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Ceramic Stationary Gas Turbine

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5.2 Ceramic Stationary Gas Turbine

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Introduction

The performance of current industrial gas turbines is limited by the temperature and strength capabilities of the metallic structural materials in the engine hot section. Because of their superior high-temperature strength and durability, ceramics can be used as structural materials for hot section components (blades, nozzles, combustor liners) in innovative designs at increased turbine firing temperatures. The benefits include the ability to increase the turbine inlet temperature (TIT) to about 1200°C (≈2200°F) or more with uncooled ceramics. It has been projected that fully optimized stationary gas turbines would have a ≈20 percent gain in thermal efficiency and ≈40 percent gain in output power in simple cycle compared to all metal-engines with air-cooled components (1). Annual fuel savings in cogeneration in the U.S. would be on the order of 0.2 Quad by 2010. Emissions reductions to under 10 ppmv NO_x are also forecast (2).

This paper describes the progress on a three-phase, 6-year program sponsored by the U.S. Department of Energy, Office of Industrial Technologies, to achieve significant performance improvements and emissions reductions in stationary gas turbines by replacing metallic hot section components with ceramic parts. Progress is being reported for the period September 1, 1994, through September 30, 1995.

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 (retrofit) of 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.

Approach

The technology base for the CSGT program is provided by the advancements in ceramic component fabrication know-how developed under past ceramic turbine programs, such as the Advanced Gas Turbines (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

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marketplace. Applications include retrofitting existing gas turbine installations and incorporating ceramic component technologies in future engine designs. The ceramic turbine technology to be developed under this program is also 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 (3).

Figure 1 is a schematic of the engine selected for ceramic insertion under the program, the Solar Centaur® 50S. The engine was formerly known as the Centaur Type 'H'. The baseline metal engine has a rated shaft thermal efficiency of 29.6 percent and an electrical output rating of 4144 kW and is fitted with a SoLoNOx™ dry, low-NO_x combustor. The gas producer turbine of the all-metal Centaur 50S has two stages and the power turbine has one stage. A single-shaft engine 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. 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 from its current turbine rotor inlet temperature (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 percent in simple cycle and 5.3 percent in cogeneration, and an increase in the electrical output from 4144 kW to 5217 kW, representing a relative increase of about 25.9 percent. Newer engines of the all-metal Centaur 50S engine model meet NO_x emissions levels of 25 ppmv over the 50-to-100 percent load range. Under the program NO_x emission levels of 25 ppmv or better must be demonstrated and the potential for much lower NO_x levels, 10 ppmv or better, must be indicated. Solar intends to demonstrate a NO_x level of 10 ppmv under the program. 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 (4).

Solar industrial gas turbines must be able to operate without interruptions, other than those resulting from scheduled maintenance for 30,000 to 40,000 hours, which is the typical time between overhaul (TBO). Ceramic components must therefore have design lives consistent with the expected TBO life. A 4,000-hour field test is planned for the program. 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.

Project Description

Project Team

Solar is the prime contractor on the program which includes participation of major ceramic component suppliers, nationally recognized test laboratories, a gas turbine manufacturer with expertise in life prediction, and an industrial cogeneration end user. The CSGT program team is summarized in Table 1.

Project Phases and Major Tasks

The program is conducted in three phases. Phase I of the program, started in September of 1992, involved concept and

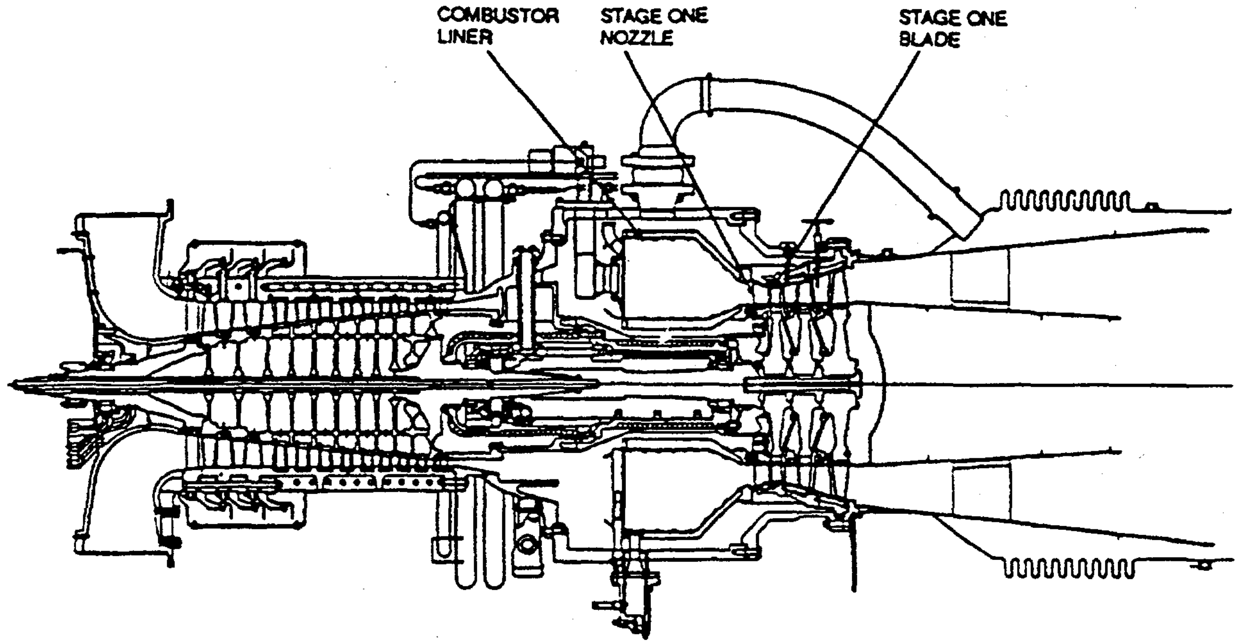


Figure 1. Solar Centaur 50S. Components for Ceramic Substitution are Indicated

preliminary engine and component design, ceramic materials selection, ceramic materials property assessment, and ceramic component fabrication planning, technical and economic evaluation, ceramic gas turbine concept assessment, and the development of a detailed work plan for Phases II and III of the program. The Phase I work has been presented at conferences (4-9) and has been fully documented in a final report (10).

The work in Phase II, started in April of 1993 and to be concluded in September of 1996, addresses detailed engine and component design (Task 7), ceramic specimen and component procurement and testing, including the testing of components in an engine rig (Task 9), low emissions combustor development (Task 10), and the development of a detailed plan for the Phase III 4,000-hour engine test (Task 11). Phase III of the program focuses on a 4,000-hour engine test at a cogeneration field site. Phase III major tasks include preparation and shakedown of the field test engine, the actual 4,000-hour field test, and ceramic component evaluation. A program management and reporting task (Task 16) accompanies the work in all phases of the program.

Figure 2 shows the program schedule. Major milestones for Phase II have been indicated.

Results

Phase II: Final Design, Material, and Component Testing

The program is currently in the third year of the 3.5-year Phase II scheduled performance period. First generation detail designs of the three ceramic components: the first-stage turbine blade, the first-stage nozzle, and the combustor liner have been completed. The starting point for the detail designs were the preliminary component designs developed

Table 1. CSGT Program Team

TEAM MEMBERS	RESPONSIBILITIES
GAS TURBINE MANUFACTURERS:	
Solar Turbines Incorporated (Solar)	* Program Management * Engine and Component Design * Materials Evaluation * Engine and Component Testing * Technical and Economic Evaluation * Technology Integration and Commercialization
Sundstrand Power Systems (SPS)	* Materials and Life Prediction Support
CERAMIC COMPONENT SUPPLIERS:	
Allied Signal 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) * Nozzle (SN-281 Si_3N_4)
Norton Advanced Ceramics (NAC)	* Rotor Blade (NT164 Si_3N_4) * Combustor Liner (NT230 SiC)
NGK Insulators Ltd. (NGK)	* Nozzle (SN-88 Si_3N_4)
Carborundum	* Combustor Liner (Hexoloy® SA)
Babcock & Wilcox (B&W)	* Combustor Liner (Al_2O_3/Al_2O_3 CFCC)
DuPont Lanxide Composites (DLC)	* Combustor Liner (SiC/SiC CFCC)
B.F. Goodrich (BFG)	* Combustor Liner (SiC/SiC CFCC)
TEST LABORATORIES:	
Caterpillar Technical Center (CAT TC)	* Non-Destructive Evaluation (NDE)
Argonne National Laboratory (ANL)	
University of Dayton Research Institute (UDRI)	* Long-Term Testing of Ceramics
Oak Ridge National Laboratory (ORNL)#	
END USER:	
ARCO Oil & Gas	* End User Representation * Cogeneration Field Test Site
CONSULTANTS	Ceramic Materials, Design, Test

Support studies at ORNL were performed under a separate contract from the U.S. Department of Energy.

