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CERAMIC STATIONARY GAS TURBINE DEVELOPMENT PROGRAM -SIXTH ANNUAL SUMMARY-

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ABSTRACT

The Ceramic Stationary Gas Turbine (CSGT) program is being performed under the sponsorship of the United States Department of Energy, Office of Industrial Technologies. The objective of the program is to improve the performance of stationary gas turbines in cogeneration through the selective replacement of cooled metallic hot section components with uncooled ceramic parts. This review summarizes the progress on Phase III of the program which involves field testing of the ceramic components at a cogeneration end user site and characterization of the ceramic components following the field test exposure.

The Solar Centaur 50S engine, which operates a turbine rotor inlet temperature (TRIT) of 1010°C (1850°F), was selected for the developmental program. The program goals include an increase in the TRIT to 1121°C (2050°F), accompanied by increases in thermal efficiency and output power. This will be accomplished by the incorporation of uncooled ceramic first stage blades and nozzles, and a "hot wall" ceramic combustor liner. The performance improvements are attributable to the increase in TRIT and the reduction in cooling air requirements for the ceramic parts. The "hot wall" ceramic liners also enable a reduction in gas turbine emissions of NOx and CO.

The component design and material selection have been definitized for the ceramic blades, nozzles and combustor liners. Each of these ceramic component designs were successfully tested in short term engine tests in the Centaur 50S engine test cell facility at Solar. Based on the results of the engine testing of the ceramic components, minor redesigns of the ceramic/metallic attachments were conducted where necessary. Based on their performance in a 100 hour cyclic in-house engine test, the ceramic components are approved for field testing. To date, four field installations of the CSGT Centaur 50S engine totaling over 4000 hours of operation have been initiated under the program at an industrial cogeneration site. This paper discusses the component design and material selection, in house engine testing, field testing, and component characterization.

NOMENCLATURE

ACI	AlliedSignal Composites Inc.
AGT	Advanced Gas Turbine
ARCO	Atlantic Richfield Company
AS-800	AlliedSignal Ceramic Components Silicon Nitride
ATTAP	Advanced Turbine Technology Applications Program
BFG	B.F. Goodrich Aerospace
CC	AlliedSignal Ceramic Components
Centaur 50S	Solar Model Centaur 50 Gas Turbine with SoLoNOx Combustor
CFCC	Continuous Fiber-reinforced Ceramic Composites
CO	Carbon Monoxide
CSGT	Ceramic Stationary Gas Turbine
CVI	Chemical Vapor Infiltration
DOE	United States Department of Energy
EBC	Environmental Barrier Coating
FPI	Fluorescent Penetrant Inspection
KICC	Kyocera Industrial Ceramics Corporation
NDE	Nondestructive Evaluation
NGK	NGK Insulators, Ltd.
NOx	Oxides of Nitrogen
OIT	Office of Industrial Technologies
ORNL	Oak Ridge National Laboratory
ppmv.	Parts Per Million by Volume
TBO	Time Before Overhaul
TRIT	Turbine Rotor Inlet Temperature

INTRODUCTION

The application of ceramic components for gas turbine engine hot sections enables a significant improvement in engine performance. Because of their superior high temperature capability, uncooled ceramic hot section components allow an increase in the turbine rotor inlet

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temperature (TRIT) of standard all-metallic gas turbine engines, resulting in improved thermal efficiency, greater output power, and reduced emissions of NOx and CO. The benefits of ceramics for gas turbines have been well documented (Anson, et. al., 1991, 1992, 1993).

Because of the benefits achievable through the incorporation of ceramic materials into gas turbine engines, the U.S. Department of Energy (DOE) Office of Industrial Technologies (OIT) initiated a program aimed at developing and demonstrating a ceramic stationary gas turbine engine for industrial cogeneration operation. Solar Turbines incorporated is the prime contractor on the CSGT program team, which includes ceramic component suppliers, nationally recognized test laboratories, and an industrial cogeneration end user.

