99-GT-395

BREAK

# THE EVALUATION OF CFCC LINERS AFTER FIELD-ENGINE TESTING IN A GAS TURBINE

Narendernath Miriyala, Jane F. Simpson,
Vijay M. Parthasarathy, and William. D. Brentnall
Solar Turbines Incorporated
San Diego, California

## ABSTRACT

In a program sponsored by the U.S. Department of Energy (DOE), Solar Turbines Incorporated is currently investigating the use of ceramics in industrial gas turbines by selectively replacing cooled metallic components with uncooled ceramic parts. As part of this program, Solar has developed CFCC (SiC/SiC) combustor liners and demonstrated their potential for low emissions in three field-engine tests for a total duration of over 3000 hours. The durability of the SiC/SiC liners appears to be primarily limited by surface recession, composite embrittlement and fiber degradation (particularly for CG-Nicalon). The microstructural, mechanical properties, and nondestructive evaluation of the CFCC liners after the three field tests are discussed in this paper.

## NOMENCLATURE

| | |
|---|---|
| ACI | AlliedSignal Composites Incorporated, Newark, DE |
| ANL | Argonne National Laboratory, Argonne, IL |
| ARCO | Atlantic Richfield Company |
| AS-800 | AlliedSignal Ceramic Components Silicon Nitride |
| BFG | BFGoodrich Aerospace, Santa Fe Springs, CA |
| BN | Boron Nitride |
| CVD | Chemical Vapor Deposition |
| CVI | Chemical Vapor Infiltration |
| CC | AlliedSignal Ceramic Components |
| Centaur 50S | Solar Model Centaur 50 Gas Turbine with SoLoNOx Combustor |
| CFCC | Continuous Fiber-reinforced Ceramic-matrix Composite |
| CG-Nicalon | Ceramic grade Nicalon (SiC) fibers made by Nippon Carbon Company, Japan |
| CO | Carbon Monoxide |
| CSGT | Ceramic Stationary Gas Turbine |
| DLC | DuPont Lanxide Composites, Newark, DE |
| DOE | U.S. Department of Energy |
| EBC | Environmental Barrier Coating |
| H₂O | Water |

| | |
|---|---|
| Hi-Nicalon | Hi-Nicalon grade SiC fibers made by Nippon Carbon Company, Japan |
| MI | Melt-Infiltrated |
| NDE | Nondestructive Evaluation |
| Nextel 440 | $Al_2O_3$-$SiO_2$-$B_2O_3$ fiber-fabric made by 3M Ceramic Fiber Products, St. Paul, MN |
| NOx | Oxides of Nitrogen |
| ORNL | Oak Ridge National Laboratory, Oak Ridge, TN |
| OIT | Office of Industrial Technologies |
| ppmv | Parts Per Million by Volume |
| PIG | Peak In the Gate |
| PyC | Pyrolytic Carbon |
| SiC | Silicon Carbide |
| TRIT | Turbine Rotor Inlet Temperature |

## INTRODUCTION

The use of ceramic components in the hot section of a gas turbine engine can result in a significant increase in TRIT, which translates into greater power output than that of all-metal engines. This would also eliminate the need for complex and expensive cooling schemes (Anson et al., 1992; van Roode et al., 1995a). The reduced cooling requirements, in turn, increase the thermal efficiency of the engine. Moreover, the incorporation of uncooled ceramic liners in the combustor of an industrial gas turbine has the potential for lowering NOx emissions to < 10 ppmv and CO emissions to 25 ppmv or less, from the current levels of about 25 ppmv NOx and 50 ppmv CO obtained by the use of the state-of-the-art "wet" or "dry" low-NOx technologies (Anson et al., 1993; van Roode et al., 1995a).

In pursuance of its mission to conserve the nation's energy resources and reduce environmental pollution, the U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT), initiated a program to develop and demonstrate a ceramic stationary gas turbine (CSGT) for power-and-steam cogeneration operation. Solar Turbines Incorporated (Solar) is the prime contractor on the program, with participation from major ceramic component suppliers, research

laboratories and an industrial cogeneration end user. The main objective of the program is to demonstrate ceramic technology by selective replacement of cooled metallic hot-section components by ceramic parts (blades, nozzles and combustor liners).

Phase I of the CSGT program involved preliminary engine and component design, ceramic materials selection, technical and economic considerations, and concept assessment (van Roode et al., 1993). Under Phase II of the program, detailed engine-and-component design and component testing were performed (van Roode et al., 1994, 1995b, 1996, 1997; and Price et al., 1998). Two SiC monolithic ceramics and two CFCCs ($Al_2O_3/Al_2O_3$ and SiC/SiC) were investigated during this phase for the combustor liner application (Simpson et al., 1997). In Phase III of the program, currently in progress, engine tests are being performed at a cogeneration site (ARCO Western Energy, Bakersfield, CA). To date, three field-engine tests were performed at the ARCO site. In the first two tests, the CSGT was retrofitted with monolithic ceramic ($Si_3N_4$) blades and CFCC (SiC/SiC) combustor liners. Only CFCC (SiC/SiC) combustor liners were used in the third field test. The evaluation of the CFCC liners after the three field tests is the focus of this paper.

