ABSTRACT

A program has been initiated under the sponsorship of the Department of Energy (DOE), Office of Industrial Technology, to improve the performance of stationary gas turbines in cogeneration through the selective replacement of metallic hot section parts with uncooled ceramic components. It is envisioned that 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. The program which started in September, 1992, takes an engine of the Solar Centaur family of industrial gas turbines, and modifies the design of the hot section to accept ceramic first stage blades and first stage nozzles, and a ceramic combustor liner. The ceramic materials selected for the blade are silicon nitride, for the nozzle silicon nitride and silicon carbide, and for the combustor liner silicon carbide as well as two continuous fiber reinforced ceramic composites, one with a silicon carbide matrix and another with an oxide matrix.

This paper outlines the approach, conceptual component design, and materials selection for the program.

INTRODUCTION

Current industrial turbine designs have service temperature limitations because of the properties of the existing metallic materials. Ceramic materials strategies combined with innovative designs can be used to achieve significant improvements in component durability and turbine performance.

The use of ceramic materials in industrial gas turbines can contribute to performance improvements in several ways:

1. increasing the turbine inlet temperature from about 900°C to 1200°C (1652°F to 2092°F) or more by use of uncooled ceramic components (blades, nozzles) in the hot section (Anson et al., 1991). The increase in turbine inlet temperature can result in a significant improvement in thermal efficiency and output power.

2. replacement of complex cooled metal blades and vanes in the turbine hot section with uncooled ceramics will reduce the associated parasitic losses from cooling, and improve engine performance.

3. advantage can be taken of the higher turbine inlet temperatures by optimizing the flowpath and aerodynamics in the turbine hot section with uncooled ceramic blades and vanes. A hot section fully optimized for ceramics will enable further improvements in gas turbine performance.

4. the use of ceramics to replace metallic combustor liners will allow operation at higher combustor wall temperatures. Lower emissions for NOx and CO are achievable with ceramic "hot wall" combustors compared to existing low emissions metallic lined combustors for turbine inlet temperatures of \( \sim 1200°C \) (2092°F) and higher.

The introduction of ceramic materials technologies in gas turbines can have significant economic benefits in terms of fuel savings and emission reductions. The incorporation of ceramic materials technologies can reduce installation and operating costs of gas turbines in cogeneration service and makes them more competitive. It has been estimated that the annual fuel savings in the U.S.A. resulting from improved efficiency associated with incorporating this technology in cogeneration applications would be on the order of \( 2 \times 10^{14} \) kJ (Anson et al., 1992).
It is against this background that the U.S. Department of Energy (DOE), Office of Industrial Technology (OIT), has initiated a program aimed at the improvement of stationary gas turbines in cogeneration through the selective replacement of metallic hot section parts with uncooled ceramic components. Solar Turbines Incorporated (Solar) of San Diego, California, is the prime contractor for the program which started in September, 1992. The program is being conducted in three phases. Phase I focuses on conceptual and preliminary design of the engine and its ceramic components, and addresses interfacing these components with the metallic support structure. Market issues and technology feasibility are also being evaluated in Phase I. Phase II addresses detailed component design, ceramic component fabrication, and ceramic component evaluation including long term materials testing and life prediction. Phase III involves the manufacture of a Centaur engine retrofitted with ceramic components and the demonstration of a 4000 hour performance test at the cogeneration test site. This paper describes the program, engine and component design, and materials selection and evaluation.

DOE CERAMIC STATIONARY GAS TURBINE (CSGT) DEVELOPMENT PROGRAM

Program Definition

The program focuses on adapting an existing natural-gas fired industrial turbine engine model to provide improved performance and durability through the use of selected ceramic components. The selected gas turbine engine is a model with proven performance, environmental, and maintenance statistics. The engine will be modified to incorporate a limited number of ceramic parts as substitutes for existing metallic components. As a minimum one stage of blades, one stage of vanes, and the combustor liner will be replaced with ceramic parts.

Under the program engine modifications will be undertaken to

- accept ceramic components designed with special attention to maintaining stresses to acceptable levels and fasten the ceramic parts to the interfacing metallic structures;
- provide a successful demonstration of structural integrity, mechanical, and vibrational stability, and safety;
- endure a minimum of 25 start-ups without rebuild of parts other than maintenance;
- demonstrate a potential for performance improvements in a non-optimized engine configuration;
- as a minimum conform to the environmental and safety standards of the conventional all-metal engine;
- and to demonstrate reliability under conditions of enhanced performance.

The ceramic stationary gas turbine to be developed under the program will include all ancillary equipment and enclosures required to operate and monitor engine performance for a 4000 hour performance test.