The CSGT program initiated in September of 1992, and is currently in the field testing phase of the program. Annual summaries of the CSGT program detailing the preliminary and detailed component designs, materials selection, concept assessment, technical and economic evaluation, specimen and component fabrication, non destructive evaluation, and component life prediction have been previously reported (van Roode et al., 1993, 19994, 1995, 1996, 1997, Price et al., 1998). This annual CSGT program summary discusses the field testing of the ceramic components and the design, development and in-house testing activities leading up to each field demonstration.

TECHNICAL APPROACH

The technology base for the CSGT program is provided by the advancements in ceramic component fabrication knowledge developed under past ceramic turbine programs, such as the Advanced Gas Turbine (AGT) Program and the Advanced Turbine Technology Applications Program (ATTAP) of the U.S. Department of Energy, Office of Transportation Technologies. The program strategy provides a strong focus on near-term ceramic turbine technology demonstration and lowering barriers for its acceptance by the marketplace. Applications include retrofitting existing gas turbine installations and incorporating ceramic component technologies in future engine designs. The ceramic turbine technology under development in this program is a key enabling technology to realize the performance and environmental goals of the Advanced Turbine Systems (ATS) program, a broad initiative of the U.S. Department of Energy, Office of Fossil Energy, and Office of Energy Efficiency and Renewable Energy, to develop the next generation of high performance gas turbines for utility and industrial applications (Report to Congress, 1994).

The engine selected for ceramic insertion under the CSGT program is the Centaur 50S engine. The baseline metal engine has a rated shaft thermal efficiency of 29.6% and an electrical output rating of 4144 kW and is fitted with a SoLoNOx dry, low NOx combustion system. The gas producer turbine of the all-metal Centaur 50S has two stages and the power turbine has one stage. A single-shaft configuration was selected for the development engine.

The Centaur 50S is being retrofitted with first stage ceramic blades and nozzles, and a ceramic combustor liner. A schematic of the Centaur 50S hot section is shown in Figure 1. The engine hot section was redesigned to adapt the ceramic parts to the existing metallic support structure. Accompanying the ceramic insertion the Centaur 50S is being uprated from its current TRIT of 1010°C (1850°F) to a TRIT of 1121°C (2050°F). The performance improvement goals include a relative increase in the electrical thermal efficiency of 5.6% in simple cycle and 5.3% in cogeneration, and an increase in the electrical output from 4144 kW to 5217 kW, representing a relative increase of about 25.9%. Newer engines of the all-metal Centaur 50S meet NOx emissions levels of 25 ppmv over the 50 to 100 percent load range. Under the program NOx emission levels of 25 ppmv or below must be demonstrated and have the potential for NOx levels of 10 ppmv or better. No CO target level was required for the program, but Solar has set a CO target of 25 ppmv. Predicted engine performance data have been reported previously (van Roode, et al., 1994).

Solar's approach to incorporating ceramics for industrial gas turbine design attempts to minimize the risks inherent in a still immature technology by using a set of guidelines which are consistent with current ceramic design practice. These include limiting the number of ceramic components, using proven ceramic design practice from past programs, selecting well characterized and promising candidate ceramic materials with potential for cost-effective scale up to production applications,