## COMBUSTOR LINER DEVELOPMENT

The intent of the CSGT combustor design effort was to effectively retrofit the two metallic cylinders (inner liner and outer liner) in the Centaur 50S annular combustor with ceramic components. Details of the combustor design can be found in Smith and Fahme, 1996 and 1997. In brief, the two liners form the primary combustor zone, and operate under the most severe operating conditions, including high flame temperatures and direct flame impingement (due to the swirling flow exiting the injectors). Based on a series of subscale combustor rig tests, SiC/SiC composite was chosen over monolithic SiC for field-engine test evaluation (Simpson et al., 1997). In the current design, the nominal dimensions of the inner liner are 33 cm inner diameter, 20 cm height and 0.25 cm thickness. The corresponding dimensions for the outer liner are 76 cm, 20 cm and 0.25 cm. The CFCC liners are encased in a metallic

housing, and Nextel 440 fabric is used as a compliant insulation layer between the liners and the metallic housing. The outer surface of the inner liner and the inner surface of the outer liner form the working surfaces in the combustor. A schematic of the CSGT hot section showing the location of the combustor liners is shown in Figure 1. The CFCC liners experience only thermal stresses, which are designed to be below the proportional limit of the composite material. The combustor liners used in the first field test were made of CG-Nicalon/SiC composite. In the second and third field tests, Hi-Nicalon/SiC liners were tested.

## FABRICATION OF CFCC LINERS

### CG-Nicalon/SiC Liners

The CG-Nicalon/SiC combustor liners were fabricated by ACI (formerly DLC). The composite system consisted of a 5-harness satin-weave fabric, a pyrolitic carbon (PyC) interface, and an enhanced-SiC matrix deposited by a CVI process. After the completion of matrix infiltration, a seal coat of SiC (approximately 0.05 mm thick) was applied to both liners, using a CVD technique. The average thicknesses of the inner and outer liners were approximately 2.6 mm and 3.9 mm, respectively. The fiber volume fraction in the two liners was approximately 0.35 to 0.40. A photograph of the CG-Nicalon/SiC inner and outer liners is presented in Figure 2.

### Hi-Nicalon/SiC Liners

The Hi-Nicalon/SiC liners were also made by ACI, using the same fabric-architecture and matrix as that of the CG-Nicalon/SiC liners. However, the interfacial coatings used in the fabrication of the two Hi-Nicalon/SiC liners were different. Boron nitride (BN) and PyC were used as the fiber-matrix interlayer in the fabrication of the inner liner and outer liner, respectively. A seal coat of SiC was applied on the two liners at the end of the enhanced-SiC matrix infiltration. The average seal coat thickness on the inner liner was approximately 0.225 mm. The corresponding value for the outer liner was estimated to be 0.15 mm. The
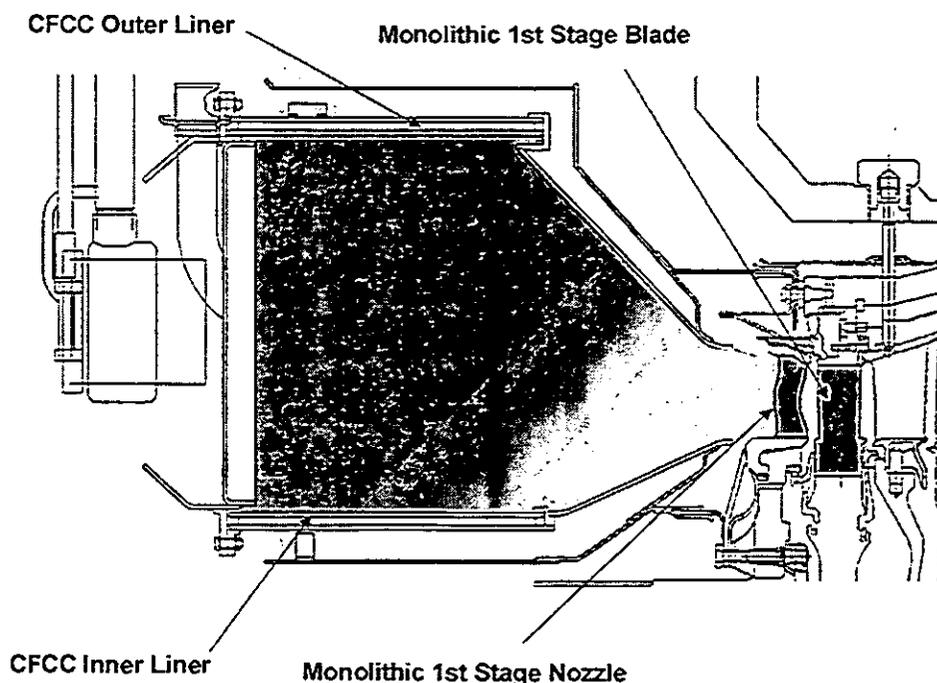
**CFCC Outer Liner**          **Monolithic 1st Stage Blade**