Program Strategy

The strategy selected by the Solar led team for this program provides a strong focus on near term demonstration of technology and lowering barriers to acceptance of the ceramic turbine technology by the market place. From this perspective it is important that the users' risk be minimized. The overall program methodology will minimize risk by:

- limiting the number of components in the development program to a single stage of blades and vanes plus the combustor liner;
- introduction of programmed start-up and shutdown procedures that are consistent with industrial usage but minimize transient stresses;
- achieving early demonstration of components in a gasifier rig which will exactly duplicate engine conditions;
- performing sufficient design iterations to reduce all sources of stresses in the components to a minimum;
- using flaw-tolerant designs which ensure that stresses and temperatures are below the creep-dominated regime;
- adopting step-wise increases in firing temperature;
- favoring materials, designs and manufacturing procedures that are well characterized and have high potential for scale-up to cost-effective production applications;

Program Team

The Solar team (Table 1) includes major ceramic component suppliers, nationally recognized test laboratories, Sundstrand Power Systems, and a cogeneration end user. With the focus being eventual commercialization of the technology, creating the conditions for the establishment of a substantial and reliable supplier base assumes paramount importance. The approach has been to select initially three suppliers for each of the program components. This strategy provides maximum assurance that several suppliers will be able to demonstrate their ceramic component fabrication technology on their best materials, and with the experience gained scale up their process for commercial part quantities when the market is ready to accept the ceramic turbine technology.

The inclusion of expert test laboratories in the Solar led team derives from the recognition that the establishment of a long term materials property data base, and the development of non-destructive and life prediction methodology are critical
TABLE 1 - PROGRAM TEAM

<table>
<thead>
<tr>
<th>CERAMIC COMPONENT SUPPLIERS</th>
<th>TEST LABORATORIES</th>
<th>SOLAR TURBINES INC.</th>
<th>ARCO OIL &amp; GAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garrett Ceramic Components</td>
<td>Caterpillar Technical Center</td>
<td>*Program Management</td>
<td>*Enduser Representation</td>
</tr>
<tr>
<td>Carborundum</td>
<td>Non-Destructive Evaluation</td>
<td>*Engine Design</td>
<td>*Commercial Application</td>
</tr>
<tr>
<td>Norton Advanced Ceramics</td>
<td>Argonne National Laboratory</td>
<td>*Materials Evaluation</td>
<td>*Cogeneration</td>
</tr>
<tr>
<td>Kyocera Ind. Ceramics Corp.</td>
<td>University of Dayton Research Institute</td>
<td>*Component Testing</td>
<td>*Field Test Site</td>
</tr>
<tr>
<td>DuPont Composites</td>
<td>Long Term Testing of Ceramics</td>
<td>*Engine Testing</td>
<td></td>
</tr>
<tr>
<td>Babcock &amp; Wilcox</td>
<td></td>
<td>*Market Evaluation</td>
<td></td>
</tr>
<tr>
<td>NGK Insulators</td>
<td></td>
<td>*Technology Integration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Commercialization</td>
<td></td>
</tr>
</tbody>
</table>

**SUNSTRAND POWER SYSTEMS**

- *Life Prediction*
- *Design Support*
- *Materials Evaluation Support*

**ENGINE SELECTION**

**Selection Criteria**

Candidate engines for the program were required by DOE to meet a number of specific technical criteria. These were:

- represent an existing domestic natural gas fired turbine engine
- operate at an air flow of 10-40 kg/s
- have a continuous duty rating
- be capable of operation at Rotor Inlet Temperature over 1000°C (1832°F) when fitted with ceramic components

**Program Activities**

- Phase I is scheduled over 6 months and is focused on engine design, concept and preliminary design of key ceramic components including interfacing the ceramics with the metallic support structures, materials selection, and technical and market assessment. The information generated in Phase I culminates in a comprehensive program plan for Phases II and III.

- Phase II addresses engine procurement, establishment of test capabilities, detailed iterative component design, long term materials testing, component evaluation, and life prediction, and low emissions combustor development. At the end of Phase II all component designs will have been proved in a gasifier rig which is a modified gas turbine engine. The final task of Phase II is the modification of the program plan for Phase III. Phase II is scheduled over two years.

