PLAN

4.1 IMPLEMENTATION STRATEGY

The foundation of program implementation will continue to be the heavy emphasis on industry's involvement, not only in the technology efforts themselves, but also in providing continuous input to the program's direction and priorities and in evaluating program progress. The program will continue to focus on long term, high-risk R&D areas identified by industry. The program now has the benefit of the continuing feedback from the Advanced Turbine Technology Applications Program and Heavy Duty Transport Program in terms of critical technology needs. We have accumulated a significant body of input from our continuing technology assessment and from the assessments done by industry committees, government agencies, and our advisory committees and workshops.

For the most part, this significant resource of industry and university input has confirmed the program direction set by the original plan, but with much specificity in terms of technology requirements. For example, emphasis on the processing and properties of ceramic matrix composites, on characterization of cyclic fatigue behavior, and on mechanical testing in uniaxial tension has resulted from the program's response to industry input since initial publication of the plan.

The identification of mechanical reliability as the highest priority technology need has been reconfirmed by the body of input gathered in the last five years. Specific, major program thrusts have been developed to respond to this need, and are identified and discussed in the following technical plan.

We are able to cooperate more closely with the ATTAP and Heavy Duty Transport Programs in the second half of our program than was possible in the first half; and, as a result, are able to reap the additional benefits of synergism with those programs in terms of iterative feedback from the fabrication and testing of engine components.

4.2 TECHNICAL APPROACH

The overall approach is illustrated in the Gantt chart shown in Fig. 11. This chart shows the major elements of the program, key milestones, and interconnections among tasks and with the OTS engine programs. Table 5 shows the state of the technology relative to the original plans and goals

of the program. In this table, major goals are listed, and the substantial completion or projected completion shown by check marks. Details of program goals or achievements are called out in tables and figures which are referenced in Table 5. A list of program tasks by work breakdown structure (WBS) number is shown in Table 8 and is referenced in Table 5 to identify tasks relevant to each specific goal. Publications and patents that document particular achievements are also called out in Table 5.

The development of improved domestic powders for processing of reliable ceramics has been consistently identified as a high priority need. Relatively high quality powders have become available recently, but the powders are expensive, and are provided only by foreign sources. In our program, pilot scale and pre-pilot facilities have been developed for the synthesis of high quality silicon carbide and silicon nitride powders. These tasks have significant industry cost shares - 60 and 20%. A patent has been issued for a unique method of synthesis of high purity silicon nitride powder precursor. The production of sufficient quantities of powder for meaningful evaluation of processability and sintering optimization is ongoing; we expect to transfer this technology to the engine programs in FY 1991. An improved process of melting and rapid solidification to form high purity zirconia powders was developed and used in the development of transformation-toughened ceramics with improved microstructures and properties.

A university program is in place to develop ultra-low thermal expansion ceramics that are stable to 1200°C. Two compositions have already been identified as capable of meeting the program's goals. The university is negotiating with domestic ceramic companies to participate in the property optimization phase of the task in order to transfer the technology.

Two large, highly cost-shared industry programs have been initiated to develop advanced processing and in-process inspection technology for monolithic silicon nitride. These programs are the focus of our thrust to develop highly reliable ceramics, which has consistently been identified as the highest priority technology need. Both of these advanced processing tasks are large enough to allow the industry contractors to develop multidisciplinary teams under the direction of the principal investigator, as was recommended by our National Materials Advisory Board advisory committee. Both industry contractors are also

Fig. 11. Technical plan and major milestones for the Ceramic Technology for Advanced Heat Engines Project.

Table 5. Present (FY 1989) status of technology relative to original plans and goals.

GOAL	FY83	FY88	FY93	REFERENCE		
				WBS NO.	PUBLICATIONS & PATENTS	TABLES & FIGURES
MATERIALS & PROCESSING						
<i>POWDER</i> (TABLE 6)				1112, 1123 3517, 4116	28-32	
HIGH QUALITY		✓	✓		33	
MODERATE COST			✓			
DOMESTIC SUPPLY			✓			
MONOLITHIC CERAMICS						
HIGH RELIABILITY VIA ADVANCED PROCESSING (TABLE 7)			✓	1141, 1143		
HIGH-TEMPERATURE STRENGTH		✓	✓		34-35	
TIME - DEPENDENT STRENGTH			✓		36	Fig.12
ADVANCED FORMING & PROCESSING			✓	1142	37-42	
IN - PROCESS NDE			✓	1141, 1143, 3511, 3515, 3516	12, 43-49	
LOW THERMAL EXPANSION			✓	1242		
COMPOSITES						
<i>TRANSFORMATION TOUGHENED</i>						
ENVIRONMENTAL DEPENDENCE		✓	✓	1232, 3314		
THERMAL STABILITY		✓	✓	1232		
ADVANCED PROCESSING		✓	✓	1232, 1233	10, 50-53	

Table 5. (Continued)

GOAL	FY83	FY88	FY93	REFERENCE		
				WBS NO.	PUBLICATIONS & PATENTS	TABLES & FIGURES
<i>WHISKER TOUGHENED</i>						
WHISKER COMPOSITE TECHNOLOGY		✓	✓	1221, 1223, 1224, 1225, 1231	54-65	
NET - SHAPE FORMING			✓	1221, 1223, 1224		
TIME - DEPENDENT STRENGTH		✓	✓			Fig. 13
OPTIMIZED WHISKER PROPERTIES			✓			
<i>COATINGS</i>						
CONTACT STRESS		✓	✓	1312, 2211	11 66	
WEAR RESISTANT			✓	1331, 1332		
THERMAL BARRIER		✓	✓		67-69	
CORROSION RESISTANT			✓	1311, 1312		
<i>JOINTS</i>			✓	1411, 1412, 1413, 1421	70-72	
DESIGN METHODOLOGY						
<i>FRICTION AND WEAR</i>						
ENGINE SIMULATION RIG		✓	✓	2221	73-76	
<i>ADVANCED STATISTICS</i>			✓	2313	77	