**CFCC Inner Liner**     **Monolithic 1st Stage Nozzle**

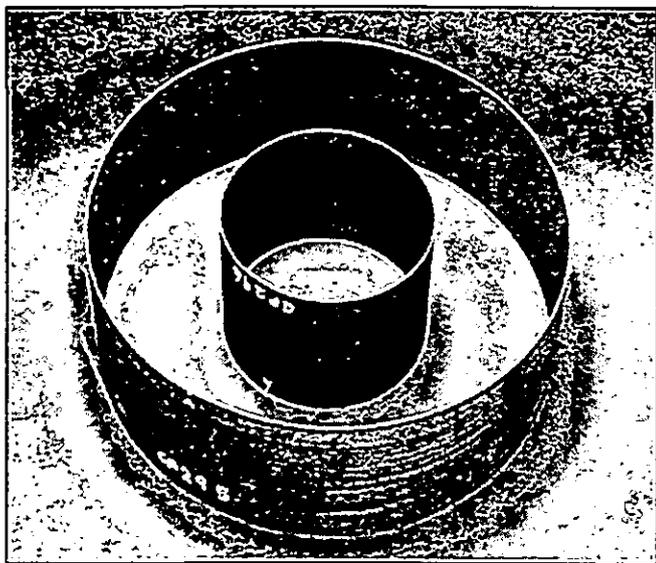**Figure 1.  Schematic of CSGT Hot Section**

**Figure 2. CG-Nicalon/SiC Combustor Liners in the As-received Condition**

average thicknesses of the inner and outer liners were approximately 2.9 mm and 2.7 mm, respectively. In both liners, the fiber volume fraction was about 0.4.

## NONDESTRUCTIVE EVALUATION OF CFCC LINERS

Before and after the field tests, the CFCC liners were examined for major defects (such as pores, cracks and delaminations), at Argonne National Laboratory (ANL), Argonne, IL and University of Wisconsin, LaCrosse, WI. An infrared thermal diffusivity image technique, and an air-coupled ultrasonic method were used to examine the liners in an on-going effort to build a database on the efficacy of the two techniques to detect flaws in CFCCs. The two NDE techniques are described in detail in Ellingson et al., 1995 and Sun et.al., 1998. In short, the thermal image technique uses the method of Parker et al. (1961) to calculate the thermal diffusivity of a specimen. The front surface of the specimen is heated instantaneously using infrared light, and the heat conduction through the specimen is measured by the speed of temperature rise on the back surface. The thermal diffusivity of the specimen is calculated using the "half-rise time," which is defined as the time it takes for the back-surface temperature to reach half of its maximum value. The defects in the material, such as cracks and delaminations, result in low thermal diffusivity values, since the diffusivity of the air gap is low.

The air-coupled ultrasonic system uses a conventional C-scan setup with the transmitting and receiving transducers arranged in coaxial transmission geometry. The acoustic waves incident on the specimen surface travel through the material and are captured by the receiving transducer. The signals received by the receiving transducer are first pre-amplified by a low-noise high-gain pre-amp attached to the back of the receiver. These signals are then gated and amplified further, and the average peak-in-the-gate (PIG) is used to produce a digital image in a 16-color coded scale. Depending on the physical properties of the material, images of different colors are produced. The through-transmission amplitude of the ultrasound through defects, such as pores, delaminations and cracks, will be higher than that of the acoustic waves through defect-free regions in the specimen.

## FIELD TESTS AT ARCO

The first field-engine test started in May 1997 at the ARCO site,

with first-stage monolithic ceramic (CC AS-800) blades and CFCC (ACI's CG-Nicalon/SiC) combustor liners. The CSGT Centaur 50 SoLoNOx engine retrofitted with the ceramic parts operated at a TRIT of 1010°C. The engine functioned normally, cogenerating electrical power and steam. The emission levels measured at 50-100 % load operation were < 15 ppmv NOx and and < 10 ppmv CO. Borescope inspection of the liners was performed after 212 hours and 533 hours of engine operation in the field. After 533 hours, visible degradation (formation of "white glass") was apparent on the outer surface of the inner liner. In contrast, the white glass formation was not observed on the inner surface of the outer liner. The engine shut down after 948 hours of field operation due to the foreign object damage (FOD) of the first-stage ceramic blades. However, the CFCC combustor liners were intact and could be easily removed from the engine for evaluation. Before the CSGT was installed at the ARCO site, the engine was subjected to a 100-hour acceptance test at Solar. Thus, the monolithic blades and CFCC liners were exposed to engine conditions for a total of 1048 hours.

