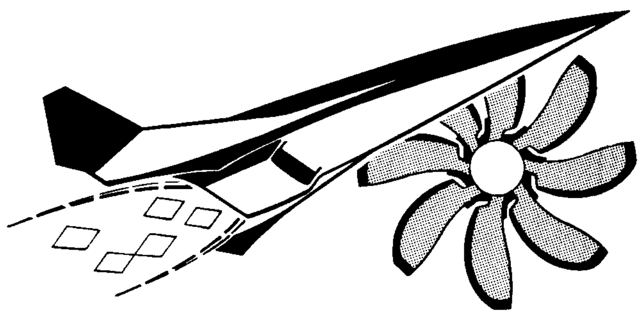
NASA Conference Publication 10003

Aeropropulsion '87

Session 1—
Aeropropulsion Materials Research



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Preprint for a conference at
NASA Lewis Research Center
Cleveland, Ohio, November 17-19, 1987

NASA

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National Aeronautics and
Space Administration

CONTENTS

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IMPACT AND PROMISE OF NASA AEROPROPULSION TECHNOLOGY

Neal T. Saunders
and
David N. Bowditch

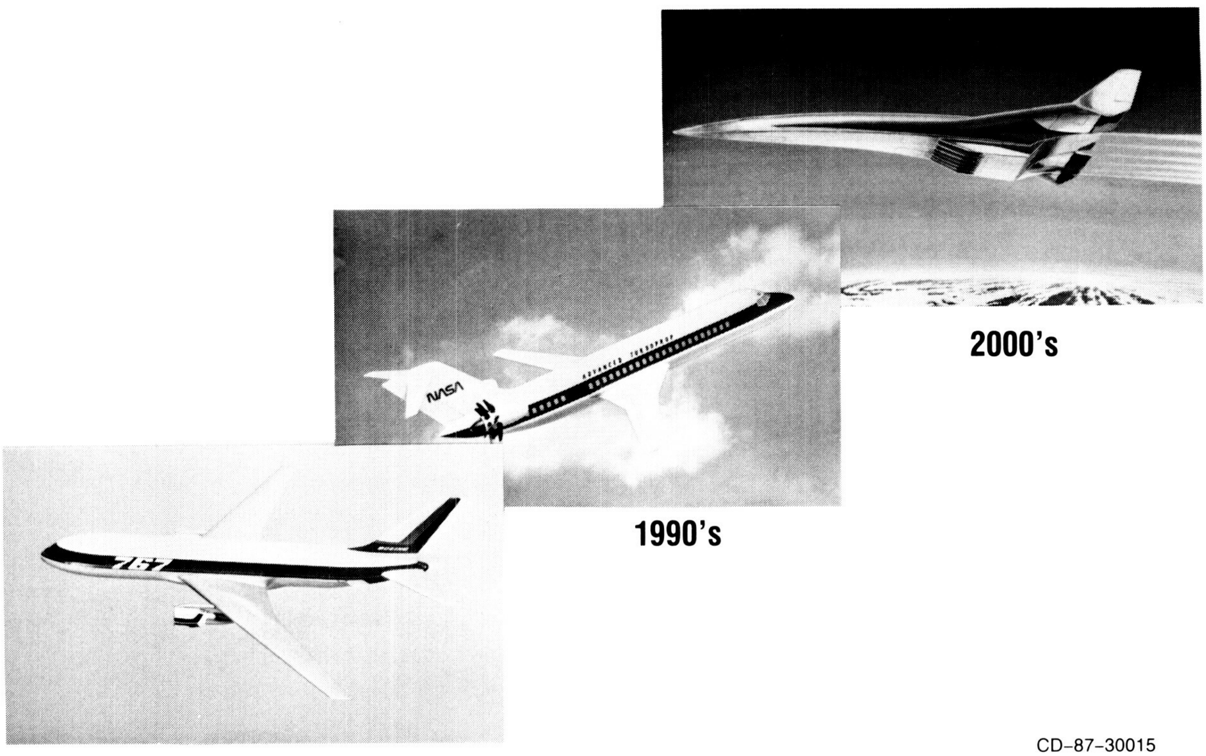
The aeropropulsion industry in the United States has established an enviable record of leading the world in aeropropulsion for commercial and military aircraft. NASA's aeropropulsion propulsion program (primarily conducted through the Lewis Research Center) has significantly contributed to that success through research and technology advances and technology demonstrations such as the Refan, Engine Component Improvement, and Energy Efficient Engine Programs. Some past NASA contributions to engines in current aircraft are reviewed, and technologies emerging from current research programs for the aircraft of the 1990's are described. Finally, current program thrusts toward improving propulsion systems in the 2000's for subsonic commercial aircraft and higher speed aircraft such as the High-Speed Civil Transport and the National Aerospace Plane (NASP) are discussed.

INTRODUCTION

Earlier this year, the aeronautics community commemorated the 50th anniversary of the first successful operation of a turbojet engine. This remarkable feat by Sir Frank Whittle represents the birth of the turbine engine industry, which has greatly refined and improved Whittle's invention into the splendid engines that are flying today. During the past 50 years, the U.S. aeropropulsion industry has developed an enviable record in leading the world in the continual development of new aircraft engines with improved performance, durability, environmental compatibility, and safety. NASA, as did its predecessor NACA, takes pride in assisting the development of this record as a long-time partner with U.S. industry in the creation and development of advanced technologies which have spurred each new generation of engines.

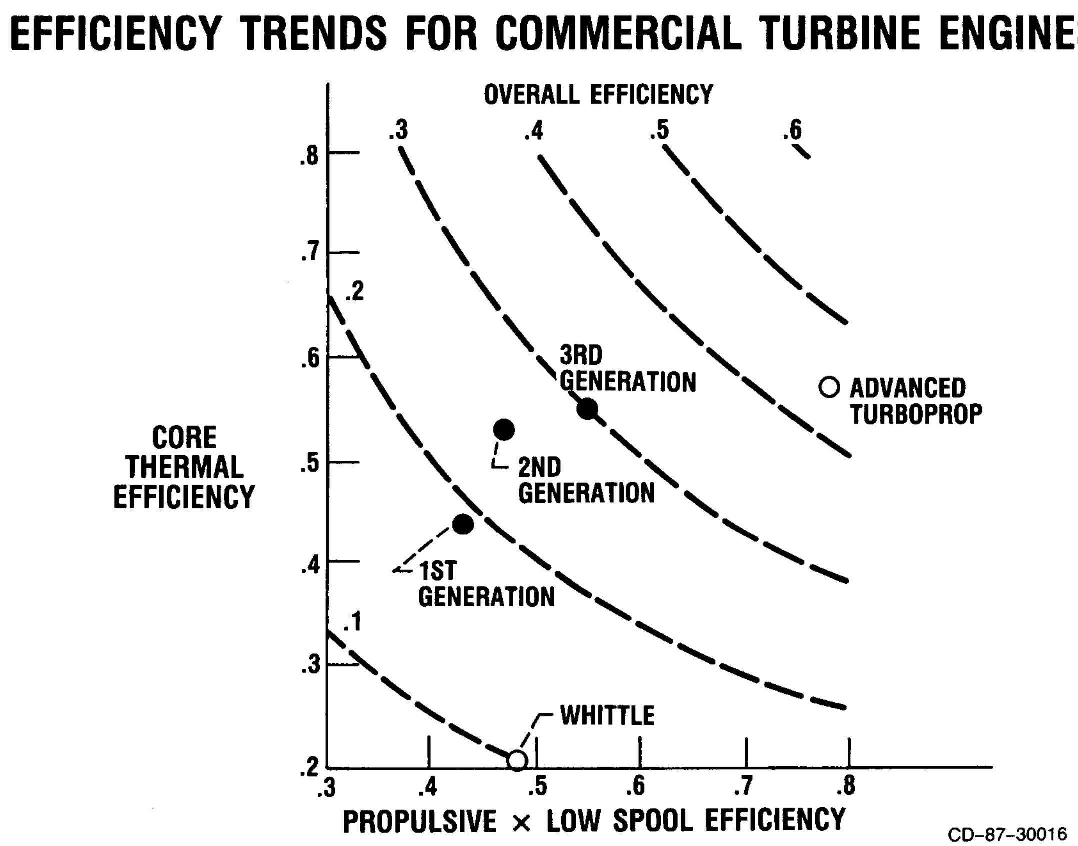
This presentation highlights some of the recent contributions of NASA's aeropulsion research and technology efforts. Several technology advances that emerged from NASA research efforts from the 1970's and early 1980's were instrumental in the development of high-bypass turbofan engines that are powering today's fleet of commerical transports. And some of our more recent efforts have been key to the development of advanced turboprop engines which will lead to the introduction of a new generation of transports in the mid-1990's. Also, we will describe some of the current research efforts that are aimed at advanced propulsion systems that might power transports in the 21st century. This includes advanced engines for both subsonic and high-speed transports such as the high-speed civil transport (HSCT) and the National Aerospace Plane (NASP).

IMPACT AND PROMISE OF NASA AEROPROPULSION TECHNOLOGY



EFFICIENCY TRENDS FOR COMMERCIAL TURBINE ENGINES

Fifty years after the Whittle engine first ran, it is interesting to review the improvement in efficiency of commerical turbofan engines. The thermal efficiency of the Whittle engine was relatively low due to its low pressure ratio and low maximum temperature. As improved materials and aerodynamics became available, these parameters increased dramatically, improving the core thermal efficiency for first-generation turbine engines. Second- and third-generation turbine engines benefitted from further increases in thermal efficiency and also obtained major improvements in propulsive efficiency by increasing the bypass ratio of the turbofan engine. Advanced turboprop engines will obtain further dramatic increases in propulsive efficiency by increasing the bypass ratio to its ultimate practical vale.

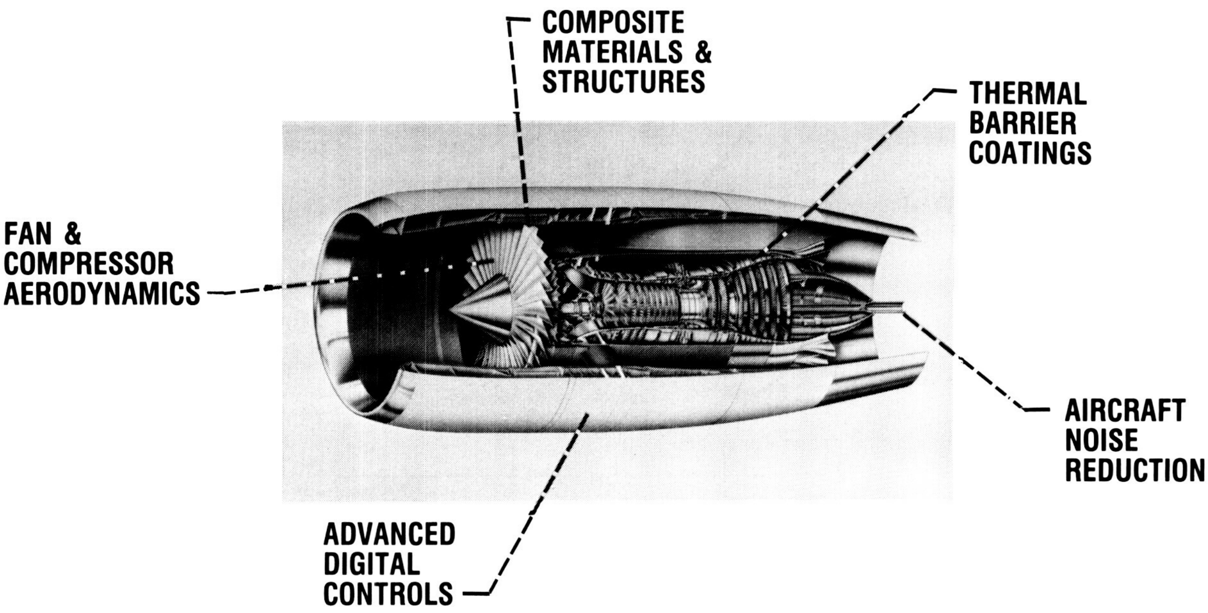


LEWIS CONTRIBUTIONS TO MODERN ENGINES

Contributions of NASA's Aeropropulsion Program have been many and varied, and some of the more significant technologies are listed on this figure. One of the more significant technology advances involved improved aerodynamic designs for fans and compressors. In the 1970's NASA, both through in-house and contract efforts, built and tested more than 100 single- and multiple-stage compressors and fans to develop and verify advanced design concepts such as high tip speeds, low source noise, controlled-diffusion blading, and low-aspect-ratio blading. These technologies were combined in the design of the compressors and fans of the Energy Efficient Engine Program, which provided unprecedented performance improvements. These components provide the basis for the fans and compressors on the newest commercial turbofan engines.

The other major NASA contributions listed in the figure (composite materials and structures, thermal barrier coatings, reduced noise and emissions, and advanced controls) are described in later figures.

LEWIS CONTRIBUTIONS TO MODERN ENGINES



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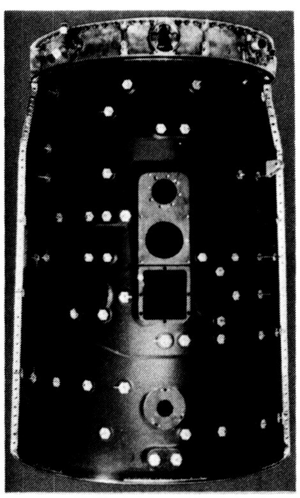
COMPOSITE MATERIALS AND STRUCTURES

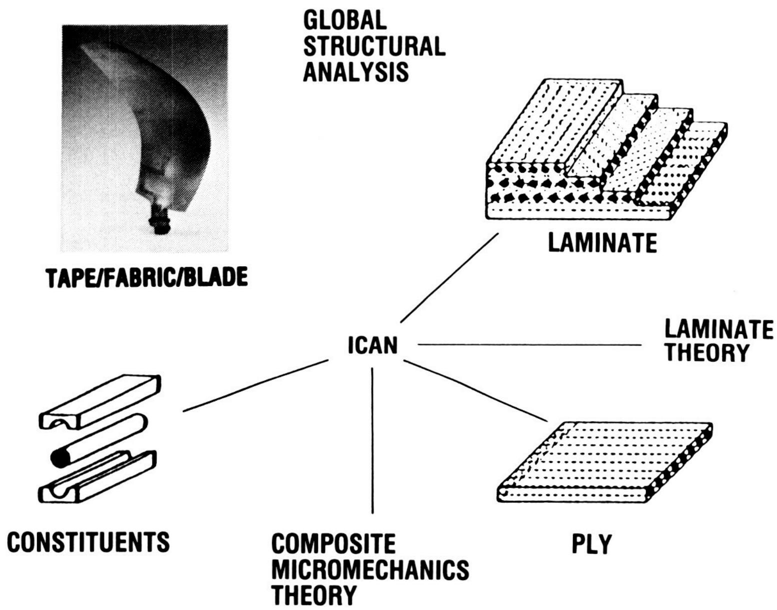
NASA Lewis Research Center has been a leader in the development of composite materials and the structural analysis necessary to provide significant reductions in engine weight and fuel usage. A PMR-15 polymer, developed at Lewis, is currently the nonmetallic composite matrix with the highest use-temperature (550 to 600 °F). Composites using graphite fibers in a PMR-15 matrix have been used to produce a lightweight fan duct for the F404 engine as illustrated in the left-side of this figure. Current research is aimed at extending the use temperature to 800 °F. For higher temperatures Lewis is investigating metal and ceramic-matrix composite materials.

To efficiently use the anisotropic composite materials, new analytical methods and computer codes had to be developed. Composites micromechanics and laminate theories have been developed through Lewis programs and incorporated into an integrated composites analyser code to predict the material properties necessary to design a component such as a fan or propeller blade. These contributions have provided significant weight reduction and permitted improved aerodynamics through thinner blades without the dampers necessary on the older metal blades.

COMPOSITE MATERIALS AND STRUCTURES



GRAPHITE/PMR-15
COMPOSITE DUCT WITH
TITANIUM FLANGES



INTEGRATED COMPOSITES ANALYSER

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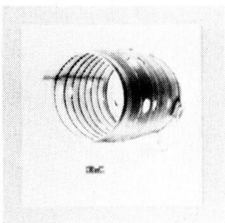
APPLICATIONS OF THERMAL BARRIER COATINGS

Ceramic thermal barrier coatings are being used in many of today's engines to extend the lives of metal parts used in combustors and turbines. The use of thermal barrier coatings by applying a ceramic coating onto a metal burner to turbine part to protect the metal and reduce its temperature was recognized in the 1960's. However, early attempts at its use were frustrated by the coating spalling off after short periods of use. NASA has led research on those coatings which has identified the failure mode as oxidation of the underlying metal and developed bond coatings and application procedures that have successfully prevented the coating failure. Increased reliability has resulted in the increased use of coatings in engines during the past two decades. Initial use was limited to a band-aiding approach to extend the life of combustor liners. During the 1980's improved thermal barrier coatings have been applied to selected areas, such as turbine vane platforms, to extend life and reduce cooling air requirements. As the technology of these coatings reaches full maturity, thermal barrier coatings will be extended to more critical areas, such as the aerodynamic surfaces of turbine blades.

APPLICATIONS OF THERMAL BARRIER COATINGS

FIRST GENERATION (1970'S)

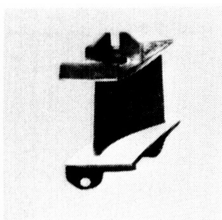
- EXTEND LIFE



COMBUSTOR LINERS

SECOND GENERATION (1980'S)

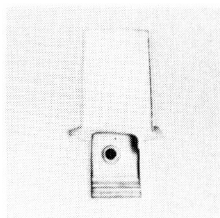
- REDUCE COOLING
- EXTEND LIFE



TURBINE VANE PLATFORMS

THIRD GENERATION (1990'S)

- EXTEND LIFE
- INCREASE TEMP.
- REDUCE COOLING



TURBINE BLADES

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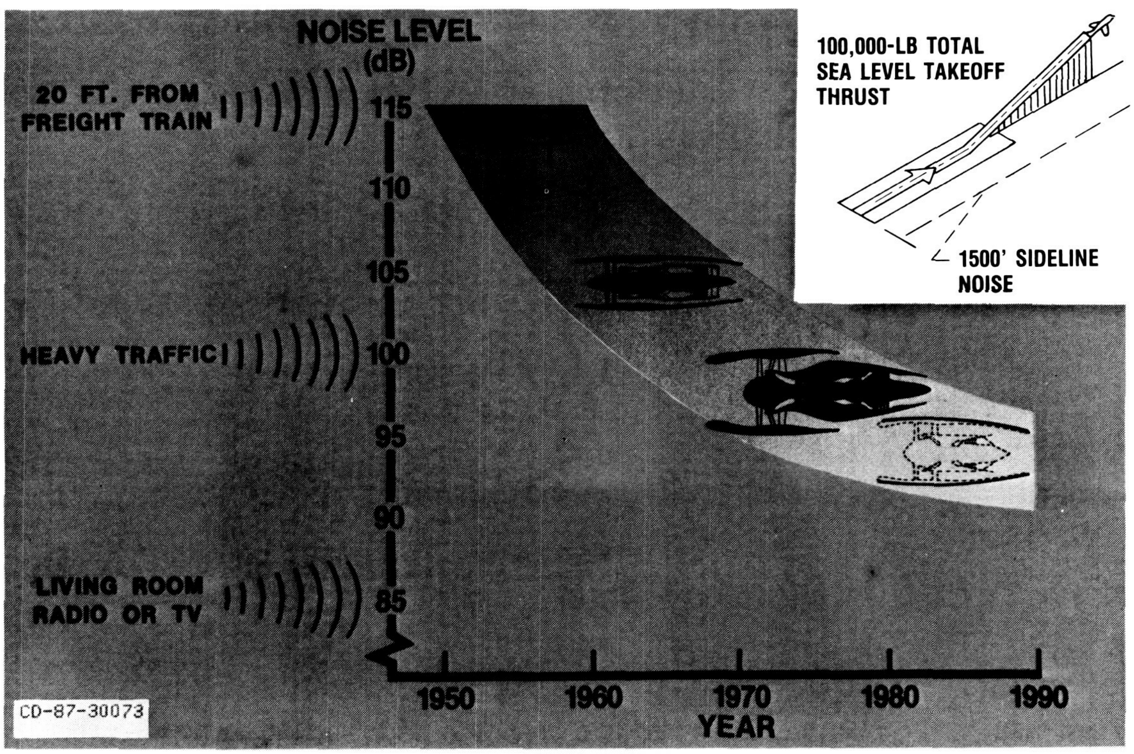
ORIGINAL PAGE IS
OF POOR QUALITY

AIRCRAFT NOISE REDUCTION

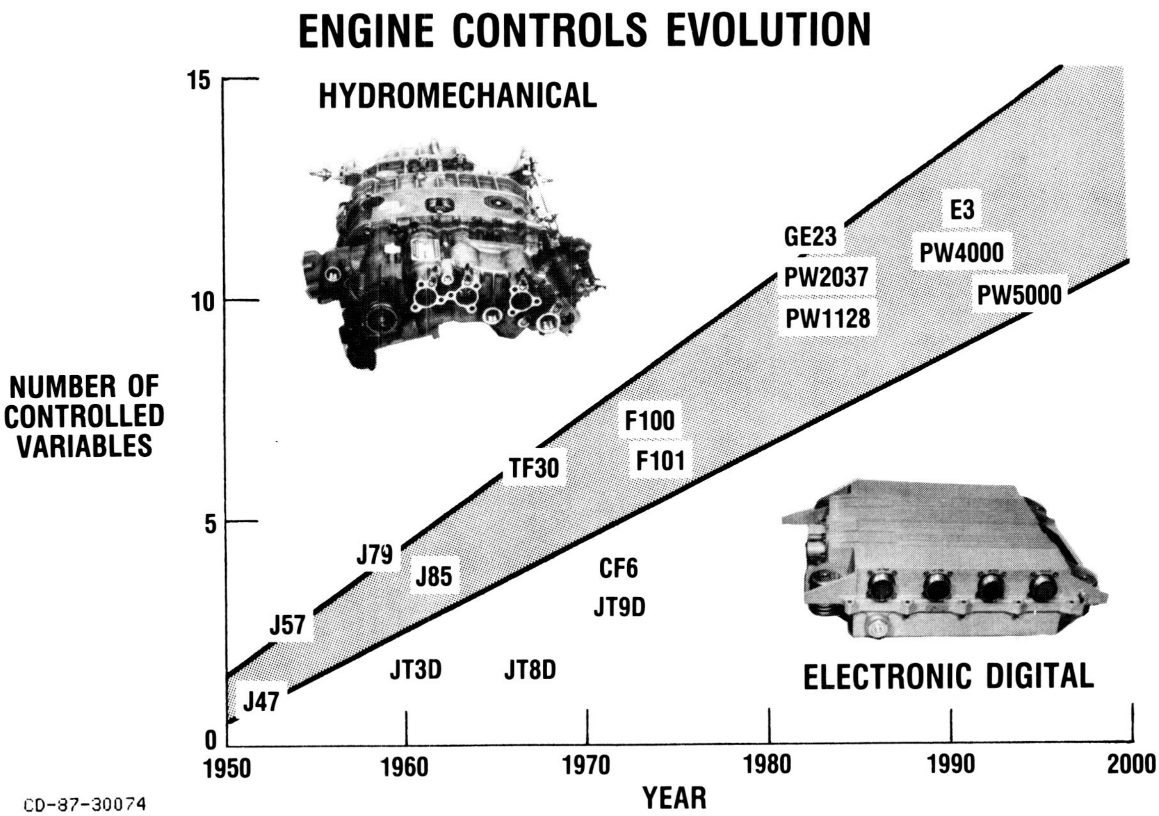
NASA has played to dual role in noise reduction of commerical turbine-powered aircraft by contributing to the technology of noise reduction and by providing unbiased exert consulting to the FAA in its rule-making role. This has resulted in the dramatic reduction in noise generated by the modern turbofan aircraft, making them the good neighbors they are today. NASA Lewis did extensive research in the sources of noise, acoustic treatment to suppress the emitted noise, and necessary procedures to measure noise in ground test facilities so that flight noise could be estimated. Both resonant and bulk absorbant wall treatments were characterized to provide the necessary data base for the nacelle designer. Lewis also developed "pumpkin" inflow control devices and anechoic wind tunnel treatments to permit the accurate measurement of fan noise in ground facilities.

AIRCRAFT NOISE REDUCTION



ENGINE CONTROLS EVOLUTION

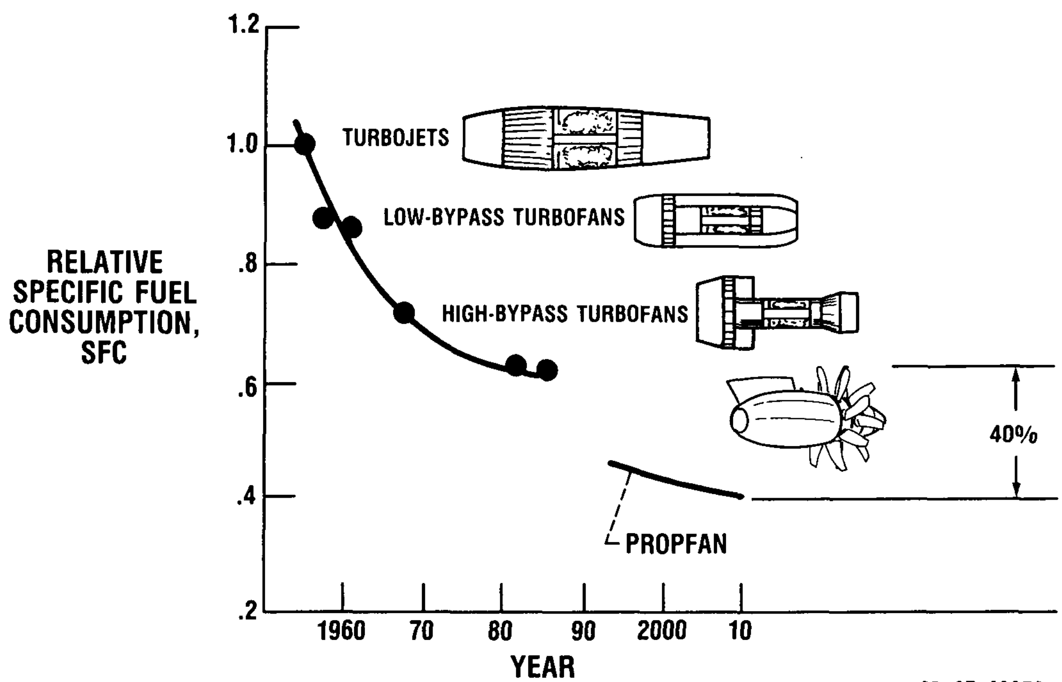
The trend in turbine engines toward more controlled variables to get improved performance and efficiency, as shown in the figure, has made it necessary to switch from the old reliable hydromechanical control to a modern, flexible digital control. The many technical barriers to this transition have been a subject of research at Lewis since a J-85 engine was first operated under digital control in 1970. To develop a formalized procedure to design controls for so may simultaneous variables, multivariable control theory for turbine engines was developed by Lewis and demonstrated in the F100 Multivariable Control Program. Since the most unreliable components of the control are the engine sensors, Lewis developed algorithms to allow the failure of sensors to be detected and accommodated while continuing to safely control the engine. Digital control is currently being used on the F100 in a supervisory trimming mode with a hydromechanical control and is being demonstrated in flight in a full authority mode in the digital electronic engine control (DEEC) for the F100 engine. It will be on most of the new high-performance engines of the 1990's and 2000's.



HIGH BYPASS ENGINES HAVE BETTER SUBSONIC PERFORMANCE

The effect of these advanced technologies on transport engines in terms of fuel usage is shown on the figure. The specific fuel consumption (SFC) of turbine engines has declined as the bypass ratio has been increased. When turbine engines were first introduced in commerical service, they were a great success as long as the fuel price was very low. To improve fuel efficiency, the bypass ratio was first increased to about 2 for the low bypass engine and finally to about 7 for the high bypass engines with resulting large decreases in SFC. When the fuel crisis hit in the mid-1970's, it became apparent that further decreases in SFC were very desirable. Therefore, the further reduction in SFC available with the ultimate in high bypass, the propeller, was recognized as a goal worth investigating.

HIGH-BYPASS ENGINES HAVE BETTER SUBSONIC PERFORMANCE



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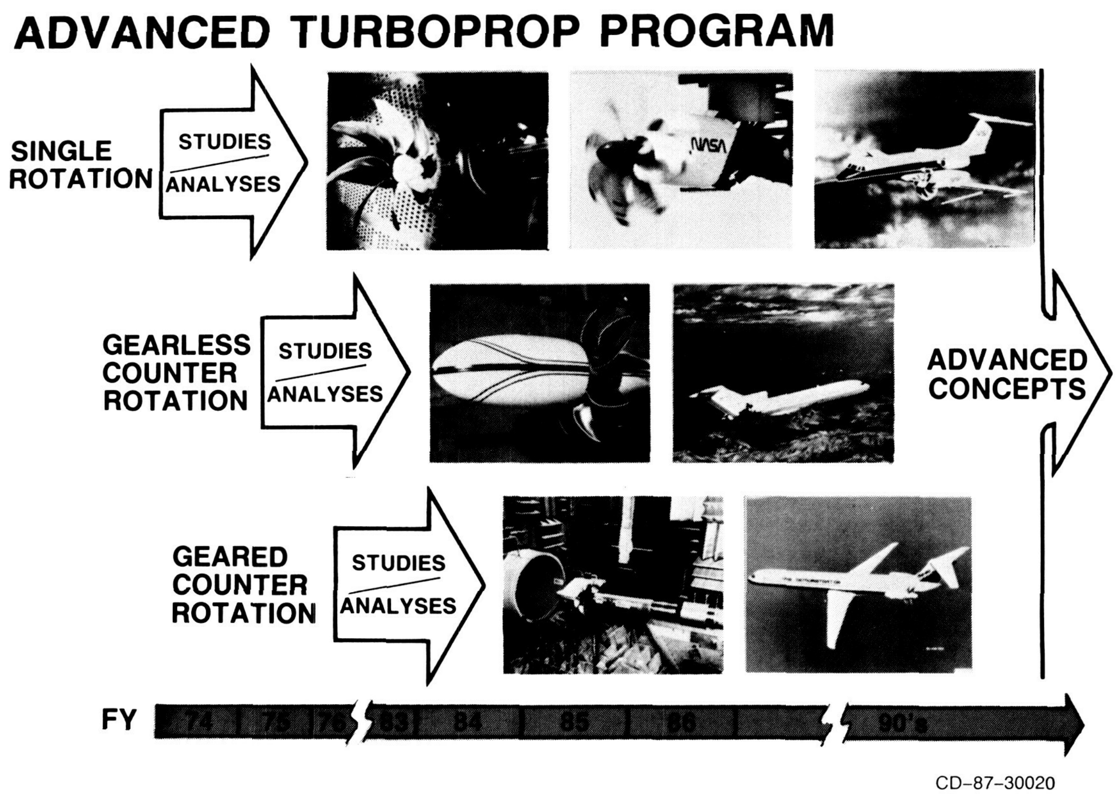
ADVANCED TURBOPROP PROGRAM

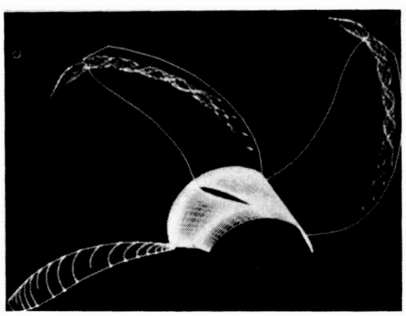
As a result of earlier turboprop experience, it was initially difficult to get the reintroduction of propellers for propulsion of commercial aircraft taken seriously. To compete with turbofan aircraft, similar speed and cabin comfort was required. Therefore, the initial research at Lewis in the late 1970's was aimed at demonstrating desirable performance and noise at higher cruise speeds than had previously been obtained with propellers. The success of this research indicted the feasibility of achieving major reductions in fuel usage with advanced propellers. However, studies and analyses indicated that the full turboprop system had to be demonstrated in flight tests. So, technology demonstration programs in mechanical systems, such as gearing and pitch-change mechanisms, and propulsion integration were initiated in the early 1980's. While single-rotation propeller systems are simpler and have application to many types of aircraft, it was recognized that the swirl loss of about 8 percent could be avoided with counterrotation. The additional benefit of propulsion integration on aircraft with tail-mounted engines further increased interest in counterrotation so that research was started in the mid-1980's. These programs have culminated in flight demonstrations of the technology by Lockheed on a Gulfstream 2, by Boeing on a 727, and by McDonnel Douglas on a MD90. NASA has been actively involved as a partner in all of these flight tests.



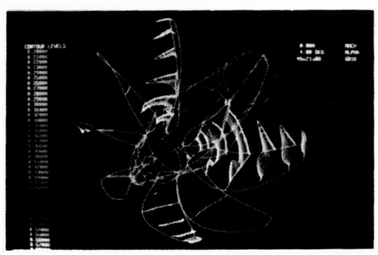
ADVANCED PROPELLER ANALYTICAL RESEARCH

The Advanced Turboprop Program has included NASA in-house research in both experimental and analytical aerodynamic, acoustic, and structural technologies. These programs have contributed to the understanding of flutter, acoustics, and aerodynamics of swept transonic propeller blading. Some recent results, shown in the figure, represent Euler solutions of the flow over the blades. At low forward speeds the leading-edge vortex system displayed in the left picture explains the good aerodynamic performance not predicted by the simpler two-dimensional aerodynamics. Unsteady Euler solutions predict the time-varying propeller aerodynamic forces shown in the center picture obtained at angle-of-attack, and the unsteady forces on he blades in a counterrotation propeller system.

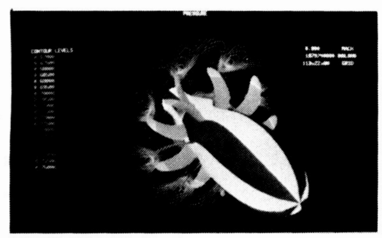
ADVANCED PROPELLER ANALYTICAL RESEARCH



LEADING EDGE VORTEX AERODYNAMICS AT LOW SPEED



UNSTEADY AERODYNAMICS AT ANGLE OF ATTACK



UNSTEADY COUNTERROTATING BLADE ROW INTERACTIONS

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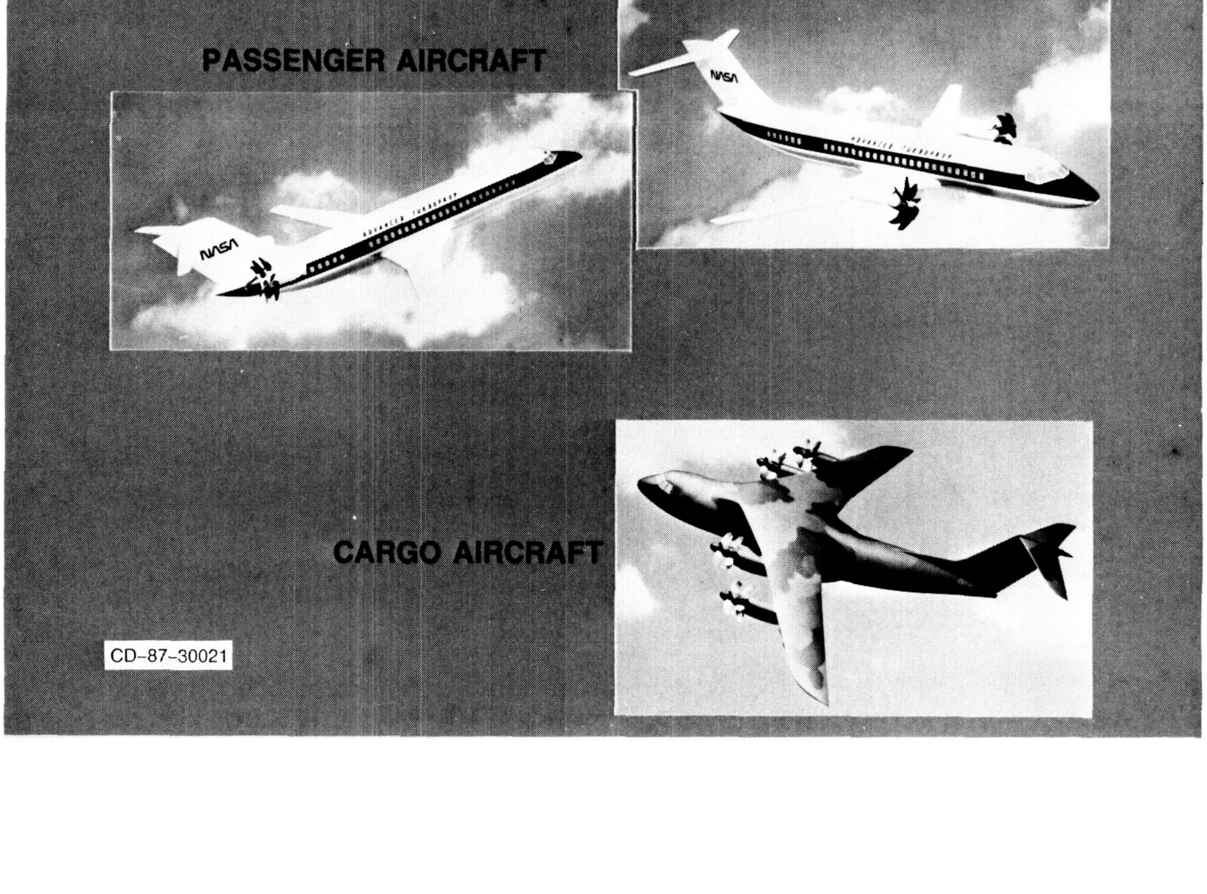
ADVANCED TURBOPROP APPLICATIONS

As a result of ongoing successful flight programs demonstrating the advanced turboprop technology, applications will be following in the near future. As the price of fuel inevitably increases, the increased efficiency of turboprop systems will be even more attractive, and transport aircraft such as the proposed Boeing 7J7 and McDonnel Douglas MD93 should become production aircraft. Advanced cargo aircraft are being considered to provide improved range and efficiency and to replace military aircraft such as the C141 and the C130.

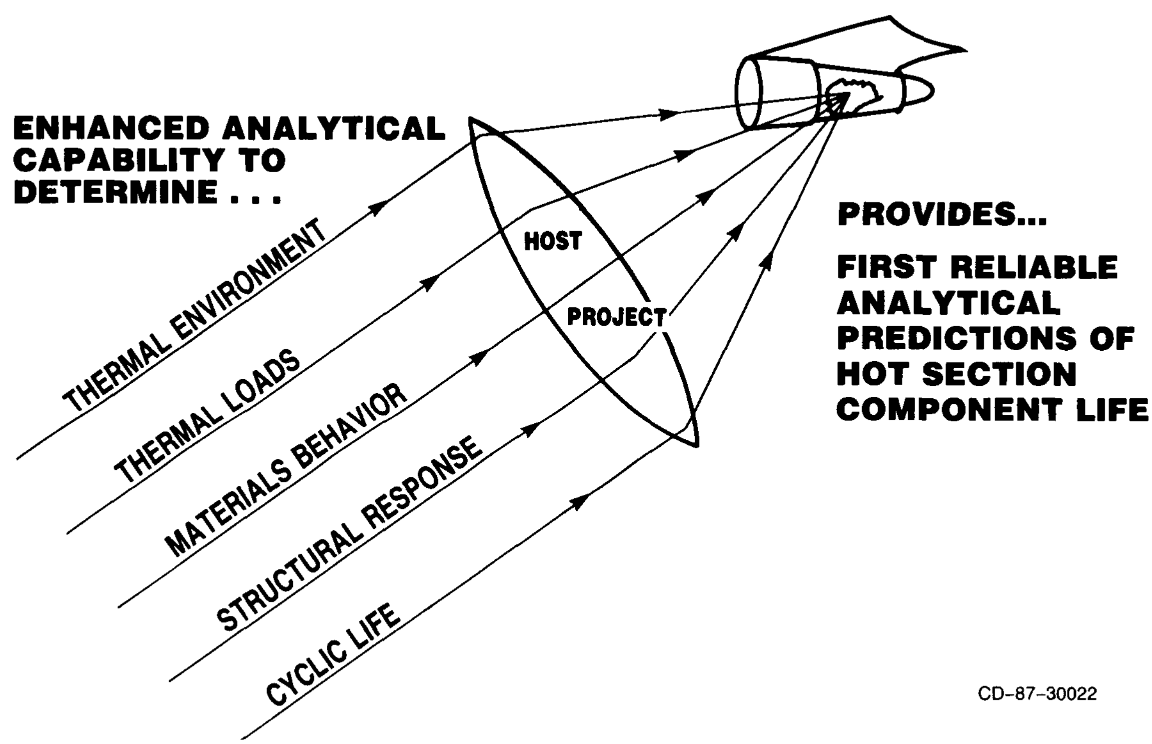


TURBINE ENGINE HOT SECTION TECHNOLOGY

NASA's Hot Section Technology (HOST) Project was conducted to focus technologies for combustors and turbines of advanced turbine engines toward more accurate predictions of hardware life. Therefore, for the first time, the aerothermodynamics to predict the thermal environment, heat transfer, and resulting thermal loads on components were combined with materials behavior to predict the structural response and resulting life. Before the HOST Project, life prediction was a primarily emperical art; if a new component differed significantly from previous experience, life prediction was inaccurate and ultimately dependent on life testing and redesign if problems arose. HOST has combined the analytical approach with the development of advanced instrumentation used in benchmark quality experiments to better characterize the actual hot-section environment and to verify computer codes. As a result, more accurate analytical predications of hot section life are now possible.

