COMBUSTOR MATERIALS REQUIREMENTS AND STATUS OF CERAMIC MATRIX COMPOSITES

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Lean And Rich Burn Combustor Designs Identified To Meet HSCT Goals

The HSCT combustor will be required to operate with either extremely rich or lean fuel/air ratios to reduce NOx emission, (Figure 1). NASA High Speed Research (HSR) sponsored programs at Pratt & Whitney (P&W) and GE Aircraft Engines (GEAE) have been studying rich and lean burn combustor design approaches which are capable of achieving the aggressive HSCT NOx emission goals. Both combustor design approaches under study, a lean premixed/prevaporized (LPP) and a rich burn/lean (RBL), will require the use of very high temperature (2400-3000F) materials to meet the HSCT emission goals of 3-8 gm/Kg. Currently available materials will not meet the projected requirements for the HSCT combustor. The development of new materials is an enabling technology for successful introduction to service of the HSCT (ref. 1).

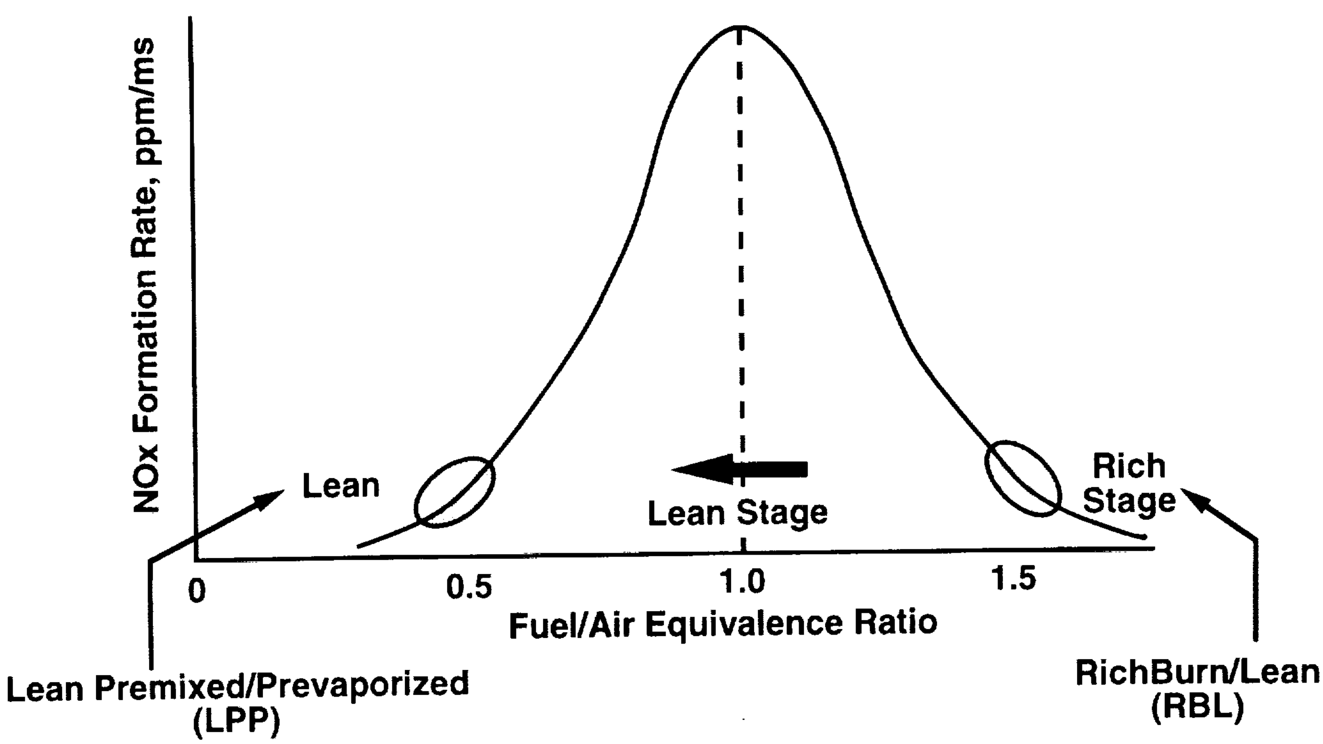
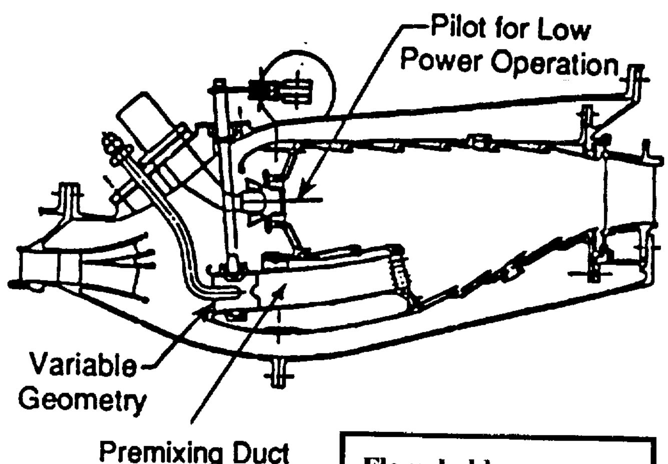