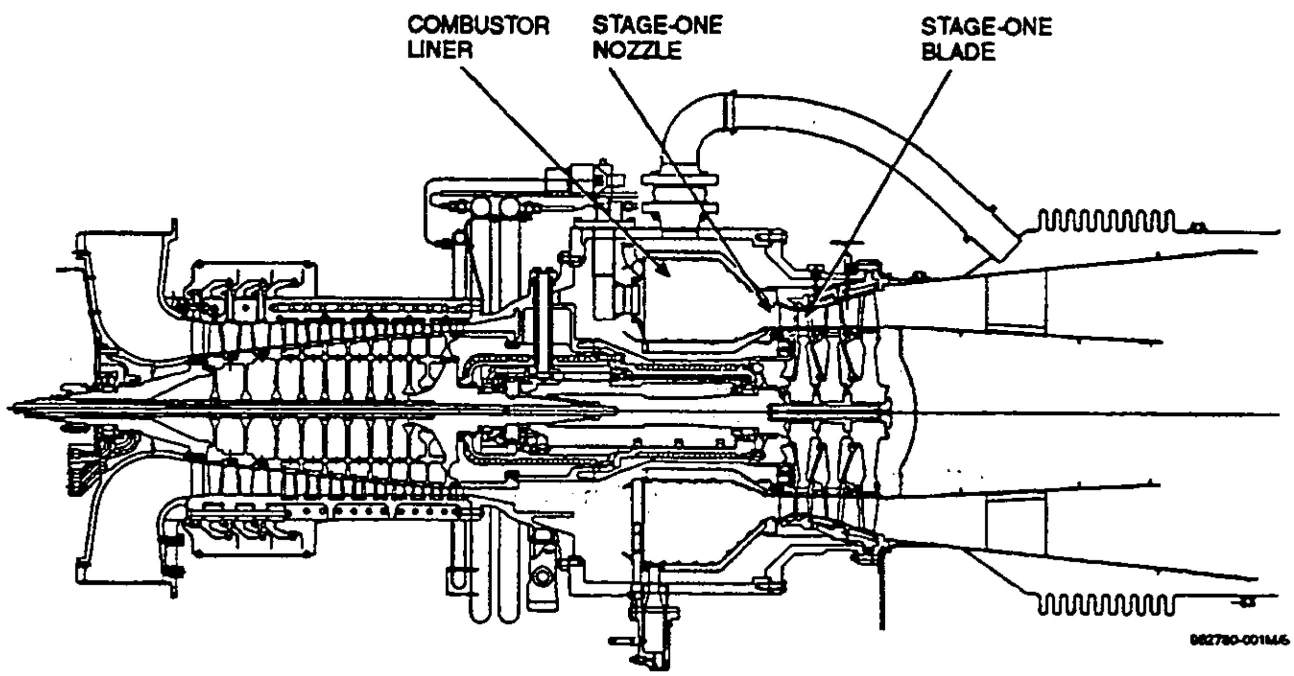

FIG. 1 - SOLAR 50S GAS TURBINE WITH COMPONENTS TARGETED FOR CERAMIC INSERTION

iterative testing with stepwise increases in firing temperatures to a modest final design TRIT, and minimizing transient and steady state stresses in the ceramic components and adjacent metal structures. The CSGT program has successfully tested ceramic component designs in an engine rig which duplicates all the conditions the ceramic components will experience during actual engine operation.

Solar's integrated design and test philosophy for ceramic insertion integrates a conservative "walk before you run" approach. In this approach, design analysis was iterated with life prediction, testing, and post-test component evaluation. In the first stage, simulated components were tested in rigs to prove key design concepts such as blade and nozzle attachment configuration, blade root compliant layers, and interfacing of ceramics to metallic support structures. In the second stage the findings from these tests were fed back into the design of first generation ceramic component prototypes which were then tested in a Centaur 50S engine modified to accept the ceramic parts. The results of the engine tests were then used to modify the ceramic part designs to the extent desired. In the final stage second generation parts with superior performance are selected for field testing at the industrial cogeneration end-user site. Details of the component testing including four field installations is given below.

COMPONENT DESIGN AND TESTING

CFCC Combustor Liners

The existing SoLoNOx combustor of the Centaur 50S engine was modified by integrating the ceramics in the linear sections of the combustor. The ceramic combustor was designed to be fully interchangeable with the production Centaur 50S dry low-NOx lean-premix (SoLoNOx) combustor. The combustor is comprised of a metallic dome section at the upstream end, two concentric continuous fiber-reinforced ceramic composite (CFCC) cylinders (in metal housings) that form the combustor primary zone, and two conical, metallic exit sections. The dome and exit sections are film cooled and are essentially identical to their all-metal production engine counterparts. A layer of compliant insulation between the ceramic liners parts and the metal housing minimizes radial contact stresses. The structural loads are carried by the metal housing. The inner and outer ceramic cylindrical liners shown in Figure 2 are 33 cm and 75 cm in diameter, respectively, and are 20 cm long. Their wall thickness is approximately 0.2-0.3 cm. The CFCC liners replace louvre-cooled Hastelloy X liners in the Centaur 50S combustor. Further details of the ceramic combustor design have been given elsewhere (Smith, et al., 1996, 1997).