TURBINE ENGINE HOT SECTION TECHNOLOGY

TECHNOLOGY FOCUSED TOWARD DURABILITY IN ADVANCED TURBINE ENGINES



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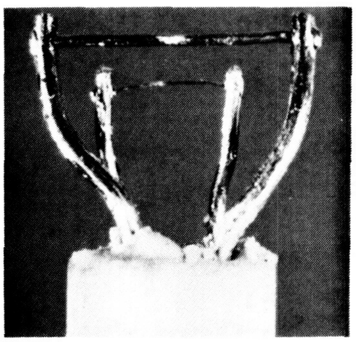
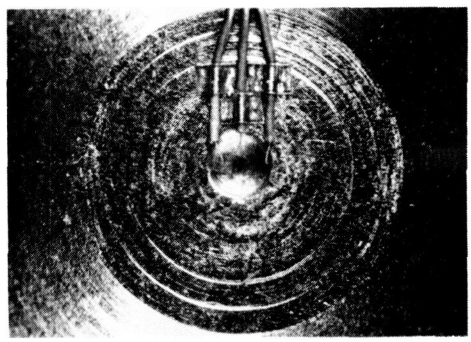
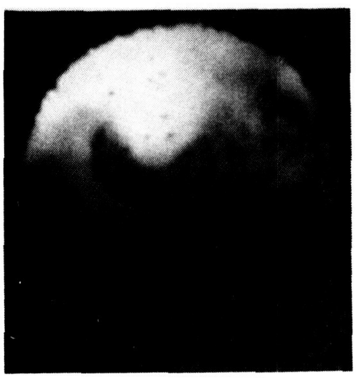
HOST instrumentation research focused on two types of instrumentation: instrumentation for characterizing the environment in the hot section and instrumentation for measuring the effect of that environment on the section components. Examples of each type are shown in the figure. The thermocouple probe is capable of measuring dynamic gas temperature fluctuations with a frequency response out to 1000 Hz. Tests of this probe in a F-100 engine at the combustor exit showed rapid dynamic gas-temperature excursions from as low as the compressor exit temperature to near stoichiometric temperatures. The lower left picture is a view of a fuel nozzle in an engine operating at full power, obtained using the new fiber optic combustor viewing system. Not only can it get such views in an operating engine for the first time, but by using laser light as an illumination source and filtering out the combustion generated light, it can look through the flame and view the opposite wall during operation. Heat flux measurements on an operating turbine vane is another new capability developed in the HOST Project. These and other new instruments are giving new understanding of the environment in the hot sections of operating turbine engines.

HOST INSTRUMENTATION TECHNOLOGY

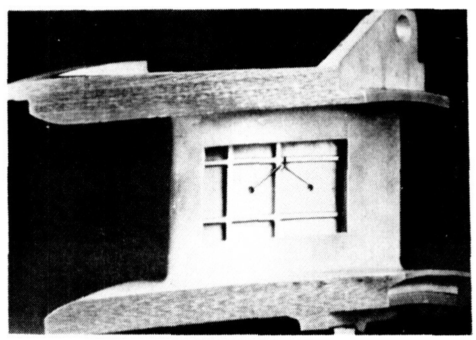


1000-Hz THERMOCOUPLE PROBE





COMBUSTOR VIEWING SYSTEM



HEAT FLUX GAGE INSTALLATION IN VANE

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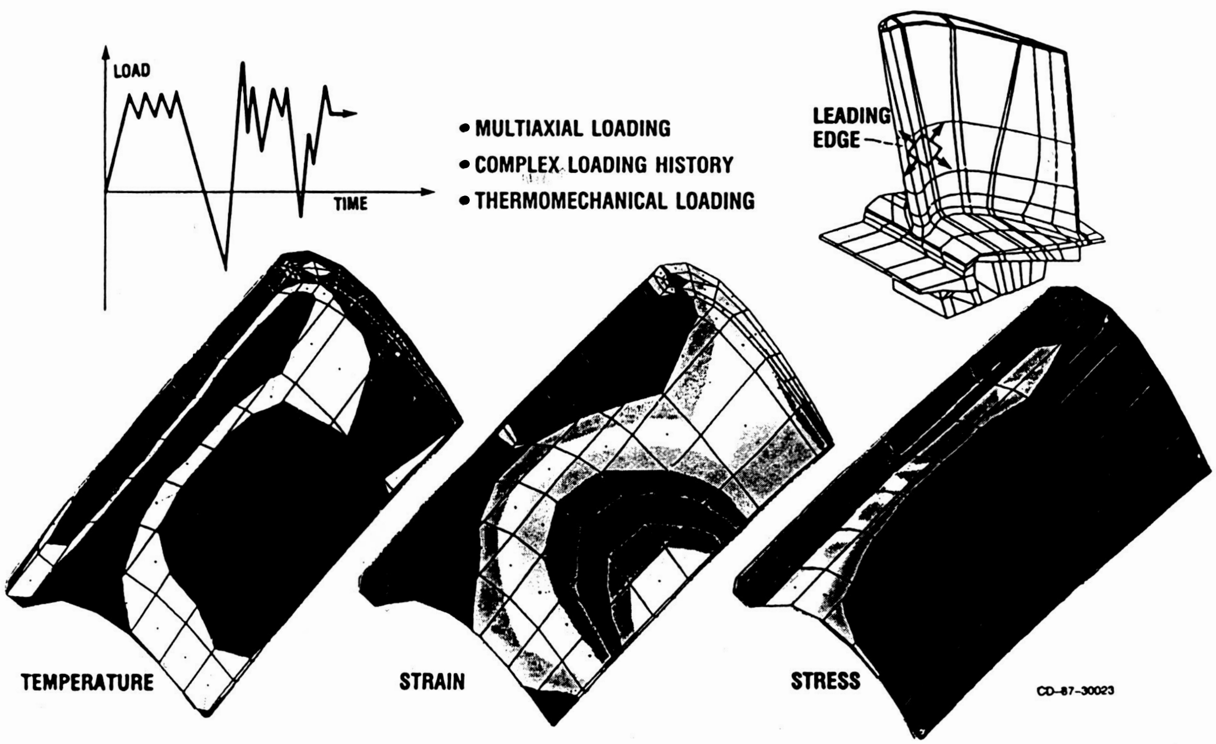
HOST PREDICTION OF OPERATING CONDITIONS AND LIFE

The prediction capability of the HOST codes is demonstrated in the figure. The variation of load with time associated with engine operation during a typical flight is shown in the upper left of the figure. The aerothermodynamic codes are used to predict the mechanical and thermal loading on the blade shown in the upper right. Heat-transfer codes are used to predict the temperature distribution in the blade, as shown in the lower left, at each instant of time. Mechanical and thermal loading distributions are used in structural analysis codes to determine the stress and strain distributions in the turbine blade. By evaluating the time varying stress and strain using a life model, failure can be predicted; in this case, at about the center of the blade leading edge. Understanding the failure mechanisms in this manner allows a designer to correct life-limiting parts before the engine runs for the first time.

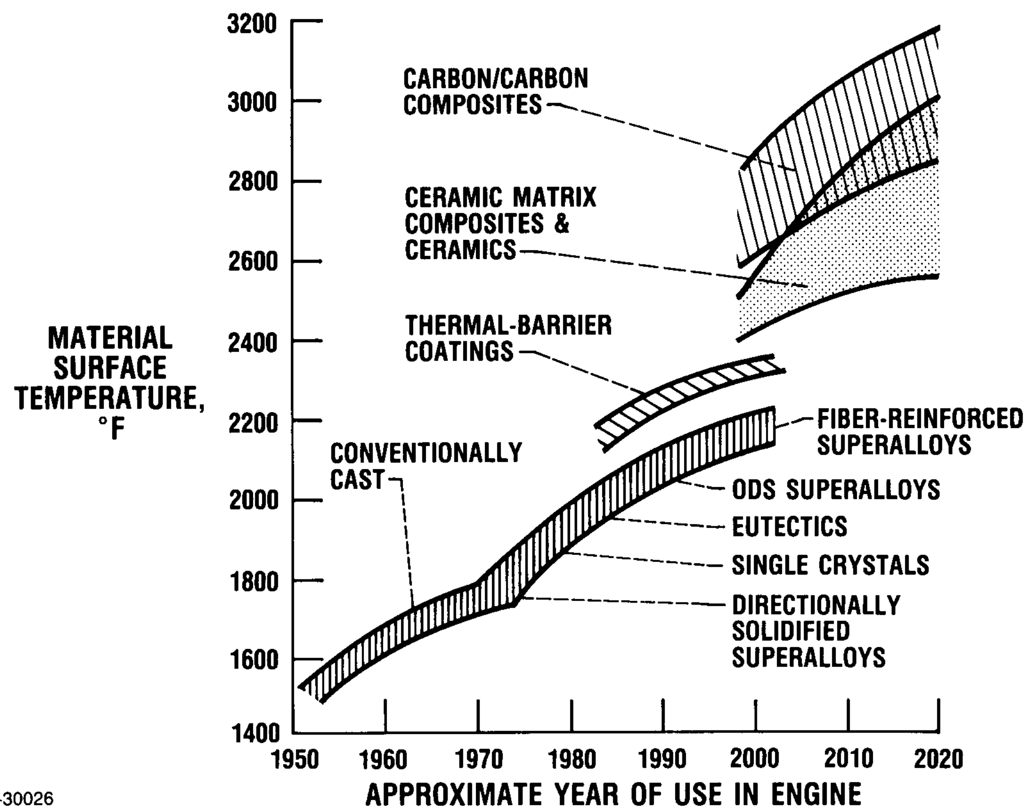
HOST PREDICTION OF OPERATING CONDITIONS AND LIFE



TURBINE BLADE MATERIALS TRENDS

From the beginning of the turbine engine in the 1930's, the materials have limited its efficiency and maximum thrust. In the 1950's and 1960's turbine blade materials were first wrought and later conventionally cast. During that period use temperatures increased at a moderate pace. Beginning in the 1970's new materials processing methods accelerated the pace at which use temperature increased. During this period, Lewis developed oxide dispersion strengthened (ODS) superalloys in-house and through contracts, spun off the technology to the industry to provide the commercial alloy MA6000. The 1950's Lewis experience with tungsten-fiber-reinforced superalloys has been recently used to manufacture the first silicon-carbide-fiber/titanium aluminide material and to characterize it. These materials, combined with Lewis-developed thermal barrier coatings, will provide surface use temperatures up to 2300 °F in the 1990's. The Advanced High Temperature Engine Materials Program, beginning this year, will develop materials like the silicon-carbide-fiber/reaction-bonded-silicon-nitride material identified in the Lewis in-house program for use in the 21st century at temperatures of 2500 °F and higher. These new materials, through new higher values of use temperature, provide the opportunity of reaching new heights in turbine engine efficiency and thrust at speeds from subsonic to high supersonic if the accompanying aerodynamic and structural technologies can also be developed to allow maximum use of the materials capabilities.

TURBINE BLADE MATERIALS TRENDS



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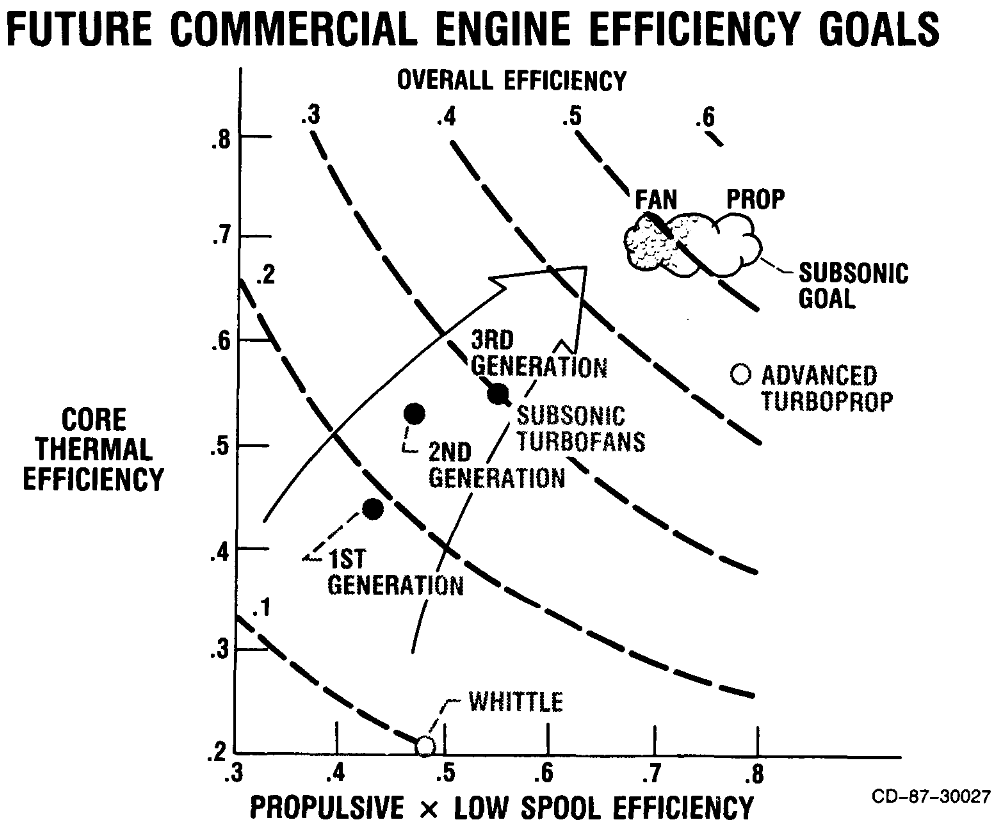
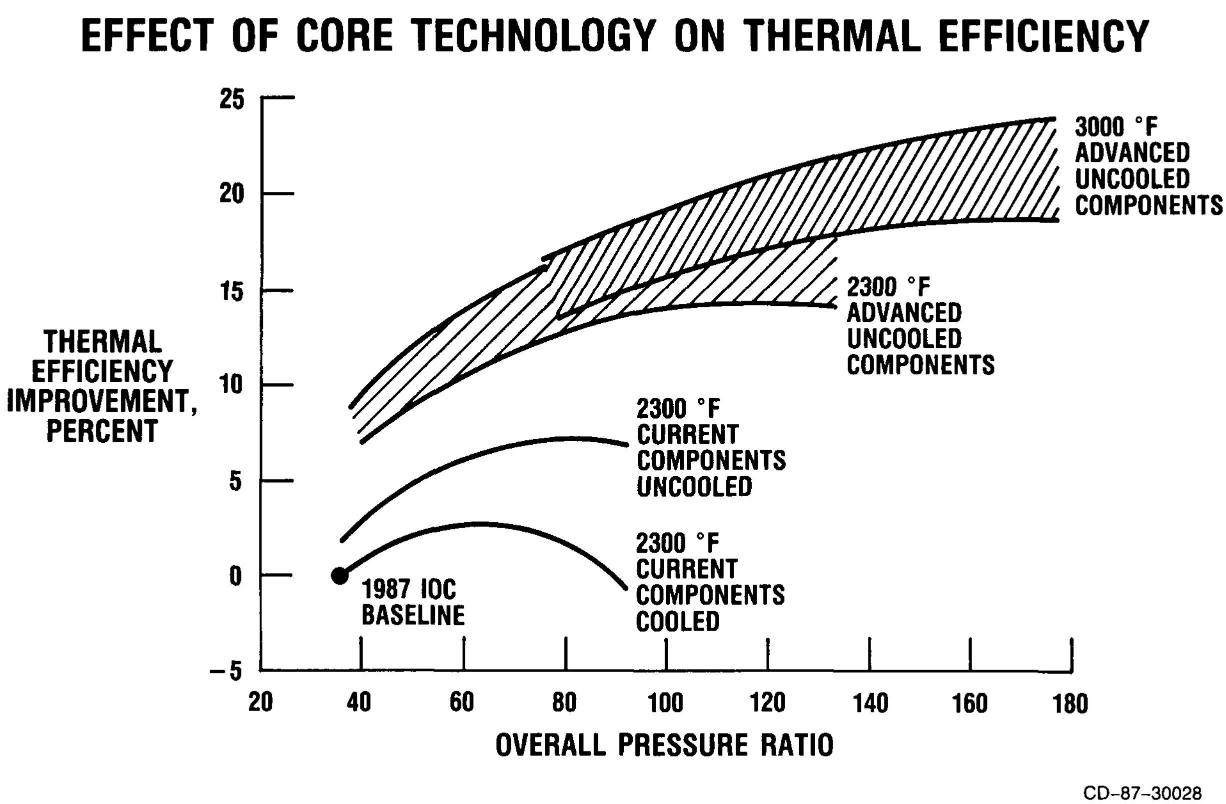
FUTURE COMMERCIAL ENGINE EFFICIENCY GOALS

Returning to the earlier figure showing the historical increases in efficiency obtained in commercial engines, the future gains obtainable with the full potential of advanced technology have been added to identify the ultimate goal for subsonic engines. The left portion of the goal corresponds to advanced turbofans and the right portion to the turboprop with its higher propulsion efficiency. Reaching that goal requires new levels of performance from all the engine components by integrating the advanced technology in materials, aerodynamics, and structures.



EFFECT OF CORE TECHNOLOGY ON THERMAL EFFICIENCY

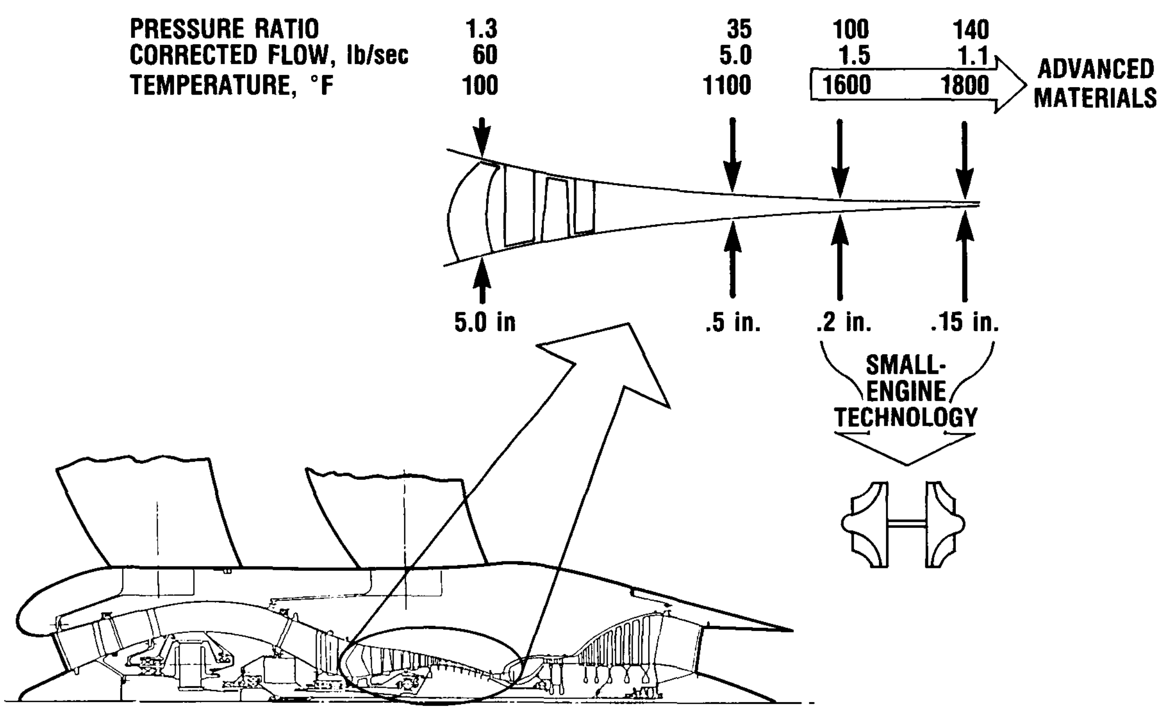
The effect of overall pressure ratio on core thermal efficiency is shown for several levels of maximum cycle temperature and whether the hot-section components are cooled. For current component capabilities of 2300 °F with cooling, there is only a minor benefit with increasing pressure ratio. However, if the components could be operated uncooled at 2300 °F (with improved materials), significant increases in efficiency could be obtained if the pressure ratio of the core was increased to 60 or more. In addition, if these components also had improved aerodynamic efficiency, further increases in efficiency could be obtained if the pressure ratio was further increased to 100 or more. Increasing component operating temperature to 3000 °F uncooled (with ceramic and carbon/carbon components) requires even higher pressure ratios to obtain maximum efficiency. It is important to note that increased temperature must be combined with more efficient components and unprecedented levels of cycle pressure ratio in order to realize major increases in core efficiency.



IMPACT OF VERY HIGH CORE PRESSURE RATIO

The core pressure ratios necessary to realize the full potential of new materials will require new aerodynamic technology for both the high compressor and turbine. As shown in the figure, at pressure ratios of about 100, new materials will be needed in the latter stages of the compressor where the temperatures reach 1600 °F and higher. These last stages will also have very low corrected weight flow and the minute passage heights characteristic of small engines. Since small engines (with centrifugal/radial flow components) have had relative low performance when compared with commercial axial-flow turbofan engines, NASA has been directing significant effort at understanding the loss mechanisms associated with these components and developing technology to minimize these losses. Thus, our small engine technology efforts might well play a key role in the future development of improved large engines.

IMPACT OF VERY HIGH CORE PRESSURE RATIO



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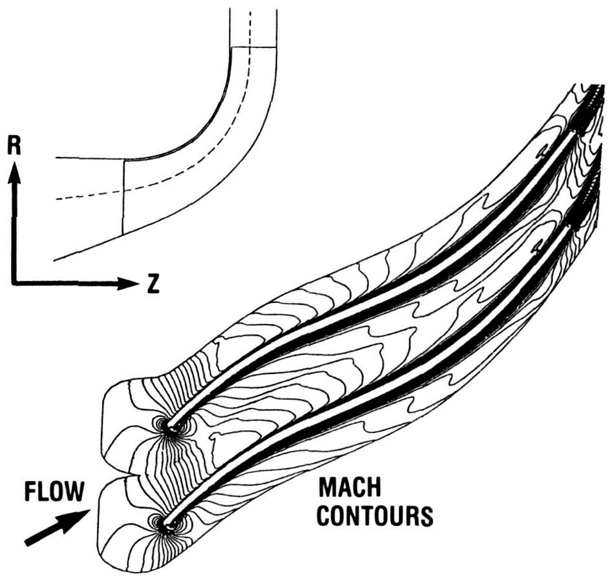
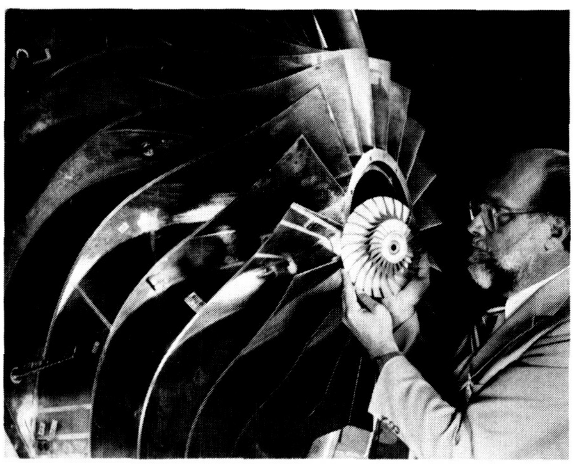
LARGE LOW SPEED CENTRIFUGAL COMPRESSOR

As part of our research efforts for small engines, we are currently assembling a large-scale low-speed centrifugal compressor to investigate the internal three-dimensional flows so that they can be predicted with resulting efficiency improvements. The rotor, shown in the picture, is 5 ft in diameter and large enough to install instrument rakes in the passages and to instrument the vanes and walls with static pressure taps. The casing is also constructed with access for laser anemometry to document the interior flow fields. Analytical codes are being developed in parallel with the experimental efforts. The left figure illustrates the initial results of a quasi-three-dimensional thin-layer analysis which represents the expected flow on the meanline of the flow passage. Results of this research should eventually lead to improved performance of centrifugal compressors for use in small engines or the latter stages of large commercial engines.

LARGE LOW-SPEED CENTRIFUGAL COMPRESSOR



QUASI-3D THIN-LAYER ANALYSIS



INSTRUMENTED ROTOR

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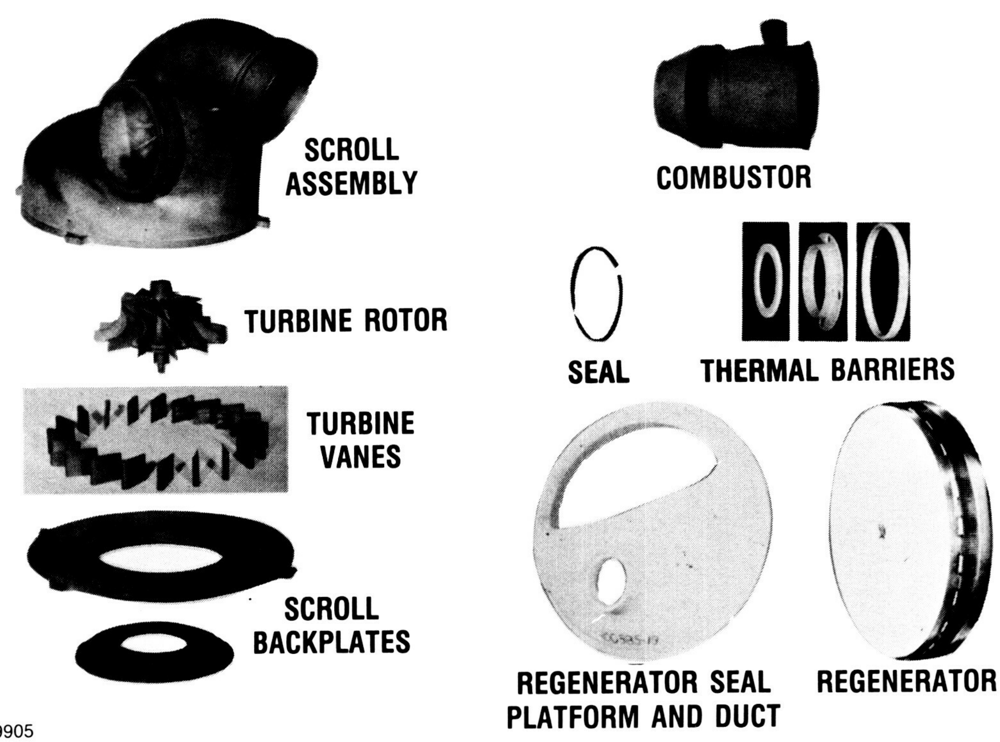
AGT 100 CERAMIC COMPONENTS

Another element in our small engine technology efforts involves ceramic uncooled, radial-flow turbomachinery. For several years Lewis has managed the Automotive Gas Turbine Program for the Department of Energy. The major emphasis of this program is to advance the technology of ceramics to a point where these brittle materials can be considered as serious candidates for use in high-performance turbomachinery. The goal of this program is to produce and demonstrate ceramic components capable of operation in an engine environment at temperatures of 2500 °F in small turbine engines. Significant progress has been made. Fabrication technology has progressed from the manufacture of simple test bars and laboratory specimens to engine quality, complex parts as shown in this figure. Static parts, like those in the figure, have been rig tested at the target temperature of 2500 °F for extended periods. All the ceramic parts, including the turbine rotor, have been demonstrated in an engine at 2200 °F for 85 hours at 70 percent of design speed. A turbine rotor has been tested in an engine at 1950 °F and 100 percent of design speed for several hours. Future work is aimed at component reliability through improved materials, design, and manufacturing techniques to improve the overall reliability of ceramic engine components.

In addition, Lewis has NASA-sponsored research efforts aimed at extending the use temperature of ceramics to 3000 °F with life similar to current engines. Thus, emphasis is on high-temperature use of ceramics and on their structural and environmental durability and reliability. The program is interdisciplinary in nature with major emphasis on materials and processing and significant efforts in design methodology and life prediction.

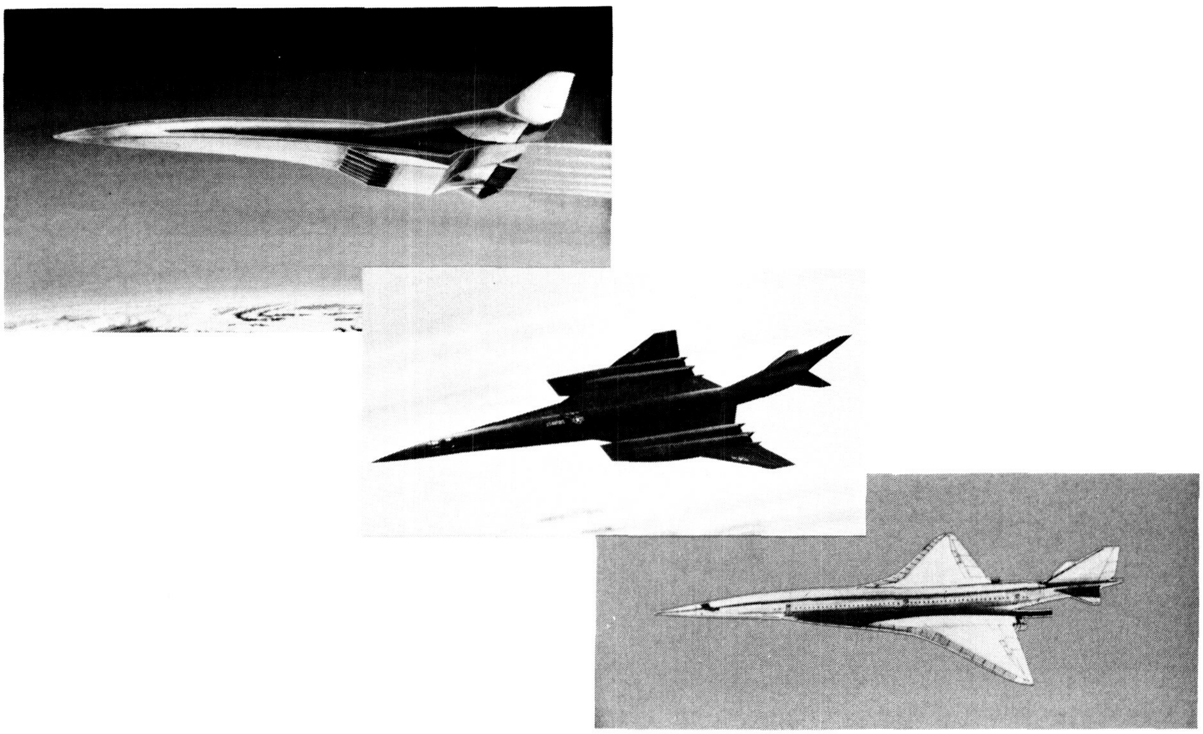
AGT 100 CERAMIC COMPONENTS



CD-87-29905

While NASA Lewis will continue to work on subsonic propulsion technology, the major part of its aeropropulsion program is shifting toward propulsion systems for long-range flight at supersonic and hypersonic speeds. The bottom picture represents configurations being studied for second-generation commercial supersonic transports that will probably be limited to turbine engine propulsion and hydrocarbon fuels. The Mach 5 military aircraft in the center of the figure is a configuration that Lewis has been investigating jointly with Langley Research Center and represents aircraft that cruises at speeds beyond those possible with turbine engines and hydrocarbon (JP type) fuels. Lewis is heavily involved in the National Aerospaceplane rogram represented by the aircraft in the upper right and has primary responsibility for maturation of the low-speed propulsion system technology. The NASA aeropropulsion program will study propulsion systems for these aircraft to provide technology for improved efficiency, specific thrust, and environmental compatibility.

LONG RANGE SUPERSONIC FLIGHT



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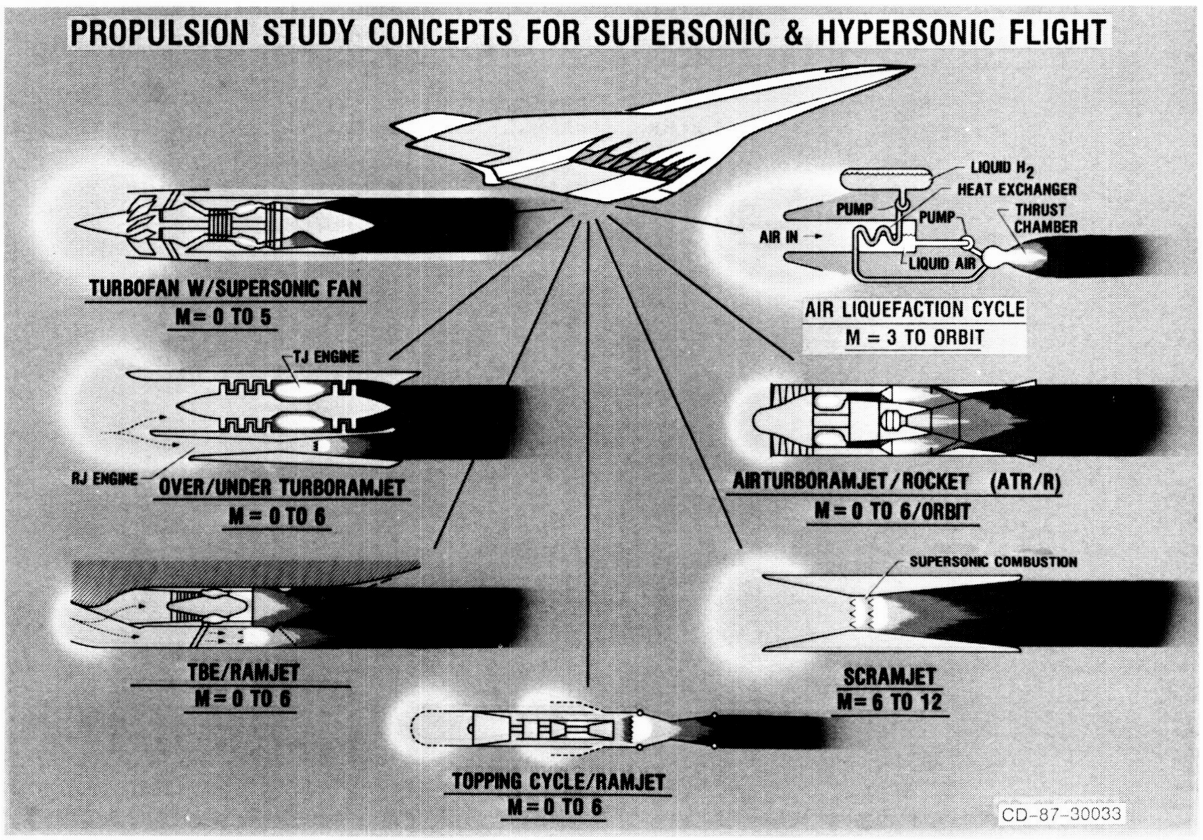
PROPULSION STUDY CONCEPTS FOR SUPERSONIC AND HYPERSONIC FLIGHT

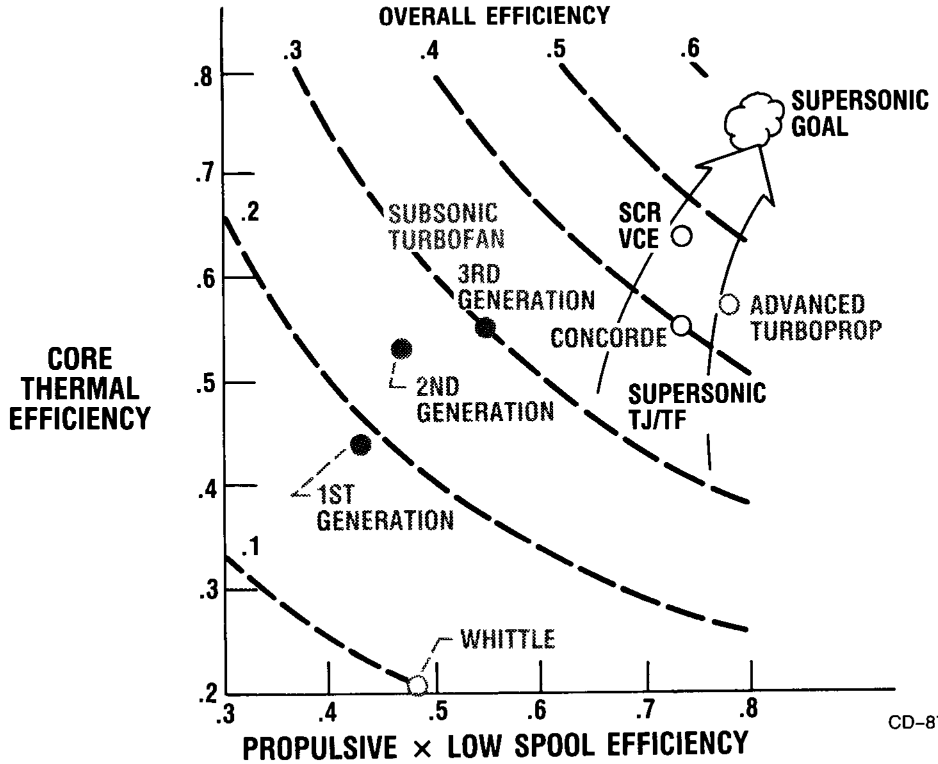
Most of the propulsion concepts under study at NASA for high-speed flight are shown in the figure. Many of them have turbine engine hardware in the prime propulsion stream, but some nonturbomachinery systems are being studied for special applications, like acceleration missions (for example, the air liquefaction cycle and scramjet cycle). High-speed cruise missions usually use turbine engines for acceleration and cruise unless the cruise temperature is excessive for the engine. In these very high-speed cases either ramjet or scramjet propulsion is used in a dual cycle. For supersonic cruise of a commercial transport, NASA, in a joint program with industry, is studying many turbine engine cycles including the turbofan with a supersonic-throughflow fan which appears to be a promising new concept.



GOAL EFFICIENCIES FOR HIGH-SPEED FLIGHT

Returning to the efficiency figure, a supersonic cruise aircraft goal has been added. Due to the large ram-pressure-ratio in supersonic flight, the Concorde propulsion system achieves a relatively high overall efficiency, in spite of its 1960's technology. However, at the termination of the NASA Supersonic Cruise Program in the early 1980's, variable cycle engines for supersonic cruise were estimated to offer a 10- to 15-percent increase in efficiency over the Concorde engine's value of 40 percent. The goal of the current NASA program is to increase that efficiency to at least 60 percent through the use of advanced materials, structures, aerodynamics, and cycles like the one using a supersonic-through-flow flow fan shown on the previous figure.

GOAL EFFICIENCIES FOR HIGH-SPEED FLIGHT



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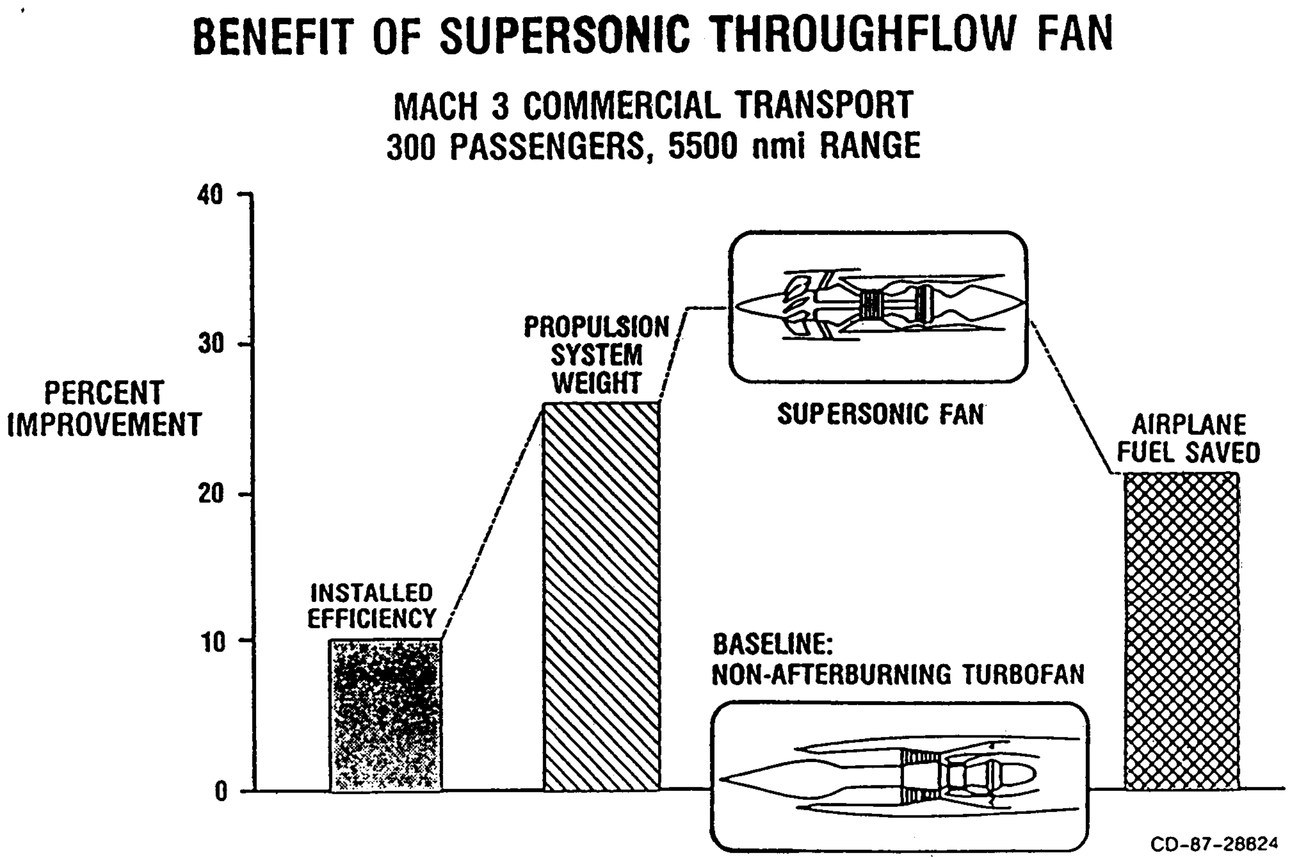
MISSION BENEFIT OF SUPERSONIC THROUGHFLOW FAN TECHNOLOGY

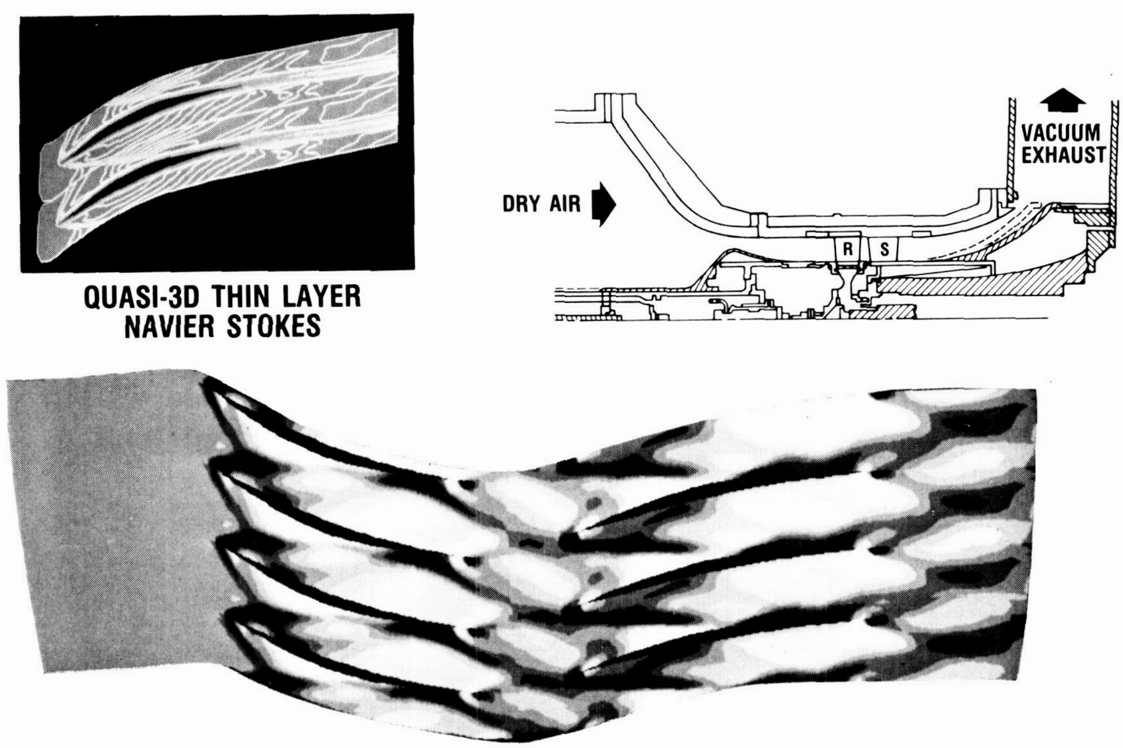
The advantages of the supersonic fan relative to a baseline afterburning turbofan are illustrated in the figure. The simpler inlet and fan are lighter weight and more efficient by avoiding the complexity of slowing the external flow to subsonic speeds before introducing it to the fan. These advantages provide about 10-percent decrease in specific fuel consumption and about 25-percent reduction in propulsion weight, which leads to a 22-percent increase in aircraft range. Since the feasibility of maintaining supersonic flow through a turbomachinery stage has never been demonstrated, Lewis has initiated an exploratory program to investigate the feasibility of the supersonic fan component.



