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POLYMER, METAL, AND CERAMIC MATRIX COMPOSITES FOR ADVANCED AIRCRAFT ENGINE APPLICATIONS

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SUMMARY

Advanced aircraft engine research within NASA Lewis is being focused on propulsion systems for subsonic, supersonic, and hypersonic aircraft. Each of these flight regimes requires different types of engines, but all require advanced materials to meet their goals of performance, thrust-to-weight ratio, and fuel efficiency. The high strength/weight and stiffness/weight properties of resin, metal, and ceramic matrix composites will play an increasingly key role in meeting these performance requirements. At NASA Lewis, research is ongoing to apply graphite/polyimide composites to engine components and to develop polymer matrices with higher operating temperature capabilities. Metal matrix composites, using magnesium, aluminum, titanium, and superalloy matrices, are being developed for application to static and rotating engine components, as well as for space applications, over a broad temperature range. Ceramic matrix composites are also being examined to increase the toughness and reliability of ceramics for application to high-temperature engine structures and components.

INTRODUCTION

Advanced aircraft engines require advanced materials to meet their goals of performance, thrust-to-weight ratio, and fuel efficiency. There are three main materials-related drivers for the development of advanced engines. First, materials and fabrication cost reductions to reduce acquisition cost and life cycle maintenance costs. Second, lower weight materials to improve specific fuel consumption and reduce overall weight of the aircraft. Third, improved materials to permit design innovations to allow improvements in the engine cycle to allow higher cycle efficiency and engine performance, such as the use of higher overall pressure ratios in the compressor stages and higher operating temperatures in the turbine stages.

The effect of these materials improvements can be demonstrated by comparing the F404 turbofan engine, used to power a current F-18 fighter, with a J79 turbojet, which powered the F-4 of 1958. Both engines have approximately the same thrust, but the F404 has twice the pressure ratio produced by only half the number of compressor stages, has half the engine weight, three-quarters of the length, and [illegible] percent of the frontal area. Also, from the cost savings aspect, the F404 achieves this thrust with 7700 fewer parts (ref. 1). Materials-related design improvements, such as these, have more than doubled the engine thrust/aircraft weight ratio of the Korean War vintage F-86 to the F-15A of the 1980's.

While conventional materials have shown significant improvements, composite materials offer the opportunity for much further gains in performance and weight reduction through development of stiffer, stronger, and lighter weight materials capable of withstanding higher operating temperatures. They also offer the opportunity to develop new materials with a unique set of properties that are not available with conventional materials. The high strength/weight and stiffness/weight properties of composite materials are already being used to design advanced airframe structures. As shown in figure 1, development of composite airframe structures started with the design and fabrication of experimental secondary structures. As experience and confidence were gained, application of composite materials was expanded to critical primary structures. A 10-yr incubation period of learning experience is usually required before a new material is accepted to be standard bill-of-materials for production airframe structures. Polymer matrix composites are being extensively used in current high-performance aircraft, such as the AV-10B and the Advanced Tactical Fighter (ref. 2).

Aircraft engines operate in a much more severe environment than that faced by airframe structures, and composite materials are just starting to be utilized in engine structures. Composite materials will play an increasingly key role in allowing advanced aircraft engines to meet their performance requirements.

It is the purpose of this paper to discuss some of the advanced aircraft engine concepts being studied at NASA Lewis, and to discuss some of the efforts underway to develop and apply advanced polymer, metal, and ceramic matrix composites to meet the increased material requirements for these advanced engine applications.

ADVANCED AIRCRAFT ENGINE CONCEPTS

NASA Thrusts in Aeronautics

One of the basic charters of NASA Lewis has traditionally been the development of advanced aircraft propulsion systems, primarily through experimental aerodynamics research, improved computational fluid dynamics, and advanced materials technology. Current emphasis of NASA aeronautics research is focused on the three main thrusts proposed in the Keyworth report on technology required for aircraft for the 21st century (ref. 3). These thrusts are: (1) to develop technology for fuel-efficient subsonic transport aircraft; (2) to develop technology for supersonic military attack and civil transport aircraft; and (3) to develop technology readiness for hypersonic and transatmospheric aircraft. Advanced aircraft to meet each of these three thrusts have a different mission (fig. 2), require different propulsion systems, and operate in different flight envelopes (fig. 3).

Current emphasis for the subsonic transport thrust is on the development of aircraft powered with advanced turboprop engines. Depending upon their configuration, these engines are also called advanced prop-fan or unducted-fan propulsion systems. Current subsonic transports use high bypass turbofan engines, but high-efficiency advanced turboprop engines offer potential fuel savings of over 30 percent for transports in the 150-passenger class size range. A typical prop-fan propulsion system is shown in figure 4. Power is generated by a turboshaft engine in which the output shaft is connected to a gearbox where the rotational speed is reduced and power is transmitted to an advanced propeller. The 8 to 12 bladed propellers are highly swept to give greater aerodynamic efficiency, higher flight speed capability, and reduced near-airport noise levels. Prop-fan aircraft are intended for use on short-haul routes of less than 500 mi and are designed to fly at speeds of Mach 0.8 to mesh with existing schedules of jet-powered transports.

The emphasis for the supersonic aircraft thrust is on the development of fuel-efficient, high-performance military attack and civil transport aircraft flying at speeds of up to Mach 5. Supersonic aircraft are powered by rotating turbomachinery engines over the Mach 1 to 4 range. Current supersonic fighters are powered by low bypass turbofan engines at speeds up to Mach 2 and by turbojet engines with afterburners to speeds above Mach 3. For advanced aircraft to operate in the high-supersonic range to Mach 5, advanced engines, such as a supersonic-fan turbofan or variable cycle engines, will be used to combine more fuel-efficient engine cycles with higher performance cycles for sustained supersonic flight and/or combat capabilities. In addition, multiple-mode engines can be used combining turbomachinery engines to gain speed and altitude sufficient for ramjet engines to accelerate the aircraft to speeds up to Mach 5.

The emphasis for the hypersonic aircraft technology thrust is in two related areas: hypersonic transports cruising in the Mach 6 to 12 range, and transatmospheric aircraft reaching orbital velocities and leaving the atmosphere. Flight profiles of both types of missions will involve conventional take-off, acceleration to hypersonic or transatmospheric cruise, and conventional landing. These aircraft will be powered by multiple-mode engines, such as an air-breathing turboramjet for the hypersonic cruise mission and an air-breathing turboramjet/rocket for exo-atmospheric missions (fig. 5). These aircraft will take off and land with conventional turbine engines, will accelerate to Mach 6 to 12 speeds with a scramjet (supersonic combustion ramjet), and will accelerate to orbital velocities with a rocket engine.

Types of Engine Cycles

Each of these flight regimes requires different types of engines for optimum performance in their flight envelope (fig. 6). All air-breathing aircraft engines get their thrust be relying on compression of incoming air, mixing and burning of fuel, and directed expansion of the hot exhaust gases out a nozzle. The engine efficiency depends upon the engine cycle, the fuel used, and the altitude/speed flight envelope in which the aircraft will operate. The aircraft speed influences the combustion behavior, while the aircraft altitude influences the air density and the amount of fuel that can be burned.

The specific impulse (engine thrust/fuel consumed) at optimum altitude of various types of engine cycles is shown in figure 7. Kerosene-based JP-type fuels are used efficiently at lower Mach numbers. As a trade-off between specific impulse and storage volume, liquified methane is used as the fuel in the Mach 4 to 5 range, however liquid hydrogen provides much greater impulse and cycle efficiency at higher speeds. As shown on figure 7, a hydrogen-fueled ramjet, operating in the Mach 4 region with a variable geometry inlet and nozzle, provides specific impulse equivalent to that of a subsonic turbojet.