Figure 1

Lean Premixed/Prevaporized(LPP) Combustor Requirements

The LPP combustor approach(Figure 2) prevaporizes the fuel and injects it into the air in a premixing passage to deliver a uniform droplet-free mixture to the combustion zone. The fuel/air ratio is set as low (lean) as possible, but above stability or inefficiency thresholds. The premixed prevaporized combustor is theoretically capable of producing very low NOx emissions. LPP combustor design approaches will require high temperature liner materials technology to reduce cooling air requirements. The ability of the liner to operate with small amounts of cooling air gives additional design flexibility in order to meet all of the combustor performance requirements. In addition, it is anticipated that the LPP approach may rely on a flame holder downstream of the premixing chamber to provide a stable flame front. Such a flameholder will require a very high temperature material. Ceramic matrix composites are the primary candidate materials for meeting the performance and durability requirements of the LPP combustor.



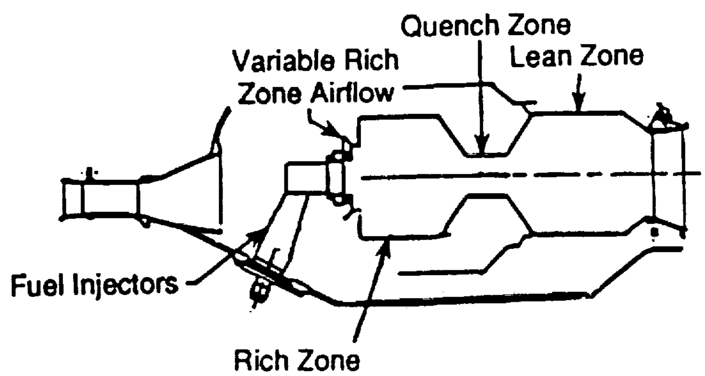
Flameholder
- Limit or Preclude Cooling Air
- Radiation Cooling
- 3000F Temperature Capability
- Oxides Candidate Materials

Liner
- Limited or No Film Cooling Air
- Convection Cooling
- High Thermal Conductivity
- 2400-2800F Temperature Capability
- SiC or Si3N4 Candidate Materials

Figure 2

Rich Burn/Lean (RBL) Combustor Requirements

The RBL combustor approach (Figure 3) reduces NOx by operating at higher fuel/air ratios than stoichiometric combustion. The rich primary zone inhibits the NOx formation process due to the the lack of available oxygen. However, large quantities of CO and smoke are formed that must be consumed in the remainder of the combustor. The rich zone fuel/air mixture must be uniform to minimize NOx formation. The required uniformity precludes the use of film cooling air in the rich zone. This leads to the need for a noneffusive cooling approach in which the liner may only be cooled externally by convection. This will impose very high temperature and heat flux conditions on the rich zone liner far in excess of current material operating temperature limits. The RBL combustor design will also require a high temperature quench and lean zone liner material to reduce cooling air requirements. Critical to the success of the RBL combustor design will be the development of high temperature liner materials. High conductivity SiC or Si_3N_4 base ceramic matrix composites are the primary candidate materials identified for meeting the temperature, performance and life goals of the RBL combustor.



Rich Zone Liner • No Film Cooling Air (Critical for low NOx)	**Quench and Lean Zone Liners** • Limited Or No Film Cooling Air
• Convection Cooling Required • High Thermal Conductivity Required • 2400 - 2800 F Temperature Capability • SiC or Si_3N_4 Candidate Materials	

Figure 3

HSCT Engine Duty Cycle More Severe Than Subsonic Transport

In addition to temperature and NOx considerations of the HSCT combustor, the liner must be durable to provide long life. An HSCT goal has been established of 18,000 hours combustor liner life. This goal is a significant challenge due to the previously described material temperature requirements of an HSCT combustor liner. The life goal is especially challenging when considering the unique mission profile of the proposed HSCT aircraft relative to current subsonic commercial aircraft (ref. 2). The very high compressor discharge temperature (T3) and combustor exit temperature (T4) associated with supersonic cruise result in more than 80% of the HSCT mission time at maximum temperature conditions (Figure 4). This compares with less than 10% of the total mission time at maximum temperatures with current subsonic commercial aircraft. Operating at extremely high temperatures over most of the flight mission results in even greater need to develop high temperature materials for the HSCT.