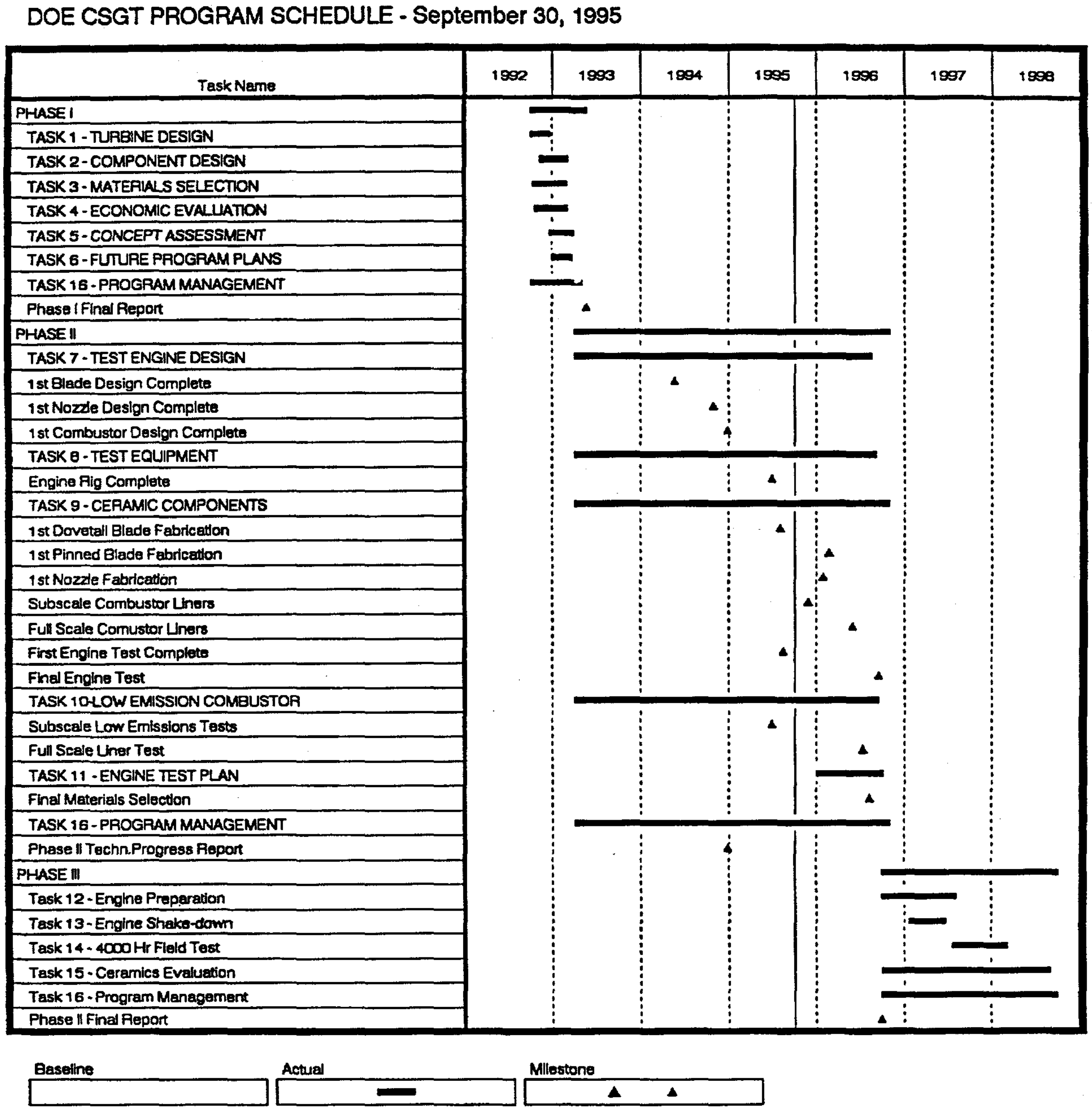


Figure 2. Program Schedule

in Phase I. In some cases significant changes had to be made to the Phase I preliminary designs to meet component life targets. For example, the attachment of one of the two blade designs, the pinned design, was modified to reduce design stress levels. In the case of the nozzle the airfoil design needed modification to reduce stress levels while retaining aerodynamic efficiency. The first generation combustor liner design is being modified after early subscale liner test results indicated the need for a more robust attachment configuration. First generation designs are nearly completed for most of the secondary hot section components adjacent to or in proximity of the ceramic parts.

Fabrication of ceramic components is in an advanced stage of completion. All first generation dovetail blades for engine testing have been delivered and first articles have been fabricated of the first generation nozzle design. Subscale combustor liner components have been fabricated by four suppliers and full-scale combustor liner components by one supplier. The ceramic components are being evaluated in rig and engine testing. Two engine tests involving ceramic blades were successfully completed during the reporting period. Combustor liner testing is in progress. Long-term testing of candidate ceramic materials in support of the design effort is continuing. NDE methodology has been fully developed for fiber-reinforced ceramic composites (CFCC) parts and is progressing for monolithic ceramics.

The Phase II work performed up until the end of 1994 has been reported in the literature (11-14). Detailed documentation of Phase II results until the end of October, 1994, can be found in a mid-phase Technical Progress Report (15). An account of program progress for the period September 1, 1994, through September 30, 1995, for each of the major tasks is given below.

Task 7: Engine and Component Design and Procurement

Figure 3 is an engine hot section layout showing broad aspects of the current design status of the three ceramic components: the annular combustor liner, the first-stage nozzle, and the first-stage blade as well as some detail of the secondary hot section components.

The critical steady-state temperatures and stresses for the ceramic components and selected candidate ceramic materials have been listed in Table 2. These design parameters will be further discussed under the narratives for the individual components.

Combustor Liner Design

The CSGT combustor is derived from the Centaur 50S SoLoNOx combustor. This is an all-metal, lean-premix, dry, low-NO_x combustor which provides NO_x levels of 25 ppmv and CO levels of 50 ppmv over the 50-to-100 percent load range for new engines. The emission levels are for operation with natural gas under conditions of 15 percent excess O_2. The combustor configuration is annular (see Figures 1 and 3). Ceramic insertion is targeted for the cylindrical sections of the outer and inner liners. The cylindrical sections are about 20 cm long. The diameters of the outer and inner liners are approximately 75 cm and 33 cm, respectively.

A key characteristic of lean-premix combustion is that as flame temperature, and consequently, NO_x emissions are lowered, CO emissions tend to increase. As a result, NO_x emissions are limited by the formation of unacceptably high CO levels. The benefit of ceramic insertion derives from the ability of a ceramic liner to operate uncooled at higher wall temperatures than a metal liner and thereby limit CO emissions. If CO emissions can be kept low by using a ceramic liner, then the flame temperature can be lowered, resulting in lower NO_x formation.

Under the CSGT program, both monolithic ceramics as well as continuous fiber-reinforced ceramic composites (CFCCs) are being considered as candidate materials for a "hot wall" combustor design. Although, in general, monolithic ceramics have greater strength than CFCCs their relatively low fracture toughness prevents their use as integral

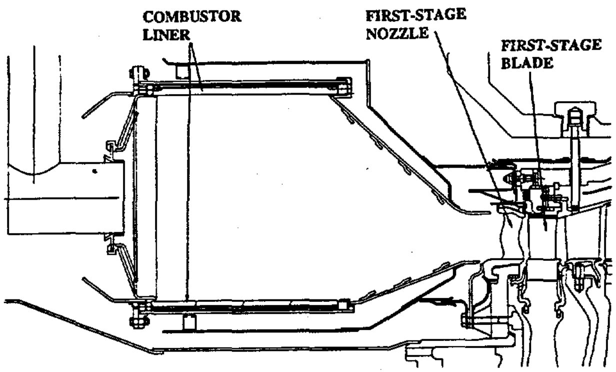


Figure 3. Schematic of CSGT Engine Hot Section

shapes for combustor liners of the size of the Centaur 50S SoLoNOx combustor. The combustor designs developed under the CSGT program incorporate monolithic ceramics in segmented (ring, tile) configurations while the much tougher CFCCs are used as integral cylinders.

The design shown in Figure 3 is a second-generation design for monolithics, showing inner rings and outer tiles. At present the tile design is only considered for the outer liner and the ring design for the inner liner. Tiles were not considered for the first generation inner liner design because the combustor pressure drop tended to disengage the tiles in that design. Rings are considered for the inner liner only, in part because of lack of supplier furnace capability, and in part because of the potential for critical defects in large outer liner rings. The other impediment is the projected cost of 75 cm diameter outer liner rings.

The rings and tiles are piloted through zirconia end elements and insulated from the metal housing using Nextel felt. Though insulated, the liner will operate below its 1204°C (2200°F) maximum design temperature limit. A metallic wave spring is used to control the axial load. The wave spring is cooled to a temperature lower than 538°C (1000°F) to prevent permanent deformation. The cooling air is exhausted into the combustion chamber. The flow is thereby minimized which prevents a detrimental effect on emissions due to flame quenching. The second generation design was

Table 2. Critical Steady-State Component Temperatures and Stresses

Component	Ceramic	Peak Temperature	Peak Stress
Blade (Airfoil)	NT164 Si_3N_4	1116°C (2041°F)	186 MPa (27 ksi)
Blade (Dovetail)	NT164 Si_3N_4	682°C (1260°F)	214 MPa (31 ksi)
Blade (Pinned Root)	SN-253 Si_3N_4	682°C (1260°F)	283 MPa (41 ksi)
Nozzle	SN-88 Si_3N_4	1297°C (1260°F)	179 MPa (26 ksi)
Combustor Tile	Hexoloy® SiC	1204°C (2200°F)	190 MPa (28 ksi)*
Combustor Ring	Hexoloy® SiC	1204°C (2200°F)	75 MPa (11 ksi)*
Combustor CFCC	SiC/SiC	1150°C (2100°F)	78 MPa (11 ksi)
Combustor CFCC	Al_2O_3/Al_2O_3	1150°C (2100°F)	163 MPa (24 ksi)

* Maximum principal stress levels established for a maximum liner wall temperature of 1366°C (2490°F) during preliminary design analyses.

developed because subscale combustor liner testing of the first generation tile design indicated an undesirable loading condition between the tiles and interfacing support structure. The second-generation design is mechanically simpler than the first-generation design and also avoids air leakage paths that would make emissions control more difficult. The interfaces between adjacent rings have an angled edge geometry. Direct contact between adjacent tiles is minimized. The detail design is presently at the stress and thermal analysis stage. The CFCC design is very similar.

Silicon carbide rather than silicon nitride ceramics were selected for the monolithic combustor liners at the preliminary design stage because of the high steady-state liner maximum design temperature, about 1366°C (2490°F). Steady-state stresses calculated for Hexoloy® SA SiC, the primary design material at this temperature, are listed in Table 2. The calculated maximum stress for the ring design was 75 MPa (11 ksi), significantly less than for the tile design which was estimated at 190 MPa (28 ksi). The reliability of the monolithic combustor designs were evaluated using the NASA CARES/LIFE and Sundstrand's SPSLIFE computer programs for life assessment (16,17). Details of the life assessment have been presented elsewhere (9). It was established that slow crack growth was the life-limiting failure mode. Probability of survival (POS) for Hexoloy® SA SiC rings was higher than for tiles. The combined fast fracture and slow crack growth POS consistent with 30,000 hours operating life at 1366°C (2490°F) was estimated at 0.9759 for one tile and at 1.0000 for one ring. To improve the POS for the tiles and to prevent sticking between adjacent tiles or rings, it was decided to lower the design liner temperature to 1204°C (2200°F) as shown in Table 2.

Because of the lowering of the design temperature, silicon nitride materials are also currently under consideration for second generation subscale and full-scale liner fabrication. Factors to be considered include estimated component stress levels in steady-state and transient operation, thermal shock resistance, estimated component life based on materials properties and predicted stress/temperature levels, and cost of fabricating prototype and commercial quantities of liner components.

CFCC's have the advantage over monolithic ceramics that they can be used as large integral shapes because of their superior fracture toughness. A disadvantage of CFCCs compared to monolithics is their relatively low strength. SiC/SiC CFCCs are limited by the first matrix cracking strength which is typically on the order of 80 MPa (12 ksi) at temperatures in excess of 500°C (932°F). The Al_2O_3/Al_2O_3 CFCC for this program is limited by the yield strength which is about 210 MPa (30 ksi). Because of the lower thermal conductivity design stresses in the Al_2O_3/Al_2O_3, CFCC are about twice those in the SiC/SiC CFCC (see Table 2). The design stresses are only slightly below the limits for the CFCC material. Efforts are underway to lower the design stresses in the integral CFCC liner designs.

Nozzle Design

The nozzle design started with the cooled two-airfoil metallic nozzle. There are 15 cooled Pt-aluminide coated two-vane FS-414 nozzles with attached tipshoes in the all-metal Centaur 50 engine. For fabrication simplicity, a single-vane ceramic nozzle concept was selected and the current integral tipshoe was decoupled from the nozzle.

Maximum steady-state stresses in the airfoil trailing edge of the initial ceramic nozzle design were high, 380-480 MPa (55-70 ksi), because of the temperature gradient set up by the combustor exit profile under "hot spot" conditions. Several alternative design solutions aimed at lowering these stresses were considered, including nozzle segmentation and airfoil cooling. Segmented designs may experience leakage and contact stress problems while materials degradation may occur as a result of surface flaws near the cooling apertures in a cooled design. These design approaches were considered but subsequently abandoned for these reasons.

