CERAMIC GAS TURBINE TECHNOLOGY DEVELOPMENT AND APPLICATIONS

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ABSTRACT
Under the ongoing DOE/NASA-funded Advanced Turbine Technology Applications Project (ATTAP), Garrett Auxiliary Power Division (GAPD) is continuing to address the issues of developing and applying structural ceramics to production gas turbine engines. Several critical technologies are being developed to advance this issue, including design methods development, component design, component fabrication, material characterization, and engine testing. The brittle nature of structural ceramics highlights concerns regarding impact damage. Through analysis and experimentation, design methods are being developed to improve the resistance of ceramic components to impact damage. Ceramic component designs now integrate these design methods into practice and proof testing methods are being developed to verify the results for actual engine components. Ceramic component fabrication processes are being optimized by selected subcontractors, resulting in deliveries of high-quality ceramic components which fully meet engine test needs. Verification of the component material properties is being achieved through comparisons of material property data from test bars cut from actual engine components with data generated from ceramic material test specimens. All these efforts are aimed at demonstrating endurance of the AGT101 all-ceramic turbine engine at the maximum operating temperature conditions up to 2500°F (1371°C).

NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AGT</td>
<td>Advanced Gas Turbine Technology Development Project</td>
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<tr>
<td>APGS</td>
<td>Auxiliary Power Generation System</td>
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<tr>
<td>APU</td>
<td>Auxiliary Power Unit</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
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<tr>
<td>ATTAP</td>
<td>Advanced Technology Turbine Applications Project</td>
</tr>
<tr>
<td>BF</td>
<td>Backface</td>
</tr>
<tr>
<td>C</td>
<td>Celsius (degrees)</td>
</tr>
<tr>
<td>CBO</td>
<td>The Carborundum Company</td>
</tr>
<tr>
<td>CL</td>
<td>Centerline</td>
</tr>
<tr>
<td>DF-2</td>
<td>Diesel Fuel No. 2</td>
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<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
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<tr>
<td>ESHP</td>
<td>Equivalent Shaft Horsepower</td>
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<tr>
<td>F</td>
<td>Fahrenheit (degrees)</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
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<td>FF</td>
<td>Fast Fracture</td>
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<tr>
<td>GAPD</td>
<td>Garrett Auxiliary Power Division</td>
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<tr>
<td>GCC</td>
<td>Garrett Ceramic Components</td>
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<tr>
<td>HIP</td>
<td>Hot Isostatic Press</td>
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<tr>
<td>hp</td>
<td>Horsepower</td>
</tr>
<tr>
<td>hr</td>
<td>Hour</td>
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<tr>
<td>in</td>
<td>Inch</td>
</tr>
<tr>
<td>IRI</td>
<td>Impact Resistance Index</td>
</tr>
<tr>
<td>IRT</td>
<td>Impact-Resistant Turbine</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>km</td>
<td>Kilometer</td>
</tr>
<tr>
<td>ksi</td>
<td>Thousands of Pounds Per Square Inch</td>
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Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cincinnati, Ohio — May 24–27, 1993
INTRODUCTION

The Advanced Turbine Technology Applications Project (ATTAP) is a continuation of activities sponsored by the U.S. Department of Energy (DOE) to develop the technology for an improved automobile propulsion system under Title III of U.S. Public Law 95-238, entitled "Automotive Propulsion Research and Development Act of 1978." ATTAP is authorized under DOE/NASA Contract DEN3-335, with the National Aeronautics and Space Administration (NASA) Lewis Engineering Research Center providing program management and administration. The project goal is to develop and demonstrate ceramic technology having the potential of operating for 3500 hours in an automotive gas turbine engine duty cycle at temperatures up to 2500°F (1371°C).

In the ATTAP program, an extensive "up-front" analysis of thermal and stress conditions, combined with an increased understanding of ceramic material properties, behavior, and failure criteria is pioneering a design methodology that addresses the peculiar requirements of ceramic materials. This endeavor has involved a wide diversity of participants, including government laboratories, universities, ceramics manufacturers, and gas turbine designers.

The development of ceramic design methods is being addressed at GAPD jointly in the ATTAP program and the Ceramic Life Prediction Program sponsored by the DOE Oak Ridge National Laboratories (ORNL). Testing of actual components to verify the predictive design capability is an ATTAP function. Hot ceramic spin disk testing and engine durability demonstrations will provide the final verification of fabrication development and design methodology.

The ATTAP program also places major emphasis on developing high-volume, near-net-shape fabrication technology, which must be demonstrated before the gas turbine engine can find acceptance in the automotive marketplace. A material properties database is being established to provide feedback for fabrication process development and design methods development.

This paper summarizes the progress of the ATTAP activities conducted during 1992 by the Garrett Auxiliary Power Division (GAPD) of Allied-Signal Aerospace Company, a unit of Allied-Signal, Inc., in developing the needed technologies for a ceramic gas turbine engine. Four ATTAP program milestones have been completed: initial ceramic materials assessment, turbine stage component design review, delivery of initial turbine stage ceramic components, and operation of an AGT101 all-ceramic engine (shown in Figure 1) to the maximum operating conditions.

