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ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROJECT (ATTAP)

1991 ANNUAL REPORT

Engineering Staff of
Garrett Auxiliary Power Division
A Unit of Allied-Signal Aerospace Company

June 1992

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN3-335

for
U.S. DEPARTMENT OF ENERGY
Office of Transportation Technologies
Heat Engine Propulsion Division
Washington, D.C. 20585

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TABLE OF CONTENTS

TABLE OF CONTENTS (Contd)

LIST OF FIGURES

LIST OF FIGURES (Contd)

LIST OF FIGURES (Contd)

LIST OF FIGURES (Contd)

LIST OF TABLES

LIST OF TABLES (Contd)

ACRONYMS AND ABBREVIATIONS

AE	Acoustic Emissions
AGT	Advanced Gas Turbine
ASEA	Swedish Subcontractor to GCC (HIP Encapsulation Process)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
atm	Atmosphere
ATTAP	Advanced Turbine Technology Applications Project
C	Celsius
CADAM	Computer Aided Design and Manufacturing
CBO	Carborundum Company
cc	Cubic Centimeters
CFDC	Combined Federal Driving Cycle
CIP	Cold Isostatic Pressing
cm	Centimeter
CMM	Coordinate Measuring Machine
CNC	Computer Numeric Control
CVD	Chemical Vapor Deposition
deg	Degrees
DOE	Department of Energy
ECU	Electronic Control Unit
EGT	Exhaust Gas Temperature
EPIC	Elastic-Plastic Impact Computations (Computer Code)
F	Fahrenheit
FEM	Finite Element Model
FOD	Foreign Object Damage
FPI	Fluorescent Penetrant Inspection
FRSL	Flat-Rated Sea Level
FSH	Flow Separator Housing
ft	Foot
g	Gram
GAPD	Garrett Auxiliary Power Division
GCC	Garrett Ceramic Components
GPa	Giga Pascal
HIP	Hot Isostatic Pressing
HP	High Pressure
hp	Horsepower
hr	Hour
ID	Inside Diameter
in	Inch
IQI	Image Quality Indicator
IRT	Impact-Resistant Turbine
ISBN	International Standard Book Number

ACRONYMS AND ABBREVIATIONS (Contd)

K	Kelvin
kg	Kilogram
K_{IC}	Critical Stress Intensity Factor
krpm	Thousands of Revolutions Per Minute
ksi	Thousands of Pounds Per Square Inch
LAS	Lithium Aluminum Silicate
lb	Pounds
lbf	Pounds Force
LP	Low Pressure
m	Meter
MFXR	Microfocus X-Ray Radiography
mg	Milligram
mm	Millimeter
mil	Thousandths of an inch
MIL-STD	Military Standard
min	Minute
MOR	Modulus of Rupture
MPa	Mega Pascal
mpg	Miles per Gallon
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NTC	Norton/TRW Ceramics
OD	Outside Diameter
ORNL	Oak Ridge National Laboratory
PEEP	Pressure-Assisted Endothermic Extraction Process
PSC	Pressure Slip Casting
psid	Pounds Per Square Inch Differential
psig	Pounds Per Square Inch Gage
QC	Quality Control
RIT	Regenerator Inlet Temperature
RPD	Reference Powertrain Design
R.T.	Room Temperature
rpm	Revolutions Per Minute

ACRONYMS AND ABBREVIATIONS (Contd)

SAE	Society of Automotive Engineers
SASC	Sintered Alpha Silicon Carbide
sec	Second
SFC	Specific Fuel Consumption
shp	Shaft Horsepower
SEM	Scanning Electron Microscope
Si_3N_4	Silcon Nitride
SiC	Silicon Carbide
Si-SiC	Siliconized Silicon Carbide
SL	Sea Level
SPC	Statistical Process Control
SLA	Stereolithographic
S/N	Serial Number
TEM	Tunneling Electron Microscope
TIT	Turbine Inlet Temperature
UDRI	University of Dayton Research Institute
U.S.	United States
VIGV	Variable Inlet Guide Vane
W	Watt
WDX	Wavelength Dispersive X-Ray
WEEP	Water Endothermic Extraction Process
X	Magnification
Y_2O_3	Yttrium Oxide
β	Beta
σ_1	First Principal Stress (SIG1)
σ_a	Stress Value From Analysis
σ_t	True Stress
μin	Microinches
μm	Microns (Thousandths of a Millimeter)
2-D	Two Dimensional
3-D	Three Dimensional

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1.0 SUMMARY

This report summarizes work performed by Garrett Auxiliary Power Division (GAPD), a unit of Allied-Signal Aerospace Company, during calendar year 1991, toward development and demonstration of structural ceramic technology for automotive gas turbine engines. This work was performed for the Department of Energy (DOE) under National Aeronautics and Space Administration (NASA) Contract DEN3-335, Advanced Turbine Technology Applications Project (ATTAP). GAPD is utilizing the AGT101 regenerated gas turbine engine developed under the previous DOE/NASA Advanced Gas Turbine (AGT) program as the ATTAP test bed for ceramic engine technology demonstration. ATTAP is focussing on improving AGT101 test bed reliability, development of ceramic design methodologies, improvement of fabrication and materials processing technology by domestic U.S. ceramics fabricators. Improved combustion system and regenerator technology, and demonstration of technology advancements will be verified in a series of durability tests. This is the fourth in a series of technical summary reports published annually over the course of the five-year contract.

1.1 Test Bed Engine Design, Analysis, and Materials Assessment

Improvements to the AGT101 engine were successfully developed, making it a more reliable test bed for verification of the ATTAP ceramic technologies. In addition to successful incorporation of the redesigned impact-resistant ceramic turbine section, the following additional improvements have been incorporated into the AGT101 test bed engine:

- Regenerator seals employing a more chemically stable and strain-tolerant coating
- Combustor with improved atomization and less tendency to coke formation
- Redesign of the critical sealing elements between the flow separator, turbine shroud, and transition duct
- Modifications to the flow separator support system
- Combined spring and seal supporting the inner turbine diffuser

Kyocera beta silicon carbide (β-SiC) material was assessed during 1991. The material assessment test results to date suggest that SC-221 is suitable for use as an ATTAP combustor baffle material.

1.2 Ceramic Component Design

Significant progress has been made in the development of design methods for predicting impact damage to ceramic components in gas turbine engines. The design methods development has been pursued in two parallel paths: modeling of local impact damage (near the point of impact), and modeling of structural damage (failure away from the point of impact, due to bending stresses). The impact methods development work has been performed in collaboration with the University of Dayton Research Institute (UDRI) in Dayton, Ohio.

In 1991, the overall approach was modified to place more emphasis on structural impact damage methods development. Two main activities were ongoing: the first was continuation of iterative impact damage resistance analyses, to arrive at an impact-resistant ceramic turbine wheel configuration having the potential for substantially improved impact tolerance. The second activity was a ceramic specimen impact test program, designed to study the mechanisms of structural impact damage and to identify the important parameters affecting ceramic structural impact damage resistance. An additional study of the effects of carbon particle pulverization during impact also was conducted.

1.3 Materials Characterization and Ceramic Component Fabrication

During 1991, mechanical property test data was acquired to characterize the following ceramic materials:

- Norton/TRW Ceramics NT154 silicon nitride
- Norton/TRW Ceramics NT230 siliconized silicon carbide (Si-SiC)
- NGK SN-88 silicon nitride
- Garrett Ceramic Components GN-10 silicon nitride
- Carborundum Co. Hexoloy SA silicon carbide

Characterization of ceramic components from cutup bars was largely shifted to the ceramics subcontractors, thereby avoiding significant duplication of effort. Historical comparison of GAPD and vendor data has shown good correlation.

Nondestructive evaluation (NDE) efforts by GAPD concentrated on component inspections and detection of test bar flaws for correlation with destructive test results.

The three selected U.S. ceramic subcontractors (Norton/TRW Ceramics, Garrett Ceramic Components, and The Carborundum Company) all successfully delivered engine-candidate components during 1991, satisfying ATTAP Milestone 3 requirements.

Norton/TRW Ceramics successfully resolved a processing problem, eliminating strength-reducing inclusions in their agglomerated NT154 silicon nitride material. Molds from a preliminary plastic pattern (generated from computer design files by stereolithography) were used to evaluate the ceramic rotor processing capability, prior to fabrication and delivery of engine-candidate parts. Ceramic rotor machining issues were successfully resolved, and by the end of 1991 spin burst testing had been accomplished, verifying the integrity of the NT154 rotors.

Mold modifications were made by Norton/TRW to enhance stator formability, and machining issues for the complex stator geometry were successfully resolved. Twenty-four NT154 ceramic stators were delivered by the end of 1991.

Garrett Ceramic Components successfully resolved a backface cracking phenomenon seen in their initial GN-10 silicon nitride rotor casting attempts, as well as an undersize shaft condition. Six dense GN-10 ceramic rotors were spin tested to burst, and all sustained speeds above the AGT101 engine operating range. Five engine-candidate rotors were delivered by the end of 1991.

The Carborundum Company was contracted to deliver five sets of three different Hexoloy SA silicon carbide AGT101 engine components: pilot combustor supports, transition ducts, and combustor baffles. The pilot combustor supports presented few difficulties for the selected isopress/green machine fabrication method, and five sets were successfully delivered. Five transition ducts, large ceramic components by most standards, also were readily fabricated and delivered. However, the combustor baffles, with tight surface tolerances on the three protruding fins, presented a machining challenge. Ultrasonic machining of the ceramic fin shape in the dense state resulted in only three acceptable components delivered from the blanks available.

Detailed accounts of subcontractor progress are given in the Appendices to this report.

1.4 Component Rig Testing

Preparation for hot spin testing of ceramic disks continued during 1991. Redesign of the attachment schemes to accommodate operation in air was accomplished. Potential dissociation of the silicon nitride test material when heated in vacuum conditions precludes using an evacuated chamber for the spin testing, as originally planned.

An optimum combustor configuration was successfully identified in combustor rig testing. The final configuration selected includes a stepped pilot combustor of smaller diameter than the main combustor body, and a simplex (single fuel discharge) fuel nozzle, incorporating an airwipe feature to preclude carbon soot buildup on the nozzle face.

Regenerator rig testing was continued, to evaluate new component designs prior to implementation in the AGT101 test bed engines, and to assess regenerator system durability and performance. The regenerator core pocket area was instrumented, tests were accomplished to measure regenerator system deflections during operation, and the regenerator seal system was tested for durability.

Structural proof tests were continued, to screen ceramic hardware for engine testing. These tests were of two types: mechanical tests, to confirm hardware integrity under pressure loads; and thermal tests in which heated airflow impinging on the component simulates thermal stresses found during actual engine operation. Additionally, a new support system design for the large lithium aluminum silicate (LAS) FSH component was successfully verified in a mechanical test rig, and a new diffuser support seal system was validated.

Rig tests exposing hardware to 2500F conditions for 13.5 hours were successfully accomplished during this reporting period. Excessive oxidation of one of the stator materials tested contraindicated further consideration for use in the test bed engines. Additional testing is scheduled during 1992.

1.5 Engine Test Bed Trials

A series of test bed trials was completed during 1991, culminating in successful operation of an all-ceramic AGT101 engine for a total of 13.3 hours. Several improvements to the test bed engine were verified during this testing. Preceding the all-ceramic engine test, an AGT101 engine with metallic components (excepting the regenerator core) was successfully operated to troubleshoot and verify operation of the electronic control unit (ECU); and a metallic AGT101 engine with ceramic turbine rotor successfully confirmed operation of the optimized combustor configuration.

2.0 INTRODUCTION

This report is the fourth in a series of Annual Technical Summary Reports for ATTAP, authorized under the DOE-sponsored NASA Contract DEN3-335. The project is administered by Mr. Thomas Strom, Project Manager, NASA-Lewis Research Center, Cleveland, Ohio. This report presents work plans and progress for calendar year 1991. Project efforts conducted under this contract are part of the DOE Gas Turbine Highway Vehicle System Program. This program is oriented to provide the United States automotive industry the high-risk, long-range technology necessary to produce gas turbine engines for automobiles with reduced fuel consumption and reduced environmental impact.

The Garrett AGT101 ATTAP test bed engine (Figure 1) is designed such that, when installed in a 3000-pound inertia weight automobile, it will provide:

- Low emissions
- Fuel economy of 42 mpg on diesel fuel
- Multifuel capability
- Competitive costs with current spark-ignition engines
- Noise and safety characteristics that meet U.S. federal standards

The AGT101 is nominally a 100-shp engine, capable of speeds to 90,000 rpm and turbine operation at inlet temperatures to 1371C (2500F) with a specific fuel consumption (SFC) level of 0.3 lb/hp-hr over much of the operating range.

