CERAMICS FOR ADVANCED O_2/H_2 APPLICATION

H. W. Carpenter

Rockwell International/Rocketdyne Division
Canoga Park, California

Abstract

Ceramics are prime candidate materials for advanced rocket engines because they possess high-temperature capability, a tolerance for agressive environments, and low density. This program was conducted to assess the applicability of structural ceramics to advanced versions of the Space Shuttle Main Engine. Operating conditions of ceramic turbine components were defined and each component in the hot-gas path was assessed in regard to materials selection, manufacturing process and feasibility, and relative structural reliability. The conclusion was that ceramic components would be viable in advanced SSME turbopumps.

Introduction

Rocket engines for space missions beyond this decade must be capable of operating for longer periods of time, withstanding more duty cycles, and be more efficient than present engines. The most advanced liquid propellant rocket engine currently available is the Space Shuttle Main Engine (SSME). Materials for high-temperature components of the engine (e.g., turbine blades, stator vanes, and other elements in the hot-gas flowpath) are approaching the limits of their capabilities. Among the materials for use in advanced rocket engines, ceramics are prime candidates because of their high-temperature capability, low density, and tolerance for aggressive environments. This program was conducted to assess the capability of refractory structural ceramics to meet the severe requirements of advanced rocket engines

An objective of this program was to identify advanced SSME-type turbine components that would be promising candidates for application of advanced structural ceramics. The classes of ceramics of interest to this study program are silicon nitride, silicon carbide, and the new generation of ceramic composites such as transformation-toughened zirconia or alumina, and particulate- or whisker-reinforced ceramic matrices. The hardware of primary interest is in the hot section of an SSME-type turbine.

The program comprised two phases: the first phase defined the operating environment in which the ceramic turbine components will be exposed and the second phase identified those components that appeared to be promising candidates for manufacture from advanced structural ceramics.

Results and Discussion

Turbine Operating Environment

The effect of operating at turbine temperatures to 3000 R were explored with the aid of engine balance computer programs. Based on this information, the operational environment of the hot-gas path components under a turbine inlet temperature of 2400 R was defined in detail to provide pressures, flowrates, turbine speeds, nozzle velocities, temperatures, etc. Engine balance studies for staged-combustion cycle engines have demonstrated that modest increases in specific impulse (I_s) and in thrust can result from increased turbine inlet temperature based on oxygen/hydrogen propellant systems. If different fuels than hydrogen are employed (e.g., methane), the situation becomes more favorable and increases in turbine temperature can provide more attractive improvements in specific impulse and thrust. Although engines based on other working cycles were not assessed during this study, future consideration should be given to the performance benefits possible due to increased turbine inlet temperature with a gas-generator cycle rocket engine. The SSME staged-combustion engine utilizes a reaction turbine, while gas-generator engines have used impulse or velocity compounded turbines. The heat transfer within gas-generator engine turbine blading is considerably less severe than in a staged-combustion engine turbine due to decreased Reynolds numbers, and this should result in significant decreased thermal stresses. In addition, the lower turbine gas exhaust temperature would relieve the necessity of ceramic components downstream of the turbine (e.g., in the combustion chamber injector).

The use of ceramic materials in the turbine hot-gas path is motivated by the increased performance possible with increased turbine inlet temperatures. Performance benefits were considered for both oxygen/hydrogen and oxygen/methane propellants using a 500,000 pound thrust staged-combustion baseline engine design. Engine specific impulse gains for several different thrust chamber area ratios and for pump discharge pressures of 10,000 psia are shown in Fig. 1 and 2 (Ref. 1).