**FIGURE 1. GARRETT AGT101 CERAMIC GAS TURBINE USED AS ATTAP TEST BED ENGINE**

GAPD's approach to meeting these milestones is illustrated in Figure 2. The effort during the last year focused on the following:
- Design methods
- Component design
- Component fabrication development
- Durability testing

**DESIGN METHODS**

The brittle nature of ceramic materials, often leading to catastrophic failure, requires sophisticated and rigorous methods capable of addressing the design requirements of ceramic components. To provide robust component design for gas turbine use, methods are needed to address the numerous failure modes of ceramics, including fast fracture, slow crack growth, creep, impact, contact, oxidation and corrosion, and thermal fatigue.

GAPD has formulated a comprehensive plan to develop verified methods to address near-term and future needs. The most urgently needed design systems are being developed now at GAPD under ATTAP and the DOE/ORNL Life...
GC10962-2

FIGURE 2. GAPD’S APPROACH IS DIRECTED AT ATTAP DURABILITY GOAL

Prediction Methodology for Ceramic Components of Advanced Heat Engines program. The ORNL program efforts are addressing fast fracture, slow crack growth and creep. ATTAP is focused on design needs to minimize impact damage. Impact damage is a concern with ceramic turbine rotors and stators, due to their vulnerability to impact from debris and/or combustion products. Design methods development at GAPD, under ATTAP and the ORNL Life Prediction program, is utilizing analytical and experimental work to develop models of material behavior, stress states, and material failure criteria. These efforts will be concluded by verifying the design approach with simulated component evaluations.

Impact Damage

The structural impact model developed under ATTAP has been used in a parametric study to identify the design variables which strongly affect component impact resistance and to find a new ceramic blade configuration with lower impact stress. In the first stage of this study, Taguchi methods were used as the screening process. The most sensitive design variables identified were blade thickness, inlet (Beta) angle, and blade fillet radius.

In the second phase, a parametric study was conducted to determine the optimal combination of these parameters providing the most impact-resistant blade design, while still accommodating turbine aerodynamic requirements. The current ATTAP impact-resistant turbine (IRT) blade design and the improved blade design were used to fabricate subelements for particle impact testing. The subelements consist of a single blade attached to a segment of the hub. Subelement 1 is the blade from the current IRT design, and Subelement 2 is the blade geometry identified in the parametric study using impact analysis. The values of the key parameters are listed in Table 1.

The third phase consisted of performing impact tests on the ceramic subelements and analyzing the results. Ten specimens of each design were divided into two groups of five specimens. The two groups were tested with either 0.10-inch (0.25-cm) or 0.20-inch (0.51-cm) diameter graphite balls, respectively, and a critical impact velocity was established for each impact condition (Table 2). The improvement in impact resistance for the improved blade design was substantial.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>0.1 Inch Projectile</th>
<th>0.2 Inch Projectile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subelement 1</td>
<td>482 ft/sec (147 m/sec)</td>
<td>152 ft/sec (46.3 m/sec)</td>
</tr>
<tr>
<td>Subelement 2</td>
<td>2256 ft/sec (688 m/sec)</td>
<td>593 ft/sec (181 m/sec)</td>
</tr>
</tbody>
</table>

A more meaningful comparison of impact resistance for different blade designs employs the Impact Resistance Index (IRI), defined as the ratio of the critical impact velocity for a particle impact divided by the actual turbine blade velocity at the engine design condition for a given particle size. The IRI values for the original AGT101 radial turbine blade, the current IRT blade (Subelement 1), and the optimal IRT blade (Subelement 2) from the parametric study are shown in Figure 3. In the IRI plot, one unit corresponds to the threshold level at which a blade can survive for a particular particle size. A particle size of 0.20 inch (0.51 cm) is used to calculate this IRI index, because it is the largest particle able to pass through the stator opening of the AGT101 engine.

To improve the structural impact model, a material model was developed to simulate the carbon particle pulverization phenomena during impact. Without a pulverization model, projectiles must be treated as elastic even though they pulverize during real impact events. Experiments established that graphite spheres impacting a silicon nitride target break up into several large fragments at an impact velocity of approximately 250 ft/sec (76.2 m/sec). Beyond an impact velocity of 300 ft/sec (91.4 m/sec), graphite balls pulverize into powder. An impact analysis using the elastic material model for the graphite balls generates higher values than the real stresses, and this discrepancy worsens with increasing impact velocity.
FIGURE 3. SIGNIFICANT IMPROVEMENT IN IMPACT RESISTANCE WAS ACHIEVED WITH NEW DESIGN METHOD

The instrumented particle impact tests conducted earlier in the ATTAP program provided important data for the development of this model. Strain gage measurements of surface tensile strain along the longitudinal direction for eight different impact velocities verified this phenomena. When the peak tensile strain values from both the strain gage recordings and from the analytical results using the elastic material model are plotted (Figure 4), it is clear that the elastic analysis does not generate the impact strain with any reasonable accuracy.

There are two basic approaches to modeling the pulverization phenomena: micromechanical and macromechanical. The micromechanical approach models the physics of the material breakup and models the process at the powder particle scale. Due to the complex details of the fracture process during pulverization and the time and expense required to numerically simulate the powder particles, this approach was not chosen. The macromechanical model makes no attempt to represent the small-scale physics of the pulverization, but rather captures the essential effects of the breakup in integrated quantities, such as energy dissipation and inelastic deformation. Therefore, this method was chosen to model the pulverization of a graphite particle during an impact event.