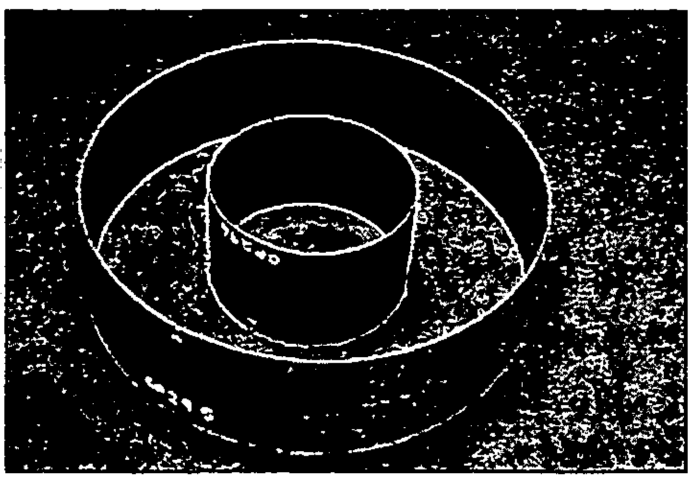

FIG. 2 - ENHANCED SiC/SiC CFCC COMBUSTOR LINERS FABRICATED BY ALLIED SIGNAL COMPOSITES, INC.

The CFCC liners under the program have primarily consisted of SiC/SiC composites manufactured by AlliedSignal Composites, Inc. (ACI) and BFGoodich Aerospace (BFG). Each CFCC combustor liner underwent extensive testing in laboratory rigs prior to engine testing. The initial screening of candidate combustor liner materials was performed using a subscale liner test in which key elements of the full scale combustor design are evaluated in a cost-effective but representative geometry. Full scale combustor rig testing was performed with an atmospheric combustor rig to establish that full scale liners can operate under the conditions of temperature that are anticipated in the engine environment. Subsequently, the liners were also tested in a pressurized full scale combustor rig to obtain an early assessment of emissions reduction potential. The liners were subsequently tested in the Centaur 50S engine. Gas turbine emissions in full scale engine tests have consistently been below the CSGT program goals of 25 ppmv NOx and 50 ppmv CO.

Prior to field testing, the CFCC liners are sent to Argonne National Laboratory (ANL) for non-destructive evaluation (NDE) and are then exposed to a 100 hour cyclic endurance test at Solar. The first field test of the CFCC combustor liners initiated in May 1997 at ARCO Western Energy (see Fig. 3) in Bakersfield, California. The CFCC liner material was ceramic-grade Nicalon enhanced-SiC/SiC (CVI) fabricated by ACI. The engine operated at the 1010°C (1850°F) TRIT of the standard all-metal engine to demonstrate performance under typical industrial operating conditions. The CSGT engine was fully operational with normal steam and electrical power production. Gas turbine emissions of below 15 ppmv NOx and 5 ppmv CO were consistent throughout the field test. The field test was terminated after 948 hours of field operation due to foreign object damage to the first stage AS-800 silicon nitride turbine blades. The CFCC liners remained intact, however oxidation of the SiC/SiC liners indicated a need for material improvements, combustor modifications to reduce CFCC wall temperature and environmental barrier coatings (EBC). Further details of this first field test were given in the fifth annual summary (Price, et al., 1997).

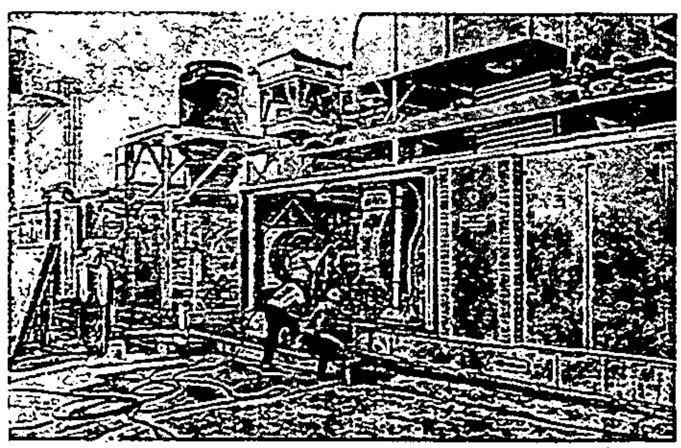

FIG. 3 - CSGT CENTAUR-50S ENGINE AT ARCO FIELD TEST SITE

A second field test of CFCC combustor liners initiated in March 1998. For this test, several changes were made to the CFCC combustor liner system in an attempt to reduce the oxidation of the enhanced