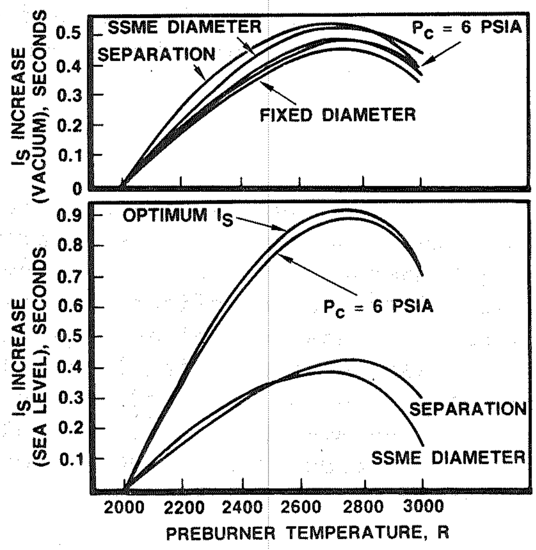

Fig. 1. Performance of a 500,000-Pound-Thrust Engine Using Oxygen/Hydrogen Propellants With Increasing Temperature

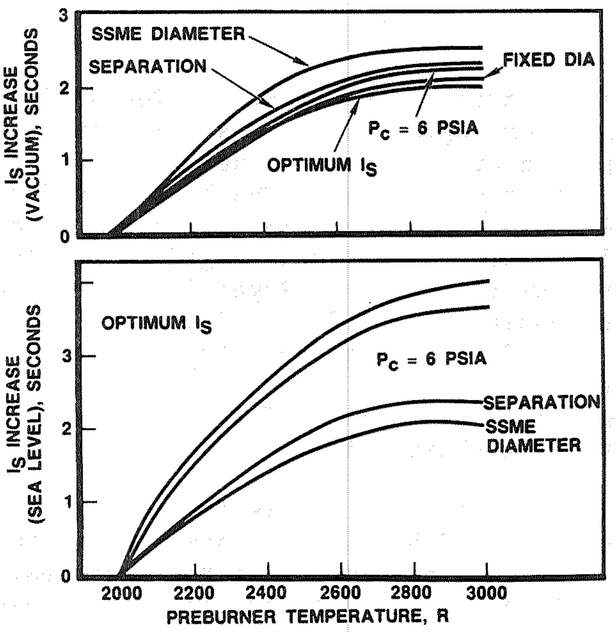

Fig. 2. Performance of a 500,000-Pound-Thrust Engine Using Oxygen/Methane Propellants With Increasing Temperature

Specific impulse increases are greatest for sea-level conditions compared to vacuum conditions, and are also significantly greater for oxygen/methane compared to oxygen/hydrogen.

Key Design Issues

Candidate ceramic components were selected for an advanced staged-combustion cycle engine to provide higher operating temperature or extended operating life, and the key design issues were defined. As part of this task, a structural analysis of an Si_3N_4 turbine vane (Fig. 3) was assessed for reliability under the operational environment of an advanced rocket engine turbine. The projected average four-point MOR strength for the Si_3N_4 body was assumed to be 90 ksi with a Weibull modulus of 15.

The maximum combined thermal and pressure stress in the hollow ceramic vane of Fig. 3 (37 ksi) occurs