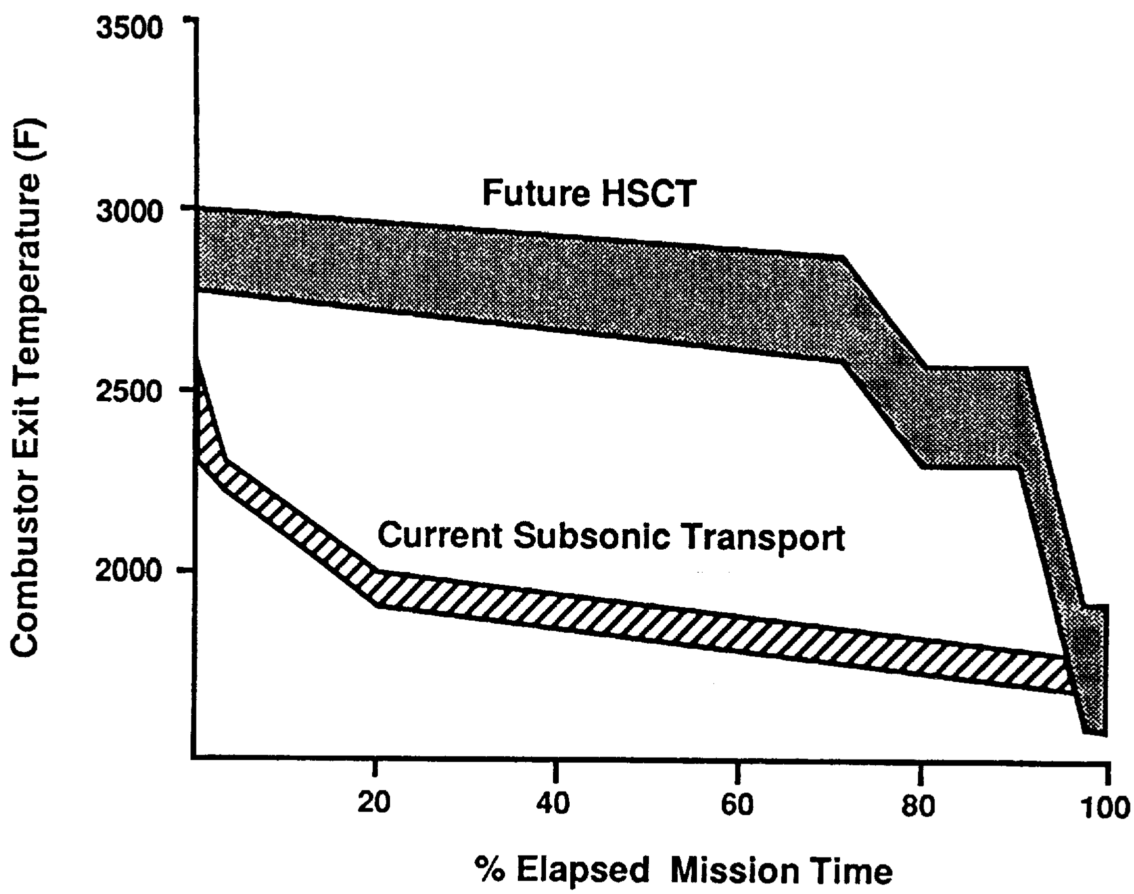


Figure 4

Key Material Requirements For The HSCT Combustor

Consideration of the HSCT mission and combustor operating requirements has led to the identification of key material requirements related to the design issues of a low NOx combustor material. These requirements are shown in Figure 5. The ability of a ceramic matrix composite material to meet these requirements will determine its applicability for the HSCT combustor. Development of the required CMC materials will have to address the fundamental composite behavior, processing, and manufacturing to insure that a balance of material performance and cost is achieved. Material and processing development must be integrated, and concurrently conducted with combustor design to insure design/materials/manufacturing compatibility for timely development of a low NOx HSCT combustor.

- **High Operating Temperature**
- **High Thermal Stress Resistance**
- **Acoustic/Vibratory Durability**
- **Environmental Durability**
- **Damage Tolerance**
- **Shape Forming Capability**
- **Reasonable Cost**

Figure 5

Thermal Conductivity of Candidate Ceramic Materials

The HSCT combustor design, performance and durability requirements drive the ceramic matrix material selection toward high thermal conductivity, thermo-oxidative stability, physical stability and low thermal expansion. Composite through-thickness conductivity is largely driven by the matrix conductivity thus dictating the choice of matrix material. The thermal conductivity of some candidate ceramic materials suitable for use as a CMC matrix above 2400°F are shown in Figure 6. The thermal conductivity of SiC and Si_3N_4, coupled with their low thermal expansion and high strength make them the primary candidate for the combustor composite matrix. $MoSi_2$ is also a candidate because of its high thermal conductivity and oxidation resistance.