ATTAP is oriented toward developing the high-risk technology of ceramic structural component design and fabrication, such that industry can carry this technology forward to production in the 1990s. The AGT101 engine, continued in use from the prior DOE-sponsored AGT Project, is being used as the Garrett ATTAP test bed engine for verification of the durability of ceramic components, and their suitability for service over the full engine operating envelope.

The ATTAP milestone schedule is depicted in Figure 2. The program will continue technology work through calendar year 1992, culminating in the demonstration of ceramic engine operation for 100 hours. Fifty percent of the engine test time will be at maximum temperature.

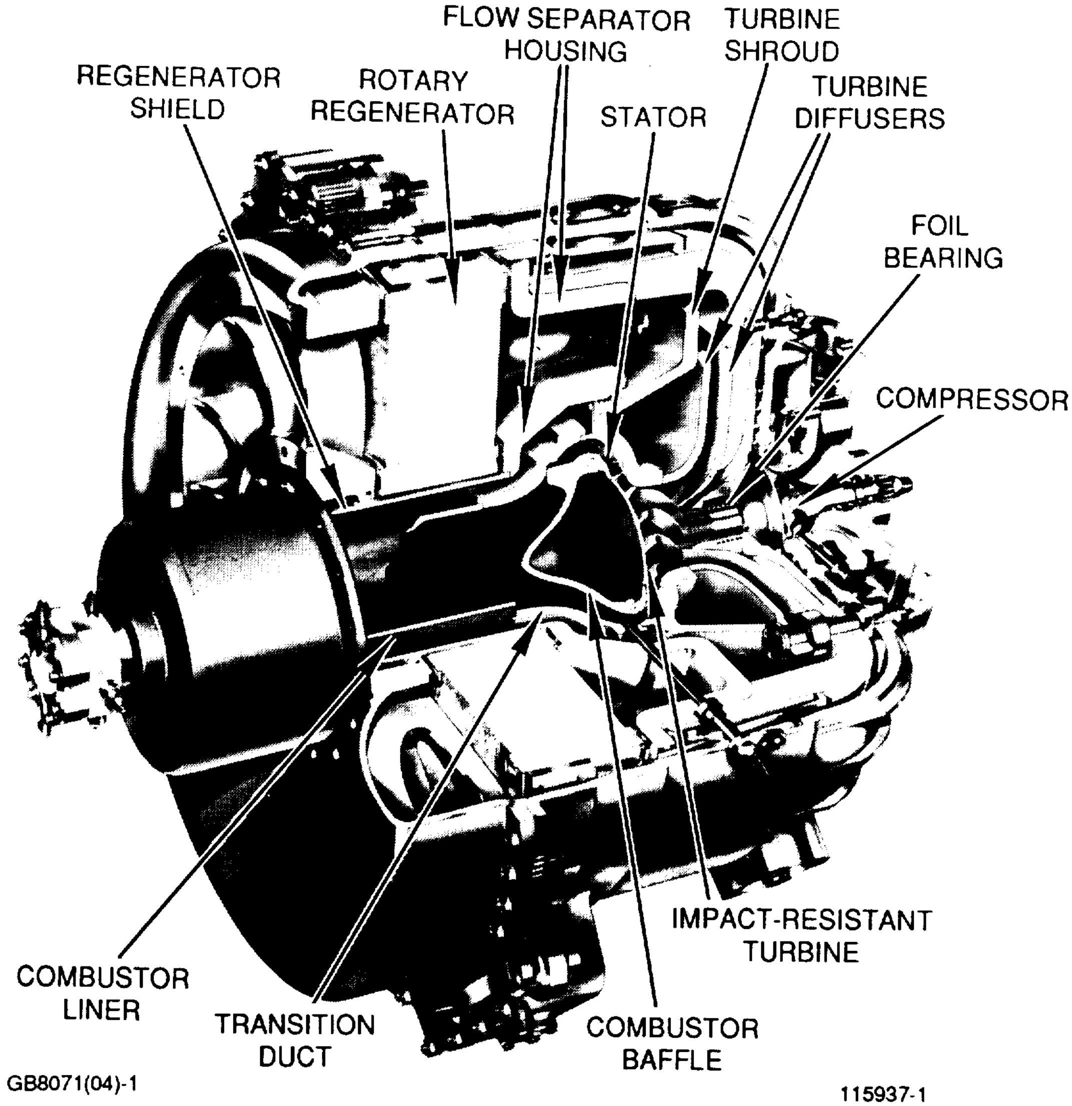

Figure 1. Garrett AGT101 Test Bed Engine

This report reviews the efforts conducted in the fourth full year of ATTAP in development of ceramic technology, and improvements made to the test bed engine and test rigs. Appendices include progress reports prepared by the major ATTAP subcontractors to GAPD: Norton/TRW Ceramics, Carborundum Company, and Garrett Ceramic Components.

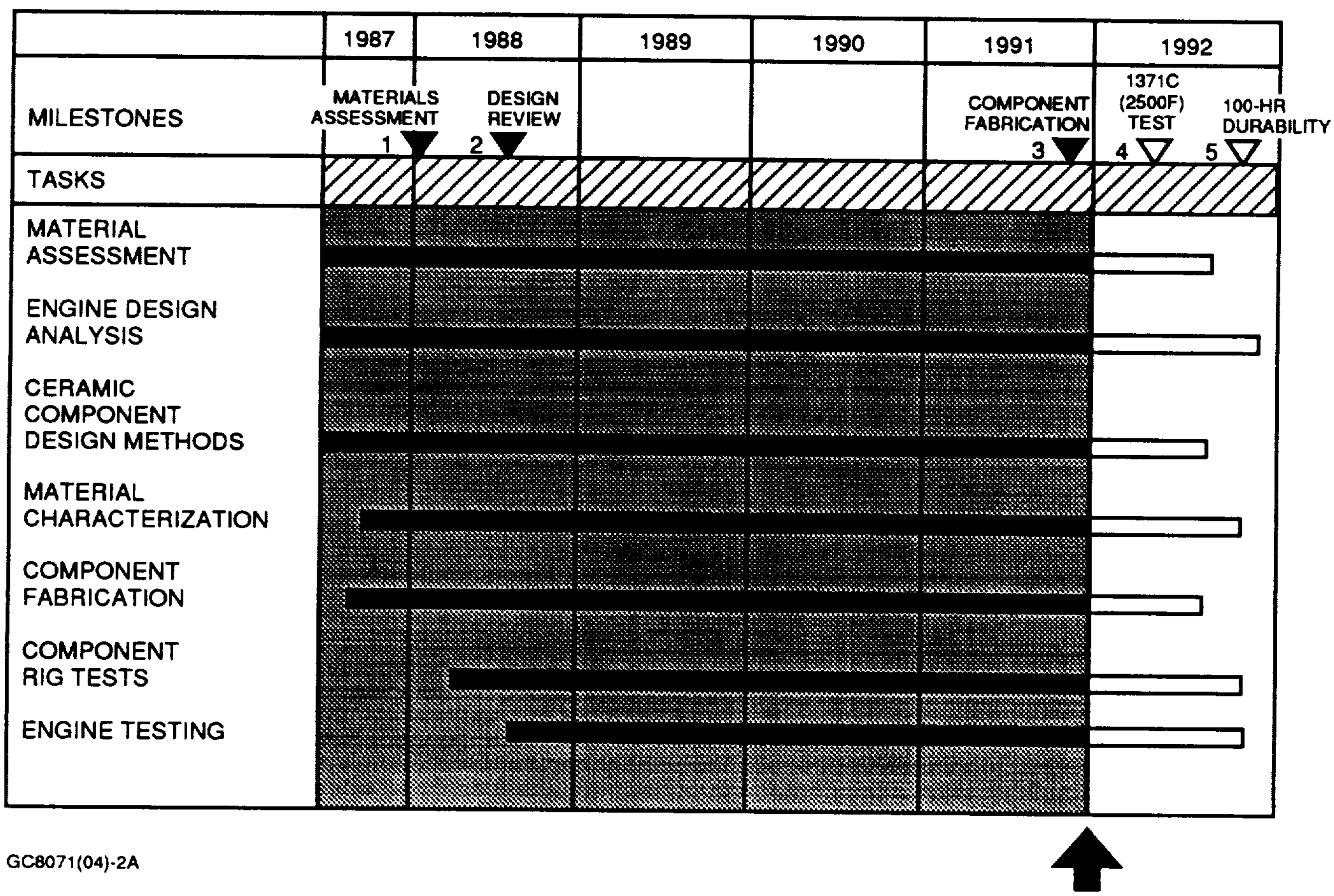

Figure 2. ATTAP Milestone Schedule.

3.0 TEST BED ENGINE DESIGN, ANALYSIS, AND MATERIALS ASSESSMENT

3.1 Materials Assessment

Kyocera SC-221 Beta Silicon Carbide

An assessment of Kyocera SC-221 beta silicon carbide was initiated in late 1991 to evaluate its potential as a candidate material for the AGT101 combustor baffle, which can reach 2600F at maximum operating conditions. Kyocera provided fifty SC-221 flexure specimens (4 x 3 x 50 mm) for this assessment. Forty specimens were fully machined, and ten had the test surface left in the as-processed condition. Flexural strength testing of machined SC-221 was performed at various temperatures between room temperature and 2600F; as-processed SC-221 strength testing was conducted at room temperature only. The test parameters are described in Section 5.1.1.

SC-221 strength test results are plotted as a function of temperature in Figure 3. For machined SC-221 specimens, the strength averaged 64.7 ksi at room temperature and increased gradually with increasing temperature to 76.5 ksi at 2600F. For as-processed SC-221 specimens, the strength averaged 56.4 ksi at room temperature, which is 12.8 percent lower than for machined SC-221.

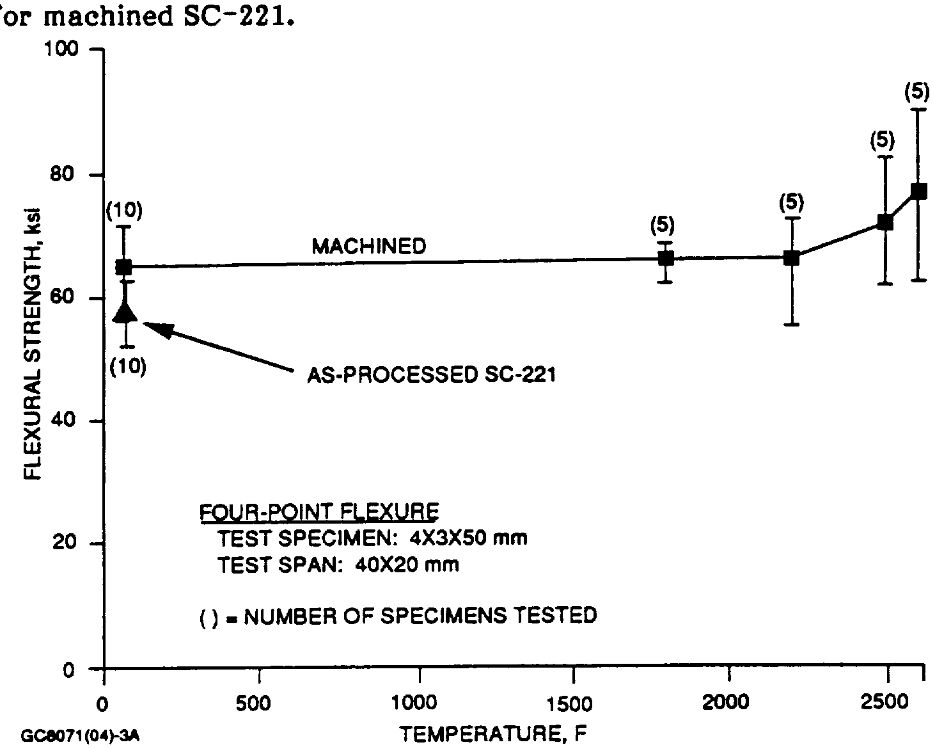

Figure 3. Kyocera SC-221 Beta SiC Exhibits Good High-Temperature Strength Retention.

The fracture origins for machined SC-221 were located predominantly at the specimen tensile surfaces. A typical failure origin for machined SC-221 is shown in Figure 4. No discernible flaws for machined surface failure origins were identified. A few internal failure origins were noted. For those instances, the fracture-originating flaws were internal pores (Figure 5). For as-processed SC-221 specimens, the predominant fracture-originating flaws are pits/porosity in the as-processed surface (Figure 6).

Material assessment test results to date suggest SC-221 is a suitable combustor baffle material. Machined SC-221 fast fracture properties are comparable with the current baffle material, Carborundum Hexoloy SA (isopressed and green machined). The as-processed surface strength for SC-221 is about 10 ksi lower than for Hexoloy SA. Characterization test activity for Kyocera SC-221 is planned during 1992.

3.2 Reference Powertrain Design (RPD)

No modifications were made to the RPD during 1991.

3.3 Reference Powertrain Design Cost Analysis

The RPD Cost Analysis is scheduled for the final year of ATTAP.