A JP-fuel burning turbojet is most efficient at speeds up to Mach 3.5. In a turbojet engine, thrust is provided through air compression and expansion by rotating turbomachinery (fig. 8(a)). Air is mechanically compressed in the compressor stages, fuel is mixed and burned in the combustor, and passed through turbine stages where work is extracted to rotate the compressor stages. The remaining air is sent out the nozzle and expanded for thrust. A turbofan engine operates in a similar manner, however a fan stage is added to move part of the air through a bypass duct to provide thrust from a large volume of slower moving air. High bypass ratio turbofan engines are used to maximize fuel economy at subsonic speeds, but the efficiency of a turbofan drops off at higher aircraft speeds. Low bypass ratio turbofans are used for maximum cycle efficiency at speeds up to about Mach 2, above which turbojet engines are used. Turbojet engines for supersonic cruise aircraft have a specially designed inlet and usually provide additional thrust from afterburners, where fuel is added to the airstream in the nozzle or bypass ducts and burned to provide additional expansion (fig. 8(b)).

The ramjet provides the most efficient engine cycle operating in the Mach 3.5 to 5 range. The ramjet has no rotating turbomachinery, but the air is compressed by the ram of the air into the inlet during supersonic flight. The air is slowed to subsonic velocity by passing around a specially designed centerbody in the inlet, fuel is mixed and burned, and passed out the nozzle (fig. 8(c)). In the Mach 5 to 12 range, the scramjet (supersonic combustion ramjet) provides the most efficient engine cycle. The scramjet operates in a similar manner to the subsonic ramjet, however, the inlet is less constrictive and allows the air to move supersonically through the engine.

Rocket engines are probably the most efficient propulsion system for vehicles operating above Mach 12 and for transatmospheric vehicles. In a rocket engine, the oxidizer and fuel are both carried within the vehicle, and are mixed, burned and passed out of a nozzle. While the specific impulse of a rocket engine is low compared to the other cycles, it uses a very light-weight engine and is the only system capable of carrying its own oxygen-source and of operating in exo-atmospheric flight.

While each of these engine cycles have an optimum operating speed and altitude, none of them are efficient over the full range of speeds from subsonic to high-supersonic or hypersonic. Multiple-mode engines are being investigated to operate over wide speed ranges. Basically, a multiple-mode engine combines several engine-types in one propulsion system, usually combining turbojet and ramjet engines. Most of the configurations under study, such as the airbreathing turboramjet, have two engines in the the same nacelle. Airflow is diverted to the turbojet at lower Mach numbers and to the ramjet at higher speeds. A similar concept is used for the airbreathing turboramjet/rocket, where the turbojet, ramjet and rocket cycles are all contained within the same nacelle. While these multiple-mode engine suffer some weight and performance penalties, they still provide more efficient operation over a broad Mach number range than would be available from any single engine cycle.

Improved Materials for Advanced Engines

Each of these engine cycles has their own individual requirements of temperature, stress, and acceptable weight and cost. Until recently, the main materials emphasis at NASA Lewis has been on developing improved materials for high-bypass turbofan engines for subsonic transport aircraft. This development has been focused on the front end of the engine (fan and compressor stages) and the hot section of the engine (combustor and turbine stages). In the colder sections of the engine, improved materials are required to reduce acquisition and maintenance costs and to reduce component weight of static components, such as nacelles, ducts, and vanes. For rotating components, such as fan and compressor blades, improved materials are required not only to reduce weight and cost, but also stronger, stiffer materials are required to increase engine efficiency by allowing higher compression ratios per stage. In the hot section of the engine, improved materials, capable of higher temperature operation and increased life, are required to improve performance, to reduce fuel consumption, and to reduce maintenance costs for components, such as combustor liners, turbine blades, and turbine vanes.

With the new emphasis on supersonic and hypersonic aircraft propulsion systems, the materials challenges become even more demanding. As the speed of the aircraft increases, the temperature of the airstream increases dramatically. Figure 9 shows a sketch of the cross section of a subsonic, high-bypass turbofan engine and a plot of the temperatures of the gas stream at various locations along the flowpath. For subsonic operation, a material capable of long-time operation at 177 °C (350 °F), such as an epoxy or aluminum matrix composite, could be usable throughout most of the flowpath up to the high-pressure compressor. With supersonic flight, the compression ram of the air entering the inlet raises the gas stream temperature within the flowpath. Operation of a turbojet engine (without a fan stage) at Mach 2.7 raises the temperature within the inlet to over 227 °C (500 °F), with subsequent increased temperatures at each point along the flowpath. Thus, for supersonic flight, higher-temperature resins or metals must be used to withstand the more severe operating conditions. In the high-supersonic range, the inlet temperature reaches 1010 °C (1850 °F) at Mach 5, at which point the inlet (and front-end engine components) have reached the normal operating temperatures of subsonic engine turbine blades. At hypersonic speeds, the temperatures continue to climb rapidly with Mach number and airstream-contacting surfaces will probably have to be regeneratively cooled with cryogenic fuel.

In view of the severe temperature, weight, reliability and cost demands of the wide range of new propulsion systems under study, advanced materials will play a key role in allowing these aircraft to reach their goals. Composite materials will play an increasingly more prominent role in the development of new materials to gain the required high-temperature strength, light weight, and thermal properties to meet these requirements. Polymer matrix composites will gain increasing importance in engines for subsonic and supersonic aircraft, while metal matrix composites will play a key role in subsonic, supersonic, and hypersonic aircraft engines, and ceramic matrix composites will become an increasingly important factor in all three types of engines.

DEVELOPMENT OF POLYMER MATRIX COMPOSITES

In the early 1940's, the urgent need for radar-transparent structural materials to protect radar systems on military aircraft stimulated considerable research and development activity in the field of fiber reinforced plastics. This need was met with the development of fiberglass/polyester composite materials. After the end of WWII, applications of reinforced plastics shifted to industrial and consumer products. According to statistics released by the Reinforced Plastics/Composites Institute of the Society of the Plastics Industries, in 1984, the total production of reinforced plastics in the U.S. amounted to nearly 2.0 billion lb. Fiberglass/polyester materials accounted for more than 85 percent of the market. Less than 1.5 percent of the total market was in the aircraft/aerospace area.

Until recently, the utilization of reinforced plastics for aircraft components has been limited to secondary structural airframe components fabricated from fiberglass/polyester or fiberglass/epoxy materials. Following the development of advanced graphite and aramid fibers, current emphasis on the application of advanced fiber/epoxy composites has been focused on primary airframe structures.

Because the aeropropulsion system presents a much more hostile environment to materials than found in airframe structural applications, the introduction of fiber reinforced plastics into aircraft engines has proceeded at a much slower pace. The earliest applications of composite materials in commercial aircraft engines date back to the early 1960's. Fiberglass/epoxy materials were used to fabricate noncritical components, such as fan duct fairings, shroud panels, seals and spacers. The limited thermo-oxidative stability and relatively low glass transition temperature restricted the use of fiber/epoxy composites to below 177 °C (350 °F). Although the so-called high-temperature-resistant polymers provided an opportunity to achieve nearly a twofold increase in use-temperature compared to fiber reinforced epoxies, the intractable nature of the early-technology high-temperature resins made it impossible to fabricate defect-free structural components. The presence of these defects or voids seriously degraded composite mechanical properties and thermo-oxidative stability.

