Ceramic Stationary Gas Turbine[1]

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Introduction

Because of their superior high temperature durability, the application of ceramics as structural materials for gas turbine hot section components will enable a significant increase in the turbine rotor inlet temperature (TRIT) of current all-metal industrial gas turbines, resulting in improved thermal efficiency, grater output power, and reduced emissions of NOx and CO. The benefits of ceramics for gas turbines have been described elsewhere (1-3). It has been projected that fully optimized stationary gas turbines would have about a 20% gain in thermal efficiency and about a 40% increase in output power in simple cycle compared to current all-metal industrial gas turbines with air-cooled components (4). Annual fuel savings in cogeneration in the U.S. would be on the order of 0.2 Quad by 2010. Emissions reductions to less than 10 ppmv NOx have also been forecast (5).

The U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT), therefore, initiated in September 1992 a program aimed at developing and demonstrating a ceramic stationary gas turbine for cogeneration operation. Solar Turbines Incorporated (Solar) is the prime contractor on the program which includes participation of major ceramic component suppliers, nationally recognized test laboratories, and an industrial cogeneration end-user. This paper summarizes the progress on Phase II and Phase III of the program from September 1996 through September 1997. The Phase II work involves the detailed engine and component design, ceramic component fabrication and testing, generating a long term materials property data base, and non-destructive evaluation (NDE) of the ceramic components. The Phase III activity involves field testing of the ceramic components at a cogeneration end user site and characterization of the ceramic components following field test operation.

Objectives

The overall objective of the DOE Ceramic stationary Gas Turbine (CSGT) Development Program is to improve the performance of stationary gas turbines in cogeneration through the selective replacement of cooled metallic hot section parts with uncooled ceramic components. The successful demonstration of ceramic gas turbine technology, and the systematic incorporation of ceramics in existing and future gas turbines will enable more efficient engine operation, resulting in significant fuel savings, increased output power, and reduced emissions.

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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 (ACTS) 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 (5).

Figure 1 is a schematic of the Solar Centaur 50S, the engine selected for ceramic insertion under the CSGT program. The baseline metal engine has a rated shaft thermal efficiency of 29.6% and an

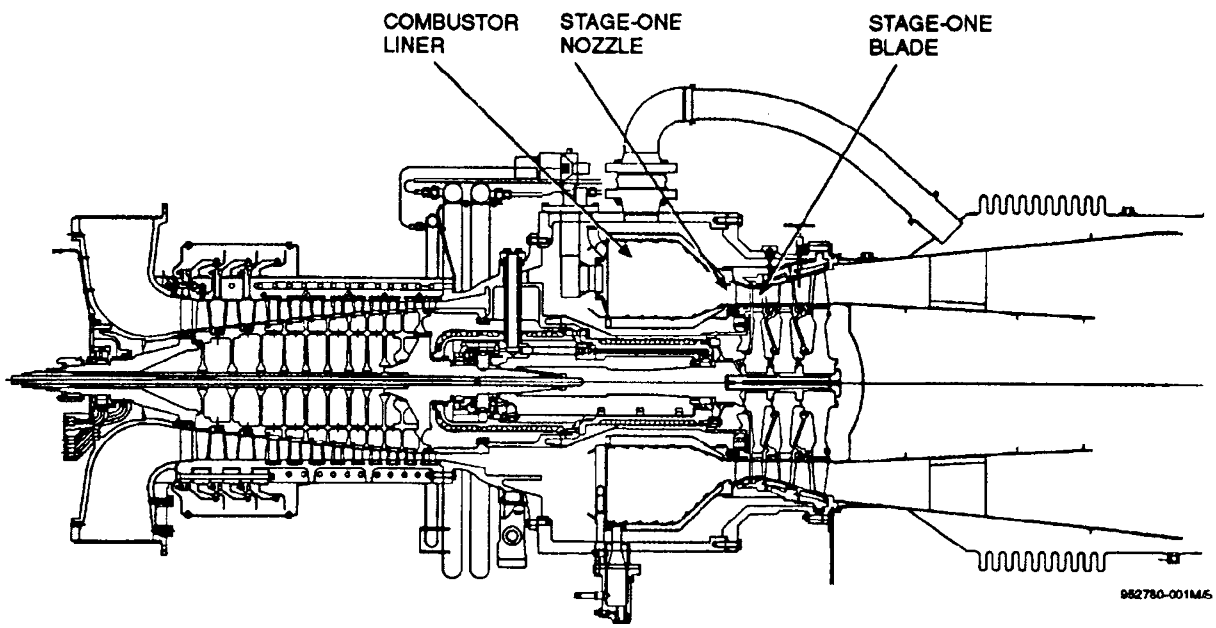

FIGURE 1. SOLAR 50S GAS TURBINE WITH COMPONENTS TARGETED FOR CERAMIC INSERTION

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 blades and nozzles, and a ceramic combustor liner. The engine hot section is being redesigned to adapt the ceramic parts to the existing metallic support structure. Accompanying the ceramic insertion the Centaur 50S is being uprated form its current TRIT of 1010°C (1850°F) to a TRIT of 1121°C (2050°F). The performance improvements 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 the potential for NOx levels of 10 ppmv or better. No CO level target was required for the program, but Solar has set a CO target of 25 ppmv. Predicted engine performance data have been reported previously (6).