3.4 Test Bed Improvements

Improvements to the AGT101 engine were developed to provide a more reliable test bed for evaluation of ATTAP ceramic components. These improvements include an impact-resistant turbine rotor, regenerator seals employing a more chemically stable and thermal-strain-tolerant coating, and a combustor with improved atomization and less tendency to coke formation. Also, redesign of structural components to accommodate the impact-resistant rotor has resulted in additional space to configure the critical sealing elements between the flow separator, turbine shroud, and transition duct. Advantage has therefore been taken to improve the design of these seals. Evaluation of a modified system to locate and support the flow separator housing has also been performed.

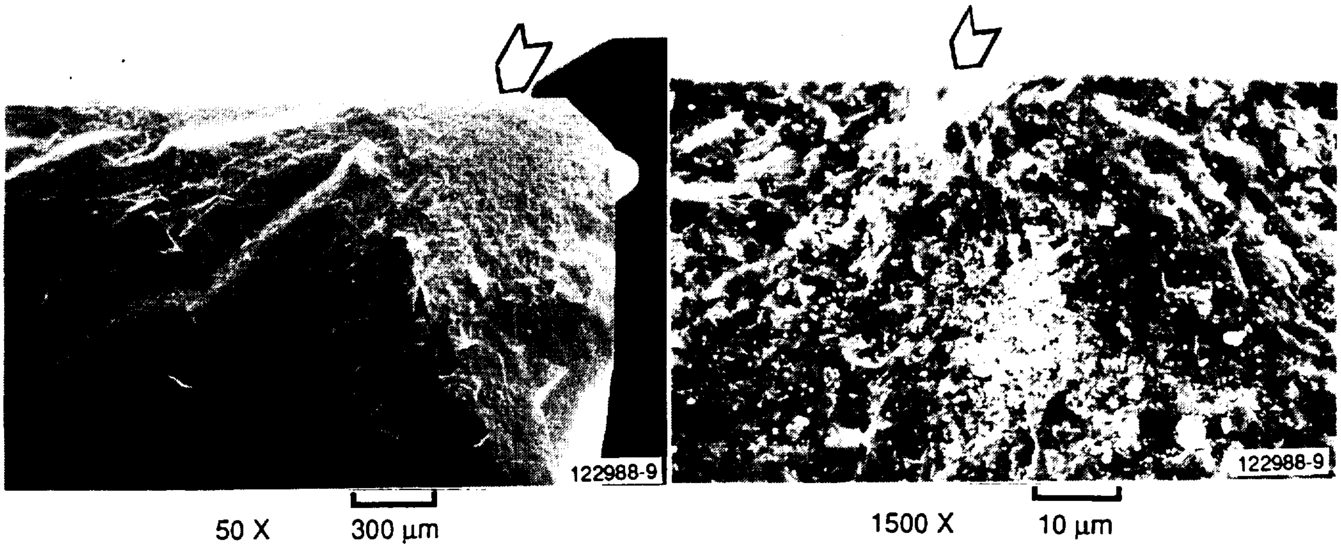

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Figure 4. Typical Fracture Surface of Kyocera SC-221 Beta SiC Test Specimen Illustrating Failure Origin at Machined Surface.

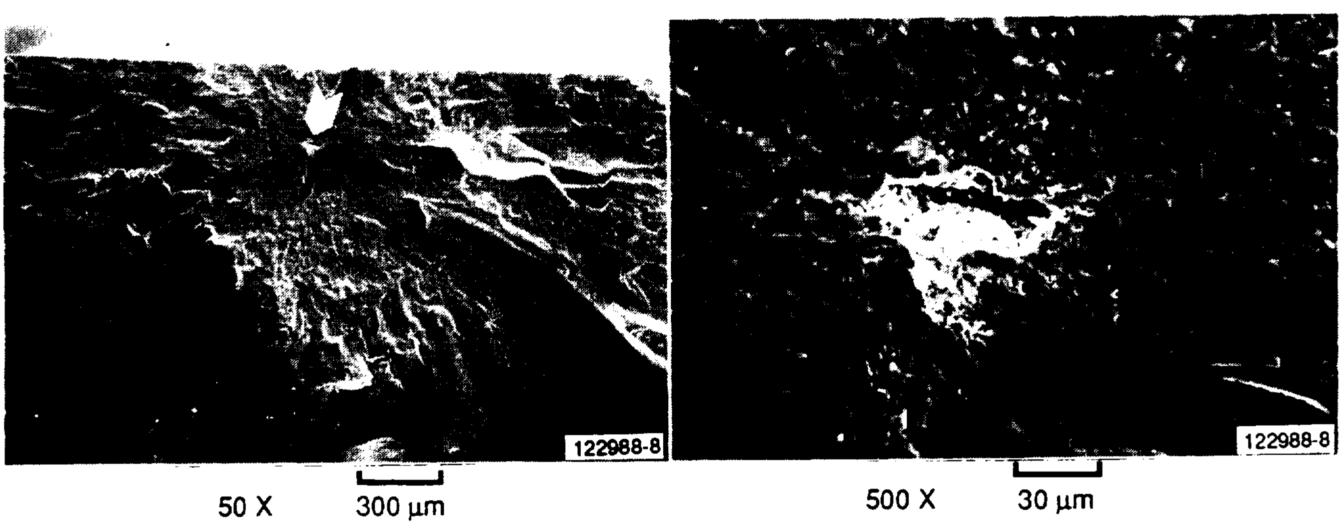

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Figure 5. Kyocera SC-221 Beta SiC Specimen Failure Originating at Internal Pore.

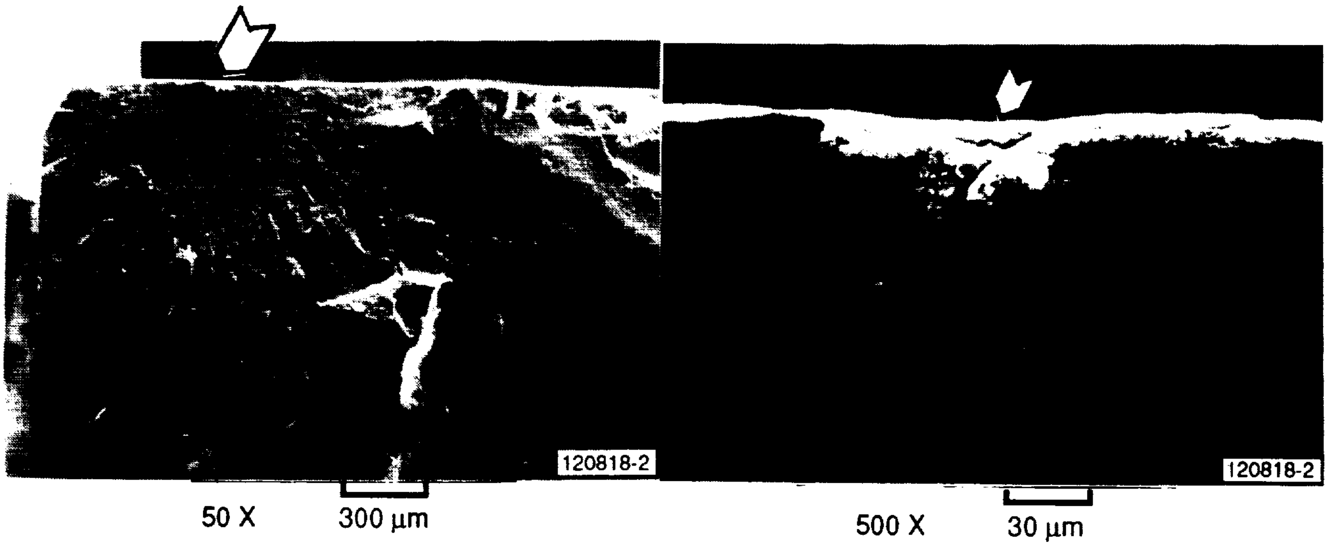

Figure 6. **Typical As-Processed Kyocera SC-221 Beta SiC Specimen Failure Originating at Surface Pit/Porosity.**

3.4.1 Regenerator Metallic Seal Development

Summary

The regenerator metallic seal coating activities underway are aimed at improving the durability of the ATTAP regenerator seal coating system. The AGT101 regenerator seal shoe consists of a Haynes 230 (nickel-based alloy) substrate with a metallic bond coating and a multilayered ceramic wearface coating (Figures 7 and 8). During 1991, evaluations of an alternate seal coating system (designated as Series 1) continued. Additionally, coating modifications aimed at improving ceramic coating thermal strain tolerance and cyclic life were evaluated.

Static Air Furnace Tests

Seal coating coupons representing the baseline and Series 1 seal coatings were heat treated in a static air furnace to evaluate dimensional stability. This study was prompted by concerns about seal swelling caused by metallic-ceramic coating interactions and bond coat oxidation. Seal coating coupons were exposed in a static air furnace for 100 hours at 1800F, the maximum regenerator inlet temperature. Thickness measurements were taken after 1, 10, and 100 hours exposure. The results are summarized in Table 1.

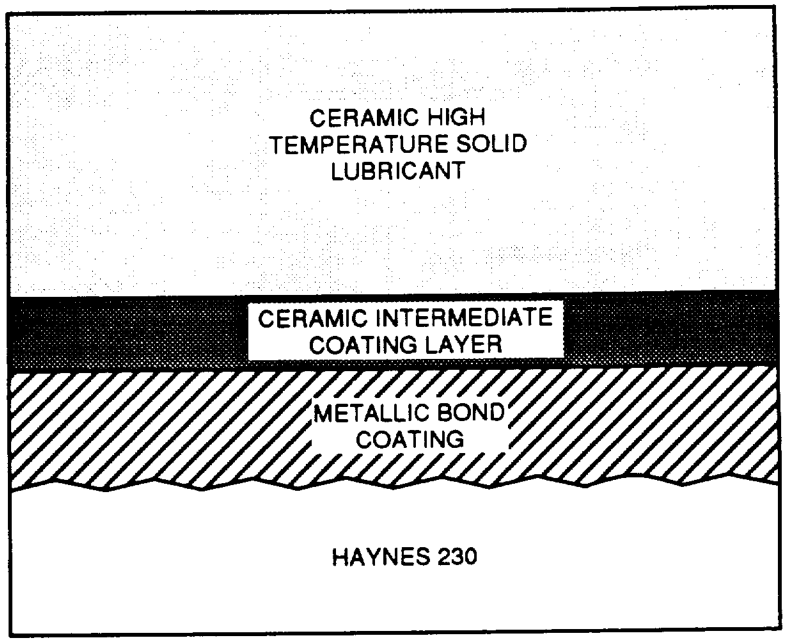

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Figure 7. Schematic of Baseline AGT101 Regenerator Hot Seal Coating.

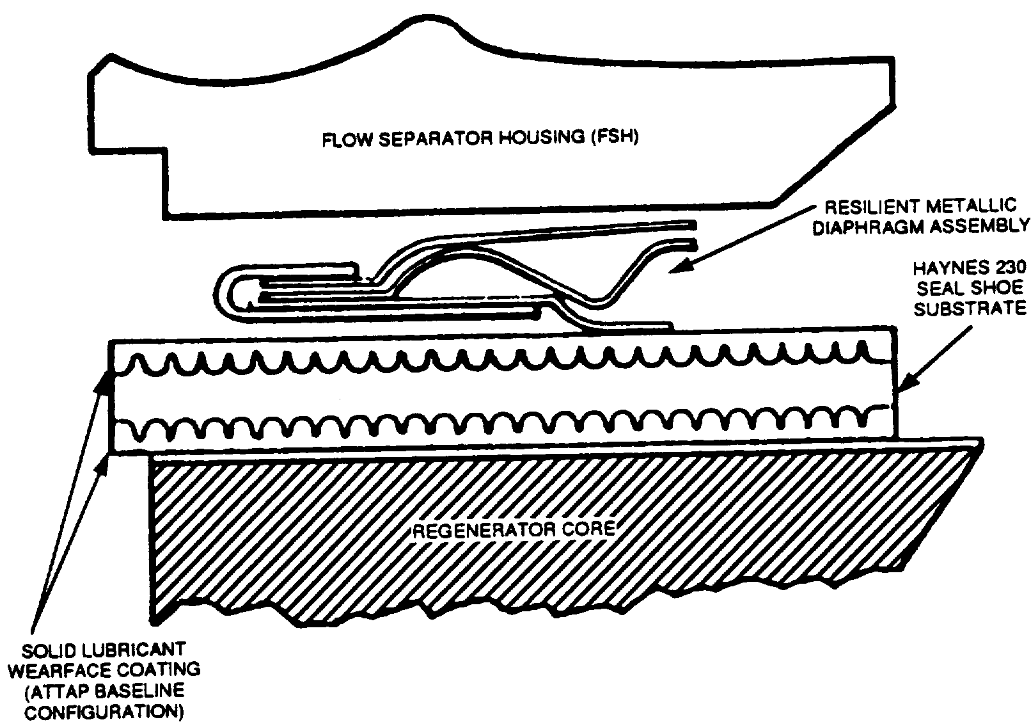

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Figure 8. Seal Coating Is Applied to Both Core and FSH Sides of the Haynes 230 Seal Shoe Substrate.