Development of High-Temperature Polyimide Resins

In response to the need for high-temperature polymers with improved processability, investigators at NASA Lewis developed the novel class of addition-type polyimides known as PMR (for the in-situ Polymerization of Monomer Reactants) polyimides (refs. 4 to 6). Figure 10 outlines some of the salient features of the PMR approach for the fabrication of composites. The PMR concept consists of impregnating the reinforcing fibers with a monomer dissolved in a low boiling point alkyl alcohol. The monomer reactant mixture contains the dimethyl ester of 3,3'4,4'-benzophenonetetracarboxylic acid (BTDE), 4,4'-methylenedianiline (MDA), and the monomethyl ester of 5-norbornene-2,3-dicarboxylic acid (NE). The number of moles of each reactant is governed by the following ratio:

$$n:(n + 1):2$$

where n, $(n + 1)$ and 2 are the number of moles of the dialkyl ester of the aromatic tetracarboxylic acid, the aromatic diamine, and NE, respectively. The PMR matrix prepared from BTDE, MDA and NE with $n = 2.087$ is known as PMR-15. Prepreg materials based on PMR-15 are commercially available in this country from the major prepreggers.

High-pressure (compression) and low-pressure (autoclave) molding cycles have been developed for fabrication of fiber reinforced PMR composites. Although the thermally-induced, addition-cure reaction of the norbornenyl group occurs at temperatures in the range of 275 to 350 °C (527 to 662 °F), nearly all of the processes developed uses a maximum cure temperature of 316 °C (600 °F). Cure times of 1 to 2 hr, followed by a free-standing postcure in air at 316 °C for 4 to 15 hr are also normally employed. Compression molding cycles generally employ high rates of heating (5 to 10 °C/min) and pressures in the range of 34.5 to 60 MPa (500 to 870 psi). Vacuum bag autoclave processes at low heating rates (2 to 4 °C/min) and pressures of 13.8 MPa (200 psi) or less have been successfully used to fabricate void-free composites.

Structural Applications of PMR-15 Polyimide Composites

Fiber reinforced PMR-15 polyimide matrix composites are finding increased acceptance as engineering materials for the design and fabrication of aerospace structural components, particularly for aeropropulsion structural components. A variety of structural components are being fabricated, ranging from small compression-molded bearings to large autoclave-molded aircraft engine cowls and ducts. Processing technology and baseline material data are also being developed for the application of PMR-15 composites in weapons systems. Fabricators involved in the manufacture of small compression-molded bearings, made from particulate or chopped fiber PMR molding compounds, have found it convenient to become captive producers of PMR-15 resin. In contrast, those involved in the fabrication of larger components, made from tape or fabric materials, have relied on traditional sources for PMR-15 prepreg.

Some representative applications of PMR-15 composities are listed in table 1. Two of these applications, the QCSEE inner cowl and the F404 outer duct, will be discussed. An inner cowl was designed and fabricated for an experimental engine, called QCSEE (Quiet Clean Short-Haul Experimental Engine), developed by General Electric under contract to NASA Lewis (ref. 7). This cowl defines the inner boundary of the fan air flowpath from the fan frame to the engine core nozzle. The cowl was autoclave-fabricated by GE using PMR-15 and Union Carbide's T300 graphite fabric. The cowl has a maximum diameter of about 91 cm (35.8 in) and is primarily of honeycomb sandwich construction. Hexcel's HRH327 fiberglass/polyimide honeycomb was used as the core material. The honeycomb core was bonded to the inner surface of the premolded outer skin with a polyimide adhesive. The cowl was installed on the QCSEE engine and did not show any degradation after more than 300 hr of ground engine testing. The maximum temperature experienced by the cowl was 260 °C (500 °F). The successful autoclave fabrication and ground engine testing of the QCSEE inner cowl established the feasibility of using PMR-15 composite materials for large engine static structures.

Under a jointly-sponsored Navy/NASA Lewis program, GE is developing a T300 graphite fabric/PMR-15 composite outer duct to replace the titanium duct presently used on the F404 engine for the Navy's F-18 strike fighter. The titanium duct is a sophisticated part made by forming and machining titanium plates, followed by chemical milling to reduce weight. The F404 composite duct differs from the QCSEE inner cowl in several important aspects. The F404 duct is a monolithic composite structure, it needs to withstand fairly high loads, and perhaps most importantly, the F404 duct is a production component and not a "one-of-a-kind" demonstration item. A full-scale composite duct, 75 cm (29.5 in) diameter by 105 cm (41.3 in) length by 0.22 cm (0.09 in) wall thickness, has been autoclave-fabricated (fig. 11). The overall duct fabrication process consists of several operations. The basic sequence consists of: (1) autoclave fabrication of the composite shell; (2) ultrasonic inspection; (3) drilling of the build-ups; and (4) attachment of the split line stiffeners. The duct has been installed on an F404 engine and has successfully undergone more than 1000 hr of engine testing (fig. 12). The fully flight-qualified T300/PMR-15 composite outer duct entered into production during the first half of 1985.

Significant cost (35 percent) and weight (15 percent) savings have resulted from the use of PMR-15 to fabricate the F404 outer duct. The graphite fiber/PMR-15 composite has successfully withstood the combined temperature and pressure environment encountered by the outer duct. The steady state temperature for this application is 250 °C (485 °F), with transients up to 288 °C (550 °F). These design requirements can be met by PMR-15, which has a continuous use-temperature in the 288 to 316 °C (550 to 600 °F) range.

In order to meet the thrust-to-weight goals that have been established for advanced fighters, a need has been identified for polymer matrix materials capable of continuous operation in the 371 to 427 °C (700 to 800 °F) temperature range. The current emphasis of the in-house research at NASA Lewis is directed toward the synthesis of matrix resins for use at 371 °C (700 °F). Preliminary results from our studies have been very encouraging.

DEVELOPMENT OF METAL MATRIX COMPOSITES

Metal matrix composites (MMC) are also under development and offer the advantages of improved high-temperature properties, increased toughness and ductility, and matrix-aided properties, such as electrical/thermal conductivity, oxidation resistance and impact resistance. Metal matrix composite development could be classed under three material application categories: light-metal matrices, high-temperature metal matrices, and specialty-metal matrices.

Light-Metal Matrix Composites

Considering the overall MMC field, the majority of development has been focused in the area of light-metal matrices, with most of the emphasis being focused on aluminum matrix composites. Discontinuous SiC particulates or whiskers are being used to reinforce Al alloys for low-cost, isotropically loaded structures. Continuous elastic monofilaments, such as boron and SiC, and multifiber yarns, such as graphite and aluminum oxide, are being used to reinforce anisotropic, high-performance aluminum matrix composites. These composites combine the light weight and ductility of the aluminum matrix with the light weight and high stiffness and strength of the reinforcement. While most effort has been focused on Al matrix composites, magnesium and titanium matrices are also being developed. Magnesium alloys are being reinforced with graphite fibers to develop composites, primarily for space applications where very light weight, high specific stiffness and near-zero coefficient of thermal expansion are required. Titanium alloys are being reinforced with SiC monofilaments to increase stiffness and temperature capability.

At NASA Lewis, the primary developmental efforts in light-metal MMCs have been concentrated on three main areas: B/Al for aircraft engine fan blades; discontinuous SiC/Al for aerospace structures; and Gr/Mg for space antennas.