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 material with potential to cost-effective scale up to production applications, iterative testing with stepwise increases in firing temperatures to a modest final design TRIT, minimizing transient and steady state stresses in the ceramic components and adjacent metal structures. The CSGT program aim to achieve early demonstration of component designs in an engine rig which duplicates all the conditions the ceramic components will experience during actual engine operation.

Solar's industrial gas turbines must be able to operate continuously without interruptions other than those resulting for scheduled maintenance for 30,000 hours which is the typical time before overhaul (TBO). Ceramic components must therefore have design lives consistent with the expected TBO life. Since the ultimate field test goal for the program was 4000 hours and to minimize the materials and design changes to the current metal engine, a design life target of 10,000 hours was selected for the engine and its components for the program.

Figure 2 illustrates the integrated design and test philosophy of the CSGT program. In this design approach, design analysis was iterated with life prediction, testing, and post-test component evaluation. In the first stage simulated components were tested in test 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. The testing was performed using various laboratory test equipment and rigs. In the second stage the findings from these tests were fed back into the design of first 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 being used for the field testing in Phase III of the program.

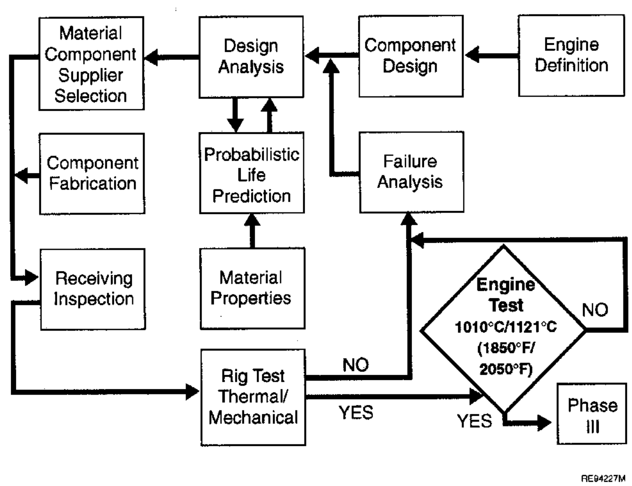

FIGURE. 2 - INTEGRATED DESIGN AND TEST PHILOSOPHY OF THE CSGT PROGRAM

Project Description

Project Team

The CSGT project team members and their responsibilities is summarized in Table 1.

Table 1 - Csgt Program Team

TEAM MEMBERS	RESPONSIBILITIES
GAS TURBINE MANUFACTURER	
Solar Turbines Incorporated (Solar)	* Program Management * Materials Selection and Evaluation * Engine and Component Design and Testing * Technical and Economic Evaluation * Technology Integration
CERAMIC COMPONENT SUPPLIERS	
AlliedSignal Ceramic Components (CC)	* Rotor Blade (GN-10 Si_3N_4, AS-800 Si_3N_4)
Kyocera Industrial Ceramics Corporation (KICC)	* Rotor Blade (SN-253 Si_3N_4, SN-281Si_3N_4)
Norton Advanced Ceramics (NAC)	* Rotor Blade (NT164 Si_3N_4) Combustor Liner (NT230 SiC)
Carborundum	* Combustor Liner (Hexoloy® SA SiC)
NGK Insulators, Ltd. (NGK)	* Nozzle (SN-88 Si_3N_4)
Babcock & Wilcox (B&W)	* Combustor Liner (alumina/alumina CFCC)
DuPont Lanxide Composites (DLC)	* Combustor Liner (SiC/SiC CFCC)
B.F. Goodrich Aerospace (BFG)	* Combustor Liner (SiC/SiC CFCC)
MATERIALS SUPPORT	
Caterpillar Technical Center (CAT TC)	* Non-Destructive Evaluation (NDE) of Ceramic Components
Argonne National Laboratory (ANL)	
University of Dayton Research Institute (UDRI)	* Long Term Testing of Ceramics
Sundstrand Power Systems (SPS)	* Life Prediction
END USER	
ARCO Western Energy (ARCO)	* End User Representation * Cogeneration Field Test Site

ceramic specimen and component procurement, fabrication and testing. Ceramic blades, nozzles and combustor liners are being tested in rigs and in a Centaur 50S engine rig. The Phase II efforts also involve long term testing of ceramics and the development of NDE methodologies for part evaluation. Phase III began in October 1997 and will continue through December 1998. The Phase III efforts include the manufacturing and instrumented engine testing of the field test engine, actual field testing of the ceramic components at a cogeneration end user site, and characterization of the components following field test exposure.

Results

Engine and Component Design and Material Selection

Figure 3 is a layout of the CSGT engine hot section showing the three key ceramic components: the CFCC combustor liner, the first stage turbine nozzle and the first stage turbine blade. The design of the ceramic interfaces can also be seen in this figure. Detail design information regarding these components has been presented in prior papers (7-10).