SiC/SiC liners experienced during the initial field test at ARCO. Design changes to the metallic portion of the liners to improve the conduction path from the CFCC liners to the metallic housings have resulted in reduced wall temperature for the CFCC liners. Material changes to the CFCC liners include using Hi-Nicalon fibers (which are stronger and more stable at higher temperatures and have higher thermal conductivity than the previous ceramic-grade Nicalon fibers), increasing the density of the CFCC liners, and increasing the thickness of the protective seal coat used for the CFCC liners. Both the inner and outer CFCC liner accrued 2258 hours of full load field operation at ARCO. Periodic boroscope inspections were conducted to track the oxidation of the liners. The field test exceeded the planned 2000 hours of exposure and was terminated in order to evaluate oxidized versus unoxidized areas of the CFCC liners. The liners remained fully intact following the test. Both liners showed surface oxidation at fuel injector impingement locations as shown in Figures 4 and 5. The inner liner underwent post-test NDE (thermal diffusivity and air-coupled ultrasound) at ANL prior to being sectioned for microscopic inspection of oxidized versus unoxidized areas. The CFCC material degradation from the field test closely matched the degradation encountered in simulated gas turbine environmental exposure testing at ORNL (More, et al., 1999), which enables the lower cost rig test at ORNL to be used to effectively screen various CFCC liner systems.

The microstructural examination of the inner liner indicated that the CFCC wall recession and fiber attack was minimal, and that the liner could have continued testing for at least 1500 additional hours. In order to further evaluate the degradation of the CFCC liners and to better understand the failure mechanisms of the CFCC liners, the decision was made to continue field testing of the outer liner. The information gained from additional testing will be valuable in helping predict the life of the CFCC liners in service.

The outer Hi-Nicalon enhanced SiC/SiC liner, which accrued 2258 hours of field operation, was installed in the CSGT Centaur 50S engine in preparation for additional field testing at ARCO. The inner liner for this field test is a Hi-Nicalon SiC/SiC liner fabricated by the melt infiltration process by BFG. This field test initiated in December 1998 and has accrued 851 hours of field operation as of January 19, 1999. The outer liner therefore has over 3100 hours of full load field operation, which is a significant milestone for the CSGT program as longer term (8000 hr) field exposures are planned for 1999.

Additional details of the rig and field testing of the CFCC liner materials is presented in a separate paper (Miriyala, et al., 1999). The next field test of CFCC combustor liners will contain environmental barrier coatings to further increase the life of the SiC/SiC CFCC liners.