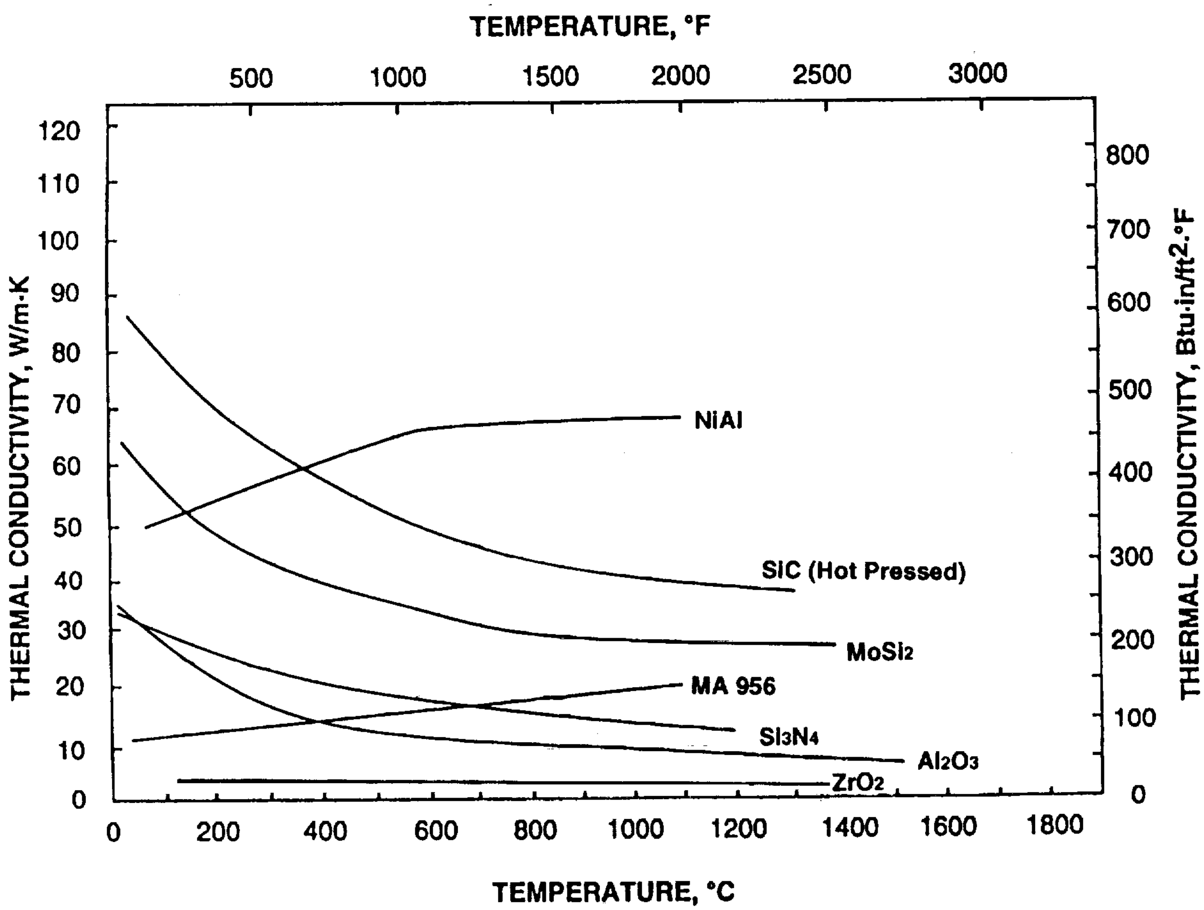


Figure 6

Thermal Stress Resistance Of Candidate Composite Systems

Design requirements for the HSCT combustor mandate that candidate advanced materials withstand temperatures of 2200° to 3000°F, depending on the thermal conductivity, while providing acceptable environmental durability in both oxidizing and reducing environments. In addition, the material system must have good high cycle fatigue resistance to withstand significant acoustic and vibratory loads. The most critical aspect of material performance derived from the design requirements is resistance to thermal stress. A material parameter commonly used to rank materials for thermal stress resistance is the thermal stress parameter $R'=\sigma k/E\alpha$, where σ=allowable yield strength, k=thermal conductivity, α=linear coefficient of thermal expansion, and E=Young's modulus. Various state-of-the art ceramic composite material systems are compared to a current combustor material (HS188) using this parameter in Figure 7. Both SCS-6 SiC fiber (Textron Specialty Materials) reinforced SiC and Si_3N_4 composites have high resistance to thermal stress.