The second field test with retrofitted ceramic parts started in February 1998. The material choice for the first-stage ceramic blades was the same as for the first field test (CC AS-800). However, the CG-Nicalon/SiC combustor liners were replaced by Hi-Nicalon/SiC liners in this test. The CSGT operated at full load for 352 hours at a TRIT of 1010°C, until the FOD of the first-stage ceramic blades occurred. At the end of this test, the Hi-Nicalon/SiC liners were in good condition, with no visible signs of white glass formation. The NOx and CO levels measured were similar to those in the first field test.

The Hi-Nicalon/SiC liners from the second field test were reused in the third field test at the ARCO site, which began in May 1998 with the CFCC liners as the only ceramic components in the engine. Borescope inspection of the liners was performed after 976, 1270, 1550, 1884, 1994 and 2114 hours of cumulative field-engine operation (second and third field tests) with the Hi-Nicalon/SiC liners. The degradation of the outer liner (the formation of white glass patches in line with the gas impingement from the injectors) was apparent after 1270 hours of exposure to the combustion environment.

On further engine testing, some of the white glass patches grew in size. However, the white glass patches were confined to only the top half of the outer liner (above the engine centerline). No white glass formation was observed in the bottom half of the outer liner (below the engine centerline). The discrepancy in the preferential formation of white glass was attributed to nonuniform heat conduction from the outer liner to the metallic housing. Due to the difference in thermal expansivities of the metallic housing and the CFCC material, it appeared that the outer liner had shifted radially towards the bottom of the combustor. As a result, there was good heat conduction from the bottom half of the outer liner to the metallic housing through the Nextel 440 insulation layer. Concomitantly, there was an air gap between the top half of the outer liner and the metallic housing. This appeared to have resulted in the top half of the outer liner operating at a significantly higher temperature than its bottom half. On the outer surface of the inner liner, the white glass formation was observed after 2114 hours of field-engine testing. At this point, it was decided to stop the field test, so that the recession of the SiC seal coat in the engine environment could be correlated to that observed in a simulated combustion environment furnace (15% steam + 85% air, 10 atmospheres pressure, 1204°C) at ORNL (More et al., 1998). The third field test was stopped after the Hi-Nicalon/SiC liners were field-engine tested for a total of 2258 hours. Prior to the installation of CSGT at the ARCO site for the second and third field tests, the engine was subjected each time to a 4-hour acceptance test at Solar. Thus, the Hi-Nicalon/SiC liners were exposed to engine conditions for a total of 2266 hours.

3

## POST FIELD-TEST EVALUATION OF CFCC LINERS

### CG-Nicalon/ SiC liners

After the CG-Nicalon/SiC liners were exposed to the combustion environment for a total of 1048 hours, white glass bubbles were observed on the outer surface of the inner liner. On the inner surface of the outer liner, twelve white glass patches in line with the fuel injector paths were observed. Thermal imaging of the inner liner revealed that the diffusivity values for all areas of the inner liner after engine testing were significantly lower as compared to those in the as-fabricated condition. Correspondingly, for the outer liner, in areas where the white glass patches were observed, the thermal diffusivity values after the engine test were significantly lower than those before the test. A reasonable correlation was observed between the thermal and air-coupled ultrasonic images of the two liners. The areas of low diffusivity in the thermal images corresponded well to the high through-transmission regions in the dry-coupled ultrasonic images.

After the completion of NDE, the two liners were sectioned for microstructural characterization and residual mechanical properties measurement. Micrographs of representative sections from the inner and outer liner are shown in Figure 3. The recession (loss in thickness) of the inner liner was measured to be 0.5 mm (approximaely 20% of the thickness of the as-fabricated component). In contrast, the recession of the outer liner was very low (< 0.1 mm) and confined to the areas in direct alignment with the fuel injectors. Silica (cristobalite) formation was observed at the sub-surface pores of both liners. Further, thermal degradation of the CG-Nicalon fibers was observed, particularly near the outer surface of the inner liner (More et al., 1998). During the field test, the temperature profile on the working surfaces of the two liners was monitored by using K-type thermocouples. Five thermocouples, which were aligned along the combustor axis, were used to measure the temperature profile of each liner. The maximum temperature recorded on the working surfaces of the inner and outer liners was approximately 1187°C. However, most of the thermocouples failed in the early part of the field test. Based on the observed recession values, it was speculated that the inner liner operated at a temperature of 1260°C or higher, and the outer liner about 50 to 75°C cooler than the inner liner. The residual tensile strength of coupons sectioned from the two liners was approximately 40 to 60% of that of the original (unexposed) material strength.