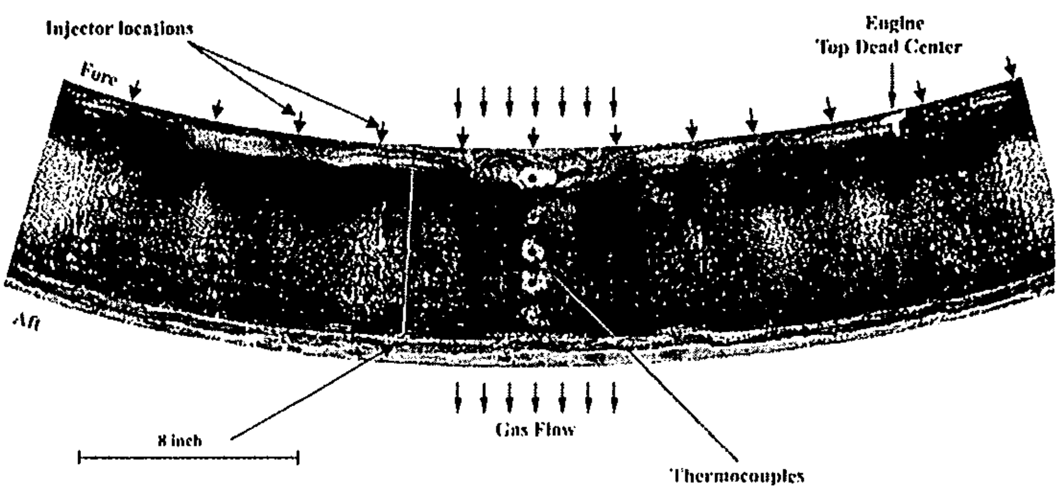

FIG. 4 - THE OUTER SURFACE OF THE HI-NICALON/SIC INNER LINER AFTER 2258 HOURS EXPOSURE TO THE COMBUSTION ENVIRONMENT

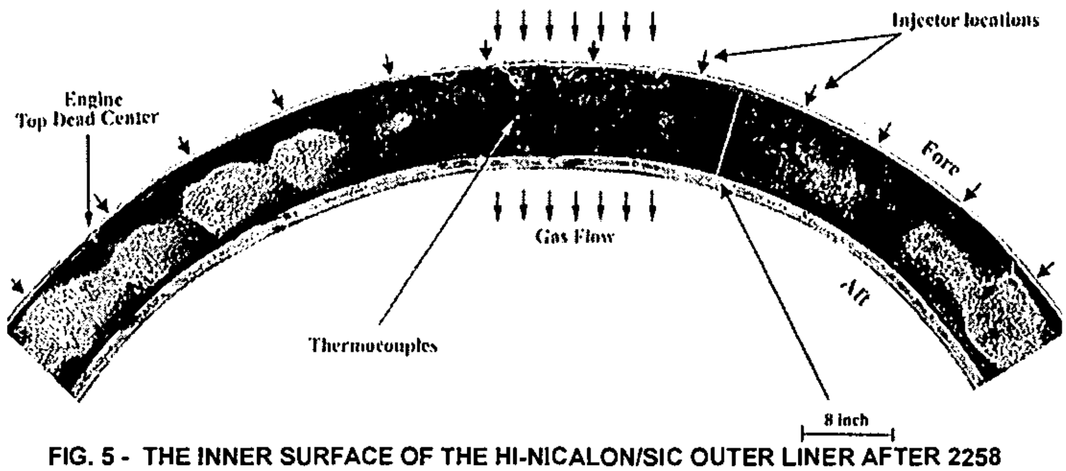

FIG. 5 - THE INNER SURFACE OF THE HI-NICALON/SIC OUTER LINER AFTER 2258 HOURS EXPOSURE TO THE COMBUSTION ENVIRONMENT

Ceramic Blades

In accordance with the low-risk design strategy of the CSGT program only the first stage of turbine blades was replaced with ceramic parts. The all-metal Centaur 50S engine has 62 first stage cooled equiaxed MAR-M247 blades coated with a Pt-aluminide diffusion coating for oxidation protection. The CSGT blade design has an airfoil shape that is almost identical to that of the metal blade, except for the absence of cooling passages. The fir tree attachment of the metal blade has been replaced with a conventional dovetail. A compliant layer between blade root and disk buffers the ceramic/metal interface. Maximum steady state stress in the dovetail blade design was estimated at 214 MPa at the blade root neck under the platform at a temperature of 682°C (1260°F). Details of the ceramic blade design have been previously reported (Jimenez, et al 1998).

Based on critical materials properties and life prediction considerations, AS-800 (AlliedSignal Ceramic Components) and SN-281 (Kyocera Industrial Ceramics Corporation) silicon nitride materials were selected for engine testing. Figure 6 shows the cooled metal first stage MAR-M247 blade and an uncooled AS-800 silicon nitride blade. All ceramic blades are inspected by x-ray and FPI, followed by proof testing to 125% design stress in Solar's cold spin test facility prior to engine testing. As with all CSGT ceramic components, the blades are subjected to a 100-hour cyclic acceptance test in the CSGT Centaur 50S gas turbine prior to being approved for field testing at ARCO.