Table 5. (Continued)

GOAL	FY83	FY88	FY93	REFERENCE		
				WBS NO.	PUBLICATIONS & PATENTS	TABLES & FIGURES
DATA BASE AND LIFE PREDICTION						
<i>TENSILE TEST</i>		✓	✓	3214, 3215, 3216, 3314	78-80	Fig. 14
<i>CYCLIC FATIGUE</i>		✓	✓	3214		
<i>DATA BASES</i> (INCLUDES AMBIENT AND HIGH-TEMPERATURE STRENGTH, FAST FRACTURE AND TIME-DEPENDENT STRENGTH, AND ENVIRONMENTAL EFFECTS).						
TRANSFORMATION - TOUGHENED		✓	✓	3117, 3113, 3211, 3213, 3314, 3315	10, 81-92	
Si ₃ N ₄ - SiC			✓	3117, 3214, 3216, 3217, 3314, 3315, 3412	93-95	
WHISKER - TOUGHENED			✓	3117, 3213, 3214, 3216, 3217, 3413	96-98	
<i>LIFE PREDICTION</i> (INCLUDING NDE)			✓	3222, 3223	99-100	

Table 6. Property goals for silicon carbide and silicon nitride powder development

1. Potential for low cost (<\$20/lb).		
2. High purity:	<u>SiC</u>	<u>Si₃N₄</u>
Cation	<0.1% Total	<0.1% Total
Anions		
Oxygen	<0.5%	<1.0%
Chlorine	<100 ppm	<100 ppm
Sulfur	<100 ppm	<100 ppm
3. Submicron particles, narrow size distribution, high surface area (>10 m ² /g).		
4. Pressureless-sinterable to high density (>98% of theoretical).		
5. Process amenable to doping with sintering aids.		
6. Process scalable to tons/year.

Fig. 12. Creep data for silicon nitride containing 6% yttria and varying concentrations of alumina. Data courtesy of GTE Labs. The 0% alumina ceramic is representative of the next generation of silicon nitride ceramics, which will contain no alumina, and have improved creep behavior.

Fig. 13. Creep behavior of silicon nitride matrix composite containing 30% SiC whiskers relative to the monolithic ceramic. Data courtesy of GTE Labs. Whisker-toughened composites have improved creep resistance and are less likely to deform in service.

Table 7. Property goals for monolithic silicon nitride and silicon carbide ceramics made by advanced processes.*

Room environment

Silicon carbide	
Mean tensile strength	500 MPa
Weibull modulus	20
Silicon nitride	
Mean tensile strength	900 MPa
Weibull modulus	20

Air environment, 1230°C

Silicon carbide	
Silicon nitride	
Mean tensile stress-rupture strength, 100 h	350 MPa

Air environment, 1370°C

Silicon carbide	
Silicon nitride	
Mean tensile strength	500 MPa

*(Tensile specimens are to have a gage section greater than 2 cc in volume.)

Table 8. Program tasks identified by WBS number

WBS No.	Company Name	Title of Project	Period of Performance
1.0 Materials and Processing			
1.1 Monolithics			
1112	Carborundum	SiC Powder Synthesis	08/84-01/89
1116	Southern Illinois University	Turbomilling of SiC Whiskers	06/87-09/90
1117	Keramont	TiB ₂ Whiskers	06/88-02/90
1118	NIST	Powder Characterization	11/88-10/90
1121	AMTL	Sintered Si ₃ N ₄	02/84-06/91
1123	Ford	Si ₃ N ₄ Powder Synthesis	02/85-12/89
1124	ORNL	Microwave Processing of Si ₃ N ₄	Ongoing
1141	Norton	Processing Monolithics	01/89-11/92
1142	ORNL	Improved Processing	Ongoing
1143	GTE Laboratories	Processing Monolithics	10/89-03/93
1144	University of California	Processing Science for Si ₃ N ₄ Ceramics	10/89-09/92
1145	Sullivan Mining Corporation	Synthesis/Fabrication of Si ₃ N ₄ Ceramics	New, 3 years
1.2 Ceramic Composites			
1221	Garrett Ceramic Components Division	Whisker-Toughened Si ₃ N ₄ (Slip Cast)	02/85-04/91
1223	GTE Laboratories	Whisker-Toughened Si ₃ N ₄ (Injection Molded)	06/85-03/90
1224	Norton	Glass-Encapsulated HIP Si ₃ N ₄ Composites	09/86-01/90
1225	University of Michigan	Fabrication of Si ₃ N ₄ /SiC Composites/Liquid Phase Sintering	01/87-07/90
1231	ORNL	Dispersion-Toughened Oxide Composites	Ongoing
1232	Norton	Synthesis/Processing of Transformation-Toughened Ceramics	11/85-09/90
1237	Ceramatec	Development of Toughened Ceramics	10/85-06/90
1242	VPI&SU	Ultra-Low Expansion Ceramics	05/86-10/92
1.3 Thermal and Wear Coatings			
1311	ORNL	Advanced Coating Technology	Ongoing
1312	GTE Laboratories	Oxidation-Resistant, Low Contact Stress Ceramic Coatings	12/86-09/91
1331	Caterpillar	Wear-Resistant Coatings	10/87-06/90
1332	Cummins	Wear-Resistant Coatings	07/87-09/90
1.4 Joining			
1411	ORNL	Metal-Ceramic Brazing	Ongoing
1412	GTE Laboratories	Metal-Ceramic Joining	08/87-12/91
1413	Battelle	Metal-Ceramic Oxides Joining	08/87-07/90
1421	Norton	Ceramic-Ceramic Joining	08/87-10/90