- Phase III which is also scheduled to last two years revolves around the 4000 hr engine test at the cogeneration site selected for the program. The efforts in this phase involve engine assembly, engine testing, the actual 4000 hr performance test, and component characterization. Program management and reporting is an ongoing activity throughout all phases of the program.
• have a pressure ratio less than 20:1
• have an axial flow geometry
• be readily adaptable to developmental needs with minimal design modifications
• have cogeneration application
• be adaptable to incorporation of a low emission combustor capable of less than 25 ppm NOx with potential for 10 ppm NOx.
• demonstrate improved fuel savings and output power (with ceramic components)

Selection of Program Engine

The engine selected for this program is the single shaft Centaur Type 'H' industrial gas turbine. This engine was introduced into the Solar product line in 1985. Of the over 300 'H' installations worldwide more than 100 are in the U.S., many of them in cogeneration applications. Field operating experience for the Centaur 'H' gas turbine engine has exceeded 1.7 million operating hours. This engine meets all of the above DOE program requirements. Figure 1 shows a layout of the Centaur 'H' engine. The three components targeted for ceramic substitution have been indicated.

Simple Cycle Operation

The Centaur 'H' engine currently operates at a maximum turbine rotor inlet temperature (TRIT) of 1010°C (1850°F) in the all-metallic configuration which is the design point that meets the customer output requirements. The engine would be effectively uprated to 1121°C (2050°F) with the introduction of ceramic components. Table 2 shows a comparison of the current 'H' engine parameters with the parameters estimated for the proposed ceramic configuration. Constant turbine efficiencies have been assumed for these estimates.

Other reasons for the choice of this engine are the excellent operating and maintenance experiences of the 'H' engine, and the engine hot section design which uses a number of scaled hardware pieces from the larger Solar Mars engine which is already available in a 1121°C (2050°F) TRIT version. Hence the increase of TRIT for the 'H' from 1010 to 1121°C (1850 to 2050°F) will not require a significant amount of redesign effort not directly related to the ceramic components.

Cogeneration Cycle Operation

Cogeneration is one of the most important processes available to conserve fuel. A cogeneration unit consisting of a ceramic gas turbine with a condensing combined cycle will provide peak electrical efficiencies of over 50%. Moving towards higher TRIT's through the use of ceramic components will increase the power-to-heat ratio. Assuming no change in the compressor, a heat recovery system offers better total efficiency at lower pressure ratios than typical simple cycle engines.

When the GenSet engine is operated in a cogeneration mode, the backpressure at the exhaust reduces to a small extent the efficiency and kW output. This reduction will depend on the installation. For typical installation with a backpressure of 7 inches of water, this reduction is 0.4% efficiency and will reduce the efficiencies equally for both the
TABLE 2 - CENTAUR 'H' GENSET COMPARED WITH CERAMIC HOT SECTION 'H' ENGINE GENSET

<table>
<thead>
<tr>
<th>ENGINE PARAMETERS</th>
<th>CURRENT</th>
<th>CERAMIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIT (°C)</td>
<td>1010</td>
<td>1121</td>
</tr>
<tr>
<td>TRIT (°F)</td>
<td>1850</td>
<td>2050</td>
</tr>
<tr>
<td>kW at GenSet Terminals</td>
<td>4040</td>
<td>5092</td>
</tr>
<tr>
<td>Thermal Efficiency</td>
<td>29.57</td>
<td>31.35</td>
</tr>
<tr>
<td>Exhaust Flow (pps)</td>
<td>40.83</td>
<td>40.95</td>
</tr>
<tr>
<td>Exhaust Gas Temperature (°C)</td>
<td>508</td>
<td>577</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft Speed (rpm)</td>
<td>14950</td>
<td>14950</td>
</tr>
<tr>
<td>Emissions (ppmv NOx)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Uncontrolled</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>-Wet</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>-SoLoNOx® (dry)**</td>
<td>42-25</td>
<td>10</td>
</tr>
</tbody>
</table>

* Maximum Continuous Duty, ISO Conditions (Sea Level, 15°C day) with Gearbox Hot Section 'H' Engine GenSet
**Solar Registered Trade Mark: Abbreviation of Solar Low NOx

The number of ceramic components for this program have been limited to the ceramic combustor liner, the first stage nozzle, and first stage rotor blade. Apart from decreasing the risk inherent in the development effort, development costs are reduced, redesign effort is minimized, and ceramic/metal interface issues are minimized.

DESIGN OF CERAMIC COMPONENTS

Design-Development Philosophy

The number of ceramic components for this program have been limited to the ceramic combustor liner, the first stage nozzle, and first stage rotor blade. Apart from decreasing the risk inherent in the development effort, development costs are reduced, redesign effort is minimized, and ceramic/metal interface issues are minimized.