A complete material pulverization model should include the definition of elastic behavior at low-stress conditions and inelastic responses at stress conditions that exceed the threshold. Without specific experimental data to suggest otherwise, the selected model assumes isotropic elastic behavior following Hooke's law at low stress levels. At higher impact velocities, the pulverization process occurs in the projectile, as a very large number of brittle fractures. Based on these observations, a principal stress criterion is established at the limit of the elastic region. Furthermore, test data shows a substantial difference in the tensile and compressive failure strengths for graphite. Therefore, the model adopted different limiting values of principal stress for the tensile and compressive regimes.

To model the inelastic behavior of the pulverizing projectile, the macromechanical model uses a linear hardening inelastic flow formulation. The main reasons behind this choice are as follows: the main emphasis was on a model that can account for the energy dissipation during pulverization and provide an increased contact area as pulverization takes place. Within the time and budget constraints of the ATTAP program, this model can at least provide an engineering solution to this complicated problem.

For the model to be a valid analytical tool, it must predict impact stress and strain for the selected ceramic material (NT154 silicon nitride) under different conditions (geometry, impact velocity, impact angle, etc.). To prove the validity of the model, ceramic material constants were calibrated with instrumented subelement impact test results. These material constants were then used to compare the analytical strain results with actual strain results from other subelement impact tests.

A strain-gaged specimen was impacted with a 0.10-inch (0.25-cm) diameter graphite ball at eight different velocities. The strain gage records for velocities of 246 ft/sec (75.0 m/sec) and 1236 ft/sec (376.7 m/sec) were used to calibrate the material constants. These constants were then held fixed in simulations of six different impact velocities. The peaks of the strain from the two sources at each impact velocity are plotted in Figure 5 for comparison. The discrepancy is within 12 percent.
A thicker specimen, 0.05 inch (0.127 cm) vs. 0.075 inch (0.191 cm), was also impacted with a 0.10-inch (0.25-cm) diameter graphite ball at eight different velocities. The predictions of peak strain for each impact velocity showed a maximum discrepancy of only 13 percent. It was shown from the comparison that the model works reasonably well in predicting the actual impact stress and strain for the given ceramic material under different conditions.

**COMPONENT DESIGN**

Previous durability testing of the AGT101 engine showed the ceramic radial turbine design to be susceptible to impact damage from combustor-generated carbon\(^2\). Inducer blade damage from carbon ingestion was the cause of an engine shutdown after 85 hours of testing. Tests performed with the Garrett AGT101 combustor rig also indicated that Number 2 diesel fuel (DF-2) used in ATTAP testing promotes the formation of carbon deposits in the combustor. To address this, concurrent efforts were initiated to improve the impact resistance of the turbine rotor and to eliminate carbon formation in the combustor.

To maintain AGT101 engine compatibility and minimize the number of components requiring modification, the new turbine design was constrained to operate within the 90,000 rpm speed and existing compressor pressure ratio and mass flow characteristics. The design for the improved, impact-resistant ATTAP turbine included:

- Reduced turbine tip speed
- Redesigned blades with impact-resistant geometry
- Ceramic material with improved strength.

The impact-resistant turbine was designed to meet ATTAP criteria for aerodynamic performance, mechanical integrity, and fabricability. The engine structures surrounding the turbine stage were redesigned to accommodate the necessary changes in the flowpath. A partial engine cross section (Figure 6) shows the redesigned turbine and surrounding structures. ATTAP efforts for 1992 concentrated on performing the risk analysis, and calculating peak stresses and probabilistic life for the impact-resistant turbine (IRT) design.

**Peak Stress Evaluation of IRT Rotor**

In performing risk analysis of mechanical components, it is the combination of the stress and temperature fields that determine the survival probabilities for fast fracture and slow crack growth. Three-dimensional finite element (FE) analysis was therefore used to predict the thermomechanical stress fields for the IRT rotor. The FE mesh, shown in Figure 7, denotes the four critical regions of the rotor: centerline (CL), backface (BF), blade suction surface (SS), and blade pressure surface (PS). Stress analyses were performed for several different operating modes, including cold rotation, and steady-state and transient engine operation.

Peak steady-state stresses for cold rotation (100,000 rpm), and at the design point [90,000 rpm, 2404\(^\circ\)F (1318\(^\circ\)C) turbine inlet temperature] are 44.5 ksi (307 MPa) and 39.3 ksi (271 MPa), respectively, both occurring on the blade SS. Peak transient stresses occur during engine accelerations, 190 and 910 seconds into the start cycle (Figure 8) defined for the 100-hour durability test. At 190 seconds, a peak stress of 44.5 ksi (307 MPa) occurs on the blade PS, whereas at 910 seconds, the rotor CL stress peaks at 39 ksi (269 MPa).

**Probabilistic Life Analysis**

The objective of performing probabilistic life analysis in the ATTAP program was to advance the state-of-the-art
### FIGURE 7. 3-D FINE ELEMENT ANALYSES RESULTS USED FOR PROBABILISTIC PREDICTIONS

