N94- 33513

NOZZLE MATERIAL REQUIREMENTS AND THE STATUS OF INTERMETALLIC MATRIX COMPOSITES

526-24
12056

A.M. Johnson
GE Aircraft Engines
Cincinnati, Ohio
and
R.J. Hecht
Pratt & Whitney
West Palm Beach, Florida

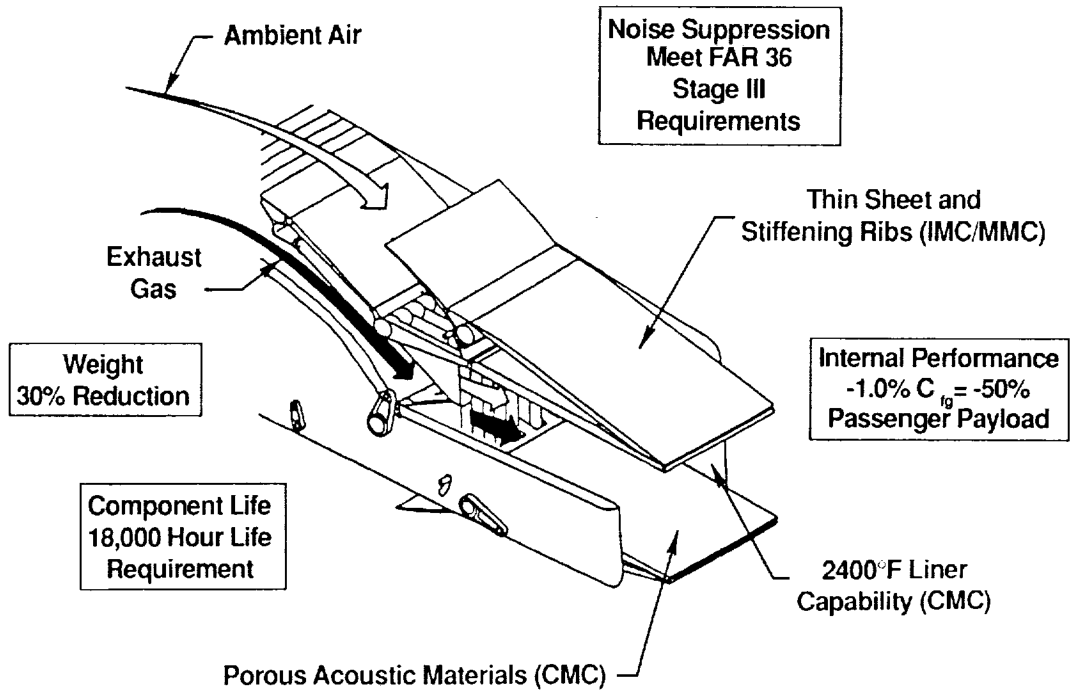
First Annual High Speed Research Work Shop
May 14 - 16, 1991

[redacted]

HSCT EXHAUST NOZZLE REQUIREMENTS

The HSCT exhaust nozzle must manage high temperature exhaust gases and pressure gradients while meeting HSCT economic and noise goals. The important features and requirements for an HSCT exhaust nozzle are shown in Figure 1 for a 2DCD(two-dimensional convergent-divergent) design. The same requirements would apply to an axi-symmetric design. Exhaust nozzle weight has an adverse effect on the overall aircraft range, payload and engine specific fuel consumption, and is therefore the primary driver for advanced exhaust nozzle materials. Because of the large airflow and pressure gradients, exhaust nozzles are extremely large and heavy when made from current materials. The use of advanced materials with higher specific strength will reduce the weight of exhaust nozzle components. In addition to the flow of high-temperature exhaust gases into the exhaust nozzle, ambient air is entrained to reduce gas exit velocities and suppress sound. This leads to components exposed to extremely high temperature gradients and, hence, high thermal stresses. Further, exhaust gases are highly oxidizing; material environmental resistance will be an important factor for long life. Several viable concepts have been identified to reduce noise through the mixture of exhaust and ambient air. Sound can be further suppressed by acoustic panels that absorb high-frequency noise (Ref. 1).