SUPERSONIC FAN FEASIBILITY DEMONSTRATION

A cross section of the supersonic fan experimental hardware is shown with several computer solutions used in its design and analysis. The supersonic fan rotor and stator are located in the center of the installation downstream of an annular sliding block nozzle, which generates the supersonic flow into the rotor. A similar sliding nozzle is located downstream of the stator to slow the flow before it enters the exhaust duct. The first test of the hardware is planned for about a year from now. The quasi-three-dimensional thin-layer Navier-Stokes solution (shown on the left) was used to optimize the pressure distribution on the blading in the presence of the blade boundary layer. The analytical results (bottom of figure) illustrate the unsteady interaction between the rotor and stator flow fields. The analytical results are processed to look like a schleiren photograph of the flow.

SUPERSONIC FAN FEASIBILITY DEMONSTRATION



QUASI-3D THIN LAYER NAVIER STOKES

UNSTEADY ROTOR/STATOR INTERACTION

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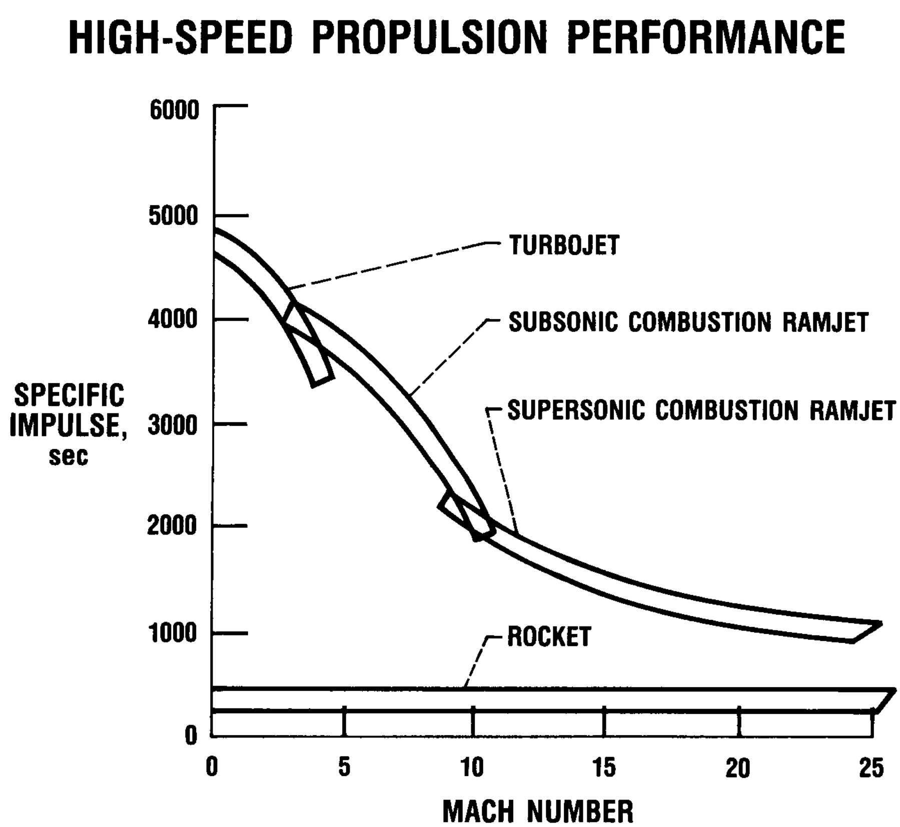
HIGH-SPEED PROPULSION PERFORMANCE

As we direct attention to higher speed regimes, hybrid propulsion systems beyond turbomachinery cycles must be considered. This figure presents the specific impulse of the basic airbreathing propulsion cycles and compares them with the best rockets. The cycles with turbomachinery provide the highest specific impulse at up to about Mach 5 where it becomes too hot for the turbomachinery to produce enough pressure ratio to overcome the inefficiency of its components. The Subsonic ramjet then provides the highest specific impulse until about Mach 10 where molecular dissociation reduces its impulse below that of the scramjet. Airbreathing cycles always have a higher impulse than rockets but are much more difficult to operate at the higher Mach numbers. Work at Lewis and other NASA centers is aimed at extending the use of airbreathing cycles to Mach numbers higher than the Mach 3+ flown by the YF12.



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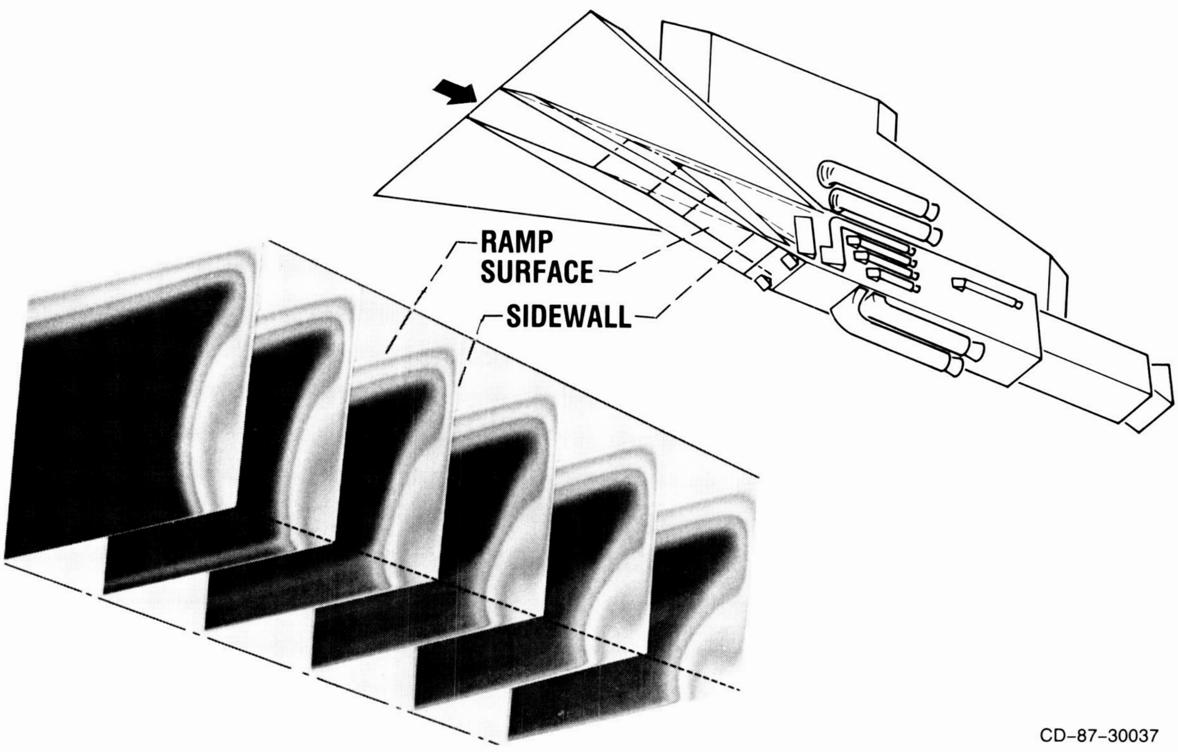
MACH 5 INLET

A joint study of a military Mach 5 cruise aircraft by Lewis and Langley Research Centers, Lockheed, and Pratt & Whitney, identified an over/under turboramjet cycle to provide desirable acceleration and cruise performance. The Mach 5 inlet illustrated in the figure represents the ramjet configuration with the turbine engine compartmented off for high-speed cruise. The inlet was recently delivered to Lewis for test in the 10 by 10-Foot Supersonic Wind Tunnel. Results of a fully viscous three-dimensional analysis displayed in the figure indicate that the sidewall boundary layer will collect on the cowl side of the inlet sidewall and cause separation, which would probably cause inlet unstart. Results such as these were used to design a bleed system that will be tested in the near future.

MACH 5.0 INLET TEST COMPOSITE



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AIRFRAME-INTEGRATED SUPERSONIC COMBUSTION RAMJET

While supersonic combustion ramjets were envisioned over 20 years ago, no one has yet proven their practical use. Langley has led the NASA scramjet propulsion program and recently demonstrated positive thrust on a scramjet configuration similar to the one shown in the figure. Similar work is now planned by the NASP contractors, as the successful operation of the scramjet cycle is necessary to achieve a single-stage-to-orbit vehicle. The environment of a scramjet module is extremely hot and can be created in test facilities on the ground for only a few minutes at Mach numbers up to 10. Therefore, scramjet operation at higher Mach numbers will be critically dependent on computational fluid dynamics for analyzing and designing future scramjet configurations.

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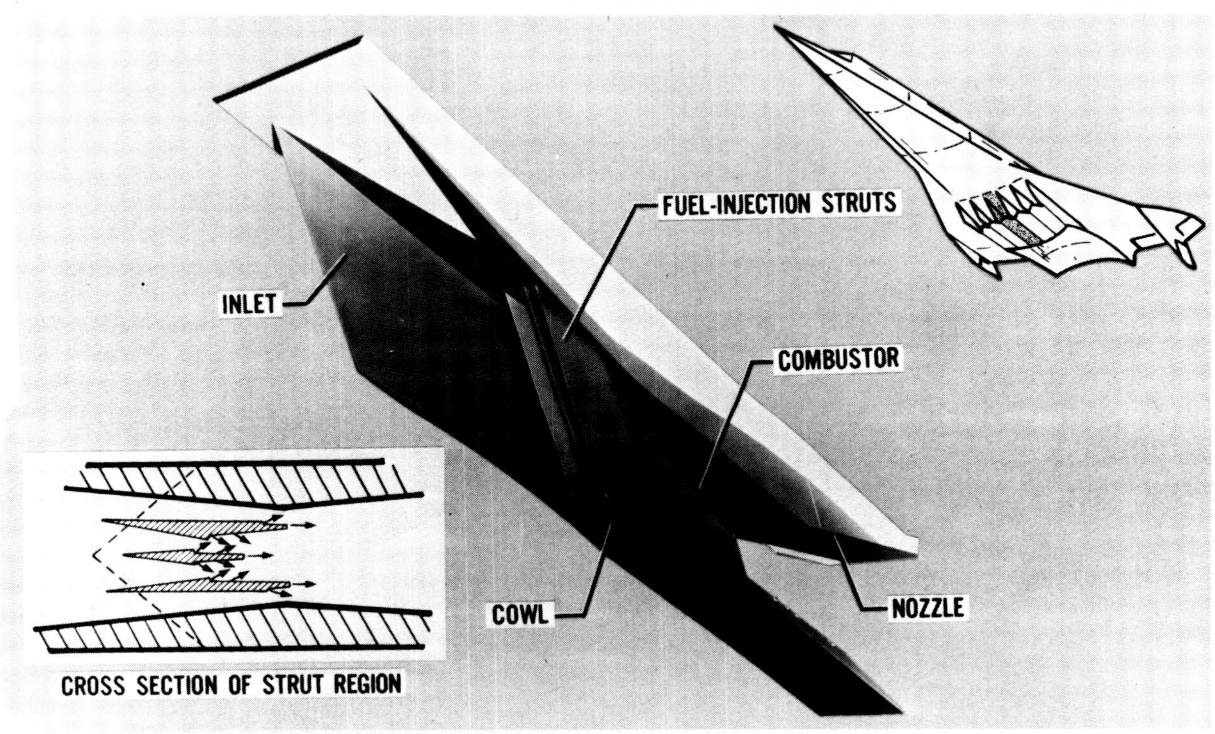
AIRFRAME-INTEGRATED SUPERSONIC COMBUSTION RAMJET



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CONCLUDING REMARKS

The U.S. aeropropulsion industry has been very successful in competing in the world market for powering modern aircraft. NASA takes great pride in its contributions to that success, some of which have been reviewed in this paper. As the world competition grows, it will become harder to maintain our current leadership. NASA's current aeropropulsion program will continue to support that leadership by emphasizing technology that will provide future opportunities for major advances in propulsion efficiency and durability. While we have reviewed the highlights of that program, which are primarily applicable to commercial aircraft, we could not cover in sufficient detail nor describe enough of its programs to provide a full appreciation of its depth and application to military aircraft. The papers that follow will provide that description of the NASA aeropropulsion program which should lead the industry into continuing to produce the best propulsion systems for commercial and military aircraft into the 21st century.

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LEWIS MATERIALS RESEARCH AND TECHNOLOGY: AN OVERVIEW

Salvatore J. Grisaffe

ABSTRACT

The Materials Division at the Lewis Research Center has a long record of contributions to both materials and process technology as well as to the understanding of key high-temperature phenomena. This paper overviews the division staff, facilities, past history, recent progress, and future interests. The papers which follow expand on some of our research areas and plans.

The Materials Division at the Lewis Research Center is NASA's focal point for high temperature materials research aimed at aerospace propulsion and power system needs. Lewis is NASA's largest materials research group. Currently the staff consists of about 99 civil servants (over 45 percent are Ph.D.'s) and 73 NRC post doctoral fellows, university consortia, support service contractors, and industrial guest investigators. Their backgrounds cover all the materials disciplines. Thirty percent of our staff represent recent graduates, reflecting an ongoing commitment to fresh ideas and new talent. Our facilities give us the capability to make, consolidate, and fabricate new materials and to test and analyze them. With the centers powerful computational capabilities, we can also model, compute, and predict material behavior.

Our job is to create new materials and new understanding in support of NASA's needs and specific materials goals. We then work to transfer the resulting knowledge, technology, and processes to the broad user community.

For those interested in collaboration on research of potential mutual interest, a description of our key facilities can be obtained by writing me a letter outlining your specific interests.

LEWIS MATERIALS DIVISION

STAFF

- 99 CIVIL SERVANTS
  - 85 PROFESSIONAL
    - 45 PERCENT PhD
    - 32 PERCENT MS

      IN

      CERAMICS/CERAMICS ENG.
      CHEMISTRY/CHEM. ENG.
      PHYSICS
      METALLURGY/MET. ENG.
      MECHANICAL ENG.
- 73 UNIVERSITY CONSORTIA, NRC POST DOCTORAL FELLOWS, SUPPORT CONTRACTORS, ETC.

FACILITIES

- LABORATORIES IN SEVEN BUILDINGS
- 40 M IN CAPITAL EQUIPMENT

  TO
  - CONSOLDIATE
  - FABRICATE
  - TEST
  - CHARACTERIZE
  - COMPUTE

MEET NASA'S MATERIALS NEED IN AEROSPACE PROPULSION AND POWER

BASIC → FOCUSED → PROJECT STUDIES

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SOME MATERIALS DIVISION CONTRIBUTIONS

In the past Lewis has made many contributions to the technology of high temperature, high performance materials. In our laboratories, as well as in conjunction with industry, Lewis has pressed the advance of such concepts as:

Metal matrix composites. - Continuous fiber reinforced metal composites were born at Lewis and the rule of mixtures was applied to property estimation.

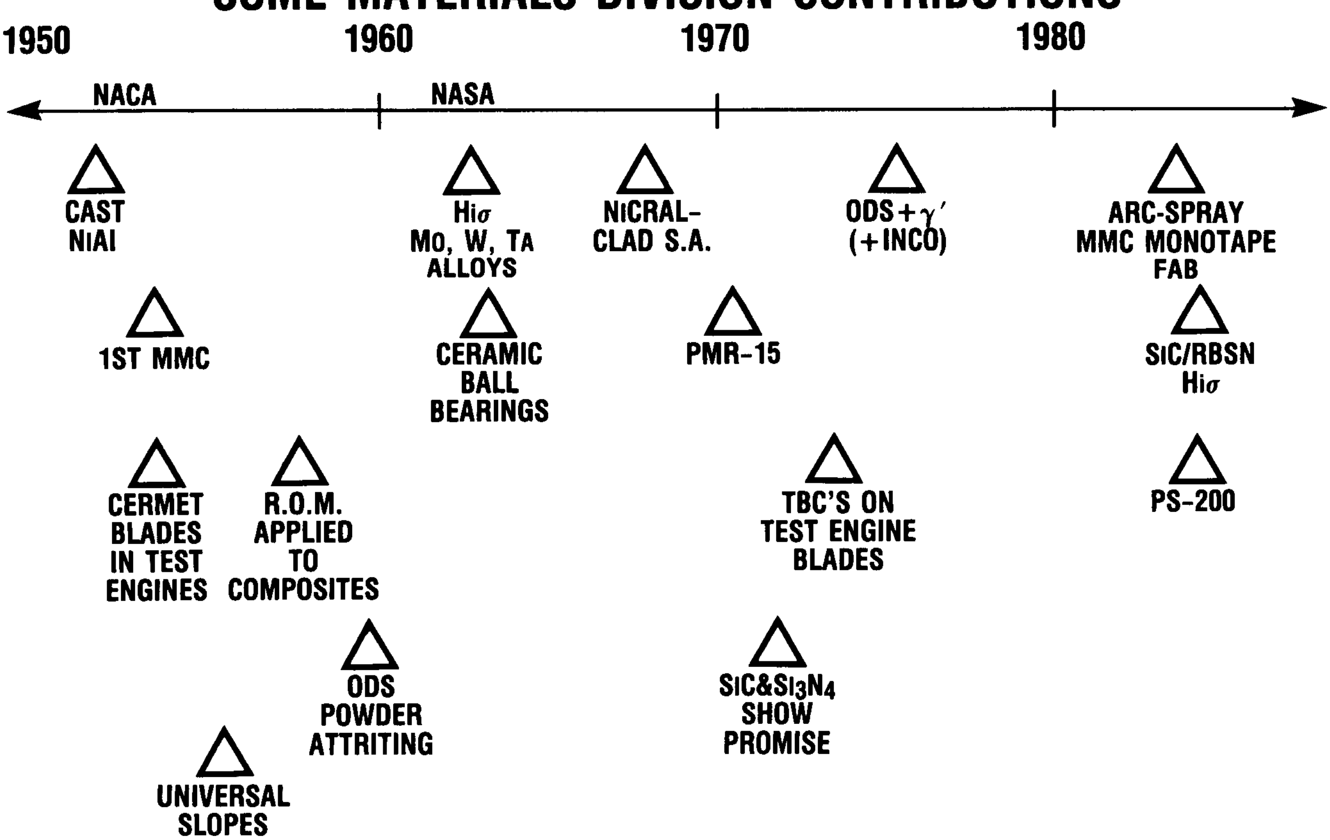
Refractory metals and compounds. - New W or Mo+Re alloys were discovered at Lewis and then strengthened via Hf&C additions. We conducted much of the early work on HfC and TaC.

Ceramics. - Lewis conducted the first engine tests on brittle cermets, developed early blade root designs for brittle materials, identified ceramic ball bearing potential, amd generated early data on Si_3N_4 and SiC ceramic potential for gas turbine service.

Coatings. - Lewis research resulted in early identification of NiCrAl and FeCrAl as surface protection systems for superalloys the first TBC's to work in oxidizing environments and to be tested on blades in engines.

Polymer composites. - PMR-15 was discovered at Lewis and we supported it through commercial introduction.

SOME MATERIALS DIVISION CONTRIBUTIONS



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COMMON MATERIAL NEEDS

Today, propulsion system limits are limiting aircraft advances. Achievement of viable high thrust-to-weight aircraft, Mach 2 to 6 aircraft, very high efficiency/pressure ratio subsonic aircraft, VSTOL, NASP, etc. depend on advances in engine materials. Similarly, in the whole arena of space propulsion and space power, the availability of high performance materials is controlling advances. Many of the same needs exist for both types of systems. Indeed, as we move toward hypersonics, toward cryogenic fueled aircraft, and toward multiple reuse rockets, the temperature, performance, and life demands show significant overlap.

COMMON MATERIAL NEEDS

AERO SYSTEMS →

- HIGH TEMPERATURE
- LIGHTWEIGHT
- HIGH STRENGTH
- ENVIRONMENTALLY RESISTANT
- LONG LIFE
- STABLE
- DESIGNABLE
- FABRICABLE
- REPAIRABLE
- PREDICTABLE

← SPACE SYSTEMS

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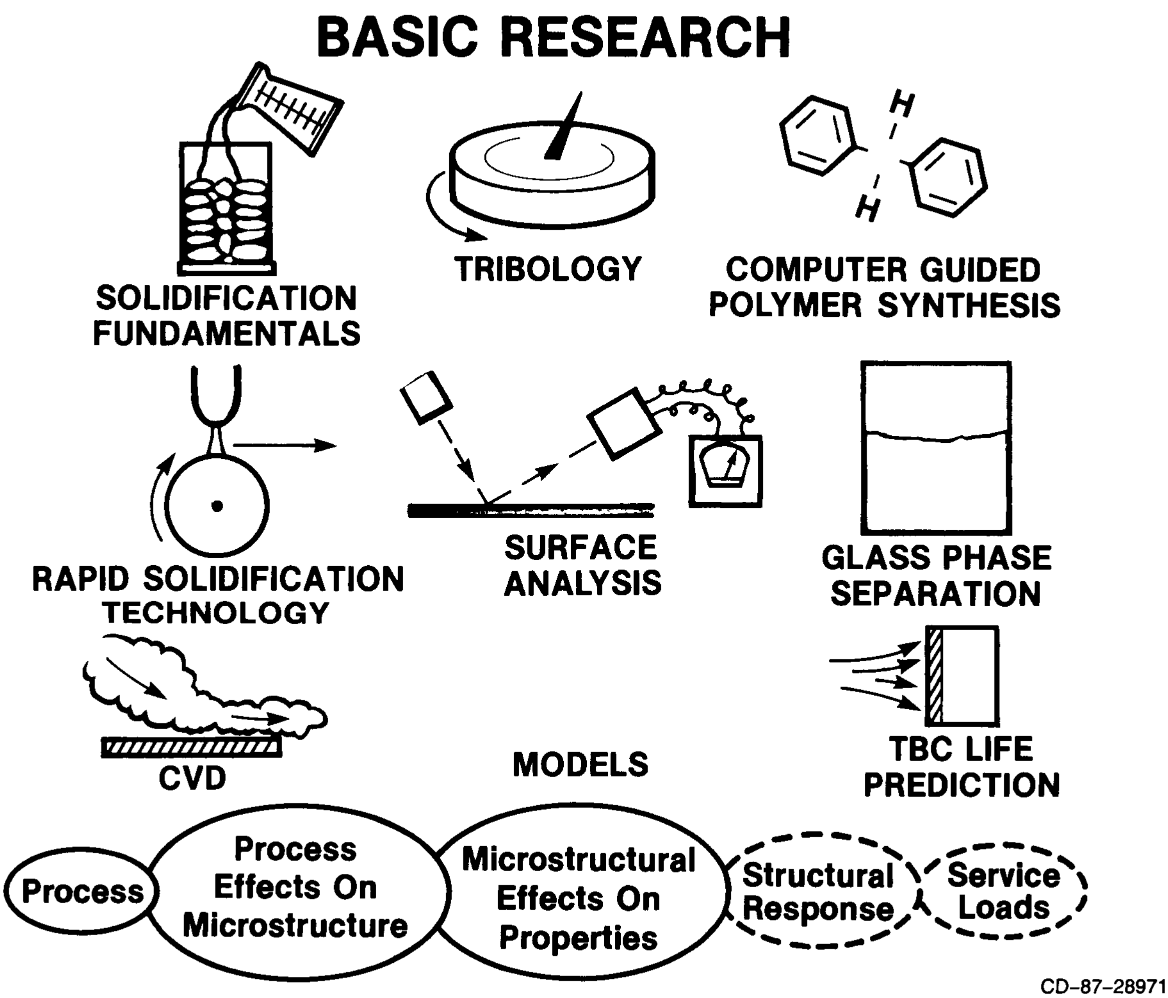
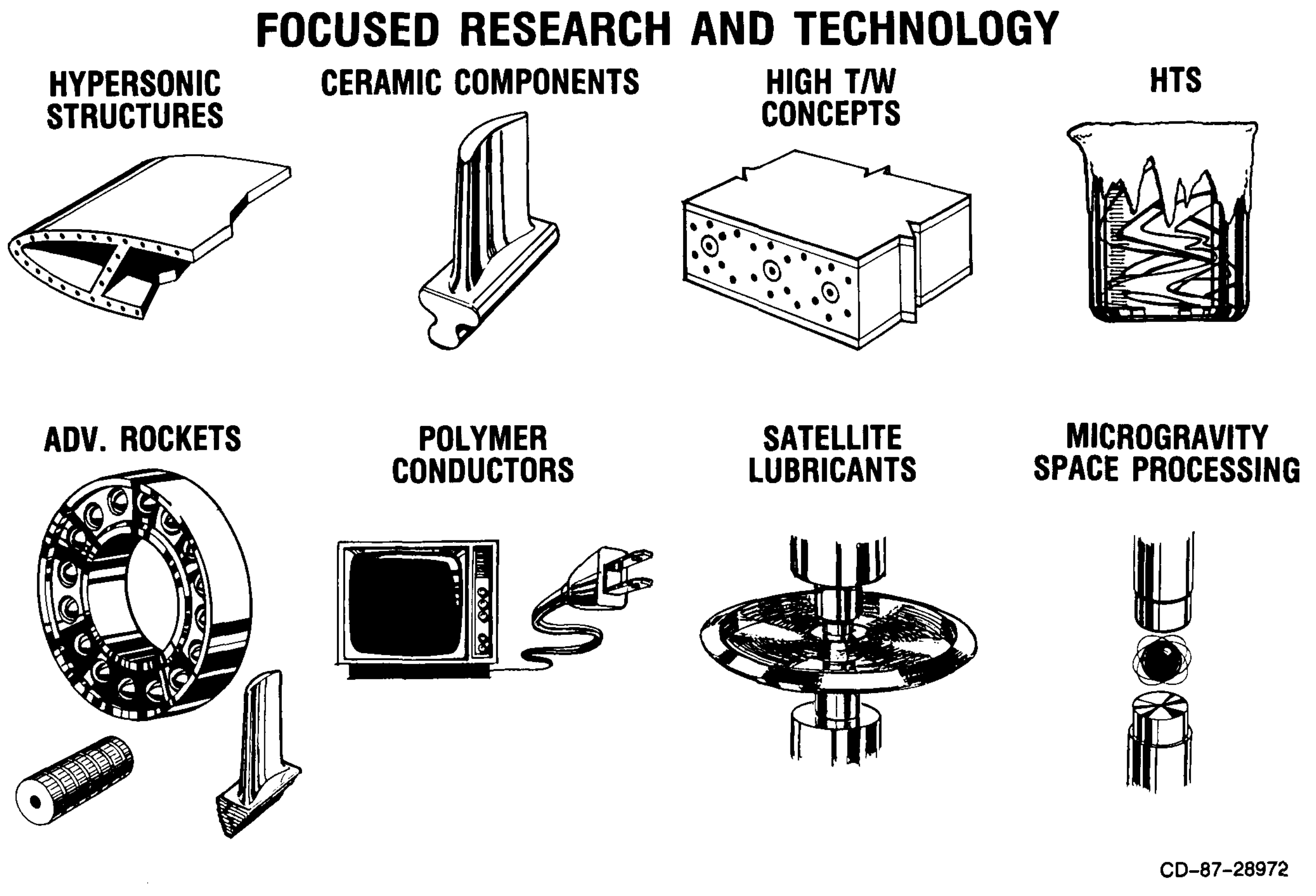
BASIC RESEARCH

In response to such requirements the Materials Division is aiming its efforts toward advanced high temperature composites capable of meeting NASA and industry needs for the year 2000 and beyond. Our work involves basic research, focused research, and direct project support and consultation. About 20 percent of our work involves exploratory research and basic studies aimed at understanding key barrier phenomena. Some of these areas are shown. Note that as part of our efforts to mathematically characterize and predict material responses, we have a growing modeling activity supporting our experiments.



FOCUSED RESEARCH AND TECHNOLOGY

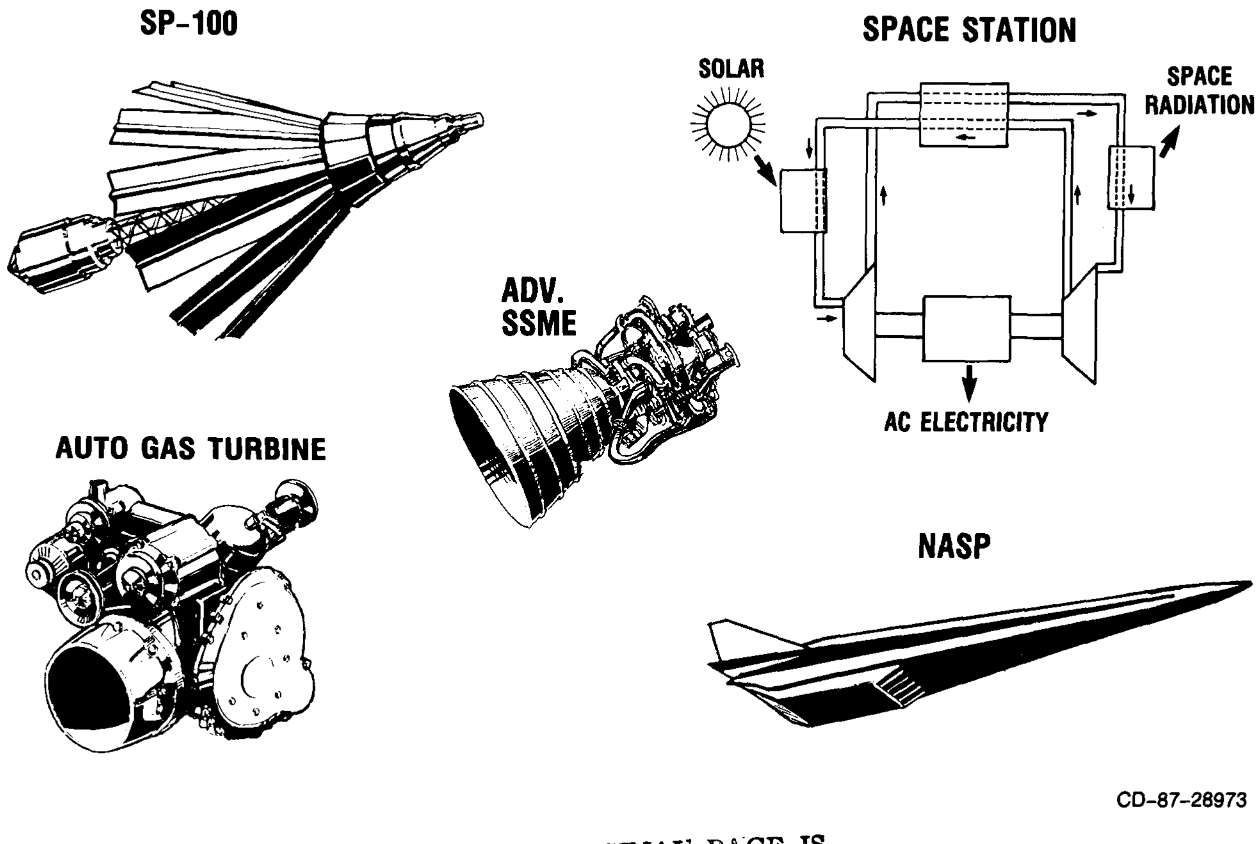
About 65 percent of our effort involves focused research -- looking at long range system needs and attacking those issues that would enable and enhance system performance. Such research covers a very broad range of NASA and industry interests. In the area of hypersonic engine structures (and advanced rocket nozzles) we are looking for high strength/high conductivity systems such as W fiber/copper composites for cooled applications as well as for high temperature ceramic composites for hard-to-cool components. Long life materials for high speed turbopump blades, bearings, etc. are being sought. Ceramic materials, intermetallic composites, and polymer conductors are all being pursued to provide lightweight high performance alternatives to current technology. In the high temperature superconductor arena we are supporting efforts aimed at NASA-specific applications. To enhance satellites and the space station's effectiveness we are working on improved lubricants as well as supporting the microgravity science and applications/commercial use of space programs. Here we do focused research on basic processing issues. Our microgravity materials science laboratory is a place where we work with industry and university investigators to help clarify their ideas and lay the ground work for potential space experiments or processing hardware.



SYSTEMS SUPPORT

About 15 percent of our effort supports systems where NASA has a major role in development. For example, our work on SP-100 includes materials for lightweight radiators, research that is clarifying the basis for Ge-Si/GaP thermoelectric performance improvements, and on high strength refractory composites for lithium-cooled heat pipes. Our support for Space Station includes identifying salts for thermal storage and corrosion resistant materials for their containment. In the auto gas turbine program that NASA manages for DOE, we have done a lot toward raising the reliability and reproducibility of monolithic ceramics and toward characterizing factors that currently limit their use.

SYSTEMS SUPPORT



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ADVANCED HIGH TEMPERATURE MATERIALS FOR TURBINE ENGINES 1988 to 1993

NASA recognized the growing relationship between materials availability and system performance limits. So this year a new effort was started. It is called Advanced High Temperature Materials for Turbine Engines. This base R&T augmentation will concentrate on accelerating the exploratory and the focused types of work -- primarily aimed at readying high temperature composites for engine consideration. With this effort we will be moving to tie together both the materials development and the structural analysis efforts from the start in an attempt to reduce the 12 to 15 year time that new materials normally take to reach system use. We are also trying to create new linkages between ourselves, industry, and the universities. This coordination will benefit U.S. aeropropulsion by concentrating the diversity of views and backgrounds on moving such revolutionary materials forward. Specifically, we expect future advances in:

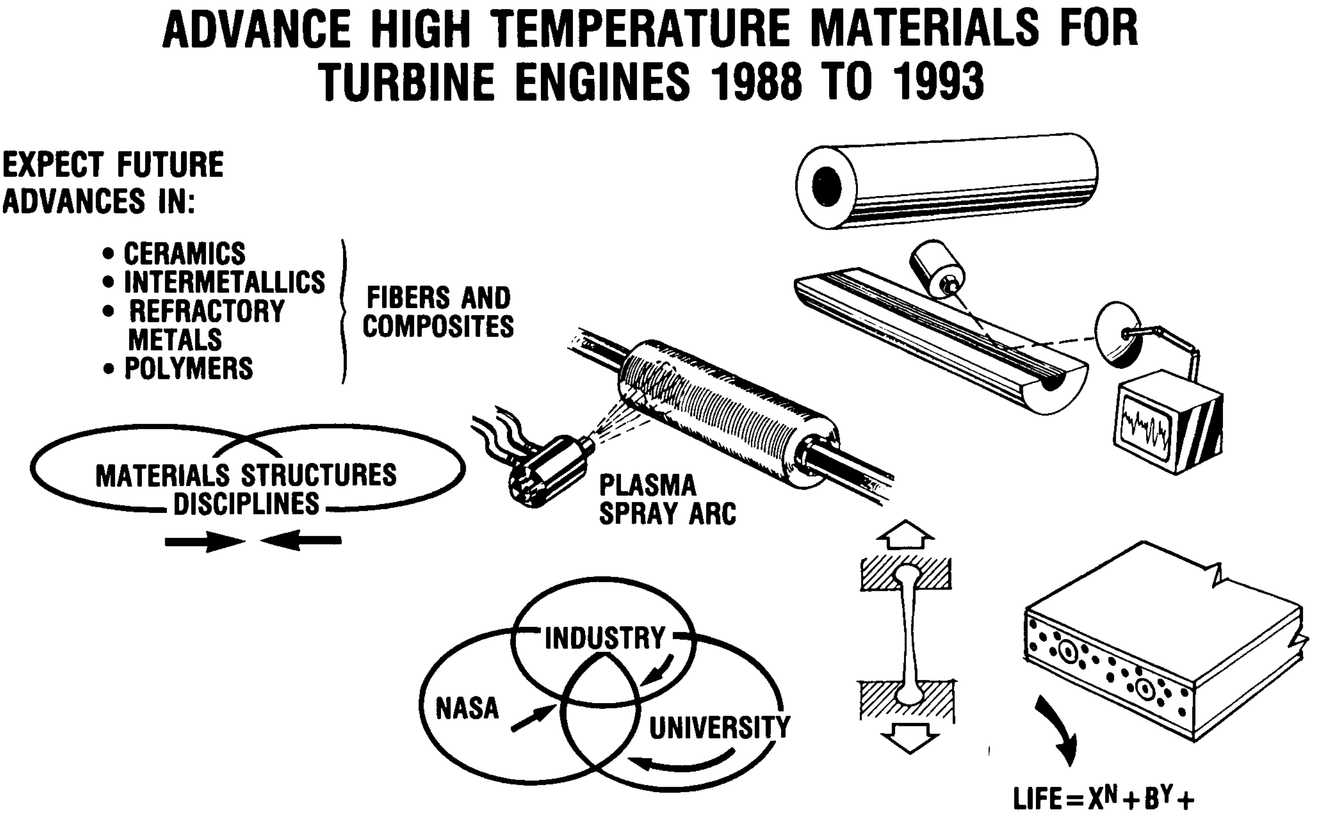
Fibers. - Improved fiber properties and temperature limits, fiber coating to control interface reactions, and interface characterization methods.

Composite fabrication. - Optimizing current processes, but looking for better ways so as to create options to make complex shapes economically in a reliable manner.

Testing and analysis. - New methods and facilities to generate high temperature property data and to verify the new analytical codes and models to guide lay-up and fabrication.

Life and failure analysis. - Better ways to relate multiphase microstructures to properties and eventually properties to component performance.

Ideas. - New ideas to help create a "next generation" basic industry capable of a strong role in world trade.



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HIGH TEMPERATURE POLYMER MATRIX COMPOSITES

Michael A. Meador

ABSTRACT

E-3798-K

With the increased emphasis on high performance aircraft the need for lightweight, thermal/oxidatively stable materials is growing. Because of their ease of fabrication, high specific strength, and ability to be tailored chemically to produce a variety of mechanical and physical properties, polymers and polymer matrix composites present themselves as attractive materials for a number of aeropropulsion applications. In the early 1970's researchers at the NASA Lewis Research Center developed a highly processable, thermally stable (600 °F) polyimide, PMR-15. Since that time, PMR-15 has become commercially available and has found use in military aircraft, in particular, the F-404 engine for the Navy's F/A-18 strike fighter. NASA Lewis's contributions to high temperature polymer matrix composite research will be discussed as well as current and future directions.

WHY POLYMERS?

Polymers have a number of properties which make them attractive candidates for aeropropulsion materials. They are lightweight (typically densities are on the order of 1.0 g/cc), corrosion resistant, and can be easily molded or shaped into complex forms. In addition to this, their chemical structure can be altered to meet a number of specific performance requirements - thermal/oxidative stability, toughness, thermal or electrical conductivity, etc.

WHY POLYMERS ?