Table 8. (Continued)

WBS No.	Company Name	Title of Project	Period of Performance
2.0 Materials Design Methodology			
2.1 Modeling			
2111	University of Tennessee	Microstructural Modeling of Cracks	06/87-02/92
2.2 Contact Interfaces			
2211	GTEC	High Temperature Coatings to Reduce Contact Stress	02/84-08/87
2212	University of Tennessee	Coating Adherence Studies/ Ion Beam Mixing	07/85-09/90
2221	Battelle	Dynamic Interfaces	09/84-07/90
2.3 New Concepts			
2313	GE	Advanced Statistical Concepts	12/84-02/91
3.0 Data Base and Life Prediction			
3.1 Structural Qualification			
3111	NIST	Failure Analysis	07/85-10/90
3112	ORNL	Physical Properties	10/86-09/89
3113	Ricardo-ITI	Radiant Heat Transfer in Ceramic Diesel Components	11/85-09/88
3114	ORNL	Microstructural Characterization of SiC and Si ₃ N ₄	Ongoing
3117	ORNL	Project Data Base	Ongoing
3.2 Time-Dependent Behavior			
3211	AMTL	Characterization of Transformation-Toughened Ceramics	02/84-06/91
3213	ORNL	Fracture Behavior of Toughened Ceramics	Ongoing
3214	ORNL	Cyclic Fatigue of Toughened Ceramics	Ongoing
3215	ORNL	Tensile Stress Rupture Development	Ongoing
3216	ORNL	Rotor Data Base Generation	Ongoing
3217	NASA-Lewis Research Center	Toughened Ceramics Life Prediction	12/87-12/90
3222	Allison	Life Prediction	11/88-12/92
3223	Garrett	Life Prediction	04/89-03/93
3.3 Environmental Effects			
3314	University of Dayton	Environmental Effects in Toughened Ceramics	07/87-08/90
3315	ORNL	LHR Diesel Coupon Tests	Ongoing
3316	Garrett Ceramic Components Division	Component Testing	10/89-10/90
3317	Carborundum	Component Testing	New, 1 year

Table 8. (Continued)

WBS No.	Company Name	Title of Project	Period of Performance
3.4 Fracture Mechanics			
3412	North Carolina A&T State University	High Temperature Tensile Testing	10/84-09/90
3413	NIST	Tensile Creep Testing	07/85-10/90
3414	Vanderbilt	Fracture Toughness of Thin Coatings	02/88-12/89
3415	Rice University	Development of Fracture Toughness Microprobe	New, 1 year
3.5 NDE Development			
3511	ORNL	Nondestructive Evaluation	Ongoing
3513	Radiation Science, Inc.	Synchrotron Radiation for Computed Tomography	06/88-07/89
3515	Argonne	Computed Tomography	10/85-09/91
3516	Argonne	NMR Inspection of Green Ceramics	06/87-12/91
3517	ORNL	Powder Characterization	Ongoing
3518	University of Wisconsin-Madison	Spectroscopic Characterization	02/89-01/92
3519	Penn State	Surface Adsorption	02/89-01/92
3520	Rutgers University	Surface Thermodynamics	02/89-01/92
3521	ORNL	NDE Standards for Advanced Ceramics	Ongoing
Technology Transfer			
4112	ORNL	Technology Assessments and Planning	Ongoing
4115	ORNL	International Exchange Agreement	Ongoing
4116	NIST	Standard Reference Materials	07/85-10/90

participants in the ATTAP Program and have plans in place to transfer the technology from their advanced processing tasks directly into the fabrication of improved components for ATTAP.

An industry program to develop and optimize transformation-toughened ceramics has resulted in the development of an improved powder synthesis method and two compositions which, when processed by the methods developed in the program, yield ceramics that meet the program goals. A number of near-term commercial applications for these materials have been spun off from the program. Property optimization will be completed in FY 1990.

A new family of ceramics toughened with single crystal whiskers was invented at ORNL in 1983. The processing, whisker-matrix interfacial behavior, and mechanical properties were first developed for alumina ceramics. Virtually all the mechanical properties of alumina: strength, toughness, creep and other time-dependent strength behavior, and thermal shock resistance, are enhanced in the composite relative to the monolithic matrix material. Our major emphasis was shifted to silicon nitride ceramics beginning in FY 1988; similar composite behavior has been developed for silicon nitride (see, for example, Fig. 13). This technology is expected to begin impacting the ATTAP Program in early FY 1990 when the first components made from whisker-toughened silicon nitride will be delivered. Mechanical reliability issues for the composites are analogous to those for monolithic ceramics; much of what is learned in the Advanced Processing of Monolithics programs will be directly transferable to the composites. However, the silicon carbide whiskers introduce additional variables, which will be resolved to provide highly reliable ceramic matrix composites.

Industry programs are in place to develop ceramic coatings for resistance to contact stress damage and corrosion of silicon nitride and silicon carbide and for wear resistance of metal alloys. We have shown conclusively that oxide coatings on silicon nitride and silicon carbide are effective in eliminating contact stress damage and sticking of gas turbine components. An adherent, oxidation-resistant coating has now been developed and successfully tested at temperatures to 1250°C. Additional work is in progress to extend the performance to 1370°C. These coatings are expected to be effective in reducing corrosion due to salt introduced in the fuel or from the atmosphere.