The TRIT will then be increased by increments of 50°C (90°F) or less to ensure that all ceramic and metal temperatures are increasing according to predictions. This will be necessary because a number of design modifications to hot section metallic components for operation at the design temperature of 1121°C (2050°F) will need to be verified before taking the engine up to the final temperature. If gasifier rig operation at 1121°C (2050°F) is successful short duration runs at higher TRITs up to 1200°C (2092°F) may be performed to evaluate growth potential of the ceramic technology.

Design Analysis

Experience in previous ceramic engine programs has highlighted the need to give special attention to any ceramic-metal interface which has the potential for both relative motion and high loading. As a result, detailed analytical studies will be undertaken for metal-ceramic interfaces to ensure that the mechanical and thermal interface stresses and loads, in magnitude and direction, are consistent with acceptable component reliability. To this end, each ceramic component will undergo extensive thermo-mechanical analysis using finite element techniques for transient and steady state conditions.

The resulting analysis output files containing both stresses and temperatures will be used as input to a probabilistic life prediction analysis package called 'SPSLIFE' which will calculate the life and reliability of the ceramic component in fast fracture, static fatigue, creep fracture and oxidation regimes. SPSLIFE is a state of the art software package developed by Sundstrand Power Systems which incorporates the 'CARES' reliability code developed by NASA as one of its functional components (Nemeth, et al., 1989). SPSLIFE uses a custom designed graphics user-interface which combines four failure mode envelopes with a complete stress-temperature profile of the analytical model, providing a very simple but effective iterative design modification capability. The software will be able to take account of strength reduction effects such as surface finish, reaction layer and poor machining by interfacing with an extensive materials database generated as part of this program.

In probabalistic terms, engine design life requirements translate into reliability for each of the over one hundred ceramic pieces in the engine to R = 99.999% or better. Using a 'fixed process' material database for well characterized ceramic materials, the design philosophy will minimize all ceramic stress-temperature combinations to a level where five-nines reliability represents a realistic objective.

Hot Section Modifications

In addition to the replacement of metal components with ceramics, several critical hot section components will have to be modified for use at 1121°C (2050°F). Disk and blade materials (for downstream turbine stages) will be changed to provide for adequate creep strengths at the higher operating temperatures, and the nozzle case support structure will require changes in material and front end design to accept the stage 1 ceramic nozzle. Exhaust gas temperature is expected to increase by approximately 69°C, but this is not expected to be a problem either for the current material or enduser requirements.
FIG 2 - ITERATIVE CERAMIC COMPONENT DESIGN-DEVELOPMENT APPROACH

FIG 3 - THE PROOF/SCREEN TEST FOLLOWS A SEQUENTIAL (LOW RISK) DEVELOPMENT FLOW PATH
Combustor Liner

The 'H' engine used for the 4000 hour test will incorporate a lean-premixed, annular, dry low NOx combustor, meeting the program goals of 25ppm NOx (at 15% O2). An important goal of this program is to demonstrate NOx emissions of 10 ppmv or less with the incorporation of a 'hot wall' versus a cooled metallic wall combustor liner. The hot wall ceramic combustor concepts are important for the following reasons:

- At combustor outlet temperatures of approximately 1200°C (2092°F) and above, it becomes increasingly difficult to provide adequate wall cooling airflow and the provision of a desirable outlet radial gas temperature profile as a larger percentage of the total airflow is required for premixing with the fuel.

- A ceramic hot wall will tend to reduce the lean extinction fuel-air ratio and lower the CO emissions that occur as this limit is approached.

- Hot combustor walls will assist in the tailoring of outlet radial temperature profiles more suited to the increase in life of ceramic and metallic turbine blades.

Demonstration of the ≤10 ppmv NOx hot wall combustor in a lean premixed system will be one of the first tests in this program, using an existing combustor test rig which can be modified for sustained elevated temperature liner walls.

Detailed design will be carried out of the hot wall combustor using two design concepts. The implementation of the ceramic materials will be in the most critical areas of the combustor where the effects on stability and CO emissions will be a maximum. The first concept is based on thin tiles supported from the metallic structure; the second involves integral liners. The tile approach is seen as a means of breaking up the complex stress fields caused by fluctuations in temperature, local gas velocity and flame luminosity. An additional design option will include a full annulus combustor constructed of Continuous Fiber-Reinforced Ceramic Matrix Composite (FRCMC) materials. The evaluation of the liner materials in rig testing comprises an important part of the program. Candidate monolithic and FRCMC liner materials will be evaluated under conditions anticipated in the full scale combustor. The best performing materials will then be tested in a full scale combustor rig and in the gasifier rig. The results of this test will determine the final combustor design and materials selection.