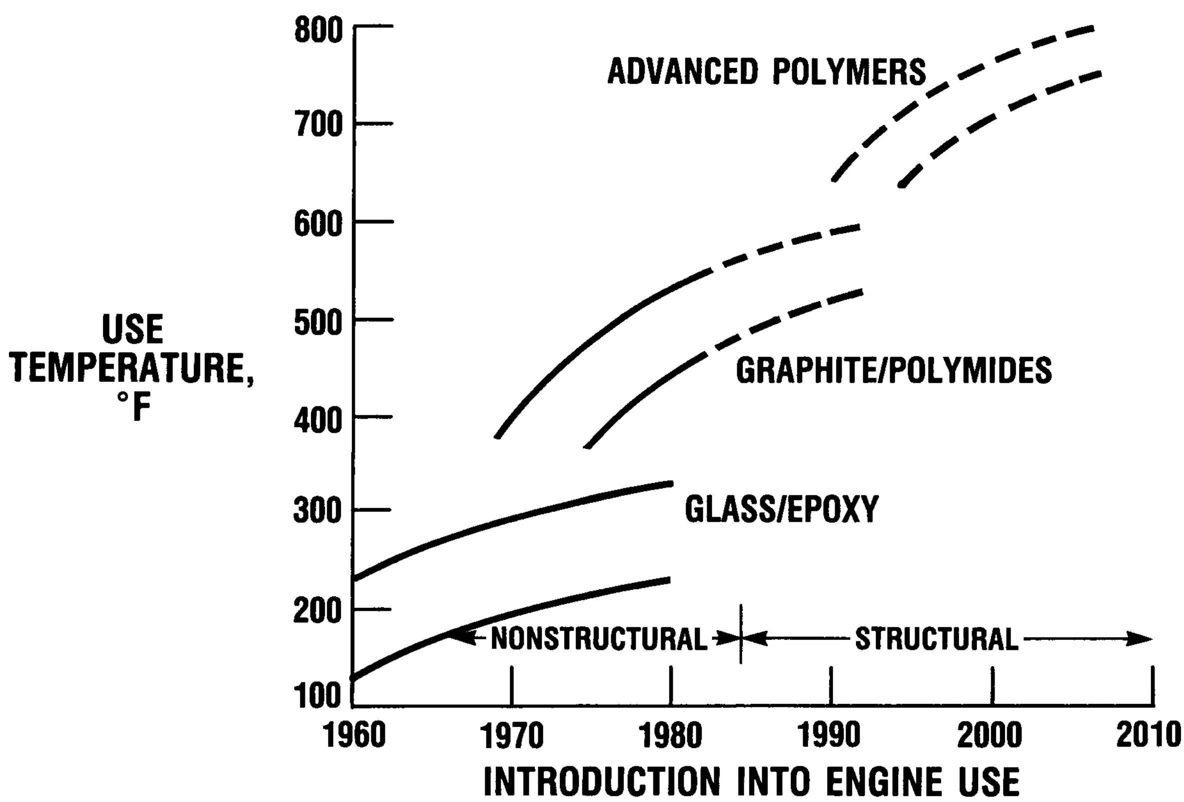
- CAN BE SHAPED OR FORMED EASILY
- LIGHTWEIGHT
- CORROSION RESISTANT
- CAN BE TAILORED TO SPECIFIC NEEDS

CD-87-29452

TRENDS FOR POLYMER COMPOSITES IN ENGINES

Polymer matrix composites have been used in engine applications since fiberglass/epoxy composites were introduced in the 1960's. Since that time, different reinforcement/resin combinations have been developed to meet increased temperature requirements. Current state-of-the-art graphite/polyimide composites are stable for thousands of hours at 600 °F. Research at the Polymers Branch of the Lewis Research Center is aimed at the development of new polymer matrix composite systems for use at 700 °F and beyond.

TRENDS FOR POLYMER COMPOSITES IN ENGINES



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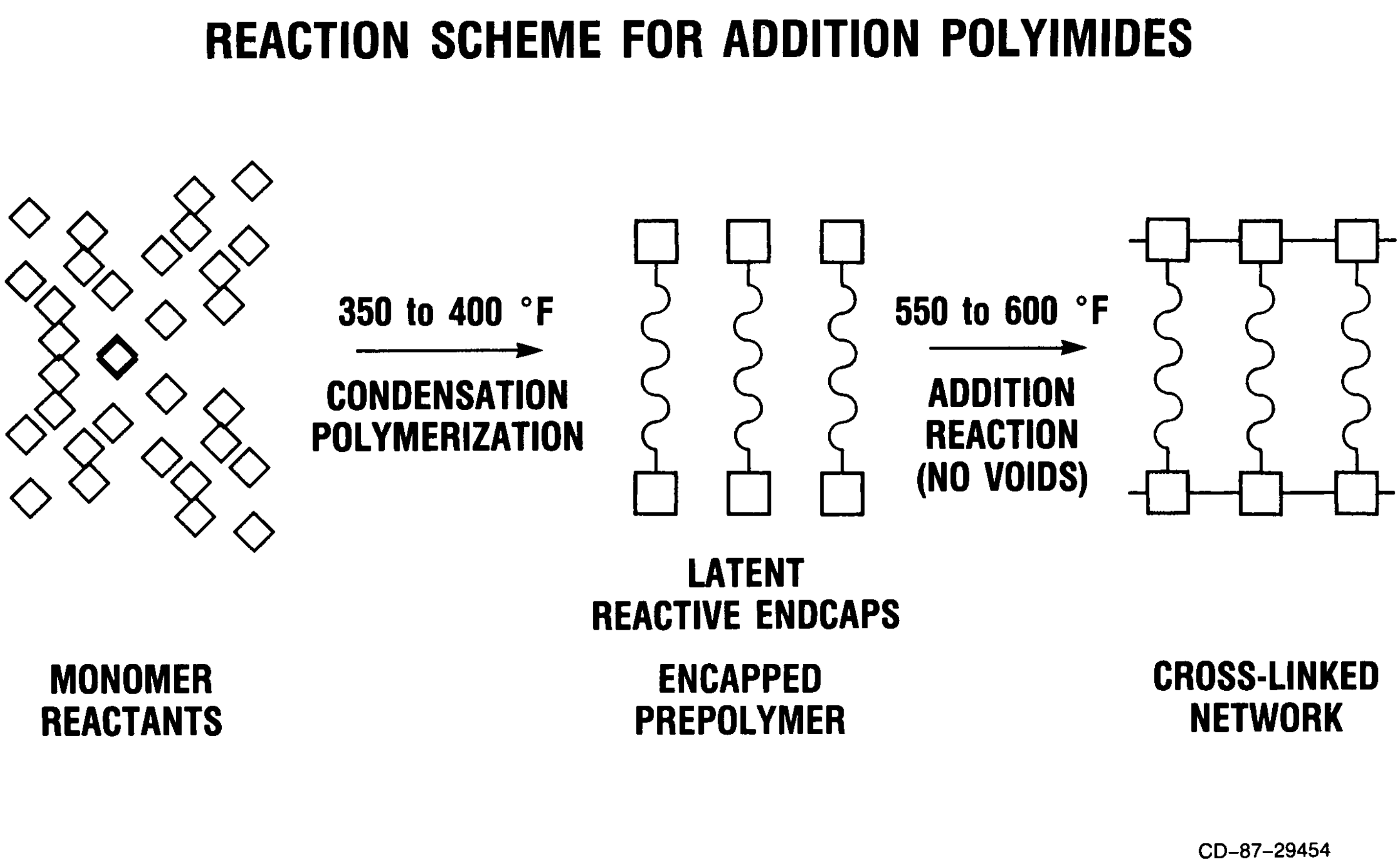
REACTION SCHEME FOR ADDITION POLYIMIDES

Composites which contain a number of air-pockets, or voids, generally have inferior mechanical properties and thermal/oxidative stability. Therefore, one of the major concerns in processing polymer matrix composites is minimizing the void content in the final composite. One approach to this (depicted in this figure) involves a two-step cure procedure. In this method a prepolymer is formed in the first step. Generally, this step involves formation of low molecular weight materials and produces volatile byproducts (condensation reaction). This prepolymer is end-capped with a group which undergoes a cross-linking reaction at a higher temperature to form a more thermally stable, tougher polymer network. Unlike the first step, the cross-linking reaction proceeds with no formation of byproducts. The result is a highly processable, void-free composite.

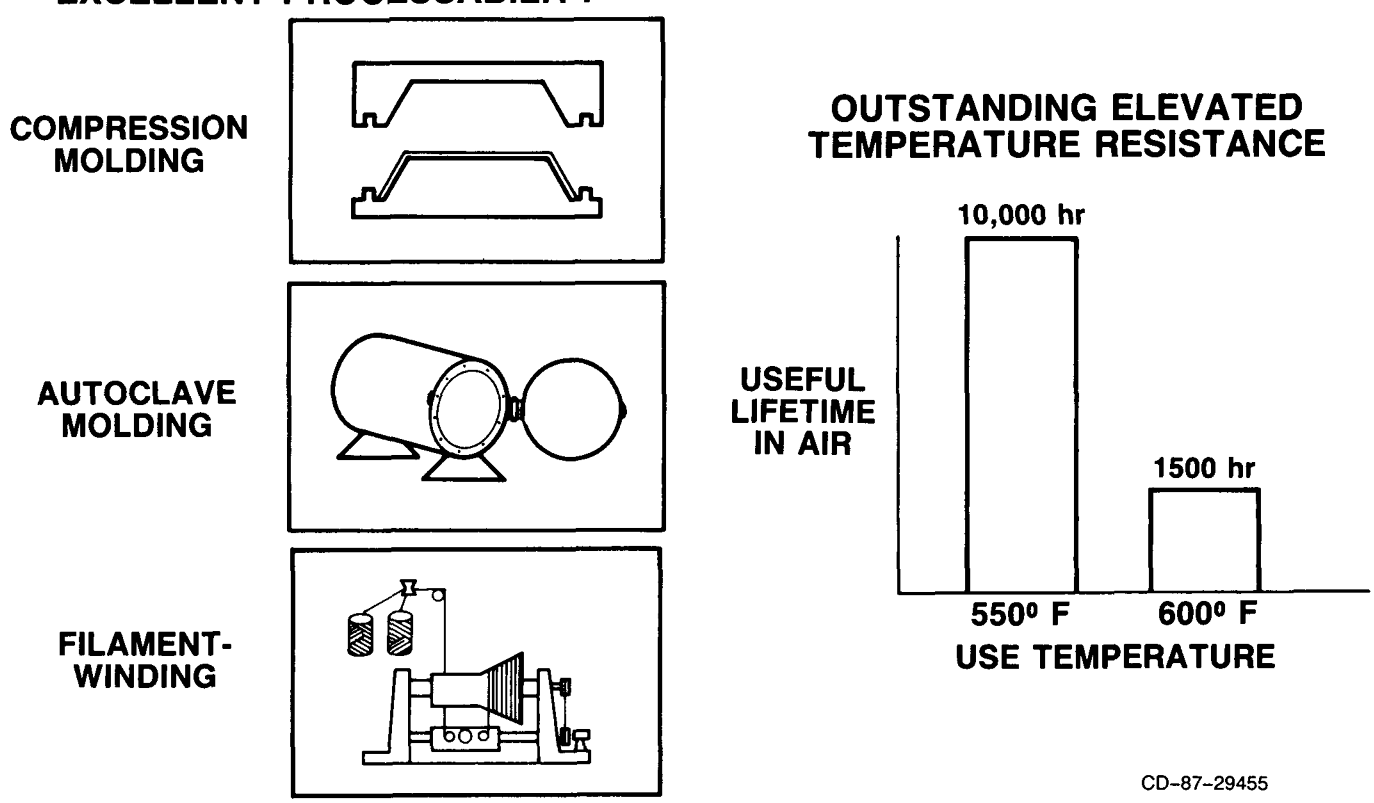


PMR POLYIMIDES

In the early 1970's researchers at NASA Lewis Research Center developed an additional curing polymide resin system known as PMR (polymerization of monomer reactants) polyimides. These polyimides, in particular PMR-15, afford exceptional thermal stability coupled with good processability. The useful lifetimes (in 60 psia) are 10 000 hr at 550 °F and 1500 hr at 600 °F.

LEWIS DEVELOPED PMR-15 POLYIMIDE TECHNOLOGY

EXCELLENT PROCESSABILITY



NAVY MANUFACTURING TECHNOLOGY

A study performed under contract to the Navy indicated that inclusion of PMR-15/graphite composites in a number of military aircraft engines, such as the F-404, F-110, and F-101, would result in considerable savings in weight and manufacturing costs.

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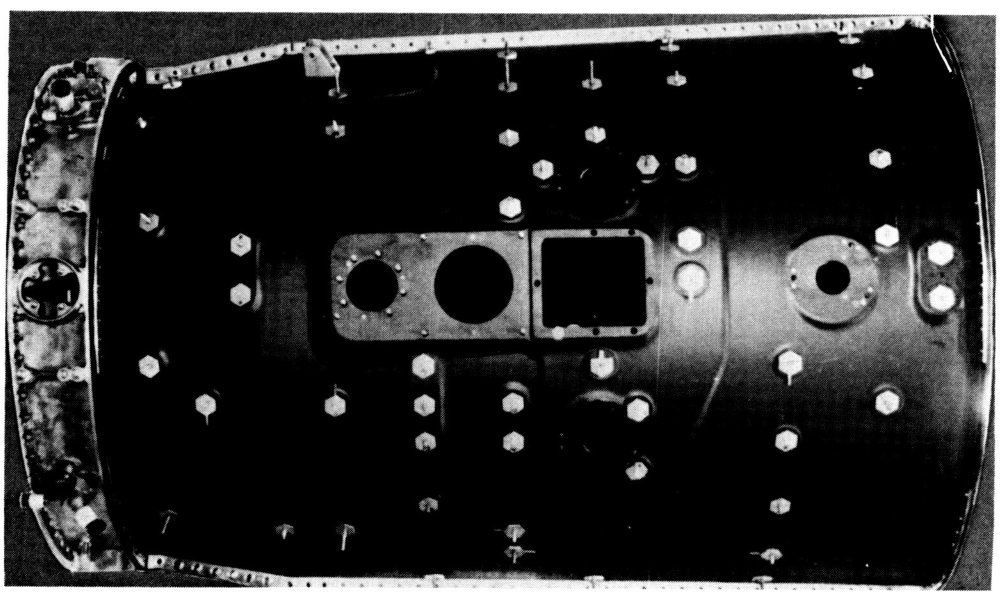
GRAPHITE/PMR-15 TITANIUM REPLACEMENT F-404 OUTER DUCT

GE is currently producing a graphite PMR-15/graphite duct for their F-404 engine. Originally made out of titanium, this duct was manufactured by forming and machining titanium plates followed by chem-milling to reduce the final weight. In initial tests, the graphite/PMR-15 replacement duct successfully completed over 1000 accelerated mission test cycles for a total engine exposure time of 700 hr. Replacement of the original titanium duct by the PMR-15/graphite ducts has resulted in a total weight savings of 7 pounds per engine. In-house studies by GE indicate that PMR-15/graphite could be used in other areas of this engine to provide similar weight reductions and production cost savings.

NAVY/NASA LeRC/GE JOINT DEVELOPMENT

WEIGHT SAVINGS **7 POUNDS/ENGINE**

PRODUCTION QUALITY DUCT



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NASA LEWIS LEADS THE WAY IN HIGH TEMPERATURE POLYMERS WITH PMR-15

Offering the combination of good processability and thermal/oxidative stability, PMR-15 is a recognized leader in high temperature polymer matrix resins. It is one of the most widely used matrix resins for 550 °F applications. Currently there are eight commercial licenses for PMR resins.

NASA-LEWIS LEADS THE WAY IN HIGH TEMPERATURE POLYMERS WITH PMR-15

- **PMR RESINS DEVELOPED IN RESPONSE TO NEED FOR A *PROCESSABLE*, HIGH TEMPERATURE MATERIAL**
- **EIGHT *COMMERCIAL* LICENSES FOR PMR RESINS. MAJOR SUPPLIERS: AMERICAN CYANAMID, CIBA-GEIGY, FERRO, FIBERITE, HEXCEL, U.S. POLYMERIC, HYSOL/GRAFIL, TRIBON.**
- **ONE OF THE MOST *WIDELY USED* MATRIX RESIN FOR 550 °F APPLICATIONS.**

CD-87-29458

LEWIS POLYMERS BRANCH WORKS CLOSELY WITH INDUSTRY

Since the development of PMR polyimides, the Polymers Branch at NASA Lewis Research Center has responded to industry needs for improvements in these resins, understanding the mechanisms for their thermal/oxidative degradation, and developing quality control methods. This work has resulted in a substantial contribution to the scientific literature and has resulted in a number of patents.

LEWIS POLYMERS BRANCH HAS WORKED CLOSELY WITH *INDUSTRY* RESPONDING TO *NEEDS* FOR IMPROVEMENTS AND FURTHER UNDERSTANDING OF THESE MATERIALS, INCLUDING:

- IMPROVED TACK/EASIER HANDLING PMR
- LOWER CURE TEMPERATURE MATERIALS
- MECHANISTIC STUDIES
- UNDERSTANDING OF STRUCTURE/PROPERTY RELATIONSHIPS
- DEGRADATION STUDIES
- IMPROVED TOUGHNESS
- IMPROVED THERMAL STABILITY
- QUALITY CONTROL PROCEDURES

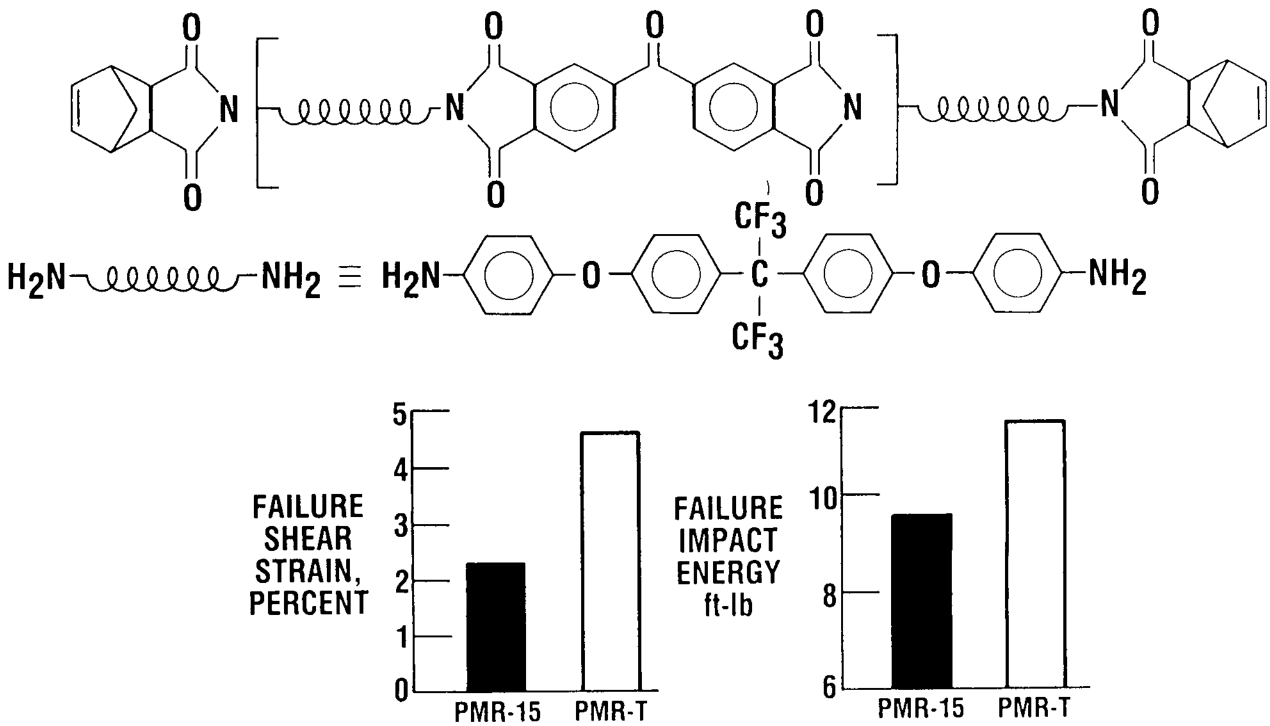
THIS WORK HAS LED TO OVER SEVENTY SCIENTIFIC PUBLICATIONS, TWELVE PATENTS AND SEVEN PATENTS PENDING.

CD-87-29459

PMR POLYMIDES WITH IMPROVED TOUGHNESS

A toughened PMR polyimide, PMR-T, was produced by substituting a flexible monomer into the original PMR formulation. The result is a two-fold increase in failure shear strain and an improvement in the impact strength.

PMR POLYIMIDES WITH IMPROVED TOUGHNESS



COMPARISON OF COMPOSITE PROPERTIES
WHICH AFFECT COMPOSITE TOUGHNESS

CD-87-29460

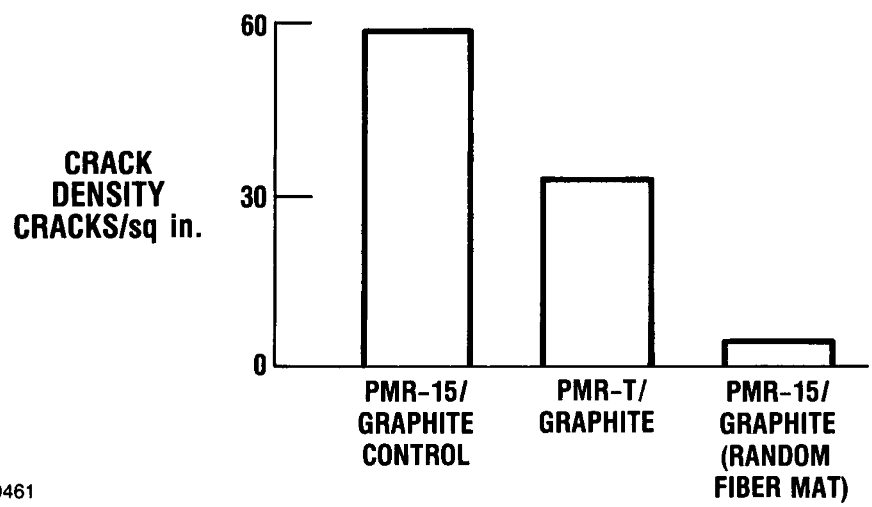
GRAPHITE/PMR COMPOSITE MATERIALS DEVELOP MICROCRACK DURING IN-SERVICE THERMOCYCLING

One concern that has arisen with graphite/PMR-15 is that these composites experience some microcracking during thermal cycling. The NASA Lewis Polymers Branch has approached this problem from two-angles - one a chemical solution, the other an engineering solution. The use of PMR-T in place of PMR-15 resulted in a 50 percent reduction in the composite trans-ply crack density after 1000 cycles (0 to 450°F). Use of a random fiber mat finish virtually eliminated microcracking in a graphite/PMR-15 composite during the same thermal cycling test.

GRAPHITE/PMR COMPOSITE MATERIALS DEVELOP MICROCRACKS DURING IN-SERVICE THERMOCYCLING WHICH CAN AFFECT MECHANICAL PROPERTIES

APPROACHES TO ELIMINATE IN-SERVICE MICROCRACKING:

1) TOUGHER POLYMER MATRIX RESIN
2) REPLACING SOME UNIDIRECTIONAL PLIES WITH RANDOM FIBER MAT

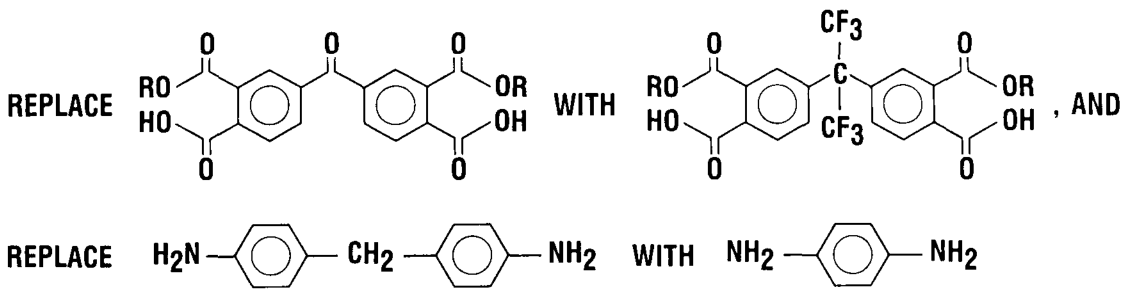


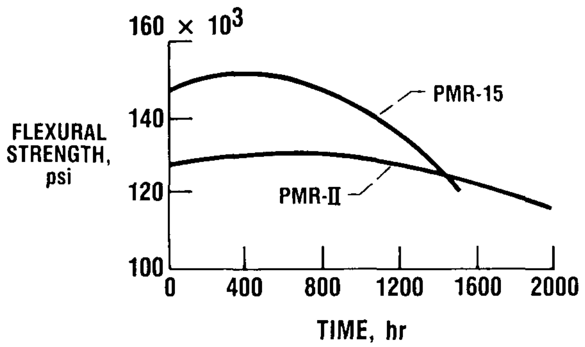
CD-87-29461

PMR-II: BETTER RETENTION OF PROPERTIES THROUGH USE OF MORE STABLE MONOMERS

Enhanced thermal/oxidative stability was achieved by the substitution of more thermally stable monomers into the original PMR composition. The resulting resin, PMR-II, a 1977 IR-100 award winner, yielded increased mechanical property retention at 600 °F in air over PMR-15.

PMR-II: BETTER RETENTION OF PROPERTIES THROUGH USE OF MORE STABLE MONOMERS





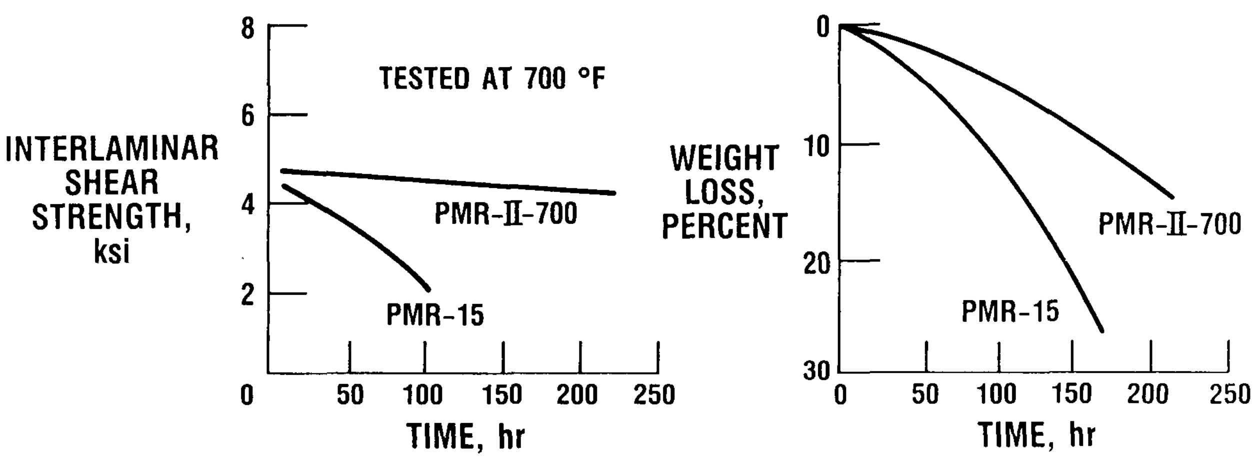
COMPARISON OF FLEXURAL STRENGTH OF PMR-15/GRAPHITE FIBER COMPOSITE WITH PMR-II/GRAPITE FIBER COMPOSITE EXPOSED AND TESTED AT 600 °F IN AIR

CD-87-29462

PMR-II-700: ENTRY INTO 700 °F APPLICATIONS

A higher molecular weight formulation of PMR-II, PMR-II-700, shows some promise as a 700 °F resin candidate. This resin has improved property retention and reduced weight loss over PMR-15 at 700 °F in air.

PMR-II-700: ENTRY INTO 700 °F APPLICATIONS



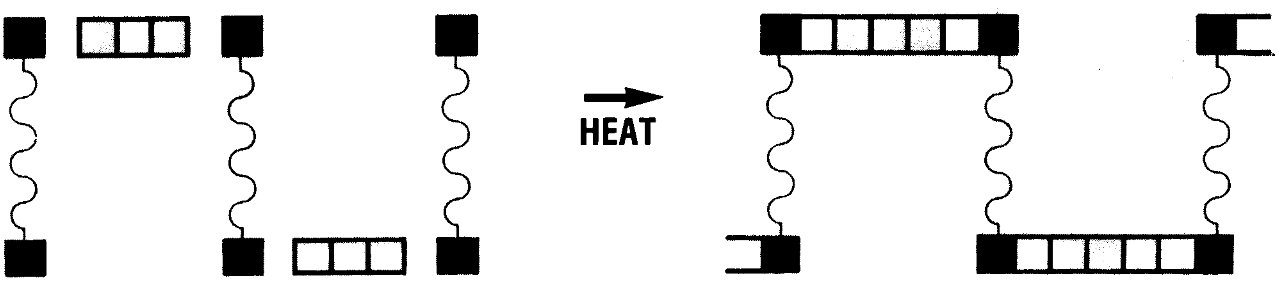
PROPERTIES OF GRAPHITE FIBER/PMR RESIN COMPOSITES AFTER EXPOSURE TO AIR AT 700 °F AND 60 PSIA

CD-87-29463

MARVIMIDES: LINEAR ADDITION COPOLYMERS WITH PARTIAL LADDER STRUCTURE

Mechanistic studies have revealed that the end cap is responsible for much of the thermal degradation in PMR-15 and similar polyimides. This is substantiated by the improved thermal/oxidative stability of PMR-II-700 in which the weight percentage of end cap is reduced by using higher molecular weight formulations. However, if use temperatures greater than 700 °F are to be realized, other approaches to high temperature matrix resins have to be developed. One such approach is MARVIMIDE, which employs a thermally stable cross-linking agent.

MARVIMIDES: LINEAR ADDITION COPOLYMERS WITH PARTIAL LADDER STRUCTURE

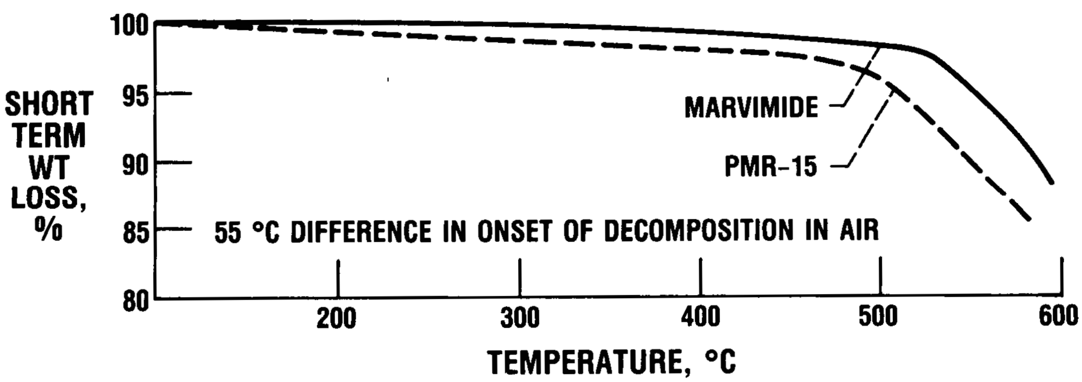


- PROCESSABLE (THERMOPLASTIC ?)
- HIGH SOFTENING TEMPERATURES
- STABLE LADDER STRUCTURES

MARVIMIDE HAS USE TEMPERATURES POTENTIALLY HIGHER THAN STATE OF THE ART (PMR-15)

The MARVIMIDE system offers good processablity, good resin flow, and produces matrix resins with superior thermal/oxidative stability and high softening temperatures (glass transition points, T_g, for unpostcured resins are as high as 420 °C). MARVIMIDE has a 100 °F higher onset of decomposition than PMR-15 in air.

MARVIMIDE HAS USE TEMPERATURES POTENTIALLY HIGHER THAN STATE OF THE ART (PMR-15)



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CREEP AND FATIGUE RESEARCH EFFORTS ON ADVANCED MATERIALS

John Gayda

ABSTRACT

Two of the more important materials problems encountered in turbine blades of aircraft engines are creep and fatigue. To withstand these high-temperature phenomena modern engines utilize single-crystal, nickel-base superalloys as the material of choice in critical applications. In this presentation we will discuss recent research activities at Lewis on single-crystal blading material as well as future research initiatives on metal matrix composites related to creep and fatigue. The goal of these research efforts is improving the understanding of microstructure-property relationships and thereby guide material development.

Although single crystals exhibit superior creep properties compared to conventionally cast, polycrystalline blading material, recent work at Lewis and other aerospace laboratories has shown that greater improvements can be attained by developing single-crystal alloys with a "rafted" microstructure. In this microstructure, the small, cuboidal γ' precipitates that strengthen these alloys are converted into nearly continuous layers or "rafts" of γ'. The factors, both internal and external, which affect raft formation have been studied from an experimental and analytical standpoint. These include the effect of stress, temperature, lattice misfit, and elastic constants of the precipitate and matrix.

In addition to creep damage, thermomechanical fatigue (TMF) of single-crystal blading material has received much attention in recent years because it is often found to be life limiting. TMF damage results from simultaneous fluctuations of temperature and mechanical loads. Recent work at Lewis on coated single crystals has identified an environmentally driven damage mechanism for the deleterious out-of-phase TMF cycle. Experimental evidence for this mechanism is presented, together with a qualitative model describing the damage mechanism.

As advanced superalloys, such as single-crystal, nickel-base alloys described here, approach their theoretical temperature limitation, research on creep and fatigue is being redirected toward lightweight, high-temperature, metal matrix composites. Future plans for modeling creep and fatigue phenomena of metal matrix composites are described for three very different systems.

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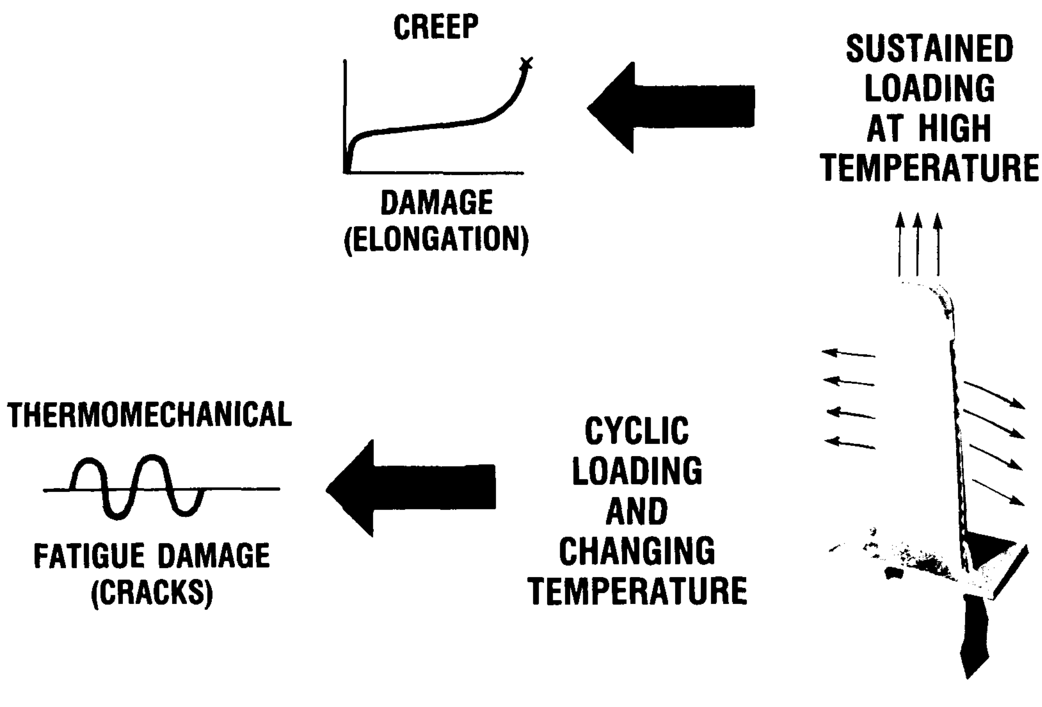
PHYSICAL ORIGIN OF CREEP AND FATIGUE DAMAGE IN TURBINE BLADES

The harsh operating environment encountered in the turbine section of an aircraft engine gives rise to numerous materials problems. Two of the more important problems are associated with creep and fatigue damage of turbine blades. Sustained, centrifugal loads on the blades at elevated temperature give rise to creep damage, a time-dependent, permanent elongation. Cyclic loads, associated with starting and stopping of the engine, coupled with the simultaneous changes in material temperature produce thermomechanical fatigue (TMF) damage. Unlike creep damage, TMF damage and subsequent growth of TMF cracks are directly dependent on the number of stress cycles the blades encounter, not the total exposure time at elevated temperatures.

PHYSICAL ORIGIN OF CREEP AND FATIGUE DAMAGE IN TURBINE BLADES



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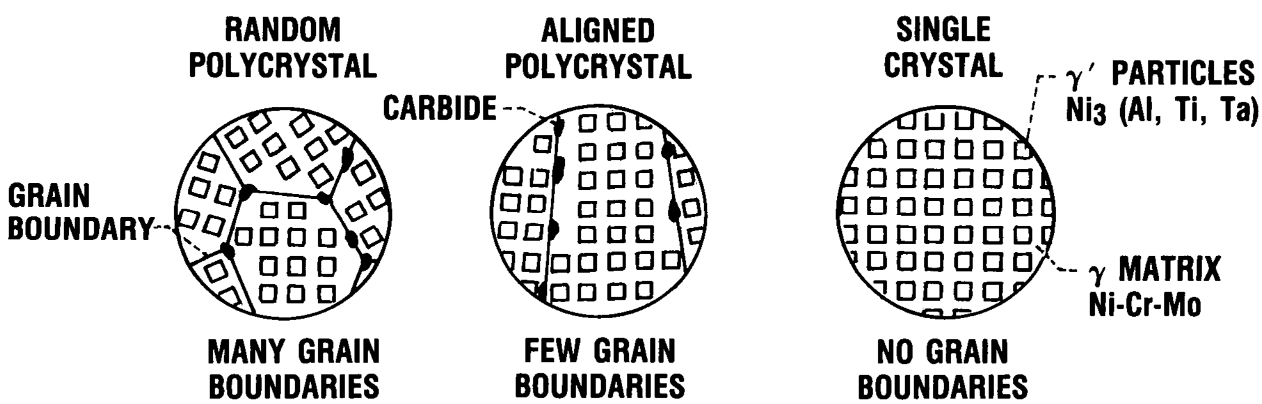
NICKEL-BASE SUPERALLOY TURBINE-BLADE MATERIALS MICROSTRUCTURES

To withstand the high-temperature loads developed in turbine blades, nickel-base superalloys are used in modern day engines. These blade alloys can be made as conventional castings or as directionally solidified castings. In the former instance, a random polycrystalline microstructure is produced, whereas, in the latter instance, an aligned polycrystalline microstructure is produced. The directionally solidified casting can also be produced such that the entire blade is a single grain or crystal. In all three forms, the superalloy derives much of its high-temperature strength from the γ' particles. Carbides are also present in the polycrystalline forms to enhance the creep strength of the grain boundaries.

NICKEL-BASE SUPERALLOY TURBINE-BLADE MATERIAL MICROSTRUCTURES



ALL THREE FORMS DERIVE HIGH-TEMPERATURE STRENGTH FROM THE γ' PRECIPITATE PARTICLES

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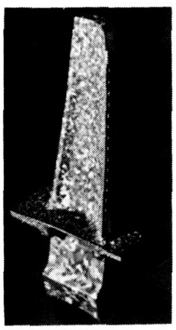
DEVELOPMENT OF NICKEL-BASE SUPERALLOY BLADING MATERIAL AND ASSOCIATED DAMAGE MECHANISMS

Of the three forms of nickel-base superalloy blading materials mentioned on the preceding page, the single-crystal form has the highest temperature, longest life capability because the detrimental effect of grain boundaries is eliminated. Further enhancement of single-crystal fatigue properties is attained by removal of carbides, which improve creep properties of grain boundaries, but also serve as initiation sites for fatigue cracks.

Materials research on single crystals at Lewis is aimed at improving the understanding of microstructure-property relationships and thus identifying ways to improve performance and to extend life by developing better materials. Examples of recent research activities in the area of creep and fatigue will be presented.

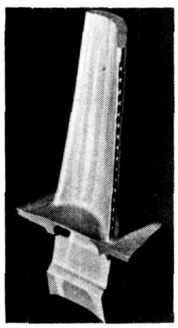
DEVELOPMENT OF NICKEL-BASE SUPERALLOY BLADING MATERIAL AND ASSOCIATED DAMAGE MECHANISMS

RANDOM POLYCRYSTAL



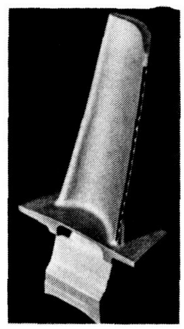
- CREEP DAMAGE
  - GRAIN BOUNDARY
  - BULK
- FATIGUE DAMAGE
  - GRAIN BOUNDARY
  - CARBIDES
  - MACROPOROSITY

ALIGNED POLYCRYSTAL



- CREEP DAMAGE
  - BULK
- FATIGUE DAMAGE
  - CARBIDES
  - MICROPOROSITY

SINGLE CRYSTAL



- CREEP DAMAGE
  - BULK
- FATIGUE DAMAGE
  - MICROPOROSITY

HIGHER TEMPERATURE CAPABILITY
LONGER LIFE ➡

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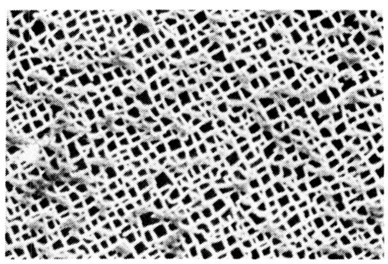
TAILORED MICROSTRUCTURE IMPROVES USEFUL LIFE

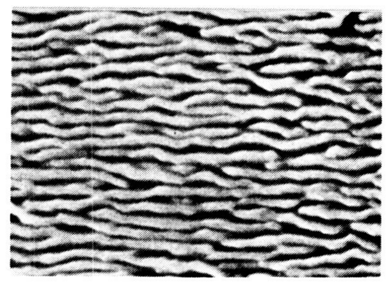
The typical heat-treated microstructure of modern single-crystal superalloys contains about 60 percent of the γ' precipitates dispersed in a continuous matrix of γ. The γ' particles are usually present as spheres or cubes after heat treatment, and an example of this microstructure is shown on the left. However, under an applied stress at elevated temperatures, these discrete γ' particles link up in certain alloys to form plates, which are commonly called γ' rafts. These γ' rafts have been shown to improve the creep life of single crystals at elevated temperatures.