TABLE 1. THICKNESS MEASUREMENTS FOR REGENERATOR SEAL COATINGS HEAT TREATED AT 1800F IN STATIC AIR FURNACE

Coating System	Coupon Starting Thickness, in	Thickness Change, mil		
		1 Hour	10 Hours	100 Hours
Baseline	0.215	+1.7	+5.5	+18.1
Series 1	0.217	-0.4	+0.4	+1.0
1 mil = 0.001 inch				

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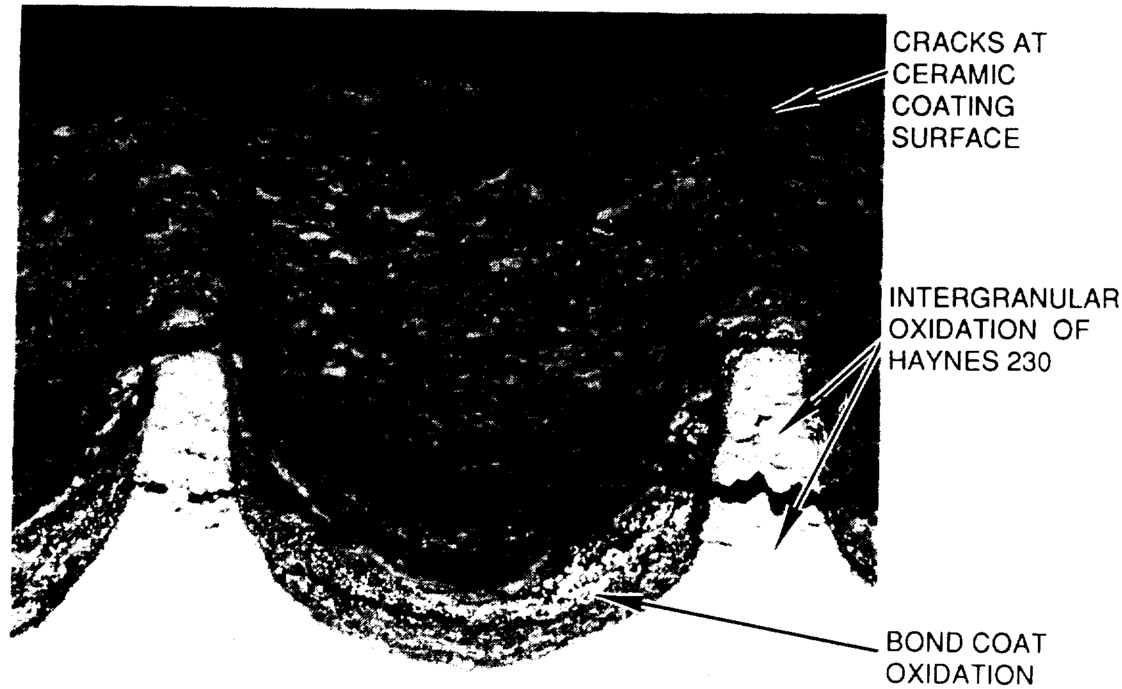
The test results indicate that the baseline system does exhibit swelling at 1800F (Figure 9). The baseline system averaged 0.018 inch (0.46 mm) increase in thickness after 100 hours exposure. This swelling may contribute to higher regenerator drive torques and accelerated seal coating wear. In contrast, the Series 1 seal coating system exhibited virtually no growth.

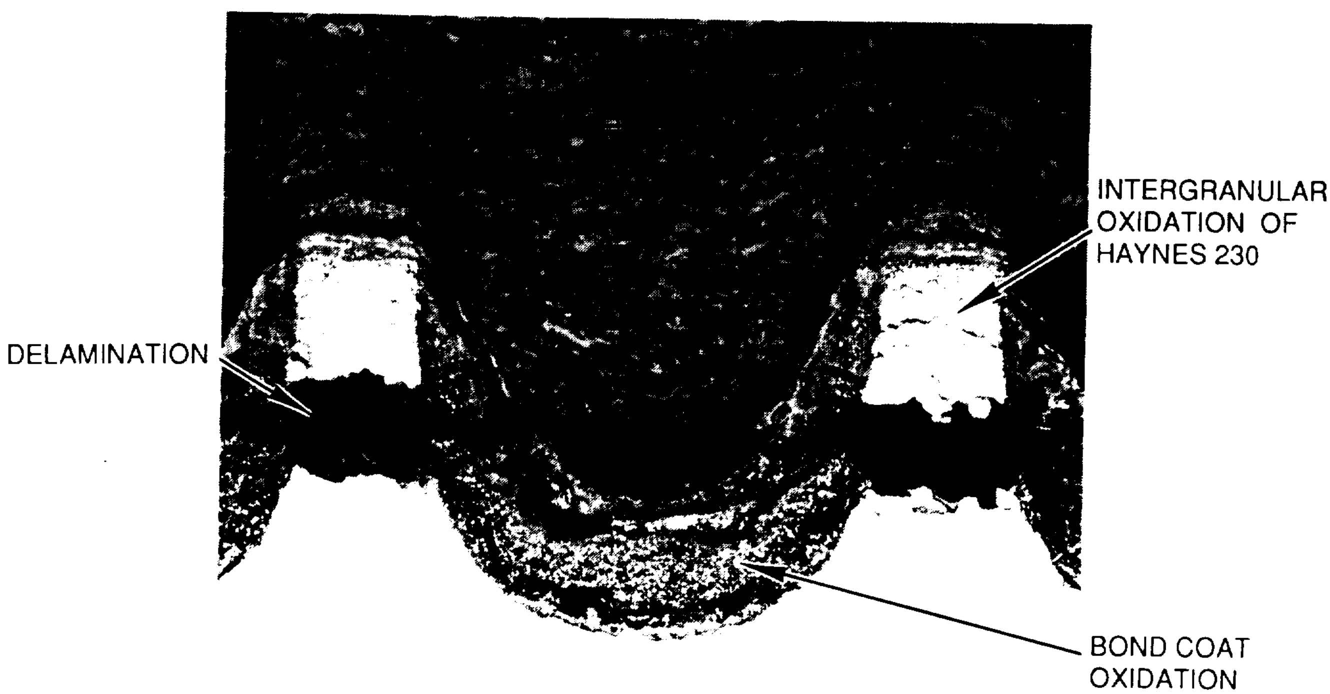
Cyclic Thermal Burner Rig Tests

Cyclic thermal burner rig tests of the baseline and Series 1 regenerator seal coating systems were performed to compare cyclic life. Additionally, coating modifications aimed at improving coating thermal strain tolerance and cyclic life were evaluated. These modifications included slotting the ceramic coating surface layer (surface segmentation) and grading the interior composition of the ceramic wearface coating (graded interlayer). The burner rig test consisted of five-minute soaks at temperature in a Jet-A fired burner exhaust with an air quench to 400F. Tests were performed using 1700F and 1800F soak temperatures. The results are summarized in Table 2.

The Series 1 seal coating system exhibited improved cyclic life compared to the baseline system in the 1700F tests. At 1800F, the cyclic life of the baseline and Series 1 coatings was poor, though the baseline coating was marginally better. The failure modes for the two coating systems also were different. Baseline coating failures resulted from reaction between the metallic bond coating and components of the ceramic coating and from bond coat oxidation. The Series 1 coating failures appeared to be mechanical (no evidence of chemical reaction).



(a) CORE SIDE (50 X MAGNIFICATION) 122988-13



(b) FSH SIDE (50 X MAGNIFICATION) 120248-11

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Figure 9. Cross Section Microstructures of (a) Regenerator Core Side and (b) FSH Side Seal Shoe Coatings After 100 Hours Exposure at 1800F RIT.

TABLE 2. REGENERATOR SEAL CYCLIC BURNER RIG TEST RESULTS

Coating Configuration	Cycles to Failure (Average)	
	1700F	1800F
Baseline	569	159
Baseline + Surface Segmentation	97	88
Series 1	865	56
Series 1 + Surface Segmentation	729	502
Series 1 + Graded Interlayer	209	135

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Surface segmentation significantly improved the cyclic life of the Series 1 coating at 1800F. For the baseline coating, surface segmentation resulted in reduced cyclic life. The coating slots appeared to accelerate metallic bond coating oxidation. The use of a graded interlayer in the Series 1 coating system provided little improvement in coating cyclic life. The failures occurred within the graded layer, suggesting poor intrinsic strength.

Evaluations planned for 1992 include testing a Series 1 coated regenerator seal shoe crossarm in the regenerator rig for comparison with the baseline regenerator seal. Although the Series 1 coating with surface segmentation performed best in the burner rig tests, regenerator rig testing will be initiated using an unsegmented Series 1 seal, because of uncertainties concerning the effects of segmentation on the tribological properties of the rubbing seal. The Series 1 coated crossarm has been fabricated and is awaiting testing.

3.4.2 Combustor Design

The main goals of the ATTAP combustor design activity in 1991 were to eliminate engine surge and to select a final combustor design for use in the AGT101 test bed engine. The cause of the AGT101 compressor surge was determined to be excessive air swirl entering the turbine nozzles. The air swirl was induced by the combustor swirler, causing the turbine nozzles to choke, producing a backpressure condition in the engine, and resulting in compressor surge. Added turbine nozzle instrumentation during the engine testing and a pretest nozzle calibration helped identify the cause of the surge phenomenon.

To eliminate the compressor surge, the combustor swirler section was modified by reducing the swirl angle from 30 degrees to zero. The modification was successfully tested on Build 52 of the metal AGT101 test bed.

There were two choices for a final combustor for use in the AGT101 metal and ceramic test bed engines: the modified (deswirled) stepped-diameter combustor (Figure 10) or the constant-diameter combustor (Figure 11). The modified stepped pilot combustor design was selected, because this combustor does not induce surge and provides easy lightoff and acceleration when coupled with the improved simplex fuel nozzle with airwipe. Figure 12 shows the improvement in lightoff range of the selected combination (simplex fuel nozzle with airwipe and modified stepped combustor), compared to the same combustor with the previous six-point fuel nozzle system.

3.4.3 Flow Separator Housing (FSH) Support

The flow separator housing (FSH) support system was successfully tested to evaluate the new rocker support system, shown in Figure 13.

For the evaluation test, an FSH and a full rocker support system were assembled in an engine configuration, as shown in Figure 14. A pressure load of 65 psig was then applied to the FSH at ambient temperature, placing a load of ≈1550 lbs on each of the three rockers located on the high-pressure side of the FSH. This rig pressure exceeds the maximum pressure load exerted on the supports in an operating engine. No damage or distortion of the FSH or support system was observed.

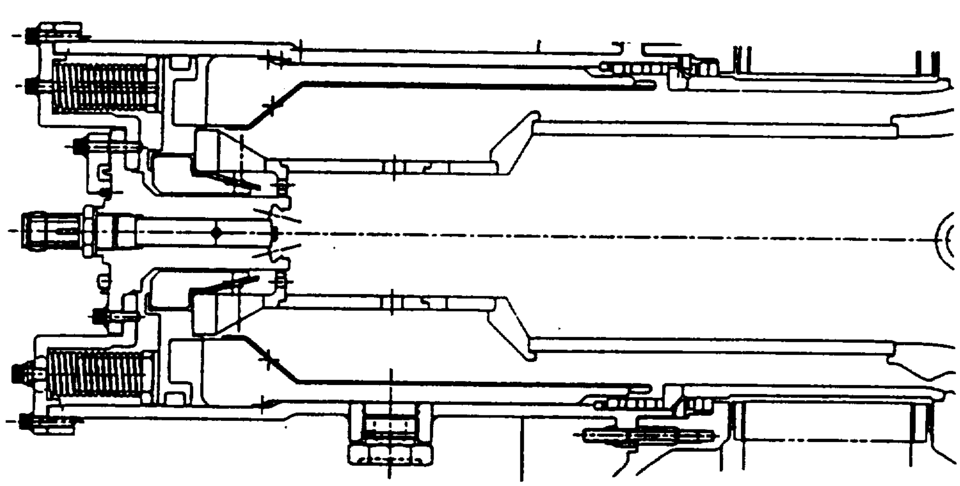

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Figure 10. Modified Deswirled Stepped Pilot Combustor Design Was Selected for Use in AGT101 Test Engines.