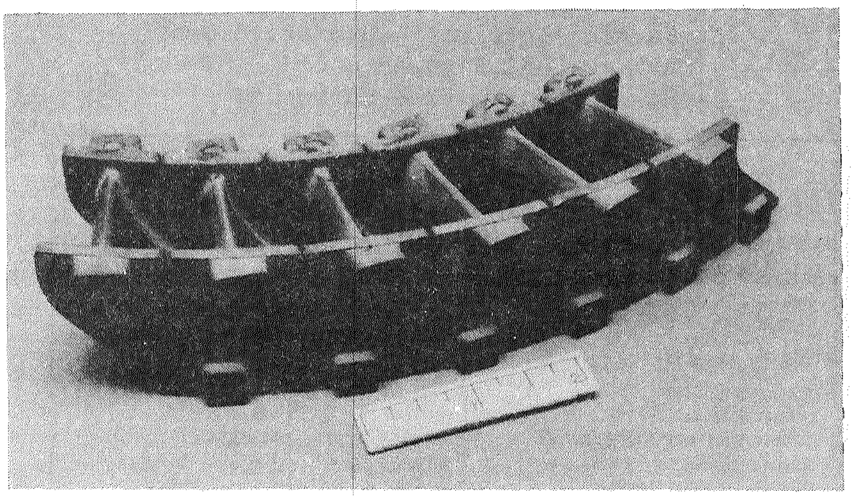

Fig. 3. Segmented Silicon Nitride Turbine Vanes

at the support rib inside the nozzle during the start-transient phase of engine hot firing. (The thermal ramp heating and cooling rates were based on those existing in the present SSME.) This translated to a reliability for any given nozzle of 0.999. Since this analysis was based on a fast fracture criterion, the reliability figure is valid for the 500 hot-firing cycles projected to be appropriate for an advanced engine. A reliability level of 0.999 indicates that the use of ceramic components in an advanced engine is feasible.

A fund of design analysis and test data are available as a result of the development of ceramic gas turbine engines for automotive applications. This information was used to compare the heat transfer conditions in a ceramic automotive gas turbine with those in an advanced rocket engine high-pressure fuel turbopump (HPFTP). This comparison is made in Table 1 (Ref. 2-7). Note that the conditions for a nozzle vane in the advanced high pressure fuel turbopump are considerably more severe than those for a nozzle vane in the automotive gas turbine environment. The film coefficient is up to 50 times higher, the pressure is 100 times higher, the thermal transients are 10 to 20

Table 1. Comparison of Thermal Environments for Ceramic Nozzles: Automotive Gas Turbine Engine vs Advanced SSME High-Pressure Fuel Turbopump

ITEM	AUTOMOTIVE AGT 101	ADVANCED SSME HPFTP (REF. 2)
FUEL	DIESEL (REF. 3)	HYDROGEN OR METHANE
OXIDIZER	AIR	LIQUID OXYGEN
FILM COEFFICIENT, BUU/HR–FT^2–R		
SPIKE AT LEADING EDGE	1000 (REF. 4)	18,000
ALONG AIRFOIL SURFACE (AVG)	200 (REF. 4)	10,000
PRESSURE, PSI (MAX)	60 (REF. 4)	6000
FOR A NOZZLE VANE		
START TRANSIENT, FT/SEC (MAX)	640 (REF. 5)	6000
COOLDOWN RATE, FT/SEC (MAX)	900 (REF. 5)	18,000*
CUTOFF TRANSIENT, FT/SEC (MAX)	900 (REF. 5)	1700
TEMPERATURE, F (MAX)		
STARTUP SPIKE	2500 (REF. 3, 4, 5)	2400
STEADY STATE	2500 (REF. 4, 5, 6)	1940
COMPUTED TENSILE STRESS, KSI (MAX)	13.4** (REF. 4)	37*** (REF. 7)
NUMBER OF ENGINE STATTS (ESTIMATED)	10,000	55 TO 700
LIFE, HOURS (ESTIMATED)	3000	7.5 TO 100

*OCCURS DURING START TEMPERATURE SPIKE
**OCCURS DURING DOWNSHOCK IN THE TRAILING EDGE NEAR THE OUTER SHROUD
***OCCURS DURING UPSHOCK IN THE STRUT INSIDE THE HOLLOW VANE

times more severe, and the nozzle vane in the advanced turbopump is projected to experience a temperature spike of 2400 F. These conditions produce a stress approximately 3 times that in the automotive nozzle. Thermal shock thus becomes a key material and design issue for ceramic rocket engine components.