Combustor Design

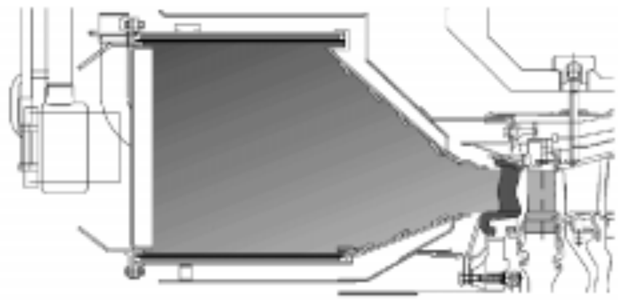
FIG. 3 - SCHEMATIC OF CSGT ENGINE HOT SECTION

The use of a ceramic gas turbine combustor is associated with two advantages over a conventional metal combustor, firing temperature can be increased without degrading combustor durability and emissions from lean premixed gas turbine combustors can be reduced using a "hot wall" (11, 12). Air saved from reduced cooling requirements for the combustor wall can be used to lean out the flame in the primary zone resulting in lower emissions of NOx. A second emission benefit is a reduction in CO quenching near the combustor wall. The existing SoLoNOx combustor of the Centaur 50S engine was modified by integrating the ceramics in the linear sections of the liners.

The ceramic combustor was designed to be fully interchangeable with the production Centaur 50S dry low-NOx lean-premix (SoLoNOx) combustor. The all-metal combustor is an annular, axial flow combustor that utilizes twelve premixing natural gas injectors. Through lean premixed combustion, NOx and CO emissions are limited to less than 25 ppmv and 50 ppmv, respectively, at the 1010°C design turbine rotor inlet temperature (TRIT) of the Centaur 50S engine.

The ceramic hot section layout of Figure 3 shows the main design features. The combustor is comprised of a metallic dome section at the upstream end, two concentric ceramic 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 essentiall 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. All pressure loads are carried by the metal housing. The inner and outer ceramic cylindrical liners 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 ceramic liners replace louvre-cooled Hastelloy X liners in the Centaur 50S combustor.

The material of choice for the ceramic liners was a continuous fiber-reinforced ceramic composite (CFCC) material based on a silicon carbide based fiber (Nicalon) fabricated by Nippon Carbon Company of Japan as reinforcement with a silicon carbide matrix incorporated by chemical vapor infiltration. CFCC's were selected over the more conventional monolithic ceramic materials because of their superior fracture toughness which gives them a distinct advantage over monolithics for large structures such as the combustor liners of the Centaur 50S engine. The current combustor liner material is the enhanced SiC/SiC CFCC of DuPont Lanxide Composites, Inc. (DLC). A set of DLC liners is shown in Figure 4. The actual materials selection process and supporting subscale component testing has been described elsewhere (9, 13).

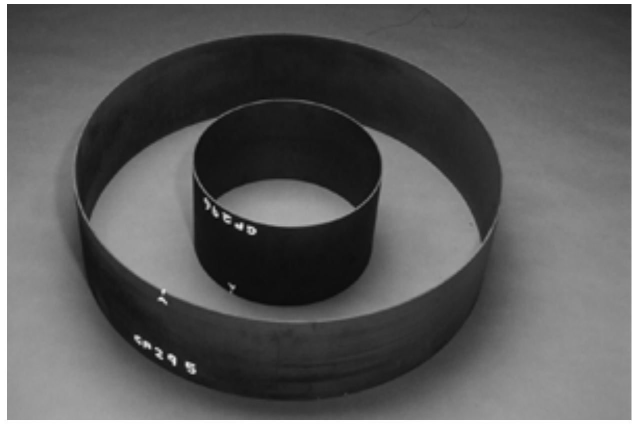

FIGURE 4. ENHANCED SIC/SIC CFCC COMBUSTOR LINERS FABRICATED BY DUPONTLANXIDE COMPOSITES

Under the CSGT program first stage all metal FS-414 nozzles are being replaced with ceramic parts. The nozzles are cooled and ccoated 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, 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 vibrational analysis.

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 5. SN-88 was selected since it met the design requirements for slow crack growth and creep which are believed to be life-limiting.

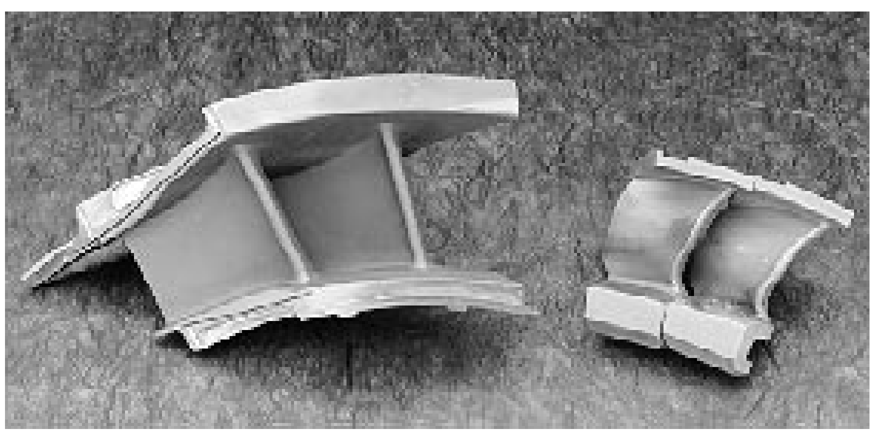

FIGURE 5. COOLED FS-414 METAL AND UNCOOLED SN-88 CERAMIC NOZZLES FOR CENTAUR 50S

Blade Design

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 aifoil 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).