Acceptable stress levels were achieved by reducing the airfoil axial chord from 3.88 cm to 1.78 cm and by reducing the vane stiffness by introducing a combination of axial and tangential curvature (bowed nozzle). Trailing edge thickness was reduced by 40 percent. The steady-state stress was lowered to 179 MPa (26 ksi) at the hot spot trailing edge where the maximum temperature was estimated at 1288°C (2350°F) (see Table 2). A solid model of the bowed nozzle which has a hook attachment is shown in Figure 4. ANSYS finite element temperature and stress maps for the bowed nozzle design are shown in Figure 5.

Long-term testing combined with life prediction using CARES/LIFE and SPSLIFE have guided the selection of the nozzle materials (9,12,13). Data from specimen testing and available ceramic materials properties were used as input to the NASA CARES/LIFE life assessment program for four candidate nozzle materials. Combined surface/volume reliability for fast fracture and slow crack growth for the four candidate materials for 10,000-hour service life was 0.2155 (NT164 Si_3N_4), 0.9999 (SN-253 Si_3N_4), 0.8831 (Hexoloy® SA SiC), and 0.9940 (SN-88 Si_3N_4). On the basis of these results, SN-88 and SN-253 Si_3N_4 ceramics were initially

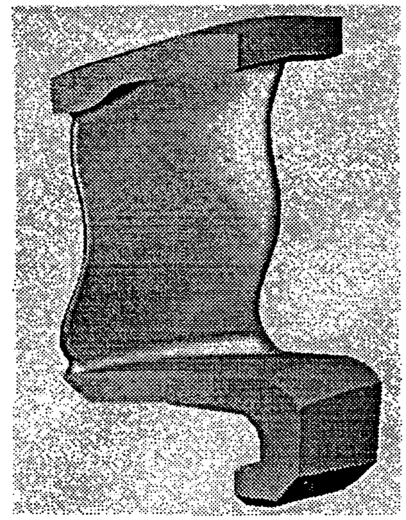
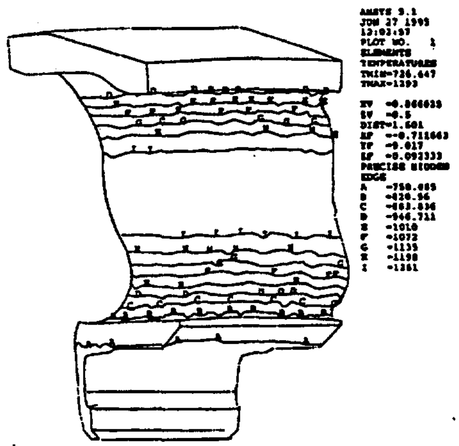


Figure 4. Bowed Nozzle Design

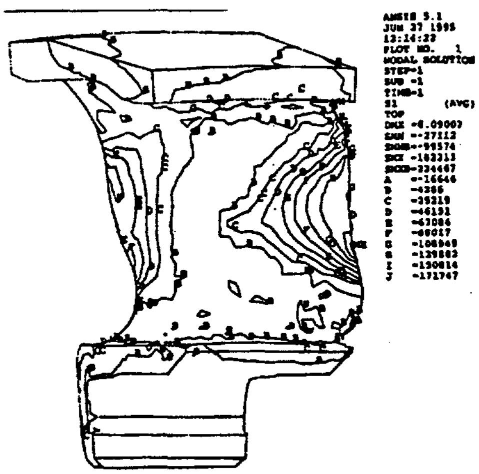
selected for nozzle development. Recently, SN-253 showed inadequate life and significant residual fast fracture strength degration during 1000-hour creep testing at 1288°C (2350°F) and 207 MPa (30 ksi). A program decision was made to continue evaluation of SN-253 in extended 5000 hours creep testing but to substitute Kyocera's SN-281 for SN-253 for nozzle fabrication on a demonstration basis. SN-281 is believed to have superior long-term properties compared to SN-253. SN-281 test specimens are being fabricated for comparison testing with other nozzle materials. SN-88 is currently the only material selected for full-scale nozzle fabrication.

Blade Designs

The current Centaur 50 engine has 62 cooled Pt-aluminide coated first-stage MAR-M-247 (equiaxed) blades. The blade airfoil shape has been largely retained in the ceramic blades with a slight modification to circumvent a predicted vibrational interference. The firtree root attachment of the current Centaur 50S metallic first-stage blade has been modified to accommodate the ceramic root to metal disk interface. Two uncooled ceramic

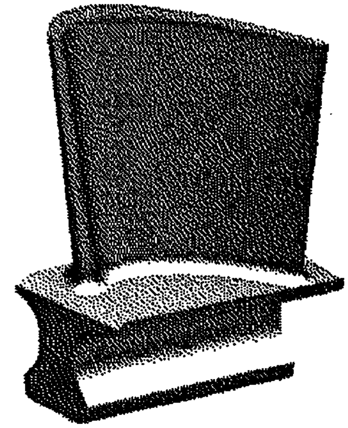


(A) Temperature Map (°C)

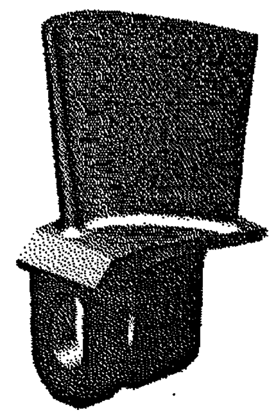


(B) Stress Map (kPa)

Figure 6. ANSYS Finite Element Temperature and Stress Maps for Bowed Nozzle



(a)



(b)

Figure 6. Solid Models of Dovetail (a) and Pinned Blade (b)

blade designs have been developed. One is based on a "dovetail" type root attachment (55° angle) using a compliant layer. The second design is based on a modified pinned root attachment. The two designs are shown as solid models in Figure 6.

Table 2 summarizes critical stresses and temperatures for the blade designs. The maximum steady-state stress for the dovetail blade design is 214 MPa (31 ksi). This level is predicted for the critical neck region in the dovetail root. The critical stress in the life limiting region on the airfoil is about 186 MPa (27 ksi). The materials selected for prototype dovetail blade fabrication were GN-10 silicon nitride from Allied Signal Ceramic Components and NT164 silicon nitride from Norton Advanced Ceramics.

The second ceramic blade design has a "pinned" type root attachment wherein a single pin retains the blade in the disk. The initial integral pinned root concept had a simple round hole and cylindrical retaining pin (11). However, steady-state stresses in this design were on the order of 550 MPa (80 ksi). These high stresses were unacceptable and the design was subsequently modified to a two-tang root with oval hole and pin to lower stresses and resolve cooling problems. The ANSYS finite element steady-state stress map for the pinned blade attachment design is shown in Figure 7. The maximum stress in the critical neck region for the pinned blade is estimated at 283 MPa (41 ksi). The critical stress is in the airfoil region at about 186 MPa (27 ksi), similar to that for the dovetail blade. The material selected for pinned blade fabrication is SN-253 silicon nitride from Kyocera Industrial Ceramic Corporation.

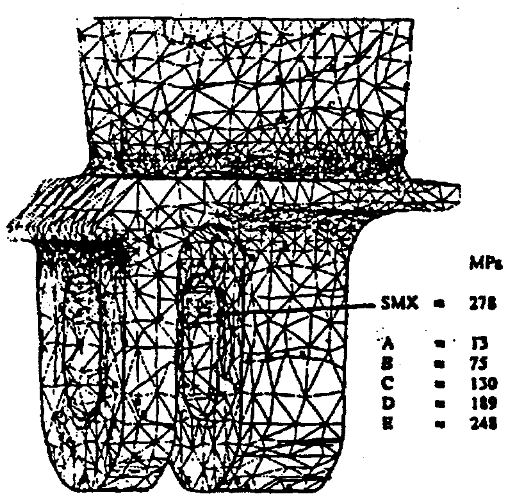


Figure 7. ANSYS Finite Element Stress Map for Pinned Blade Design

The materials properties were incorporated in CARES/LIFE life prediction for the blade designs. POS values for 30,000 hours were estimated to be about 0.98 for the HIP-sintered materials, GN-10 and NT164, based on an extrapolation of earlier data for NT154 Si_3N_4, a predecessor material for NT164 (9). Slow crack growth is the life limiting mode. The estimated POS values for these materials are too low for service applications. Review of materials selection and/or blade redesign will be required to obtain acceptable POS values. Service life for SN-253 is believed to be adequate based on dynamic fatigue data. Creep is not believed to be life limiting for the temperature range of the blade.

Secondary Component Design

Redesign of the components interfacing with the ceramics is an important effort under the program. Redesign is required to ensure thermal matching of adjacent ceramic and metal parts. Several design changes were also made to accommodate the heat management in view of the increase in TRIT from 1010°C (1850°F) to 1121°C (2050°F) and elimination of cooling in the first stage blade and nozzle. At the writing of this report, the secondary component designs are nearly completed. Extensive changes were made in the designs of the support structure of the combustor liner, in the designs of the support structures interfacing with the inner and outer nozzle shrouds, and in the first stage disk. Some of the materials changes for the secondary components have been summarized in Table 3. The primary design of the secondary components in the area adjacent to the ceramic parts are shown in Figure 3.

The changes to the secondary components have been backed up by extensive mechanical design and analysis and heat transfer analyses to establish potential interferences, overstress conditions, and localized overheating. The interested reader is referred to the Phase II Technical Progress Report for a detailed account of the concepts behind the secondary component redesign (15).

Table 3. Materials Changes for Secondary Components

Component	Current Material	New Material
Stage 1 Disk	V-57	Waspalloy
Front and Aft Rim Seals	Not in Current Centaur 50	Waspalloy
Stage 2 Disk	V-57	Waspalloy
Stage 2 Blade	IN-738LC	DS MAR-M247
Stage 1 Diaphragm	N-155	IN-903
Stage 2 Diaphragm	N-155 To Accommodate Aft Rim Seal	Waspalloy
Outer Shroud Sealing	New Design to Accommodate Ceramic Nozzle	IN-718, Haynes A230

Because monolithic ceramics are characterized by their low fracture toughness and low impact resistance, a basic design philosophy in this program has been to avoid a blade rub at all times under engine operating conditions. As a prerequisite it is mandatory to predict accurately the turbine blade axial and radial clearances for the whole operating cycle. Therefore, a model was developed to predict temperatures and displacements of ceramic and interfacing metal engine components during steady-state and transient engine operation. The results of these analyses are being used to set cold assembly clearances and control blade closures.

Task 8: Design and Procurement of Test Facilities

The work in this task involves setting up the test facilities to evaluate the ceramic stationary gas turbine components. Existing test facilities for materials property testing, spin testing, and combustor liner testing were modified if needed for the testing envisioned. A standard Centaur 50 engine was procured and modified to accept the ceramic hardware as detailed under Task 7.

Ceramic Materials Testing

Solar has extensive test equipment for materials property characterization including metallographic equipment, SEM/EDX, and various SATEC, MTS, and ATS test equipment for flexure, tensile, creep, and fatigue testing. Flexure, tensile, and creep testing can be performed up to 1700°C (3092°F). Special Waspalloy grips were fabricated for the testing of various blade root configurations. Waspalloy was selected since it is the first stage disk design material.

Cold Spin Rig

The CSGT program requires the use of a vacuum spin pit to test and evaluate various candidate monolithic ceramic inserted turbine blade attachment geometries along with candidate compliant layer materials. The rig must be capable of providing a centrifugal load on blades to at least 150 percent of the engine design load without introducing any loading conditions or forcing functions on the blades that would not be experienced in the actual engine environment. Prior spin pit experience has shown that the required spin pit partial pressure must be controlled in the range of 200 to 300 milli-torr to ensure stable test rotor operation.