### Hi-Nicalon/SiC liners

The outer surface of the inner liner and the inner surface of the outer liner after 2266 hours of exposure to engine conditions are shown in Figures 4 and 5, respectively. Some areas of heavy oxidation (white glass patches) were observed on the outer surface of the inner liner (Fig. 4) and the inner surface of the outer liner (Fig. 5). Thermal images of the inner liner before and after engine testing are presented in Figure 6. The areas of reduced thermal diffusivity after exposure to the combustion environment correlated to the areas of heavy oxidation. In accordance with the lower diffusivity regions in the thermal images of the inner liner after exposure to the engine conditions, the ultrasonic transmission was significantly higher than that of the liner in the as-received condition.

To correlate the CFCC material behavior to that in a simulated combustion environment furnace at ORNL, the inner liner was sectioned for detailed study. Microstructural examination revealed that the maximum recession of the inner liner (about 0.4 mm) was in the region where the white glass patches were observed on the outer surface (Fig. 7). The recession of the liner in this region consisted of 0.2 mm each of the SiC seal coat and the Hi-Nicalon/SiC composite. Silica (cristobalite) formation was observed in the white glass patches, as well as at sub-surface pores. As in the first field test, the temperature on the working
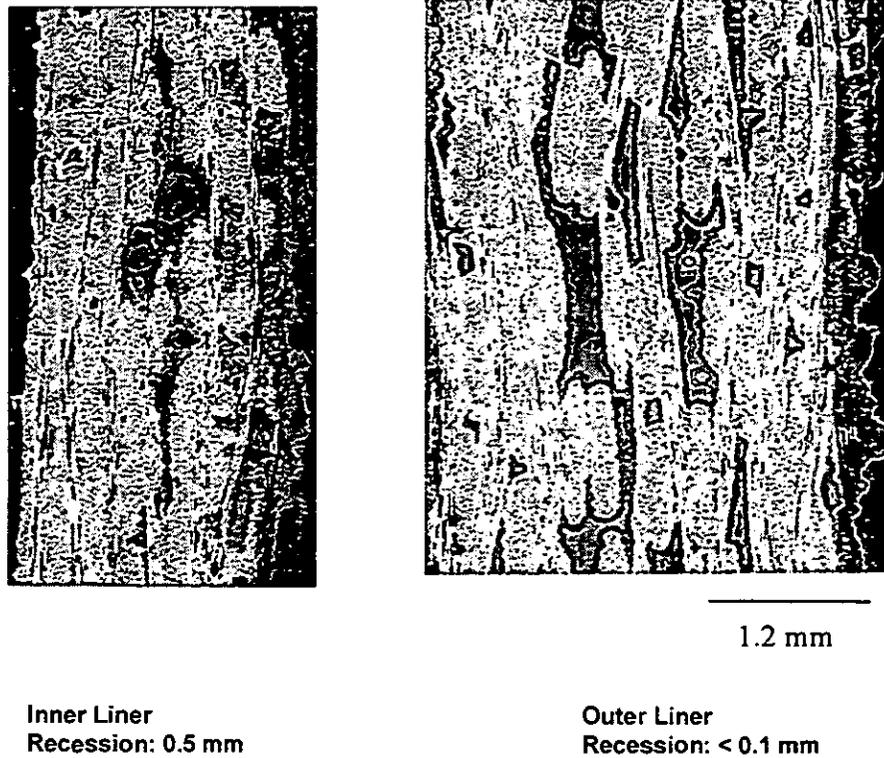