Based on critical materials properties and life prediction considerations AS-800 (AlliedSignal Ceramic Components) and SN-281 (Kyocera Industrial Ceramics Corporation) silicon nitrides were selected for engine testing. Figure 6 shows the cooled metal first stage MAR-M247 blade and an uncooled AS-800 silicon nitride blade.

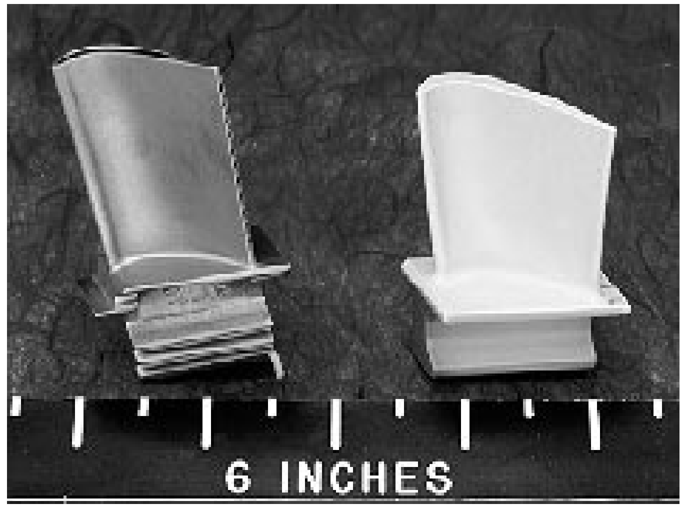

FIGURE 6. COOLED MAR-M247 METAL AND UNCOOLED AS-800 BLADES FOR CENTAUR 50 ENGINE

A significant difference between operation of the Centaur 50S engine with of the metal and ceramic blades is clearance control. The metal blade is designed for a hot clearance of 0.5 mm which is achieved by applying a rub-tolerant coating to the first stage nozzle tip seal. The ceramic blade has a design hot clearance of 1.3 mm. and is designed to operate with open clearances. Operating the engine with this wide clearance results in a performance loss. To fully realize the benefits of operating the engine with ceramic blades and nozzles will require the development of tip seals with abradable coatings that can accommodate a rub by ceramic blade tips. Development of abradable coatings is ongoing under other Solar development programs.

Secondary Component Design

A signficant redesign effort was performed for the secondary components interfacing with the ceramic parts. The redesign effort involved the incorporation of rim seals on the first stage disk, changes to the first stage diaphragm and attachment of the first stage nozzle at the inner shroud, and changes to seals and related parts interfacing with the nozzle outer shroud. The design changes have been detailed elsewhere (9, 10).

IN-HOUSE COMPONENT AND ENGINE TESTING

Component Testing

All ceramic components were tested extensively in laboratory rigs prior to engine testing. For example, the blade root configurations were evaluated in an attachment tensile test to establish the optimal blade root angle and compliant layer system. Full blades were tested in a cold spin test at 125% of design load to ensure that they were free of life limiting defects. Nozzles were proof tested in a thermal gradient proof test rig and a mechanical attachment test rig in which stress levels in excess of those in service eliminated defective parts.

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 essessment of emissions reduction potential. The liners were subsequently tested in the Centaur 50S engine.

Emissions of NOx and CO were promising based on subscale and full scale test data. At full load in the high pressure rig NOx levels <25 ppmv and CO levels <5 ppmv were determined.

Engine Testing

The engine test strategy is based on initially evaluating each ceramic component separately, before testing the components in combination, in the Centaur 50S engine. This methodology minimizes the possibility of secondary damage to downstream prototype ceramic components in the case of an upstream ceramic component failure. The engine tests are initially performed at the baseline TRIT of 1010°C (1850°F) for each ceramic component system prior to testing these components in combination. In subsequent testing, ceramic components are being combined and the engine again is operated at the baseline TRIT. The final test at a TRIT of 1121°C (2050°F) will be conducted with all three ceramic components the blade, the nozzle, and a set of combustor liners.

The engine used for in-house testing is shown in Figure 7. Table 2 summarizes the test data obtained to-date. All tests except one were conducted at the baseline TRIT of 1010°C (1850°F) of the all-metal engine.