HSCT Exhaust Nozzle Requirements



KEY MATERIAL REQUIREMENTS FOR THE HSCT EXHAUST NOZZLE

The HSCT exhaust nozzle operating requirements lead to the need for materials with the characteristics shown in Figure 2. Since currently available structural materials are being utilized to their maximum capability, advanced materials with significantly enhanced properties will be needed to meet nozzle goals. The most promising class of materials are continuous fiber reinforced composites. The matrix can be a metal, intermetallic compound or ceramic. The reinforcing fibers are generally high strength ceramics although refractory metals may also be utilized. Accordingly, these materials are generally referred to as either MMC's (metal matrix composites), IMC's (intermetallic matrix composites) or CMC's (ceramic matrix composites). Designing, developing and scaling-up composite materials with a good balance of high temperature properties (especially specific strength) and sufficient shape making capability to be made into large, complex structures is a substantial challenge.

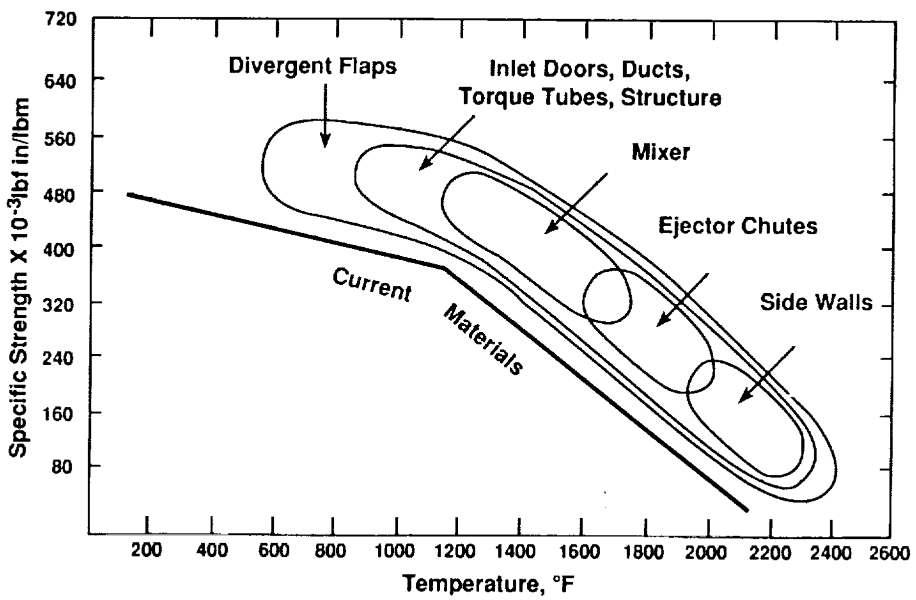
Key Material Requirements for the HSCT Exhaust Nozzle

- High specific strength
- Thermal stability
- Environmental resistance
- Thermal/mechanical/acoustic fatigue resistance
- Thermal shock/stress capability
- Damage tolerance
- Good fabricability
- Affordable cost

HSCT EXHAUST NOZZLE COMPONENT/MATERIAL GOALS

Preliminary design studies have shown that substantial weight savings can be identified for HSCT exhaust nozzle components utilizing high strength advanced materials. Figure 3 shows the nominal range of desired improvement in specific strength vs. temperature for various nozzle components. The line marked "current materials" generally represents the upper limits of specific strength vs. temperature relationships for titanium, nickel, iron and cobalt based alloys. The upper boundary of the component envelopes shown coincides with estimates of the potential capabilities of MMC, IMC and CMC materials under consideration. This figure indicates that a wide range of component operating conditions are anticipated for which advanced structural materials are needed.