Two diesel engine manufacturers are engineering and evaluating coatings for piston ring-cylinder wall applications, to reduce friction and wear in advanced engines. Reference processes will be chosen in FY 1989.

Parallel programs are in place in industry to develop ceramic joining technology for joining (1) silicon nitride or silicon carbide to silicon nitride or silicon carbide, (2) the above ceramics to metal alloys, and (3) oxide ceramics to other oxide ceramics or to cast iron. Each of these programs has a strong analytical task in prediction and evaluation of stresses due to differential thermal expansions of substrate and joint materials, so that models may be developed to allow the routine design of reliable joints. This technology is expected to be transferred to the engine programs by FY 1992.

There are two principal tasks in Design Methodology, development of advanced statistical tools and evaluation of friction and wear of candidate engine materials. The design of components with ceramics requires that strength be treated as a statistical parameter, using Weibull statistics. Many of the tools needed to realistically use Weibull statistics were not available when we began. An industry task was begun in 1984 and has continued to the present to develop the required statistical and mathematical tools. A methodology has now been developed for determining Weibull modulus from data on different-sized test bars. This will be extended to different sizes and shapes of test bars, arbitrary stress states, and an estimator of the confidence of the Weibull modulus so determined. This work will be integrated into the Ceramic Life Prediction task by means of the principal investigators directly participating in that task, and incorporated into a computer design code.

Friction and wear of candidate diesel engine materials are being evaluated in a rig that simulates the conditions in a low heat rejection diesel engine, but is much less expensive and time-consuming to run. The ranking of materials by friction coefficient from these tests has been shown to qualitatively agree with results taken directly from engines. The rig is now being used to evaluate new candidate materials and higher temperature lubricants as they are developed.

In Data Base and Life Prediction, we have developed and transferred to industry the hardware that makes uniaxial tension testing of ceramics a practical reality (Fig. 14). Industrial designers have always needed tensile strength

Fig. 14. Tensile testing machines in the High Temperature Materials Laboratory, Oak Ridge National Laboratory. The development of practical tensile testing of ceramics is having a revolutionary effect in both materials development and mechanical characterization

data, but the needed data were not available. Tensile testing, including fast fracture, fatigue, and creep testing has become an important element in our program, and is having a revolutionary effect on ceramic design and life prediction technology.

Cyclic fatigue testing, done in uniaxial tension, is a second major breakthrough. Engine component designers have dealt with cyclic fatigue problems in metals for many years, and have been reluctant to run ceramic components in their engines without prior knowledge of the cyclic fatigue behavior. Cyclic fatigue testing has become an integral part of our efforts in mechanical property characterization.

A very extensive mechanical property data base has been developed for transformation-toughened ceramics and published in hard copy. These data include characterization of strength degradation at high temperatures and also at 200-300°C, which was identified early on in the program as an important issue. The time- and environment-dependent strength at elevated temperatures has been characterized for a large number of both domestic and foreign materials. This effort has shifted its emphasis to silicon nitride and silicon carbide ceramics in support of the Ceramic Life Prediction efforts and as design data for ATTAP.

Two large, cost-shared programs were begun in early FY 1989 to develop and demonstrate methodology for predicting the service life of specific engine components from various test bar data. These programs include the incorporation of nondestructive testing (NDE) methods and data into an Integrated Life Prediction methodology. These programs are large enough to allow the industry contractors to form multidisciplinary teams under the control of the principal investigator, as recommended by our NMAB advisory committee.

An in-depth needs assessment of NDE revealed that the highest priority needs were for in-process NDE inspections, as part of an advanced processing methodology for high reliability; and for NDE inspections as part of an integrated Ceramic Life Prediction methodology. As a result, the major focus of NDE tasks in our program is in the Advanced Ceramic Processing and Ceramic Life Prediction programs. In addition to those efforts, we have developed ultrasonic and X-ray inspections to augment mechanical testing and have procured a state-of-the-art X-ray tomography unit at ORNL for the use of the participants in the program.

4.3 RECOMMENDATIONS FOR FUTURE WORK

4.3.1 Cost Effective Ceramics for Near-Term Applications in Heat Engines

A critical need has been identified for a program to systematically reduce the cost of ceramic components for near-term (within five years) use in gasoline and diesel engines and ceramic gas turbine engines. The anticipated reduction of cost due to scale up alone will not be enough to make the cost of ceramic components competitive. A preliminary assessment of needs has identified the following program elements: Economic Process Modeling; Machining and Finishing; Raw Materials; Processing and Process Equipment; Yield Improvement by Statistical Process Control, Robotics, and Intelligent Processing; Engine Subsystem Economic Design Studies; Testing and Performance Standards; and Database. A new project within the Advanced Materials Development Program to address these needs, beginning in FY91 and continuing for five years, is recommended.

4.3.2 Materials for Alternate Fuel Engines

The Alternative Motor Fuels Act of 1989 and the proposed Clean Air Act will create numerous materials problems for the U.S. engine industry, particularly with compatibility of materials with alcohol fuels; corrosion; and tribology of fuel pump and fuel injector components. The industry will have to find near-term solutions to these problems by FY92. However, the near-term solutions are expected to be expensive, involving overdesign of components in order to meet the statutory deadlines. The need for a focused five year project to develop cost-effective materials solutions for these problems has been identified. This project, which would involve metal alloys and polymers as well as ceramics, may be developed as a project within the Advanced Materials Development Program.