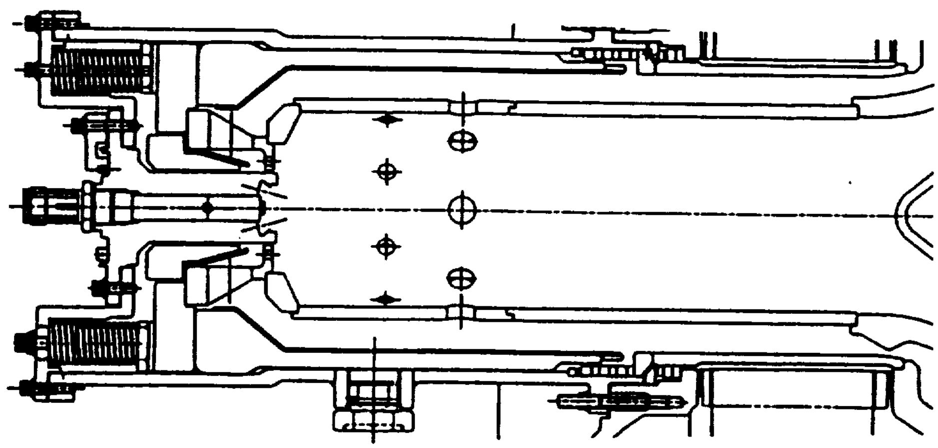

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Figure 11. Constant Diameter Pilot Combustor Design.

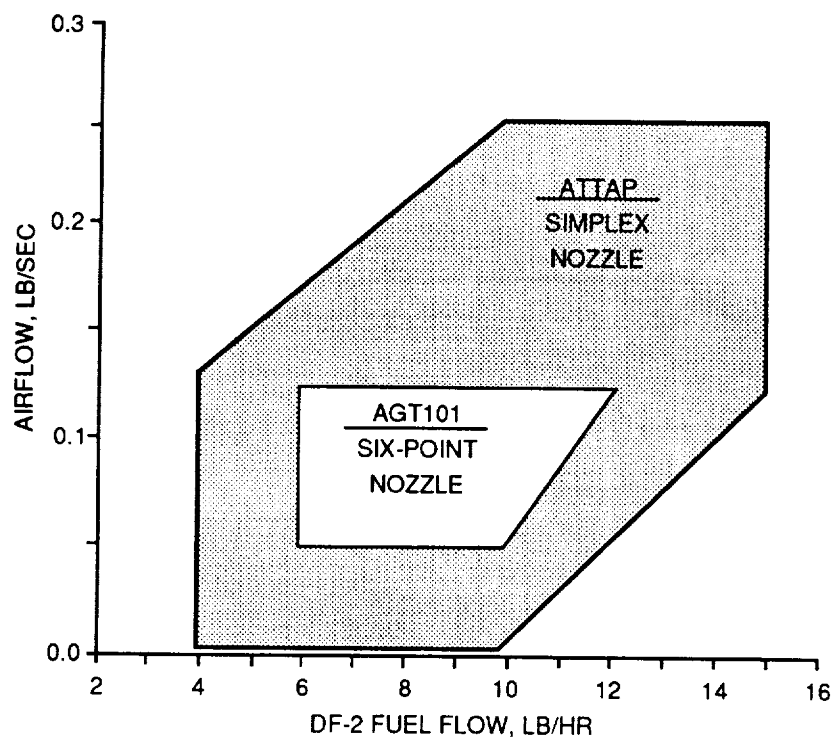

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Figure 12. Final Combustor and Fuel Nozzle Combination Selected Shows Improved Lightoff Range.

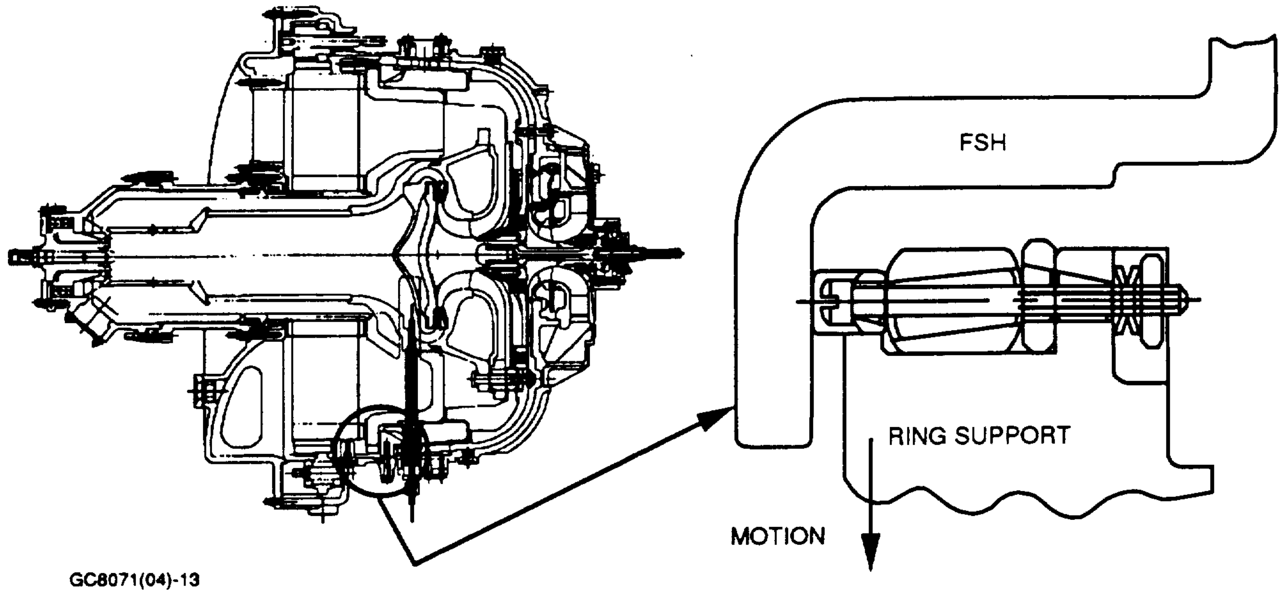

Figure 13. Redesigned FSH Support System Allows Ring Support to Thermally Expand Without FSH Damage.

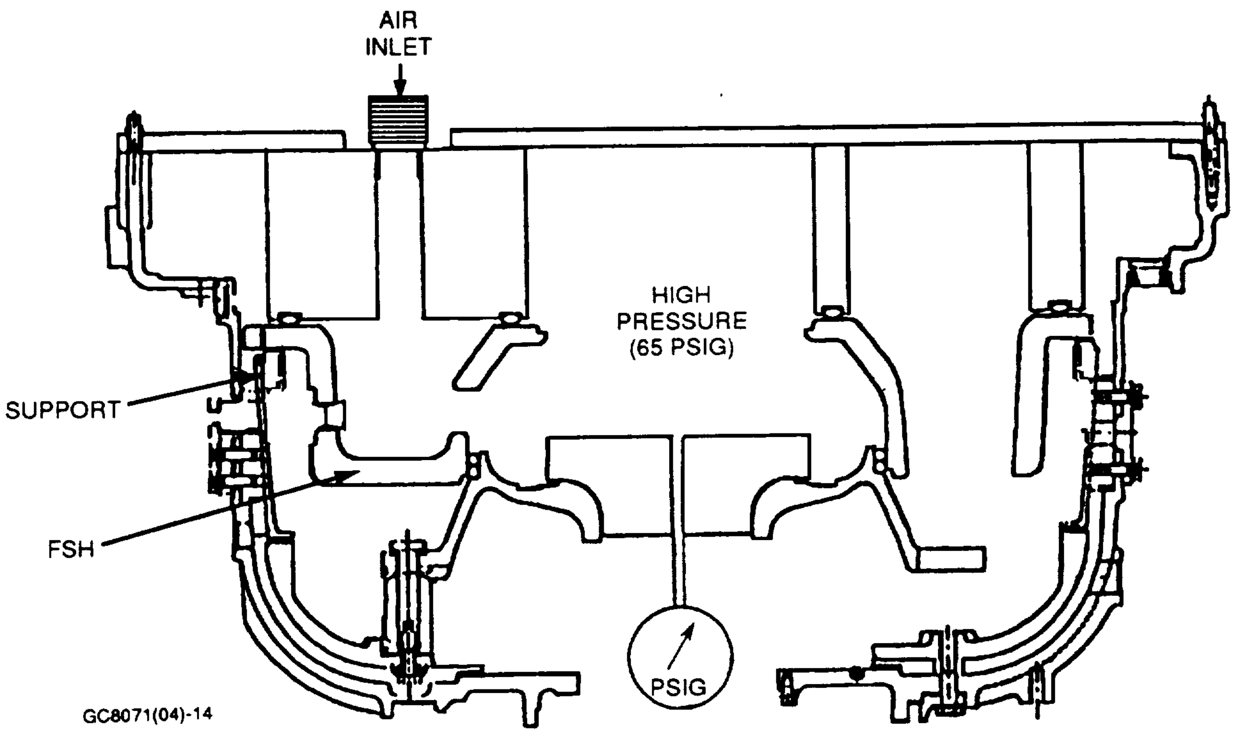

Figure 14. Multiple Support Test Rig Simulated Engine Pressure Loads on the FSH and Supports.

The next phase of testing was to place the full support system in the hot regenerator rig. This rig closely simulates engine conditions in the support area. The FSH support accumulated 52 hours of testing in the hot regenerator rig, completing the required testing prior to use of the FSH support in a ceramic engine.

During the first ATTAP ceramic engine test, the FSH support system accumulated 7.3 hours of testing. This successful engine test concluded development of the FSH support system, which is now considered standard engine hardware.

3.4.4 Spring Seal Design

An improved spring seal (Figure 15) capable of operating under very tight thermo-mechanical constraints, was designed, bench tested, and found to operate successfully in the AGT101 test bed engine. The seal blocks 1800F exhaust gasses from entering the insulation space between the compressor housing and the inner diffuser.

The existing design, which utilized a coil spring and ball (Figure 15, top), exhibited several problems: erosion of the insulation material in the space between the inner diffuser and the compressor housing, and creep of the IN750 coil springs; both resulting in excessive hot gas flow into the insulating space. Erosion debris has been found in critical parts such as the foil bearing, and creep has resulted in weakening of the spring load necessary to prevent fluttering of the ceramic inner diffuser, which is believed to be responsible for chipping of ceramic parts in contact, such as the diffuser spacers.

The improved Belleville leaf spring design (Figure 15, bottom) serves to provide acceptable loads under all temperature conditions, and reduce erosive hot gas flow by providing a better seal. Cobalt base HA-188 alloy was chosen for the spacer, due to superior behavior (high lubricity) in contact against ceramics. The spacer also serves as a radiation shield to protect the springs from the heat of the diffuser. Nickel-base Waspalloy springs ensure high creep resistance (a minimum of 100 hours at 1300F and 70 ksi). The ductile iron pilot ring is welded to the ductile iron compressor housing, for thermal matching. To prevent creep of the Waspalloy springs, the outer periphery of the spring system is insulated by a ceramic fabric (Nextel) rope.