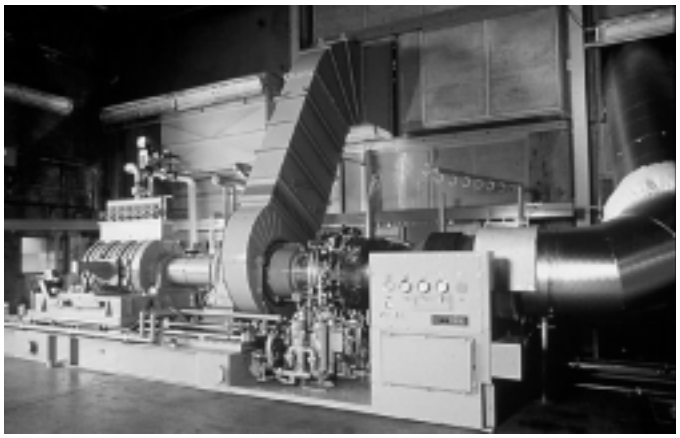

FIGURE 7. CSGT CENTAUR 50S GAS TURBINE

Table 2. Centaur 50S In House Engine Test Summary

	Blades	**Nozzle**	**Combustor Liners**
Ceramics	NT-164, GN-10, AS-800	SN-88	BFG SiC/SiC DLC SiC/SiC
Total Test Time	223 hrs	9 hrs	252 hrs
Time at Full Load	182 hrs	1 hr	197 hrs
Max. Time on Single Build at Full Load	100 hrs (AS-800)	1 hr	100 hrs (DLC)
Nominal TRIT	1010°C (1850°F)	1010°C (1850°F)	1010°C (1850°F)

The first ceramic engine tests which started in August 1995 were short (1-2 hrs) and were intended to validate the dovetail blade design. The tests were performed with NT164 and GN-10 silicon nitride dovetail blades. The ceramic components and interfacing secondary components performed as expected and demon-strated good durability. Subsequently, an engine test was conducted with BFG SiC/SiC CFCC liners for a total of 12 hrs at full load over several cycles. This test established that the CFCC material was adequate. Emission levels determined in that test were very promising. NOx levels <15 ppmv and CO levels around 5 ppmv were typically measured at a 3% pilot fuel setting (11, 12). The measured emissions levels goals were well below the CSGT program goals of 25 ppmv NOx and 50 ppmv CO. The CFCC liners were in good condition following the tests.

These initial successful tests with a single ceramic component were followed by engine testing of both ceramic blades and combustor liners simultanesously. Several tests were performed over a number of days incorporating cold and hot restarts. These tests culminated in a 100 hr cyclic test conducted in April 1997 in which second generation (AS-800 silicon nitride) blades were tested alongside with second generation (DLC enhanced SiC/SiC CFCC) combustor liners. A total of 12 cold starts and 15 hot restarts were accumulated over the 100 hrs duration of the test. Final inspection revealed the ceramic and interfacing metal parts to be in excellent condition. This engine configura-tion was then used for the first field test. Figure 8 shows the rotor assembly with AS-800 first stage blades prior to engine testing. Figure 9 shows the CFCC outer and inner liners of the combustor following the 100 hr engine test.