5. MANAGEMENT PLAN

5.1 MANAGEMENT PLAN DOCUMENT

The Office of Transportation Systems, under the Assistant Secretary for Conservation and Renewable Energy, is responsible for managing this program and the advanced automotive heat engine programs. DOE is responsible for establishing the program goal and objectives, implementation policies, and funding levels, and is also responsible for coordination with other federal agencies and DOE offices.

In accordance with the DOE policy of decentralizing project management to field and laboratory sites with established capabilities, DOE-OTS assigned responsibility for the day-to-day management of the Ceramic Technology for Advanced Heat Engines Program to the Oak Ridge Operations Office (ORO) as the principal field office and to ORNL as the lead national laboratory. ORNL's project management responsibilities include technical project planning, implementation, and control.

This program is managed in accordance with a management plan prepared by ORNL and approved by OTS (ref. 101). The management plan specifies the OTS, ORO, and ORNL organizational interfaces, responsibilities, program implementation and procurement policies, and management controls. The DOE, ORO, and ORNL organizational interfaces are shown in Fig. 15. The formal program direction and budget guidance are provided to ORO by OTS through program guidance letters. The ORO is responsible for managing the prime contract, currently with Martin Marietta Energy Systems, Inc., for the operation of ORNL.

The management controls for this program include financial and technical progress reports and periodic program review and coordination meetings. Bimonthly project review meetings are conducted. Bimonthly management reports provide technical highlights and details of the financial, procurement, and milestone status of all in-house and subcontracted work. Semiannual technical progress reports, topical reports, and open literature publications on appropriate completed work are issued. Program results are also reported at annual DOE-OTS Contractors' Coordination meetings.

ORNL is responsible for implementing the program direction with budget guidance from OTS

Fig. 15. Overview of DOE, ORO, and ORNL organizational interfaces.

through ORO. A program implementation plan is prepared annually by ORNL in the form of a work authorization system (a three-year annual operating plan) for approval by DOE. The plan includes detailed cost projections, funding distribution, milestones, and technical descriptions of in-house and subcontracted tasks.

5.2 PROGRAM ADVISORY AND CONSULTATIVE GROUPS

A program review and workshop for the Transportation Program (Electric Vehicles, Advanced Gas Turbine, Low Heat Rejection Diesel, and Advanced Materials - Ceramic Technology for Advanced Heat Engines) was held by the Assistant Secretary for Conservation and Renewable Energy, U. S. Department of Energy, in Oak Ridge, Tennessee, on November 19-20, 1986 (ref. 102). Separate industry panels were formed for each of the programs to be reviewed. The panels met first in a plenary session, and then in separate sessions for each program panel. The observations and recommendations of the Advanced Materials Panel were as follows:

Observations: Current ceramic materials do not perform adequately in heat engines, failure varies from infant mortality during proof testing to time-dependent failure during service. The cost of current ceramics is still too high (cost is the responsibility of the ceramic suppliers, not the government programs). Failure is generally catastrophic; critical issues are flaw size, fracture toughness, time-dependent failure, and Weibull modulus as a measure of reliability. The engine manufacturers have good capability for finite element analysis and design relative to bend strength, Weibull modulus, thermal expansion, and thermal conductivity; but do not have predictive methodology for time-dependent properties and impact conditions. The engine manufacturers need to quantify the material property requirements for their engines. The ceramic community does not have adequate methodology for characterizing fracture toughness and tensile strength. Ceramic materials have been in a constant state of evolution; as a result, large data bases do not exist. One can compare structural ceramics today to the early stages of superalloy development.

Summary and Recommendations: The current Advanced Materials Development Program is directed toward addressing specific needs of advanced engines. The panel concurs with the

program priorities and distribution of funds among program elements. The ceramic program needs the flexibility to adapt to changing program priorities as the technology is developed. The panel stated that coordination between the ceramic program and the engine programs should be continued and strengthened.

The National Materials Advisory Board completed an assessment of our program in 1987 (ref. 103). A committee, established within the 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. The committee's recommendations, along with DOE's responses, were as follows:

1. The committee supports the program, the Program Plan, and the overall framework of the program. They recommend the Plan be updated as needed, when funding and technical considerations dictate.

We are in the process of revising the Program Plan.

2. The committee recommended that our program be coordinated much more closely with the new Advanced Turbine Technology Applications program than had been with the Advanced Gas Turbine program.

We concur with the committee. The goals and schedules of these programs are much more amenable to close coordination than was the case with the AGT program. We had the first of a series of coordination meetings at ORNL on September 14, 1987. This meeting involved DOE program management, ORNL and NASA project management, the two ATTAP contractors, and the major ceramic subcontractors.

3. An analysis of the progress of the program should be made annually and used to evaluate and integrate the accomplishments of the individually funded projects.

We now prepare a very extensive annual operating plan (AOP), which is used monthly in our detailed project reviews, and which is revised on at least a quarterly basis.

4. The committee recommended that plans and priorities be reevaluated annually in concert with recommendation 3.

By reviewing the entire program against the AOP on a monthly basis, we exceed the committee's recommendation.

5. The committee suggested that programs be funded at a higher level, instead of many small programs, in order to form critically sized groups, and to delegate technical coordination to the principal investigator for the effort.

We concurred with the committee. Four new programs are now being initiated. Two are in Ceramic Life Prediction and are funded at \$2.5M and \$3.3M including 20-30% cost sharing. The other two are in Advanced Ceramic Processing at funding levels of \$5.4M and \$4M, again including 20-30% cost share.