Ceramic Nozzle Design

A small amount of preliminary analysis has already been undertaken for the ceramic stage 1 nozzle which will replace the existing cooled two-vane metallic nozzle. An important aspect of the ceramic nozzle design involves the 'hot spot' profile and its effect on the trailing edge stress distribution. Peak nozzle temperatures are expected to reach ~1290°C (2354°F) for a ~0.2 combustor pattern factor. The design will concentrate on minimizing the trailing edge stresses, either by selective cutting back of the high stress area, or new design concepts which are not sensitive to the differences in temperature between the airfoil and the inner/outer shrouds. Another area of importance is the interface between the ceramic shroud and any sheetmetal providing gaspath sealing. Design issues will be solved by two important factors:

- Consideration of unconventional and innovative designs which will minimize cooling of adjacent metallic components.

- Adherence to a number of simple design criteria such as single vane segments to minimize thermal stresses, simple shapes to minimize surface irregularities and crowned/flat interfaces for both dimensional control and minimizing the thermal conduction path.

Ceramic Blade Design

The airfoil of the ceramic blade will have the same aerodynamic profile as the current 'H' engine first stage blade, but the root attachment will be different from the current "fir tree" design. The design challenge is to provide a suitable attachment to the disk which minimizes or eliminates sliding friction at the centrifugally loaded attachment interface. Several concepts are being considered; those that show most potential will undergo extensive analysis prior to final selection of the primary concept. All promising concepts will be evaluated in cold spin testing of blades. One of the final candidates will likely be the conventional 60 degree dovetail design with compliant layer. This configuration has been demonstrated relatively successfully for short periods of time in a number of rigs and engine programs by other gas turbine manufacturers (Richerson, et al., 1981; Peschel et al., 1977) and therefore can be used as a baseline concept for other designs.

The dovetail concept has already undergone preliminary analysis in order to establish the approximate levels of stress the airfoil and attachment will experience in the engine. Figures 4 and 5 show temperature and stress maps from a steady state ANSYS analysis indicating an expected maximum stress of 155 MPa (22.5 ksi) occurring in the attachment radius just below the platform. This stress level resulted in an acceptable calculated reliability, [R(t)], in fast fracture. Given that this is only a preliminary steady state analysis, further work will be done to optimize the root design and establish transient stress levels.

As for the nozzle, alternative designs of the blade attachment will incorporate a few simple criteria essential for high reliability concepts such as elimination of the compliant layer, minimizing the sliding of the disk/blade contact area, and, of course, simplicity. In addition to observing criteria for ceramic design, all the usual blade design issues must be addressed, including dynamic response, avoidance of engine order interferences, blade damping and tip rub.

MATERIALS SELECTION

The rapid progress in ceramic process technology over the past few years and demonstrated performance in automotive applications has created a substantial data base...
Three materials suppliers for each component were selected to provide alternate sources and provide an optimal pathway to flaw tolerant designs and use at temperatures below the creep damage regime was adopted. Materials and supplier selection was made with reference to the completeness of materials properties data base and the experience/track record of the suppliers in fabricating similar components. Three materials suppliers for each component were selected to provide alternate sources and provide an optimal pathway to technology demonstration and eventual commercialization.

**Selected Materials**

Candidate materials for blade, nozzle, and combustor liners are presented in Table 3. Initial selection was made on the basis of the material's predicted durability under the conditions of the TRIT and component stresses and temperatures. Two silicon nitride materials (NT-154, Norton Advanced Ceramics; SN-88, NGK Insulators, Ltd.) and one silicon carbide material (Hexoloy® SA, Carborundum) were selected for the nozzle. The materials selection for the nozzle was made based on the known superior short term creep properties of these materials which were believed to provide adequate long term performance at the selected TRIT of the engine. Long term testing will be required to confirm these life predictions and this is planned for Phase II of the program. The long term testing includes work at the University of Dayton Research Institute (UDRI) discussed below. The next step in the materials selection will be to design by the life prediction method discussed previously in which the critical flaw size is calculated from fracture toughness and compared with the detectability limit. Detection of changes in fracture toughness with time, temperature, and stress will be another goal of long-term testing.

The materials data base will be the starting point for the ceramic suppliers was considered in the materials selection process:

**Blades.** Garrett Ceramic Composites (GCC) of Allied-Signal Aerospace has fabricated GN-10 silicon nitride rotor blades for Solar of a design similar to that used for the "H" engine. Kyocera has fabricated several hundred SN-252 silicon nitride rotor blades. Norton Advanced Ceramics (NAC) has fabricated NT-154 silicon nitride rotor blades. All three materials are predicted to have adequate creep life for the "H" engine blade. Only silicon nitrides were considered for this application since silicon carbides may not have adequate strength under transient conditions.