Based on the recommendations of Test Devices, Inc. of Hudson, MA, a number of modifications were made to the existing spin rig equipment including incorporating high strength cover bolts and lid retention dogs with limit switches (to prevent drive operation until the lid is closed), installation of a non-contact vibration monitor (to measure the vibration of the spindle and shut down the drive if vibration exceeds a threshold), upgrading of the lubrication equipment (to prevent failure of the turbine bearing and consequent loss of the test article), upgrading of the vacuum system, and the installation of an automatic control system using an industrial programmable logic controller (PLC).

The upgraded cold spin rig during the proof testing of two NT164 first stage blades are shown in Figure 8. The blades are held in disk slots at a 180° spacial separation.

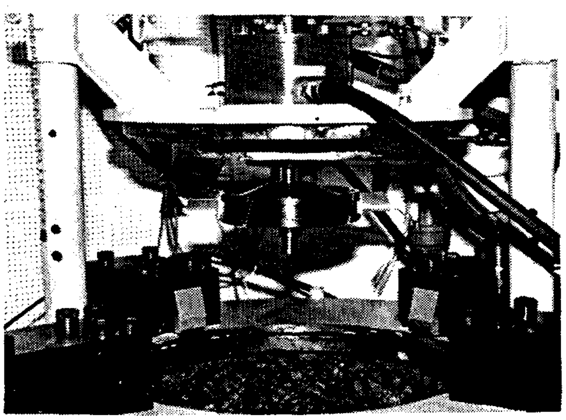


Figure 8. The Upgraded Cold Spin Rig With Two NT164 Blades During Proof Testing

Hot Spin Rig Testing

Solar's blade spin rigs are currently not set up to conduct hot spin testing. Although the current upgraded cold spin rig can be further modified for hot spin testing, a program decision was made to use the services of Test Devices, Inc. for any hot spin testing required under the program.

Mechanical Nozzle Attachment Rig

The aerodynamic load on the airfoil produces analytically predicted stresses in the ceramic to metallic attachment region (surface contact) and in the trailing edge inner airfoil root fillet. The purpose of the mechanical nozzle attachment rig is to assess the design contact loads and resulting stresses. The rig which was specifically designed and fabricated for the CSGT nozzle testing imposes the aerodynamic loads analytically predicted for the nozzle segment on the attachment region through the use of a mechanical loading device (air cylinder). The rig has been designed with the option for mounting to a shaker table for vibratory testing.

Thermal Nozzle Test Rig

A second nozzle rig is being designed to produce a thermal gradient in excess of that expected in "hot spot" locations during engine operation. Application of the temperature gradient will produce stress conditions intended to proof test the nozzle durability prior to installation in an engine. The test will be used to eliminate nozzles that exhibit unacceptable materials flaws.

Subscale Combustor Rig

Solar's subscale test facility has the capacity to achieve engine rated temperatures and pressures while maintaining a single injector's mass flow into the rig. All subscale testing of the monolithic and CFCC subscale combustor liners will be conducted with a production Centaur 50S SoLoNOx fuel injector. The facility is instrumented for temperature, pressure, and flow measurements. Exhaust emissions are monitored using a state-of-the-art Rosemount analytical continuous emission monitoring system (CEMS). To prevent the ceramic liners from exceeding a wall temperature of 1204°C (2200°F), a fuel shutoff system has been installed. The system is integrated with 15 Type K thermocouples that are instrumented on the liner wall.

Atmospheric Combustion Rig

Full-scale combustor liners will first be tested in an atmospheric combustor facility. This rig will provide a preliminary indication of the performance of the full-scale combustor hardware. The facility which can accommodate three combustor modules provides hot air to the rig at atmospheric pressure. A complete set of 12 Centaur 50 SoLoNOx fuel injectors is used to run the rig, and the flow function is matched to the engine design point. A thermocouple rake system provides temperature data for pattern factor and radial profile calculations. Exhaust emissions are monitored by a CEMS, and data is captured by a Daytronics and VAX RETS data acquisition system. TRIT conditions and liner wall temperatures expected in the engine can be closely simulated. The rig is being used without extensive modification for ceramic combustor liner testing.

High-Pressure Combustion Rig

The high-pressure test facility (loop rig) is a recuperated Centaur T4000 (early version of the Solar Centaur 40 engine) which provides an appropriate test vehicle for the full-scale ceramic combustor liner hardware. Full air flow (~16 kg/s) can be obtained with a maximum pressure of approximately 724 kPa (105 psig). The engine is fully instrumented with an Allen-Bradley controls system and has a complete data acquisition system, including Kessler type pressure oscillation sensors for monitoring the combustor harmonic frequencies. Pattern factor and radial profiles are measured with a Type K thermocouple rake assembly. Emissions can be taken at the exit of the combustor plane or at the exhaust stack by a CEMS. Load transients and fast shutdowns can be performed on this engine. These will provide data for the heat transfer and stress models. This rig is being used on the CSGT program without modification.

Engine Rig

The engine test rig is the test bed apparatus for the CSGT program to demonstrate the use of advanced ceramic components for the first stage rotor blade, first stage nozzle, and the combustor liner. The rig consists of a production Centaur 50 turbine engine, standard cold end drive gearbox, standard engine/generator mounting skid, and a (non-standard) 7000 hp Hoffman water-brake dynamometer. The engine rig will be operated to a maximum (TRIT) of 1121°C (2050°F) at 100 percent (14,950 rpm) engine speed which equates to a tip speed of approximately 407 m/s. The engine rig will evaluate ceramic hot section components in a typical Solar Turbines generator-set operating environment.

Prior DOE-sponsored ceramic engine programs have shown that ceramic components are evaluated most accurately in the actual engine environment for which the components have been designed. Smaller subassembly test rigs can typically only partially reproduce the engine operating environment, and therefore cannot completely be relied upon to expose ceramic components to all engine induced temperature and stress conditions prior to actual engine testing. The engine test bed engine thus serves the CSGT program as the final qualification test for all ceramic components before they are installed in the 4,000-hour field test engine.

The CSGT rig engine (S/N 442H) is a new sales order engine with all hardware dedicated to the CSGT program. The engine was assembled in the Solar Kearny Mesa facility and was acceptance tested at the Harbor Drive facility in the cold end drive test cell. The acceptance test was performed to production test standards for the Centaur 50 engine, and the engine was accepted after having achieved the required performance within the vibration limitations specified in the standard test specification. The Centaur 50S CSGT engine rig is shown in the test cell in Figure 9.

Task 9: Ceramic Component Iterative Design, Manufacturing, and Testing

Work under Task 9 includes fabrication of specimens, subscale and full-scale components, testing of specimens, blade attachment specimens, and prototype blades and nozzles. Testing of subscale combustor liners and of full-scale combustor liners prior to engine testing is performed under Task 10.

Full-Scale and Subscale Ceramic Component Fabrication

During the reporting period a number of first generation full-scale and subscale components were received from the suppliers. Components received to-date have been listed in Table 4.

During the reporting period Norton Advanced Ceramics made a business decision to abandon high-temperature ceramic gas turbine development work and to focus more fully on automotive component and ball-bearing activities. This decision affects the CSGT program in the sense that NAC has stated its preference not to fabricate second generation components. Solar is not considering NAC in the selection process for second generation component fabrication, for this reason.

Examples of silicon nitride blade and nozzle components delivered to-date are shown in Figure 10. Full-scale SiC/SiC CFCC combustor liners from B.F. Goodrich are shown in Figure 11.

Receiving/Inspection

A detailed procedure has been implemented at Solar to control receipt and inspection of all CSGT ceramic parts. This procedure is described in some detail in the mid-term Phase II Technical Progress Report (15). The procedure involves tracking of all contract property, inspection practices, and corrective action. Guidelines for visual inspection, part identification, dimensional inspection, and fluorescent dye penetrant inspection have been outlined in appropriate Solar specifications. Solar's requirements for supplier inspection have been detailed in supplier materials specifications. Action on discrepant parts is taken by a Materials Review Board (MRB).

Eighty-five (85) NT164 blades were received from NAC and 94 GN-10 blades from CC. All of these parts have been inspected visually, dimensionally, and by fluorescent dye penetrant inspection (FPI) using improved methodology developed by ANL. Based on these inspection techniques, 15 NT164 blades were rejected for the first engine build. Three NT164 blades were forwarded to ANL for NDE. Of the 94 GN-10

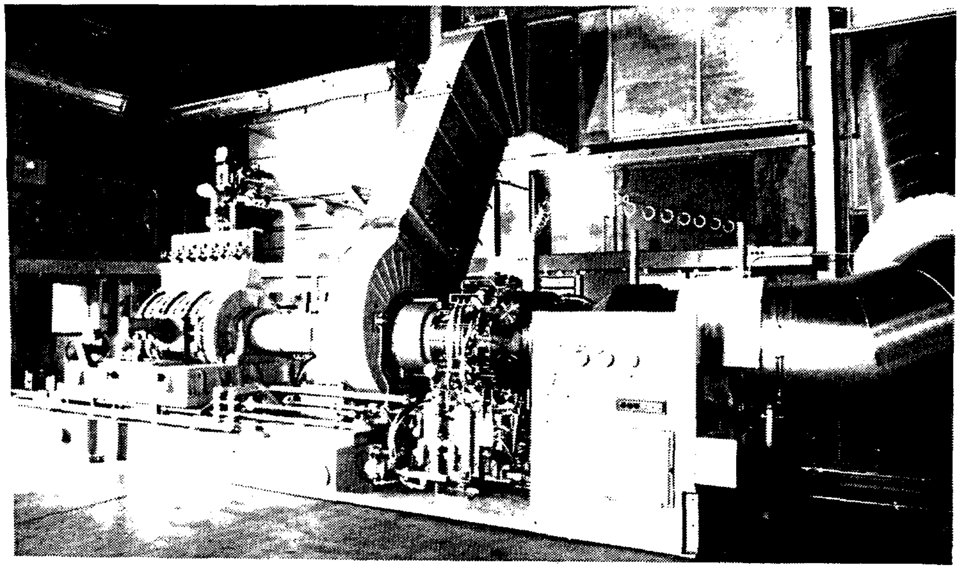


Figure 9. CSGT Centaur 50S Engine Rig

blades received from CC, only one blade was rejected. Following visual inspection 70 NT164 blades were frequency inspected and the data taken as a whole indicate a very consistent set of frequencies for the first three important modes. The standard deviation for all modes was approximately 10 to 12 percent of the frequency being measured. This scatter is somewhat greater than for the metal nozzles, but it is probably indicative of frequency variations brought about by inconsistent dimensional control of the airfoil shape in the fabrication process. Frequency scatter for the GN-10 blades was appreciably better than for the NT164 blades, the standard deviation being approximately 7 percent.

Two first article nozzles from NGK were visually inspected. Their general appearance appeared to be in very good condition. A sudden transition in thickness near the trailing edge is due to the mode of machining in the green state and will be corrected by NGK. Some additional machining will also be required for the outer shroud slash angles to more accurately match drawing requirements.