6. The committee recommended the contracting procedures for the program be reviewed and changed in order to reduce the time required to place a contract. In particular, problems with DOE advanced patent waiver requests were singled out as an area where the process might be streamlined.

We are continuing to place contracts by competitive bidding, as originally planned. The law regarding waiver of patent rights has been changed to make the waivers almost automatic for universities and small businesses, but waiver requests for large industrial companies must still be handled on a case-by-case basis. Legislation which would streamline the process for large companies has been introduced in Congress, but none has been passed to date. The ORNL project office continues to work with the DOE Oak Ridge Operations Office in order to facilitate the processing of the patent waiver requests. (See section 7 for a list of patent waivers granted.)

7. The committee recommended that a significant effort in the generation of a mechanical properties data base for high temperature ceramics be initiated.

We have developed a high-temperature tensile testing method and testing apparatus which now make it possible to generate the kind of engineering data that mechanical designers can realistically use. We are now beginning a very significant effort, with projects at the University of Dayton, ORNL, North Carolina A&T, and the National Institute of Standards and Technology (NIST) to generate the data and compile the data in a user-friendly electronic data base.

8. The committee recommended that an engineering cost analysis be done and goals set in the reduction of material cost.

We agree that cost is important, but feel it is

too early to enter into cost reduction programs, and those programs might better be done by industry. We must first develop technically adequate ceramics, then means of reducing the cost can be addressed. The CE Program Review 1986 report (ref. 102) documents the industry perspective that cost reduction programs are best left to the private sector. We are requiring certain principles of cost-effective engineering in our program (e.g., all our ceramic material development efforts require near-net-shape processing), and there is great emphasis on quality and yield in our program.

9. The committee questioned the cost-effectiveness of the work done in cooperation with Germany and Sweden in the IEA Annex II agreement. In particular, they felt that testing of material strength in flexure should be deferred until such time that tensile testing could be done. They suggested the American Society for Testing and Materials (ASTM) and National Institute of Standards and Technology be included in the effort, and that Japan be brought into the agreement.

The U.S. participants in Annex II are paying their own way. The program is only paying the cost of specimens and management. The objective of this effort is to develop international standards. The effort required to generate consensus standards involves round robin testing and the development of a consensus. Flexural testing is the state-of-the-art for most of the participants, who have no knowledge of tensile testing, and who must be shown that the additional cost of tensile testing is warranted. The National Institute of Standards and Technology has been brought into the effort per the committee's recommendation. NIST has an active role in all subtasks, and in fact, has the role of task leader for the U.S. for Subtask II, Powder Characterization.

The ASTM works entirely by means of volunteers from other organizations. A new ASTM Advanced Ceramics Committee (C28) has been formed this year, with the leadership coming from participants in our IEA program. The key people in the ASTM with respect to structural ceramics are, in fact, already participants in Annex II. We do not think it feasible for ASTM to participate as an organization. The Japanese were approached initially and several times since, and have opted not to join Annex II. However, it is planned to include Japan in the next set of subtasks, which is now being planned and which will likely include

tensile testing as the committee recommended.

10. The committee recommended we abandon our technology transfer program and revert to the published DOE guidelines.

We strongly disagreed with the committee on this point. Our policy has been to involve industry in the planning and implementation of the program, which has been very successful and has been highly praised by industry. Over half of the R&D funds in the program is allocated to industry subcontracts. The suggested alternative would be to do all the R&D at universities and national laboratories, and then "teach" the people in industry what was learned.

11. The committee recommended more emphasis be placed on the development of toughened ceramic composites.

We concur in this recommendation, and have already begun phase II of a very ambitious, and so far successful, ceramic composite development program.

6. RESOURCE PLAN

The continuing and new Government funding for structural ceramics research and development, since the start of the CTAHE program in FY 1983, is given in Table 9. Estimated funding is given for FY 1990 through FY 1993. While the funding for ceramics is spread throughout the Federal Government, the amount outside the DOE Office of Transportation Systems programs applicable to automotive heat engines is probably about 30%. The other programs are either for very basic ceramic research or emphasize ceramic fiber composites or very high temperature (3000-4000°F) applications. This situation is different from when the CTAHE program began, when similar materials objectives among the Federal ceramic programs required very close coordination to avoid unwanted duplication of effort.

The Advanced Materials Development (ceramic research) program, together with the companion Vehicle Propulsion R&D (component/system development) program are today the only United States programs devoted to brittle ceramic technology development and proof-of-concept demonstration in gas turbine and diesel engines. The current situation goes back to 1978 when the Defense Advanced Research Projects Agency program for Brittle Materials Design, High Temperature Gas Turbine Engines, ended and the lead for this technology R&D transferred to the DOE's Advanced Gas Turbine program. (The Army depends to a large degree on the ceramic technology base generated by the DOE CTAHE Project.) Both DOE and NASA recognized that further fundamental ceramic research would be needed before ceramics could be proven in high performance structural applications. In 1982, NASA and DOE both made plans for ceramic technology for advanced heat engines programs. In planning and implementing these programs, there was very close coordination between the DOE/ORNL and NASA Lewis Research Center. However, during the first few years, the DOE CTAHE program grew in size and funding support, while the NASA program did not. Eventually the NASA program emphasis was shifted from monolithic ceramics to continuous fiber reinforced ceramic composites and very high temperature (4000°F, recently revised to 3000°F) monolithics and composites, because of NASA's priority interest in the space shuttle, space station, and the aerospace plane programs.