TAILORED MICROSTRUCTURE IMPROVES USEFUL LIFE*

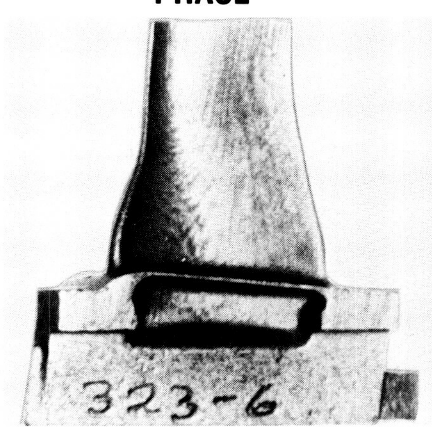


60 $^{V}/_{0}$ FINE γ' STRENGTHENING PHASE

1 μm

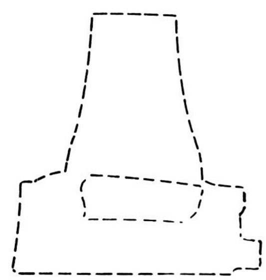


RAFTED γ'



SINGLE-CRYSTAL BLADE

APPLIED STRESS



IMPROVED SINGLE-CRYSTAL BLADE, LONGER LIFE

*MACKAY AND EBERT, SCRIPTA MET, 1983

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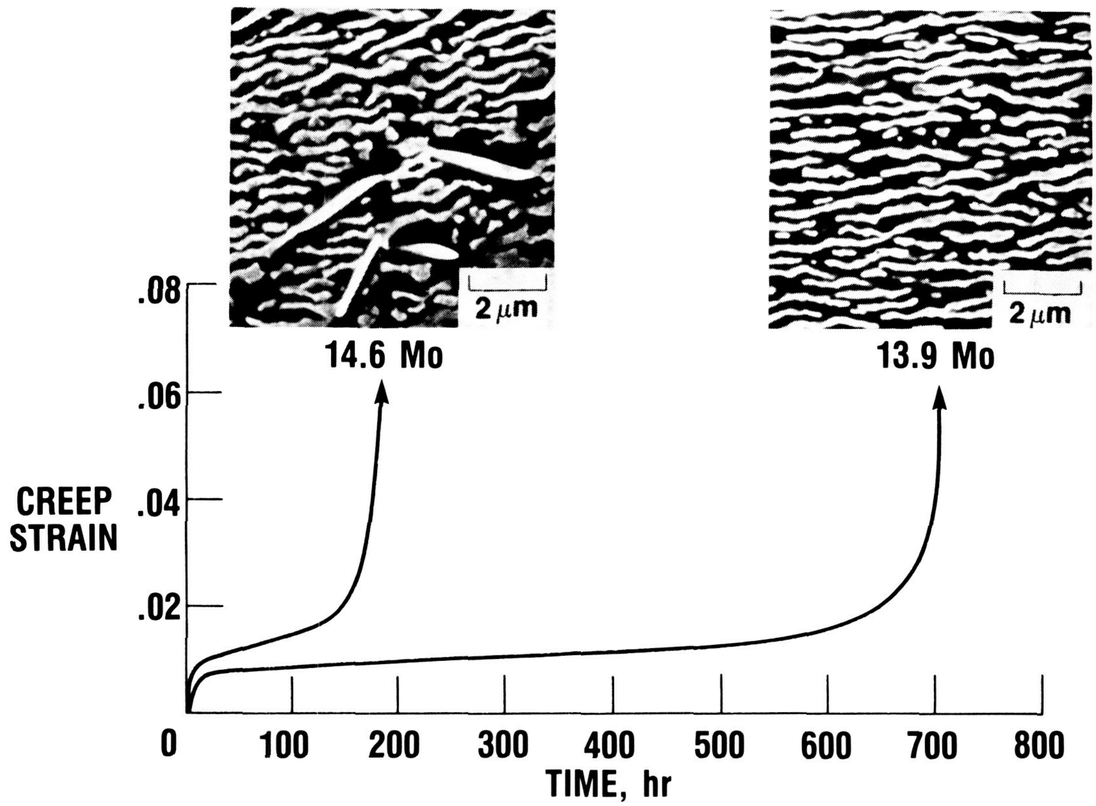
SUPERSATURATED ALLOY DEGRADES CREEP PROPERTIES

The γ' rafts have a beneficial effect on creep life if they form rapidly and are relatively perfect. An example of a "perfect" rafted microstructure is shown on the right for a single-crystal alloy containing 13.9 percent molybdenum. However, when the molybdenum content of the alloy was increased slightly to 14.6 percent, an additional phase forms which causes imperfections or gaps in the rafts. An example of this discontinuous rafted structure is shown on the left. The degradation in raft perfection causes a dramatic decrease in the creep life. Thus, our research is aimed at understanding the mechanisms of this phenomenon to exploit the maximum benefit from rafted microstructures.

SUPERSATURATED ALLOY DEGRADES CREEP PROPERTIES*



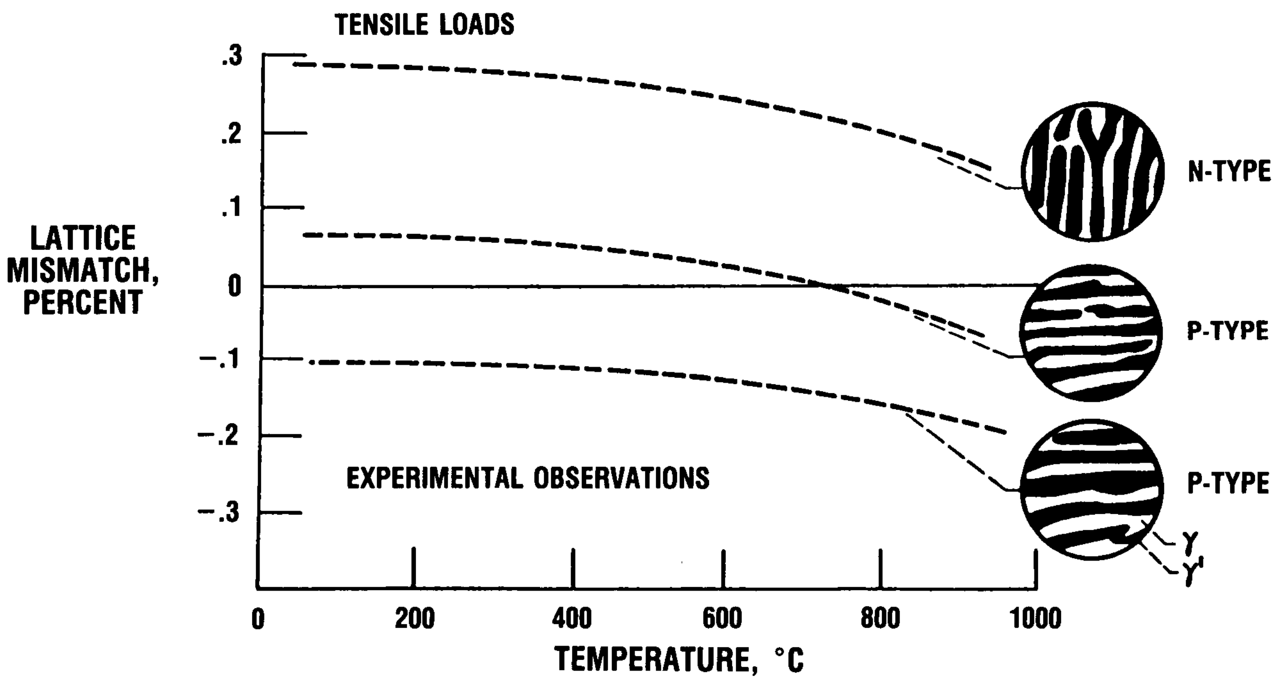
*MACKAY AND EBERT, 5TH INTERNATIONAL SYMPOSIUM ON SUPERALLOYS, 1984

CD-87-28776

INFLUENCE OF ELEVATED-TEMPERATURE LATTICE MISMATCH ON γ' PLATE ORIENTATION

A major factor which influences γ' rafting behavior is the lattice mismatch. The magnitude of the lattice mismatch indicates the difference in lattice parameters (the dimensions of the atomic structure) between the γ and γ' phases. The sign of the mismatch is one factor which determines the orientation of the rafted structure. Superalloys with large, negative values of lattice mismatch form rafts perpendicular (P-type) to the applied tensile axis, whereas alloys with large, positive values of mismatch form rafts parallel (N-type) to the applied tensile axis. However, the sign of the mismatch can actually change from positive to negative as temperature increases. Thus P-type rafts can form at elevated temperatures in some alloys which have a small positive mismatch at room temperature. It is therefore important to obtain lattice mismatch measurements at elevated temperatures in order to make accurate predictions of raft orientation.

INFLUENCE OF ELEVATED-TEMPERATURE LATTICE MISMATCH ON γ' PLATE ORIENTATION*



*MACKAY AND NATHAL, MICON SYMPOSIUM, 1986

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MODELING STRESS-ASSISTED PRECIPITATE GROWTH

To gain more insight, we developed (with D. Srolovitz now at the University of Michigan) a field-oriented, microstructural lattice model to simulate the rafting phenomenon. In this approach the microstucture is discretized onto a fine lattice. Each element in the lattice is labeled accordingly as γ or γ'. Diffusion, that is, physical transport of material at elevated temperatures, is simulated by allowing exchanges of neighboring elements if the exchange lowers the total energy of the system. A Monte Carlo approach is used to select the exchange site, whereas the change in energy associated with the stress fields, that is, precipitate misfit and external creep load, is computed by using a finite-element technique.

MODELING STRESS-ASSISTED PRECIPITATE GROWTH

MONTE CARLO TECHNIQUE FOR DIFFUSION SIMULATION

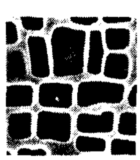
FINITE-ELEMENT TECHNIQUE FOR STRESS FIELD SIMULATION

↓

MERGE THESE EXISTING "TOOLS" INTO A TIME EFFICIENT COMPUTER CODE

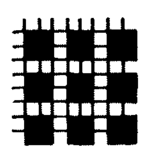
↓

ANALYTICALLY EVALUATE KEY MICROSTRUCTURAL PARAMETERS TO MODEL γ' RAFTING IN SINGLE CRYSTALS



REAL MICROSTRUCTURE

→



SIMULATION LATTICE

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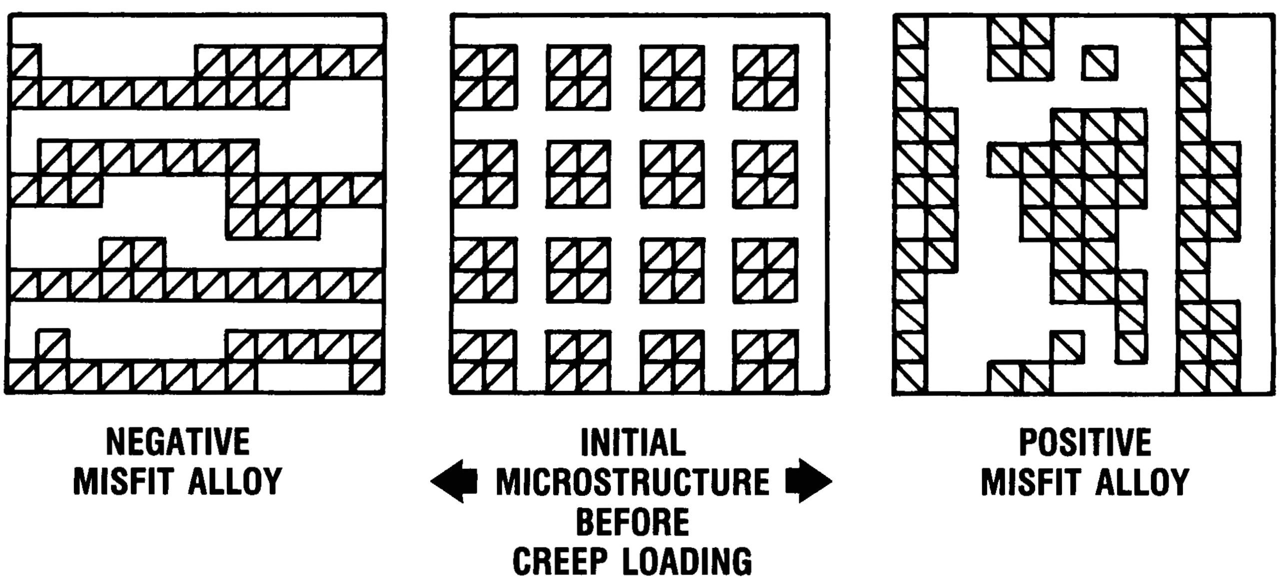
PREDICTED RAFTING BEHAVIOR OF POSITIVE AND NEGATIVE MISFIT ALLOYS AGREES WITH EXPERIMENT

To date, simulations of the rafting phenomenon in single crystals agree with real world behavior. The orientation of the rafted structure under tensile loads and its dependence on precipitate misfit is illustrated here. The two alloys shown have identical properties and starting microstructures, except that one has a negative misfit and the other has a positive misfit. Rafting simulations run on both alloys show that rafts develop which are perpendicular to the stress axis for negative misfit but parallel to the stress axis for positive misfit. This is consistent with the experimental results.

PREDICTED RAFTING BEHAVIOR OF POSITIVE AND NEGATIVE MISFIT ALLOYS AGREES WITH EXPERIMENT*



*SROLOVITZ, HASSOLD, AND GAYDA, INTERNATIONAL SYMPOSIUM OF ORDERING PROCESSES IN CONDENSED MATTER, 1987

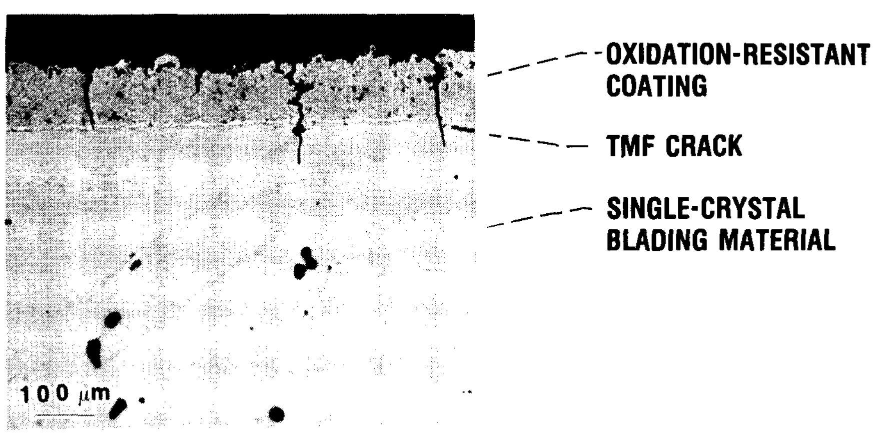
CD-87-28779

ALTHOUGH CREEP IS IMPORTANT, THERMOMECHANICAL FATIGUE (TMF) CRACKING OF COATED SINGLE CRYSTALS IS OFTEN LIFE LIMITING

Although the creep damage produced at high temperatures by sustained loads affects the life of single-crystal turbine blades, failure is often attributed to thermo-mechanical fatigue damage. This damage is produced by the application of cyclic loads during heating and cooling of the blade. The damage often starts as cracks in the oxidation-resistant coating applied to single-crystal turbine blades. These cracks grow into the single crystal and eventually cause failure of the blade.

ALTHOUGH CREEP IS IMPORTANT, THERMOMECHANICAL FATIGUE (TMF) CRACKING OF COATED SINGLE CRYSTALS IS OFTEN LIFE LIMITING

- CYCLIC LOADS
- HEATING AND COOLING



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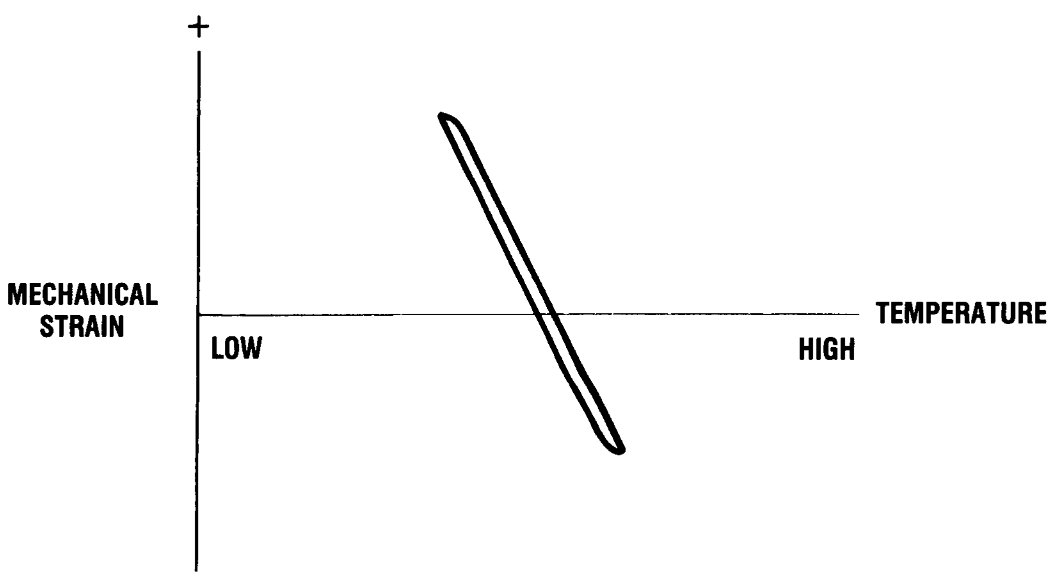
IT IS KNOWN THAT TMF LIFE IS LOW FOR CYCLES IMPOSING TENSION AT TEMPERATURES $\lesssim$ 800 °C

Thermomechanical fatigue (TMF) is particularly harmful in cycles where tensile loads are applied at temperatures below 800 °C, where ductility of superalloys is lowest. A TMF cycle of this type is termed out-of-phase (OP) and is often encountered in real engine cycles. Here the load and temperature change in opposite directions at the same time. This cycle produces tensile mechanical strains at the minimum temperature and compressive mechanical strains at the maximum temperature. Analysis is complicated, since the mechanical strain due to the changing load is mixed with thermal strains due to the changing temperature.

IT IS KNOWN THAT TMF LIFE IS LOW FOR CYCLES IMPOSING TENSION AT TEMPERATURES $\lesssim$800 °C



THIS CYCLE TYPE IS TERMED OUT-OF-PHASE (OP), SINCE MAXIMUM TEMPERATURE COINCIDES WITH MINIMUM (-) STRAIN; SIMILAR SITUATIONS ARE ENCOUNTERED IN REAL ENGINE CYCLES

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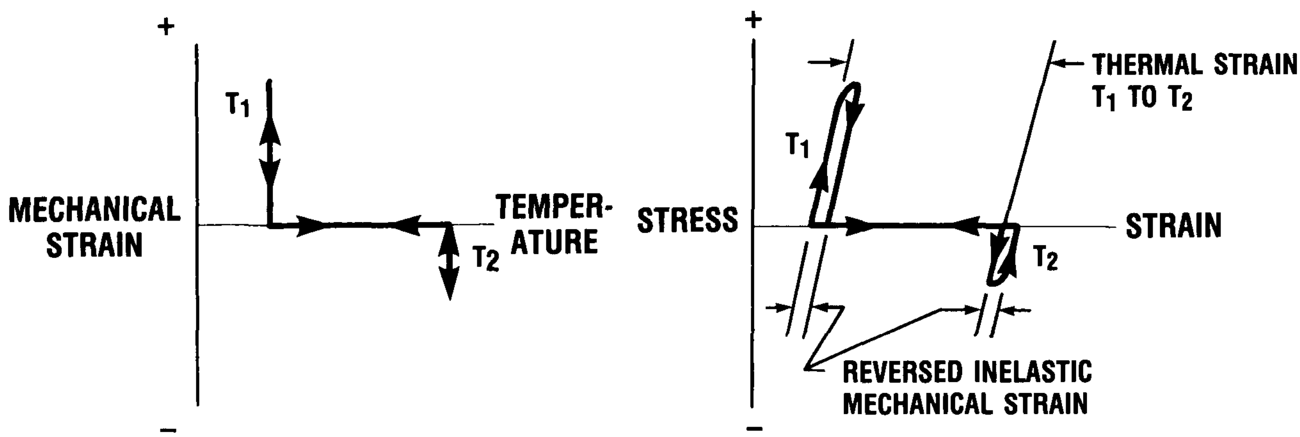
A SIMPLIFIED BITHERMAL TMF TEST ALLOWS STRAINS TO BE SEPARATED

A large body of knowledge exists on fatigue damage produced by cyclic loads at constant temperature. This understanding cannot be easily applied to the TMF problem, where cyclic loads produce damage at continuously changing temperatures. But the "bithermal" TMF cycle provides the means to apply this knowledge. In this simplified TMF cycle, equal amounts of inelastic mechanical strain, of opposite sign, are applied at the temperature extremes in the cycle. The inelastic strain is a permanent, or nonrecoverable, strain which produces damage within the material.

A SIMPLIFIED BITHERMAL TMF TEST ALLOWS STRAINS TO BE SEPARATED

OUT-OF-PHASE (OP) BITHERMAL TEST



FIXED TEMPERATURES AND REVERSED INELASTIC STRAIN LINK TMF BEHAVIOR TO UNDERSTANDING OF ISOTHERMAL FATIGUE MECHANISMS AT T_1 AND T_2

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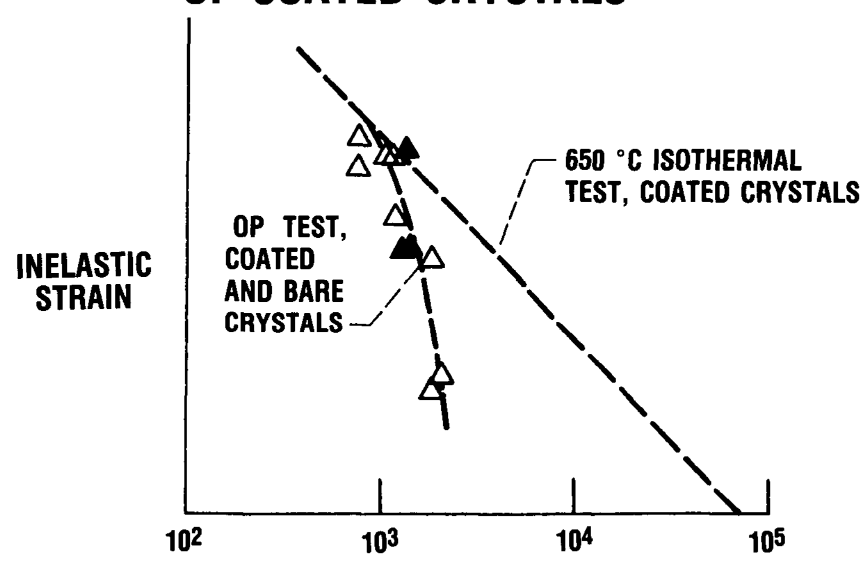
IN 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST, SURFACE CRACKS INITIATE EARLY IN COATED AND BARE CRYSTALS AS IN 650 °C ISOTHERMAL TEST OF COATED CRYSTALS

The bithermal TMF cycle produces the same type of damage as the more realistic TMF cycle. In out-of-phase (OP) tests where the temperature is changed between 650 and 1050 °C, both cycles produce premature surface cracks. Surface cracking also occurs in constant-temperature fatigue tests at 650 °C, and, at high cyclic strains, all cycles have comparable life. But in tests at low cyclic strains, the OP TMF life is up to 10 times shorter than in tests at 650 °C.

IN 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST, SURFACE CRACKS INITIATE EARLY IN COATED AND BARE CRYSTALS AS IN 650 °C ISOTHERMAL TEST OF COATED CRYSTALS*



HOWEVER, IN THE LOW-STRAIN REGIME, OP TEST LIFE IS EVEN SHORTER THAN AT 650 °C

*GAYDA, GABB, AND MINER, NASA TM 89831, 1987

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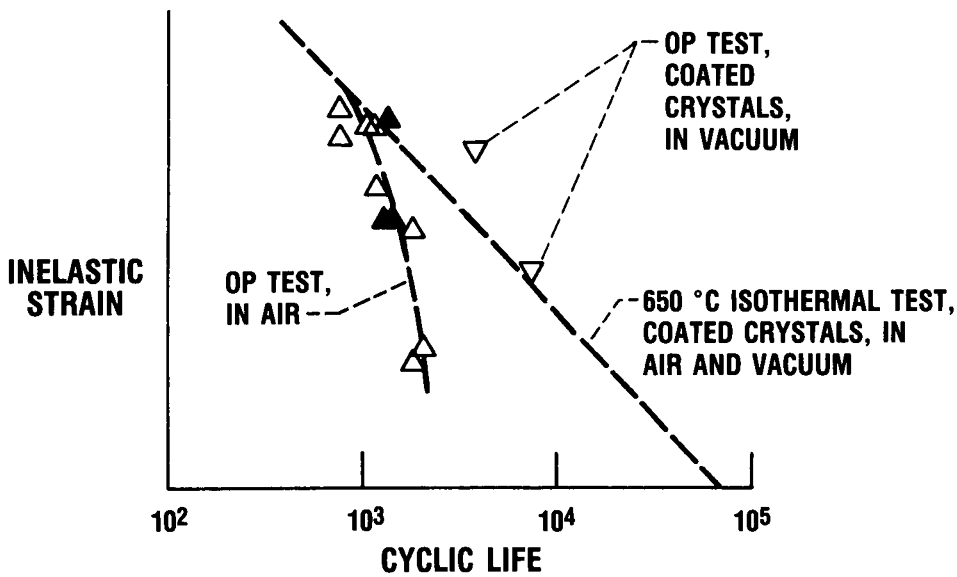
LOW 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST LIFE IN LOW-STRAIN REGIME IS LARGELY AN EFFECT OF OXIDATION AT 1050 °C

At low strains, foreshortening of cyclic life in the OP bithermal TMF test results in part from oxidation damage at 1050 °C. When these tests are performed in vacuum, the OP bithermal TMF test lives increase and are approximately equivalent to the constant-temperature tests at 650 °C. Early surface cracking occurs in all of these tests, the OP bithermal TMF tests and the constant-temperature tests at 650 °C in both air and vacuum. Therefore oxidation at 1050 °C apparently accelerates growth of surface cracks in the OP bithermal TMF test.

LOW 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST LIFE IN LOW-STRAIN REGIME IS LARGELY AN EFFECT OF OXIDATION AT 1050 °C*



EARLY CRACK INITIATION IS OBSERVED IN ALL THESE TESTS. THE OP TEST REDUCES CRACK PROPAGATION PORTION OF LIFE.

*GAYDA, GABB, AND MINER, NASA TM 89831, 1987

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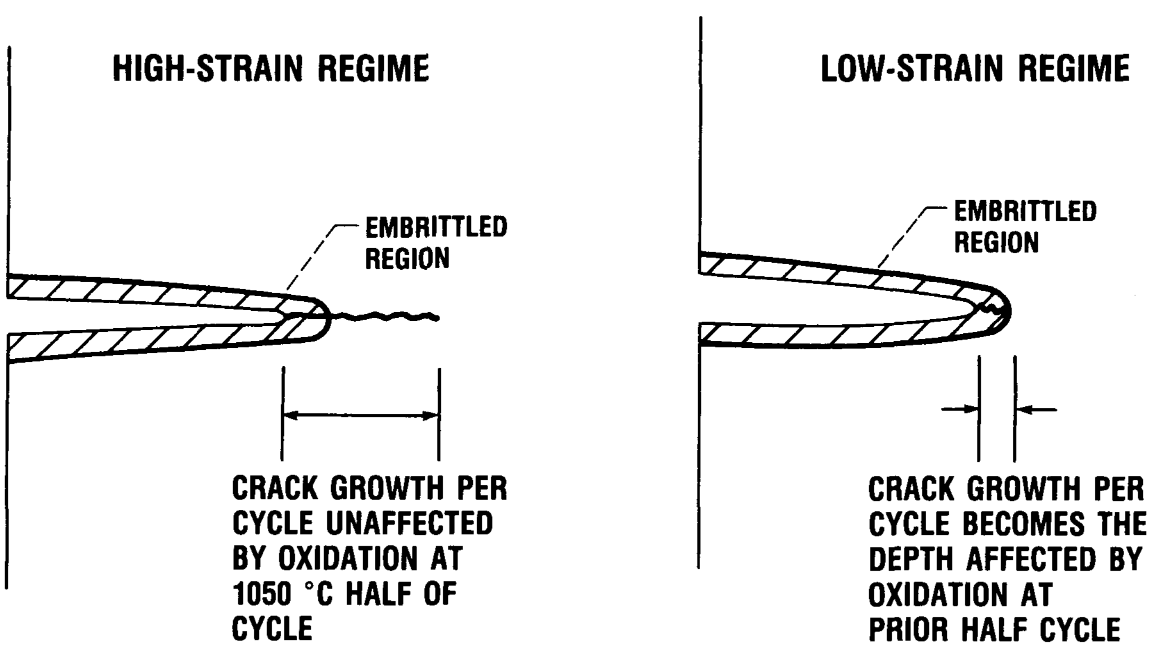
A MODEL FOR OUT-OF-PHASE BITHERMAL CRACK GROWTH

Presented here is a schematic illustration of the damage mechanism for the OP bithermal cycle, which explains life degradation at low strains. Surface cracks appear early in all tests. The crack tips are oxidized and thereby embrittled at 1050 °C. In tests employing large cyclic strains, the crack grows far beyond the embrittled region during a single cycle. Therefore the crack growth resistance of the unoxidized superalloy controls life, and oxidation at 1050 °C has little effect. But in tests at small cyclic strains, crack growth in the superalloy is slow compared to the advance of the oxidized region. Fracture of this environmentally damaged zone requires little load at low temperatures, such as 650 °C, and therefore provides a faster crack growth rate and shorter life at lower cyclic strains.

A MODEL FOR OUT-OF-PHASE BITHERMAL CRACK GROWTH



IN THE LOW-STRAIN REGIME, CRACK GROWTH RATE BECOMES NEARLY INDEPENDENT OF STRAIN RANGE

CD-87-28785

METALS SCIENCE BRANCH QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

As superalloys approach their theoretical temperature limitation, a new generation of lightweight, high-temperature, metal matrix composites are being considered as alternate materials for advanced aircraft engines. One of the most serious problems encountered in the development of these new-generation composite materials is durability. An area of critical concern here is thermomechanical fatigue, because differences in the thermal expansion coefficients between fiber and matrix create additional problems not found in more conventional materials, such as the single-crystal superalloys.

METALS SCIENCE BRANCH

QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

NASA NEEDS: DEVELOP COMPOSITE MATERIALS WHICH HAVE HIGHER TEMPERATURE CAPABILITY, WHICH ARE LIGHTER, AND WHICH SHOW DURABILITY AS GOOD AS OR BETTER THAN CONVENTIONAL SUPERALLOYS

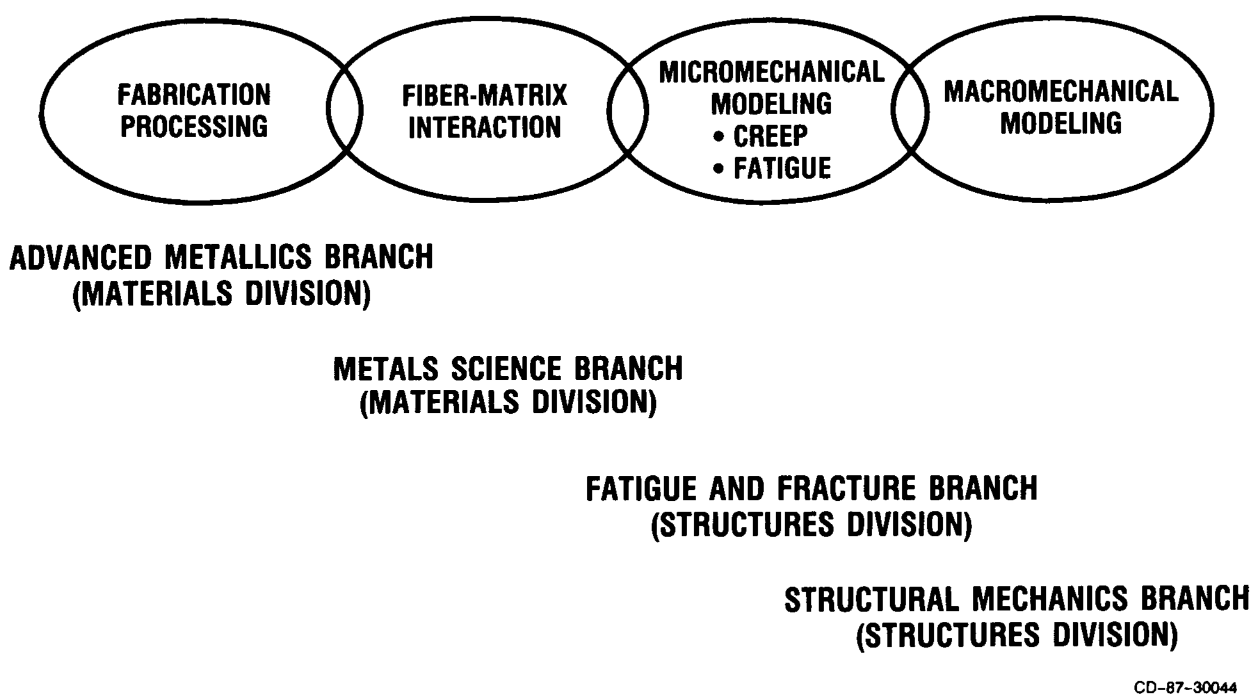
OBJECTIVE: PROVIDE THE ANALYTICAL TOOLS FOR COMPOSITE DEVELOPMENT. SPECIFICALLY, DEVELOP A PHYSICALLY BASED MODEL FOR FATIGUE AND CREEP OF METAL MATRIX COMPOSITES BY 1992.

CD-87-28786

METAL MATRIX COMPOSITE PROGRAM REQUIRES NUMEROUS SKILLS

The work in high-temperature, metal matrix composites requires many diverse skills. To address this need, activities at Lewis involve personnel from four branches and two divisions. Micromechanical modeling of fatigue on these materials will be the primary responsibility of the Metals Science Branch and the Fatigue and Fracture Branch.

METAL MATRIX COMPOSITE PROGRAM REQUIRES NUMEROUS SKILLS



CURRENT PROGRAM FOR QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

Models for fatigue behavior of metal matrix composites will be developed and validated on three diverse systems: W/Cu, SiC/Ti alloy, and SiC/FeAl. These systems are representative of ductile fiber/ductile matrix, brittle fiber/ductile matrix, and brittle fiber/brittle matrix composites, respectively. Characterization and actual testing of fiber, matrix, and composite will be a key part of the program early on, as will the use of a simple, one-dimensional, two-bar model to analyze this data. Eventually a three-dimensional model which incorporates viscoplastic theory for time-dependent effects will be developed and validated under a nonisothermal, multiaxial stress state.

CURRENT PROGRAM FOR QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

MODEL MATERIAL SYSTEMS

- DUCTILE FIBER/DUCTILE MATRIX = W/Cu
- BRITTLE FIBER/DUCTILE MATRIX = SiC/Ti ALLOY
- BRITTLE FIBER/BRITTLE MATRIX = SiC/FeAl

CHARACTERIZATION AND TESTING

- FIBER, MATRIX, AND COMPOSITE CHARACTERIZATION
- ISOTHERMAL AND THERMOMECHANICAL FATIGUE
- UNIAXIAL AND MULTIAXIAL STRESSES

MODELING THERMOMECHANICAL FATIGUE

- ONE-DIMENSIONAL MODEL WITH TIME-DEPENDENT EFFECTS
- THREE-DIMENSIONAL MODEL USING ADVANCED VISCOPLASTICITY APPROACH FOR TIME-DEPENDENT EFFECTS

CD-87-28787

DEVELOPMENT OF A NEW GENERATION OF HIGH-TEMPERATURE COMPOSITE MATERIALS

Pamela K. Brindley

ABSTRACT

There are ever-increasing demands to develop low-density materials that maintain high strength and stiffness properties at elevated temperatures. Such materials are essential if the requirements for advanced aircraft, space power generation, and space station plans are to be realized. Metal matrix composites and intermetallic matrix composites are currently being investigated at NASA Lewis for such applications because they offer potential increases in strength, stiffness, and use temperature at a lower density than the most advanced single-crystal superalloys presently available. Today's discussion centers around the intermetallic matrix composites proposed by Lewis for meeting advanced aeropropulsion requirements. The fabrication process currently being used at Lewis to produce intermetallic matrix composites will be reviewed, and the properties of one such composite, SiC/Ti_3Al+Nb, will be presented. In addition, the direction of future research will be outlined, including plans for enhanced fabrication of aluminide composites by the arc spray technique and fiber development by the floating-zone process.

LEWIS INVOLVEMENT IN COMPOSITE MATERIALS DEVELOPMENT

Lewis has been working on composite materials for many years. Our efforts have focused on producing and characterizing metal matrix composite materials to obtain strength and density ratio improvements and higher operating temperatures than possible with currently available materials. Concurrently a technology base of high-temperature composite materials has been established. A model developed during the generation of this technology base is the well-known rule of mixtures (ROM), which is commonly used to predict composite properties from the behavior of the components. Some of the metal matrix composite systems that have been and are currently being examined at Lewis are listed in this figure alongside the areas for which these composites are targeted for possible use, including model systems studies and space power, space shuttle, and propulsion system components.

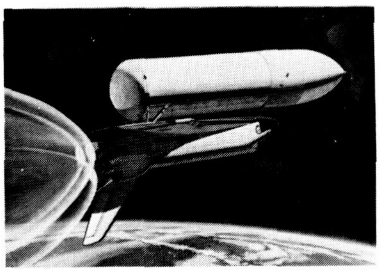
LEWIS INVOLVEMENT IN COMPOSITE MATERIALS DEVELOPMENT

W/Cu (-Zr)
W/FeCrAlY

MODEL SYSTEM STUDIES
RULE OF MIXTURES

W/Nb (-1Zr)
Gr/Cu

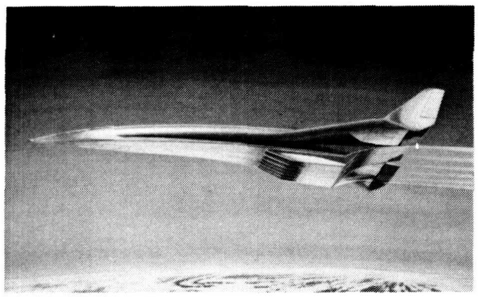
SPACE POWER COMPONENTS



W/FeCrAlY
W/INCOLOY 903 AND 907
W/WASPOLOY
W/316 STAINLESS
SiC/SUPERALLOY
B_4C-B/SUPERALLOY

SPACE SHUTTLE MAIN ENGINE COMPONENTS

Gr/Cu
SiC/Fe-40Al
SiC/NiAl
SiC/Ti_3Al + Nb



PROPULSION SYSTEM COMPONENTS

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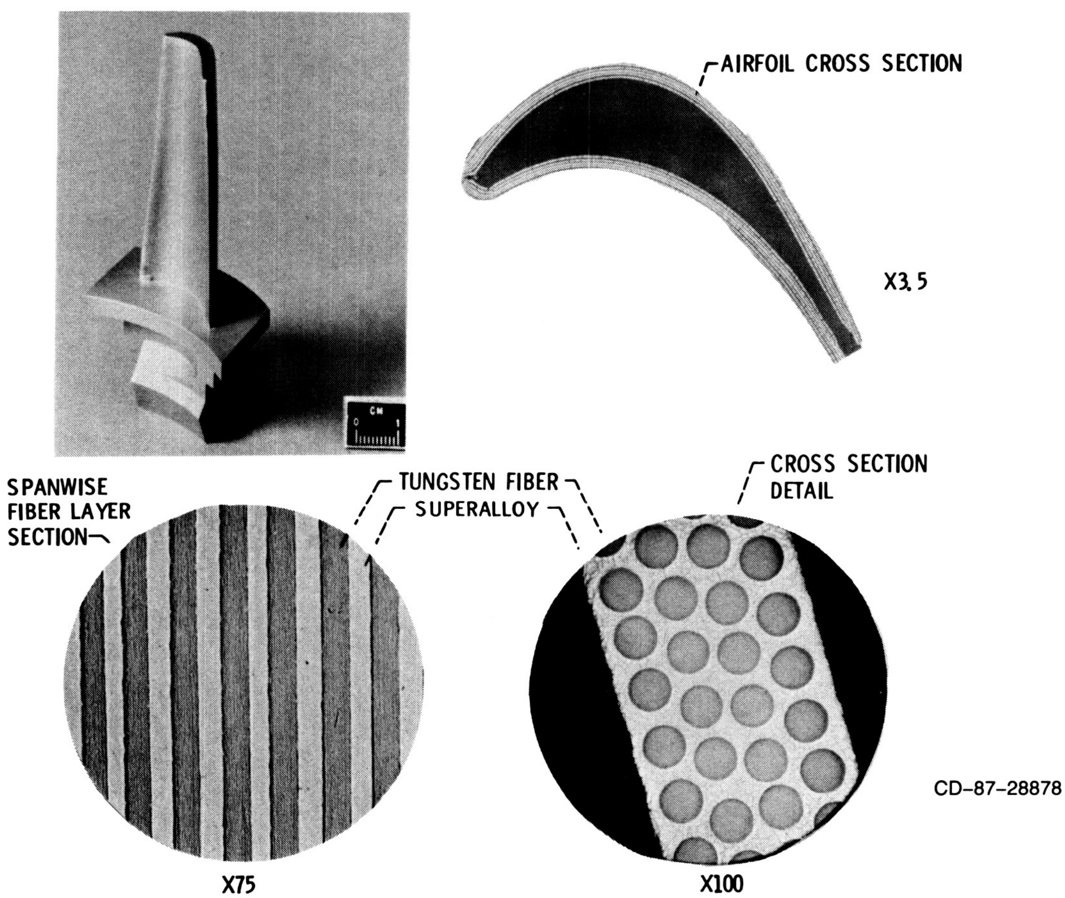
TUNGSTEN-FIBER-REINFORCED SUPERALLOY COMPOSITE BLADE

Another highlight of past work performed at Lewis is the fabrication of a tungsten-fiber-reinforced superalloy composite in the shape of a turbine blade. This proof of concept showed that production of intricately shaped composite components is indeed attainable. The composite blade was designed after a JT9D blade. It is hollow and contains cooling channels along the trailing edge. Note also that the uniformity of the fiber spacing in the longitudinal and transverse cross sections is uniform. The powder cloth method, which will be discussed shortly, was employed in fabricating this blade.