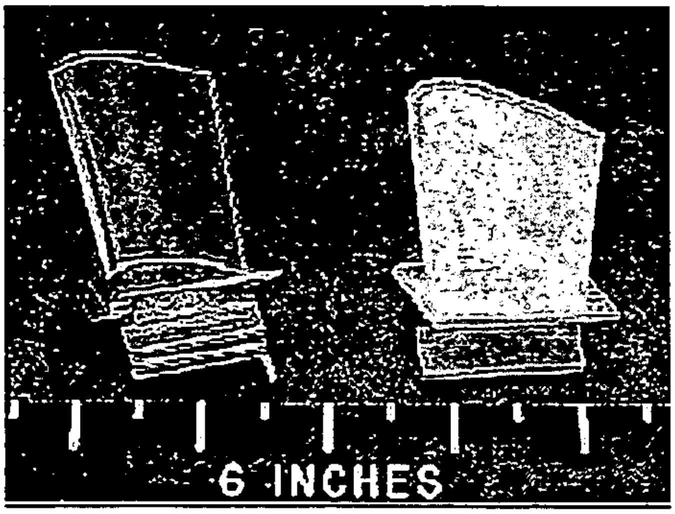

FIG. 6 - COOLED MAR-M247 METAL (L) AND UNCOOLED AS-800 (R) BLADES FOR CENTAUR 50 ENGINE

The first field test of ceramic blades in the CSGT Centaur 50S engine initiated in May 1997. Sixty-two AS-800 silicon nitride first stage blades accrued 948 hours of full load operation prior to termination due to foreign object damage of the blade airfoils from a metallic combustor assembly pin. The dovetail blade attachment/ compliant layer system performed as designed. Details of this field test and failure investigation has been previously documented (Price, et al., 1998, Jimenez, et al., 1998),

The second field test of first stage ceramic blades initiated in March 1998. Again, 62 AS-800 dovetail blades were proof tested, subjected to the 100 hour cyclic endurance test, and then approved for field testing at ARCO. Although the 55 degree dovetail attachment/ compliant layer system performed well during the first field test, the dovetail angle was changed from 55 degrees to 45 degrees for this test to reduce the possibility of pinching or wedging of the ceramic dovetail in the metallic disk. After only 352 hours of full load exposure, the field test was again terminated due to foreign object damage of the ceramic blade airfoils. The failure investigation revealed that a loose connection at a thermocouple junction box resulted in a false signal being sent to the control system, indicating that the power was oscillating from 3800 KW to 1800 KW in two second intervals. This false signal caused violent combustor instability, as the control system tried to keep up with the power fluctuations. Although the loose connection was corrected prior to the blade failure, the combustor instability is believed to have resulted in the tearing of a piece of stainless steel at a braze joint in the compressor, which impacted the ceramic blade airfoils, causing failure. The failure occurred three hours after the loose connection was corrected, and metallurgical analysis of the mating surface where the stainless steel piece was missing indicated that the tear had just occurred.

This second blade airfoil failure due to foreign object damage has resulted in a reevaluation of the retrofitted first stage ceramic blade design. A foreign object impact study of ceramic blade and nozzle candidate materials has been initiated. Various method of improving the impact resistance of the silicon nitride airfoils are being examined including improving the materials impact resistance/fracture toughness, redesigning the airfoils to have more robust leading edges, and energy absorbing coatings.

Ceramic Nozzles

The CSGT Centaur 50S first stage all metal FS-414 nozzles are being replaced with ceramic nozzles. The standard cooled nozzles are coated with a Pt,Rh-aluminide diffusion coating. The ceramic nozzle design is significantly different from the metal nozzle. It is uncooled and single vane compared to the two-vane cooled metal nozzle, and the tip seal has been decoupled (a metal tip seal is attached to the nozzle case). These design changes were made to simplify the fabrication of the ceramic components. The nozzle attachment has been modified to accommodate the ceramic-to-metal interface to the first stage diaphragm. The number of nozzles was increased from 15 two-vane segments to 42 single-vane segments based on the results of a vibration analysis. Details of the nozzle design have been published (Faulder, et al., 1998).