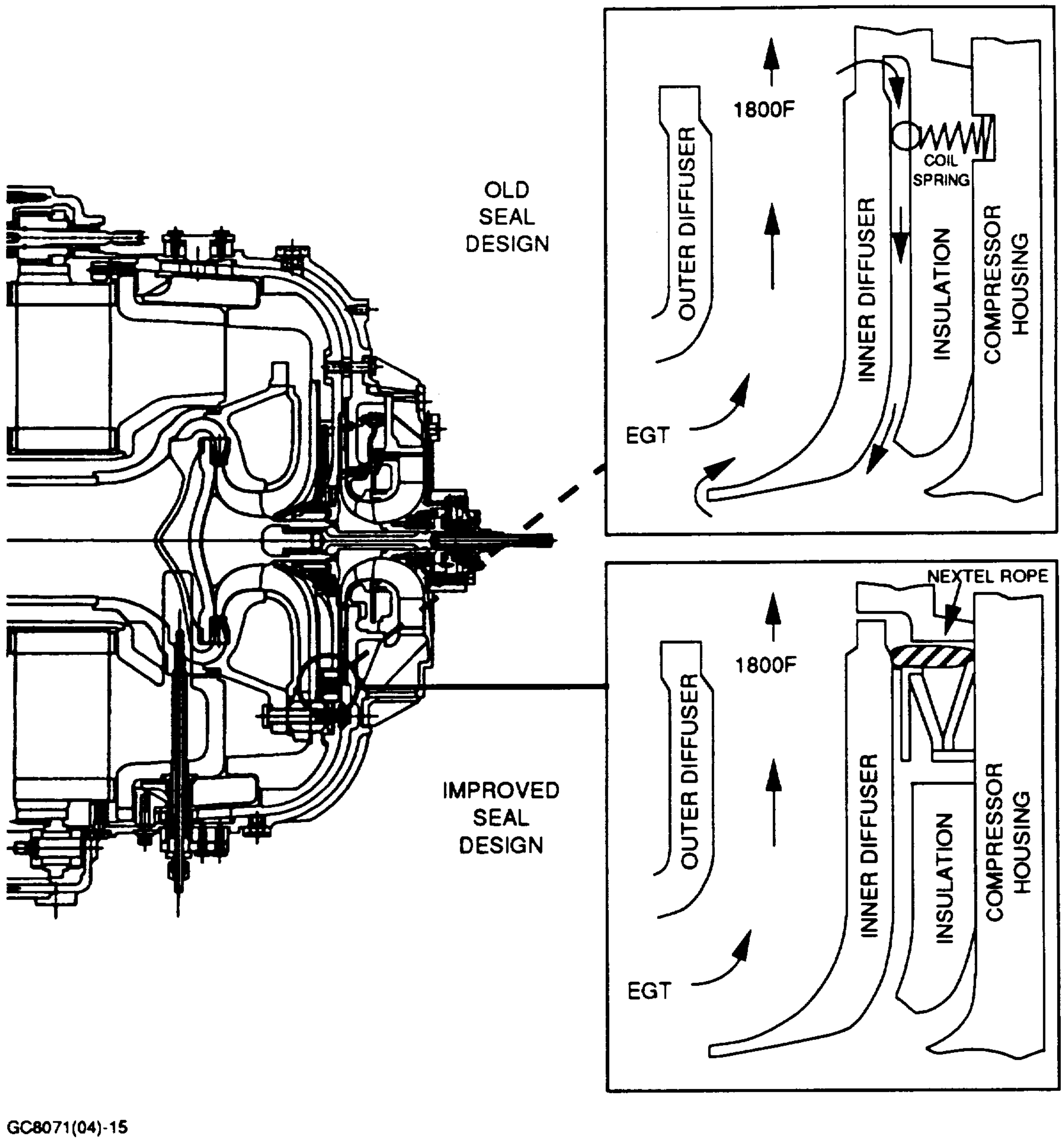

Figure 15. Existing Coil Spring Seal Design (Top) Failed to Seal Effectively. Improved Leaf Spring Seal Design (Bottom) Seals Erosive Gas Flow and Provides Sufficient Axial Load Over All Operating Conditions.

The new spring seal system must operate within a fairly narrow load range providing a minimum of 50 lbf load when cold, to prevent ceramic parts chatter during engine startup, but remaining below approximately 300 lbf load when hot, to prevent contact damage to the ceramic parts in the load path during engine operation. The new design achieves a minimum load of 50 lbf cold and a maximum load of 290 lbf hot, fulfilling the design goals, and ensuring seal integrity is maintained under all conditions. Hot gas pressure will not crack open the apex of the V-shaped spring assembly, since the design crack pressure is 11 psid, much higher than the expected gas pressure of 1 psid.

The new design was bench tested before being installed in the engine test bed. The bench test results were very encouraging, and showed good correlation with the design analysis results (Figure 16). The new system was next installed in the regenerator test rig, and then in the AGT101 test bed engine. The performance of the new spring seal design has been found to be satisfactory in all cases.

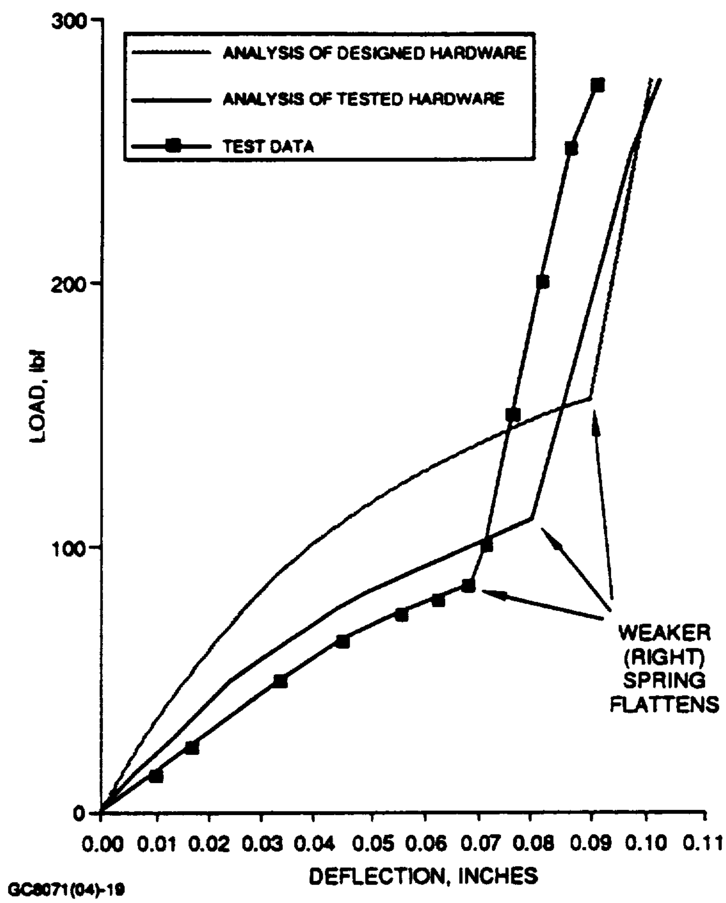

Figure 16. Spring Seal Test Data Shows Good Correlation With Analysis.

4.0 CERAMIC COMPONENT DESIGN

4.1 Design Methods for Impact Damage Resistance

Significant progress has been made in the development of design methods for predicting impact damage to ceramic components in gas turbine engines. The design methods development has been pursued in two parallel paths; modeling of local impact damage (near the point of impact), and structural impact damage (failure away from the point of impact, due to bending stresses). The impact methods development work has been performed in collaboration with the University of Dayton Research Institute (UDRI).

In 1991, the overall approach was modified to place more emphasis on structural impact damage methods development. Two main activities were ongoing: the first was continuation of iterative impact damage resistance analyses, to arrive at an impact-resistant ceramic turbine wheel configuration having the potential for substantially improved impact tolerance. The second activity was a ceramic specimen impact test program, designed to study the mechanisms of structural impact damage and to identify the important parameters affecting ceramic structural impact damage resistance. An additional study of the effects of carbon particle pulverization during impact was also conducted.

4.1.1 Local Impact Damage Model

During the first half of 1991, the efforts in local impact model development focused on a scheme to determine the material constants for use in the model. The most important material constants were determined to be: initial microcrack size, number of flaws per unit volume, and crack propagation rate under compression. The local impact model developed with the two-dimensional computer code (EPIC-2D) was successfully converted to a three-dimensional version (EPIC-3D). UDRI completed a technical report detailing this work, and the computer codes were delivered and installed on the GAPD computer system.

4.1.2 Structural Impact Damage Model

In the course of the two-phase Taguchi study conducted during 1990, it was established that the most sensitive parameters affecting ceramic turbine blade impact resistance were blade thickness, blade inlet (beta) angle, and fillet radius (Figure 17). The interaction between these parameters was found to be negligible, in terms of impact resistance. Based on this knowledge and taking into account aerodynamic considerations, twelve additional ceramic turbine blade configurations were analyzed for impact resistance.

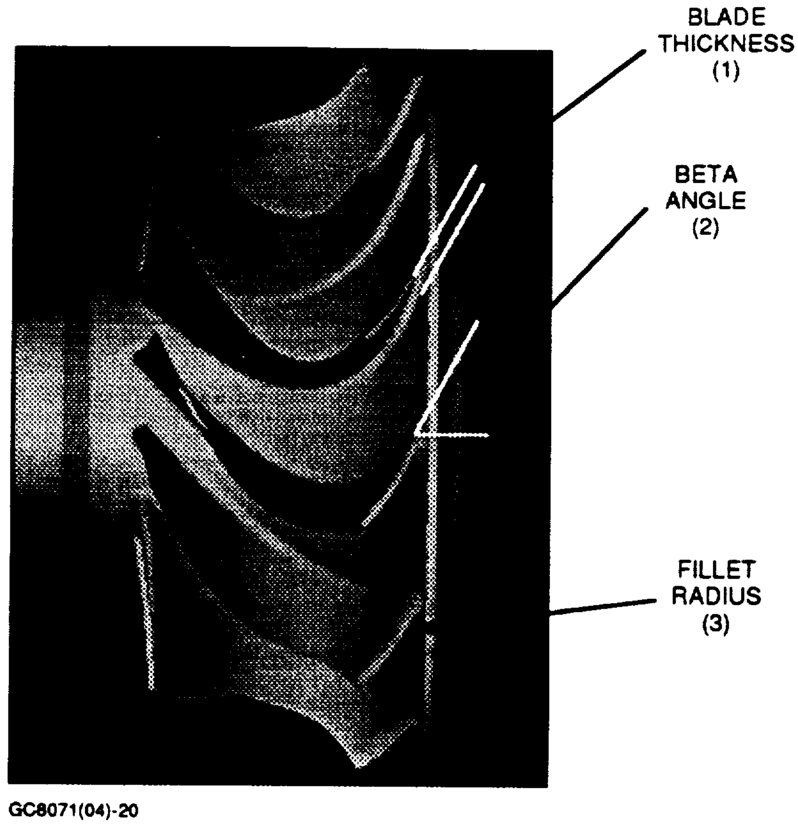

Figure 17. Three Ceramic Blade Design Parameters Were Found to Have the Greatest Influence on Impact Resistance.

The results of the analyses are plotted in Figure 18. The blade with a leading edge thickness of 0.15 inch and 61 degrees inlet beta angle had a maximum impact stress of 160 ksi when impacted with a 0.1 inch graphite ball at full tip speed (1850 ft/sec). The maximum impact stress value for the best configuration is approximately 39 percent of the value for the current impact-resistant blade. This decrease in impact stress represents a substantial improvement in turbine blade impact resistance.

It is important to note that the impact stress values shown in Figure 18 are higher than the values expected in an operating engine. This is because the graphite particles modeled in the analyses were assumed to remain elastic, regardless of the very high stress level, due to a lack of capability to simulate the graphite pulverization that would occur during an actual impact. Experimental evidence shows that graphite projectiles of 0.1 inch diameter pulverize at approximately 300 ft/sec impact velocity. By giving the projectile infinite strength in the analyses, the predicted impact stress in the target blade must be artificially higher than the actual impact stress. This problem will be discussed in greater detail later in this section.

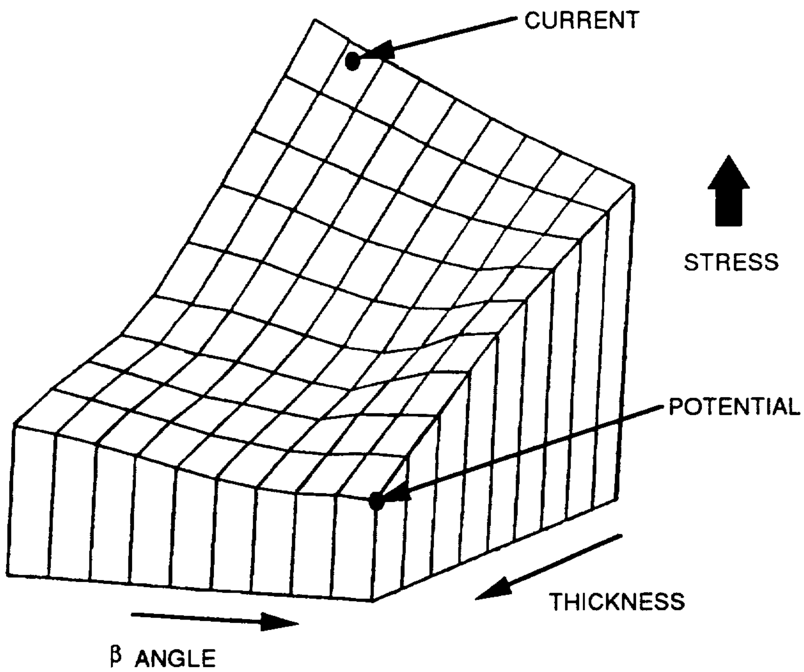

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Figure 18. Impact Analyses Identified a Blade Design With 60 Percent Less Impact Stress.

Two ceramic blade subelements were designed for impact testing. One is based on the current AGT101 impact-resistant engine configuration, and the other configuration is based on the results of the impact analyses (Figure 19). Fifteen test articles of each configuration were fabricated by Norton/TRW Ceramics, and are undergoing dimensional and surface integrity inspections by GAPD. Particle impact tests will be conducted on these subelements using 0.1 and 0.2 inch diameter graphite spheres. The tests are intended to verify the impact analyses.

To evaluate the effects of structural variables on impact resistance, a particle impact test program was conducted at UDRI. The test variables are given in Table 3. The test specimens were machined at GAPD from SN-84 sintered silicon nitride plates (Figure 20). A tapered shape was selected for the test specimens, to avoid failure at the grip area and to emulate the shape of actual turbine blades. The baseline test setup is shown in Figure 21.