1.2 mm

Inner Liner
Recession: 0.5 mm

Outer Liner
Recession: < 0.1 mm

Figure 3.  Representative Cross-Sections of the CG-Nicalon/SiC Liners After
1048 Hours Exposure to the Combustion Environment
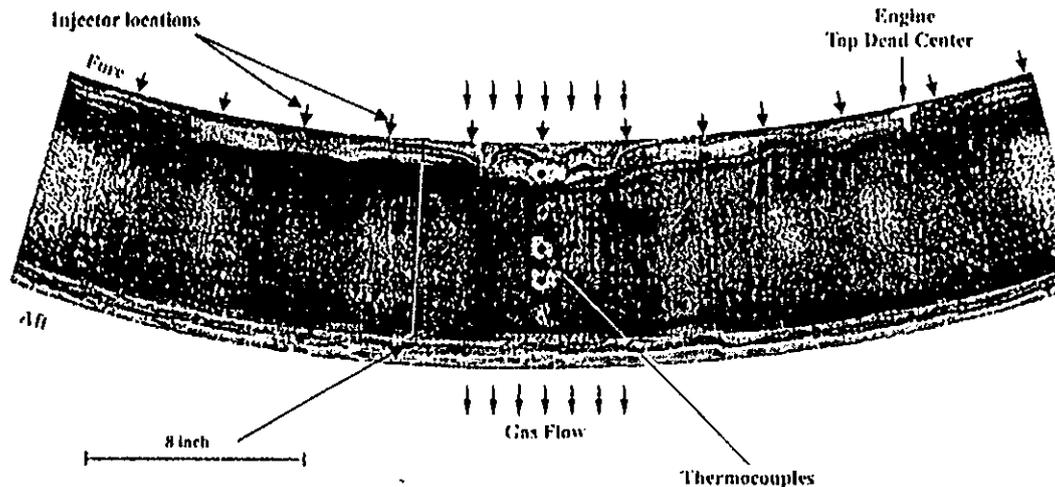
**Figure 4. The Outer Surface of the Hi-Nicalon/SiC Inner Liner After 2266 Hours Exposure to the Combustion Environment**
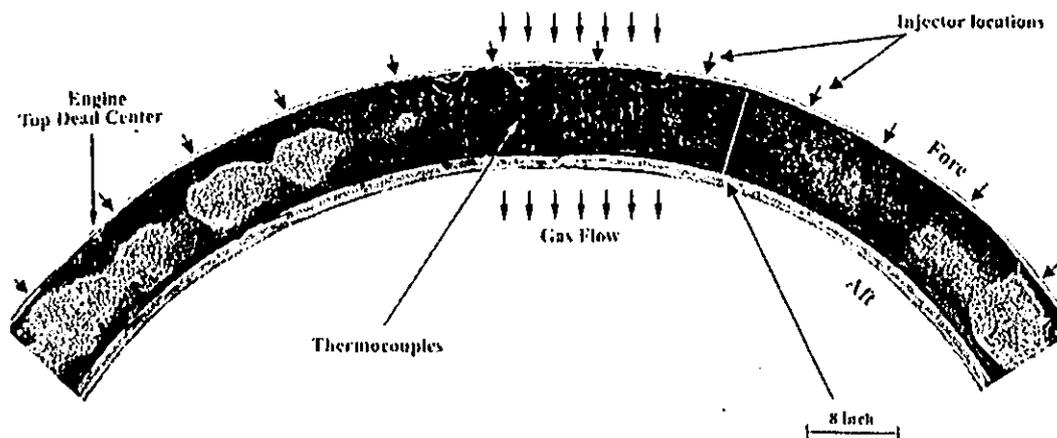


**Figure 5. The Inner Surface of the Hi-Nicalon/SiC Outer Liner After 2266 Hours Exposure To the Combustion Environment**

surfaces of each liner was also measured by using five K-type thermocouples aligned along the combustor axis. It turned out that the thermocouples were located in the relatively cooler regions of both liners (where there were no white glass patches). Many of the thermocouples failed in the early part of engine testing. The highest temperature recorded on the inner and outer liners in the first few hundred hours of the third field-engine test was 1175°C. The maximum recession of the inner liner near the thermocouples, after 2266 hours of exposure to engine environment, was approximately 0.2 mm (close to the average SiC seal coat thickness). In the ORNL furnace, the recession of the SiC seal coat at 1204°C was approximately 0.05 mm per 500 hours exposure in the simulated combustion environment. Apparently, the furnace tests at ORNL simulated our combustion environment reasonably well.

Flexure and tension tests were performed at room temperature on specimens obtained from different areas of the inner liner. The residual flexural strength of the composite in the region of heavy oxidation (white glass patches) was about 30 to 35 % of the relatively unoxidized material (specimens obtained from the aft and fore ends of the liner, which were encased in the metallic housing). Tension tests also indicated that the formation of white glass on the outer surface of the inner liner resulted in a significant reduction in the strength of the composite material.

It is well known that SiC/SiC composites show good oxidation resistance and mechanical properties retention when exposed to dry air at atmospheric pressure for a short time (a few hours). However, the presence of $H_2O$ in the combustion environment accelerates the oxidation of SiC (Jacobson, S. J., 1993). Apparently, the accelerated oxidation of SiC by the high pressure, high moisture containing combustion gases flowing at relatively high velocities has resulted in significantly lower residual mechanical properties of the CG-Nicalon/SiC and Hi-Nicalon/SiC liners, particularly in the areas containing the white glass patches.