Fan blades represent about 10 percent of the engine weight and about 1 percent of total gross weight of a typical high-bypass turbofan-powered subsonic transport aircraft. The use of light-weight, high-stiffness B/Al composites would allow fan blades to be redesigned to increase efficiency by reducing airflow constriction through removal of midspan shrouds (fig. 13). The high stiffness of B/Al would also allow the blades to be swept to increase efficiency, as well as reducing weight of the fan stage and associated structures and shafting. The major barrier restricting the use of B/Al fan blades has been the lack of adequate impact resistance and foreign object damage tolerance for B/Al composites. Modification of materials and processing parameters has demonstrated a fourfold increase in the impact resistance of B/Al composites for fan blade applications (ref. 8).

NASA Lewis has also been investigating the behavior of Al matrix composites containing discontinuous SiC whisker, nodule and particulate reinforcement. The results obtained indicate that the elastic modulus of these composites could be doubled and that the ultimate tensile strength could be significantly improved over unreinforced aluminum alloys (ref. 9). These potentially low-cost composites can use conventional aluminum metal forming techniques and are now available for commercial applications and show good potential for a variety of aerospace structural applications.

Additional work at NASA Lewis has been directed towards the application of Gr/Mg composites to antenna structures for advanced space communication satellites. The high specific stiffness, high thermal conductivity and near-zero coefficient of thermal expansion of these composites allow the antenna parabola dish and supporting masts to maintain critical dimensional tolerances required for antenna structures operating in the 30-20 GHz and higher transmission bands.

High-Temperature Metal Matrix Composites

The majority of effort in the area of high-temperature MMCs has focused on the development of fiber reinforced superalloys. These composite use high-strength, high-temperature fibers to reinforce superalloy matrices. Proper materials and fabrication process selection allows the fibers to retain their high-temperature properties, while providing a ductile, oxidation-resistant matrix to complement the properties of the fibers. Fiber reinforced superalloys have demonstrated a significant increase in allowable operating temperature over competitive superalloys and single crystals under engine conditions. Most of this effort has been with tungsten fiber reinforced superalloy matrix composites, but other high-temperature composites, such as tungsten fiber reinforced niobium and SiC reinforced superalloys, are also being studied.

The major emphasis at NASA Lewis has been focused on the development of high-temperature MMCs to increase creep properties and allowable operating temperatures for turbine blade and vane applications in aircraft engines (fig. 14). The basic technical barrier to be overcome with fiber reinforced superalloys is fiber/matrix compatibility to prevent degradation of the properties of the reinforcing fiber (ref. 10). In the worst case, the fiber and matrix react during high-temperature fabrication or service, forming brittle intermetallic compounds or dissolving the fiber. It was also found that conventional nickel-base superalloys can cause a diffusion-triggered recrystallization within the tungsten wire, causing the fiber to lose its strength and ductility with time. To reduce these degradation reactions, modified Fe-Cr-Al-Y superalloys are being used as a matrix material, because iron-base alloys have much better compatibility with the tungsten fiber and provide an oxidation-resistant, high thermal conductivity, ductile matrix to complement the properties of the tungsten fibers.

Specialty-Metal Matrix Composites

Specialty-matrix composites are those which have a specific combination of fiber and matrix required to meet a given application. Copper matrix composites, reinforced with tungsten fibers or graphite yarns, are an example of this type of composite. The W/Cu composites take advantage of the high-temperature strength and stiffness of tungsten fibers and the superior thermal and electrical conductivity of both W and Cu, to make a composite with a high-temperature strength superior to any high-conductivity copper alloy. The Gr/Cu composites also have an outstanding thermal conductivity, and in addition they give a lower density, higher modulus composite material with a a wide range of available thermal expansion coefficients.

NASA Lewis is currently studying W/Cu composites for application to cryogenically cooled thrust chamber liners for rocket engines. Current liners have a limited life because the severe thermal stresses across the chamber liner walls cause the currently-used copper alloys to yield and deform. This leads to thinning of the liner walls through creep-ratcheting and eventually the walls crack and fail with repeated thermal cycles. The improved high-temperature strength and high thermal conductivity of the W/Cu composites would increase the strength of the walls of the thrust chamber liner, while retaining efficient heat transfer from the coolant, and offers the potential of longer life, more reliable rocket engine operation (fig. 15). In addition, because of their high stiffness and thermal conductivity at elevated temperatures, Gr/Cu composites are being considered for heat-rejecting radiators for space power systems (ref. 11).

DEVELOPMENT OF CERAMIC MATRIX COMPOSITES

Although there are many lightweight ceramic materials which can be utilized for aerospace applications, the silicon-based ceramics, such as silicon carbide (SiC) and silicon nitride (Si_3N_4) offer the best potential for high-temperature structural components. This is based upon their high stiffness, good high-temperature strength, thermal stability, and resistance to thermal shock and oxidative environments. Currently the structural potential of these materials, in monolithic form, is being evaluated in engine demonstration programs such as the Advanced Gas Turbine (AGT) project sponsored by the Dept. of Energy and under the technical management of NASA Lewis. The objective of this project is to develop a competitive fuel-efficient automobile engine by use of a gas turbine engine with an all-ceramic hot section (ref. 12). A monolithic SiC turbine rotor fabricated for AGT is shown in figure 16.

The fact that monolithic ceramics have yet to be applied to structural components in nonterrestrial engines is due primarily to their poor structural reliability and/or reproducibility. Because of their low fracture toughness, these materials display a high sensitivity to small cracks or flaws within their microstructure. Under applied external loads, these cracks grow unstably in the ceramic, leading to brittle, catastrophic material failure. Since the incidence and size of these flaws are difficult to control during conventional ceramic processing and also during operation in aggressive environments, monolithic ceramics typically display a wide variation in strength properties. This lack of structural reliability is a major concern to designers and is currently limiting the application of ceramics for advanced aircraft engine applications.

One approach to improve the reliability of ceramics is by the use of ceramic matrix composites (CMC). As with other composite systems, the reinforcing ceramic second phase can have a variety of shapes ranging from nearly spherical particulates, through whiskers and chopped fibers, to effectively continuous fibers. With the proper mechanical, physical and chemical properties, the reinforcing phase can introduce a variety of internal deformation and fracture mechanisms which will decrease matrix flaw sensitivity and increase fracture toughness of the ceramic (ref. 13).

Low aspect (length/diameter) ratio particulate and whisker reinforcements lend themselves to conventional ceramics processing methods which use powder blending methods to form green compacts prior to firing. Thus, besides offering three-dimensional toughening, these reinforcements also offer economic advantages, and as such, are well suited for large volume ceramic matrix composite production, such as for automotive engine applications. For this reason, the Dept. of Energy is also actively engaged in CMC research and development studies aimed at low aspect ratio reinforcement for automotive and other terrestrial applications.

In terms of performance, however, high aspect ratio second phases, such as continuous fibers, have structural advantages over particulates and whiskers. For example, if the fibers possess a high modulus, a small diameter (<10 μm), and are aligned with high volume fraction in the principal load direction, both the stress and strain levels required for matrix flaw propagation can be increased significantly (ref. 14). In addition, if the fibers are considerably stronger than the matrix, and are properly bonded to the matrix, then unstable matrix cracks can pass around the fiber, and not through them, so that after a matrix fracture, the reinforcing fibers remain intact and prevent catastrophic failure of the composite. Further loading would allow continued matrix cracking, but without composite failure until the fiber bundle strength is reached at a much greater fracture strain that that of the monolithic ceramic matrix. This type of improved microscopic and macroscopic toughening behavior has been observed in CMC consisting of glass matrices reinforced with continuous SiC and graphite fibers (ref. 15), and should also be effective for other fiber-reinforced CMC systems.