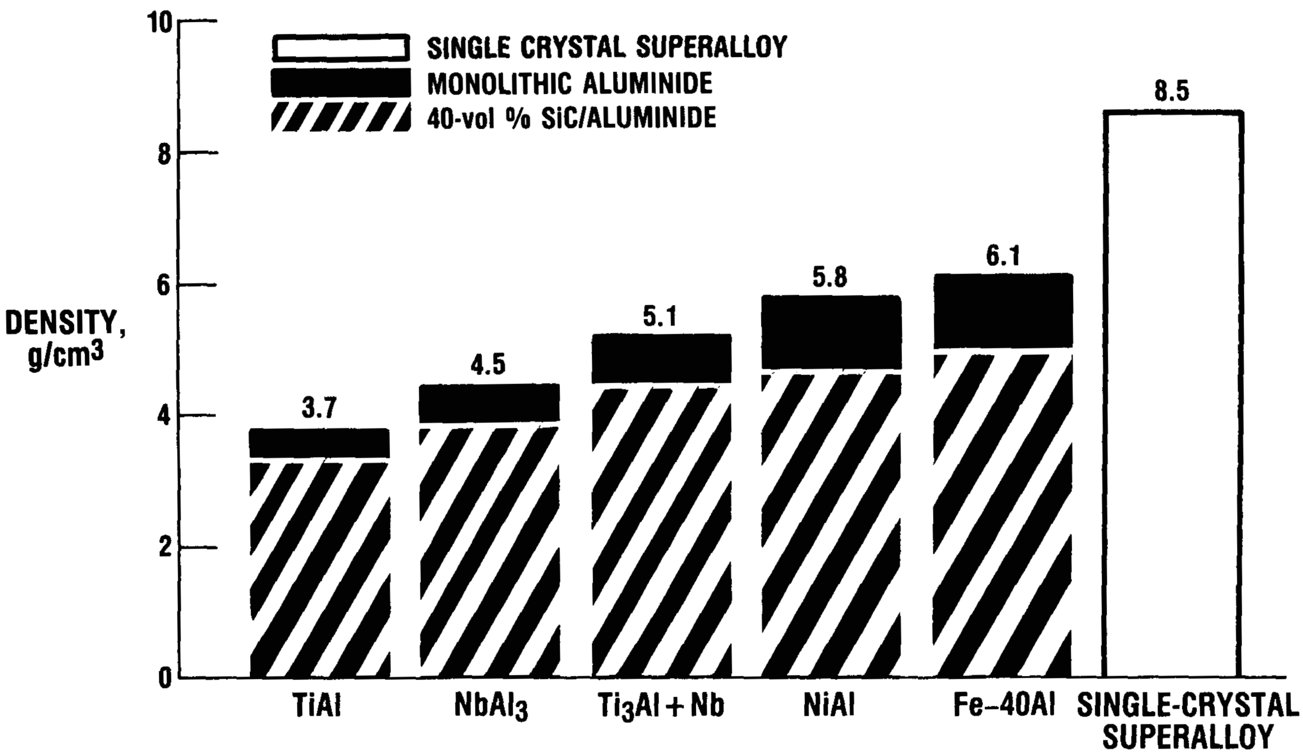
TUNGSTEN-FIBER-REINFORCED SUPERALLOY COMPOSITE BLADE



DENSITY COMPARISON OF ALUMINIDES AND SUPERALLOY

Our current efforts in advanced materials for aeropropulsion applications center around the development of continuously reinforced aluminide matrix composites because of the potential these composites have to outperform existing superalloys. The primary properties requiring improvement if we are to realize hypersonic travel include lower density, strength at temperatures beyond 1800 °F, higher strength/density ratio and stiffness over the entire temperature range, and enhanced oxidation resistance or thermal barrier coating compatibility. Comparing the densities of several aluminides targeted for development and the nominal density of a superalloy clearly shows the advantage of pursuing aluminides. Furthermore, when these aluminides are reinforced with 40-vol % SiC, the densities are even more attractive. It is important to note here that even though monolithic aluminides offer potential over superalloys on a density basis, they are not as competitive on a strength basis unless reinforced. Thus fiber reinforcement is required to attain the best strength/density ratio improvement over superalloys.

DENSITY COMPARISON OF ALUMINIDES AND SUPERALLOY



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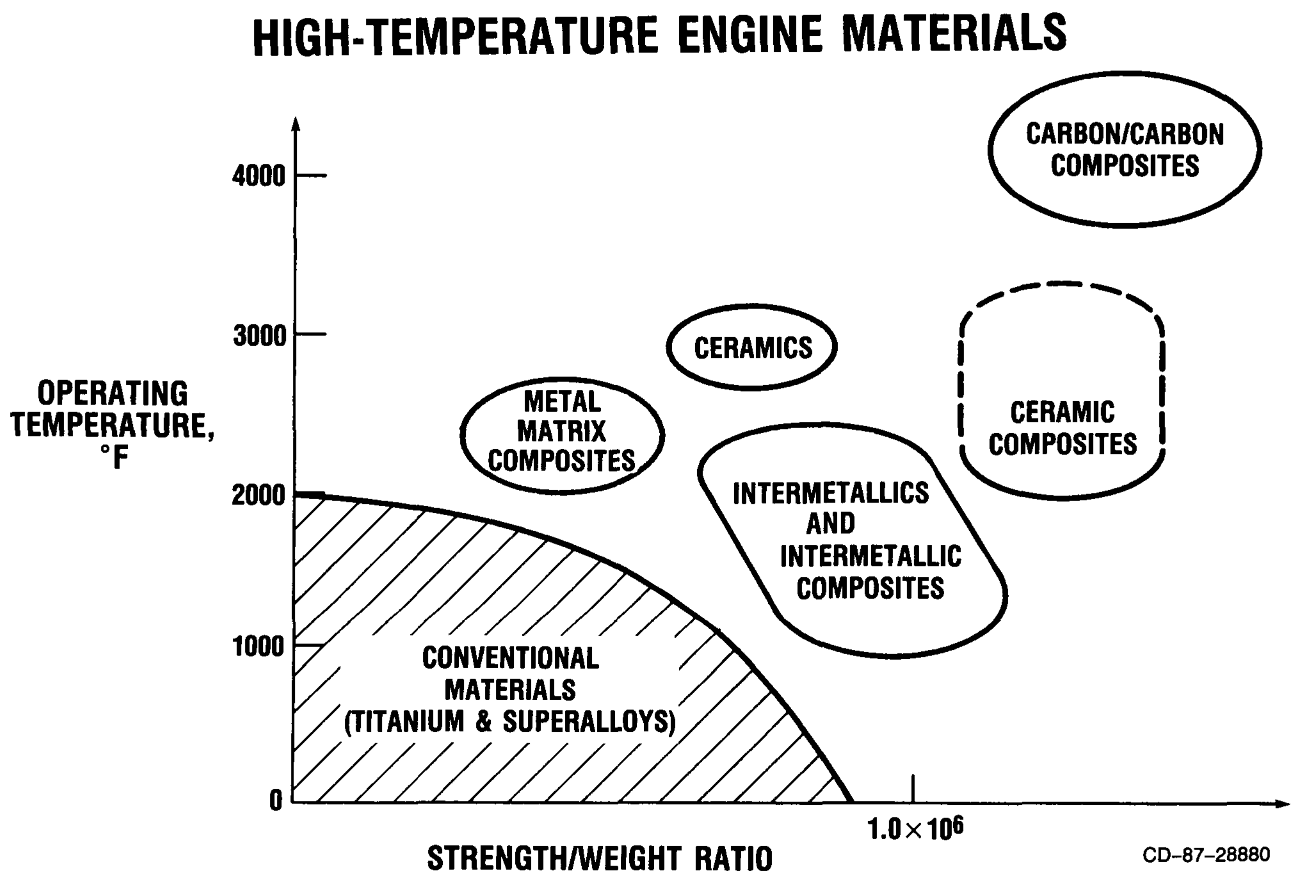
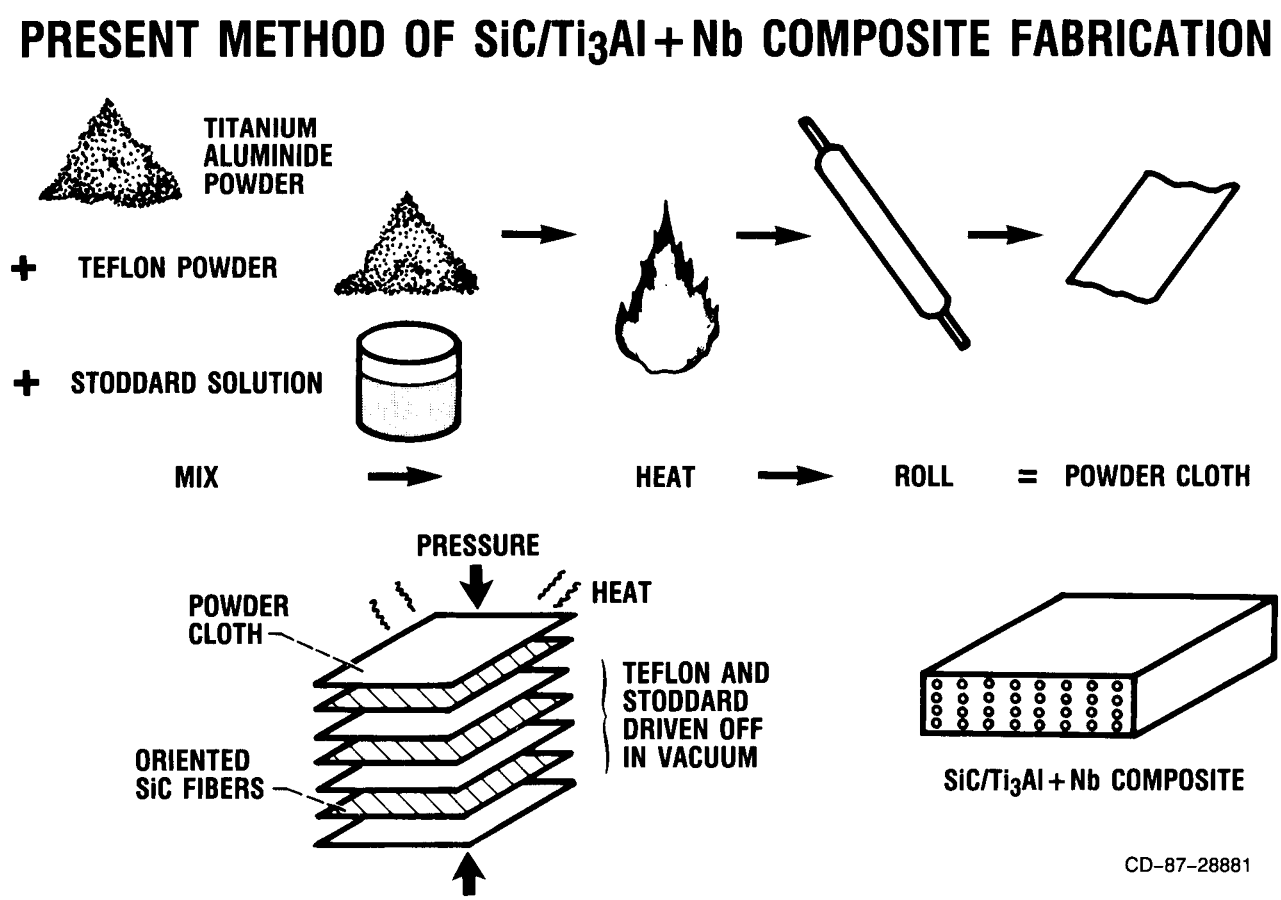
HIGH-TEMPERATURE ENGINE MATERIALS

The enhanced strength/density ratio and increased operating temperature potential that metal matrix and intermetallic matrix composites offer over conventional materials are shown in this graph. Included also is the longer-term development of ceramics, ceramic composites, and carbon/carbon composites.



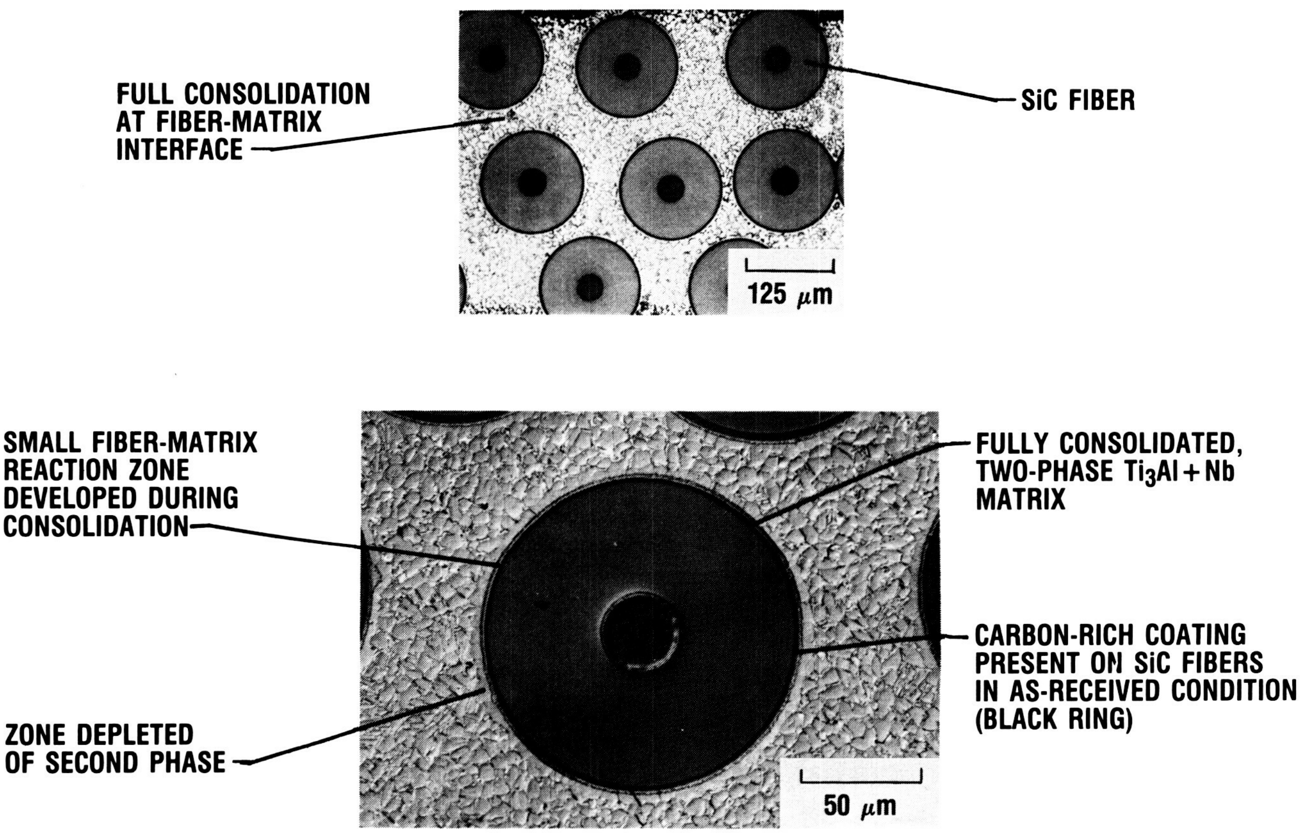
PRESENT METHOD OF SiC/Ti_3Al+Nb COMPOSITE FABRICATION

The process Lewis presently uses to produce aluminide matrix composites is illustrated here for SiC/Ti_3Al+Nb. This fabrication process is called the powder cloth method. Prealloyed titanium aluminide powder is mixed with Teflon powder and a solvent in a blender. The mixture is heated to drive off the excess solvent and to provide the proper consistency for the rolling operation from which a powder cloth is obtained. These metallic powder cloths are the matrix of the composite. Mats of full-length SiC fibers are layered between the metallic powder cloths until the desired number of fiber layers is obtained. These layers of SiC fibers can be oriented as desired to obtain maximum properties in particular directions. The entire layup is placed in a hot press and diffusion bonded. The Teflon and remaining solvent are driven off in vacuum before the diffusion bonding occurs. The resultant SiC/Ti_3Al+Nb composite is a 2- by 6-in. plate of a desired thickness, which is tested to characterize its properties.



AS-FABRICATED SiC/Ti_3Al+Nb

Two views of an actual SiC/Ti_3Al+Nb composite produced by the powder cloth technique are shown. The overall view shows a fully consolidated composite: no voids or cracks are evident in the matrix. The magnified view reveals the fiber and matrix to be fully consolidated. Other features include a two-phase Ti_3Al+Nb matrix, a small reaction zone between the SiC fiber and the Ti_3Al+Nb due to fabrication, and a zone surrounding the fiber and the reaction zone that appears to be depleted of the second phase. These features can be directly related to mechanical properties and will be elaborated on later.



AS-FABRICATED SiC/Ti_3Al + Nb

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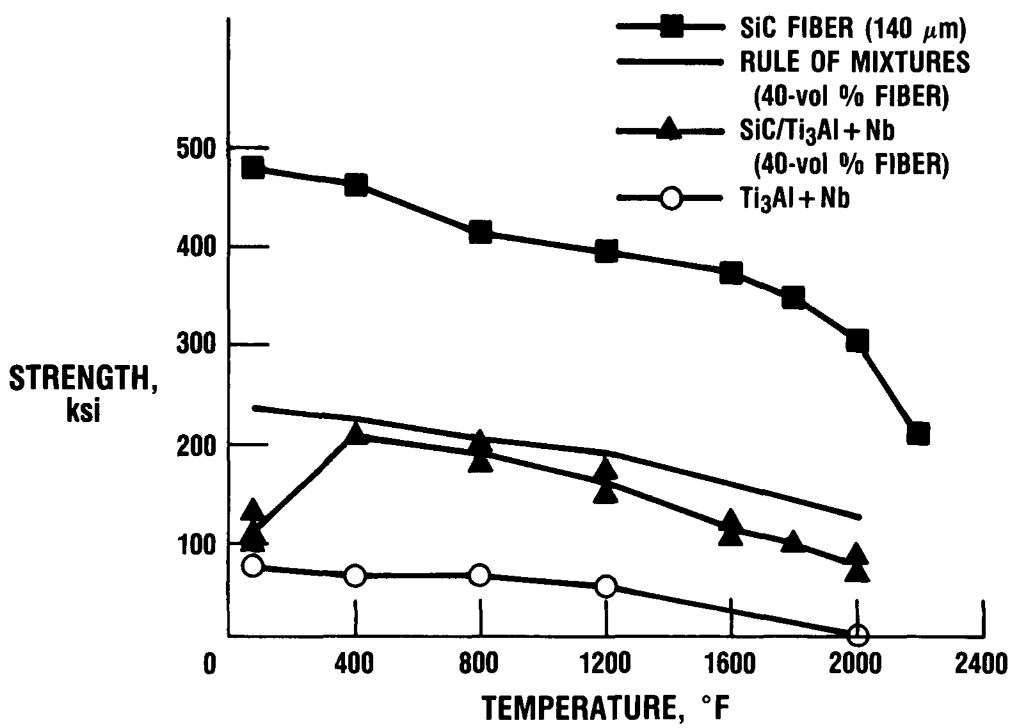
COMPARISON OF PREDICTED AND ACTUAL SiC/Ti_3Al+Nb STRENGTH

The experimentally measured strengths of the SiC fiber, the Ti_3Al+Nb matrix-only material, and the SiC/Ti_3Al+Nb composite are plotted versus temperature. The fiber and the matrix-only data were used with the rule of mixtures (ROM) to compute predicted strengths. The ROM is basically a weighted average that predicts composite strength on the basis of the volume fractions of fiber and matrix present in the material. The composites tested contained 40-vol % SiC fiber. The actual composite values obtained were comparable to the ROM in the intermediate temperature regime, but lower than expected at room temperature and at 1200 °F and above. The presence of excess oxygen is known to limit matrix ductility in Ti_3Al+Nb. The matrix material employed here contained 1000 to 1200 ppm oxygen. It was therefore thought that the oxygen was responsible for the lower strength values observed at room temperature by not allowing the fiber to attain its full strength potential. This was further substantiated by the lack of ductility observed in the room-temperature fracture surfaces. It should be possible to solve this room-temperature strength difficulty by using powder with lower oxygen content as well as through unique processing techniques. These ideas are being pursued. Debonding and fiber pullout are likely contributors to the strength falloff observed at elevated temperatures as shown in the next two figures.

COMPARISON OF PREDICTED AND ACTUAL SiC/Ti_3Al+Nb STRENGTH



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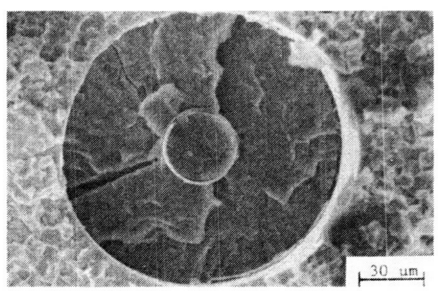
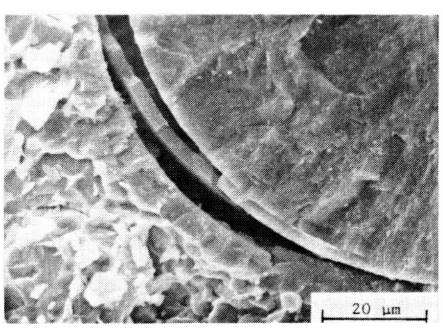
TENSILE FRACTURE SURFACES OF SiC/Ti_3Al+Nb SHOWING DEBONDING

An understanding of the mode by which aluminide composites fracture is one of the goals of this work. This understanding will help us design these materials to obtain ROM strengths at all temperatures. This figure and the following one contain photographs of as-fractured SiC/Ti_3Al+Nb surfaces after tensile testing. The test temperatures are indicated below each photograph. Note that as test temperature increases, so does the amount of debonding, or fiber-matrix separation. At room temperature the bond between fiber and matrix appears to remain intact, allowing for load transfer from the matrix to the fiber. However, at 1200 °F and above, some debonding is evident for these individual fibers. Since load transfer cannot occur in these debonded regions, it is plausible that debonding contributes to the falloff from ROM strengths observed at elevated temperatures.

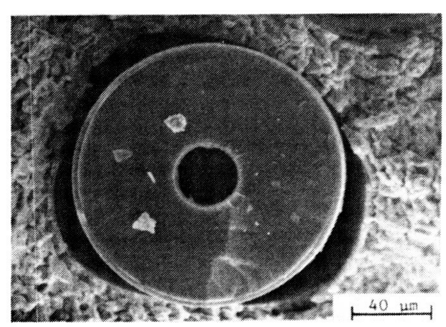
TENSILE FRACTURE SURFACES OF SiC/Ti_3Al+Nb SHOWING DEBONDING



23 °C (73 °F)



650 °C (1202 °F)



1100 °C (2012 °F)

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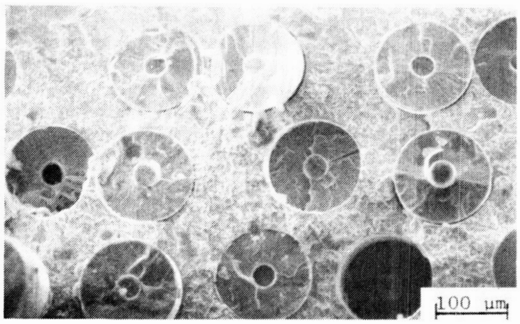
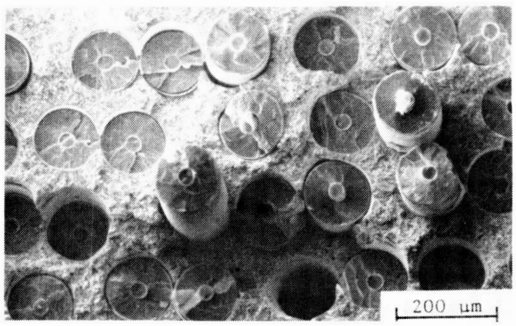
TENSILE FRACTURE SURFACES OF SiC/Ti_3Al+Nb SHOWING FIBER PULLOUT

Fiber pullout was also observed in the fracture surfaces of the SiC/Ti_3Al+Nb composite tested over a range of temperatures. Note that very little fiber pullout is evident at room temperature but that increasing amounts of fiber pullout are obvious as the test temperature is increased. Such observations suggest that fiber pullout is another possible contributor to the falloff in ROM strengths observed at elevated temperatures.

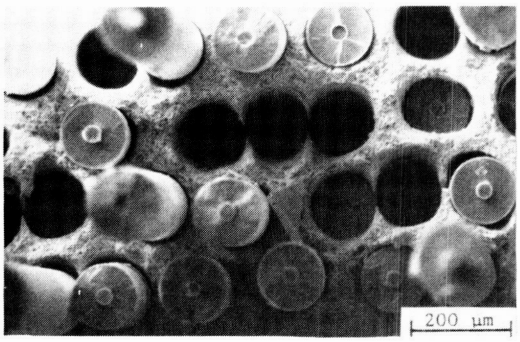
TENSILE FRACTURE SURFACES OF SiC/Ti_3Al+Nb SHOWING FIBER PULLOUT



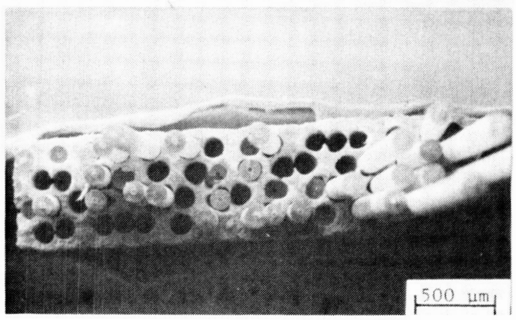
23 °C (73 °F)



425 °C (797 °F)



875 °C (1607 °F)



1100 °C (2012 °F)

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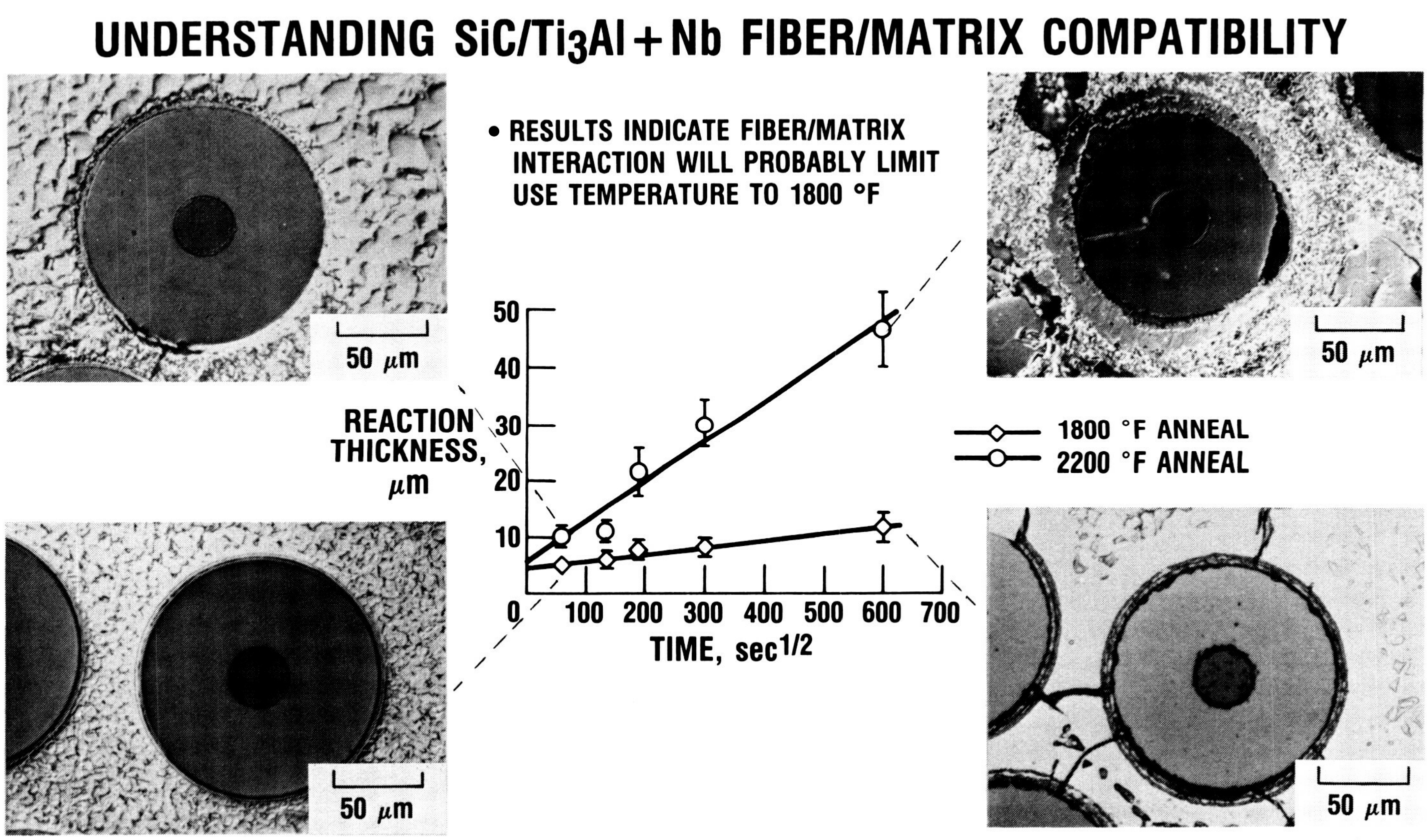
UNDERSTANDING SiC/Ti_3Al+Nb FIBER/MATRIX COMPATIBILITY

An understanding of fiber/matrix chemical compatibility is necessary to determine how long a particular composite will be able to function at a given operating temperature. In general, a large reaction zone between the fiber and the matrix is not acceptable because it is accompanied by a decrease in mechanical properties. However, a small reaction-zone is acceptable. The challenge is to determine the acceptable reaction-zone thickness for each composite system. The first step in determining acceptable limits is to anneal coupons of the composite at various times and temperatures. SiC/Ti_3Al+Nb was annealed at 1800 and 2200 °F for 1 to 100 hr to determine the rate of chemical reaction between the fiber and the matrix at various temperatures. The results indicate that fiber/matrix reaction will probably limit the use temperature to 1800 °F for any application with extended life. The next step in determining reaction-zone effects on mechanical properties is to test SiC/Ti_3Al+Nb containing various quantities of reaction zone over a range of temperatures.



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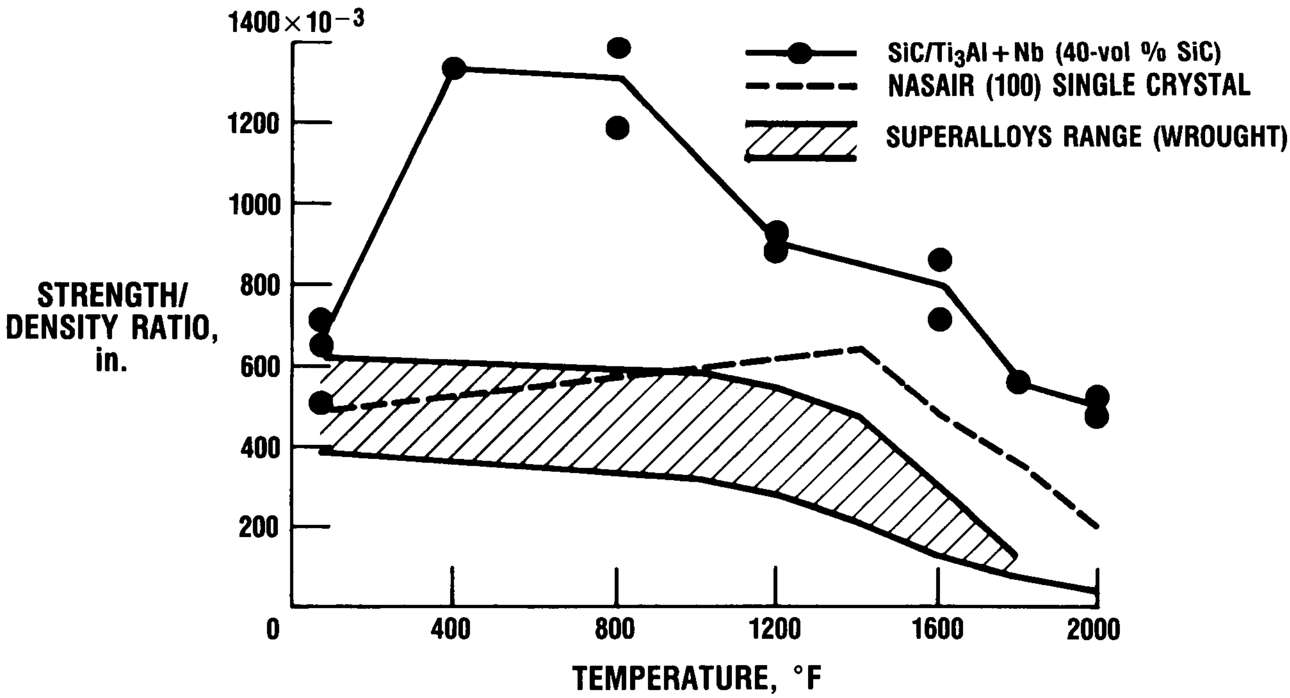
SUPERIOR TENSILE PROPERTIES OF SiC/Ti_3Al+Nb COMPOSITE COMPARED WITH EXISTING SUPERALLOYS

Comparing SiC/Ti_3Al+Nb composite tensile properties on a strength/density ratio basis with those of a range of wrought superalloys and a single-crystal superalloy shows that the superior tensile properties predicted for aluminide matrix composites are attainable.

SUPERIOR TENSILE PROPERTIES OF SiC/Ti_3Al+Nb COMPOSITE COMPARED WITH EXISTING SUPERALLOYS



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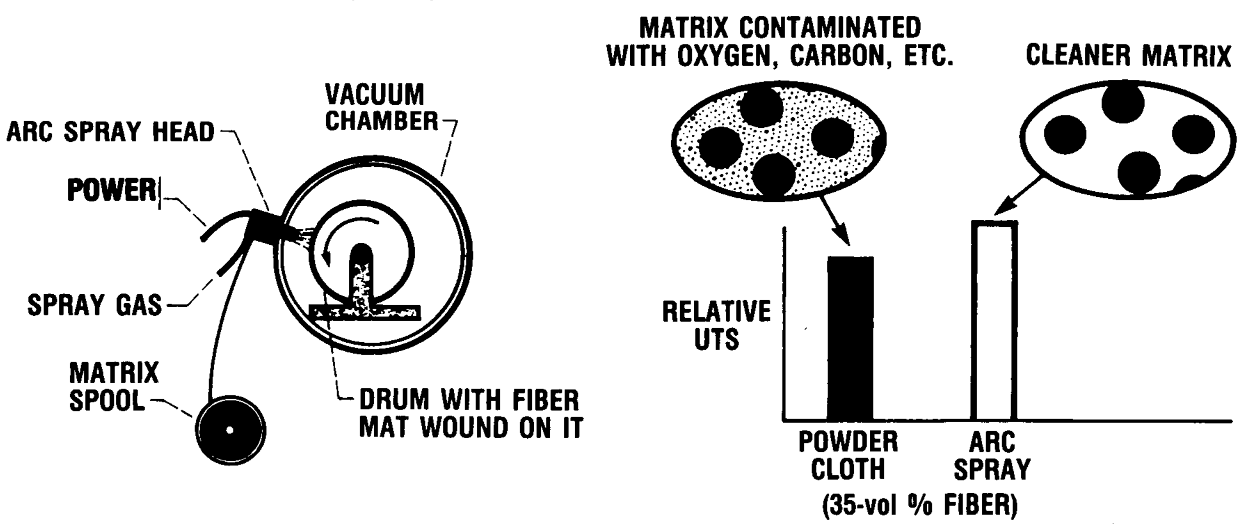
FUTURE SiC/Ti_3Al+Nb WORK EMPLOYS LEWIS-DEVELOPED ARC SPRAY FABRICATION PROCESS

Future work on aluminide matrix composites includes investigating alternative processing techniques in order to obtain higher production rates and, more importantly, cleaner matrix materials. Low-temperature ductility in the Ti_3Al+Nb system, for instance, is greatly improved by decreasing the residual oxygen and carbon. For this reason we are presently pursuing the development of Ti_3Al+Nb in wire form, since it is not readily available, to be used in our arc spray facility. It is anticipated that the arc spray process will maintain a Ti_3Al+Nb matrix with a lower oxygen and carbon content than can the powder cloth technique for two reasons. First, powder inherently contains more oxygen than does wire because of its larger surface/volume ratio: there is more available surface for oxidation in the powder. Second, the capabilities of the arc spray process have been proven and documented in several composite systems, all of which show minimal oxygen and carbon pickup during processing.

FUTURE SiC/Ti_3Al+Nb WORK EMPLOYS LEWIS-DEVELOPED ARC SPRAY FABRICATION PROCESS

BENEFITS

- HIGHER PRODUCTION RATES—AUTOMATED
- CLEANER MATRIX—ENHANCED DUCTILITY AND STRENGTH
- PROVEN PROCESS CAPABILITIES IN OTHER COMPOSITE SYSTEMS: W/SUPERALLOYS, W/Nb-1Zr, W/Cu, AND SiC/Nb-1Zr



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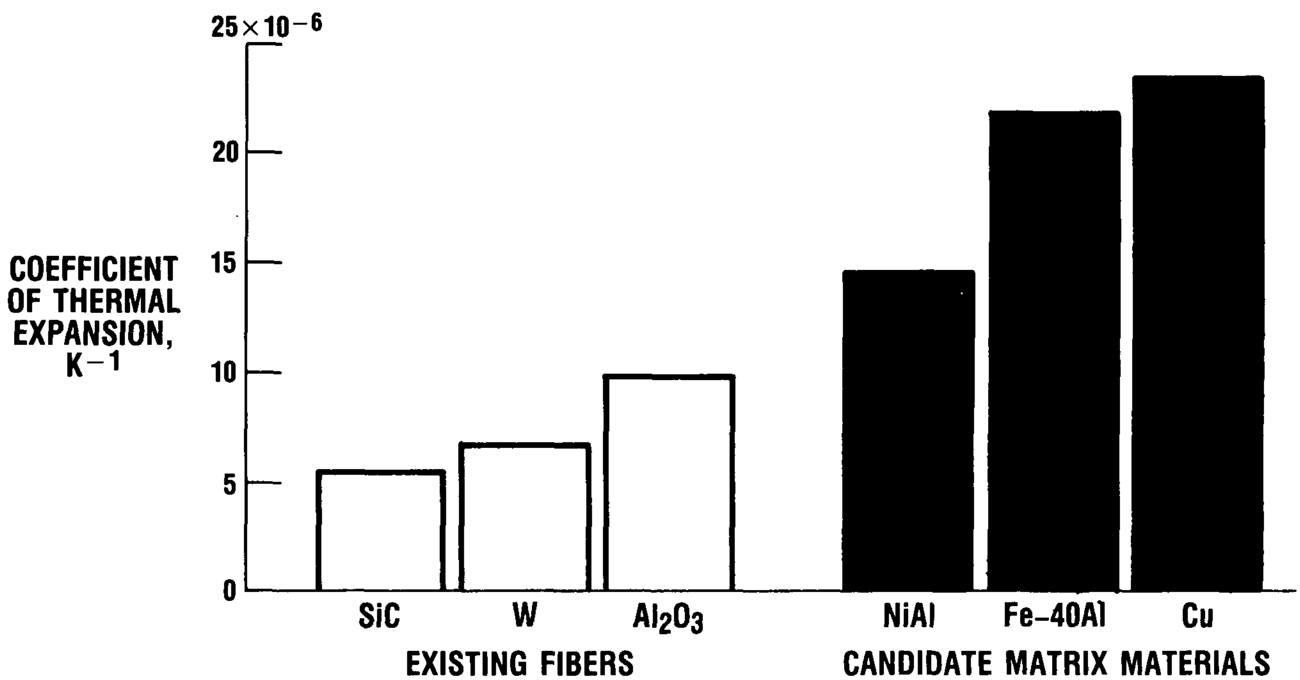
COMPARISON OF FIBER AND MATRIX EXPANSION SHOWING NEED FOR NEW FIBER DEVELOPMENT

Fiber development to match the fiber coefficient of thermal expansion closely to that of the matrix is planned to begin in the near future. A thermal expansion mismatch can result in a buildup of residual stresses within a composite subjected to thermal cycling during fabrication and service. The stress accumulation can cause premature failure of a composite component as a minimum, or catastrophic failure under severe thermal cycle conditions as an extreme. Thus the fiber and matrix expansion coefficients must be closely matched. An examination of thermal expansion coefficients of available fibers, such as SiC and Al_2O_3, and some aluminides quickly reveals the two- to fivefold difference in expansion between fibers and matrices. It is most reasonable to investigate the development of fibers from materials with thermal expansion coefficients nearer to that of the matrix, since the matrix materials have been chosen based on density, oxidation resistance, and higher operating temperature as previously discussed.

COMPARISON OF FIBER AND MATRIX EXPANSION SHOWING NEED FOR NEW FIBER DEVELOPMENT



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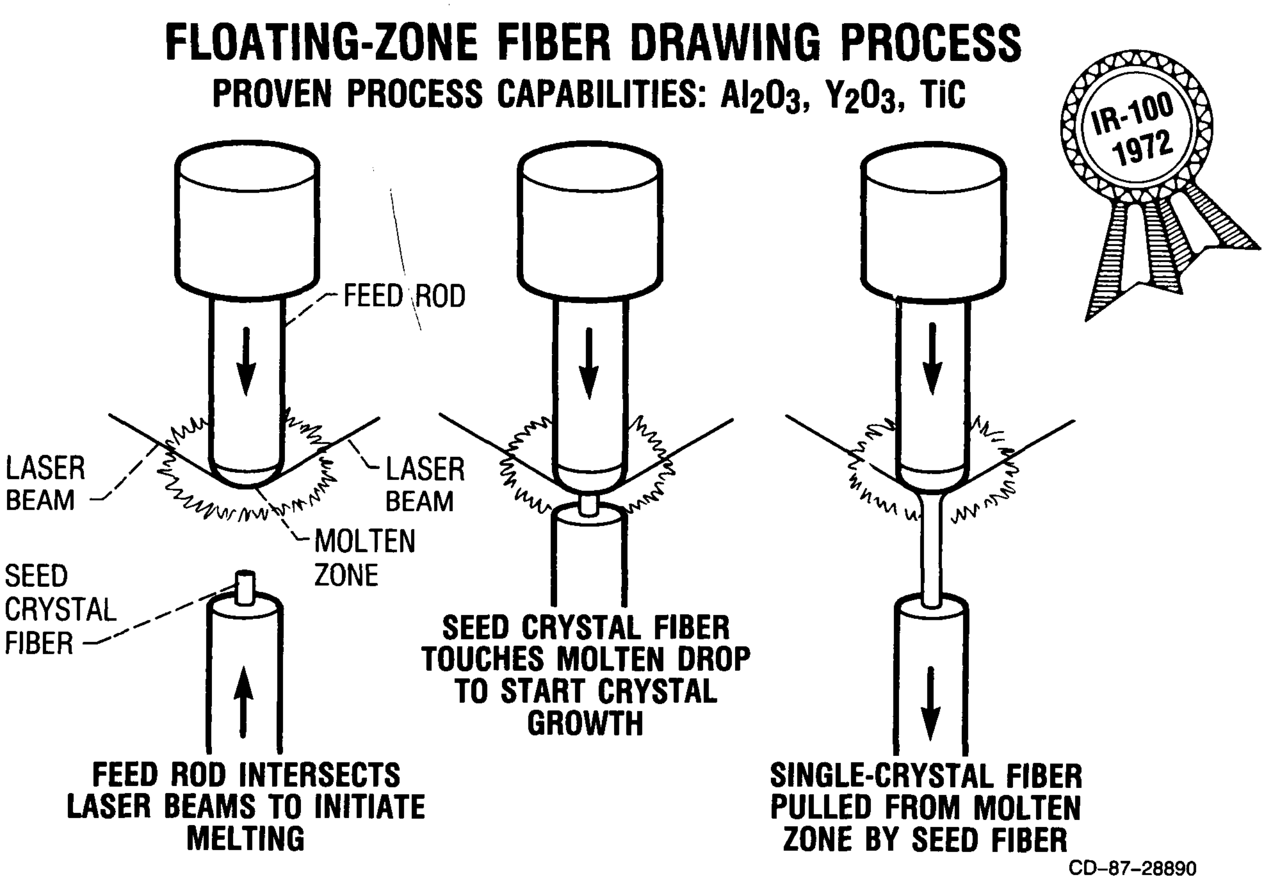
FLOATING-ZONE FIBER DRAWING PROCESS

A floating-zone fiber drawing process, developed in conjunction with A.D. Little, is being procured for laboratory-scale production of a range of fibers with high thermal expansion coefficients. In the floating-zone process a laser beam melts a polycrystalline feed rod. Once the feed rod becomes molten, a single-crystal seed rod of desired orientation is brought into contact with the feed rod to start crystal growth. A single-crystal fiber is then pulled from the molten zone as the feed rod is traversed through the laser beam. The capabilities of the floating-zone process have been proven in the production of Al_2O_3, Y_2O_3, and TiC single-crystal fibers. This apparatus will be used to discern which materials of high thermal expansion coefficient are most promising for large-scale fiber processing, perhaps by chemical vapor deposition, on the basis of producibility, strength, and chemical compatibility with the matrix materials.