Ceramic Processing and Properties

Candidate Materials. Structural ceramic materials were evaluated for components in advanced SSME-type turbopumps. To qualify as a candidate ceramic material for SSME turbine components, the material should:

1. Exhibit adequate structural strength to the service temperature.

2. Possess a high Weibull modulus. A typical value for advanced structural ceramics is 8, but values above 20 are reported.
3. Be highly resistant to thermal shock. Thus, the material should have high strength, a low thermal expansion, and preferrably a low elastic modulus. A high value of thermal conductivity also can be beneficial.
4. Be highly resistant to reaction with combustion products.
5. Maintain its toughness, stability, and strength over the design life of advanced turbines.
6. Be fabricable in complex shapes with close tolerances and at reasonable costs.
7. Have an acceptably high fracture toughness.

Efforts to develop strong, reliable structural ceramics for a variety of heat engines have been underway for the past decade, principally in the United States, Great Britain, Japan, Sweden. and West Germany. The emphasis so far has been directed at automotive applications and it is from these programs that many of the engineering properties data have been generated. Materials that can be considered as candidates for advanced rocket engine applications are:

1. Si_3N_4 (SN)
2. SiC (SC)
3. Partially stabilized ZrO_2 (PSZ)
4. Transformation-toughened ceramics
5. Particulate-toughened ceramics
6. Fiber-reinforced ceramics
7. Carbon-carbon composites with a protective coating

The materials that have exhibited the greatest promise for high-performance applications are Si_3N_4

and SiC. These materials include sintered Si_3N_4 (SSN), reaction-bonded Si_3N_4 (RBSN), sintered reaction-bonded Si_3N_4 (SRBSN), sintered SiC (SSC), and reaction-bonded SiC (RBSN). RBSC is also referred to as siliconized SiC (Si/SC). These materials are families of materials where the members have compositional modifications and are made by different fabrication routes. The microstructural features of these family members can be radically different and, as a consequence, so can the properties. Thus, it is essential to be aware of the basic fabrication processes.

Strength. The relative strengths of typical ceramic materials are shown in Fig. 4 (Ref. 8-12). The materials exhibiting the highest strengths are dense

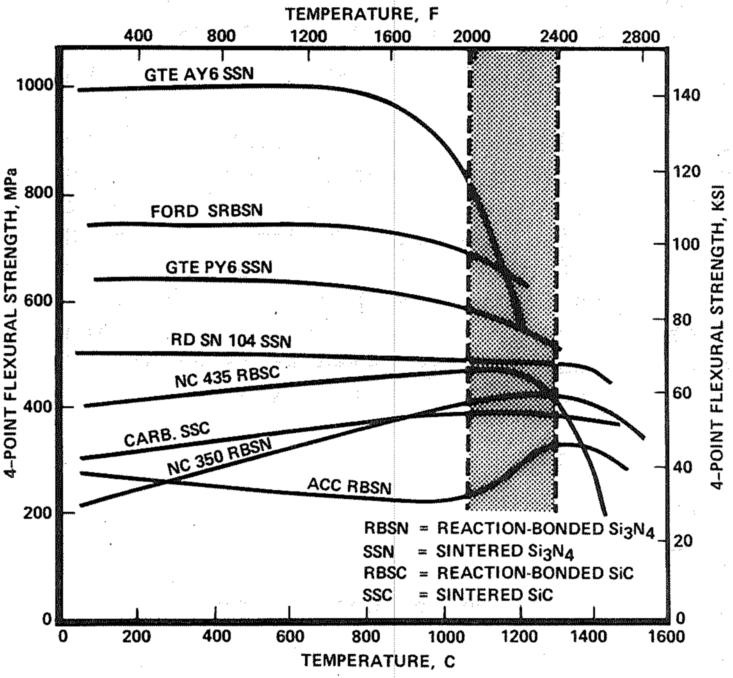

Fig. 4. Comparative Strengths of Representative Structural Ceramics

sintered silicon nitrides (SSN). Four-point bending strengths as high as 141 ksi have been reported (Ref. 8). The relative low strength of RBSN is a result of its high porosity. Above 2400 F, however, RBSN has a strength level competitive with that of dense Si_3N_4. This is because RBSN does not contain a glassy phase in the grain boundaries. The relative strength ranges of the SiC materials are between those of dense SSN and RBSN.