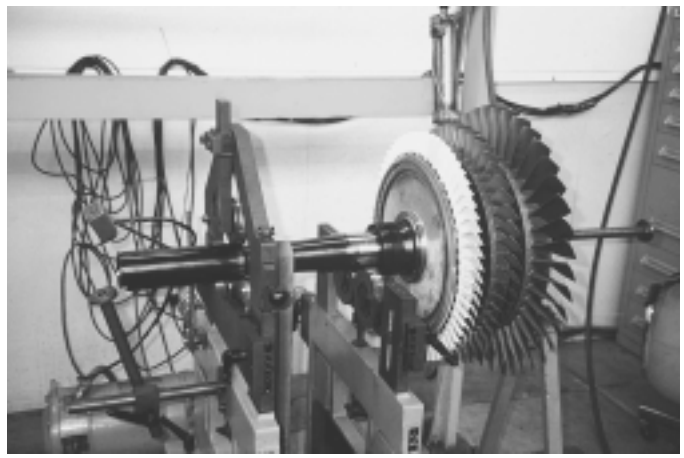

FIGURE 8. CSGT ROTOR WITH AS-800 FIRST STAGE BLADES PRIOR TO 100 HR ENGINE TEST

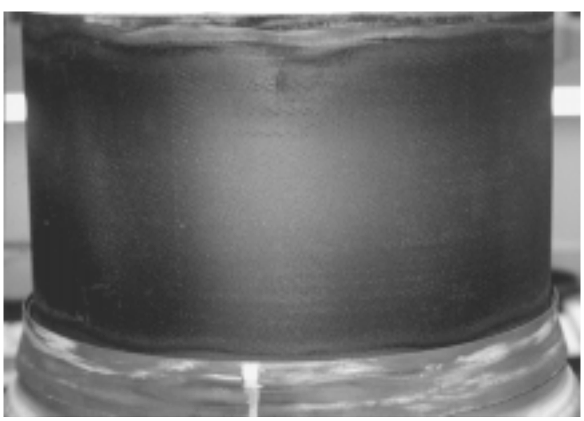

FIGURE 9. DLC SIC/SIC CFCC OUTER AND INNER LINERS FOLLOWING THE 100 HR ENGINE TEST

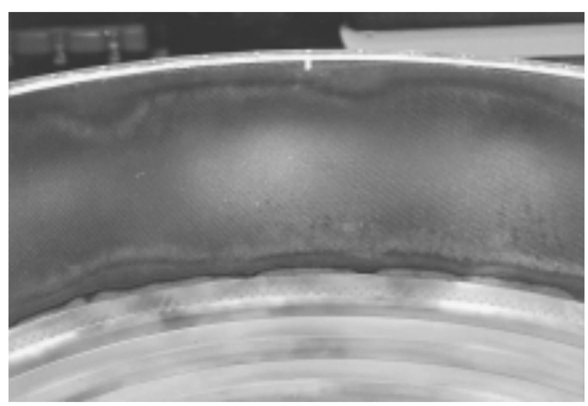

FIGURE 9. DLC SIC/SIC CFCC OUTER AND INNER LINERS FOLLOWING THE 100 HR ENGINE TEST

Recently, the first test was also conducted in which the SN-88 ceramic nozzle was evaluated. The test lasted for 9 hrs, 1 hr of which was at full load. The test was mostly successful, some minor chipping had been noticed at the inner and outer shroud areas contacting the metal suggestive of a localized excessive contact stress condition. Redesign efforts are currently underway to alleviate this stress condition. The main focus of the test will be to combine all three ceramic components, CFCC combustor liners, first stage blades, and first stage nozzles in the engine builds, and to operate the engine at the ultimate design TRIT of 1121°C (2050°F). A final 100 hr test will be conducted prior to the final 4,000 hr field test scheduled for Phase III of the program.

FIELD TESTING

In May 1997 the CSGT program experienced its most significant accomplishment to-date. The CSGT T5901 Centaur 50 SoLoNOx engine retrofitted with CFCC combustor liners and AS-800 first stage ceramic turbine blades was shipped to ARCO Western Energy Bakersfield enhanced oil recovery site for the first field test of ceramic hot section components in an industrial gas turbine engine. This engine replaced one of ARCO's existing gas turbines, a model T5501 Centaur 50, operated with water injection for NOx control. ARCO's control system was upgraded to allow operation in the SoLoNOx mode.

The field test started on May 21. A view of the test engine at the field test site is shown in Figure 10. The engine is operating at the 1010°C (1850°F TRIT) of the standard all-metal engine to demonstrate performance under typical industrial operating conditions. As of June 30 the CSGT engine has logged over 900 hours of maximum load operation with 15 start cycles and is continuing to accrue hours. The CSGT engine has been fully operational with normal steam and electrical power production. Boroscope inspections, conducted after 212 hours and 533 hrs showed no change in the appearance of the CFCC combustor liners and first stage ceramic turbine blades as compared to the appearance after the 100 hour acceptance test at Solar. The field test duration is scheduled for 2000 hours of maximum load operation with periodic boroscope inspections.

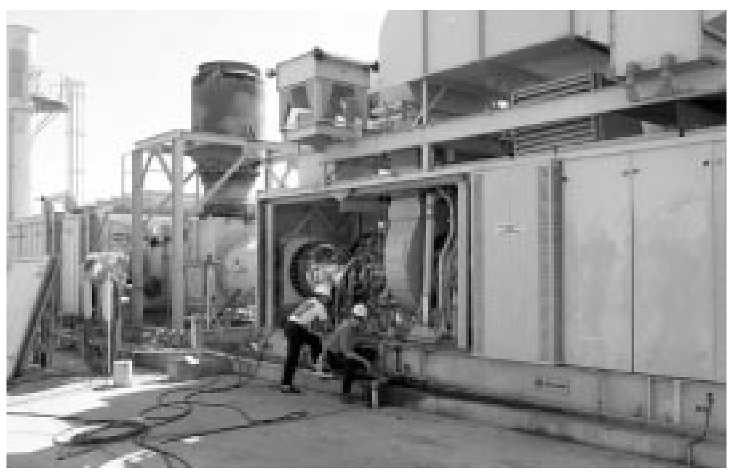

FIGURE 10. CSGT CENTAUR-50S ENGINE AT ARCO FIELD TEST SITE

On July 1, 1997, after 948 hours of full load operation, the CSGT engine shut down due to turbine underspeed. After several failed attempts to restart the engine, a boroscope inspection revealed that the 62 turbine blade airfoils had failed during service, which has now been attributed to probable impact damage from a locating pin from the inner liner of the combustor. ARCO's water-injected Centaur 50 T5501 was quickly reinstalled and the CSGT engine was returned to Solar for failure analysis.