In light of the opportunity for obtaining optimum structural reliability with high aspect ratio second phases, current CMC efforts at NASA Lewis are primarily aimed at developing structurally reliable composites consisting of silicon-based ceramic matrices reinforced by high modulus continuous fibers, such as SiC. On the theoretical side, these developmental efforts are being supported by microstructural design studies using analytical and computer approaches. Data input for verifying and optimizing the design theory are obtained from mechanical and physical testing on both practical and model CMC.

On the practical side, CMC research is addressing two primary obstacles currently limiting the attainment of quality high-temperature ceramic composites reinforced with long fibers. These include the development of: (1) high strength, high modulus, small diameter, continuous length fibers whose mechanical properties are not drastically degraded by composite processing or use conditions; and (2) net shape composite processing methods which result in uniform microstructures of nondegraded, aligned fibers surrounded by low porosity matrices. Fiber and matrix properties are dictated on the basis of making optimium use of available toughening mechanisms (ref. 14).

Fiber development at NASA Lewis is being initially approached by evaluation of the mechanical, physical, and chemical properties of commercially available high-performance fibers. Major emphasis is focused on SiC fibers produced by chemical vapor deposition (CVD) because in their as-produced state, CVD fibers offer significantly greater tensile strength and modulus than continuous SiC fibers produced by other methods, such as polymer pyrolysis (ref. 14). Current research is examining the thermal stability of CVD SiC fibers in terms of high-temperature resistance to stress and gaseous environments and compatability with various matrix compositions. Where environmentally-induced reaction effects have been observed, fiber coating approaches are being examined to eliminate or delay degradation in fiber properties. Besides acting as diffusion barriers, fiber coatings can also provide a means of tailoring the strength of the fiber/matrix interfacial bond, a parameter of prime importance for avoiding CMC catastrophic failure.

A variety of CMC processing approaches are also being investigated that will allow the infiltration of fiber arrays by ceramic precursors which can then be densified at temperatures low enough to prevent fiber degradation. These include such approaches as reaction bonding, polymer pyrolysis, chemical vapor deposition, sol gel processing, and other new innovative methods. For those approaches, such as polymer pyrolysis, in which matrix shrinkage effects can occur, methods for introducing ceramic particulate fillers, as well as high char yield polymers, are also being examined (ref. 16).

A CMC approach that was recently developed at NASA Lewis and shows promise for yielding strong and tough high-temperature composites is the formation of reaction-bonded Si_3N_4 (RBSN) matrices reinforced by continuous CVD SiC fibers (ref. 17). Commercially available large diameter (140 μm) SiC monofilament fibers are uniformly distributed within a Si_3N_4 matrix with fiber content up to 40 vol %. Stress-strain curves for this material show the development of multiple matrix cracks before the composite ultimately fails due to fiber bundle fracture. Because of the large diameter of the CVD fibers, first matrix cracking appears at strain levels no greater than those for fracture of unreinforced monolithic RBSN. However, because of the high modulus of the fibers (390 GPa-56 Msi) relative to that of the matrix (approximately 90 GPa-13 Msi), the stress level for matrix cracking is greater than that for unreinforced RBSN and increases with fiber content. When compared to the current state-of-the-art monolithic RBSN, the high fiber content composites not only display an equivalent strength for matrix cracking, but also demonstrate a significantly greater fiber-controlled ultimate strength (fig. 17).

In summary, in terms of engine applications, the development of CMC is at the present time an emerging technology, still in its infancy. As indicated in the previous discussion, theory is preceeding at a faster pace than practice, but nevertheless is giving direction to the development of structurally reliable high-temperature CMC. A good example is the SiC/RBSN composite where, although the structural properties are good now, further improvement should be expected by utilizing lower porosity matrices, smaller diameter fibers, and higher fiber content. Thus the successful output of research and development from CMC studies at NASA Lewis and other laboratories should increase rapidly within the next few years, making available a variety of high-temperature CMC with sufficient structural reliability to be serious candidates for application to advanced aircraft engine components.

CONCLUSIONS

Advanced aircraft propulsions systems, for subsonic, supersonic and hypersonic flight operations, all require advanced materials to meet their performance goals. Advanced polymer, metal, and ceramic matrix composites show very good potential for applications to aircraft engines and aircraft/spacecraft structures over a broad temperature range.

1. The high stiffness/weight and strength/weight ratio of composite materials offer significant advantages in reducing weight and increasing efficiency of aircraft engines and aerospace structures.

2. Graphite/polyimide composites are currently being used for outer ducts on production aircraft. Efforts continue to be underway to increase the processability and temperature capability of polymers to produce better composites.

3. Metal matrix composites offer potential for improved aircraft engine and spacecraft structures over a broad temperature range. Development effort has been focused on B/Al for fan blades, W/superalloy for turbine blades and other composites for special requirements.

4. Ceramic matrix composites are a new emerging technology to improve the toughness and reliability of ceramics for very high-temperature applications, such as those found in engine hot section components.

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Table 1. - Applications of PMR-15 Composites

Component	Agency	Contractor
QCSEE inner cowl	NASA Lewis	GE
F404 outer duct	Navy/NASA Lewis	GF
F110 inner duct	Air Force	GE
T700 swirl frame	Army	GE
JT8D reverser stang fairing	NASA Lewis	McDonnell-Douglas
Shuttle orbitor aft body flap	NASA Lewis	Boeing
Ion thruster beam shield	NASA Lewis	Hughes

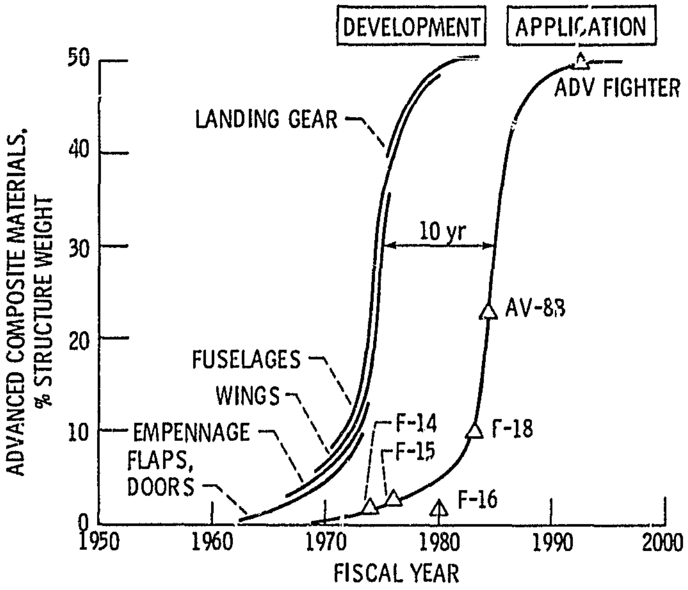


Figure 1. - Development of polymer matrix composites for airframe applications. (Ref. 2).

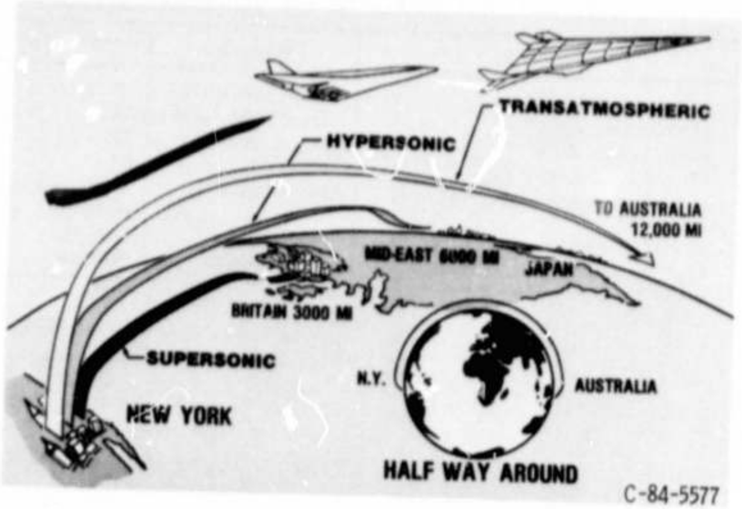


Figure 2. - Future two-hour high-speed air transportation flights.