Table 9. Structural ceramic technology: Federal government funded R&D
(in millions of dollars)

	FY 1983	FY 1984	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989	Estimated FY 1990	Estimated FY 1991	Estimated FY 1992	Estimated FY 1993
Department of Energy:											
Conservation and renewable energy:											
Vehicle propulsion	11.4	12.7	11.9	10.0	12.0	12.0	13.5	9.0	9.0	9.0	9.0
Advanced materials	3.5	4.8	6.0	8.7	12.9	13.5	15.0	15.0	16.0	15.0	15.0
Industrial programs	1.0	2.3	1.7	1.5	1.9	1.8	2.3	2.5	3.0	3.0	3.0
Energy utilization research	0.5	1.5	1.8	1.8	2.8	2.9	0.6	0.6	0.6	0.6	0.6
Fossil energy:											
Advanced research and technology development	1.0	1.1	1.5	1.2	2.0	2.5	2.7	2.6	2.6	2.6	2.6
Energy research:											
Basic energy science	3.0	4.4	4.6	4.5	4.5	4.0	4.0	4.0	4.0	4.0	4.0
NASA:											
Lewis Research Center	1.0	3.0	6.0	6.0	6.2	7.5	7.5	8.0	8.0	8.0	8.0
National Science Foundation	2.9	3.3	3.6	3.6	3.7	3.0	3.2	3.0	3.0	3.0	3.0
National Institute of Standards and Technology				2.2	2.4	3.0	3.0	3.0	3.0	3.0	3.0
Department of Defense:											
Defense ARPA	7.7	8.2	9.4	10.0	7.3	9.9	7.0	5.0	5.0	5.0	5.0
U.S. Air Force	3.0	3.4	4.7	4.7	2.5	4.3	4.0	7.0	8.0	7.0	5.0
U.S. Army	4.7	6.0	2.5	4.4	3.6	3.1	2.3	2.0	2.0	2.0	2.0
U.S. Navy	1.2	1.3	1.4	2.3	1.9	2.4	2.3	2.0	2.0	2.0	2.0
Total	40.9	52.0	55.1	60.9	63.7	69.9	67.4	63.7	66.2	64.2	62.2

Table 10. Projected Federal agency funding
for ceramic technology applicable to automotive heat engines

	FY 1983	FY 1984	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989	FY 1990	FY 1991	FY 1992	FY 1993	Grand Total
Department of Energy												
Advanced Materials	3.5	4.9	6.0	8.7	12.9	13.5	15.0	14.8	16.0	15.0	15.0	
Other DOE	6.3	8.7	8.6	7.7	8.8	11.0	12.2	13.9	13.5	9.8	7.4	
NASA	0.9	0.8	1.6	1.4	3.3	3.6	2.7	3.0	3.0	3.0	3.0	
National Science Foundation	1.5	1.7	1.7	1.7	1.9	1.5	1.6	1.5	1.5	1.5	1.5	
Department of Defense	5.0	5.7	5.4	6.4	4.6	5.9	4.7	4.8	5.1	4.8	4.2	
Total	17.2	21.8	23.3	25.9	31.5	35.5	36.2	38.0	39.1	34.1	31.1	333.7

Fig. 16. Funding by year for the period FY 1983-1993.

It is generally accepted that brittle ceramics must be proven in ordinary terrestrial applications before they will be considered for the more stringent reliability requirement applications for aerospace systems, or for large industrial power systems. The application of monolithic ceramics, whisker-toughened composites, and ceramic coatings in structural applications is a difficult challenge because these materials are brittle -- break suddenly under increasing stress. The emphasis now in most of the DoD, NASA, and other DOE programs is on continuous fiber ceramic reinforced ceramic composites, analogous to carbon-carbon composites, which fail "gracefully" -- break slowly under increasing stress. These fiber composites are being developed for the Strategic Defense Initiative (SDI), National Aerospace Plane (NASP), and other sophisticated military applications. These applications are quite different from the commercial automotive market where the ceramics must be both reliable and very low cost.

The original Program Plan estimated the total resources necessary for completion of the program to be \$140 million. A revised estimate, from a 1988 perspective of the total effort required to realize our goals (see Technical Plan), is \$300M over 10 years, of which approximately one third is to be provided by the DOE Advanced Materials Development Program. Estimates were made of the resources to be committed to relevant structural ceramic research by other government funding sources and a funding plan developed

Fig. 17. Cumulative funding for the period FY 1983-1993.

Fig. 18. Capital equipment funds for the period FY 1983-1993.

that took credit for all the applicable ceramic research expected in the U. S. government and industry (Table 10).

Table 10 was developed by estimating the fraction of the funds from each program that is relevant to our program plan. The factors used were as follows: Vehicles and Propulsion (ATTAP), 30% from 83-87, 50% from 88-93; Industrial Programs, 60% from 83-88 and 30% from 89-93, reflecting a change in emphasis toward continuous fiber composites. A factor of 50% was estimated for Energy Conversion and Utilization. A 50% factor was estimated for Fossil Energy AR&TD and for Basic Energy Science, as well as for the National Science Foundation and the National Institute of Standards and Technology budgets. A factor of 30% was used for NASA's programs for the reasons discussed above. A factor of 30% was used for DoD's programs, which are also largely concerned with continuous fiber composites and extremely high temperatures. The total resources available and pertinent are estimated to be about \$330M.

The funding for the CTAHE Project by year for the entire 1983-1993 period is shown in Fig. 16, and the cumulative funding for that period is shown in Fig. 17.