Failure analysis of the blades indicated that all of the fractures were above the blade platform and none of the dovetails were pinched in disk (which was the cause of the previous blade failure), indicating that the redesign of the dovetail attachment was successful. The compliant layer attachment system appeared to have performed as designed. There was no evidence of contact on the first stage tip shoes. During teardown of the combustor, a locating pin (0.75" x 0.375" diam. tool steel) used during assembly of the combustor dome was found to be missing for the inner liner. The missing pin was at the bottom dead center location. Witness marks inside the housing of inner liner indicated that the pin had moved to the aft end of the liner to a location near 0.400 dilution holes. It was determined that the pin exited one of the dilution holes and continued through the first stage nozzles into the ceramic turbine blades. Selected AS-800 blade roots from the ARCO field test failure were sent to ORNL for examination of the fracture surfaces. Evaluations to date have shown no sign of slow crack growth in the remaining blade airfoil.

The ceramic combustor liners remained intact following the engine shutdown. Over 1000 hrs of cumulative engine test data (test cell and field test data) to-date have demonstrated that a simple modification to the Centaur 50S SoLoNOx combustor, involving replacement of the currently louvre-cooled metal liners with uncooled liners fabricated from continuous fiber-reinforced ceramic composite (CFCC) materials, results in significantly improved levels of NOx and CO at the 1850°F TRIT of the Centaur 50S engine. NOx levels from 10-15 ppmv and CO levels of around 5 ppmv have routinely been measured over the 50-100% load range for the CSGT engine operating on natural gas at ARCO. The outer CFCC combustor liner showed minor indications of oxidation following the field test. The inner CFCC liner exhibited a higher degree of uniform oxidation which will limit the life of the liner. The maximum inner liner temperature measured was 2170ºF, which was about 100-150ºF higher than the outer liner.

Following examination of the oxidation of the enhanced SiC/SiC CFCC combustor liners at Solar, the oxidized liners from the ARCO field test were sent to Argonne National Laboratory for NDE. Following NDE, the liners will be returned to DLC for destructive evaluation. The liners will be sectioned for microscopic examination as well as residual strength measurements.

In an attempt to reduce the CFCC liner temperature prior to the next field test, trip strips are being added to the metallic combustor housings. Additional insulation material between the CFCC liners and the metallic housing is also being added to increase the conduction path from the CFCC liners to the metallic housings. Alternate materials with higher thermal conductivities which will further increase the conduction path are also being considered. Plasma sprayed oxide coatings for oxidation protection of the SiC/SiC liners are also being considered for future testing.

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. A Centaur 50S engine with ceramic first stage blades and combustor liners started a 2000 hr field test on May 21 at the baseline TRIT of 1010°C (1850°F) of the all metal engine. The engine field test accumulated 948 houres of full loadoperation prior to engine shutdown due to foreign impact damage of the 2st stage AS-800 turbine lades. The impact damage occurrred due to a metallic locating pin used during combustor assembly impacting the first stage blades. The metallic locating pin has been eliminated and a second 2000 hour field test of ceramic blades and a modified CFCC combustion liner system has been scheduled for early 1998.

Application and Benefits

The objective of the CSGT program is to demonstrate ceramic gas turbine technology with the aim at eventual commercialization and ensuring national energy savings and emissions reduction. The economic and technical potential of the ceramic gas turbine technology has been analyzed and described in the Phase I Final Report for the CSGT program (14).

Performance Benefits

The benefits of the technology derive (1) from the incremental value associated with the fuel savings and output power increase resulting from replacing cooled metal hot section components with uncooled or minimally cooled ceramic parts coupled with the increase in firing temperature these part allow, and (2) from the value represented by the reduction in emissions of NOx, CO, and UH (unburned hydrocarbons) in ceramic engines compared to all-metal baseline engines. The added value can be estimated at the level of individual engine installation sand can be extrapolated to the aggregate of installed power-generating capacity making assumptions about the level of market penetration of the ceramic technology.

The incorporation of ceramic hot section components in existing gas turbine installations int he context of a TRIT uprate in a retrofit scenario similar to that for the CSGT engine is expected to result in a moderate improvement in fuel efficiency of about 5 to 6 percent and a significant increase input power of as much as 25 percent. These gains represent added value to the turbomachinery equipment which can be quantified. The interested reader is referred to the Phase I final report for a quantitative estimation of value added to gas turbine from ceramic insertion (14). When ceramic insertion is integrated in a comprehensive redesign of the engine hot section its value to the gas turbine is further enhanced. Improvements in fuel efficiency of about 20 percent and increases in output power of about 40 percent are achievable. The greatest potential for ceramic gas turbine technology can be expected when used as one of a number of design tools in truly “clean sheet designs. There the benefits of reduced cooling and higher firing temperature can be combined with heat recovery, and possibly, at more advanced stages, with intercooling and chemical recuperation.

Emisisons Reduction

In addition to improvements derived from enhanced fuel efficiency and increased output power significant benefits are anticipated because of the ability of ceramic “hot wall” combustors to lower emissions of NOx. The true value is represented by the actual reduction in the gas urbine exhaust emissions burden ont he environment and the potential for significant cost savings to the end user of gas turbine euqipment by eliminating the need for water inejction or expensive post-exhaust cleanup equipment such as selective catalytic raeducion (SCR).