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>SS</th>
<th>PS</th>
<th>BF</th>
<th>CL</th>
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</thead>
<tbody>
<tr>
<td>COLD SPIN</td>
<td>35.9</td>
<td>22.4</td>
<td>29.8</td>
<td>29.4</td>
</tr>
<tr>
<td></td>
<td>(248)</td>
<td>(154)</td>
<td>(206)</td>
<td>(203)</td>
</tr>
<tr>
<td>STEADY-STATE</td>
<td>39.3</td>
<td>23.2</td>
<td>33.5</td>
<td>33.0</td>
</tr>
<tr>
<td></td>
<td>(271)</td>
<td>(160)</td>
<td>(231)</td>
<td>(228)</td>
</tr>
<tr>
<td>190 SEC</td>
<td>18.0</td>
<td>44.6</td>
<td>32.0</td>
<td>39.6</td>
</tr>
<tr>
<td></td>
<td>(124)</td>
<td>(308)</td>
<td>(221)</td>
<td>(273)</td>
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<tr>
<td>910 SEC</td>
<td>25.0</td>
<td>36.0</td>
<td>32.0</td>
<td>39.0</td>
</tr>
<tr>
<td></td>
<td>(172)</td>
<td>(248)</td>
<td>(221)</td>
<td>(259)</td>
</tr>
</tbody>
</table>

### FIGURE 8. MILESTONE 5 100-HOUR DURABILITY/START TEST CYCLE WAS DEFINED.

While predicting the life of the IRT rotor when subjected to realistic engine conditions. A convenient way of evaluating portions of the methodology is to compare results of room temperature burst tests with analytical predictions. Such comparisons were made for rotors fabricated from Garrett Ceramic Components (GCC) GN-10 and Norton/TRW Ceramics (NTC) NT154.

Some notable features of the probabilistic life analysis include: (a) placing confidence bands around the fast fracture predictions, (b) use of pooled data sets and censoring to estimate the Weibull parameters, and (c) computation of total reliability determined from independent failure modes (volume, as-processed surface, and machined surface).

Two sets of mechanical property data were used to generate the statistical properties required for the fast fracture and slow crack growth life analyses. The first set utilized NT154 and GN-10 Mil-B test specimens, size-scaled to reflect Weibull data for unit size, to generate the mechanical properties values (Figure 9) needed to calculate the fast fracture (FF) probability of failure. The second set of test specimens was used to generate mechanical property data (Figure 10 and 11) to predict the slow crack growth (SCG) probability of failure.

### Room Temperature Burst Analysis

Confidence intervals were calculated for fast fracture, and the results were compared with actual rotor burst test data. The analysis is designed to predict that 90 percent of the time, the actual data should fall within the confidence bands. When analytical results were compared with the rotor burst data available (from six GN-10 rotors and two NT154 rotors), the outcome was encouraging (Figure 12). Whatever discrepancies that exist between observed and predicted behavior are attributable to either the quality of the test data, prediction methodology, or both. The capabilities of the methodologies are being thoroughly evaluated in the DOE/ORNL Ceramic Life Prediction Program.

### Fast Fracture During Engine Operation

Fast fracture methodology was applied to predict the reliability under thermomechanical loading for the ATTAP 100-hour durability test cycle load and unload transients. The results are shown in Figure 13. The scatter bands in Figure 13 depict the confidence intervals at the two critical time-points for both materials. It is predicted that at 910 seconds after engine light-off, with a 90 percent confidence calculation, the FF probability of failure (PF) for NT154 lies within 3 and 25 percent, with the nominal being 11.7 percent. Likewise for GN-10, the corresponding range is between 0.5
and 10 percent, with the nominal being 2.1 percent. Thus NT154 has a significantly higher FF when compared to GN-10 (analytically). However, the experimental cold burst spin test data does not support this position. This discrepancy may be attributed to inherent assumptions in the probabilistic life analysis or the quality of the test data used to generate the Weibull and characteristic strength properties of GN-10 and NT154.

**Slow Crack Growth During Engine Steady-State Operation**

Slow crack growth (SCG) behavior was investigated for the AGT101 rotor at the steady-state condition of 2404F (1318°C) turbine inlet temperature and 90,000 rpm. The prediction methodology so far cannot establish a measure of confidence, as has been done for FF. The SCG results for GN-10 and NT154 rotors are shown in Figure 14. Here again, GN-10 is predicted to be superior to NT154. This is attributed to the higher Weibull modulus of GN-10.

The results as plotted apply to rotors that have not been proof tested. If a rotor is spin tested to withstand the stresses of steady-state operation prior to being used in an engine, then its FF risk (SCG at time zero) reduces to zero. Thus, the SCG probability of failure of a proof-tested rotor after 100 hours operation is approximately six percent for GN-10 and approximately nine percent for NT154.
The failure mode for SCG is predicted to be from the as-processed surface for GN-10, and from volume failure for NT154. Even though NT154 is predicted to have a higher SCG probability of failure compared to GN-10, it has a more favorable SCG curve, as shown in Figure 14. After 100 hours of operation, the data for GN-10 lies very close to the knee of the S-shaped curve, whereas, for NT154, the knee is very soft. This trend puts NT154 in a better position against uncertainties in analytical predictions.

**COMPONENT FABRICATION DEVELOPMENT**

In recognition of the need to maintain a competitive position for domestic U.S. suppliers in critical ceramic technologies, the ATTAP program has placed heavy emphasis on the role played by the ceramics subcontractors. The development of fabrication techniques to produce high-quality, reliable ceramic components is critical to the continued growth of ceramic applications. For ATTAP, the U.S. suppliers are concentrating on technologies to fabricate the complex shapes needed for gas turbines. This forming technology must not sacrifice the temperature capability, nor the strength, reliability, and durability properties which make ceramic materials so desirable.