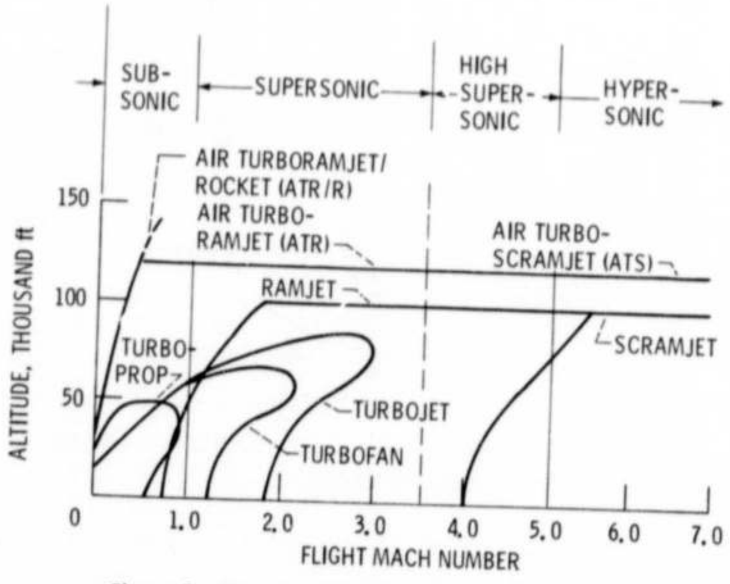


Figure 3. - Flight envelopes of various propulsion systems.

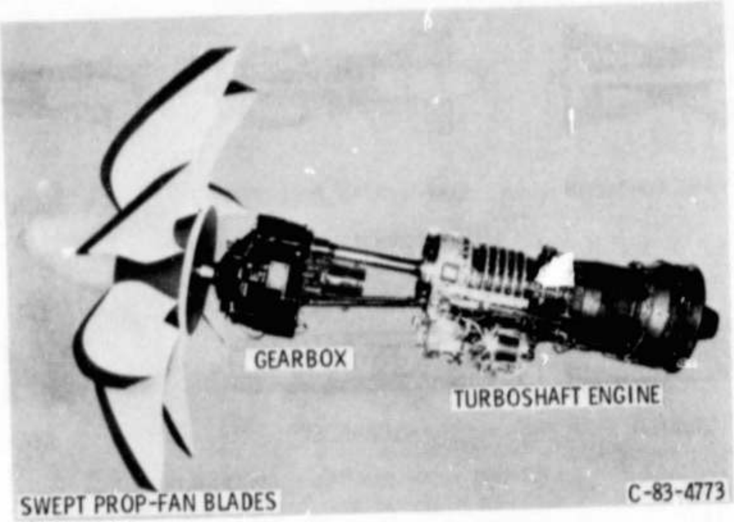


Figure 4. - Prop-fan propulsion system.

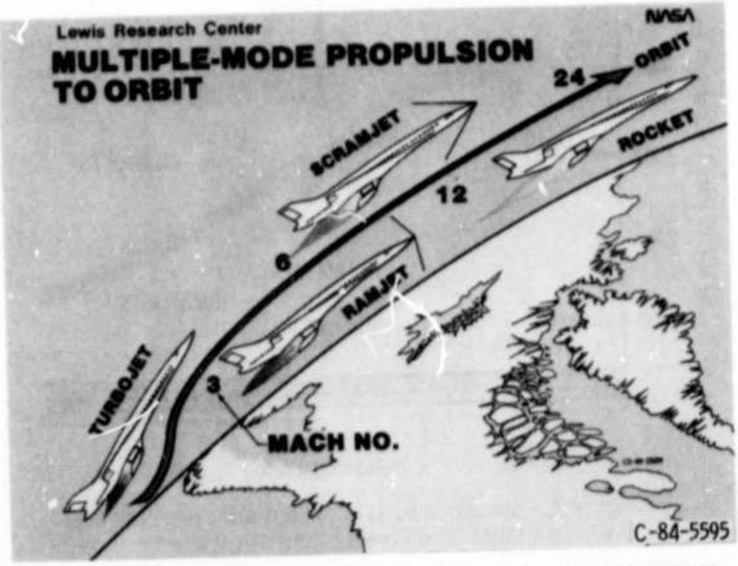
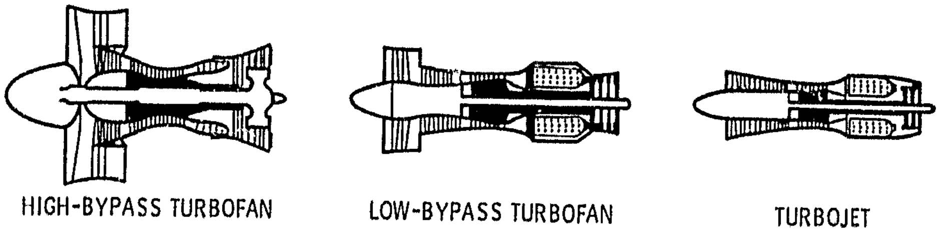
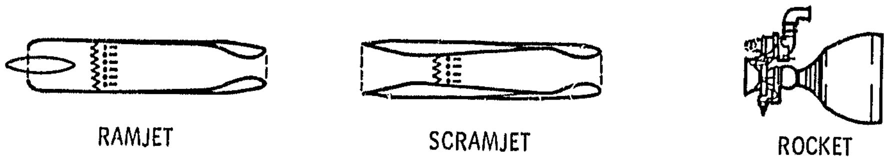


Figure 5. - Projected multiple-mode propulsion system for orbital flight.



(a) Subsonic/Supersonic engines



(b) High-supersonic/Hypersonic engines.

Figure 6. - Types of aircraft engines used for different flight envelopes.

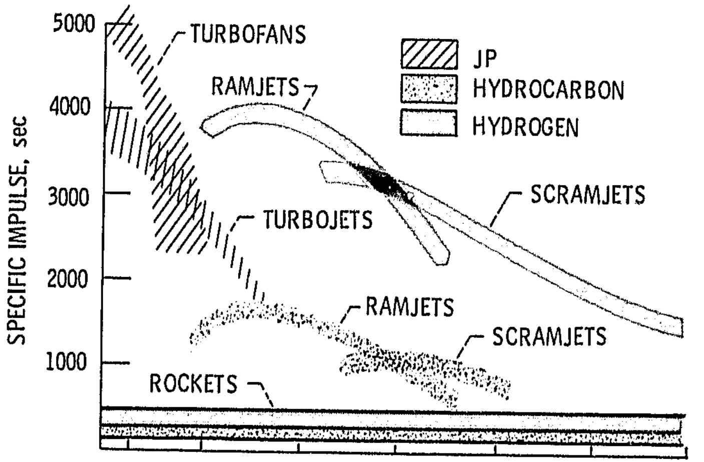
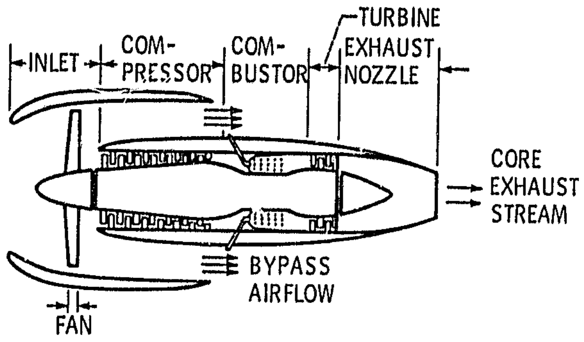
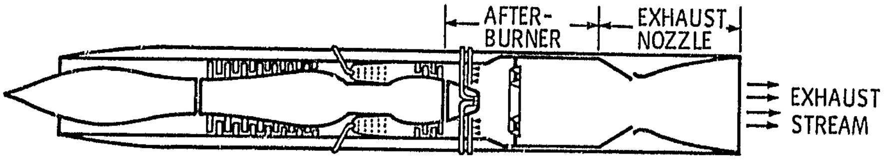