It must be pointed out that the strength values reported in Fig. 4 are typical values, not design strength values. These typical strength values must be adjusted to produce design values based on size, test configuration, stress state in the hardware, and the required reliability.

Resist to Thermal Shock. Resistance to thermal shock is a critical consideration for ceramic turbopump components. Extensive testing has been performed on the subject materials (Ref. 13) by plotting (Fig. 5) the maximum quench temperature difference before

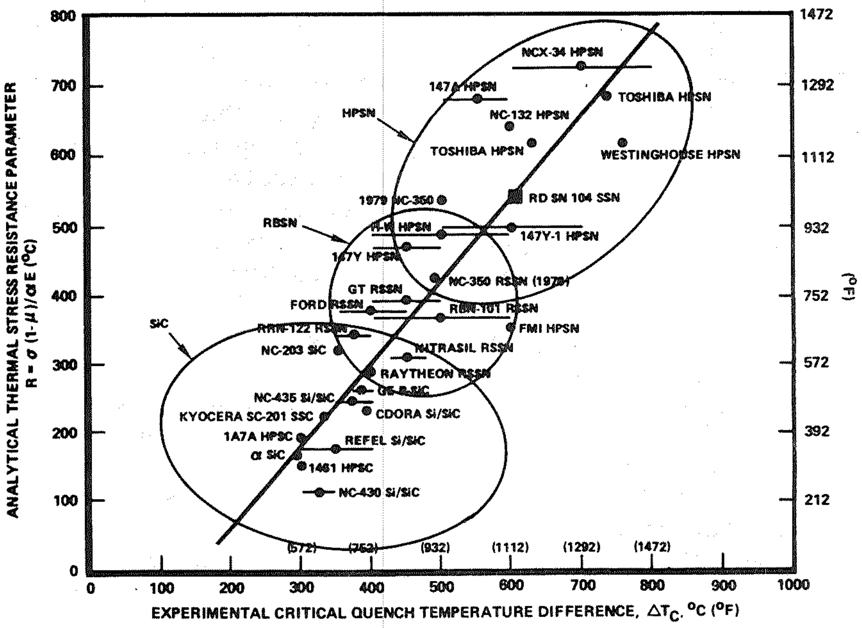

Fig. 5. Resistance to Thermal Shock of Candidate Materials

damage due to thermal shock occurred versus an analytical figure of merit, R, where:

$$R = \frac{\sigma(1 - \mu)}{\alpha E}$$

σ = average flexural strength

μ = Poisson's ratio

α = thermal expansion coefficient

E = elastic modulus

The materials that best resist thermal shock are located in the upper right while those that least resist thermal shock are located in the lower left. Each of three families of materials are clustered together. Hot-pressed Si_3N_4 (HPSN) exhibits the highest resistance to thermal shock, RBSN is next, while SiC materials exhibit the poorest resistance. Although SSN materials were not tested, they would be expected to fall in the circle drawn around the HPSN materials. SSN would exhibit similar results to those of HPSN because the microstructural features are similar and because it exhibits the same mechanical properties. The figure of merit for RD SN 104 SSN, shown by the square symbol in Fig. 5, falls in the center of the circle drawn around the HPSN data. HPSN offers limited use as turbine components because hardware is so expensive to make due to the extensive diamond grinding that is required.

Time-Dependent and Cyclic Properties. Long-term and cyclic properties, such as static fatigue, creep, and cyclic fatigue, are not yet well characterized on the newer SSN materials. Projections were made, however, based on data from similar materials. The effects of time-dependent and cyclic properties were small at the steady-state temperature, 1940 F, for 100 hours, and the stresses involving these properties are much lower than those that would cause fast fracture. Thus, the suitability of ceramics for turbopump application was demonstrated by satisfying fast-fracture criteria.