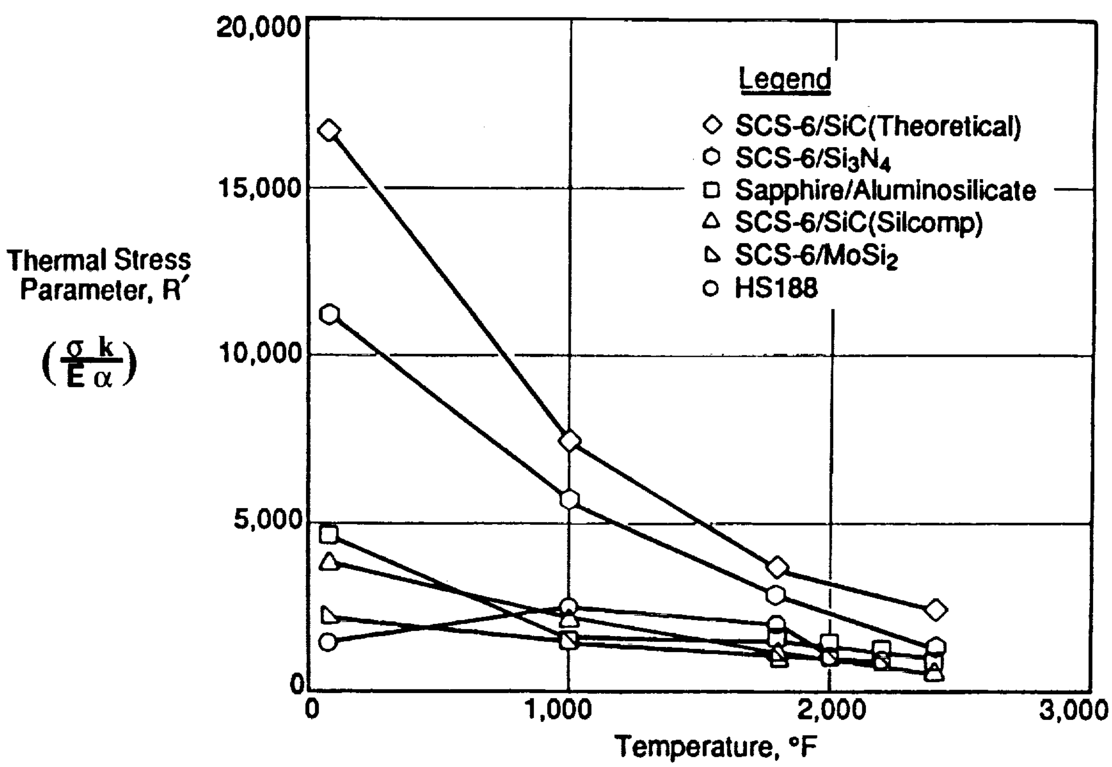
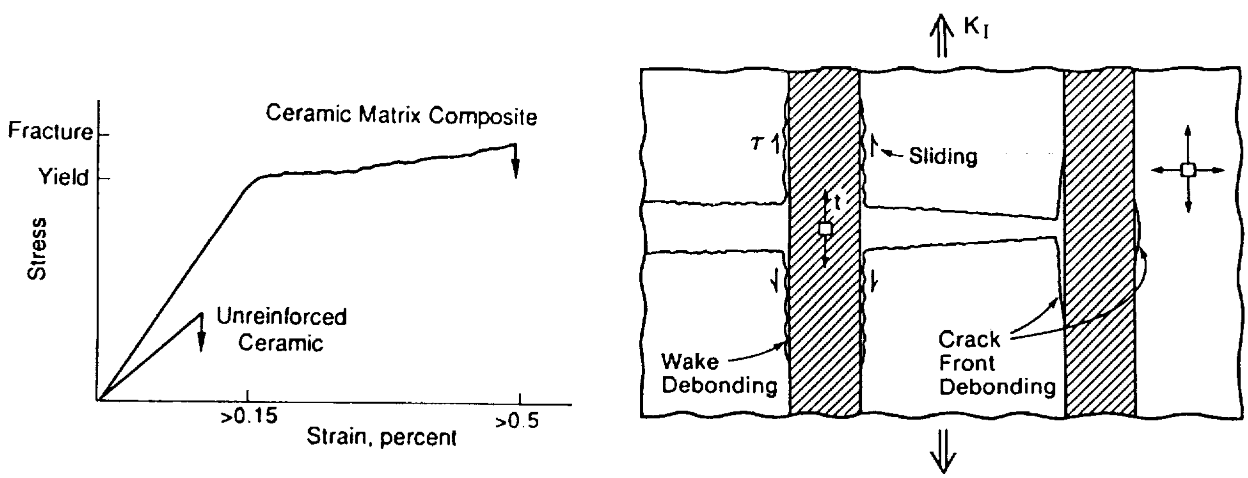