Three U.S. subcontractors were selected by GAPD to develop fabrication methods for high-quality ceramic components: Norton/TRW Ceramics (NTC), Garrett Ceramic Components (GCC), and The Carborundum Company.
Ceramic Material Evaluation

During this past year, several ceramic component materials were characterized (Table 3). The materials characterization activity is focused on testing materials fabricated using the same process path used for the respective engine components. This provides a more accurate database for component design and design methodology development. Additionally, since all ATTAP ceramic components are fabricated near-net-shape, each having a combination of machined and as-processed surfaces, GAPD evaluates fully-machined and as-processed test specimens so properties are available for both surface conditions to support design activities.

NT154 silicon nitride from NTC is currently used for the AGT101 turbine rotor and stators. Since two types of mold materials are used for pressure slip casting these components, the flexural strengths of as-processed surface test specimens cast from both mold materials were characterized. The results indicated that both mold materials yielded equivalent as-processed surface properties. The as-processed surface strengths averaged approximately 75 ksi (517 MPa) from room temperature up to 2500°F (1371°C).

NTC's NT230 siliconized silicon carbide is a candidate ATTAP transition duct material; the first component was delivered in Fall 1992. The as-processed surface strength and the flexural stress rupture properties of NT230 were measured and found to be competitive with the primary ATTAP transition duct material, Carborundum's Hexoloy SA sintered alpha silicon carbide. NT230 as-processed surface strength is approximately 50 ksi (345 MPa) from room temperature up to 2500°F (1371°C). NT230 exhibited 100-hour stress rupture capability greater than 55 ksi (379 MPa) at 2400°F (1315°C) and 40 ksi (276 MPa) at 2500°F (1371°C).

NGK's SN-88 silicon nitride is a component material candidate for the ATTAP transition duct, combustor baffle, and seal rings. The machined and as-processed surface strength and the flexural stress rupture properties were measured during 1992, and SN-88 exhibited excellent high-temperature properties. The machined and as-processed surface strengths averaged better than 90 ksi (621 MPa) and 80 ksi (552 MPa), respectively, up to 2600°F (1425°C). Additionally, SN-88 exhibited 100-hour stress rupture capability greater than 80 ksi (552 MPa) at 2400°F (1315°C) and greater than 70 ksi (482 MPa) at 2500°F (1371°C).

Subcontractor Fabrication Development

Norton/TRW Ceramics. NTC was contracted to develop fabrication processes for rotors and stators with their NT154 silicon nitride, and to deliver components to support engine testing. Pressure slip casting followed by hot isostatic press (HIP) densification was the fabrication approach used.

Rotor process development included development of a mold system incorporating porous and nonporous surfaces to define casting behavior, and development of an aqueous-based slip system to simplify the overall process and to afford better dimensional control of the final part, due to increased green densities over the previous system.

Further rotor issues that were addressed included initial difficulty in balancing rotor components within specification. Improvements to the machining setup were made to better locate the geometric center of the machined rotor in line with the mass center of the rotor. NTC also was able to define machining parameters which allowed relatively rapid stock removal without any apparent damage to the underlying subsurface material. Machining time for a rotor component in the range of eight hours was achieved. A total of nine engine-quality rotors were delivered for evaluation in the AGT101 engine test bed.
TABLE 3. CERAMIC MATERIALS EVALUATED DURING 1992

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Material</th>
<th>Processing</th>
<th>Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norton/TRW Ceramics</td>
<td>NT154 Si3N4</td>
<td>Pressure slip cast and HIPped</td>
<td>• As-processed surface FF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Tensile creep rupture (in-progress)</td>
</tr>
<tr>
<td>Norton/TRW Ceramics</td>
<td>NT-230 siliconized SiC</td>
<td>Pressure slip cast and reaction sintered</td>
<td>• As-processed surface FF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Stress rupture</td>
</tr>
<tr>
<td>Garrett Ceramic</td>
<td>GN-10 Si3N4</td>
<td>Pressure slip cast and HIPped</td>
<td>• Tensile creep rupture (in-progress)</td>
</tr>
<tr>
<td>Components</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>NGK-Locke, Inc.</td>
<td>SN-88 Si3N4</td>
<td>Cold isostatically pressed and sintered</td>
<td>• As-processed and machined surface FF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Stress rupture</td>
</tr>
</tbody>
</table>

Issues concerning stator fabrication had primarily to do with casting methods. The initial stators produced showed anisotropic shrinkage, with the result that dimensions across the stator vane (platform-to-platform distance) were undersized. This presented a challenge for machining setup of this part, which has a rather complex geometry. Fixturing made to the print specification required adjustments to accommodate the decreased vane width. This condition also decreased the flowpath area from the design condition.

A second pattern was made for subsequent deliveries, to address the anisotropic shrinkage. Stators delivered later in 1992 showed better conformance with print dimensions and allowed for straight-forward machining without adjustments to the fixturing. A total of 177 stator segments were delivered to GAPD for evaluation in the AGT101 engine test bed.

Garrett Ceramic Components. GCC was contracted to develop fabrication processes for rotors with their GN-10 silicon nitride, and to deliver components to support engine testing. As with NTC, pressure slip casting followed by HIPping was the fabrication approach employed.

GCC sought specifically to improve the strength of as-HIPped surfaces of their GN-10 material. GN10 surface strength typically falls short of the strength of machined surfaces of HIPped silicon nitrides by 40 ksi or more. Other property improvements were sought as well and the results are listed in Table 4. The approaches to achieving these improvements fell into the following three areas:

a) Modifications to the existing process including:
   • HIP and post-HIP heat treatment
   • Modification to the calcining cycle or the drying cycle
   • Abrasive machining to remove the surface reaction layer
b) Improvements to the slip process
c) Use of an alternative, higher purity ceramic powder.