Blade Attachment Testing

Testing of ceramic inserted blade attachment concepts to a metallic disk involves a matrix of both static and dynamic tests. Since ceramic blade to metallic disk attachments typically degrade due to the combination of (1) centrifugal (CF) blade loads on a ceramic to metallic interface and (2) relative motion (tangential sliding) at the loaded interface due to thermal expansion of the disk rim, all CSGT blade attachment testing focuses on these two primary conditions.

Attachment tensile testing for the dovetail design and an early version of the pinned root blade design have been reported previously (11,14). Testing for the dovetail blade design has been conducted with appropriate compliant layer systems designed to

Table 4. First Generation Full-Scale and Subscale Components Received To-Date

Supplier	Material	(Subscale) Component	Delivery Status
AlliedSignal Ceramic Components (CC)	GN-10 Si_3N_4	94 Dovetail Blades (+ Co-Proc. Flexure Bars)	6 AS-800 Si_3N_4 Dovetail Blades Due
Norton Advanced Ceramics (NAC)	NT164 Si_3N_4	85 Dovetail Blades (+ Co-Proc. Flexure Bars)	Complete
Kyocera Industrial Ceramics Corporation (KICC)	SN-253 Si_3N_4	2 Pinned Blade Pre-Prototypes	80 SN-253 Si_3N_4 Pinned Blades Due
NGK Insulators, Ltd. (NGK)	SN-88 Si_3N_4	2 First Article Nozzles, 1 Pre-Prototype Nozzle	100 SN-88 Si_3N_4 Nozzles Due
Carborundum	Hexoloy® SA SiC	3 Sets (5/Set) Subscale Combustor Liner Tiles	Complete
Norton Advanced Ceramics (NAC)	NT230 SiC	6 Combustor Liner Rings	Complete
Babcock & Wilcox (B&W)	Al_2O_3/Al_2O_3 CFCC	4 Subscale Combustor Cylinders (+ Co-Processed Test Specimen)	Complete
DuPont Lanxide Composites (DLC)	SiC/SiC CFCC	4 Subscale Combustor Liners (+ Co-Processed Test Specimens)	Complete
B.F. Goodrich (BFG)	SiC/SiC CFCC	2 Sets of Full-Scale Liners (2/set) (+ Co-Processed Test Specimens)	Complete

accommodate the relative motion of the ceramic blade and disk under conditions of temperature cycling.

The results of the testing to-date show the following trends:

1. Dovetail attachment specimens tested at room temperature fail at typically 3-4X the nominal design stress.

2. At temperatures typical for the blade root in service (about 682°C, 1260°F) dovetail attachment specimens fail at lower loads but, still, the failures occur at 2-3X the design stress. Some pinching of the dovetail blade in the grip side that had not failed was observed for this test.

3. Reducing the dovetail angle from 60 percent to 55 percent appeared to have had a beneficial effect. Following attachment testing to 100 percent of design load at the approximate blade root service temperature, the attachment was found to be free in the bottom grip and mildly wedged in the top grip.

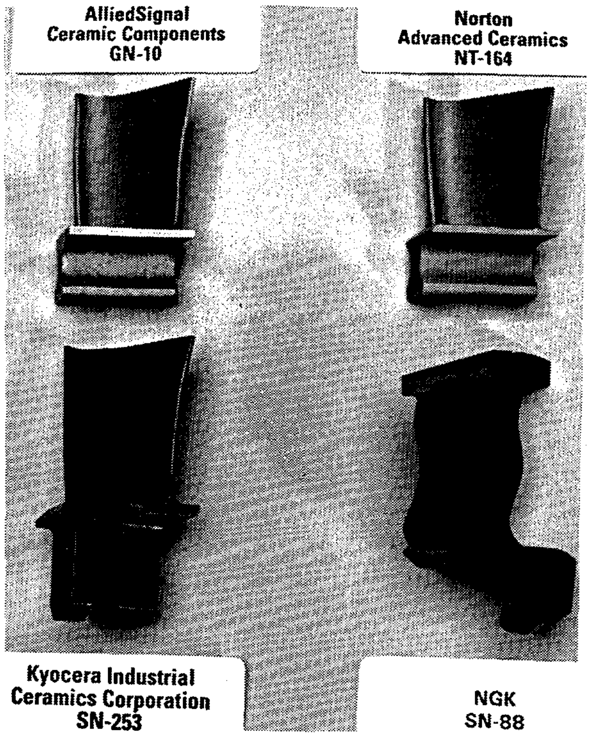


Figure 10. Fabricated Dovetail and Pinned Root Blades and Bowed Nozzle

Only slight heating was required to loosen the specimen.

4. The incorporation of a friction-reducing additive or surface appears to reduce the incidence of sticking in cyclic testing at the approximate blade root design service temperature.

5. Testing with attachment specimens representative of the current pinned blade design indicated failure at approximately 183 percent of design load at room temperature. No compliant layer system was used in these tests.

6. Attachment testing on the new pinned blade root design at a root service temperature of about 682°C (1260°F) resulted in failure at approximately 155 percent of design load.

In summary, dovetail blades appear to present a more comfortable design margin than pinned blades based on attachment test data to-date.

Cold Spin Testing

Blades are being subjected to spin testing to evaluate the blade root attachment and ceramic materials performance. Initial cold spin testing was conducted on simulated blades which were machined from attachment specimens. The design rotational speed of the first stage dovetail blades is 21,625 rpm (the rpm is higher than for the actual engine disk because of the smaller size of the spin disk). Cold spin testing has been conducted on simulated dovetail blades of the three candidate blade materials at rotational speeds corresponding to up to 35,989 rpm (200 percent of design load). All simulated blades survived the spin tests.

All first stage blades that had passed visual and dimensional inspection from NAC (75) and CC (93) thus far have been cold spin proof tested at 125 percent design CF load (112 percent speed). A random blade from each of these suppliers has been taken to 200 percent CF load (141 percent speed) successfully. Figure 8 shows two of the NT164 blades following a cold spin proof test.

Hot Spin Testing

Following the cold spin proof tests, a series of hot spin tests was conducted at Test Devices, Inc. of Hudson, MA. Test objectives were to confirm the integrity of the compliant layer system after thermal and CF load cycling. It was felt that successful results from this series of tests must be obtained prior

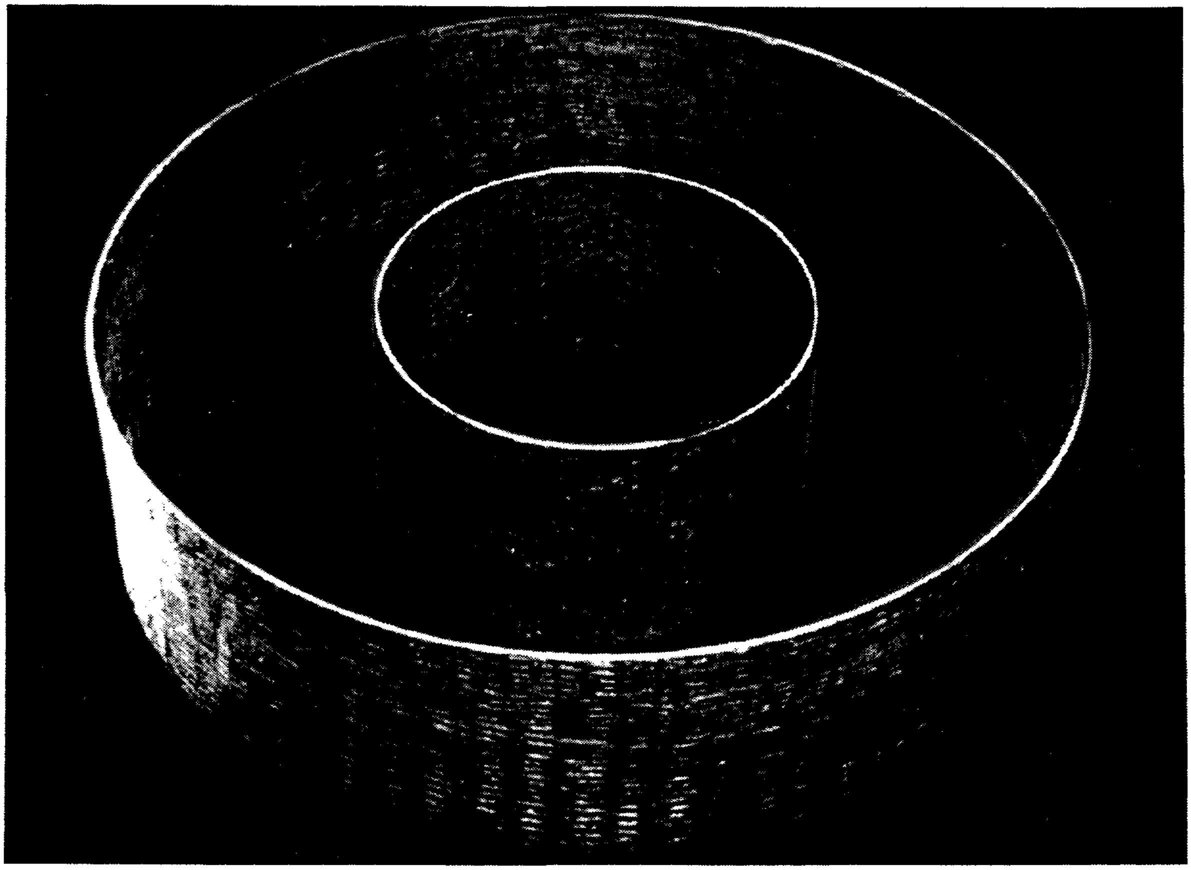


Figure 11. Set of B.F. Goodrich Full-Scale Combustor Liners

to conducting the first engine test with ceramic dovetail blades.

Three dovetail blades of each of NT164 and GN-10 were hot spin tested at 125 percent design load at 682°C (1260°F). Good results were obtained for each material in three separate tests with a maximum of 25 load cycles (0 to 125 percent load) with the current standard compliant layer system of a Ni-base alloy with friction-reducing surface. No sticking was observed for any of the tests performed. A detailed analysis of the compliant layer systems after the hot spin tests is under way in order to assess long-term behavior.

Engine Testing

In the engine test planning for the CSGT gasifier test rig, a strategy was defined in which each individual ceramic component is fully evaluated by initially testing it with the remaining flowpath components fabricated from metallics. This methodology will help prevent secondary damage to downstream ceramic components. The engine is to be tested at the standard operating TRIT of 1010°C (1850°F) for each ceramic component system prior to testing these components in combination. In subsequent testing, ceramic components will be combined and installed and the engine will again be operated at the standard TRIT. The final test at a TRIT of 1010°C (1850°F) will be conducted with an engine build incorporating one of the two ceramic blade designs (to be decided), the ceramic nozzle, and a ceramic combustor liner system.

Once all three components have been combined in a build and satisfactorily evaluated at a TRIT of 1010°C (1850°F), an increase in TRIT to 1121°C (2050°F) will be incrementally imposed until a steady-state operating condition at the final temperature regime is achieved. This test strategy was determined to be the lowest risk approach to evaluating the ceramic components in an engine test bed and was used as the basis for all subsequent planning decisions and scheduling of the engine tests. The current test plan is summarized in Table 5.

