# CERAMICS FOR ADVANCED $O_2/H_2$ APPLICATION

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## Abstract

Ceramics are prime candidate materials for ad-
vanced rocket engines because they possess high-
temperature capability, a tolerance for agressive en-
vironments, and low density. This program was con-
ducted to assess the applicability of structural cer-
amics to advanced versions of the Space Shuttle Main
Engine. Operating conditions of ceramic turbine com-
ponents were defined and each component in the hot-
gas path was assessed in regard to materials selec-
tion, 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 en-
gine (e.g., turbine blades, stator vanes, and other
elements in the hot-gas flowpath) are approaching
the limits of their capabilities. Among the mate-
rials for use in advanced rocket engines, ceramics
are prime candidates because of their high-tempera-
ture 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 con-
siderably less severe than in a staged-combustion en-
gine turbine due to decreased Reynolds numbers, and
this should result in significant decreased thermal
stresses. In addition, the lower turbine gas ex-
haust 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 pos-
sible with increased turbine inlet temperatures. Per-
formance 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 pres-
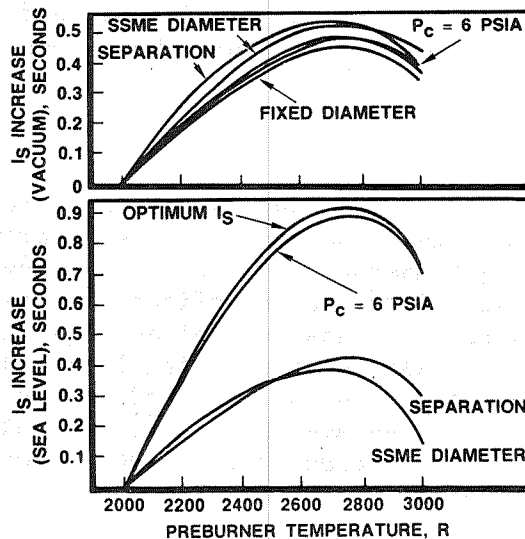sures of 10,000 psia are shown in Fig. 1 and 2 (Ref. 1).



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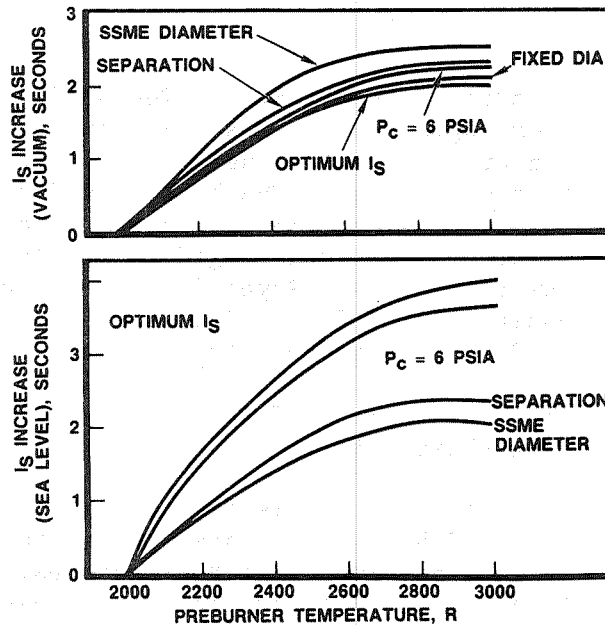Increasing Temperature