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SELF-LUBRICATING COATINGS FOR HIGH-TEMPERATURE APPLICATIONS

Harold E. Sliney

ABSTRACT

Some present-day aeropropulsion systems already impose severe demands on the thermal and oxidative stability of lubricant, bearing, and seal materials. These demands will be much more severe for systems planned to be operational around the turn of the century. The complex gas turbine engines in modern aircraft contain many variable-geometry components with load-bearing surfaces that must be self-lubricating at high temperatures and high gas pressures. In hypersonic aircraft of the future the propulsion systems will also incorporate variable-angle air inlet ramps that will need seal surfaces having the ability to slide with low friction and wear at very high temperatures. In addition, the airframe control surface bearings may see high temperatures and certainly will need to be protected by sliding-contact control surface seals that will be the first line of defense against the temperatures generated by aerodynamic heating at hypersonic velocities.

Solid lubricants with maximum temperature capabilities of about 1100 °C are known. Unfortunately, none of the solid lubricants with the highest temperature capabilities are effective below approximately 400 °C. However, research at Lewis shows that silver and stable fluorides such as calcium and barium fluoride act synergistically to provide lubrication from below room temperature to approximately 900 °C.

This talk describes plasma-sprayed, self-lubricating composite coatings that have been developed at Lewis. Background information is given on coatings, designated as PS100 and PS101, that contain the solid lubricants in a Nichrome matrix. These coatings have low friction coefficients over a wide temperature range, but they have inadequate wear resistance for some long-duration applications. Wear resistance was dramatically improved in a recently developed coating, PS200, by replacing the Nichrome matrix material with metal-bonded chromium carbide containing dispersed silver and calcium fluoride/barium fluoride eutectic (CaF_2/BaF_2). The lubricants control friction and the carbide matrix provides excellent wear resistance. Successful tests of these coatings as backup lubricants for compliant gas bearings in turbomachinery and as self-lubricating cylinder liners in a four-cylinder Stirling engine are discussed.

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WHY HIGH-TEMPERATURE SOLID LUBRICANTS?

High temperatures in many advanced aerospace and terrestrial applications preclude the use of conventional liquid lubricants on many of the bearing and seal surfaces. This table illustrates some of these applications and the typical temperatures of the surfaces that require lubrication.

WHY HIGH-TEMPERATURE SOLID LUBRICANTS?

CURRENT AND FUTURE NEEDS FOR HIGH-TEMPERATURE SOLID LUBRICANTS	TEMPERATURE, °C
• AIRCRAFT GAS TURBINE ENGINES	
VARIABLE STATOR-VANE BUSHINGS	
COMPRESSORS—CURRENT	350
TURBINES—NEAR FUTURE	1000
THRUST-REVERSAL BEARINGS	800
• SUPERSONIC AIRCRAFT (MACH 3-5)	
CONTROL-SURFACE BEARINGS	350
CONTROL-SURFACE RUB SEALS	650
• HYPERSONIC AIRCRAFT	
CONTROL-SURFACE RUB SEALS	500-2000
• ROTARY ENGINES FOR GENERAL AVIATION	
APEX SEALS	300-650
• ADIABATIC DIESEL CYLINDER LINERS	600-1100
• STIRLING ENGINES	760-1100
• AUTOMOTIVE GAS TURBINE ENGINES	
REGENERATOR WEAR FACE SEALS	260-1100
FOIL BEARINGS (MAIN SHAFT)	650

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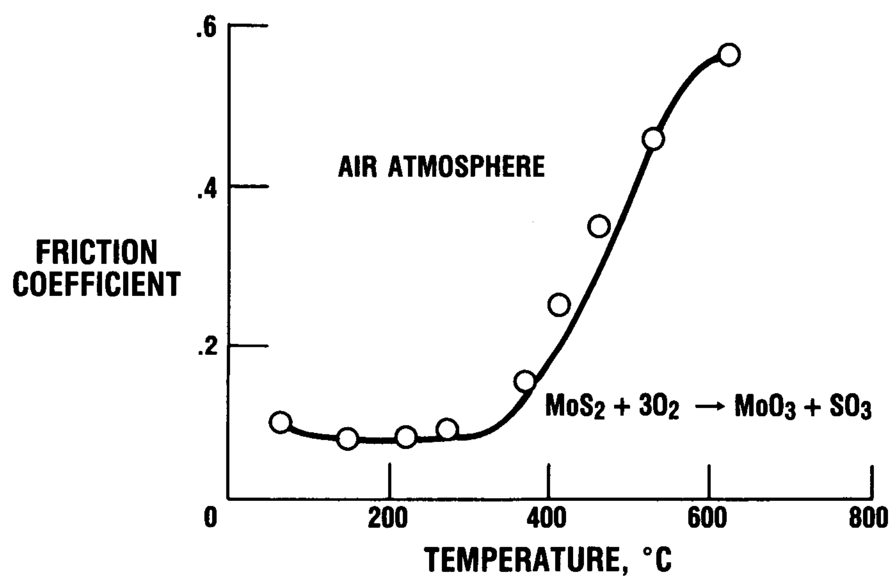
EFFECT OF OXIDATION ON LUBRICATION WITH MOLYBDENUM DISULFIDE

Conventional solid lubricants such as molybdenum disulfide and graphite have limited high-temperature capability because they oxidize in air at temperatures below 500 °C. The sharp rise in the friction coefficient of molybdenum disulfide as the temperature is increased above approximately 350 °C is caused by oxidation of the solid lubricant to solid molybdenum trioxide and gaseous sulfur oxides.

EFFECT OF OXIDATION ON LUBRICATION WITH MOLYBDENUM DISULFIDE



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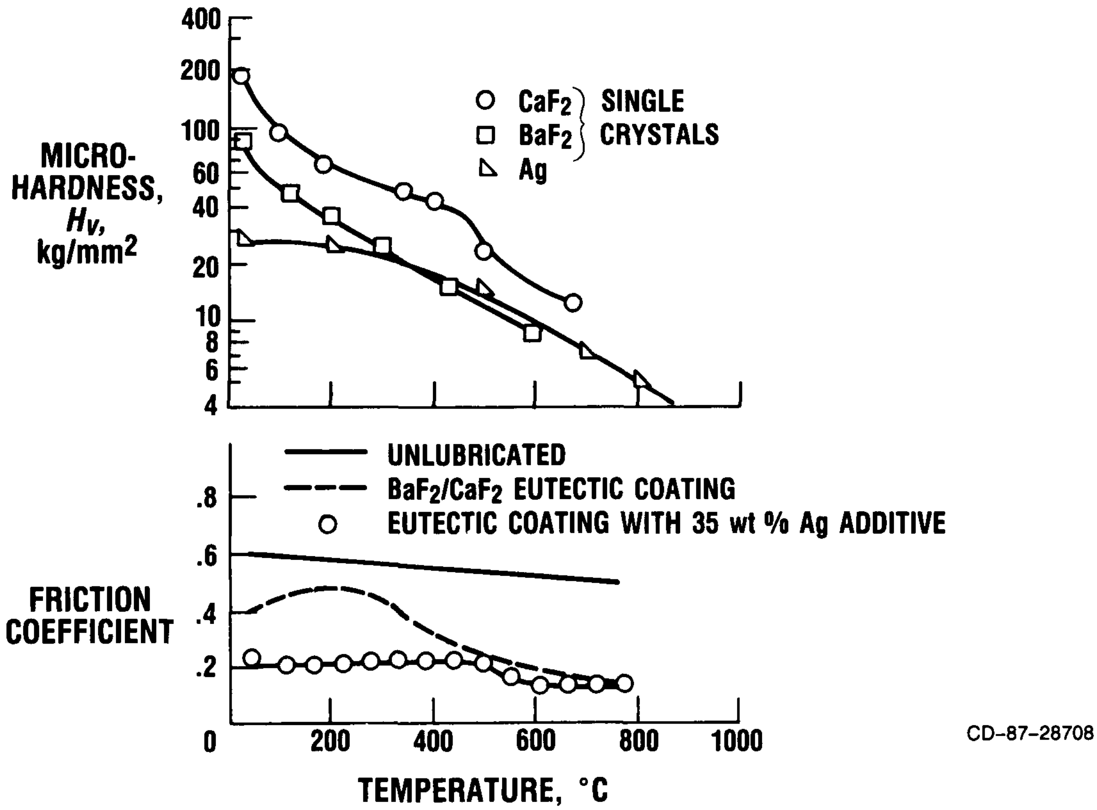
EFFECT OF TEMPERATURE ON MICROHARDNESS AND

FRICTION COEFFICIENTS OF COATING MATERIALS

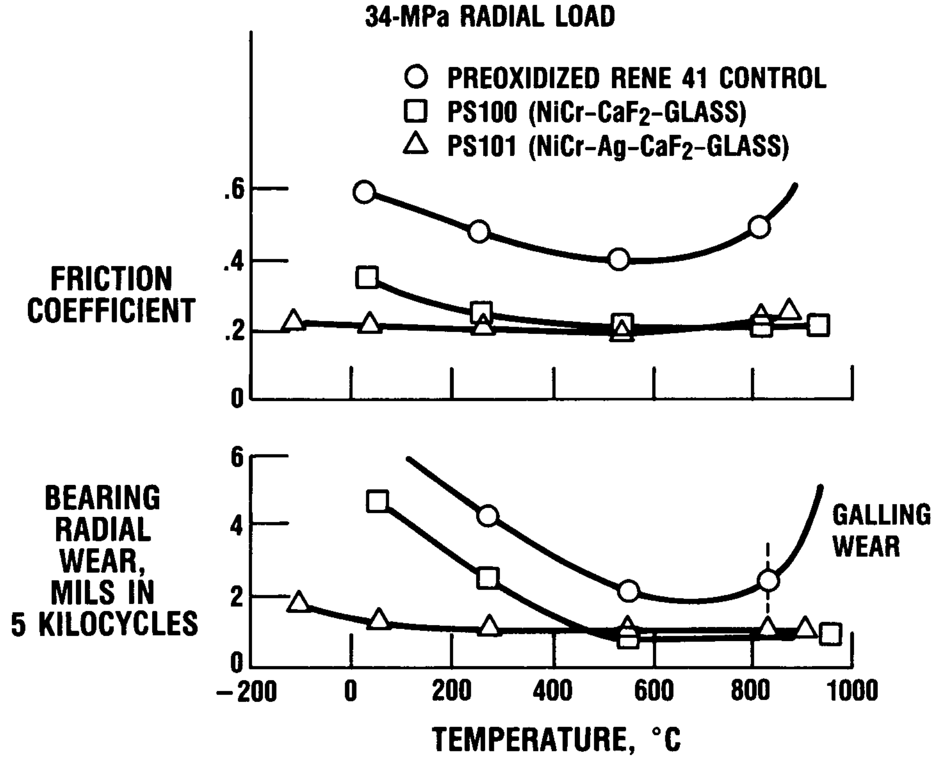
There appears to be a correlation of the hardness and frictional properties of stable fluorides and silver. Silver is very soft at room temperature and is a good thin-film solid lubricant from room temperature to approximately 500 °C, but it becomes too soft to lubricate at higher temperatures. Calcium fluoride and barium fluoride do not lubricate below approximately 400 °C but provide lubrication at higher temperatures. Silver and the fluorides therefore act synergistically in PS200 to provide wide-temperature-spectrum lubrication.

EFFECT OF TEMPERATURE ON MICROHARDNESS AND FRICTION COEFFICIENTS OF COATING MATERIALS



The effect of temperature on the friction and wear properties of Nichrome-based, plasma spray coatings containing solid lubricants was determined. The PS100 composition, which contained calcium fluoride as the only lubricant, lubricated above approximately 400 °C, but not at lower temperatures. The transition from high to low friction and wear corresponded to the brittle-to-ductile transition temperature of calcium fluoride at high shear rates. Adding silver as the second lubricant in PS101 resulted in a coating with good lubricating properties from -60 to 900 °C. The Nichrome-based coatings exhibited moderate ductility. This property and their good lubricating properties have led to their application in high-temperature, lightly loaded shaft seals, where some degree of compliance is desirable in the seal material.

PLASMA-SPRAYED COATINGS FOR SELF-ALIGNING OSCILLATING BEARINGS



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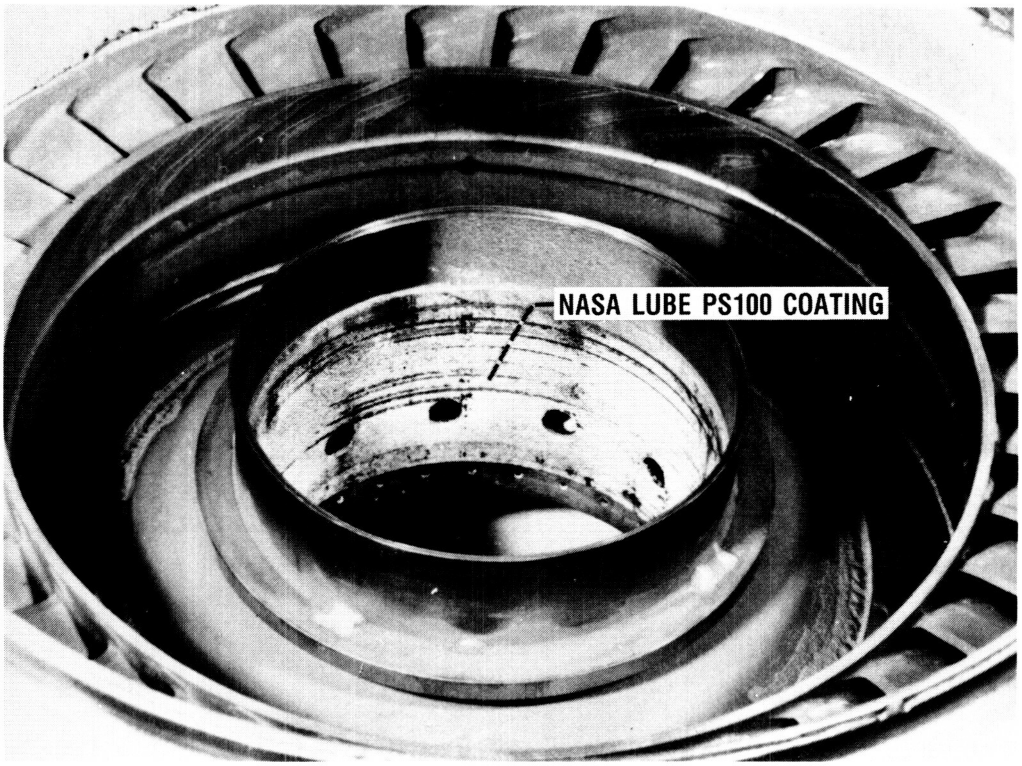
COMPRESSOR/TURBINE SHAFT SEAL OPERATES AT 650 °C

A knife-edge shaft seal from a gas turbine engine was coated with PS100 because PS100 is nongalling in sliding contact with the nickel alloy shaft material and is sufficiently compliant to be plastically deformed by circumferential knife edges on the rotating shaft. Further advantages of this coating, when compared with a porous abradable seal material, are superior erosion resistance and the virtual elimination of secondary leakage. Both of these advantages can be attributed to the absence of the continuous pore structure that is characteristic of abradable seal materials.

COMPRESSOR/TURBINE SHAFT SEAL OPERATES AT 650 °C



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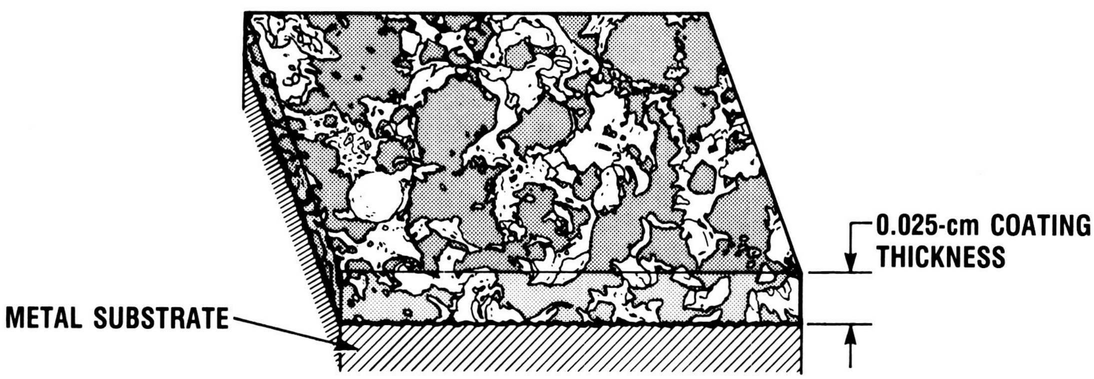
THE CONCEPT

This figure illustrates the concept of a very wear-resistant, self-lubricating composite coating material (PS200) that was developed at NASA Lewis. The composition is applied by plasma spraying a blend of chromium carbide, silver, and a CaF_2/BaF_2 eutectic. The function of each component is summarized in the figure. PS200 lubricates from room temperature to 900 °C in oxidizing or reducing atmospheres.

THE CONCEPT

PS200—A PLASMA-SPRAYED COMPOSITE SOLID LUBRICANT COATING



COMPOSITION	FUNCTION
32% Ni ALLOY 48% Cr_3C_2	WEAR AND OXIDATION RESISTANCE
10% Ag	LOW-TEMPERATURE LUBRICATION
10% BaF_2/CaF_2 EUTECTIC	HIGH-TEMPERATURE LUBRICATION

- LUBRICATES IN AIR, HELIUM, OR HYDROGEN TO 900 °C

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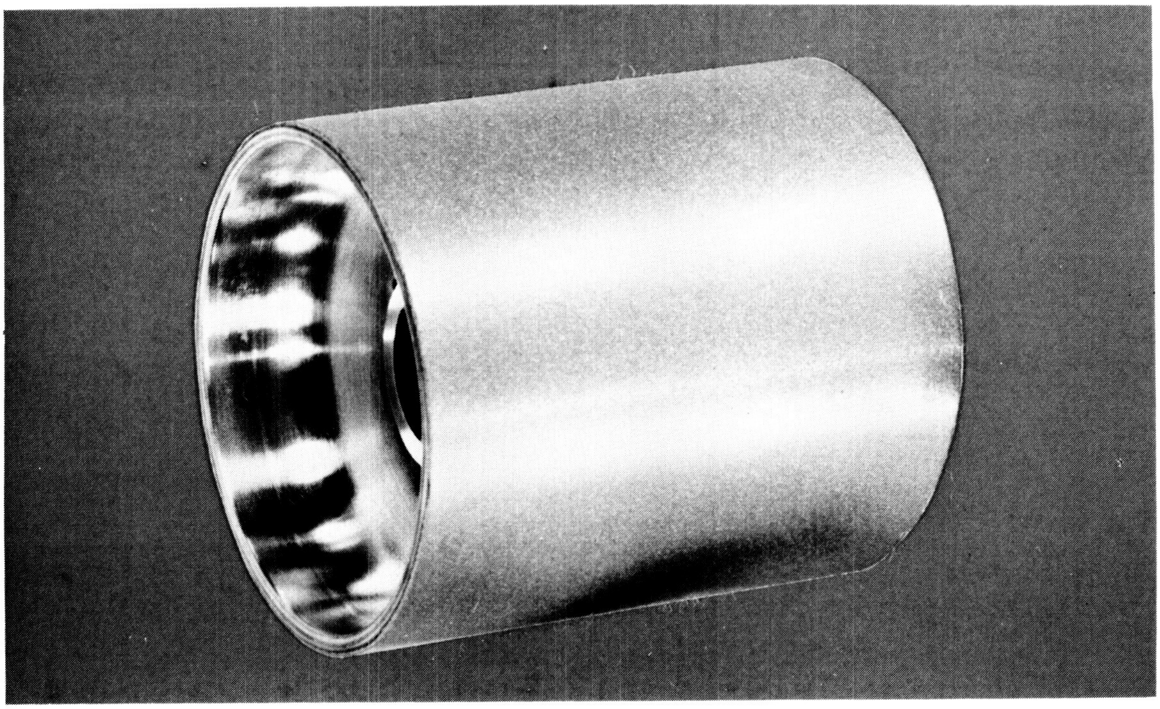
GAS BEARING JOURNAL COATED WITH PS200 AND FINISHED BY DIAMOND GRINDING

A 64-mm-diameter gas bearing journal was coated with PS200. The coating was diamond ground after the plasma-sprayed coating was applied. Even without optical magnification the composite nature of the coating is apparent. (Bright speckles of silver are uniformly distributed throughout the coating.)

GAS BEARING JOURNAL COATED WITH PS200 AND FINISHED BY DIAMOND GRINDING



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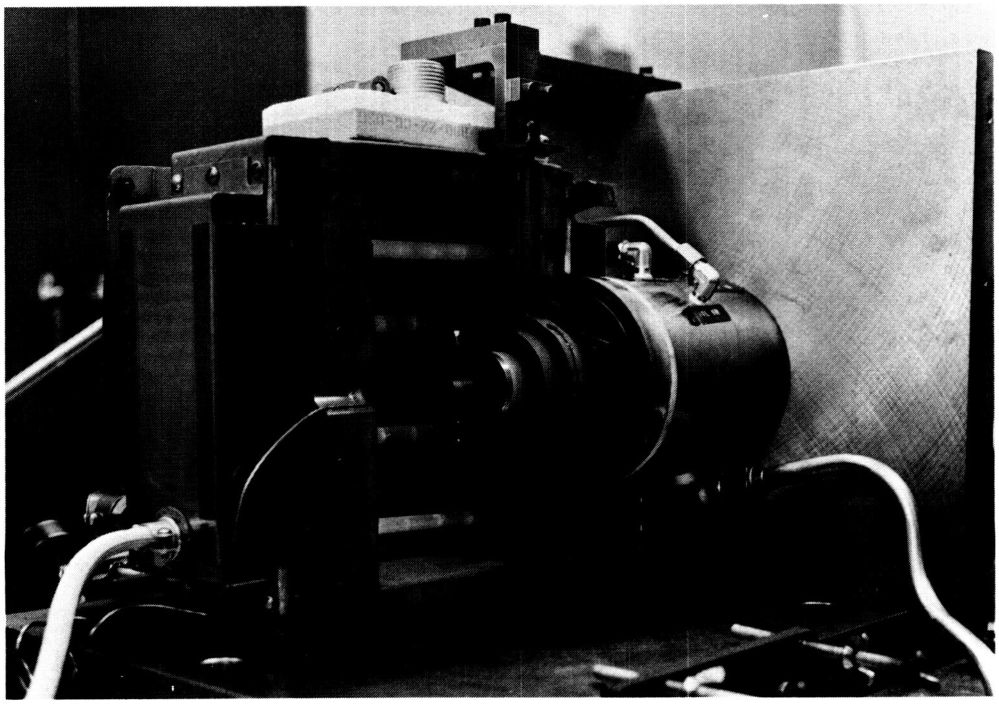
FOIL BEARING UNDER TEST AT 700 °C

One-half of the furnace surrounding the test bearing housing was removed to show a foil bearing under test at 700 °C. Bearing/journal assemblies lubricated with PS200 coatings on the journal have successfully completed over 10 000 start/stop cycles (20 000 rubs) in tests of this type.

FOIL BEARING UNDER TEST AT 700 °C



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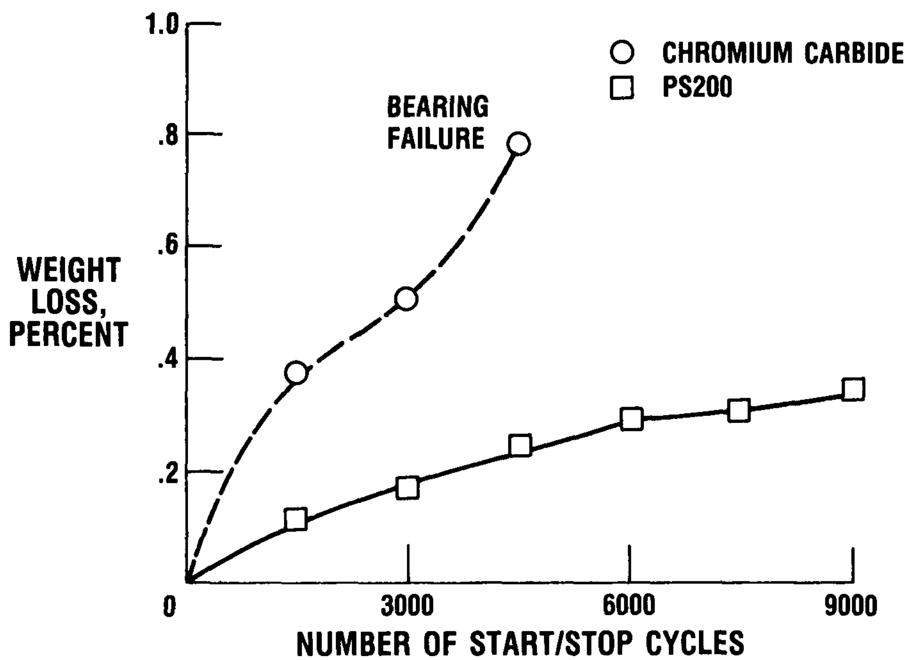
WEAR PROFILES OF PREOXIDIZED INCONEL X-750 FOIL BEARINGS RUN AGAINST JOURNALS LUBRICATED WITH PLASMA-SPRAYED CHROMIUM CARBIDE OR PS200

Inconel X-750 foil bearings wore less rapidly sliding against PS200 than against a baseline chromium carbide coating without solid lubricant additions. Foil bearings sliding against PS200 repeatedly survived the specified 9000 start/stop cycles at programmed temperatures to 650 °C and were in very good condition at the completion of those tests. On the other hand, foil bearings sliding against the baseline coating were excessively worn after 3000 start/stop cycles.

WEAR PROFILES OF PREOXIDIZED INCONEL X-750 FOIL BEARINGS RUN AGAINST JOURNALS LUBRICATED WITH PLASMA-SPRAYED CHROMIUM CARBIDE OR PS200



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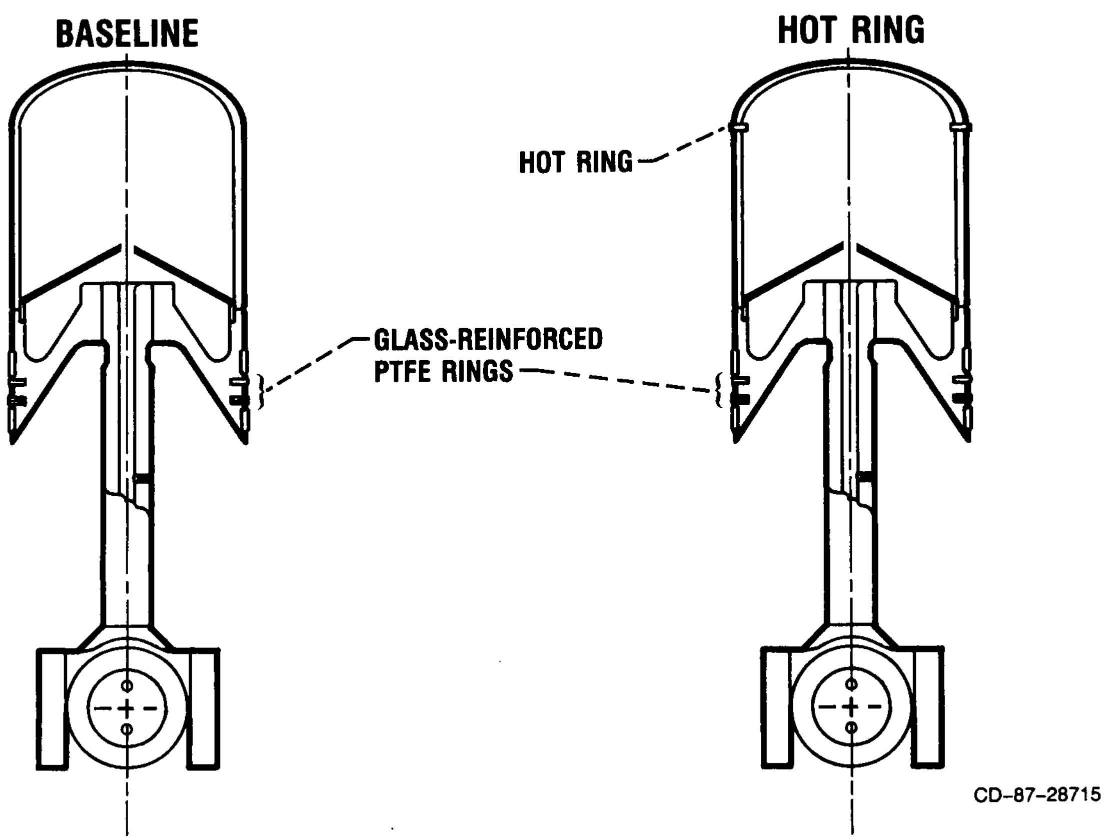
APPLICATION EXAMPLE: STIRLING ENGINE HOT PISTON RING TESTS

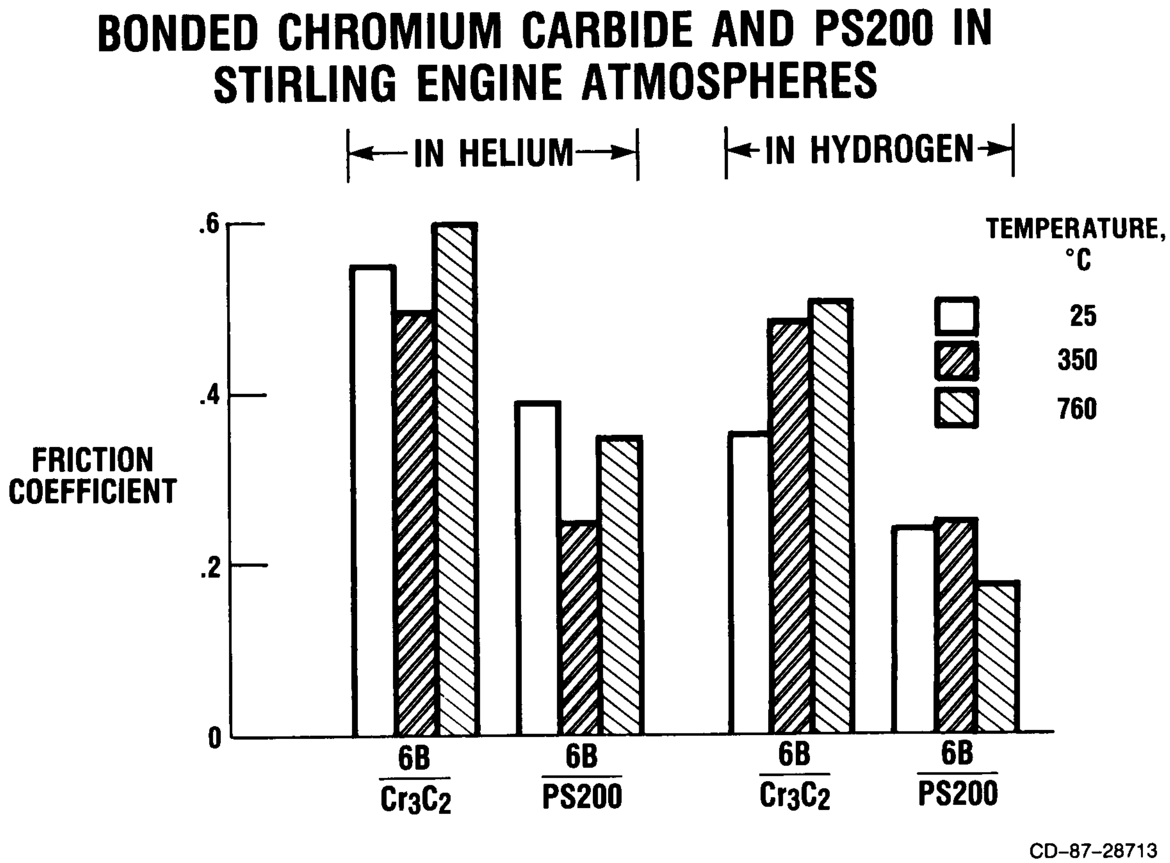
The Stirling engine is an externally heated engine. The working fluid in the thermodynamic cycle is typically gaseous hydrogen. Oil lubrication is not used in the piston/cylinder region of the engine. Conventionally, glass-reinforced polytetrafluoroethylene (PTFE) seal rings are located near the bottom of the pistons in the cooler region of the cylinders (<280 °C) because of the temperature limitations of PTFE. The use of PS200 as a cylinder liner material allowed the metal piston ring to be placed at the top of the piston, where the top ring reversal temperature is 760 °C.

APPLICATION EXAMPLE: STIRLING ENGINE HOT PISTON RING TESTS



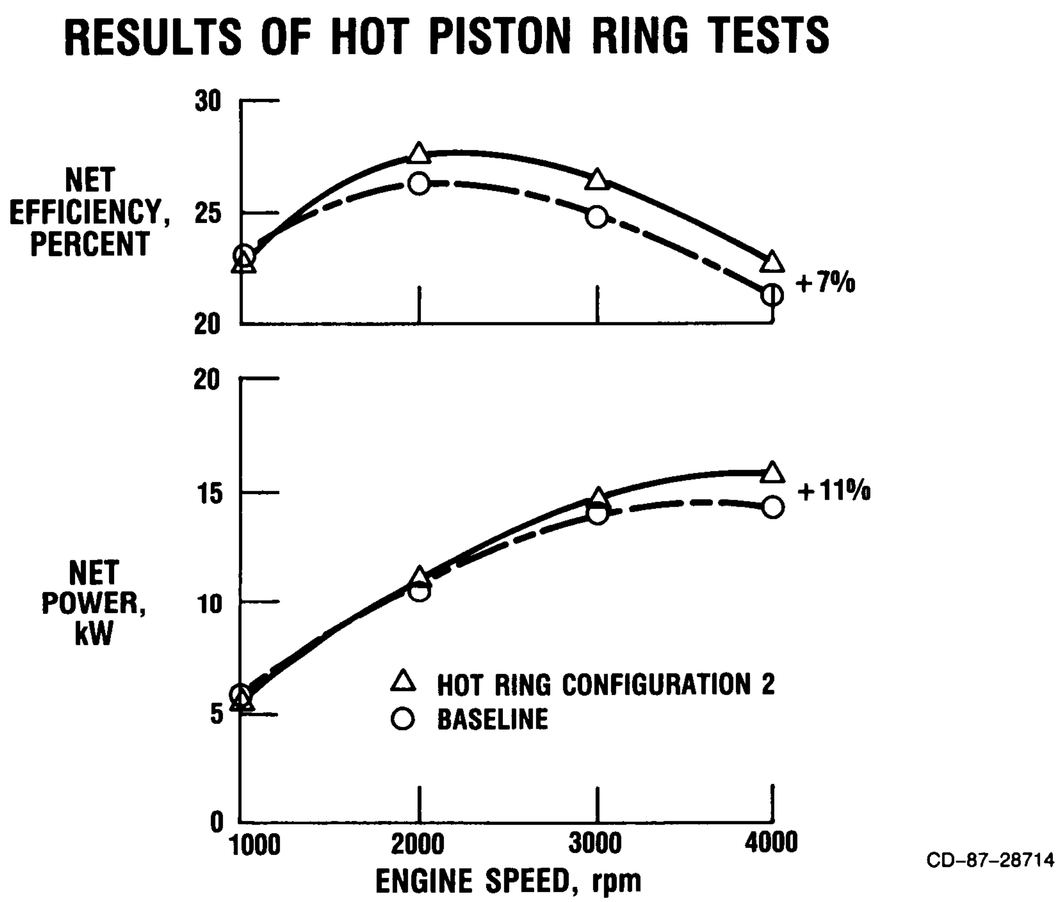
BONDED CHROMIUM CARBIDE AND PS200 IN STIRLING ENGINE ATMOSPHERES

Stellite 6B sliding on PS200 in helium or in hydrogen at 25, 350, and 760 °C demonstrated good frictional properties and excellent wear resistance in laboratory bench tests. These results led to the selection of this material combination for the piston rings and cylinder liner coating in a four-cylinder Stirling engine.



RESULTS OF HOT PISTON RING TESTS

Using a metallic top piston ring sliding against a PS200 piston liner provided a 7 percent increase in net engine efficiency as compared with a baseline engine equipped only with glass-reinforced PTFE rings near the bottom of the piston. The efficiency increase has been attributed to a closing of the clearance gap between the piston and the cylinder wall (appendix gap), which reduced heat loss to the cylinder walls. The 7 percent gain in efficiency correlates well with a theoretical computation that predicted up to a 10 percent efficiency gain if the appendix gap losses could be eliminated.



CERAMICS FOR ENGINES

James D. Kiser,
Stanley R. Levine,
and
James A. DiCarlo

ABSTRACT

Structural ceramics have been under nearly continuous development for various heat engine applications since the early 1970's. These efforts have been sustained by the unique properties that ceramics offer in the areas of high-temperature strength, environmental resistance, and low density and the large benefits in system efficiency and performance that can result. But the promise of ceramics has not been realized because their brittle nature results in high sensitivity to microscopic flaws and catastrophic fracture behavior. This has translated into low reliability for ceramic components and thus limited application in engines. For structural ceramics to successfully make inroads into the terrestrial heat engine market requires further advances in low cost, net shape fabrication of higher reliability components, and improvements in properties such as toughness, strength, etc. These advances will lead to very limited use of ceramics in noncritical applications in aerospace engines. For critical aerospace applications, an additional requirement is that the components display markedly improved toughness and noncatastrophic or graceful fracture. Thus our major emphasis on fiber-reinforced ceramics.

The NASA Lewis Research Center's Ceramic Technology Program is focused on aerospace propulsion and power needs. Thus, emphasis is on high-temperature use of ceramics and on their structural and environmental durability and reliability. The program is interdisciplinary in nature with major emphasis on materials and processing, but with significant efforts in design methodology and life prediction. About thirty-five researchers in the Materials and Structures Divisions are involved in the project. Strong interactions and collaborations between materials efforts and NDE, corrosion, fracture, and design methodology exist.