Application of Ceramics

The application of ceramic components is beneficial because it enables a higher compoentn temperauter in a simpler and therefore, less costly, design and/or it reduces the need for parat cooling and the use of protective coaiangs. When considering the cost associatedwith utilizing ceramic blaes and nozzles, one can assume that cermaics will be (1) more expensive than uncooledj parts of conventional superalloys, (2) are of comparable cost as cooled conventional superalloy parts, and (3) can be signficantly less expensive than parts fabricated of cooled and coated advanced superalloys.

Where the design temperatur alllows the use of uncooled superalloy componetns, there is no advantage in using ceramic parts unless othe benefits are sought (e.g., a reduction in stress on a disk by using lighter ceramic blades). As a result, thee is no benefit in considering ceamic blades for engines with a TRIT under ~900°C (~1650°F) or ceramic nozles for engines with a TRIT under ~850°C (~1560°F). The lower temperature limit for the nozzle is attributable to the need to design for “hot spot” conditions. Under these temperature limits uncooled meal parts function satisfactorily and they can be faricated at a fraction of the cost of cermaic parts assuming aerospace quantities of componetns (i.e., 10,000 s/year).

When cooled superalloy comonetns are replaced, the cost of ceramic and metal parts are expected to be of similar magnitude and the benefits of eliinating cooling facor the use of ceramics. The replaement of expensive cooled and coated advanced superalloy components with uncooled ceramic parts is articularly attractive since a component cost reduction is accompanied by a performance improvement derived rom the elimination of cooling.

An interesting scenario is presented by an engine uprate as is represented by the CSGT engine. Here the scenario involves a significant performance improvement because of the increase in TRIT. But the TRIT increase also necessitates an upgrade in component structural materials from affordable conventionally cooled and meal parts to advanced cooled and coated superalloy parts. Here ceramics provide the double advantage of enabling the improved engine performance at a potential cost reduction.

The application of ceramic combustor liners needs to be viewed somewhat differently than the application of ceramic blades and vanes. The benefits associated with emissions control are substantial and the potential to meet regulatory emission standards without the need for expensive add-ons represents a substantial value to the end user. Therefore, broadly speaking, the cost of a ceramic combustor liner can be higher than the cost of a comparable metal part. Also, because of the potential emissions benefits ceramic combustors are expected to find applications in many engine models over a wide range of TRIT values.

Special consideration must be given to small engines. These engines often compete with diesel and/or gas engine and the allowable incremental cost is constrained by the package cost of these competing prime movers. The allowable cost range will be less elastic than for larger engines. Overall package cost targets will put restrictions on the cost of the combustor liner components.

A somewhat similar situation may arise in the case of a retrofit of a small engine. There is a limit to what an established end user is willing to pay for a retrofit package even if emissions benefits are substantial. Unless the end user is forced to meet tighter emissions regulations, it is unlikely a substantial increase in the cost of an overhaul is acceptable and, again, the increase in the cost of a combustor liner will be limited.

Timeframe for Commercialization

It is not possible at this point to present a firm target date for commercialization of the ceramic engine, since many factors are involved, but a likely scenario can be delineated, based on the timeline for the CSGT program. The commercialization timeframe can be represented as follows:

- 1992-1995: Ceramic component development
- 1995-1996: Engine testing and design validation
- 1996-1999: Ceramic field testing
    - 19997/1998: CSGT engine field testing
    - Multiple engine field tests
- 1999-2002: Ceramic engine product development
- 2002: Earliest introduction of ceramic engine components in commercial engine
    - Combustor liners first
    - Nozzles next
    - Rotating components last
- 2005: Significant penetration of retrofit markets
- 2010: Established mature market for ceramic engines

The above time schedule assumes demonstration of technical feasibility through successful field testing, favorable economic conditions (fuel and electricity prices), and market acceptance.

National Energy conservation and Environmental Benefits

Estimates of potential national energy savings and emissions reductions as a result of implementing ceramic gas turbine technologies in industrial engines (0.5-25 MW output) were made as part of the Phase I work (14). Potential annual national energy savings have been estimated to range from 0.076-0.28 quads (1 quad = 10^{15} Btus) by 2010. The lower end of the range assumes a modest penetration of the projected engine fleet with first generation retrofits. The higher end of the range assumes that the entire installed fleet will consist of second generation ceramic engines.

An estimate has also been made of the emissions benefits of the ceramic gas turbine. Assuming an across the fleet reduction of NOx to 10 pmv, the total NOx savings for the U.S industrial engine fleet are estimated to be about 4.5×10^5 tonnes of NOx.

Future Activities

Additional field testing of ceramic blades and the modified CFCC combustion liner system is planned to begin at ARCO early 1998. The test is planned to last for 2000 hours at the Centaur 50S TRIT of 1010°C (1850°F). An engine test of the redesigned SN-88 silicon nit ride nozzle is scheduled for testing at Solar late 1997. Later in 1998, a third field test containing ceramic blades, nozzles and CFCC combustor liners is planned at ARCO for 4000 hours at the increased TRIT of 1121°C (2050°F).

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