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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
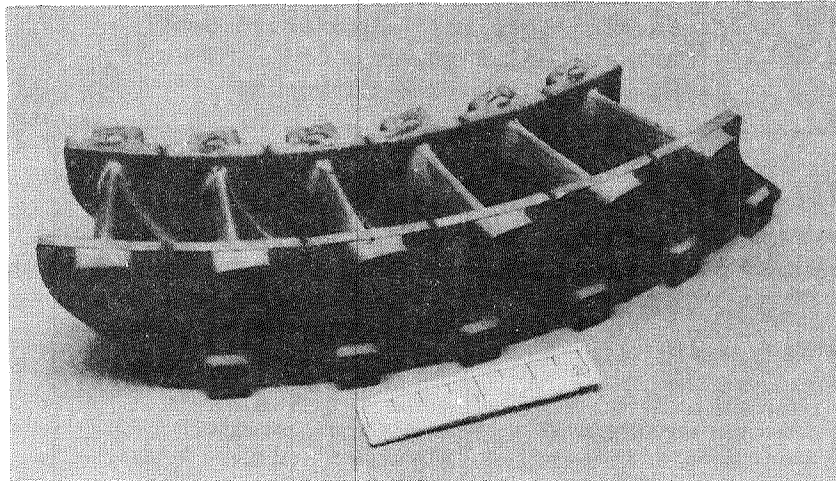in the hollow ceramic vane of Fig. 3 (37 ksi) occurs

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 ex-
isting in the present SSME.)  This translated to a re-
liability 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 en-
gine.  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 avail-
able as a result of the development of ceramic gas
turbine engines for automotive applications.  This in-
formation was used to compare the heat transfer condi-
tions in a ceramic automotive gas turbine with those
in an advanced rocket engine high-pressure fuel turbo-
pump (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 consider-
ably more severe than those for a nozzle vane in the
automotive gas turbine environment.  The film coeffi-
cient is up to 50 times higher, the pressure is 100
times higher, the thermal transients are 10 to 20

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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 approxi-
mately 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 mate-
rials 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.

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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
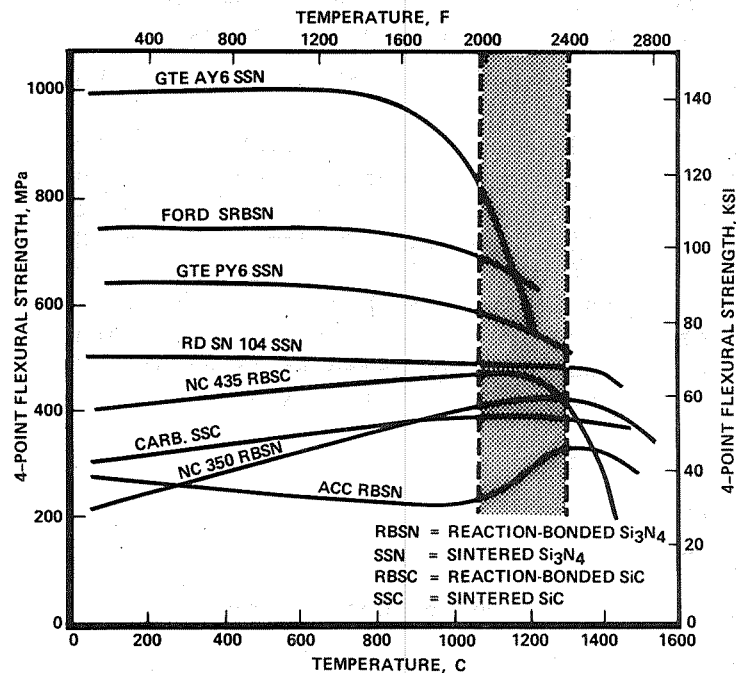