Based on the evaluation of the SiC/SiC liners after the three field-engine tests, it appeared that the damaging mechanisms responsible for the degradation of the CFCC liners were surface recession, oxidation embrittlement of the composite and fiber degradation (especially for CG-Nicalon). For longer durability, it is evident that the SiC/SiC liners must be protected with environmental barrier coatings (EBCs). Solar is currently investigating the behavior of several promising EBCs in the simulated combustion environment furnace at ORNL. The durability of the SiC/SiC liners can also be increased by reducing the hot-wall temperature through the use of more efficient cooling methods, so as to increase the heat conduction from the liners to the metallic housing.

**FUTURE PLANS**

The outer liner used in the second and third field tests will be reused in the next field test at ARCO, which is scheduled to start in December

5

(a)

Top Dead Center



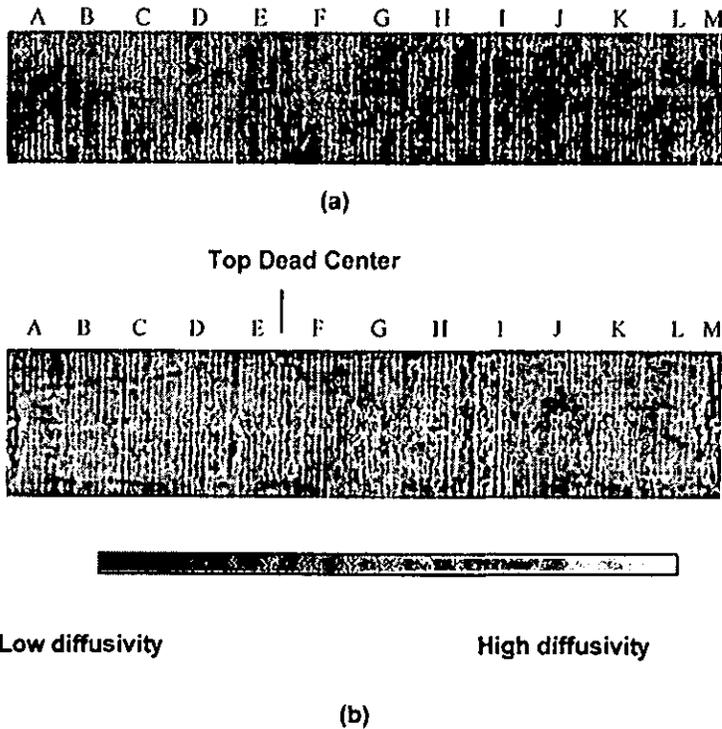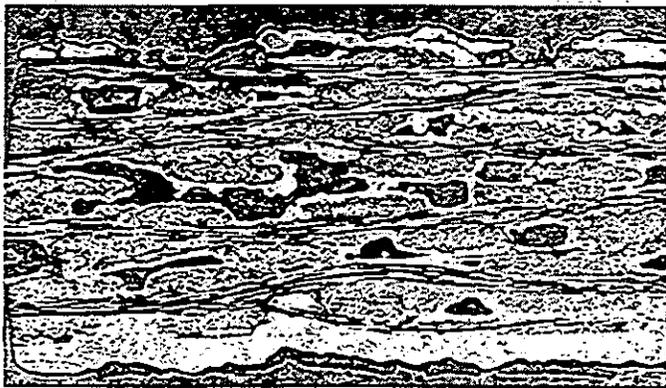Low diffusivity                    High diffusivity

(b)

**Figure 6.  Thermal Diffusivity Images of the Hi-Nicalon/SiC Inner Liner: (a) in the As-fabricated Condition, and (b) after 2266 Hours Exposure to the Combustion Environment**



1 mm

**Figure 7.  Representative Cross-Section of the Hi-Nicalon/ Inner Liner After 2266 Hours Exposure to the Combustion Environment**

1998. A BFG Hi-Nicalon/melt infiltrated (MI) SiC inner liner will be used in this test. In the subsequent field tests, it is planned to use SiC/SiC liners protected with EBCs.

## SUMMARY

SiC/SiC liners were successfully field-engine tested in an industrial gas turbine for over 3000 hours, demonstrating the potential for significantly lower NOx and CO emissions than that of the currently used all-metal engines. In the first field-engine test, CG-Nicalon/SiC liners with a thin SiC seal coat were used. After exposure to the combustion environment for 1048 hours, thermal degradation of the CG-Nicalon

fibers was observed. The maximum recession of the inner liner was 0.5 mm. In the second and third field tests, the CG-Nicalon liners with thinner seal coat were replaced with Hi-Nicalon/SiC liners with thicker seal coat. The maximum recession of the Hi-Nicalon inner liner after 2266 hours of exposure to engine conditions was 0.4 mm. It appears that the durability of the SiC/SiC liners in industrial gas turbines is determined primarily by surface recession, composite embrittlement and fiber degradation (particularly for CG-Nicalon). Successful development and application of EBCs is necessary for improved performance of SiC-based materials in the combustion environment.