HSCT Exhaust Nozzle Component/ Material Goals



PRIMARY HSCT EXHAUST NOZZLE MATERIAL CANDIDATES

The primary candidate materials under consideration by (GEAE) GE Aircraft Engines and (P&W) Pratt & Whitney for the HSCT exhaust nozzle are shown in Figure 4. IMC's based on $MoSi_2$ (molybdenum disilicide) and NiAl (nickel aluminide) and CMC's based on Al_2O_3 have the highest temperature capability due to relatively good inherent oxidation resistance. However, the systems have low ductility and may be difficult to fabricate. MMC's utilizing MCrAlY's (where M can be Fe, Ni, Co or a combination thereof) are much more ductile but are limited to lower temperatures due to strength. The fiber of choice for both IMC's and MMC's is a single crystal aluminum oxide (Al_2O_3) due to its high strength, temperature resistance chemical stability and compatible thermal coefficient of expansion. Oxide/oxide CMC's have potential as sound absorbers when fabricated in a low density form. IMC's and CMC's use reinforcements for both strengthening and toughening. MMC's use reinforcements primarily to improve strength.

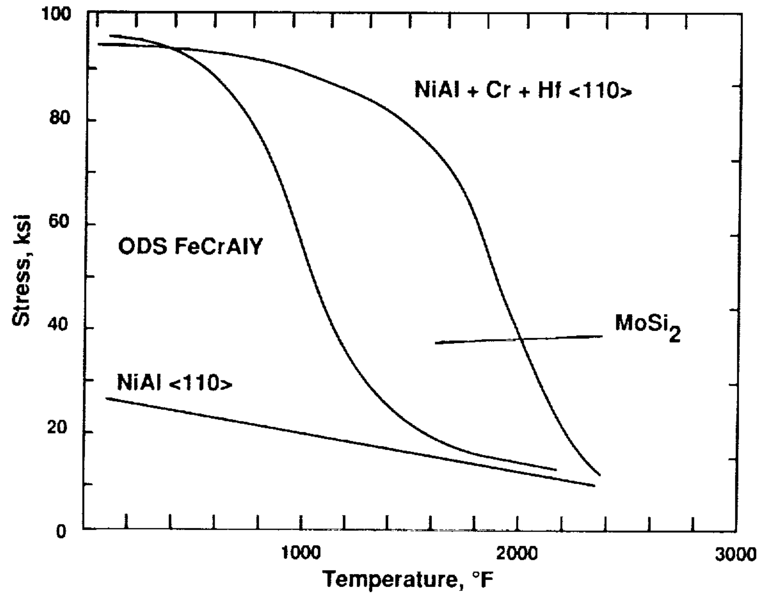
Primary HSCT Exhaust Nozzle Material Candidates

Type	Matrix	Reinforcement
IMC	$MoSi_2$ NiAl	Al_2O_3
MMC	M Cr Al Y Superalloys	Al_2O_3
CMC	Al_2O_3	Al_2O_3

ULTIMATE TENSILE STRENGTH OF CANDIDATE MATRIX MATERIALS

Matrix materials are considered to dominate composite temperature capability, and therefore matrix materials are generally first selected based on environmental resistance and strength at temperature. Potential matrix materials that offer both high strength and oxidation resistance are included in Figure 5, which shows the wide range of tensile strength characteristics exhibited. In this case, the NiAl is in a single crystal form grown in the <110> crystallographic direction (Ref. 2). Note the potent effect of alloying with small amounts of Cr and Hf on NiAl strength. The ODS (oxide dispersion strengthened) FeCrAlY was directionally recrystallized and the $MoSi_2$ (Ref. 3) was in a polycrystalline form. Environmental and thermal barrier coatings may increase a material's ultimate temperature capability and are frequently developed with the base material as a system.