Fig. 4. Comparative Strengths of Representative Structural Ceramics

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

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its high porosity. Above 2400 F, however, RBSN has a
strength level competitive with that of dense Si₃N₄.
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 turbo-
pump components. Extensive testing has been performed
on the subject materials (Ref. 13) by plotting (Fig.
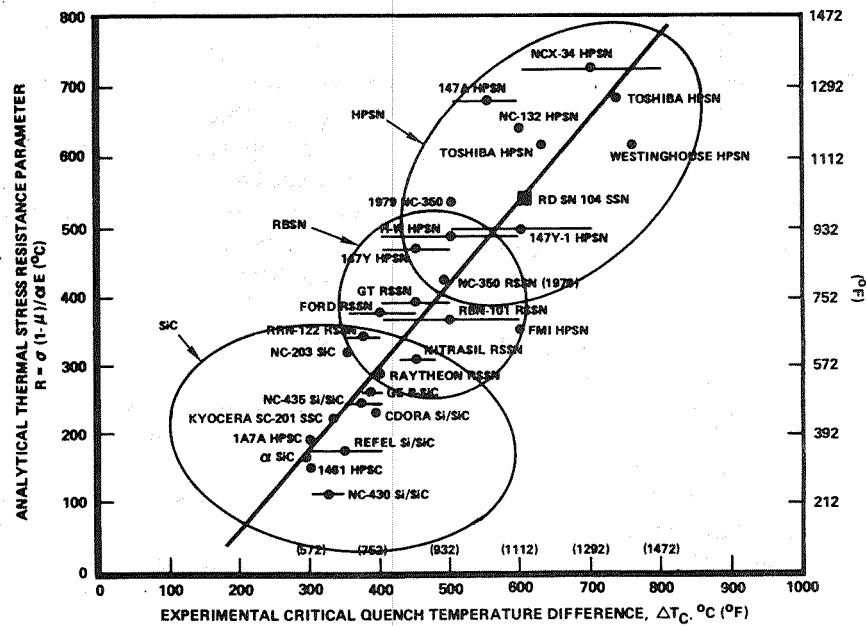5) the maximum quench temperature difference before



Fig. 5. Resistance to Thermal Shock
of Candidate Materials

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

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

$\sigma$ = average flexural strength

$\mu$ = Poisson's ratio

$\alpha$ = 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
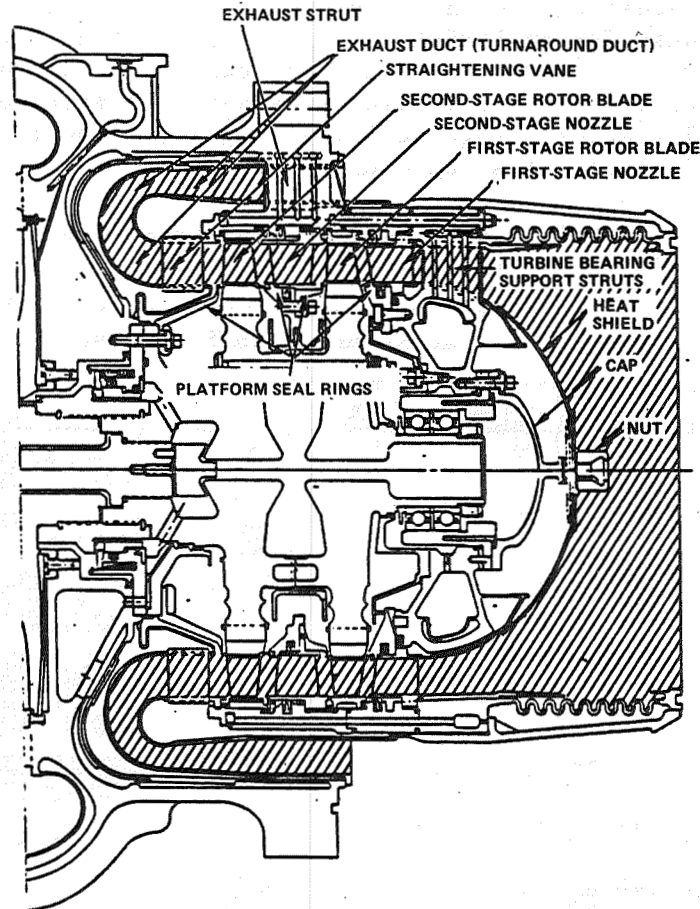


Fig. 6. Potential Components for Ceramics in the Hot-Gas Path of the Turbine Section in the SSME High Pressure Fuel Turbopump

basis for evaluation. Components showing good poten-
tial for benefit include stator nozzles, rotor blades,
exhaust straightening vanes, and turbine inlet and ex-
haust 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 turbo-
pump are attention to attachment techniques, avoidance
of excessive contact loading stresses, and fabricabil-
ity. The major design challenge appears to be in de-
vising methods of attachment.