The first engine test was performed on August 18, 1995. The test which lasted for 1 hour at a nominal TRIT of 1010°C (1850°F) and 100 percent load was performed with the CSGT Centaur 50S test engine incorporating a full first stage disk of NT164 dovetail blades (62 blades). To avoid any chance of a tip rub the blades were run with wide open cold clearances. The target clearance was 1.27 mm, which is 0.76 mm wider than in the metal Centaur 50S in which a tip rub is normally incurred during the initial start-up of the engine. The engine was run with a SoLoNOx combustor modified to generate a non-standard combustor exit temperature profile defined by the design heat balances for the ceramic blade and (future) nozzle with adjacent support structure.

Upon disassembly the NT164 blades showed no evidence of degradation. Some of the compliant layers showed evidence of impact, but the compliant layer system overall performed as expected. Some design changes have been incorporated into the compliant layer system to eliminate impact in future runs. The NT164 blades will be used in future runs, the first one of which is a cyclic test (Build No. 4 in Table 5).

The second engine test was performed with GN-10 dovetail blades in the first stage. The test was very similar to the first test except that the engine was initially operated at 95 percent speed to avoid a possible vibrational interference estimated to be present at about 105 percent speed. After successful operation for 1 hour at 95 percent speed, the engine speed was carefully increased to 100 percent speed and operated at full load for an additional hour under conditions nominally identical to those of the NT164 blade engine test. Table 6 lists performance parameters for the first two engine tests and for a comparable run with the all-metal engine. GN-10 blades are currently being examined. Data analysis for both runs is in progress.

Figure 12 shows the first stage disk with NT164 dovetail blades during engine assembly. The disk was thermally painted to obtain an indication of its temperature profile during operation. Figure 13 shows the disk following completion of the first engine test.

Long-Term Data Base

Work is ongoing at Solar and the University of Dayton Research Institute (UDRI) to generate a long-term data base. Testing involves baseline fast fracture tensile and flexure testing, tensile and flexure dynamic fatigue testing to assess evidence of slow crack growth, and short-term and extended creep testing. A sizable data base has been generated to-date for the program blade and nozzle materials (11,14). Support work is also ongoing at Oak Ridge National Laboratory and UDRI under a separate support contract.

Table 5. Engine Test Schedule

Build No.	TRIT (°C, °F)	Description	Status
1	1010, 1850	NT164 Dovetail Blades, Metal Nozzle	Completed
2	1010, 1850	GN-10 Dovetail Blades, Metal Nozzle	Completed
3	1010, 1850	BFG CFCC Combustor, Metal Blades, and Nozzles	
4	1010, 1850	BFG CFCC Combustor, NT164 Blades, Metal Nozzle, Cyclic Test	
5	1010, 1850	Instrumented Engine Test - All Metallic - Generate Boundary Conditions	
6	1010, 1850	KICC Pinned Blades, Metal Nozzle	
7	1010, 1850	NGK Nozzles, Metal Blades	
8	1010, 1850	BFG CFCC Combustor, Ceramic Blades (To Be Selected), NGK Nozzle	
8a	1010 --> 1121 1850 --> 2050	BFG CFCC Combustor, Ceramic Blades (To Be Selected), NGK Nozzle (Continue Test of Build No. 8)	
8b	1121, 2050	BFG CFCC Combustor, Ceramic Blades (To Be Selected), NGK Nozzle, 10 Hours (Continue Test of Build No. 8a)	
9	1010, 1850	2nd Gen. Ceramic Combustor, Ceramic Blades, Metal Nozzles	
10	1010 --> 1121 1850 --> 2050	2nd Gen. Ceramic Combustor, Ceramic Blades, Ceramic Nozzles, 10 Hours	
10a	1010 --> 1121 1850 --> 2050	2nd Gen. Ceramic Combustor, Ceramic Blades, Ceramic Nozzles, 50 Hours	

Four candidate nozzle materials were subjected to fast fracture and dynamic fatigue testing at UDRI and Solar. These materials were NT164, SN-88, and SN-253 Si_3N_4 and Hexoloy® SA SiC. Based on the UDRI and Solar data and on life prediction assessment using the NASA CARES/LIFE program, SN-88 and SN-253 were subsequently selected for short-term (1000 hours) and long-term (5000, 10,000 hours) tensile creep testing at UDRI. Short-term creep testing was also performed for Hexoloy® SA SiC. Data for the creep tests performed to-date have been listed in Table 7.

During the 1000 hours creep screening tests, SN-88 was the only material for which all tensile specimens survived. The residual tensile strength values measured at 1288°C (2350°F) ranged from 367 to 387 MPa (53 to 56 ksi). This compares well with an average fast fracture strength of the material prior to testing of 461 MPa (67 ksi). The one SN-253 specimen that did not fail in the 1000-hour

Table 6. Performance of the First Two Ceramic Engine Tests and All-Metal Engine Baseline

	All-Metal Engine	NT164 Blade Test - Build No. 1	GN-10 Blade Test - Build No. 2	GN-10 Blade Test - Build No. 2
Date	7/19/95	8/18/95	9/21/95	9/21/95
Shaft Speed	100.0%	100.6%	95.2%	100.6%
TRIT °C (°F)	1007 (1845)	1022 (1872)	1017 (1863)	1019 (1867)
Thermal Efficiency	28.8	27.9	25.7	28.1
Shaft Horse Power	5257	5246	4370	5225

* Corrected to 27°C/80°F, sea level, rel. hum.: 60%, zero inlet, and exhaust losses.

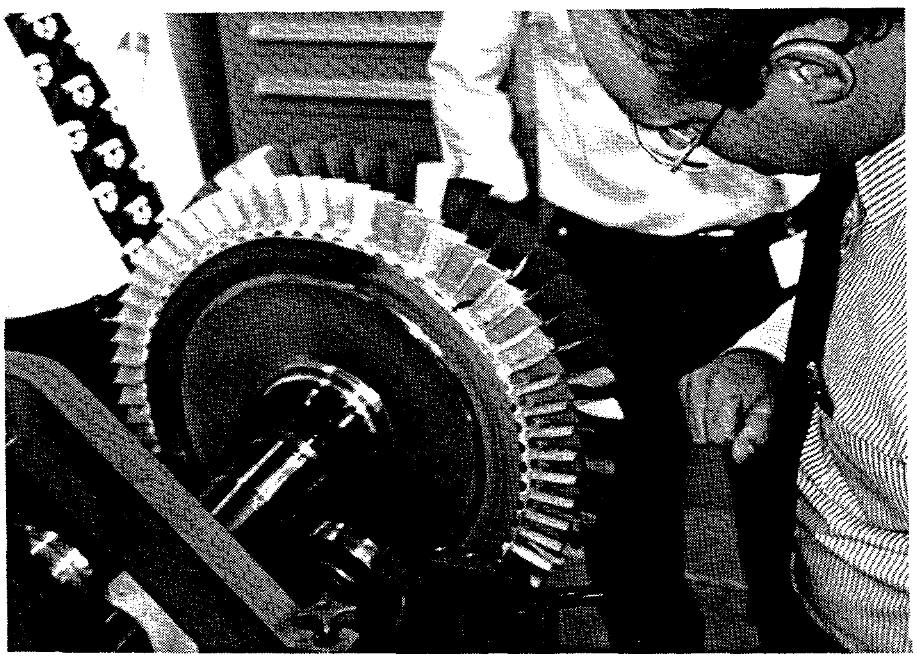


Figure 12. First Stage Disk with NT164 Dovetail Blades During Engine Assembly

creep test had a residual tensile strength at 1288°C (2350°F) of 205 MPa (30 ksi), a significant drop from the 590 MPa (86 ksi) tensile strength before exposure. One of the two Hexoloy® SA specimens which did not fail had a residual tensile strength at 1288°C (2350°F) of 467 MPa (68 ksi), similar to the pre-exposure fast fracture tensile strength of 453 MPa (66 ksi). The second surviving specimen showed a dramatic drop in strength. The data confirm earlier observations about Hexoloy® SA. The material exhibits either

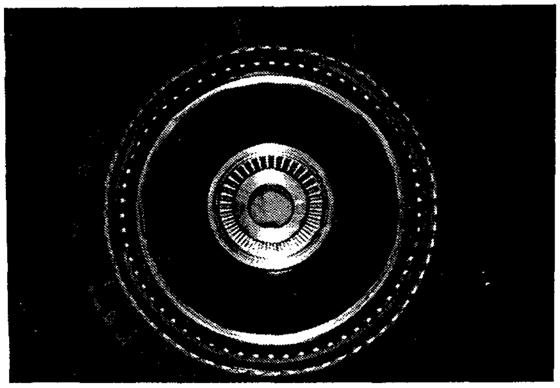


Figure 13. First Stage Disk with NT164 Dovetail Blades After Engine Disassembly

little slow crack growth or creep, or the strength degrades rapidly because of intrinsic flaws in the specimen.

Since SN-253 was selected as one of the two nozzle materials, a decision was made to continue long-term testing of this material. However, the two specimens slated for the 10,000-hour creep test at the design stress of 186 MPa (27 ksi) and a temperature of 1288°C (2350°F) failed after 1343 hours and 764 hours, respectively. It was subsequently decided to eliminate SN-253 as a nozzle material and discontinue planned further long-term creep testing. A new KICC material, SN-281 Si_3N_4, which reportedly has improved properties is being considered as a back-up material and tensile specimen procurement is in progress. SN-281 specimens will be tested in fast fracture and dynamic fatigue tensile tests and in short-term (1000 hours) creep testing at UDRI.

The long-term test data indicates that SN-88 is currently the only nozzle material that has the potential of meeting the design life criteria of the nozzle under the critical hot spot conditions. Continued long-term creep testing will indicate to what extent SN-88 will survive over the planned 5,000 to 10,000 hours duration of the test plan.

Nondestructive Evaluation

Development of appropriate nondestructive evaluation (NDE) methodology is performed in a collaborative effort by the Caterpillar Technical Center (CAT TC) and Argonne National Laboratory (ANL). The initial methodology development work and component evaluations are the responsibility of ANL while CAT TC has responsibility for the coordination of the NDE effort and for technology transfer to Solar.

NDE techniques considered for monolithic ceramics are principally visual inspection, density measurements, microfocus X-ray radiography, fluorescent dye penetrant inspection (FPI), laser scatter, and acoustic resonance. ANL has successfully improved the detection limit of the FPI technique by incorporating an optical magnification (> 25X) procedure. Surface flaws can be detected down to 0.5 mm with the improved technique compared to a limit of about 1.2 mm with conventional FPI. ANL also incorporated a boroscope extension to view visually inaccessible areas such as the internal surfaces of the pin contact area of the pinned blade root.

ANL is able to perform state-of-the-art microfocus X-ray radiography on the CSGT monolithic hot section components with acceptable resolution, but the penetrating power of the current 120 kVp X-ray head does not allow comprehensive 3-D scanning of critical sections of the ceramic blade and nozzle components. ANL is considering upgrading its equipment to include a 225 kVp or 320 kVp X-ray head for improved resolution.