Modifications by GCC to the GN-10 HIP process and post-HIP heat treatments did not produce the desired improvements in mechanical properties. Neither did modification to the slip process, which gave high-density gradients in the "green" part. Alternative powder trials at first gave problems with cracking during drying, but subsequent trials proved more successful, and the alternative powder was adopted by GCC as part of their updated process for GN-10. A refinement to the calcining cycle, while unfortunately providing a softer, more delicate "green" part, did yield some improvement in surface strength, but not to the degree desired.

In the trials performed by GCC, flow machining was unable to penetrate the HIP surface reaction layer by an amount sufficient to restore material bulk properties. With the exception of the goal for surface properties, all target mechanical properties of GN-10 were successfully accomplished by GCC.

Five GN-10 rotors were delivered to GAPD for evaluation in the AGT101 test bed engine. Some of these exhibited an excessive unbalance condition, due to the disparity between the mass center and the geometric center of the machined part. Stricter machining setups were implemented to address this concern, with subsequent machined rotors exhibiting less stock removal required for balance.

TABLE 4. NOTICEABLE GAINS WERE ACHIEVED IN GCC ROTOR PROPERTIES

<table>
<thead>
<tr>
<th></th>
<th>Previous</th>
<th>Target</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-processed flexure strength, ksi (MPa)</td>
<td>RT 2200F (1204°C)</td>
<td>73 (503)</td>
<td>100 (689)</td>
</tr>
<tr>
<td></td>
<td>2200F (1204°C)</td>
<td>58 (400)</td>
<td>85 (586)</td>
</tr>
<tr>
<td>Tensile strength, ksi (MPa)</td>
<td>RT 2500F (1371°C)</td>
<td>92.7 (639)</td>
<td>110 (758)</td>
</tr>
<tr>
<td></td>
<td>2500F (1371°C)</td>
<td>38 (262)</td>
<td>60 (414)</td>
</tr>
<tr>
<td>Stress rupture life, (hours)</td>
<td>70 ksi and 2200F (483 MPa and 1204°C)</td>
<td>&lt;80</td>
<td>&gt;80</td>
</tr>
<tr>
<td>Weibull modulus (RT)</td>
<td>18.6</td>
<td>20</td>
<td>22</td>
</tr>
</tbody>
</table>

RT = Room temperature. N/A = Not Applicable.
The Carborundum Company. CBO was successful in supporting the ATTAP program with ceramic hardware for engine testing. Components delivered included transition ducts, combustor baffles, and pilot combustor supports made from Hexoloy SA sintered alpha silicon carbide, fabricated by an isopressing and green machining process, followed by firing and dense machining of critical close-tolerance features.

Transition duct fabrication was eased by incorporation of a fully-machined outside diameter (OD) at the large end. A previous design had three individual features on the OD to accommodate the thermocouple ports, which added asymmetry to the cast part. Improvement of this feature was a result of close coordination with CBO during the design phase. Baffle fins presented a challenge for fabrication. The approach chosen was to green machine a rectangular shape, and then machine the dense part to the airfoil shape with ultrasonic machining. The ultrasonic machining was not as quick or as easy as first envisioned, with the resulting actual yields being well under the estimated yields. However, sufficient hardware to successfully support engine testing was delivered, and modifications to the design and the fabrication approach were identified to alleviate the problem in any future effort with a similar component.

The pilot combustor supports lent themselves well to this fabrication approach. The many holes with fairly tight tolerances were readily machined into the green components, and shrinkages during sintering were small enough that the process proved itself capable of producing parts to print. For a small production order such as envisioned for most of today's gas turbine applications, the isopress and green machining approach was successfully demonstrated as a viable technique.

As part of the CBO component fabrication effort, material specimens were tested to establish the material property capability of the isopress and green machining fabrication process. Target values of 50 ksi (345 MPa) at room temperature, with a Weibull modulus of 7.5 or better as measured by the maximum likelihood method, were exceeded in all batches tested.

Flexural strength test results for machined and as-processed Hexoloy SA silicon carbide are plotted as a function of temperature in Figure 16. The 1991 Hexoloy SA flexural stress rupture test results are summarized in Figure 17 and show much improved stress rupture capabilities compared to the 1985 vintage injection molded Hexoloy SA used in the previous AGT program.

Kyocera and NGK. These Japanese suppliers have continued to provide support throughout the ATTAP program. By using Kyocera and NGK to provide various pieces of engine hardware, domestic vendors are able to focus on the enhancement of materials and manufacturing processes by concentrating on specific hardware items. NGK has supplied hardware using two types of silicon nitride, SN-88 and SN-94, while Kyocera has utilized SN-251 silicon nitride.

Component Testing 2500F (1371C) Rig Testing. Ceramic components were subjected to high-temperature test exposures up to 2500F (1371C) in this specialized test rig. The rig used ceramic hardware to simulate the hot gas flowpath of an engine. Testing was designed to provide information about oxidation, sticking, and interfaces between a variety of materials exposed to the combustor discharge. The testing exposed ceramic silicon nitride stators from two subcontractors to a stator inlet temperature of 2500F (1371C) for 50 hours at an average airflow of 9.5 lb/min (4.3 kg/min). After exposure, the ceramic stators were then destructively evaluated. NT154 stators from Norton/TRW Ceramics exhibited no signs of deterioration. However, SN-251 stators from Kyocera did show signs of subsurface oxidation. This oxidation caused a reduction in stress rupture life. A small amount of pitting was also observed on the SN-251 stators, an additional sign of material degradation.