Assessment of candidate hot-gas ceramic path com-
ponents 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 | DEVELOP-MENT 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 STRUC-TURAL ANALYSIS AND SOME REDESIGN. |
| CAP | HIGH | HIGH | FLANGE | MOD | | HIGH LOADS FLANGE ATTACMMENT | HIGH RISK FOR A CERAMIC COMPONENT WITH MODER-ATE 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 CONFIGURA-TIONS AND ATTACHMENT CONSIDERATIONS. |
| EXHAUST STRAIGHTENING VANES | MOD | MOD– HIGH | WELDED | LOW | 3 | METHOD OF ATTACH-MENT. ACCOMMODA-TING THERMAL EXPANSION | LOW RISK, PROVIDED A SUITABLE ATTACHMENT METHOD CAN BE DESIGNED. |
| EXHAUST DUCT | MOD | MOD– HIGH | WELDED | VERY HIGH | | FABRICATION, ATTACHMENT. | THE PRESENT CONFIGURA-TION WOULD BE VERY DIF-FICULT 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 RE-TAINED 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 RE-PLACED 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.

## References

1.  High-Temperature Turbine Program, Air Force Contract F04611-81-C-0053.

2.  Pidcoke, L. and J. Gerstley, Transient Thermal Analysis of a 500K $H_2/O_2$ First-Stage Fuel Turbine Ceramic Nozzle Vane, Rocketdyne Report No. ATU-83-5179, 8 December 1983.

3.  Trela, W., Personal Communication, Ford Motor Company, 21 March 1984.

4.  Caverly, J. C. and D. L. Hartsock, Evaluation of Ceramics for Stator Applications - Gas Turbine Engines, Final Report, NASA CR-165270, November 1980.

5.  Johnson, C. F. and D. L. Hartsock, "Thermal Response of Ceramic Turbine Stators," Ceramics for High-Performance Applications, J. J. Burke, A. E. Gorum, and R. N. Katz, Editors, Brook Hill, pp. 549-562, 1974.

6.  Carpenter, H. W., Ceramic Turbine Elements, Monthly Report for February 1984, Contract NAS8-35327, 10 March 1984.

7.  Rollins, C. T., High-Temperature Turbine Ceramic Nozzle Structural Analysis, Rocketdyne Internal Report, IL-4-21-003, 5 March 1984.

8.  Pasto, A. F., J. T. Niel, and C. L. Quackerbush, "Microstructural Effects Influencing Strength of Sintered Silicon Nitride," presented at the International Conference on Ultrastructure Processing of Ceramics, Glasses, and Composites, Gainsville, Florida, 13-17 February 1983.

9.  Quackerbush, D. L., ibid.

10. Mangels, J. A. and G. J. Tennehouse, "Densification of Reaction-Bonded $Si_3N_4$," <u>American Ceramic Society Bulletin 59</u> (12), p. 1216, 1980.

11. Larsen, D. C., <u>Property Screening and Evaluation of Ceramic Turbine Materials</u>, AFML-TR-4188, October 1979.

12. Schnittgrund, G. D., <u>Interim Report on Silicon Nitride Development</u>, Rocketdyne IL-169-271, 18 September 1980.

13. Larsen, D. C. and J. W. Adams, "Property Screening and Evaluation of Ceramic Turbine Materials," <u>Semi-Annual Interim Technical Report No. 11</u>, Contract No. F33615-79-6-5100, November 1981.

14. <u>Ceramic Technology for Advanced Heat Engines</u>, Preliminary Progress Plan, Oakridge National Laboratory, Materials and Ceramic Division, Contract NoW-7405, 26 July 1983.