Table 7. Creep Test Data for Three Candidate Nozzle Materials

Ceramic (No. of Specimens)	Stress (MPa, ksi)/ Temperature (°C, °F)	Planned Test Time	Time Until Failure	Residual Tensile Strength (MPa, ksi)
SN-88 Si_3N_4 (3)	207 MPa/1288°C 30 ksi/2350°F	1000 Hours	No Failure at 1000 Hours (3)	387 MPa/56 ksi 367 MPa/53 ksi 379 MPa/55 ksi
SN-253 Si_3N_4 (3)	207 MPa/1288°C 30 ksi/2350°F	1000 Hours	997 Hours 658 Hours No Failure at 1000 Hours	205 MPa/30 ksi
Hexoloy® SA SiC (3)	207 MPa/1288°C 30 ksi/2350°F	1000 Hours	367 Hours No Failure at 1000 Hours (2)	250 MPa/36 ksi 467 MPa/68 ksi
SN-88 Si_3N_4 (2)	186 MPa/1288°C 27 ksi/2350°F	10,000 Hours	Time as of 9/21/95: 2706 Hours, 2446 Hours	
SN-88 Si_3N_4 (4)	186 MPa/1288°C 27 ksi/2350°F	5000 Hours	Time as of 9/18/95: 1196 Hours, 1220 Hours	
SN-253 Si_3N_4 (2)	186 MPa/1288°C 27 ksi/2350°F	10,000 Hours	1343 Hours 764 Hours	
SN-253 Si_3N_4 (4)	186 MPa/1288°C 27 ksi/2350°F	5,000 Hours	Not Started Because of Early Failures in 10,000-Hour Test	
SN-88 Si_3N_4 (1)	172 MPa/1288°C 25 ksi/2350°F	10,000 Hours	Time as of 9/21/95: 860 Hours	

The predominant techniques used for the CFCC materials are infrared imaging and selected area computed tomography (CT). Sub-scale combustor liners have been examined in the as-received state and following combustor rig testing. Pre-existing defects such as low-density regions and delaminations have been detected. Figure 14 shows infrared imaging scans of DLC SiC/SiC CFCC combustor liners before and after a 10-hour subscale liner test. It can be seen that a region of low density or possibly minor delamination extended during the test.

Task 10: Low Emission Combustor

This task involves the subscale and full-scale combustor liner testing of the designs developed under Task 7.

Subscale Testing

The objective of subscale testing is to demonstrate key attributes of the full-scale liners in a cost-effective but representative geometry. These key attributes include liner design features such as attachment to the metallic support structure, materials durability, and emissions potential. The test articles for subscale combustor liner testing are 20 cm

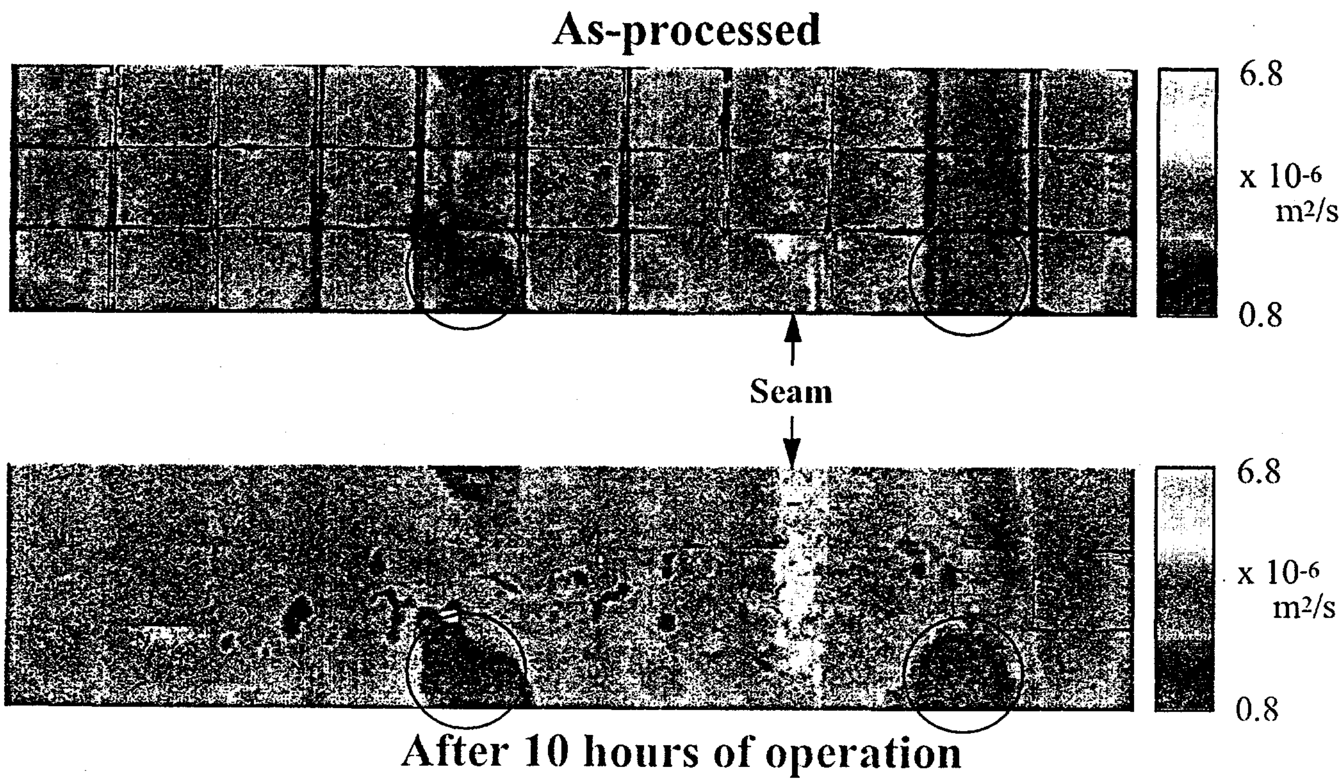


Figure 14. Infrared Imaging Scans of DLC SiC/SiC Subscale CFCC Combustor Liner Before and After 10 Hours Combustor Rig Test

diameter by 20 cm long cylinders fabricated by candidate monolithic and CFCC combustor suppliers. Two subscale combustor rigs are being used for the testing. Both systems are based on a simple can type geometry with a single production SoLoNOx fuel injector. The first rig has been used primarily to assess the low emissions potential of the ceramic liners and the testing to-date has been done exclusively with CFCC materials. This rig will also be used for durability testing. The CFCC liner is contained within a metallic cylinder and is held in position with a Nextel 440 insulating blanket. The ceramic liner is freed from any mechanical loads in this configuration. The second rig simulates the attachment mechanism and metallic support structure of the combustor. It has been used both for CFCC liner and monolithic tile testing. The container can consists of metallic strips held together by two clamping rings in a barrel-and-stave arrangement. In the monolithic tile and ring configurations, the liners are loaded by three external tie bolts. The loads are transferred by small ceramic balls positioned in radial grooves at the edges of the liner assemblies. Table 8 summarizes the subscale liner tests planned and the status of the testing to-date.

Attachment/Durability Testing

The only monolithic test completed to-date involved Hexoloy® SA tiles in a subscale combustor configuration which was a miniature version of the full-scale configuration. Following completion of the tests, the tiles showed cracks which were initiated from the edges at the contact areas with the metal support structure and at the interfaces between the tiles. Although thermal shock was not

Table 8. Subscale Liner Tests Status

Test Configuration	Material	Purpose	Nominal Condition	Duration	Results
2-D CFCC	DLC SiC/SiC	Attachment/ Durability	1177°C (2150°F)	1 Hour	Pre-Existing Delamination Can Intact
2-D CFCC	DLC SiC/SiC	Attachment/ Durability	1177°C (2150°F)	10 Hours	Pre-Existing Delamination Extended Can Intact
2-D CFCC	DLC SiC/SiC	Attachment/ Durability	1177°C (2150°F)	100 Hours	TBD
2-D CFCC	DLC SiC/SiC	Emissions	871°-1177°C (1600°-2150°F)	2x 2 Hours	<10 ppmv NO_x, CO Can Intact
Fil.-Wound CFCC	B&W Al_2O_3/Al_2O_3	Attachment/ Durability	1038°C (1900°F)	1 Hour	Pre-Existing Delamination Extended
3-D CFCC (Nextel 610)	B&W Al_2O_3/ Al_2O_3	Attachment/ Durability	1177°C (2150°F)	1 Hour	Possible Low-Density Region, Can Intact
3-D CFCC (Nextel 610)	B&W Al_2O_3/ Al_2O_3	Attachment/ Durability	1177°C (2150°F)	10 Hours	Three Axial Cracks, Can Maintain Integrity
3-D CFCC (Nextel 720)	B&W Al_2O_3/ Al_2O_3	Attachment/ Durability	1177°C (2150°F)	100 Hours	TBD
Tiles (Shiplapped)	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	1 Hour	Tiles Cracked, Interference
Tiles (Bevelled)	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	1 Hour	TBD
Tiles (Bevelled)	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	10 Hours	TBD
Rings	NAC NT230 SiC	Attachment/ Durability	1204°C (2200°F)	1 Hour	TBD
Rings	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	1 Hour	TBD
Rings	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	10 Hours	TBD

excluded as a contributor to the tile failure, it was concluded that the design of the metallic support structure was deficient in preventing undesirable levels of load transfer to the tiles. Design changes to the combustor liner were therefore implemented. Future testing will establish more clearly the durability of the monolithics once an improved design is implemented in the subscale tests.

The CFCC subscale testing indicated that notwithstanding materials imperfections as evidenced by localized low density regions and/or delaminations the CFCC liners generally retained their integrity during the testing. These tests were generally conducted in the first rig configuration which has minimal loading on the liners.

Emissions Testing

The purpose of the emissions testing was two-fold. The DOE SOW requires demonstrating NO_x levels < 25 ppmv and showing the potential of NO_x levels < 10 ppmv with a ceramic "hot wall" combustor. Solar's own goal was to demonstrate NO_x levels < 10 ppmv on the CSGT engine. The initial development was performed on a single-fuel injector can type geometry because (1) its simple geometry, (2) common test configuration with the subscale testing for attachment/durability, and (3) its easy scale up to an off-line can type combustor in case an annular combustor system cannot meet the target NO_x levels.

Two tests were conducted to establish the low emissions reduction potential of the ceramics. A DLC SiC/SiC CFCC can liner was used in these tests. The results of the test are shown in Figure 15.

In these tests the CFCC liner was used as a generic ceramic substrate and compared with a conventional metallic louvre-cooled liner (which is the common configuration for the Solar engine combustors) and a metallic effusion-cooled liner which represents an advanced liner cooling technique. As can be seen in Figure 15, the NO_x levels of the louvre- and effusion-cooled liner are typically > 20 ppmv over the fuel:air ratio range investigated for all three combustor liner systems. The level of CO increases sharply

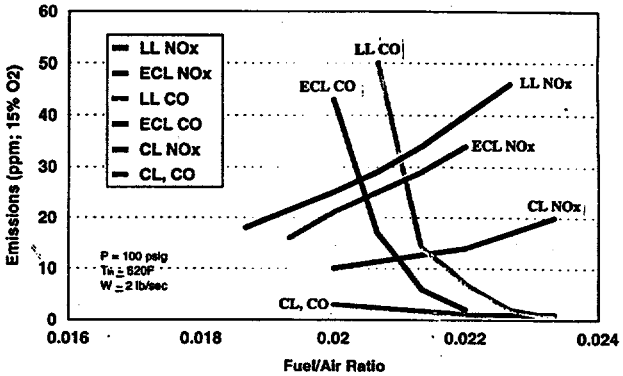


Figure 15. Emission Levels of NO_x and CO as a Function of Fuel:Air Ratio for Metallic and CFCC Liners

with decreasing fuel:air ratio. In generally, the levels of NO_x and CO are somewhat lower for the effusion-cooled liner compared with the louvre-cooled liner.