## ACKNOWLEDGMENTS

## REFERENCES

Anson, D., Sheppard, W. J. and Parks, Jr., W. P., 1993, "Advanced Small Gas Turbines for Cogeneration," paper presented at the 7th Congress and Exposition: Gas turbines in Power Generation and Utility, Industrial and Independent Power Generation," Bournemouth, England, U.K., September, 1993.

6

Anson, D., Parks, Jr., W. P., Evensen, O., and van Roode, M., 1992 "Impact of Ceramic Components in Gas Turbines for Industrial Cogeneration," ASME Paper 92-GT-393, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Cologne, Germany, June, 1992.

Ellingson, W. A., Rothermal, S. A., and Simpson, J. F., 1995, "Nondestructive Characterization of Ceramic Composites Used as Combustor Liners in Advanced Gas turbines," ASME Paper 95-GT-404, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, Texas, June, 1995.

Jacobson, N. S., 1993, "Corrosion of Silicon-Based Ceramics in Combustion Environments," Journal of the American Ceramic Society, Vol. 76, No. 1, 1993, pp. 3-28.

More, K. L., Tortorelli, P. F., Ferber, M. K., Keiser, J. R., Walker, L. R., Geer, T. S., Miriyala, N., Brentnall, W.D., and Price, J. R., 1998, "Exposure of Ceramics and Ceramic Matrix Composites in a Simulated Combustion Environment," paper to be presented at the International Gas Turbine and Aeroengine Congress and Exhibition, Indianapolis, Indiana, June, 1999.

Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L., 1961, "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity," Journal of Applied Physics, Vol. 32, pp. 1679-1684, 1961.

Price, J.R., Jimenez, O., Faulder, L., Edwards, B., and Parthasarathy, V., 1998 "Ceramic Stationary Gas Turbine Development Program – Fifth Annual Summary," ASME Paper 98-GT-181, presented at the International Gas Turbine and Aeroengine Congress and Exhibition, Stockholm, Sweden, June, 1998.

Simpson, J. F., Parthasarathy, V. M., Pillai, T. A. K., Deemer, C., Ellingson, W. A., 1997, "Testing of Monolithic Ceramics and Fiber Reinforced Ceramic Composites for Gas Turbine Combustors," Ceramic Engineering and Science Proceedings, Vol. 18, No. 4, 1997, pp. 229-238.

Smith, K. O., and Fahme, A., 1996, "Experimental Assessment of the Emissions Benefits of a Ceramic Gas Turbine Combustor," ASME Paper 96-GT-318, presented at the International Gas Turbine and Aeroengine Congress and Exhibition, Birmingham, U K., June, 1996.

Smith, K., and Fahme, A., 1997, "Testing of a Full Scale, Low Emissions, Ceramic Gas Turbine Combustor," ASME Paper 97-GT-156, presented at the International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, Florida., June, 1997.

Sun, J. G., Petrak, D. R., Pillai, T. A. K., Deemer, C., and Ellingson, W. A., 1998, "Nondestructive Evaluation and Characterization of Damage and Repair for Continuous Fiber Ceramic Composite Panels," paper presented at the 22nd Annual Cocoa Beach Conference and Exposition, Cocoa Beach, Florida, January, 1998.

van Roode, M., Brentnall, W. D., Norton, P. F., and Pytanowski, G. P., 1993, "Ceramic Stationary Gas Turbine Development," ASME Paper 93-GT-309, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Cincinnati, Ohio, June, 1993.

van Roode, M., Brentnall, W. D., Norton, P. F., and Boyd, G. L., 1994, "Ceramic Stationary Gas Turbine Development," ASME Paper 94-GT-313, presented at the International Gas Turbine and Aeroengine Congress and Exposition, The Hague, Netherlands, June, 1994.

van Roode, M. V., Rohy, D. A., Waslo, S. and Parks, Jr., W. P., 1995a, Paper 95-YOKOHAMA-IGTC-127, presented at 1995 Yokohoma International Gas Turbine Congress held in Yokohoma, Japan, October, 1995.

van Roode, M., Brentnall, W. D., Norton, P. F., and Edwards, B. D., 1995b, "Ceramic Stationary Gas Turbine Development," ASME Paper 95-GT-459, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, Texas, June, 1995.

van Roode, M., Brentnall, W. D., Smith, K. O., Edwards, B. D., and Norton, P. F., 1996, "Ceramic Stationary Gas Turbine Development – Third Annual Summary," ASME Paper 96-GT-460, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Birmingham, U. K., June, 1996.

van Roode, M., Brentnall, W. D., Smith, K. O., Edwards, B. D., McClain, J., and Price, J. R. 1997, "Ceramic Stationary Gas Turbine Development – Fourth Annual Summary," ASME Paper 97-GT-317, presented at the International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, Florida., June, 1997.