**Nozzles.** NGK Insulators, Ltd (NGK) has fabricated non-integral stationary turbine nozzles of a size similar to that required for the program in off-shore ceramics programs using SN-88 silicon nitride. NGK will be used as a part supplier in Phase II. NAC and Carborundum have not fabricated large size nozzles yet but they have fabricated smaller vanes. Both a silicon nitride (NT-154, NAC) and a silicon carbide (Hexoloy® SA, Carborundum) were selected for the nozzle. The silicon carbide is known to have excellent creep resistance.

**Combustor Liners.** Materials were selected on the basis of known high temperature resistance (monolithic silicon carbide - Hexalloy® SA, Carborundum, alumina/alumina FRCMC, Babcock & Wilcox - SiC/SiC, DuPont Composites). Continuous fiber reinforced ceramic composites (FRCMC's) were included in the materials selection process because of the potential to fabricate large integral liners. Solar is involved in several FRCMC programs with combustor liner applications concurrent with this program and it is expected that novel FRCMC technologies will benefit this program.

**Material and Component Evaluation**

Tests will be performed to verify materials properties,
develop property data where none currently exists, (e.g., long term creep and dynamic loading) provide data under conditions specific to hardware designs, evaluate design approaches (attachments, dovetail designs, compliant layers) and to evaluate component performance. Table 4 shows the result of a survey to determine current availability of mechanical and physical property data required or of interest in design of components for several silicon based materials.

A major objective in Phase I of the program is to develop a complete properties data base as possible to facilitate preliminary designs and to provide baseline data for life prediction. Component testing in simple rigs or other test equipment and in a gasifier rig which exactly duplicates engine build and operating conditions will be used to evaluate design modifications and provide the data base for life prediction modelling. Engine testing at a field site will verify materials selection and durability of component designs.

### Materials Test Plan

Materials testing is being performed at the materials suppliers, outside laboratories and in-house at Solar, to provide needed data as indicated in Table 4 and additionally to evaluate machined and unmachined surface effects as

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**FIG 6 - MATERIALS SELECTION AND EVALUATION METHODOLOGY**

**TABLE 3 - CANDIDATE BLADE, NOZZLE AND COMBUSTOR LINER MATERIALS CONSIDERED FOR EVALUATION IN THE PROGRAM**

<table>
<thead>
<tr>
<th>Blade</th>
<th>Nozzle</th>
<th>Combustor Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic</td>
<td>Monolithic</td>
<td>Monolithic Composite</td>
</tr>
<tr>
<td>G-10 Si₃N₄</td>
<td>NT-154 Si₃N₄</td>
<td>Hexaloy® SA Al₂O₃</td>
</tr>
<tr>
<td>NT-154 Si₃N₄</td>
<td>SN-88 Si₃N₄</td>
<td>FRCMC SiC/SiC</td>
</tr>
<tr>
<td>SN-252 Si₃N₄</td>
<td></td>
<td>FRCMC Al₂O₃</td>
</tr>
</tbody>
</table>

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these relate to finished components. The most extensive testing will be to determine long term mechanical properties of four candidate ceramic materials. These tests will be performed at the University of Dayton Research Institute (UDRI). The test plan is summarized in Table 5 and includes fast fracture tensile at two loading rates, static fatigue, cyclic tensile fatigue, and up to 10,000 hour creep testing.

Fracture analysis will be performed to determine origin and fracture mode. Weibull analysis to determine Weibull modulus and dynamic fatigue analysis to determine crack growth exponent and material environmental constant, will also be performed.

Life Predictions

The criteria defined to provide a low risk incorporation of ceramics into industrial gas turbine engines are pertinent to the life prediction approach. These are:

- Design for stresses and temperatures that are below the creep-dominated regime.
- Introduce programmed start-up and shut-down procedures that are consistent with industrial usage but minimize transient stresses.