The CFCC liner shows significantly lower values of NO_x and CO compared with the metal liners. NO_x levels of about 10 ppmv were established for the CFCC liner compared to NO_x levels of 20 to 30 ppmv for the metal liners. CO levels were < 5 ppmv over the fuel:air ratio range investigated. The low CO levels present an opportunity to further lean out the flame to lower fuel:air ratios with reduced risk of a flame-out. This is expected to further reduce the level of NO_x in the combustor.

The tests have shown the potential of a "hot wall" combustor for reducing NO_x and CO levels significantly below those of metallic systems. Further development of the emissions potential will be conducted on full-scale systems.

Full-Scale Combustor Testing

Initially full-scale combustor testing was not envisioned till the end of Phase II. It was moved forward to enable time for sufficient iterative combustor emissions development to achieve the target NO_x level under the program. Also, the availability of a full-scale combustor at an earlier stage in Phase II was deemed desirable to enable simultaneous testing of multiple components. For this reason full-scale SiC/SiC CFCC liners were procured on a part supply basis from B.F. Goodrich because of their ability to meet the schedule for delivery. The BFG liners are considered a generic ceramic substrate useful for demonstrating the "hot wall" effect for the reduction of NO_x and CO, for emissions reduction development, and for development of the required radial profile and pattern factor essential for delivering the design heat flows to the critical nozzle vane and shroud areas.

To-date the testing of full-scale combustor liners has included an atmospheric and a high-pressure evaluation in combustor rigs. The atmospheric rig enables establishment of initial component temperatures while the high-pressure rig more accurately simulates engine combustor conditions. The latter rig enables emissions measurements, for example. To-date one set of BFG liners has been tested in both rigs. Test data have been summarized in Table 9.

The liners performed satisfactorily in the full-scale rig tests. No obvious signs of degradation were noticed upon inspection of the components following the testing. The liners will subsequently be tested in the engine rig (Table 6, Build No. 3).

Application and Benefits

The objective of the CSGT program is to demonstrate ceramic gas turbine technology with the aim at eventual commercialization and ensuing 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 (10).

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 parts allow, and (2) from the value represented by the reduction in emissions of NO_x, CO, and UHC (unburned hydrocarbons) in ceramic engines compared to all-metal baseline engines. The added value can be estimated at the level of individual engine installations and 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 in the 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 in output 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 turbines from ceramic insertion (10). 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

Table 9. Data from Atmospheric and High-Pressure Rig Testing for B.F. Goodrich Full-Scale Liners

Test (Duration)	Pressure	Max. Combustor Outlet Temp.	Max. Inner/ Outer Wall Temp.	Full Load Emissions	Liner Condition
Atmospheric (1 Hour, 2 Cycles)	1 atm	1049°C (1920°F)	950°C (1742°F) 1022°C (1872°F)	Not Evaluated	No Visible Degradation
High Pressure (3 Hours, 1 Cycle)	120 psia	1071°C (1959°F)	1120°C (2048°F) 1107°C (2025°F)	50 ppmv NO_x 6 ppmv CO	Liner Intact Some Degradation of Surface Coating

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 such as those of the Advanced Turbine System program. 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.

Emissions 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 NO_x, CO, and UHC. The true value is represented by the actual reduction in the gas turbine exhaust emissions burden on the environment and the potential for significant cost savings to the end user of gas turbine equipment by eliminating the need for water injection or expensive post-exhaust cleanup equipment such as selective catalytic reduction (SCR).

Application of Ceramics

The application of ceramic components is beneficial because it enables a higher component temperature in a simpler and therefore, less costly, design and/or it reduces the need for part cooling and the use of protective coatings. When considering the cost associated with utilizing ceramic blades and nozzles, one can assume that ceramics will be (1) more expensive than uncooled parts of conventional superalloys, (2) are of comparable cost as cooled conventional superalloy parts, and (3) can be significantly less expensive than parts fabricated of cooled and coated advanced superalloys.

Where the design temperature allows the use of uncooled superalloy components, there is no advantage in using ceramic parts unless other benefits are sought (e.g., a reduction in stress on a disk by using lighter ceramic blades). As a result, there is no benefit in considering ceramic blades for engines with a TRIT under ~900°C (~1650°F) or ceramic nozzles 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 metal parts function satisfactorily and they can be fabricated at a fraction of the cost of ceramic parts assuming aerospace quantities of components (i.e., 10,000s/year).

When cooled superalloy components are replaced, the cost of ceramic and metal parts are expected to be of similar magnitude and the benefits of eliminating cooling favor the use of ceramics. The replacement of expensive cooled and coated advanced superalloy components with uncooled ceramic parts is particularly attractive since a component cost reduction is accompanied by a performance improvement derived from 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 metal 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 engines 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 engine field testing.
    - 1997/1998: 4,000-hour CSGT engine field test.

- Multiple engine field tests.

- 1998-2000: Ceramic engine product development.

- 2000: 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) have been made as part of the Phase I work. 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 this 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 NO_x to 10 ppmv, the total NO_x savings for the U.S. industrial engine fleet are estimated to be about 4.5 x 10^5 tonnes of NO_x.

Future Activities

Phase II work to-date has essentially involved completion of the first generation ceramic component designs and the design of the interfacing metallic support structures, fabrication of subscale components and full-scale prototypes, set-up and modification of test rig facilities, testing of specimens and subscale components, the generation of a long-term data base, and the development of supporting technologies such as NDE. Testing of full-scale prototype components in rigs and in the program engine was started at the end of the reporting period.

The work for the remainder of Phase II involves the following activities:

- Completion of the fabrication of all first generation ceramic components and testing of these components in proof rigs and in the engine rig. The final demonstration of the designs evolved during Phases I and II will be a successful 50-hour engine test at a TRIT of 1121°C (2050°F) incorporating all conditions typically expected during operation of an engine in the field.

- Modification of ceramic component and secondary component designs based on the results of testing of the first generation hardware. The modifications should eliminate any materials and design imperfections identified in the rig and engine testing.

- The selection of the designs, materials, and suppliers for the components to be tested in the final Phase II engine tests and in the 4,000-hour Phase III field test.

- Fabrication of the second generation components for final engine testing and field testing.

- Establishment of long-term test data base for the critical failure modes (fatigue, creep, oxidation) expected to affect the performance of the ceramic parts in the field testing. Creep data for up to 10,000 hours of exposure will be generated.

- The establishment of NDE methodology for monolithic ceramic and CFCC gas turbine components that will enable assessment of component integrity in the as-received state and following service in an engine.

- Development of a detailed plan for the Phase III 4,000-hour engine test at the ARCO Oil & Gas Bakersfield site.

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References

1. Anson, D., W.J. Sheppard, L.D. Norland, and M. DeCorso, "Application of Ceramics to Industrial Gas Turbines; Tasks 2, 3, and 4, Economics, Market Analysis and R&D Plan," Tasks 2, 3, and 4 Final Report, Battelle Memorial Institute, DOE Contract No. DE-AC02-89CE40979, 1991.

2. Anson, D., W.J. Sheppard, and W.P. Parks, Jr., "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 1-4, 1992.

3. "Report to Congress, **Comprehensive Program Plan for Advanced Turbine Systems.**" U.S. Department of Energy, Office of Fossil Energy, Office of Energy Efficiency and Renewable Energy. February, 1994.

4. van Roode, M., W.D. Brentnall, P.F. Norton, and G.L. Boyd, "Ceramic Stationary Gas Turbine Development Program - First Annual Summary." ASME Paper 94-GT-313, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, The Hague, The Netherlands, June 13-16, 1994.

5. van Roode, M., W.D. Brentnall, P.F. Norton, and G.P. Pytanowski, "Ceramic Stationary Gas Turbine Development," ASME Paper 93-GT-309, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Cincinnati, Ohio, May 24-27, 1993.

6. van Roode, M., W.D. Brentnall, P.F. Norton, and G.L. Boyd, "Ceramic Stationary Gas Turbine Development Program - First Annual Summary," ASME Paper 94-GT-313, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, The Hague, The Netherlands, June 13-16, 1994.

7. Anson, D., W.P. Parks, Jr., O. Evensen, and M. van Roode, 1993, "Advanced Small Gas Turbines for Cogeneration," Paper Presented at the 7th Congress and Exposition Gas Turbines in Cogeneration and Utility, Industrial and Independent Power Generation, Bournemouth, England, U.K., September 21-23, 1993.

8. van Roode, M., "Ceramic Retrofit Program," Paper Presented at the Joint Contractors Meeting, FE/EE Advanced Turbine Systems Conference, FE Fuel Cells and Coal-Fired Heat Engines Conference, U.S. Department of Energy, Office of Fossil Energy, Morgantown Energy Technology Center, Morgantown, West Virginia, August 3-5, 1993.

9. Saith, A., P.F. Norton, and V.M. Parthasarathy, "Application of SPSLIFE to Preliminary Design Evaluation and Life Assessment of CSGT Components," ASME Paper 94-GT-420, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, The Hague, The Netherlands, June 13-16, 1994.

10. "Ceramic Stationary Gas Turbine Development Program," Phase I Final Report, Solar Turbines Incorporated, DOE Contract No. DE-AC02-92CE40960. In print.

11. van Roode, M., "Ceramic Retrofit Program," Proceedings of the Advanced Turbine Systems Annual Program Review Meeting, Joint Contractors Meeting, Washington, D.C., November 9-11, 1994.

12. van Roode, M., W.D. Brentnall, P.F. Norton, and B.D. Edwards, "Ceramic Stationary Gas Turbine Development Program - Second Annual Summary." ASME Paper 95-GT-459, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, TX, U.S.A., June 5-8, 1995.

13. Norton, P.F., G.A. Frey, H. Bagheri, A. Fierstein, C. Twardochleb, O. Jimenez, and A. Saith. "Ceramic Stationary Gas Turbine Development Program - Design and Life Assessment of Ceramic Components." ASME Paper 95-GT-383, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, TX, U.S.A., June 5-8, 1995.

14. Parthasarathy, V.M., J.R. Price, W.D. Brentnall, G. Graves, and S. Goodrich, "Material Characterization of Candidate Silicon Based Ceramics for Stationary Gas Turbine Applications." ASME Paper 95-GT-249, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, TX, U.S.A., June 5-8, 1995.

15. "Ceramic Stationary Gas Turbine Development Program," Phase II Technical Progress Report, Solar Turbines Incorporated, DOE Contract No. DE-AC02-92CE40960. In print.

16. Nemeth, N.N., J.M. Mandersheid, and J.P. Geykenyesi, "Ceramics Analysis and Reliability Evaluation of Structures (CARES)," NASA Technical Paper 2916, 1989.

17. Bornemisza, T., and A. Saith, "SPSLIFE: A User Friendly Approach to the Structural Design and Life Assessment of Ceramic Components," ASME Paper 94-GT-486 at the International Gas Turbine and Aeroengine Congress and Exposition, The Hague, The Netherlands, June 13-16, 1994.