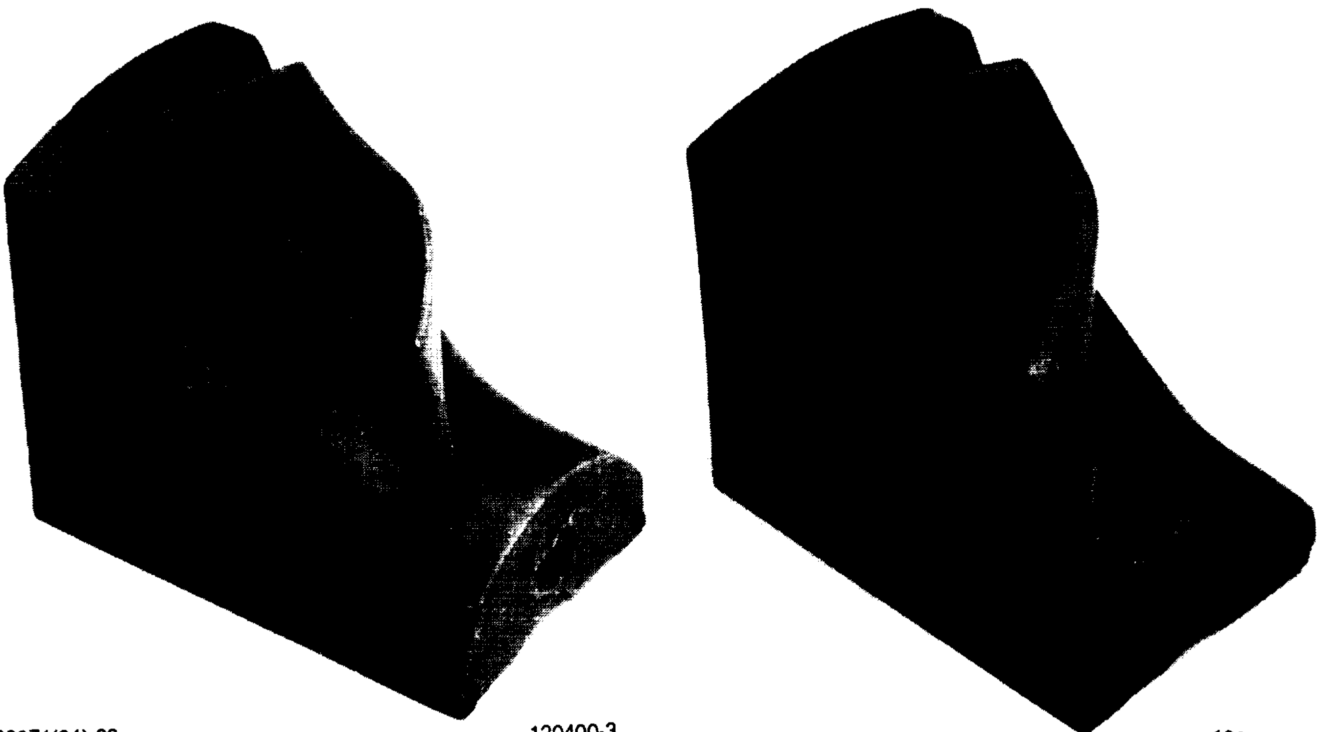

Figure 19. Ceramic Blade Subelements Were Designed and Fabricated for Verification Impact Tests.

TABLE 3. STRUCTURAL IMPACT TEST MATRIX AND RESULTS

Variable	Unit	Range
Thickness at tip	inch	0.050 – 0.075
Fillet radius (Figure 20)	inch	0.00 – 0.50
Taper angle (see Figure 21)	Deg	1.0 – 1.6
Overhang (Figure 21)	Inch	0.90 – 1.75
Impact location (Figure 21)	Inch	0.175 – 0.875
Ball material	--	Graphite or Si_3N_4
Impact angle	Deg	90 – 45
Surface machining	--	Longitudinal or Transverse
Curvature	--	Yes or No
Temperature	F	75 or 2300

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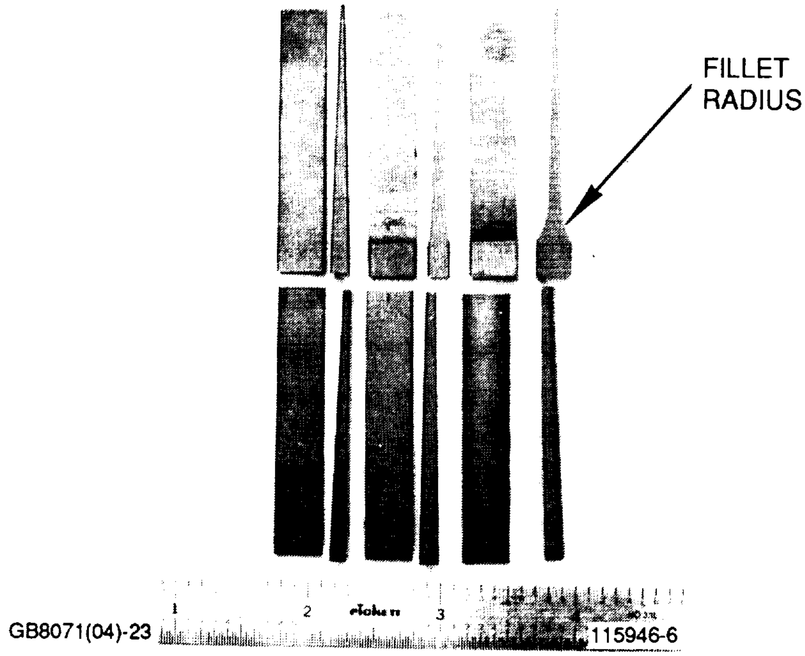

Figure 20. **Tapered SN-84 Silicon Nitride Test Specimens Were Used in Impact Tests to Evaluate Structural Impact Resistance.**

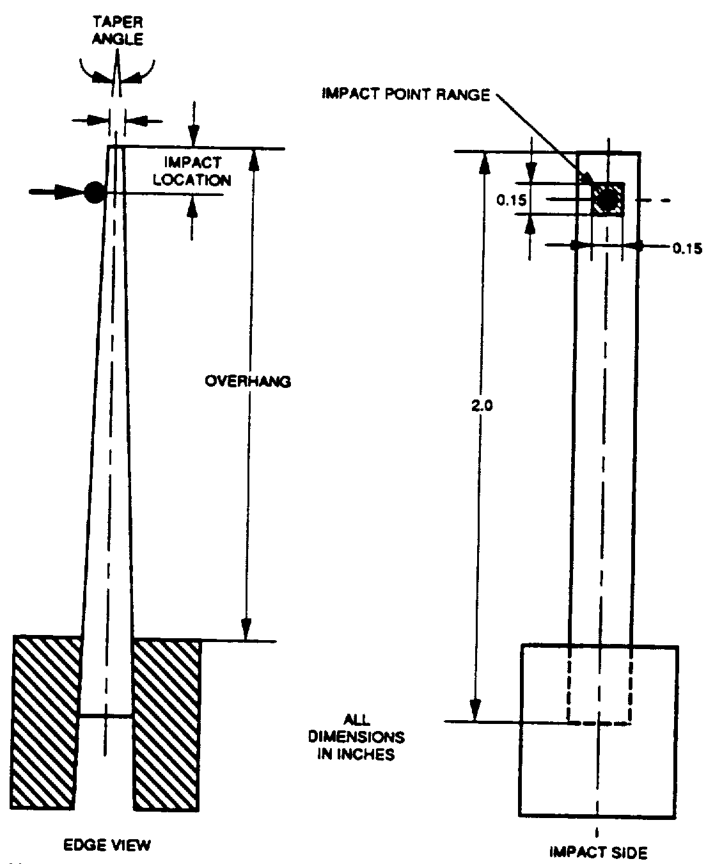

Figure 21. **Baseline Test Setup Used to Simulate Turbine Blade Impact.**

Approximately 10 specimens were tested in each of 17 groups. Each specimen was impacted by a given projectile type and size, beginning at a relatively low impact velocity, and continuing with projectiles of the same type at increasing velocities, until failure occurred. Without exception, failure resulted in total specimen fracture. The next specimen in the same group was then tested at an impact velocity slightly lower than the critical failure velocity for the first specimen, and smaller increments in velocity were used, again increasing the impact velocity until fracture occurred. The critical impact velocity at which structural failure occurred was calculated by averaging the readings for all specimens in each group.

Bending strain was recorded with strain gages at selected locations on specimens with varying overhang during the impact tests. The strain values (obtained as a function of time) were compared with strain values predicted by the computer impact simulations. The peak strain values recorded from elastic impacts (in which the graphite projectiles did not fracture) show close agreement with the analytical predictions. However, for impact velocities above the critical value at which the graphite projectiles pulverize, the predicted strain values are increasingly higher than the peak values actually recorded in the impact tests (Figure 22). In the computer simulations, the graphite projectiles are treated as elastic bodies, whereas in the actual tests above the critical velocity, the graphite projectiles pulverize. Until the pulverization process can be accurately modeled, an empirical factor will be calculated to correct the predicted impact stress values (Figure 22).

In all previous impact tests conducted under ATTAP, graphite spheres have been used as projectiles, assuming the mechanical properties of graphite were similar to combustor carbon (the major source of turbine blade impact damage during actual engine operation). To test this assumption, eleven combustor carbon spheres of two diameters (six 0.1 inch and five 0.2 inch) were used in impact tests on SN-84 silicon nitride test specimens to determine if the same impact force occurred compared to graphite spheres at a given velocity. The targets were instrumented with strain gages to measure the peak bending strain, as an indication of the impact force.

The results of the carbon projectile impact tests showed that lower impact forces were measured with the combustor carbon projectiles than for graphite projectiles at the same impact velocity. Therefore, conclusions drawn from the graphite projectile impact test data should be considered as conservative, with respect to actual engine impact damage effects expected from combustor carbon.

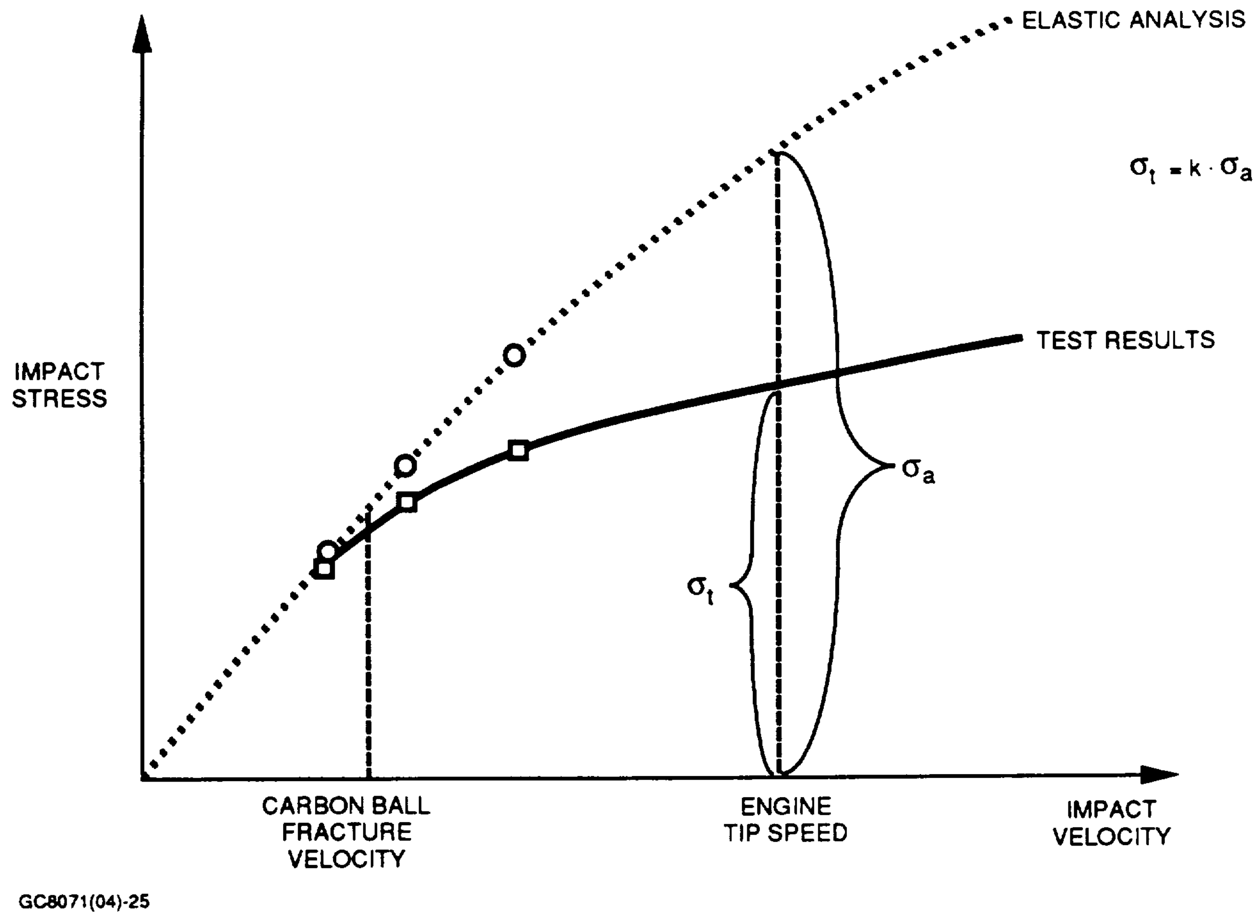

Figure 22. A Correction Factor for Graphite Pulverization Was Determined.