![FIGURE 16. MACHINED AND AS-PROCESSED (ISOPRESSED AND GREEN MACHINED) CARBORUNDUM CO. HEXOLOY SA SPECIMENS EXHIBIT SIMILAR FLEXURAL STRENGTH CHARACTERISTICS](https://example.com/figure16)

![FIGURE 17. 1991 VINTAGE ISOPRESSED HEXOLOY SA FLEXURAL STRESS RUPTURE TEST RESULTS.](https://example.com/figure17)
Impact-Resistant Turbine Aerodynamic Rig Testing.
The impact-resistant turbine designed in 1990 was intended to match the baseline level performance of the AGT101 radial ceramic turbine. Two designs were generated, with 1850 ft/sec (564 m/sec) and 1700 ft/sec (518 m/sec) blade tip speeds, respectively, bracketing the aerodynamic and particle impact considerations. To verify performance, a turbine rig was designed, fabricated, and constructed to allow aerodynamic testing of the 1850 ft/sec (564 m/sec) tip speed turbine. The rig was installed in the dynamometer test facility at GAPD and the efficiency map in Figure 18 was acquired.

The turbine design point, at a pressure ratio of 4.23 at 100 percent corrected speed, yielded an efficiency 2.80 percent below that of the AGT101 radial turbine. Diagnostic measurements indicated the sources of the performance decrements, which were caused by a flow separation in the rotor and strong vortices through the vane passages. Also, the nozzle throat was sized too large, which added losses due to the higher flow through the components.

Thermal Furnace Proof Testing — Previously, hot combustion flow rigs were utilized to simulate engine cycles for the purpose of proof testing/qualifying components. However, because of the expense and difficulties of controlling and calibrating the hot flow rig to simulate engine characteristics, a new proof test method and rig was devised. The primary goals of this new test rig were: 1) To achieve the desired stress fields and maximum stress without need for an elaborate controller to adjust rig input parameters based on temperature feedback; and 2) To test one component at a time rather than a subassembly, thus providing better control of the test.

Figure 19 shows the basic components of the new test rig. The proof test cycle for a given component is a function of the preset furnace temperature, the exposure time, and the insulation configuration. The component is selectively insulated such that the maximum stress distribution during the proof test cycle will simulate 125 percent of the actual engine operating stress. Furnace proof cycles and fixtures were developed and utilized for the following AGT101 engine structures:

- Turbine shroud
- Inner Diffuser
- Baffle
- Outer Diffuser

The furnace proof test method has significant advantages over use of hot flow rigs. The proof test fabrication effort was significantly reduced, since a single furnace is utilized for all components. The component insulation is the only portion of the fixture customized for each part, which significantly reduces the costs associated with proof tests. The furnace proof test is also easily controlled, thus reducing the risk of hardware failure due to rig malfunctions.

A calibration test of the furnace was initially accomplished to characterize the furnace heat flux at various setpoint temperatures. This enabled calculation of a stress cycle for each component. Temperature measurements during the initial proof test of each component type verified the analytical predictions (Figure 20).

Spring Seal Proof Test. A proof test fixture was designed for the new inner and outer spring seals which are utilized on the impact-resistant configuration of the AGT101 test bed. The fixture was designed to simulate the interface between the seals and the actual engine hardware (Figure 21). The deflection provided by each fixture provides a peak stress of 125 percent of the actual worst-case engine condition. The upper plate bottoms out when the maximum deflection and stress is attained. The bottom plate is adaptable to both upper plate configurations.

The fixture is designed to mount in an Instron machine which is capable of providing load-versus-deflection data. The actual load-versus-deflection data measured closely resembles that predicted (Figure 22). This verified the stress predictions for the spring, and verified the elastic modulus for the silicon nitride material.
Regenerator Rig Testing. Besides being used to test the regenerator system, several other design improvements were tested in the regenerator rig prior to incorporation into the ACT101 engine test bed. Two of the most recent improvements include a redesigned combustor load spring system and a regenerator core anti-tilt roller.

The new combustor cap spring baffle configuration was designed to keep the combustor load springs cool throughout engine operation (Figure 23). Prior regenerator rig testing indicated spring operating temperature measured up to 1300F (704C), which is above the acceptable operating level for the spring material. The springs supply the compressive load needed to maintain the ceramic combustor hardware stack, as well as the load required to maintain the seal of the flow separator housing seal rings. Operation at elevated temperature caused the springs to creep over an extended period of time and lose their compressive load. Incorporating the new design lowered the operating temperature of the springs to under 1000F (538C), which provides acceptable operation.