Figure 7

Fiber And Fiber-Matrix Interface Key
To CMC Toughness

CMC's potentially offer the high temperature performance of monolithic ceramics with improved toughness and reliability. The key to these improvements is the fiber reinforced and its ability to dissipate energy and exhibit tough behavior. For CMC's where the matrix modulus is high relative to the fiber reinforcement (Ef<Em), material toughness is dominated by the fiber/matrix interface and the characteristics it possesses. For this case, the fiber/matrix interface can deflect matrix cracks that develop at low strain levels, resulting in fiber debonding (Figure 8) (ref. 3). This debonding dissipates energy associated with matrix cracking and isolates the fiber from the cracked matrix thus preventing fiber fracture. To enhance its effectiveness, it is desirable that the fiber/matrix interface possess relatively low shear strength in order to promote debonding. The materials typically used for interface coatings, such as carbon and boronnitride, are susceptible to oxidative attack which reduces fiber/matrix interface performance, resulting in decreased toughness. The environmental stability of these interface materials becomes significant with regard to damage tolerance and long term durability.



Fiber Coatings Required To Achieve Needed Fracture Toughness

Figure 8

C-6.

Surface Treatements Identified For Increased CMC Capability

The CMC system selected for the HSCT combustor application must be environmentally stable for long times. Depending on the design, the gas environment in the combustor can be oxidizing or alternating between reducing and oxidizing. In oxidizing environments (lean burn), protection of the candidate CMC systems is provided by formation of a dense, protective oxide film on the surface. In reducing environments (rich burn), SiO_2 forming system as SiC, Si_3N_4 and $MoSi_2$ may undergo more accelerated (active) oxidation, leading to higher liner surface recession rates than in a lean burn environment. If a problem, chemical surface stability can be enhanced through surface treatment or coatings. Coatings can also be used to provide thermal insulation (i.e., thermal barrier) to increase liner temperature capability. Emissivity control coatings can be used to minimize the effects of radiation from the hot liner inner surfaces. Coatings can provide fiber-to-matrix thermo-chemical and environmental stability as well as enhance composite fracture toughness. Figure 9 shows the types of coating processes available for enhancing the capability and performance of HSCT composite liners.

Function	Candidate Coating Type	Processing
Thermal Control (Thermal Barrier)	$ZrO_2(Y_2O_3)$	Plasma Spray Electron Beam Vapor Deposition
Thermal Control (Radiation)	Metallic	Plasma Spray
Environmental Control (Combustion Effects)	Al_2O_3 Y_2O_3	Chemical Vapor Deposition Sol-Gel Physical Vapor Deposition
Fiber-Matrix Interface Control (Fracture Toughness)	Oxides Nitrides Carbides Silicides	Chemical Vapor Deposition Sol-Gel Physical Vapor Deposition Polymer Precursor

Figure 9

Fiber Tensile Strength

Fiber properties are critical to the CMC combustor liner design and performance . Initial design and material trade studies performed under NASA HSR Phase I have shown that a ceramic matrix composite combustor liner must be thin-walled and have high thermal conductivity at the operating temperature to reduce thermal gradients. This implies the need for a fine diameter fiber in the CMC structure that has high thermal conductivity. Because of the high conductivity and strength of SiC it is the primary candidate to reinforce SiC and Si3N4. The primary limitations of currently available SiC fibers are poor thermochemical stability and low tensile strength at temperatures above 2000°F (Figure 10) (ref. 4). Efforts being conducted under NASA HiTEMP on improving the stoichiometry of SiC fiber through process development indicate that these limitations can be overcome (ref. 5).