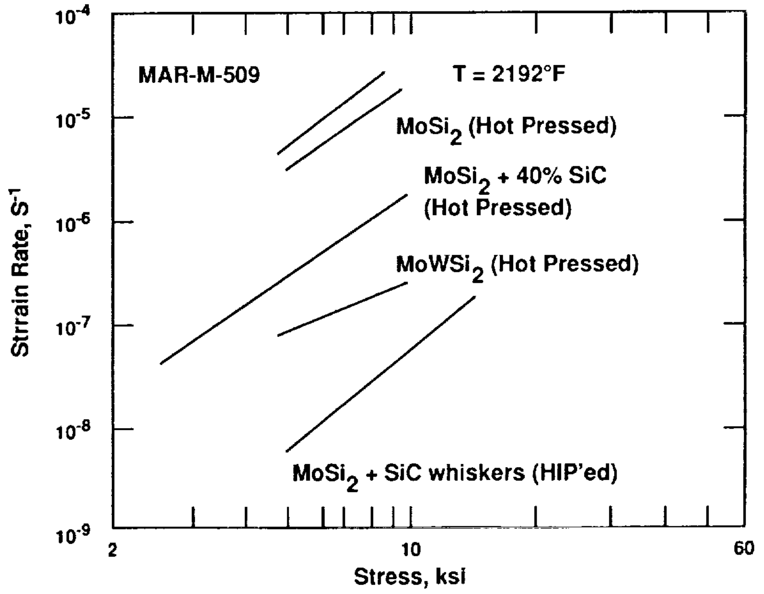
Ultimate Tensile Strength of Candidate Matrix Materials



COMPOSITION AND PROCESSING EFFECTS ON $MoSi_2$ CREEP RESISTANCE

In addition to matrix alloying, processing can have significant effects on matrix material strength and ductility. Figure 6 shows the effects of several variations of alloying, processing and reinforcements on $MoSi_2$ composite creep strength (Ref. 4). The 40% SiC (silicon carbide) was added as a small particulate to $MoSi_2$ powder prior to hot pressing. Similarly, fine SiC whiskers were added to $MoSi_2$ powder prior to HIP (hot isostatic pressing). The $MoSi_2$ - containing high aspect ratio and high strength SiC whiskers consolidated by HIP shows the lowest creep behavior of the materials shown. MAR-M-509 is a conventional, monolithic superalloy with high cobalt content.

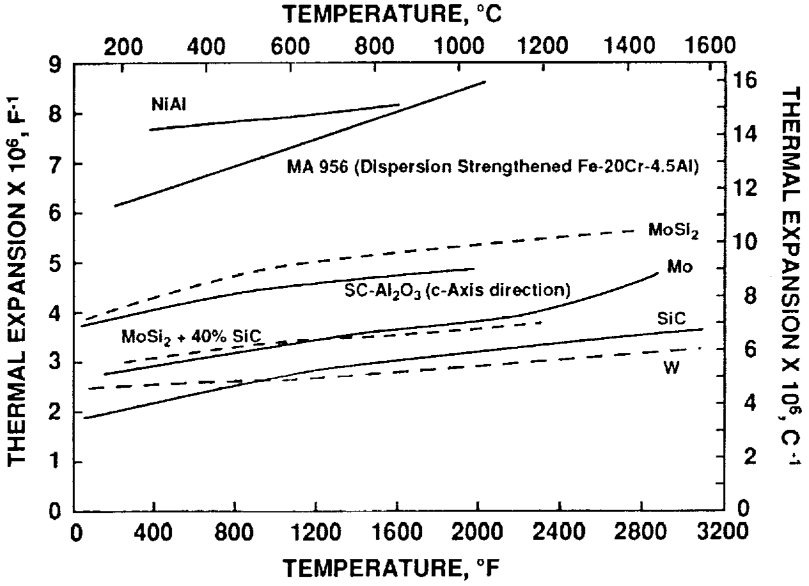
Composition and Processing Effects on $MoSi_2$ Creep Resistance



THERMAL EXPANSION OF SEVERAL CANDIDATE MATERIALS

Figure 7 shows the CTE (coefficient of thermal expansion) for several candiate matrix and reinforcing materials. The close match of $MoSi_2$ and Al_2O_3 makes this combination of matrix and reinforcement particularly interesting from the standpoint of potential thermal fatigure resistance. Note also that the CTE of the $MoSi_2$ + 40% SiC is substantially lower than that of $MoSi_2$ alone, as would be expected from the position of the SiC in the figure. In general, the CTE mismatch of a composite system is determined by the matrix and reinforcement composition and interface coatings.