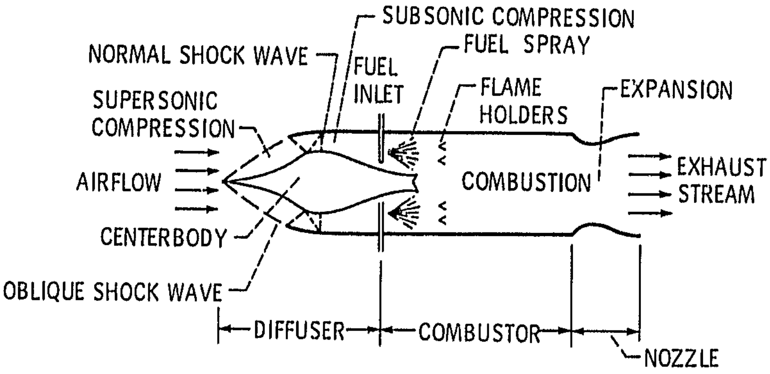
Figure 7. - Specific impulse at various Mach numbers at optimum altitude for different propulsion systems.



(a) Subsonic turbofan.



(b) Supersonic turbojet.



(c) High-supersonic Ramjet.

Figure 8. - Schematic diagrams of various propulsion systems.

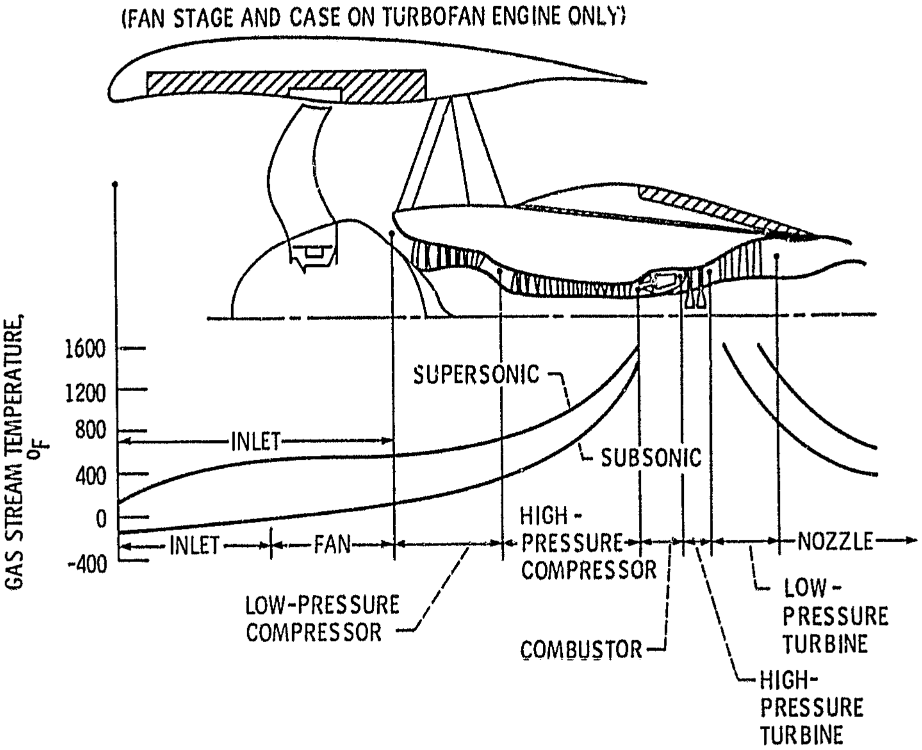


Figure 9. - Comparison of typical airstream gas temperatures along core flowpath of advanced subsonic turbofan and supersonic turbojet engines.

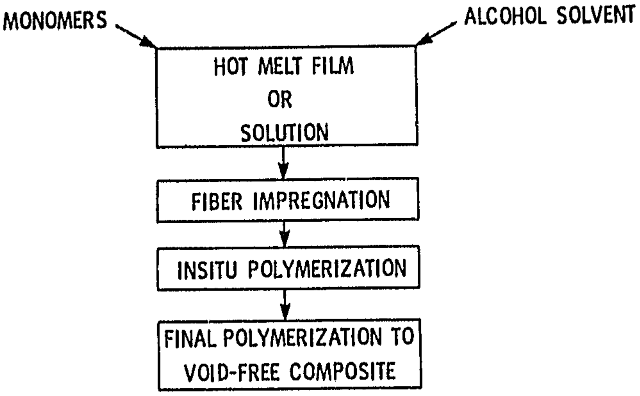


Figure 10. - PMR approach for composite fabrication.

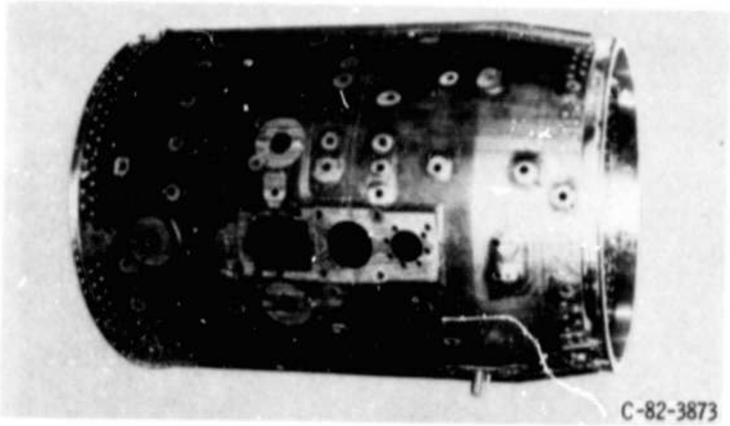


Figure 11. - Graphite fiber/PMR-15 composite outer duct for F404 engine (29.5 in diameter x 41.3 in long x 0.09 in wall thickness).

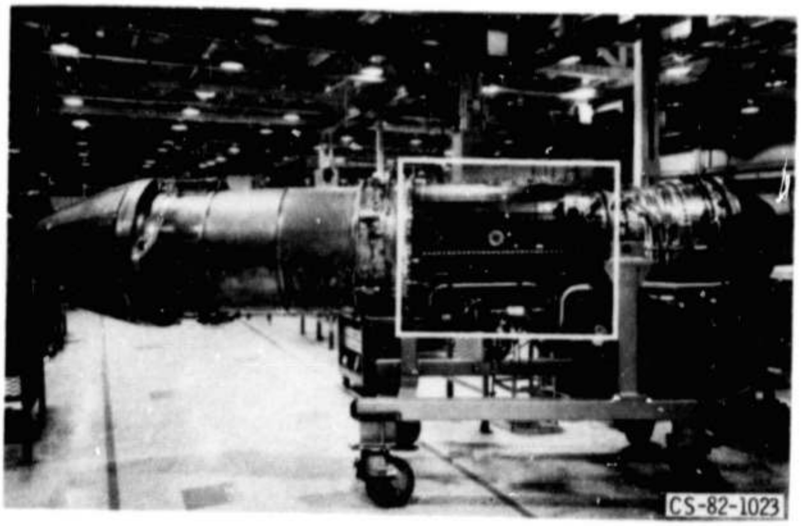


Figure 12. - Graphite fiber/PMR-15 composite outer duct installed on an F404 engine (composite duct located directly above carriage in square-outline region).