For each component, an attempt will be made to design for flaw tolerance. First, design stresses will be selected so that the critical flaw size (for surface and for volume flaws) is large enough to be detected by non-destructive evaluation or by proof testing. This will provide a significant margin of safety to prevent instantaneous failure upon initial loading. Second, design stresses will be selected so that the critical flaw size is large enough to maintain component integrity for the amount of slow crack growth, creep, oxidation, etc. occurring during service (including any slow crack growth that may occur during shut-down portion of the proof test). This will greatly lower the probability of failure between overhauls. Figure 7 shows the relationship between applied stress and critical flaw size for different values of material fracture toughness (Bomemisza, 1991).
### TABLE 5 - LONG TERM MATERIAL TEST PLAN AT UDRI

<table>
<thead>
<tr>
<th>TEST TYPE</th>
<th>TEST DESCRIPTION</th>
<th>NO. OF TEST SPECIMENS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing on four candidate silicon based ceramic materials NT-154 (NAC), Hexoloy SA (Carborundum), SN-252 (Kyocera), SN-88 (NGK)</td>
<td>Fast Fracture Tensile Strength&lt;br&gt;Temperature = Airfoil T&lt;sub&gt;max&lt;/sub&gt;&lt;br&gt;Crosshead Speed = 0.004 cm/s</td>
<td>10 Tensile Specimens per Supplier</td>
</tr>
<tr>
<td></td>
<td>Slow Fracture Tensile Strength&lt;br&gt;Temperature = Airfoil T&lt;sub&gt;max&lt;/sub&gt;&lt;br&gt;Crosshead Speed = 0.00004 cm/s</td>
<td>10 Tensile Specimens per Supplier</td>
</tr>
<tr>
<td></td>
<td>Cycle Fatigue&lt;br&gt;Temperature = Airfoil T&lt;sub&gt;max&lt;/sub&gt;&lt;br&gt;Cycle From 35-172 MPa (5-25 ksi)&lt;br&gt;5000 Cycles</td>
<td>3 Tensile Specimens per Supplier</td>
</tr>
<tr>
<td></td>
<td>Constant Stress Varying Temperature&lt;br&gt;Constant Stress 172 MPa (25 ksi)&lt;br&gt;Temperature Step 1 1177°C (2150°F) 100 hrs&lt;br&gt;Temperature Step 2 1232°C (2250°F) 100 hrs&lt;br&gt;Temperature Step 3 1286°C (2350°F) 100 hrs&lt;br&gt;Temperature Step 4 1343°C (2450°F) 100 hrs</td>
<td>3 Tensile Specimen per Supplier</td>
</tr>
<tr>
<td></td>
<td>Creep Tests&lt;br&gt;Stress Level 35-172 MPa (5-25 ksi)&lt;br&gt;Temperature = Airfoil T&lt;sub&gt;max&lt;/sub&gt;&lt;br&gt;Time 500 Hours</td>
<td>3 Tensile Specimens per Supplier</td>
</tr>
<tr>
<td><strong>SHORT LIST OF TWO MATERIALS BASED ON THE ABOVE TESTS</strong></td>
<td>Creep Tests&lt;br&gt;Stress Level 35-172 MPa (5-25 ksi)&lt;br&gt;Temperature = Airfoil T&lt;sub&gt;max&lt;/sub&gt;&lt;br&gt;Time 1000 Hours</td>
<td>6 Tensile Specimens per Supplier</td>
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**FIG 7 - STRESS VS CRITICAL FLAW SIZE AND STRESS INTENSITY**

The NASA/CARES computer programs for volume and surface flaws will be utilized together with finite element stress results and appropriate materials data to arrive at an acceptable probability of fast fracture. An attempt will be made to ensure that different flaw populations are adequately represented in the materials data. Proof stress levels will be selected to truncate failure distributions. Methodology will be selected to deal with lower surface strength (due to poor surface finish, reaction layer, poor machining, etc.), additional flaw distributions introduced by ceramic-to-ceramic joints in the component, and for assessment of material strength under multiaxial stress conditions.

For static fatigue analysis, an updated CARES program will be used, incorporating the Evans-Wiederhom approach. Static/dynamic fatigue data will be used to evaluate the Paris equation constants. Design stresses will be determined for acceptable life and probability of survival. The SPRLIFE computer code described previously will be used for life prediction based on an integration of all important failure modes.

Hot and cold spin tests for non-airfoil and airfoil blades will be performed to proof test blade materials and shapes. As part of the life prediction work, an assessment will be made of the proof-test method, i.e., that cumulative proof-test-induced damage does not occur.

Creep deformation can be significantly influenced by the degree of crystallization of the grain boundary phase. Microstructure will be characterized before and after creep testing to ensure validity of results. Creep curves will be obtained as a function of stress and temperature. Larson-
Miller plots will be made, and the value of the Larson-Miller constant will be optimized. Creep and oxidation models proposed in the literature will be reviewed, and a specific methodology will be selected. The selected oxidation model will be quantified using oxidation data for different temperatures. This will permit the calculation of an allowable stress for each temperature, given a desired life and the operating environment of the component.