Component and Materials Identification

Each potential component for ceramics in the hot-gas path (Fig. 6) of an advanced high pressure fuel turbopump was assessed in terms of fabrication feasibility and structural risk. Information generated in Tasks 1, 2, and 3, plus component designs from the existing high pressure fuel turbopump, was used as a

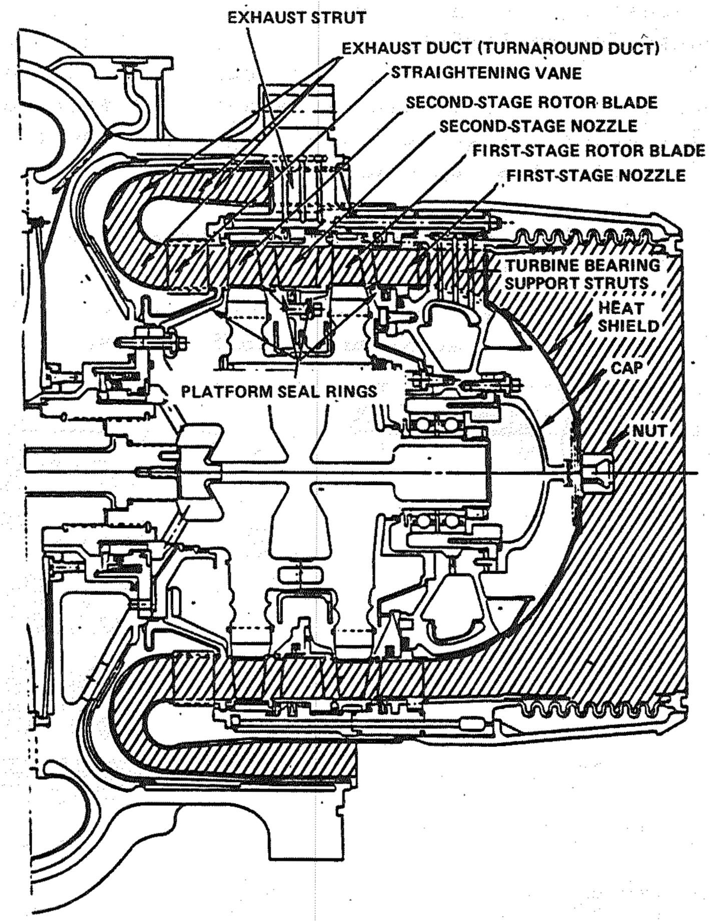

Fig. 6. Potential Components for Ceramics in the Hot-Gas Path of the Turbine Section in the SSME High Pressure Fuel Turbopump

basis for evaluation. Components showing good potential for benefit include stator nozzles, rotor blades, exhaust straightening vanes, and turbine inlet and exhaust struts.

Several of the turbine components can be made from high-performance ceramic materials at moderate to low risk. Experience has shown that ceramic components can replace metallic hardware only after careful and often major redesign. The most evident features of ceramic components for an SSME-type high pressure fuel turbopump are attention to attachment techniques, avoidance of excessive contact loading stresses, and fabricability. The major design challenge appears to be in devising methods of attachment.

Assessment of candidate hot-gas ceramic path components is summarized in Table 2.