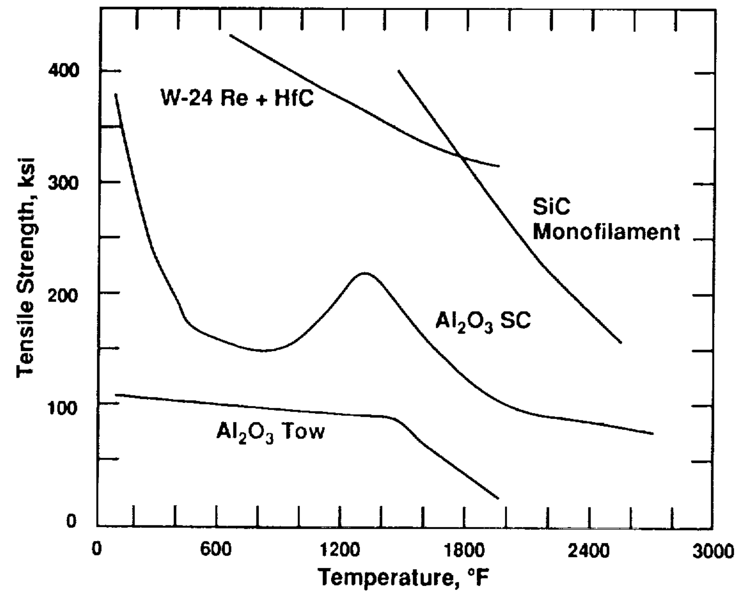
Thermal Expansion of Several Candidate Materials



TENSILE STRENGTH OF REINFORCING FIBERS

Figure 8 shows the wide range in tensile strength behavior exhibited by four different reinforcing fibers (Ref.'s 5,6,7,8). The high temperature strength advantage obtainable through processing is demonstrated by comparison of the Al_2O_3 single crystal monofilament and Al_2O_3 polycrystalline tow data. However, single crystal processing generally involves slower processing and therefore higher costs.

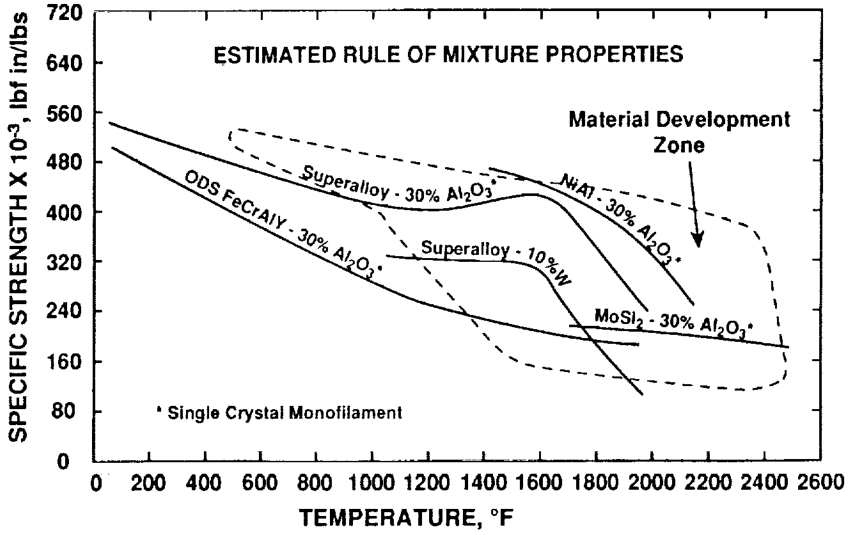
Tensile Strength of Reinforcing Fibers



SPECIFIC STRENGTH OF SEVERAL CANDIDATE IMC AND MMC SYSTEMS

The specific strengths of several candidate composite systems were calculated using a rule-of-mixture approach as shown in Figure 9 (Ref. 9). In this case, the composite specific strength is assumed to be equal to the sum of the weighted strengths of the constituents. This approach is useful for estimating design trade-offs for the different composite systems. The area marked "material development zone" is bounded on the lower side by current material capabilities and on the upper side by the maximum assumed properties for this study. It is apparent that no single material system is likely to have superior properties in comparison to others over the entire strength/temperature range.