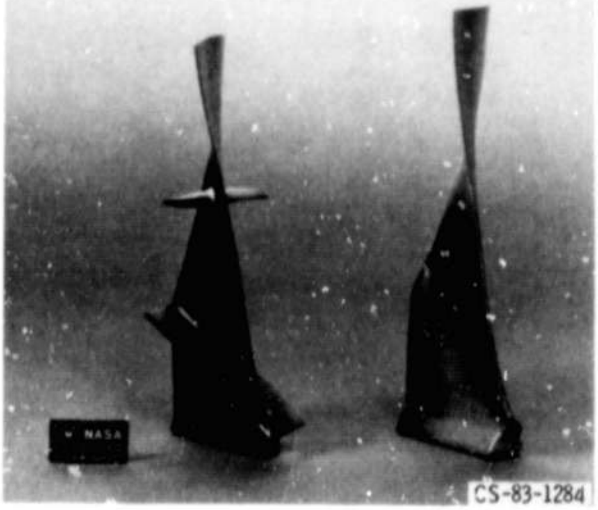


Figure 13. - Comparison of production titanium F404 supersonic fan blade with experimental boron/aluminum blade.

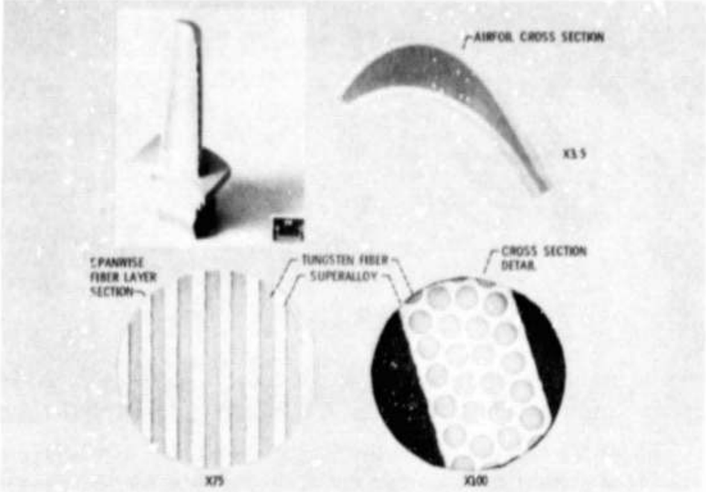


Figure 14. - Tungsten fiber reinforced superalloy composite turbine blade.

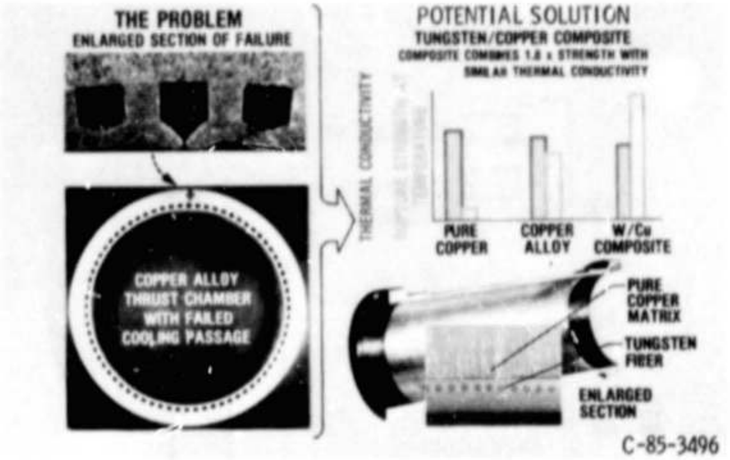


Figure 15. - Tungsten fiber reinforced copper rocket combustion chamber.

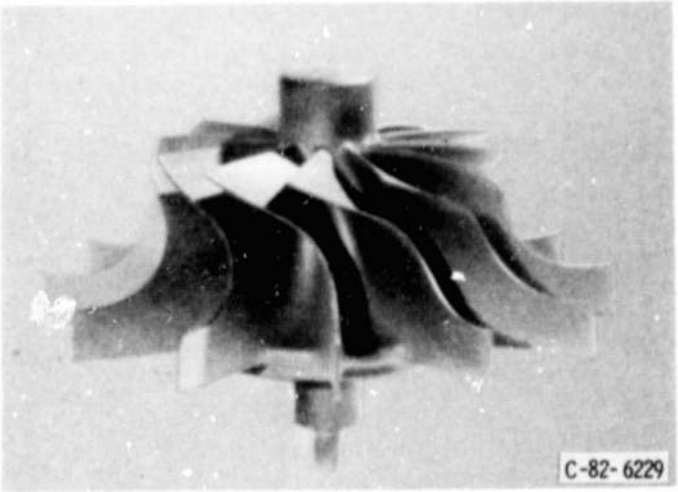


Figure 16. - Monolithic SiC ceramic rotor for AGT engines.

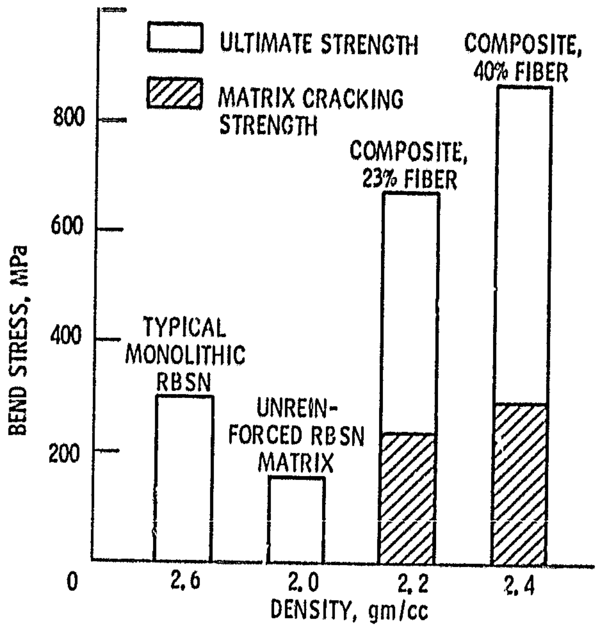


Figure 17. - Structural property improvement of reaction-bonded silicon nitride (RBSN) by silicon carbide fiber reinforcement. (Ref. 17).

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15. Supplementary Notes

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16. Abstract

Advanced aircraft engine research within NASA Lewis is being focused on propulsion systems for subsonic, supersonic, and hypersonic aircraft. Each of these flight regimes requires different types of engines, but all require advanced materials to meet their goals of performance, thrust-to-weight ratio, and fuel efficiency. The high strength/weight and stiffness/weight properties of resin, metal, and ceramic matrix composites will play an increasingly key role in meeting these performance requirements. At NASA Lewis, research is ongoing to apply graphite/polyimide composites to engine components and to develop polymer matrices with higher operating temperature capabilities. Metal matrix composites, using magnesium, aluminum, titanium, and superalloy matrices, are being developed for application to static and rotating engine components, as well as for space applications, over a broad temperature range. Ceramic matrix composites are also being examined to increase the toughness and reliability of ceramics for application to high-temperature engine structures and components.

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