Table 2. Assessment of Ceramic Components in the Hot-Gas Path of an Advanced SSME-Type HPFTP

COMPONENT	STRUCTURAL LOADS		CURRENT ATTACHMENT METHOD	FAB RISK	DEVELOPMENT PRIORITY	PRIMARY CONCERNS	COMMENTS
	MECH	THERM					
FIRST-STAGE NOZZLES	MOD	HIGH	LUGS	LOW	1	CONTACT STRESSES. TRANSIENT THERMAL STRESSES.	PRIMARY CANDIDATE FOR CERAMICS. STRUCTURAL ANALYSIS SHOWS THAT CERAMICS ARE VIABLE.
ROTOR BLADES	HIGH	HIGH	ROOT	LOW	2	CONTACT STRESSES. TRANSIENT THERMAL STRESSES. LACK OF FATIGUE DATA.	CENTRIFUGAL LOADS WILL BE LOWER THAN FOR METAL BLADES.
HEAT SHIELD	MOD	HIGH	NUT	MOD	4	CONTACT STRESSES. PRESSURE LOADING.	PROMISING CANDIDATE FOR CERAMICS BUT WOULD REQUIRE DETAILED STRUCTURAL ANALYSIS AND SOME REDESIGN.
CAP	HIGH	HIGH	FLANGE	MOD	--	HIGH LOADS FLANGE ATTACMMENT	HIGH RISK FOR A CERAMIC COMPONENT WITH MODERATE REWARD. A METAL CAP WILL BE SATISFACTORY BECAUSE IT IS COOLED BY LH_2 AND IT IS NOT EXPOSED DIRECTLY TO HOT GASES.
TURBINE BLADE PLATFORM SEALS	MOD	HIGH	FLOATING SCREW	LOW–MOD	5	CONTACT STRESSES. RUBBING ON METAL PARTS.	FEASIBLE BUT REQUIRES REDESIGN OF CONFIGURATIONS AND ATTACHMENT CONSIDERATIONS.
EXHAUST STRAIGHTENING VANES	MOD	MOD–HIGH	WELDED	LOW	3	METHOD OF ATTACHMENT. ACCOMMODATING THERMAL EXPANSION	LOW RISK, PROVIDED A SUITABLE ATTACHMENT METHOD CAN BE DESIGNED.
EXHAUST DUCT	MOD	MOD–HIGH	WELDED	VERY HIGH	--	FABRICATION, ATTACHMENT.	THE PRESENT CONFIGURATION WOULD BE VERY DIFFICULT TO FABRICATE.
INLET AND EXHAUST STRUTS	HIGH	MOD–HIGH	INTEGRAL WITH SURROUNDING STRUCTURE	LOW	--	TENACITY OF CERAMIC COATINGS ON METAL STRUTS.	EXISTING COOLED METAL DESIGN COULD BE RETAINED BY PROTECTING THE STRUTS WITH A THIN CERAMIC THERMAL BARRIER.
INLET AND EXHAUST STRUT CANS	LOW	HIGH	WELDED	NOT FEASIBLE	--	THIN, COMPLEXLY SHAPED.	THESE CANS WOULD BE REPLACED WITH A CERAMIC THERMAL BARRIER.

Conclusions and Recommendations

Structural analysis based on finite element models and reliability calculations showed that properly designed ceramic turbine elements would be viable under the extremely hostile environment of an advanced SSME-type engine. Critical factors are high-thermal stresses caused by the extreme thermal shocks occurring during startup and shutdown, and the contact stresses generated by attachment methods.

An immediate concern is to experimentally evaluate high-performance structural ceramic materials under the severe thermal transient conditions of the SSME. The viability of ceramics under these conditions needs to be verified and candidate materials need to be compared and ranked in order of resistance to extreme thermal shock.

Longer range recommendations for future effort include additional tasks that will complement the so-called "Automotive Ceramic Initiative" program as planned and funded by NASA and DOE (Ref. 14). These additional tasks, listed below, are specific to rocket engine applications:

1. Expand data base to supply design properties specifically for advanced rocket engines.
2. Implement brittle materials design methodology to account for manrated systems.
3. Develop ceramic hardware fabrication processes for producing net-shape advanced rocket engine components of superior quality.
4. Adapt nondestructive evaluation and proof testing methods to advanced rocket engine hardware.
5. Develop prototype testing devices for evaluating ceramic components under advanced SSME-type environmental conditions of high pressure and extreme thermal shock.

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