CERAMICS FOR ENGINES

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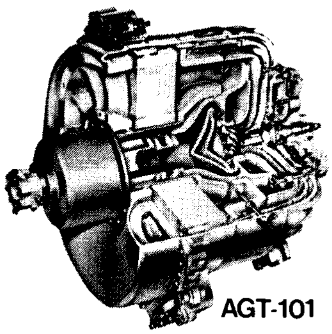
CERAMICS FOR ENGINES



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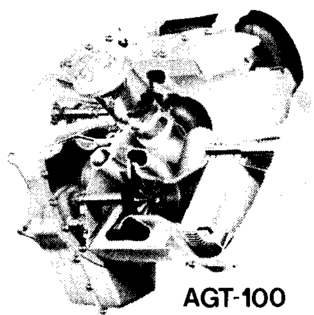

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CERAMIC PROPERTIES
- HIGH-TEMPERATURE STRENGTH
- ENVIRONMENTAL RESISTANCE
- LOW DENSITY

↓

IMPROVED EFFICIENCY AND PERFORMANCE

BUT

- HIGH CERAMIC SENSITIVITY TO FLAWS
- BRITTLE CATASTROPHIC FAILURE

↓

- LOW RELIABILITY
- LIMITED APPLICATION

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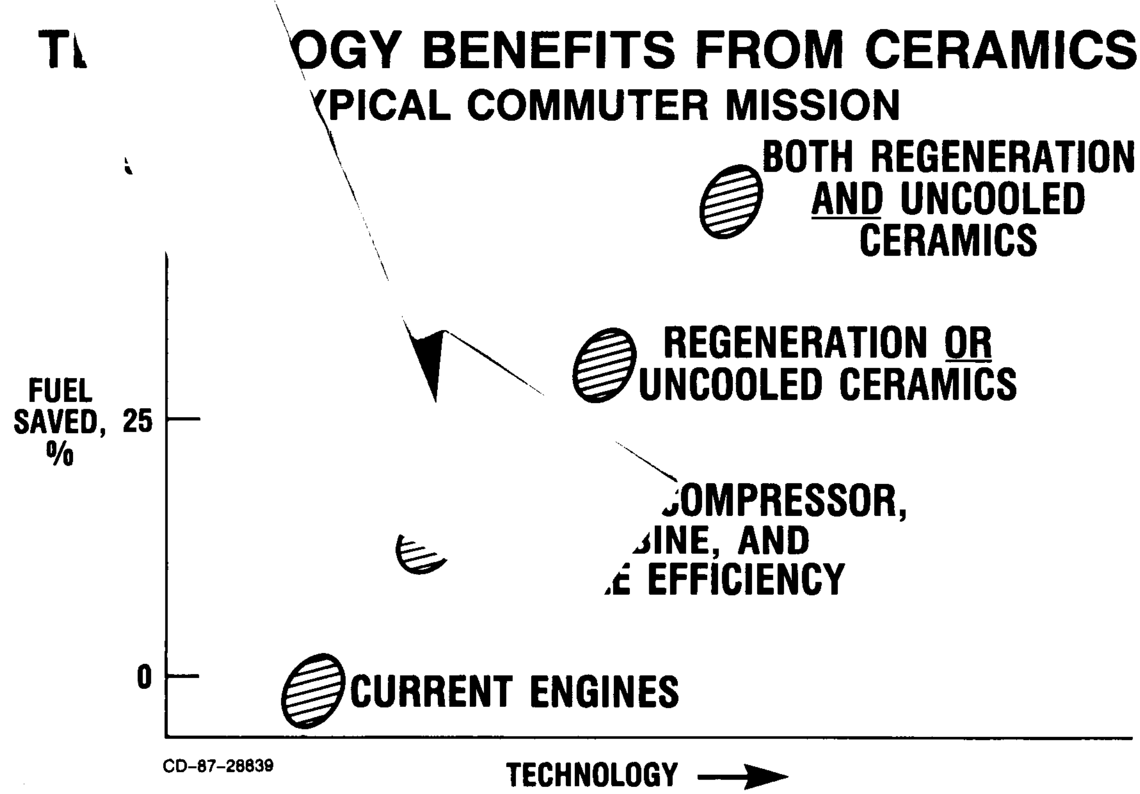
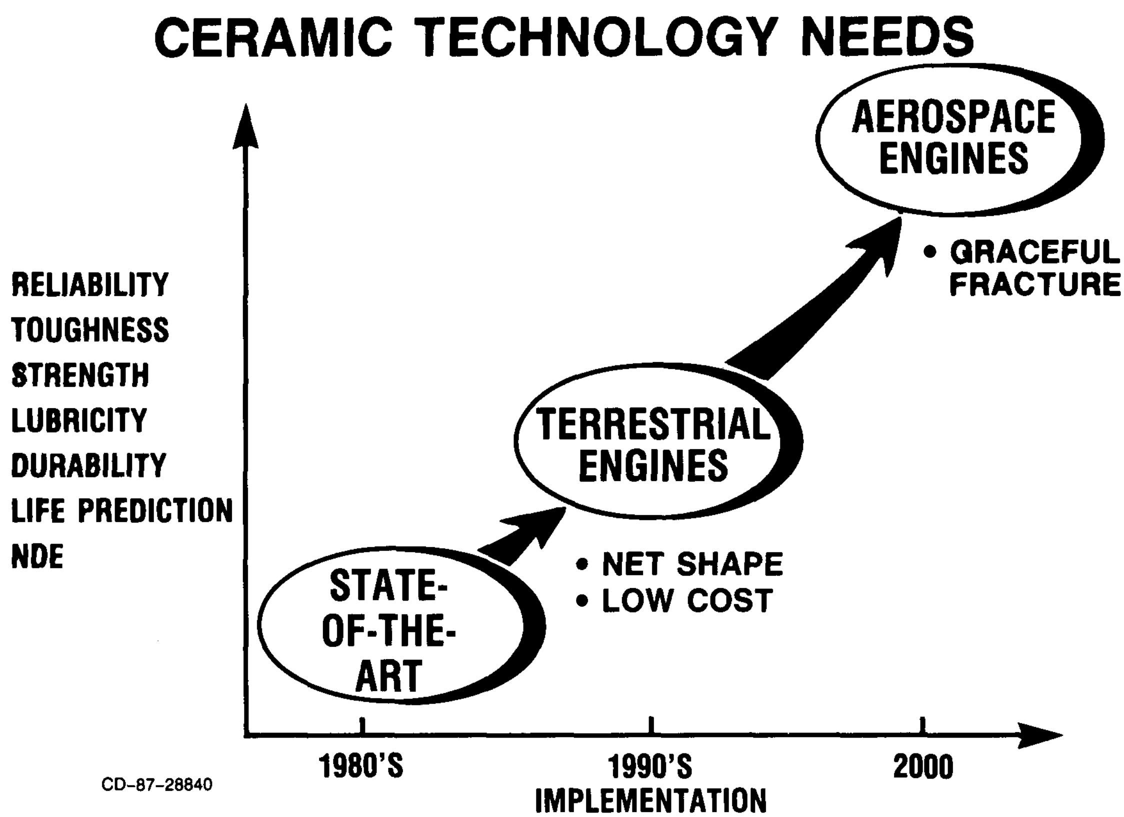
TECHNOLOGY BENEFITS FROM CERAMICS

The results of recent studies of ceramic applications in small aeropropulsion engines have revealed that substantial benefits are possible over current engine technology. Small gains can be obtained via improved aerodynamic and cycle efficiency. Much larger benefits are possible by going to a regenerated cycle or by going to an uncooled hot section. Both of these approaches require ceramics, i.e., a ceramic regenerator for weight considerations and ceramic hot-section components to overcome the need for hot-section component cooling.



CERAMIC TECHNOLOGY NEEDS

For structural ceramics to successfully make inroads into the terrestrial heat engine market, further advances are necessary in net shape fabrication of components with greater reliability and lower cost. The cost constraint as well as technical constraints currently dictate use of monolithic or possibly particulate or whisker-toughened ceramics. Improvements in properties such as toughness, strength, lubricity, and durability may also be needed for specific applications. In addition, technology advances in life prediction and nondestructive evaluation are required. These advances in technology will lead to very limited use of ceramics in noncritical applications in aerospace engines. For critical aerospace applications, an additional requirement is that the components display markedly improved toughness and noncatastrophic or graceful fracture. Thus our major emphasis on fiber-reinforced ceramics.



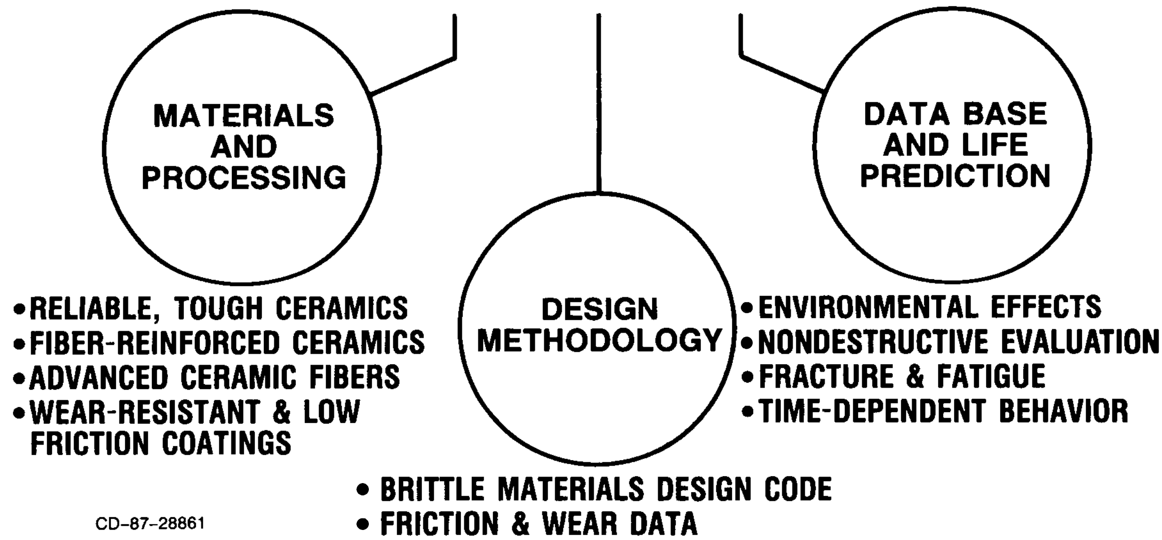
CERAMIC TECHNOLOGY

The NASA Lewis Research Center's Ceramic Technology Program is focused on aerospace propulsion and power needs. Thus, emphasis is on high-temperature use of ceramics and on their structural and environmental durability and reliability. The program is interdisciplinary in nature with major emphasis on materials and processing, but with significant efforts in design methodology and life prediction. About thirty-five researchers in the Materials and Structures Divisions are involved in the project. Strong interactions and collaborations between materials efforts and NDE, corrosion, fracture, and design methodology exist.

CERAMIC TECHNOLOGY

OBJECTIVE

IDENTIFY AND DEVELOP CERAMICS/COMPOSITES WITH STRENGTH, TOUGHNESS, RELIABILITY, AND DURABILITY SUFFICIENT FOR USE AT TEMPERATURES TO 1650 °C (3000 °F) AND ABOVE IN FUTURE ADVANCED AEROSPACE PROPULSION AND POWER SYSTEMS.



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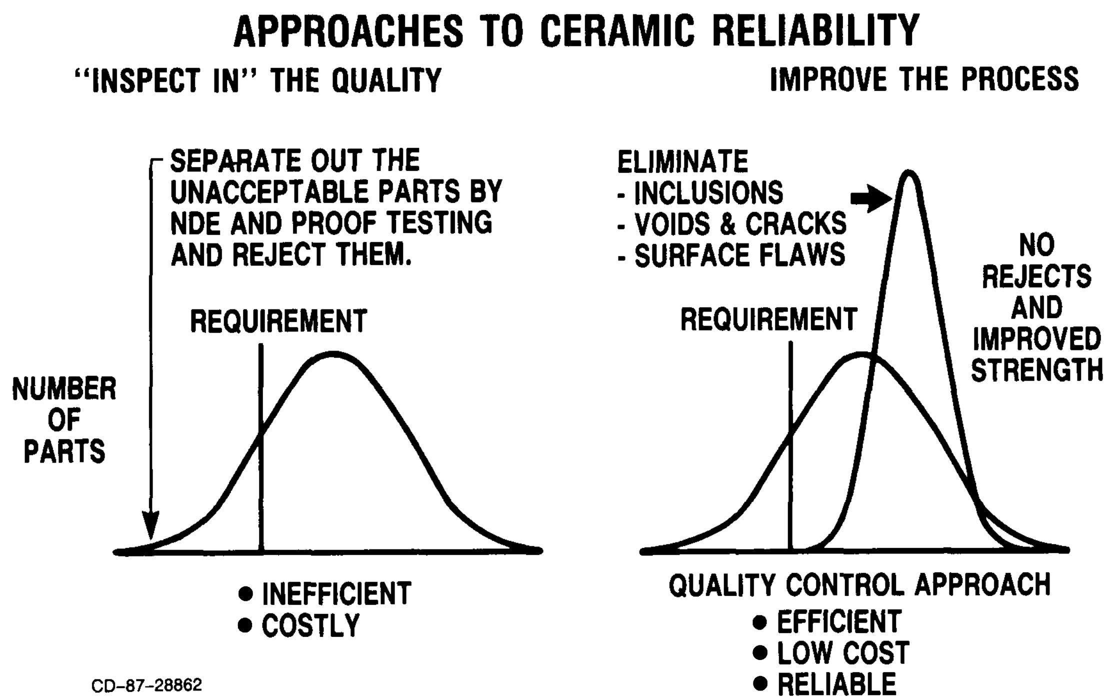
APPROACHES TO CERAMIC RELIABILITY

Two basic forms of reliability can be defined for ceramics. The first is a statistical reliability as illustrated in the figure. Ceramics typically display a broad distribution of strengths. In the inspection approach to reliability, we would separate unacceptable parts by NDE and proof testing and reject them. A more efficient and cost-effective approach lies in improved processing that increases strength and yields no defects.

We define the second form of reliability as functional reliability because it relates to how well a component performs its function during system assembly and service. Thus, factors such as fracture toughness, impact resistance, and failure mode (graceful versus catastrophic), which are governed by micro- and macrostructure, need to be considered. Specifically, particulate and whisker phases can improve fracture toughness and continuous fiber additions can also provide a noncatastrophic failure mechanism. This brings us into the realm of engineered microstructures, i.e., composites.



CURRENT NASA LEWIS MATERIALS EFFORTS
- TOUGHENED CERAMICS -

Research is focused on SiC and Si_3N_4 because these materials offer the desired combination of high-temperature strength, thermal shock resistance, and environmental durability. We are concluding efforts on SiC and Si_3N_4 reliability improvement. Future efforts are being focused on determining the potential of these materials for use in the 1300 to 1600 °C range. This requires improvements in strength and toughness and an understanding of how these improvements translate into use potential. These efforts are synergistic with our effort in fiber-reinforced ceramics where much of our emphasis is on SiC and Si_3N_4 materials.

CURRENT NASA LEWIS MATERIALS EFFORTS
—TOUGHENED CERAMICS—

FOCUS: SiC & Si_3N_4 FOR USE POTENTIAL ABOVE ~1300 °C

- **RELIABILITY IMPROVEMENT**
- **IMPROVED Si_3N_4 HIGH-TEMPERATURE STRENGTH**
- **IMPROVED SiC & Si_3N_4 FRACTURE TOUGHNESS**
- **LIFE PREDICTION OF WHISKER-TOUGHENED SiC & Si_3N_4**

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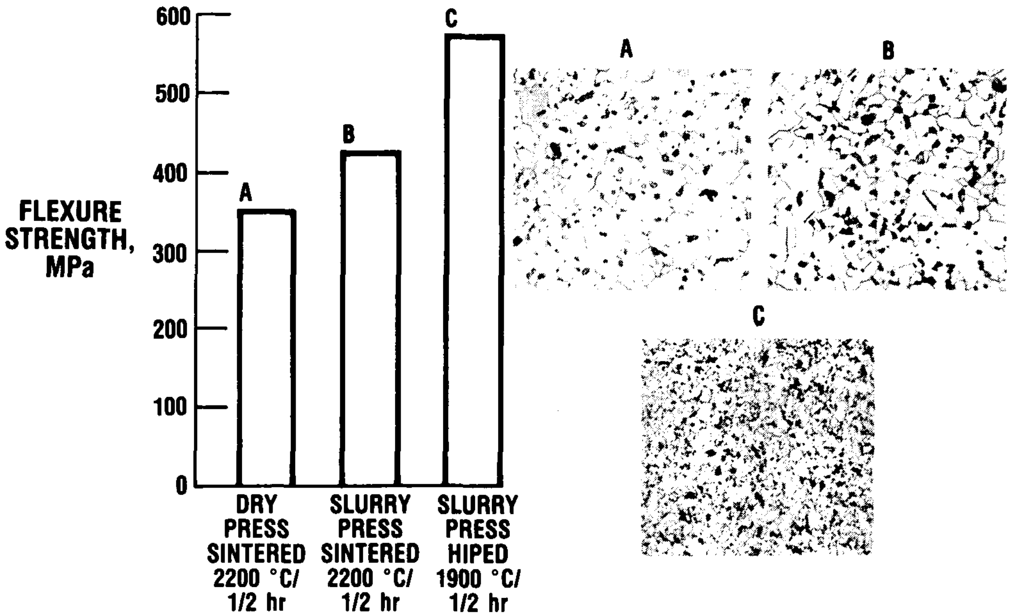
IMPROVED SILICON CARBIDE BY HOT-ISOSTATIC PRESSING

Some recent progress at the NASA Lewis Research Center in improving the strength of silicon carbide is illustrated. Materials fabricated by dry pressing or slurry pressing, followed by sintering at 2200 °C for 30 min, have four-point flexural strengths of about 345 and 414 MPa, respectively. Hot-isostatic pressing tantalum-encapsulated, green, slurry-pressed specimens at 1900 °C for 30 min improves strength to about 552 MPa while achieving the same density. This densification at a much lower temperature yields a much finer grain size and a shift in the strength-limiting flaw from internal defects, such as pores and agglomerates, to surface machining defects. Improvements are being sought to reduce sensitivity to surface flaws.

IMPROVED SILICON CARBIDE BY HOT-ISOSTATIC PRESSING



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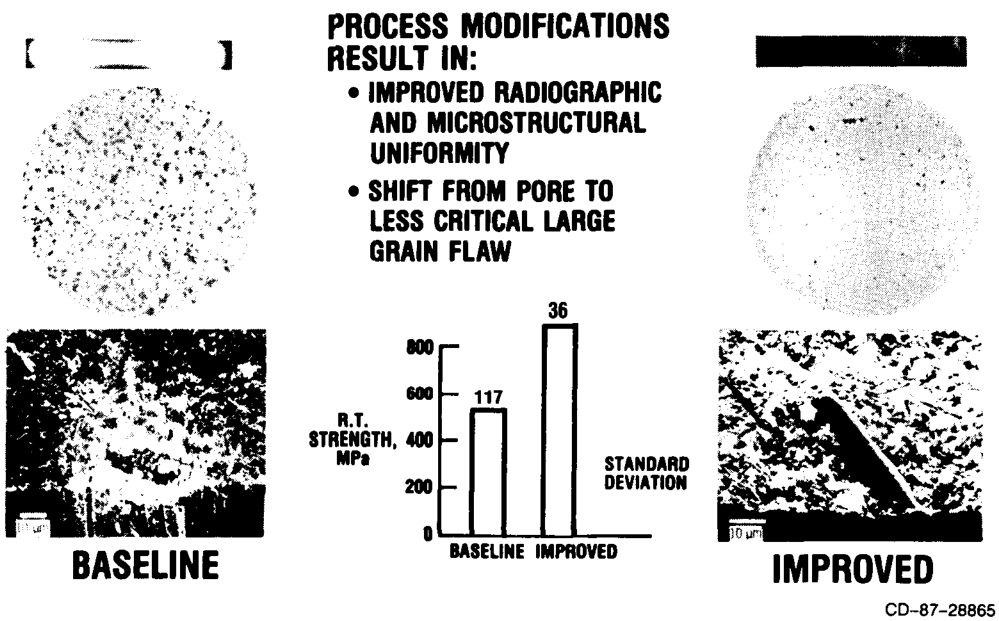
NASA 6Y SINTERED SILICON NITRIDE IMPROVED BY RADIOGRAPHICALLY-GUIDED PROCESSING CHANGES

In the area of silicon nitride processing, an improved NASA 6Y (6 wt % Y_2O_3) sintered Si_3N_4 composition was realized by iterative utilization of conventional x-radiography to characterize structural (density) uniformity as affected by systematic changes in powder processing and sintering parameters. Four-point flexural strength was improved 56 percent and the standard deviation was reduced by more than a factor of three. Correlated with these improvements were improved microstructures and a change in critical flaw character.

NASA 6Y SINTERED SILICON NITRIDE IMPROVED BY RADIOGRAPHICALLY-GUIDED PROCESSING CHANGES



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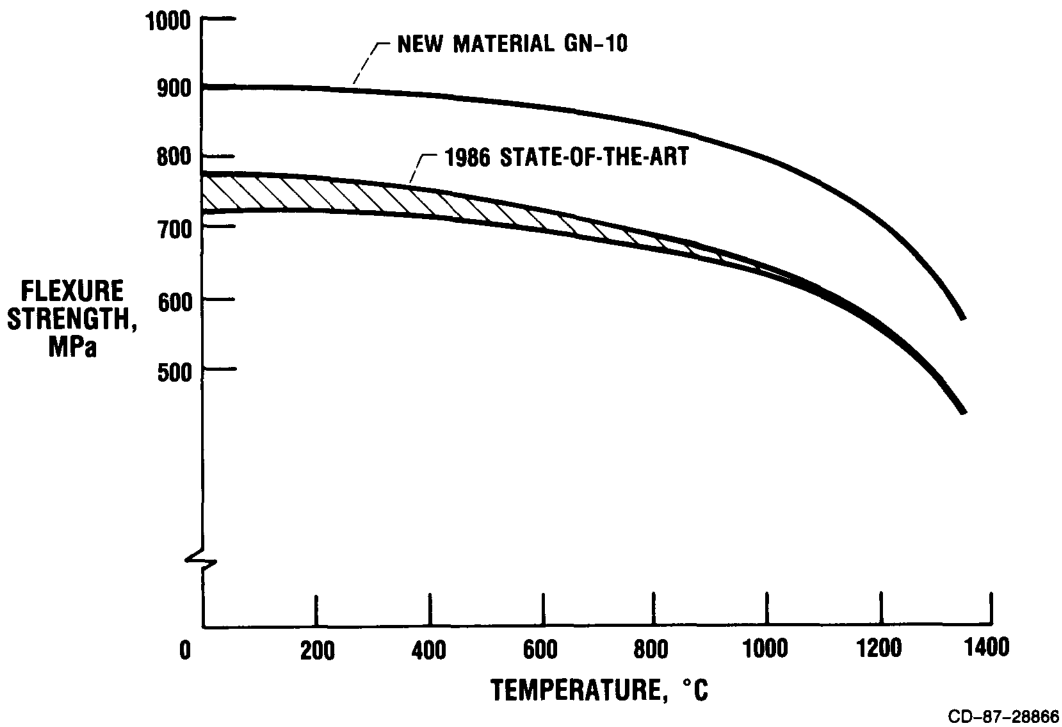
NASA has supported major contract research efforts to improve the statistical reliability and strength of silicon nitride (Garrett Ceramic Components Division) and silicon carbide (Ford Motor Co.) via improved processing centered about injection molding. Both efforts have made good progress toward the goals of 100 percent improvement in Weibull modulus and 20 percent improvement in strength. The effort at Garrett is essentially complete. One Garrett accomplishment, as shown in the accompanying figure, was the development of material GN-10, which appears to have significantly advanced the state-of-the-art.

IMPROVEMENTS IN SINTERED SILICON NITRIDE



FIBER-REINFORCED CERAMICS APPROACH TO RELIABILITY

Improved ceramic strength, toughness, and reliability can be achieved by incorporating continuous ceramic fibers. This gives stress-strain behavior that mimics a metal and noncatastrophic or "graceful" failure. The penalty for doing this is greater fabrication difficulty. Also, available fibers for high-temperature (1400 °C) ceramic matrix composites are limited, and the proper fiber-matrix bond must be maintained in fabrication as well as during the life of the composite. Too strong a bond yields a loss in toughness and a reversion to monolithic ceramic behavior, while too weak a bond yields loss in stiffness, strength, and toughness.

FIBER-REINFORCED CERAMICS APPROACH TO RELIABILITY

INCORPORATE CONTINUOUS CERAMIC FILAMENTS HAVING GREATER STIFFNESS THAN MATRIX

- **ADVANTAGES**
  - IMPROVED TOUGHNESS IMPARTED BY CRACK DEFLECTION AND CRACK BRIDGING
  - INCREASED MODULUS AND STRESS TO FAILURE
  - "METALLIKE" STRESS-STRAIN BEHAVIOR
  - GRACEFUL FAILURE
- **DISADVANTAGES**
  - PROCESSING MORE DIFFICULT
  - AVAILABLE FIBERS LIMITED
  - CONTROL OF FIBER-MATRIX BOND REQUIRED

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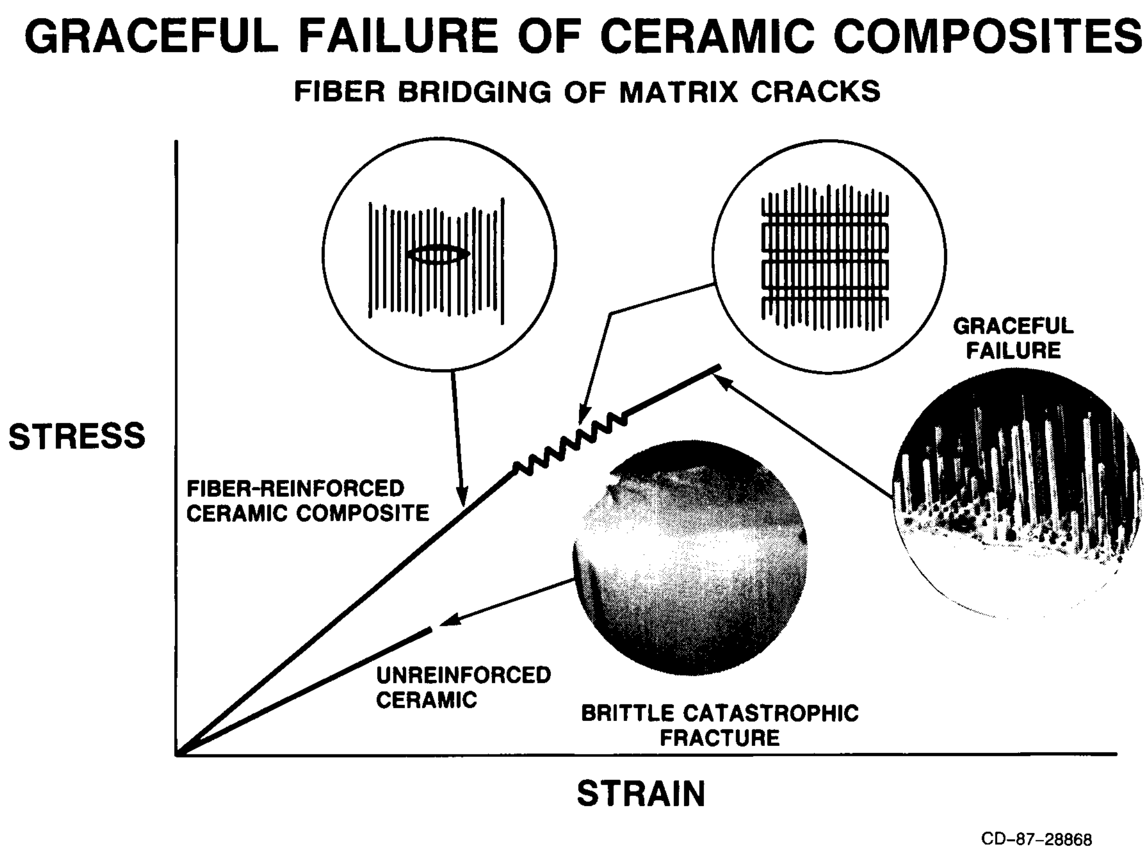
Reinforcing with ceramic fibers having a modulus and ultimate strength greater than the monolithic ceramic used as the matrix material yields ceramic composites with greater stiffness and greater strength at first matrix cracking. If small diameter fibers are used, matrix crack propagation can be delayed by the bridging mechanism depicted in the figure insert. This results in matrix failure for the composite at a stress and strain level higher than for the monolithic ceramic. If the fiber-matrix interfacial bonding is optimum, matrix cracks propagate around the fibers and not through them. Once matrix cracks start to form, they occur at a regular spacing. The ceramic is then held together by the load-carrying capacity of the fibers until they begin to fracture in a statistical manner. The net result for a tough ceramic composite having an optimum bond between the matrix and fiber is that a metallike stress-strain curve is displayed with first-matrix cracking stress corresponding to the yield stress of metals and fiber fracture corresponding to the ultimate strength.



CURRENT NASA LEWIS MATERIALS EFFORTS

- Fiber-Reinforced Ceramics -

The focus of current NASA Lewis research in fiber-reinforced ceramics (FRC) is on the development of fabrication approaches that yield good matrix properties and can be carried out with minimal degradation of fiber strength. Four approaches that are being pursued are outlined. Extension of the capability of FRC via development of advanced fibers and fiber coatings is a second area of focus. The third area of focus is assessment of FRC capability to perform in applications such as NASP and rocket propulsion systems. These efforts thus focus on key issues associated with each application, such as process scale-up to enable component fabrication, compatibility with the environment, and resistance to thermal shock.

CURRENT NASA LEWIS MATERIALS EFFORTS —FIBER-REINFORCED CERAMICS—

I. PROCESSING STUDIES
- OPTIMUM MATRIX PROPERTIES
- FIBER STRENGTH RETENTION

			ADVANTAGE
Si POWDER + HEAT + N_2 GAS	➡	Si_3N_4	STRONG MATRIX
SiC POLYMER + HEAT	➡	SiC	LOW-COST PROCESSING
C POLYMER + HEAT + Si GAS	➡	SiC	TAILORABLE MATRIX
Al-O SOL GEL + HEAT	➡	Al_2O_3	OXIDATION RESISTANCE

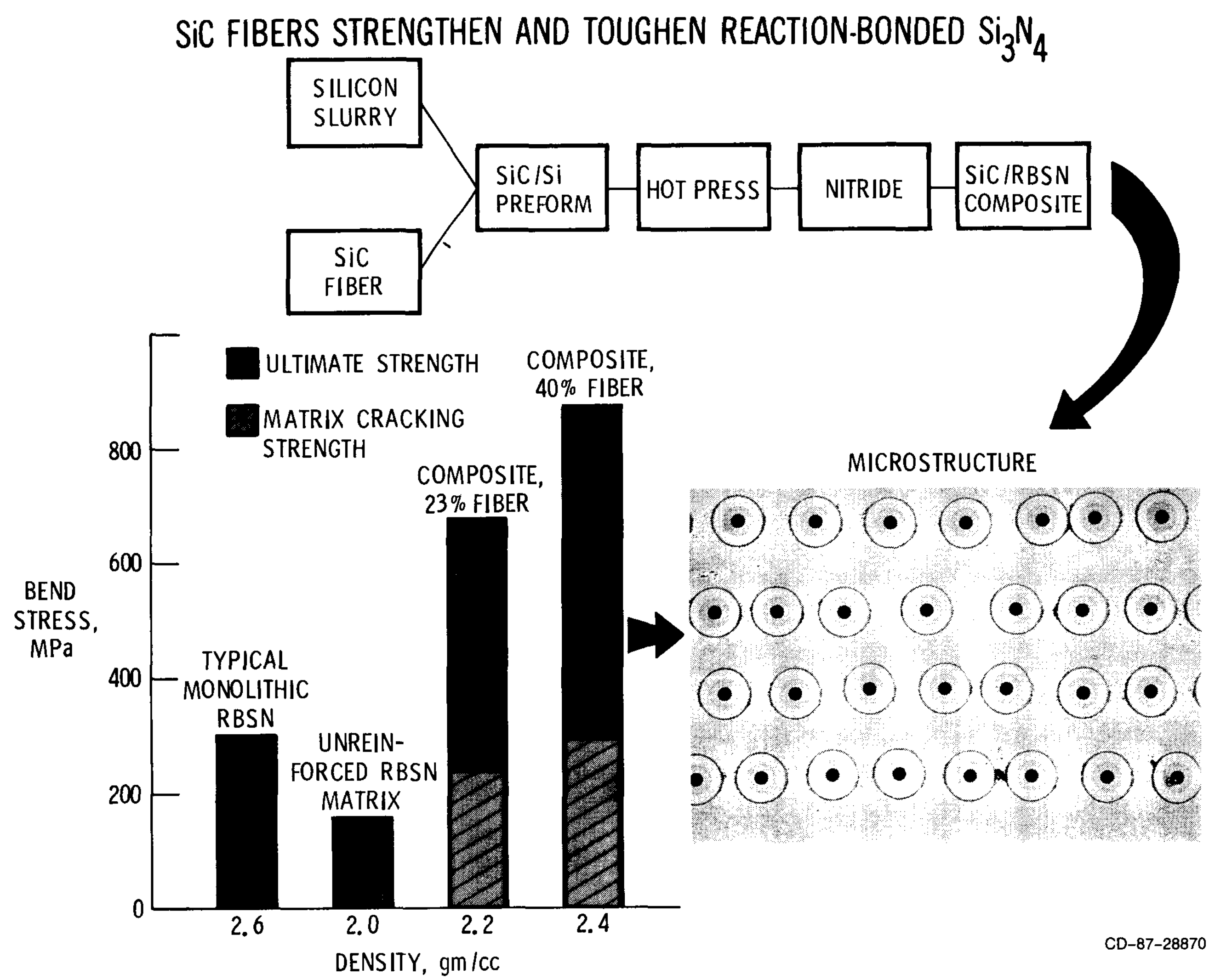
II. ADVANCED FIBER STUDIES
- HIGH STRENGTH
- STRENGTH STABILITY TO >1650 °C (3000 °F)
- ENVIRONMENTAL PROTECTION
- OPTIMUM FIBER-MATRIX BOND

III. FRC APPLICATIONS
- NASP
- ROCKET PROPULSION

CD-87-28869

SiC FIBERS STRENGTHEN AND TOUGHEN REACTION BONDED Si_3N_4

The fabrication sequence, microstructure, and mechanical properties of the high strength and toughness SiC fiber-reinforced, reaction-bonded silicon nitride composite recently developed at NASA Lewis are summarized in this figure. Silicon and SiC fiber monotapes are interleaved and subjected to a mild hot-pressing step to burn out the binder and provide some green strength. The composite is then nitrided to convert the silicon to Si_3N_4. The resultant composite microstructure contains high levels of porosity, particularly between fibers. In four-point flexural testing, the composite exhibits a first-matrix cracking strength comparable to typical monolithic RBSN even though the matrix density at 2.0 gm/cm^3 is far lower than that of monolithic RBSN. The ultimate strength of the composite is more than twice that of a typical RBSN at both 23 and 40 percent fiber loading.

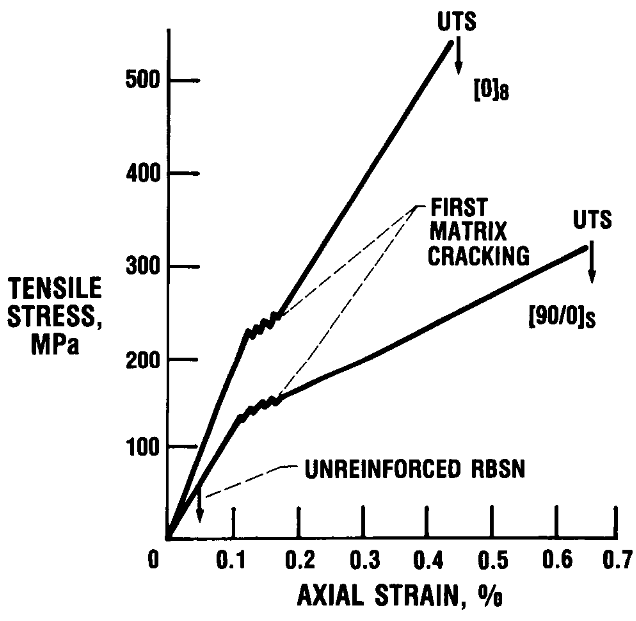


SiC/RBSN COMPOSITES FRACTURE GRACEFULLY

Tensile stress-strain data and fracture behavior of 30 vol % SiC/RBSN composites are illustrated in this figure. An additional strain occurs after matrix fracture at about 0.12 percent strain. The stress at failure is much higher than for first matrix cracking. The fracture surface exhibits the moderate fiber pullout required for achieving a strong, tough ceramic matrix composite. It is expected that with the development of high strength, smaller diameter SiC fibers, the fracture properties of the SiC/RBSN will improve significantly.

SiC/RBSN COMPOSITES FRACTURE GRACEFULLY

ROOM-TEMPERATURE TENSILE STRESS-STRAIN BEHAVIOR FOR SiC/RBSN COMPOSITE LAMINATES ($V_f \sim 0.3$)



FRACTURED SPECIMEN

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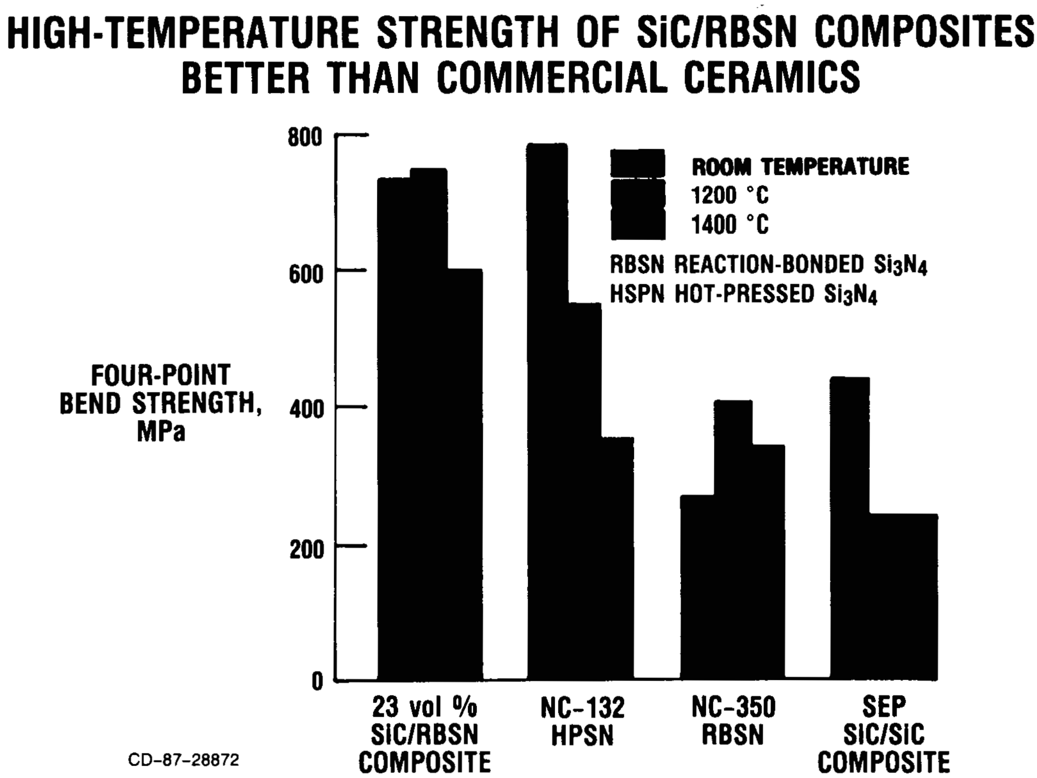
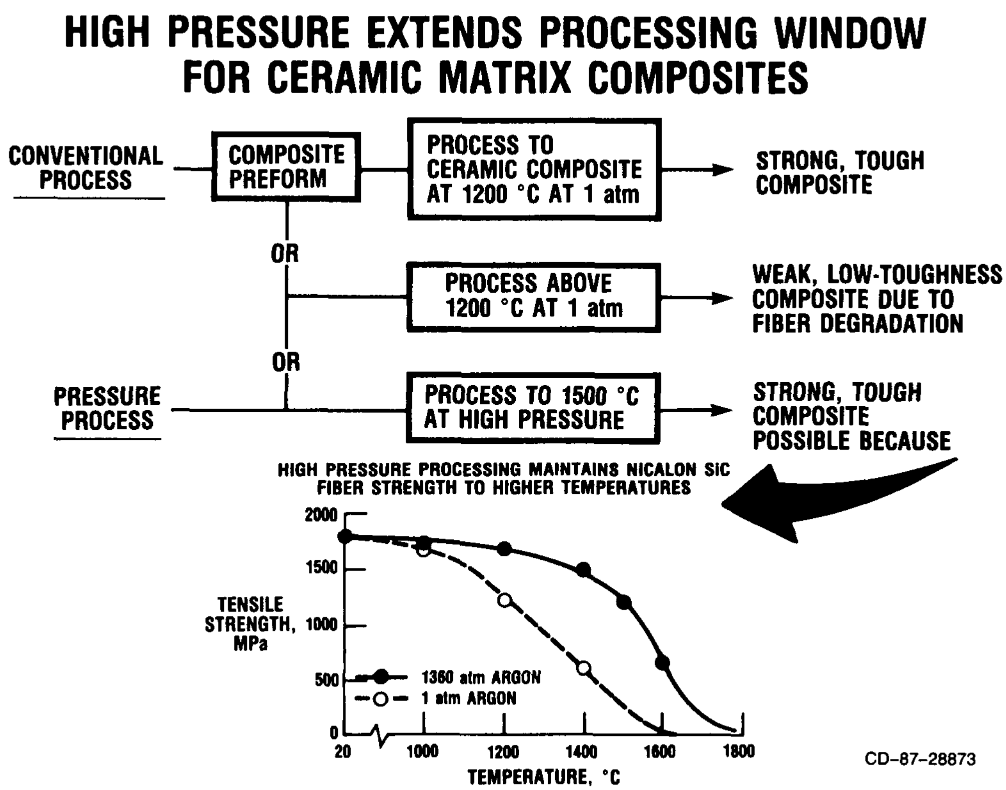
HIGH-TEMPERATURE STRENGTH OF SiC/RBSN COMPOSITES
BETTER THAN COMMERCIAL CERAMICS

Four-point bend strengths for SiC/RBSN at room temperature, 1200 °C (2200 °F) and 1400 °C (2550 °F) are compared with data for fully dense, hot-pressed Si_3N_4, reaction-bonded Si_3N_4, and SEP SiC/SiC composite (one-dimensional). At elevated temperature, 23 vol % SiC/RBSN is stronger than both monolithics and more than twice as strong as the SEP SiC/SiC composite.



HIGH PRESSURE EXTENDS PROCESSING WINDOW
FOR CERAMIC MATRIX COMPOSITES

An example of studies aimed at improved ceramic fibers can be found in a recent in-house study of post-processing of Nicalon SiC fibers. This research involved high-temperature/high-pressure treatments of Nicalon in an attempt to determine if the fiber properties could be improved or stabilized. Results are summarized in the graph. Treatment at 1360 atm in argon results in about a 300 °C increase in the maximum exposure temperature for onset of strength degradation. This effect is transitory in nature. Thus, exposure to high temperature at 1 atm after pressure treatment gives the same results as exposure of a nontreated fiber. However, if high-temperature exposure is necessary only for processing of the composite, the pressure treatment approach has significant merit.



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CONCLUDING REMARKS

For ceramics to achieve their promise, reliable and economical fabrication processes must be developed for monolithic, whisker-toughened, and fiber-reinforced ceramics. In addition, a basic understanding of the materials science of ceramics is required to enable the development of the processing and of the design and life prediction methodologies that will enable them to be utilized.

CONCLUDING REMARKS

MATERIAL CLASS	KEY TECHNOLOGIES	
TOUGHENED CERAMICS	RELIABLE FABRICATION LIFE PREDICTION	MATERIALS SCIENCE FOUNDATION
FIBER-REINFORCED CERAMICS	ADVANCED FIBERS AND COATINGS FABRICATION LIFE PREDICTION	MATERIALS SCIENCE FOUNDATION

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16. Abstract

The advanced materials program at the Lewis Research Center has a long record of contributions to both materials and process technology as well as to the understanding of key high-temperature phenomena. This session overviews the program in terms of staff, facilities, past history, recent progress, and future interests. The papers included in the session expand on some selected research areas and plans.

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