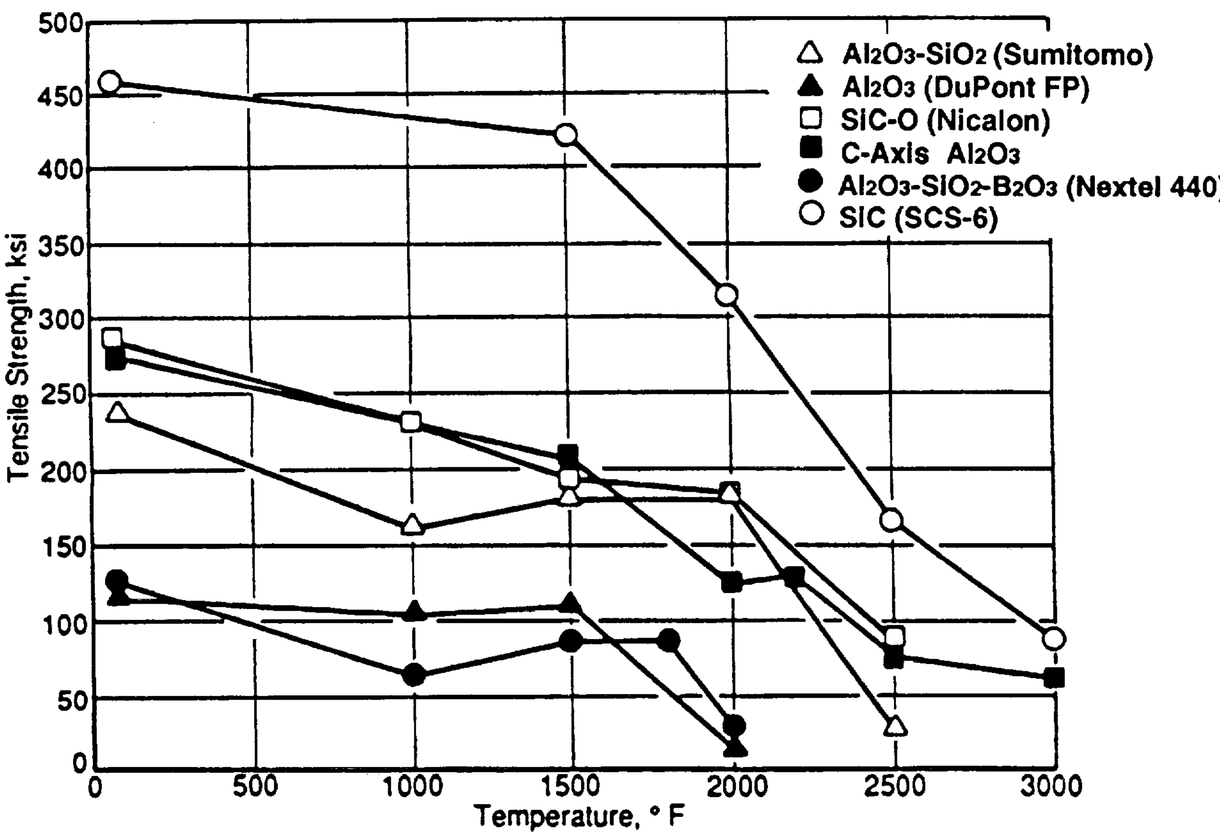


Figure 10

Fiber Creep Resistance

Long time operation of the HSCT will require that the CMC liner materials be creep resistant. Matrix as well as fiber creep resistance must be addressed and maximized. The creep resistance of SCS-6 and Nicalon (Dow Corning Corporation) fibers are compared to single crystal Al_2O_3 fibers and sintered SiC in Figure 11 (ref. 6, 7, 8). Stoichiometic SiC fibers should exhibit creep resistance similar to high purity sintered SiC, which is superior to that of c-axis single crystal sapphire (ref. 9). Improvements in SiC fiber stoichiometry can increase creep resistance, temperature capability, and life of SiC and Si_3N_4 composites.