Specific Strength of Several Candidate IMC and MMC Systems



FIBER/MATRIX INTERFACE COATINGS KEY TO TOUGHNESS

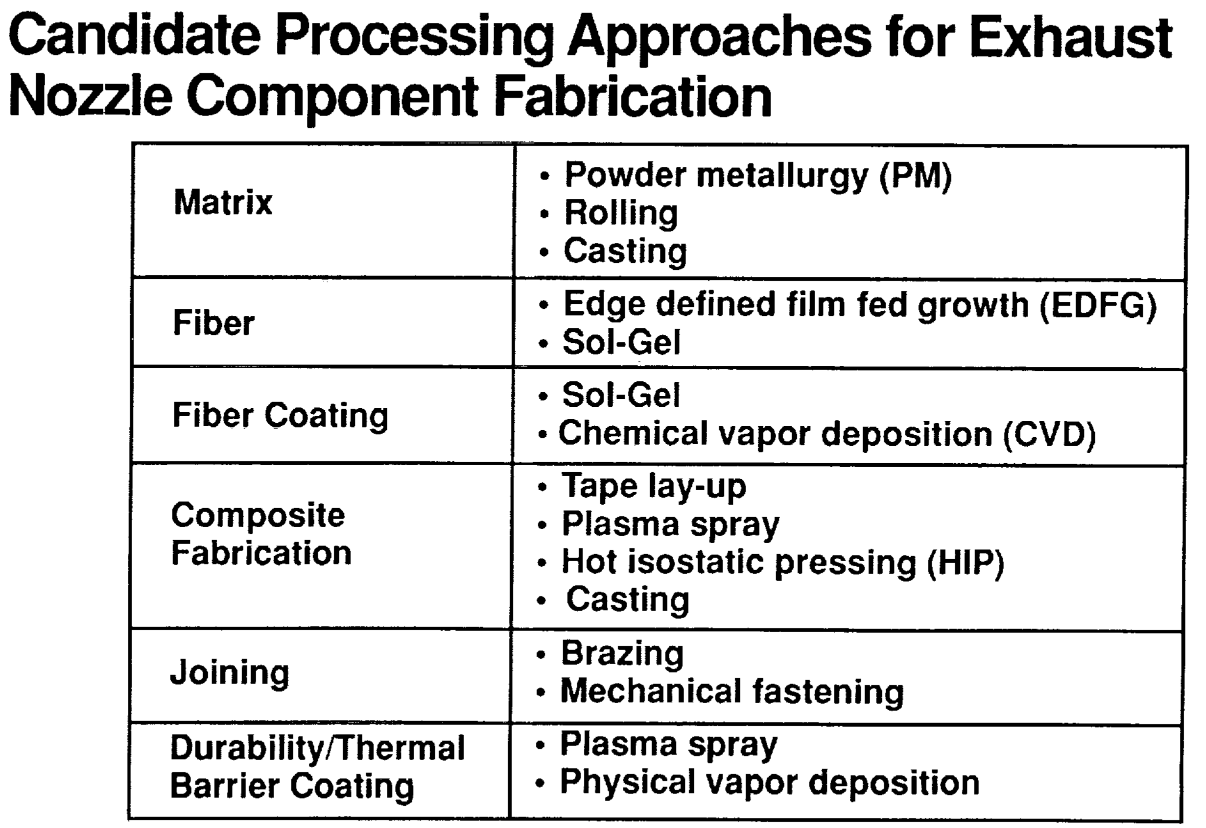
The characteristics of the interface between the fiber and matrix of any composite system have a profound effect on the properties of the composite. Toughness is particularly affected, as well as thermal fatigue resistance and long term thermal stability. For these reasons coatings are generally applied to the fiber prior to composite fabrication. The method chosen to deposit the coating as well as coating composition and thickness must be based on the fiber and matrix behavior and the results desired. Interface control is essential to composite design and is therefore receiving a substantial amount of attention worldwide. Both analytical and experimental approaches are actively being pursued.