Another design evaluated in the regenerator rig was the regenerator core anti-tilt roller. Prior rig tests showed displacement and tilt of the core occurred during engine operation. The maximum deflection measured was 0.028 in (0.07 cm) at the outer periphery during the maximum rig temperatures and pressures. The tilt of the regenerator core increased the leakage across the face of the hot seal as well as increasing the load on the cold seal, which causes an increase in the core torque. The anti-tilt roller was designed to eliminate this tilt by reacting the pressure forces of the airflow through the regenerator core ring gear (Figure 24), thus reducing the leakage and torque.
ENGINE TESTING

Engine testing with the all-ceramic AGT101 test bed will provide a final measure of verification of the ceramic components as well as the design methods and processes that went into their making. This activity is planned in three phases:

- Qualify ceramic impact-resistant rotors in the ceramic/metal AGT101 test bed
- Conduct maximum operating condition engine testing
- Conduct engine endurance testing

The first two of these phases have been successfully completed, and 38 hours test time have been completed at 2200°F (1204°C) TIT during the AGT101 endurance tests.

Ceramic Rotor Qualification Testing in the Ceramic/Metal AGT101 Test Bed. The AGT101 ceramic/metal engine is used to qualify ceramic impact-resistant turbine rotors for use in the all-ceramic AGT101 test bed. The engine consists of metal impact-resistant flow components, a ceramic regenerator core, a ceramic stepped-pilot combustor, and a ceramic impact-resistant turbine rotor. The rotor qualification test profile consists of accelerating the engine from 60,000 to 90,000 rpm in 5 to 15 seconds while simultaneously loading the engine to a turbine inlet temperature (TIT) of 1650°F (899°C), the maximum TIT attainable for the ceramic/metal test bed.

Operating the engine through this transient test cycle exposes the ceramic rotor to the thermomechanical loadings experienced in the all-ceramic engine. Successful completion of the transient test cycle qualifies the ceramic rotor for use in the all-ceramic AGT101 engine. One GN-10 and two NT154 rotors have been qualified in the ceramic/metal AGT101 engine.

AGT101 All-Ceramic Engine Tests. The GAPD AGT101 engine is being utilized in the ATTAP program as a test bed to demonstrate the durability of ceramic engine hardware under actual gas turbine engine operating conditions. During 1992, work with the AGT101 all-ceramic test bed focused on completing incorporation of the engine design improvements and accomplishing the maximum engine operating condition testing and the engine endurance testing.

Two major design improvements have been implemented into the all-ceramic AGT101 test bed engine. These are the anti-tilt roller system and the redesigned combustor load spring system.

Milestone 4 requires operation of an all-ceramic AGT101 engine at the maximum operating conditions at speeds from 50,000 to 90,000 rpm. Maximum operating conditions are limited by the 1800°F (982°C) maximum regenerator inlet temperature (RIT). This testing is intended to verify the durability of the engine components under short-term steady-state operating conditions, and the transient stresses of the start cycle.
The major engine testing accomplished to date is completion of the maximum operating condition engine test. The engine ran for a total of 6.1 hours up to a maximum TIT of 2354°F (1290°C). The maximum operating conditions of 1800°F (982°C) RI T and 90,000 rpm were held for a total of 1.5 hours.

The AGT101 endurance test requires 100 hours operation of the all-ceramic engine. The actual testing accomplished 38 hours at 2200°F (1204°C) turbine inlet temperature; testing was terminated due to failures of two lithium aluminosilicate (LAS) flow separator housings. Table 5 provides a summary of the engine testing completed under the ATTAP program.
This demonstration program will replace the existing 331-200 metallic first-stage turbine nozzle and blades with ceramic components. Engine and component integrity will be demonstrated in laboratory and endurance testing and eventually in a field evaluation. Effort during 1992 focused on design of the ceramic turbine blade and nozzle, and modification of the supporting metallic structures to incorporate the ceramic components.

The 331-200/250 APU family has been in production since the early 1980s. This gas turbine has provided auxiliary power for wide-body commercial airliners such as the Boeing 757, 767, and Airbus A310 aircraft. More recently, the APU has been installed on the USAF C-17 transport aircraft.

**G250 Auxiliary Power Generation System.** GAPD is incorporating ceramic turbine nozzles into its newest design, the 400-horsepower G250 APU for the USAF F-22 Advanced Tactical Fighter aircraft. This program is currently in the engine development phase, with the first engine run scheduled for September 1993. Testing at GAPD will continue into 1997, and initial deliveries of the APU are scheduled for the 1994-1995 timeframe. The G250 APU ceramic stator makes use of the high-temperature capabilities of silicon nitride, and employs single-vane segments to form the stator ring.

**SUMMARY AND CONCLUSIONS**

GAPD’s ATTAP program has developed the near-term ceramic technology base while the production-oriented programs continue to advance the state-of-the-art in ceramic gas turbine engine applications. An integrated design methodology is being developed under ATTAP and the DOE/ORNL Ceramic Life Prediction program to address fast fracture, time-dependent, and impact conditions. These methodologies have been utilized to provide robust turbine component designs for ATTAP and additional production-oriented programs. Critical engine systems have been enhanced to provide improved durability. Subcontractor ceramic fabrication efforts are meeting the needs of ATTAP and the production-oriented programs for ceramic material properties and complex shape fabrication capabilities. These efforts continue to focus on the DOE and GAPD goal of successfully integrating ceramics into gas turbine engines.

**ACKNOWLEDGMENTS**

The authors are grateful to the Department of Energy for making this research possible and to the program management at the NASA Lewis Research Center. We would also like to thank J. Cuccio, M. Easley, C. Irwin, E. Blumer, M. Meyer, R. Ullah, M. Rettler, J. Schienle, J. Song, and R. Strong at GAPD for technical support of the program efforts and contributing portions of the paper. Finally we would like to acknowledge the efforts of G.A. Lucas in editing and preparing this paper for publication.

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