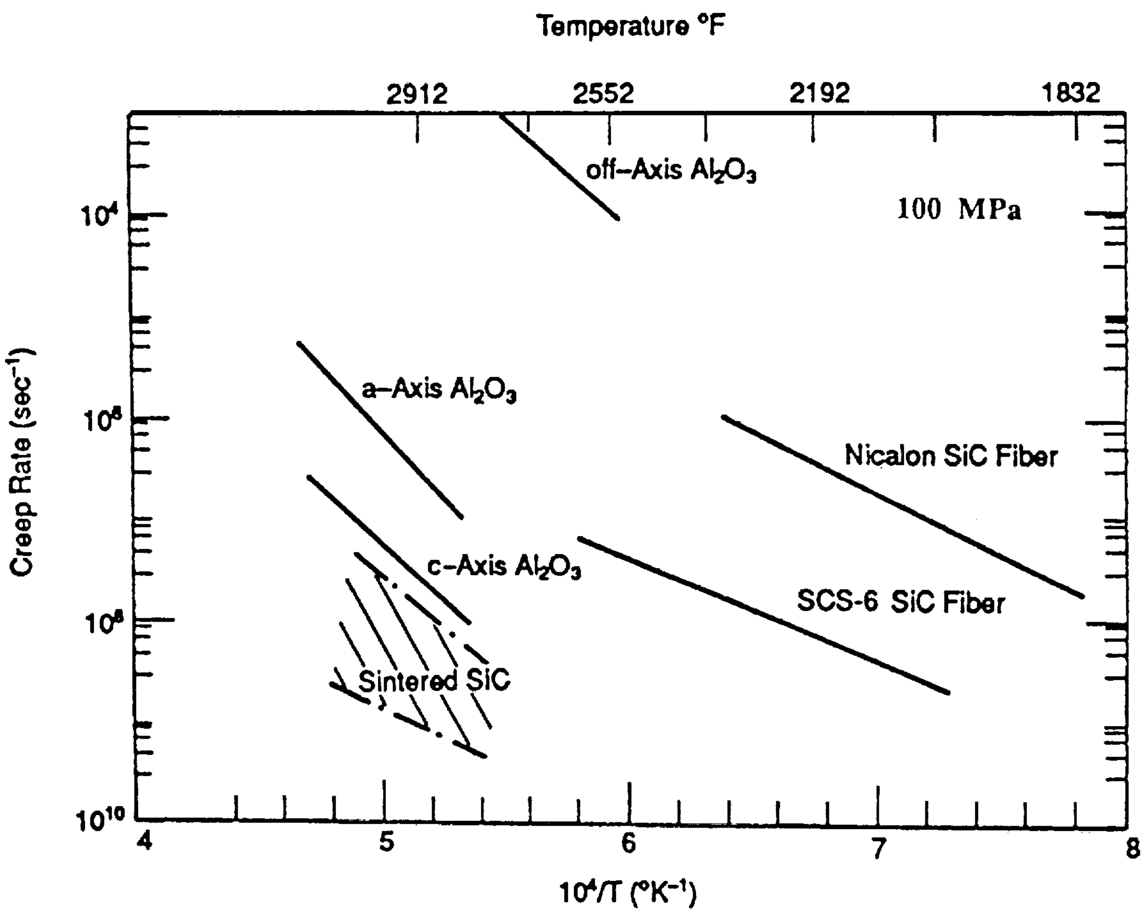


Figure 11

Candidate Ceramic Matrix Composite Processing Methods

In recent years, a number of manufacturing methods have been developed for the fabrication of CMC composite systems. A summary of major CMC fabrication processes is detailed in Figure 12. The most mature CMC fabrication technologies are CVI (chemical vapor infiltration) and hot pressing. The CVI process , liquid infiltration/reaction, liquid metal oxidation/reaction and polymer pyrolysis processing methods have the capability to produce near net shape CMC components, and are the primary processing approaches for HSCT liner fabrication. Processing is an integral part of CMC development and must be addressed concurrently with the combustor material and design development. Processing routes may vary widely depending on the matrix, fiber architecture (2D vs 3D), fiber type (monofilament vs tow) and fiber coating.

CMC Process	Matrix	Advantages
Chemical Vapor Infiltration (CVI)	SiC, Si_3N_4, $MoSi_2$	Complex Shape Capability, Industrial Base Exists
Liquid Infiltration/Reaction	SiC/Si, $MoSi_2$	Low Porosity, Complex Shape Capability
Hot Pressing/HIP	SiC, Si_3N_4, $MoSi_2$	Low Porosity, High X-Ply Strength
Direct Oxidation/Reaction of Metals	Al_2O_3, Si_3N_4, AlN	Low Porosity, Shape Capability, Low Cost
Reaction Bonding/HIP	Si_3N_4, SiC	Dense Matrix, Reasonable Shape Capability
Polymer Precursor	Si_3N_4,SiC	ComplexShape Capability, Low Cost, Industrial Base

Figure 12

Summary

The development of improved CMC materials will be critical for meeting the performance and durability goals of the HSCT combustor. High conductivity, high strength SiC and Si_3N_4 composite systems have the potential to meet current projected combustor requirements. Enhancement of SiC fiber capability is needed to increase high temperature strength retention and composite creep resistance. Fiber matrix interface control through the use of a debond coating will be required to achieve the required composite fracture toughness. If the rich burn/lean (RBL) combustor design approach is selected for the HSCT combustor, then the environmental issues of SiO_2-forming, SiC and Si_3N_4 composite systems must be addressed. The temperature capability of these CMC systems can be increased by the use of protective and insulative coatings. Processing development will be pivotal in meeting the goals and requirements of the combustor, and must be concurrently addressed and integrated with material and component design.

- **Ceramic Matrix Composites Have Required High Temperature Capability**
- **High Thermal Conductivity SiC and Si3N4 Composite Systems Are Primary Candidates**
- **SiC Fiber Enhancements Needed To Provide Long Term, High Temperature Durability**
- **Fiber Coatings Will Be Required To Achieve Needed Fracture Toughness**
- **Rich Burn Combustion Environment May Limit Si02-Forming CMC System Capability**
- **CMC Processing Selection Will Be Driven By Material And Component Design**
- **Component Design/Material/Processing Development Must Be Integrated To Meet HSCT Schedules**

Figure 13

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