Fiber/Matrix Interface Coatings Key to Toughness

- Improve inherent fiber properties
- Create chemically stable interface
- Reduce fiber/matrix thermal expansion mismatch
- Control fiber/matrix bonding

CANDIDATE PROCESSING APPROACHES FOR EXHAUST NOZZLE COMPONENT FABRICATION

Figure 11 shows a partial listing of candidate processes under consideration for development of HSCT exhaust nozzle structures. The number of possible combinations of matrix, fiber and interface compositions and associated processes is large. It would be impractical to attempt to investigate every possible combination in detail. Therefore the best possible use must be made of previous experience, analytical modeling, statistically designed experiments and careful analysis of the data. Factors to be evaluated for process selection for development and scale-up include a)inherent variability, b)ability to be analyzed, monitored and controlled, and c)economic factors such as basic cost and capital equipment requirements.



Candidate Processing Approaches for Exhaust Nozzle Component Fabrication

Matrix	• Powder metallurgy (PM) • Rolling • Casting
Fiber	• Edge defined film fed growth (EDFG) • Sol-Gel
Fiber Coating	• Sol-Gel • Chemical vapor deposition (CVD)
Composite Fabrication	• Tape lay-up • Plasma spray • Hot isostatic pressing (HIP) • Casting
Joining	• Brazing • Mechanical fastening
Durability/Thermal Barrier Coating	• Plasma spray • Physical vapor deposition

COMPOSITE CHARACTERIZATION, ANALYSIS, DESIGN AND LIFE METHODS CONSIDERATIONS

As composite systems are identified for feasibility evaluation, a rigorous approach is required to assure that all important aspects of the component design, manufacture and service are considered (Ref. 10). Due to the inherent anisotropic properties of continuous fiber reinforced composites they must be tailored for the specific application to which they will be applied. Consequently, processing, mechanical property evaluation and component testing must be done on a component by component basis.

Composite Characterization, Analysis, Design and Life Methods Considerations

- Mechanical testing methods
- Brittle vs ductile composite behavior
- Integrated models
  - Heat transfer
  - Constitutive behavior
  - Damage accumulation
- Fabrication/Service effects
  - Time dependent
  - Environmental
  - Residual stresses

SUMMARY

Advanced materials including MMC's, IMC's and CMC's have considerable potential for reducing the weight, increasing the performance and reducing the noise of the HSCT exhaust nozzle. However, substantial challenges must be overcome before such materials can be utilized as structural materials in high performance aircraft engines.

Summary

- HSCT exhaust nozzle material requirements are complex and challenging
- Application of advanced composite materials could significantly reduce nozzle weight
- Several candidate materials and processes have been identified
- Successful and timely development of composite components will require integration of materials, design and manufacturing efforts

REFERENCES

1. Stine, F.R.: Personal Communication, GEAE.

2. Darolia, R.: NiAl Alloys for High Temperature Structural Applications. JOM, March 1991.

3. Maloney, M.: Development of Refractory Metal Fiber Reinforced MoSi2 - Proceedings; 15th Annual Conference on Advanced Ceramics and Composites.

4. Bose, S. and Maloney, M.J.: Unpublished Research, P&W and DARPA Contract No. N00014-87-C-0862..

5. Hong, W.S.; Rigdon, M.A.; Fortenberry, N.L.: Reinforcement Options for High Temperature Tensile Testing Results for Ceramic Fibers, IDA Paper P-2483, DARPA, Dec. 1990.

6. Petrasek, D.W.: NASA Tech NICAL Publication TND-6881.

7. Schoenberg, T. and Kumnick, A.: NASA HiTemp, June 1989, Page 1-1.

8. Hurst, J.B.: NASA LeRC, NASA Lewis, July 1990.

9. Amato, R.A.: Personal Communication, GEAE.

10. Johnson, A.M.; Wright, P.K.: Application of Advanced Materials to Aircraft Gas Turbine Engines, AIAA 90-2281, July 1990.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the GE and P&W personnel who provided information presented in this paper, in particular: D. Anton, M. Emiliani, M. Maloney, S. Singerman and D. Shaw of Pratt & Whitney, and R. Amato, M. Gigliotti, M. Jackson and R. Stine of General Electric. The assistance of A. Brown and B. Davis in the preparation of this paper is greatly appreciated.