Capital equipment funds must be so designated. Operating funds cannot be used for capital equipment items, no matter how critically needed. As a rule, capital equipment funds equivalent to about 10% of the operating budget are needed. The capital equipment funding through FY 1989 has been erratic (Fig. 18), but has allowed the program to buy a state-of-the-art x-ray computed tomography inspection device, a high-pressure sintering furnace, and four tensile testing machines, as well as several smaller items. Special equipment items for advanced ceramic processing, testing, and inspection are critically needed to meet the goals of the program. Detailed equipment needs and justifications are included in the three year operating plan that is prepared annually for the CTAHE Project. The capital equipment funds appropriated through FY 1989 and requested from FY 1990 through FY 1993 are shown in Fig. 18.

7. PROCUREMENT PLAN

7.1 PROCUREMENT PROCEDURES

The cooperative involvement of U.S. industrial, government laboratory, and university communities has been instrumental in achieving the objectives of this program thus far. The major roles of ORNL in managing this program are to encourage the participation of qualified subcontractors, to coordinate the various R&D activities closely, and to disseminate the results of these activities to appropriate program participants and government agencies. Because ORNL subcontracts most of the program funding, informing potential subcontractors of current procurement policies is important.

Generally, R&D is accomplished by subcontracts with industrial research centers, universities, and DOE and other government research laboratories according to their staff and facility capabilities and their responsiveness to program needs. Industrial and university participants are selected on the basis of competitive research proposals submitted in response to a request for proposal (RFP). The contracting is done by Martin Marietta Energy Systems, Inc. (hereafter referred to as "Energy Systems"). All R&D contracting is done in accordance with DOE-ORO-approved purchasing procedures.

In most cases research of a specific nature is required, particularly from industrial sources; therefore, research proposals are solicited by Energy Systems RFPs. Proposals submitted in response to the RFPs are evaluated on technical merit by an evaluation team assembled by the project manager. The evaluation teams are comprised of technically and contractually qualified Energy Systems personnel chosen by the ORNL project manager in concert with the Energy Systems Purchasing organization. Expert consultants acting as technical advisors, and representatives from OTS, ORO, and other government agencies, may also participate on technical evaluation teams. Any information designated as proprietary shall be limited to evaluators signing a proprietary agreement. Proposals are selected based on the results of the evaluation team.

Although most procurements result from a competitive selection process, Sole-Source

Table 11. Status of advance patent waivers granted by DOE
for the Advanced Materials Program

Company	Title of Project
<u>Granted</u>	
Carborundum Company	SiC Powder Synthesis
Caterpillar	Wear-Resistant Coatings
Ceramatec	Development of Toughened Ceramics
Cummins	Wear-Resistant Coatings
Ford Motor Company	Si ₃ N ₄ Powder Synthesis
Garrett Ceramic Components Division	Whisker-Toughened Si ₃ N ₄ (Slip Cast)
GTE Laboratories	Whisker Toughened Si ₃ N ₄ (Injection Molded)
GTE Laboratories	Oxidation-Resistant, Low Contact Stress Ceramic Coatings
GTE Laboratories	Metal-Ceramic Joining
Ricardo-ITI	Radiant Heat Transfer in Ceramic Diesel Components
Norton Company	Glass Encapsulated HIP Si ₃ N ₄ Composites
Norton Company	Synthesis/Processing of Transformation- Toughened Ceramics
Norton Company	Ceramic-Ceramic Joining
Radiation Science, Inc.	Synchrotron Radiation for Computed Tomography
<u>Pending</u>	
Allison Turbine Division	Life Prediction Methodology
Garrett Auxiliary Power Division	Life Prediction Methodology
GTE Laboratories	Processing Monolithics
Norton Company	Processing Monolithics

Subcontracts are awarded when one source has an exclusive capability to perform the work within the time required and at a reasonable price. Unsolicited proposals are submitted to DOE HQ for processing and appropriate action, in accordance with DOE procurement regulations.

For R&D that might best be performed by other DOE laboratories, procurement is accomplished by an Energy Systems' Memorandum Purchase Order. ORO coordinates any necessary approvals with those field offices having purview over the concerned laboratory. In those instances in which R&D assistance is desired from a non-DOE government laboratory, ORO negotiates an Interagency Agreement with the other agency.

analysis, or testing capability for applications of interest to the industrial partner. The DOE regulations for collaborative agreements have been greatly simplified by passage of the Stevenson-Wydler Act, which provides authority for government laboratories to enter into cooperative research and development agreements (CRADAS), and the development of DOE strategy for implementation of the Stevenson-Wydler Act.

7.2 ASSIGNMENT OF PATENT RIGHTS

As a result of passage of Public Law 96-517, rules on patent rights of individuals, educational institutions, business firms, and the government have been modified. Rule changes concern ownership, disclosure, and commercial development of patented information and equipment and components. Generally, small businesses or nonprofit organizations within the meaning of Public Law 96-517 (Sect. 201, Chap. 38 of Title of the U.S. Code) can secure greater patent rights than those set forth in the DOE procurement regulations (Chap. 9-9). Small businesses and universities are automatically granted an advance waiver. For subcontractors not directly affected by this statute, DOE must consider each patent waiver petition on a case-by-case basis. However, experience has been that, under DOE procurement regulations, an advance patent waiver may be granted only if there is a waiver of subcontract fee plus direct cost-sharing of 20% or more of the total cost of the R&D. A list of the status of advance patent waivers granted by DOE for the Advanced Materials Program can be seen in Table 11.

In the case of national laboratory programs that may have near-term spinoffs, collaborative research agreements with industry will be developed. In collaborative programs typically there will be no funds exchanged, although there are provisions for funds-in and funds-out agreements. The government laboratory will leverage the in-house program work by cooperating with one or more industrial partners. The industrial partner will contribute to the national laboratory program by providing materials,

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