Experimental results often show failure at lower stresses under cyclic fatigue conditions. Methodology will be selected for designing under cyclic fatigue conditions. Appropriate data will be obtained and analyzed, and design stresses will be correspondingly adjusted.

A stress versus temperature graph will be prepared for each component. The stress-temperature profile of the entire component will be mapped on this graph. Characteristic curves showing allowable stress versus temperature will be superimposed on the plot for:

(a) fast fracture, different probability
(b) slow crack growth, different probabilities
(c) creep
(d) oxidation

This map will provide a visual representation of the degree of risk associated with each component.

The life prediction methodology discussed above will be used to assess the life of selected "calibration" components that can be tested in a simulated engine environment. Several components will be tested, and theoretically assessed lives will be compared with actual experimental results. Based on these results, iterative adjustments will be made to the methodology, and calibration curves will be prepared to create an acceptable match between theoretical predictions and experimental data.

Component Evaluation/Testing

Materials evaluation and life prediction will be correlated with component evaluation/testing indicated in Figures 2, 3, and 6. The component evaluation/testing can be grouped in the following three categories:

1. Evaluation of as fabricated component integrity and quality. This is done at the supplier level using established Non Destructive Evaluation (NDE) techniques such as fluorescent dye penetrant inspection, microfocus X-ray, as well as visual, microscopic, and dimensional inspection.

2. Proof testing of the components. The objective of proof testing is to screen parts and eliminate those that are defective prior to advanced rig and engine testing. Proof testing is most useful for rotor blades where realistic stresses can be induced in cold spin testing, and critical stress/temperature conditions can be simulated in hot spin testing using a limited number of parts. Proof testing of stationary components (nozzles, and combustor liners) is potentially less useful since the complex stress states experienced in these components can only be simulated under actual engine conditions.

3. Rig testing of the components. Combustor rigs and the gasifier rig are the primary means to evaluate component performance under conditions similar to those of the engine environment. The ceramic rotor blades and nozzles will be tested in the gasifier rig at increasing TRIT values while the combustor components will be tested in dedicated combustor rigs and eventually in the gasifier rig. A typical test sequence in the gasifier rig would involve:

- Ceramic nozzles, metallic blades; metallic combustor liner.
- Ceramic blades, metallic nozzles, metallic combustor liner.
- Ceramic blades, ceramic nozzles, metallic combustor liner.
- Ceramic blades, ceramic nozzles, ceramic combustor liner.

All component testing described in 1-3 is planned for Phase II and it is envisioned that gasifier rig testing involving all three ceramic components will be performed towards the end of the Phase II performance period.

4. Field testing of components. The 4000 hour field test planned for Phase III is the ultimate demonstration of component performance. The industrial operating conditions including scheduled shutdowns for regular inspections and maintenance as well as unplanned shutdowns, and excursions will provide the conditions to demonstrate the ruggedness and viability of the ceramic turbine technology for commercial applications.

5. Component characterization. Methodology will be developed under the program for inspection of component integrity and degradation. A significant effort is planned under the program for the development of appropriate NDE technology. The development of NDE techniques will be performed by Argonne National Laboratory and Caterpillar Technical Center. The emphasis of this work will be less on development of NDE methodology for inspection of parts at various stages of the fabrication process but rather on methods development for NDE inspection of parts that have accumulated a significant number of service hours. Existing NDE methodology will be assessed in Phase I of the program, but novel approaches will also be considered. The bulk of the NDE methodology development will be performed under Phase II of the program in conjunction with laboratory and rig testing, and life prediction. Phase III will afford the opportunity to establish the usefulness of the test methods under field conditions.

SUMMARY

A program has started under the sponsorship of the U.S. Department of Energy, Office of Industrial Technology to
evaluate and demonstrate the improvement of the performance of stationary gas turbines in cogeneration through the selective replacement of metallic hot section parts with uncooled ceramic components. The program takes an engine of the Solar Centaur family and modifies the design of the hot section to accept ceramic first stage blades and nozzles, and a ceramic combustor liner.

The work is performed by a team led by Solar Turbines Incorporated with Sundstrand Power Systems, major ceramic component suppliers, test laboratories, and a cogeneration end user. The ceramic materials selected include monolithic silicon nitrides and silicon carbide, and continuous fiber-reinforced composites.

Work under the program involves all stages of component design, including modification of the gas turbine to accept the ceramic components, and technology assessment and market evaluation. Ceramic components will be fabricated and evaluated in rig and engine testing. Supportive activities include long term materials properties testing, NDE methodology development, and ceramic component life prediction. The program will culminate in a 4000 hour engine test at a cogeneration end user site.

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REFERENCES