The ceramic nozzle airfoil is different from the metal airfoil as well. Finite element stress/ temperature analysis and life prediction showed that replacing the metal airfoils with a ceramic vane of the same geometric configuration would result in an unacceptably high stress level incompatible with long service life. The airfoil chord was therefore reduced in half and the airfoil was bowed axially and tangentially compared to the current cooled metal nozzle. The redesign resulted in a significant drop in the maximum steady state stress levels from about 480 MPa to about 162 MPa at the estimated "hot spot" temperature at the vane trailing edge of 1288°C (2350°F). The stress levels were calculated using SN-88 silicon nitride (NGK Insulators, Ltd.), the material selected for nozzle fabrication. The cooled metal FS-414 nozzle and the SN-88 silicon nitride nozzle are shown in Figure 7. SN-88 was selected since it met the design requirements for slow crack growth and creep which are believed to be life-limiting. All nozzles undergo x-ray and FPI, followed by mechanical and thermal proof testing prior to engine testing.

The first engine test of 42 SN-88 silicon nozzles was conducted in April 1997. The nozzles successfully completed a nine-hour test in the CSGT Centaur 50S developmental gas turbine at Solar. During teardown of the nozzle assembly, some minor chipping was found at the inner and outer shroud areas contacting the metal suggestive of a

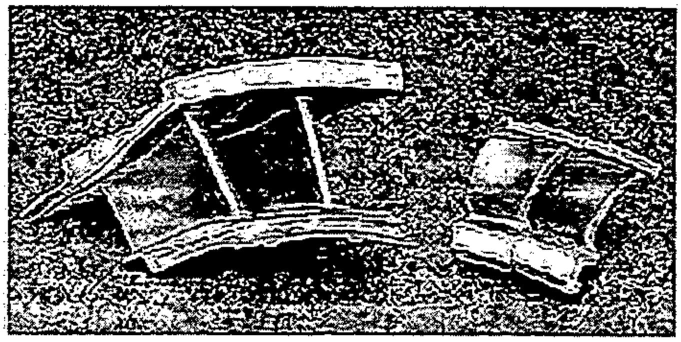

FIG. 7 - COOLED FS-414 METAL (L) AND UNCOOLED SN-88 CERAMIC (R) NOZZLES FOR CENTAUR 50S

localized excessive contact stress condition. The ceramic nozzle/ metallic attachment was redesigned to eliminate the chipping (Faulder, et al., 1998).

A 10 hour engine test of the SN-88 nozzles was conducted using the modified nozzle attachment design. The redesign of the inner hook and outer shroud attachments was effective in eliminating the chipping of the ceramic nozzles. The SN-88 nozzles were approved for a 100 hour cyclic endurance test in the CSGT Centaur 50S engine. This 100 hour test initiated in September 1998. The test consisted of cold and hot engine restarts and shutdown cycles that increased in the severity of stresses and thermal gradients on the nozzle. Boroscope inspections were conducted after shutdown cycles. After 68 hours of cyclic engine testing, the boroscope inspection revealed cracking in several airfoils, and the test was terminated for detailed evaluation. The detailed failure investigation is ongoing at Solar, ORNL and at NGK. No chipping was found in the attachment areas of the nozzles Initial evaluations indicate that the airfoil cracks may have resulted from a combination of thermal shock and mechanical loading of the nozzles. Selected nozzles were sent to ORNL for evaluation. Discussions with ORNL indicated that material degradation in the gas turbine environment may have also played a role in the failure of the nozzles. Further details will be given as they are available.

SUMMARY

A Solar Turbines Incorporated Centaur 50S gas turbine is being retrofitted with ceramic first stage blades, first stage nozzles, and combustor liners for improved performance and lower emissions. The component designs have been completed and have been validated in rig and engine testing. CFCC combustor liner have surpassed 3000 hours of field operations. Environmental barrier coatings for the CFCC liners are being developed to further increase the life of the liners. Ceramic blades surpassed 1000 hours of full load engine operation. The blade attachment performed well during field testing, however foreign object damage has resulted in failure of the ceramic blade airfoil during two field tests. Methods of improving the impact resistance of ceramic airfoils are being examined. The ceramic nozzle testing reached 68 hours of cyclic engine testing prior to cracks initiating in the airfoil. Failure investigation of the cracked nozzle airfoils is ongoing. The next planned CSGT field test consisting of CFCC combustor liners with EBCs is planned for March 1999.

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