4.2 Ceramic Components Analysis

In the fall of 1991, three-dimensional stress analyses of the impact-resistant turbine rotor were initiated, in preparation for the 100-hour (Milestone 5) and 300-hour durability (Milestone 6) testing. At the close of the reporting period, the analysis work was still underway.

5.0 MATERIALS CHARACTERIZATION AND CERAMIC COMPONENT FABRICATION

5.1 Materials Characterization

5.1.1 Property Measurements

Flexural strength and stress rupture tests performed during 1991 used test specimens and support spans in accordance with American Society for Testing and Materials (ASTM) Specification C1161, Configuration B. The nominal test parameters are listed in Table 4.

TABLE 4. FLEXURAL STRENGTH AND STRESS RUPTURE TEST PARAMETERS

Specimen Dimensions:	Width =	4 mm	(0.157 in)
	Thickness =	3 mm	(0.118 in)
	Length =	50 mm	(2.0 in)
Support Spans:	Inner =	20 mm	(0.787 in)
	Outer =	40 mm	(1.574 in)
Displacement Rate:		0.5 mm/min	(0.02 in/min)

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Some strength evaluations included specimens with the test surface left in the as-processed condition. The purpose of these tests was to identify differences in strength compared to machined properties, since flowpath surfaces of the AGT101 ceramic components are typically as-processed; when possible, component machining is limited to mating surfaces with tight tolerances. The as-processed surface strength data is important for reliability analyses of components with highly stressed, as-processed surfaces.

Flexural testing was performed at room and elevated temperatures. All elevated temperature tests were conducted in a static air furnace environment.

Flexural strength testing was also performed using test specimens with a larger cross-section. The purpose of these tests was to evaluate the effect of a larger volume on strength, and to generate a more accurate assessment of volume strength properties than provided by the smaller ASTM C1161, Configuration B specimen. These "large bar" flexural tests were conducted at room temperature only. The test parameters are listed in Table 5.

TABLE 5. LARGE BAR FLEXURAL STRENGTH TEST PARAMETERS

Specimen Dimensions:	Width =	6.4 mm	(0.25 in)
	Thickness =	12.7 mm	(0.50 in)
	Length =	102.0 mm	(4.00 in)
Support Spans:	Inner =	44.5 mm	(1.75 in)
	Outer =	89.0 mm	(3.50 in)
Displacement Rate:		0.5 mm/min	(0.02 in/min)

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The Weibull modulus for analysis of four-point flexural strength data was calculated for sample sizes of 20 and greater using a "Lotus 1-2-3" spreadsheet developed by Professor M. Ferber of the University of Illinois. The reported Weibull values were calculated using the maximum likelihood method.

The fracture surfaces of all specimens were visually examined at 40X magnification to identify the fracture origin locations. Selected specimens were evaluated further using scanning electron microscopy (SEM) to document typical fracture-originating flaw types.

5.1.1.1 Norton/TRW NT154 Silicon Nitride Material Characterization

Flexural strength testing of Norton/TRW NT154 silicon nitride (Si_3N_4) with as-processed surfaces was performed. This test material was produced using the same fabrication process used for 1991 NT154 rotor and stator deliveries. The flexural strength and fractography results are summarized in Table 6. The strength data is plotted as a function of temperature in Figure 23.

At room temperature, NT154 average strength was 71.5 ksi, with a Weibull modulus of 8.0. The room temperature strength is low compared to NT154 machined strength properties, which typically average better than 120 ksi. The as-processed surface strength approaches machined NT154 strength with increasing temperature. As-processed NT154 increased in strength to approximately 80 ksi average at 2200F and 2500F. At 2500F, the as-processed surface strength is equivalent to machined surface strength for NT154.

TABLE 6. NORTON/TRW NT154 AS-PROCESSED SILICON NITRIDE FLEXURAL STRENGTH TEST RESULTS

Material:	NT154 Silicon Nitride			Date Received:		April 1991
Condition:	As-Processed					
Test:	4-Point Flexure			Test Specimen:		4 x 3 mm
				Test Spans:		40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent* Surface Fractures	Percent* Internal Fractures	Predominant Fracture Origins
Room Temperature	71.5	30	8.0	100	0	Surface: Pits Internal: Fe Inclusions
1800	69.5	10	--	100	0	
2200	81.1	10	--	100	0	
2500	80.1	10	--	80	20	

*Origins do not total 100 percent in all instances, since some were damaged or missing.

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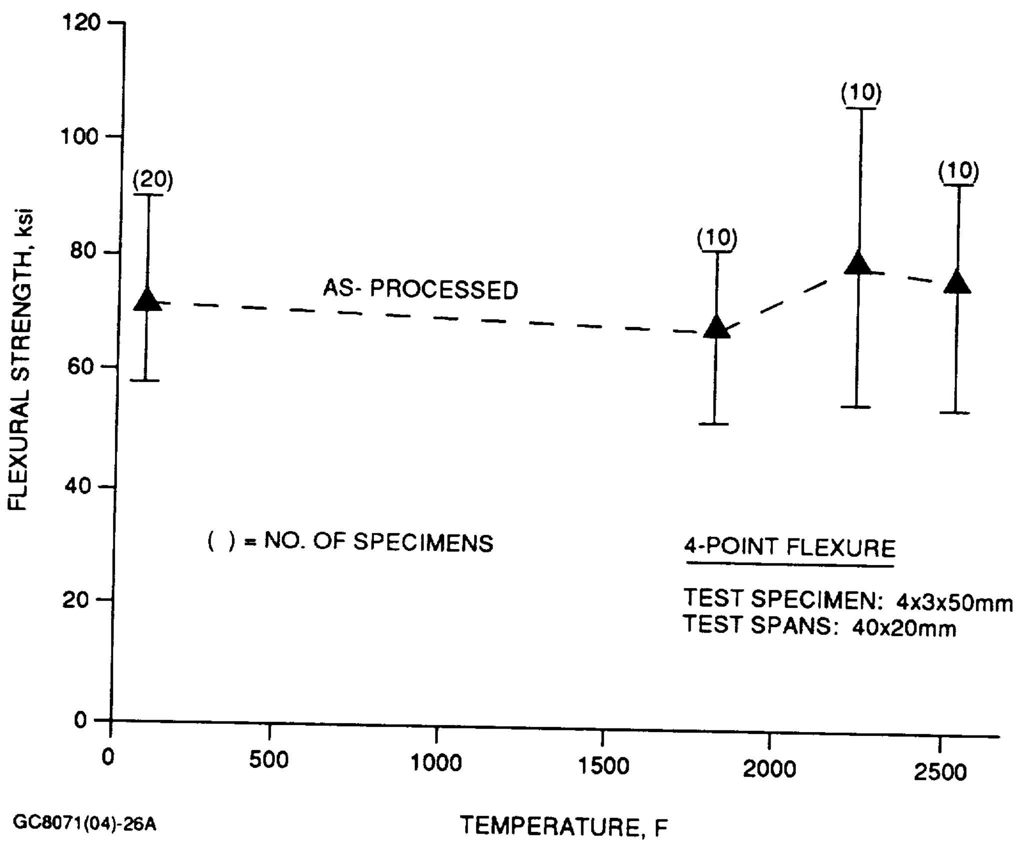

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Figure 23. NT154 As-Processed Surface Strength (Using Current Norton/TRW ATTAP Rotor and Stator Fabrication Process).

All observed specimen failures for tests between room temperature and 2200F originated from the as-processed surface. The dominant fracture-originating flaws were pits in the as-processed surface (Figure 24). At 2500F, a few internal failures originating from iron-based inclusions were noted.

5.1.1.2 Norton/TRW NT230 Siliconized Silicon Carbide Material Characterization

The flexural strength of Norton/TRW NT230 siliconized silicon carbide (Si-SiC) was measured. Testing included "B-sized" specimens with machined and as-processed test surfaces, and large flexure bars. Flexural stress rupture testing of machined and as-processed specimens is in progress.

Flexural strength test results for machined and as-processed NT-230 Si-SiC are summarized in Tables 7 and 8, respectively. The machined and as-processed surface strength properties are plotted as a function of temperature in Figure 25. At room temperature, the machined NT230 specimen strength averaged 55.3 ksi with a Weibull modulus of 10.6. The as-processed NT230 strength was approximately 40 percent lower than machined NT230. As-processed NT230 strength averaged 33.9 ksi, with a Weibull modulus of 12.1. NT230 exhibited slightly higher average strength at elevated temperatures. The average flexural strength for machined and as-processed NT230 increased to 68.5 ksi and 41.0 ksi, respectively, at 2500F.

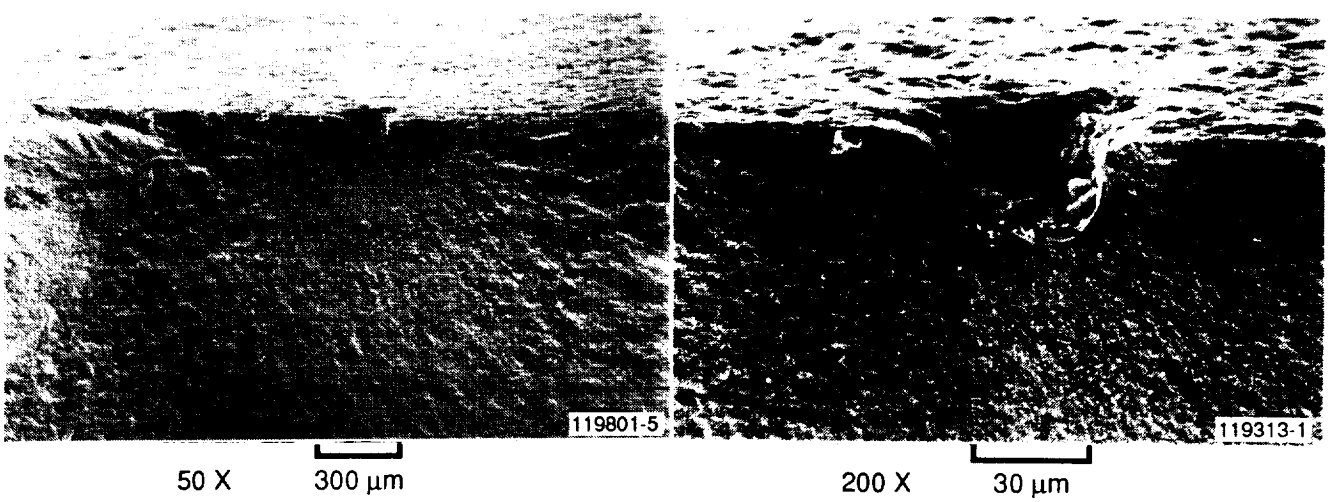

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Figure 24. As-Processed NT154 Specimen Failure Originating From Surface Pit.

TABLE 7. NORTON/TRW NT230 SILICONIZED SiC MACHINED SURFACE FLEXURAL STRENGTH TEST RESULTS

Material: NT-230 Si-SiC — **Date Received**: 05-91
Condition: Machined
Test: 4-Point Flexure — Test Specimen: 4 x 3 mm
Test Spans: 40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent* Surface Fractures	Percent* Internal Fractures	Predominant Fracture Origins
Room Temperature	55.3	30	10.6	73	20	**Surface** Pores, porous regions, and pores inside pockets of silicon **Internal** Pores, porous regions, and pores inside pockets of silicon
1400	59.6	10	--	60	40	
1800	61.5	9	--	78	22	
2000	64.3	10	--	60	40	
2200	63.9	30	14.7	70	27	
2300	61.6	10	--	70	30	
2400	63.8	10	--	70	30	
2500	68.5	10	--	90	10	

*Origins do not total 100 percent in all instances, since some were damaged or missing.

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TABLE 8. NORTON/TRW NT230 SILICONIZED SiC AS-PROCESSED SURFACE FLEXURAL STRENGTH TEST RESULTS

Material: NT-230 Si-SiC — **Date Received**: 05-91
Condition: As-Processed
Test: 4-Point Flexure — Test Specimen: 4 x 3 mm
Test Spans: 40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent Surface Fractures	Percent Internal Fractures	Predominant Fracture Origins
Room Temperature	33.9	19	12.1	100	0	Surface – Minor microstructural anomalies
1800	36.7	10	--	100	0	
2200	38.2	10	--	100	0	
2500	41.0	10	--	100	0	

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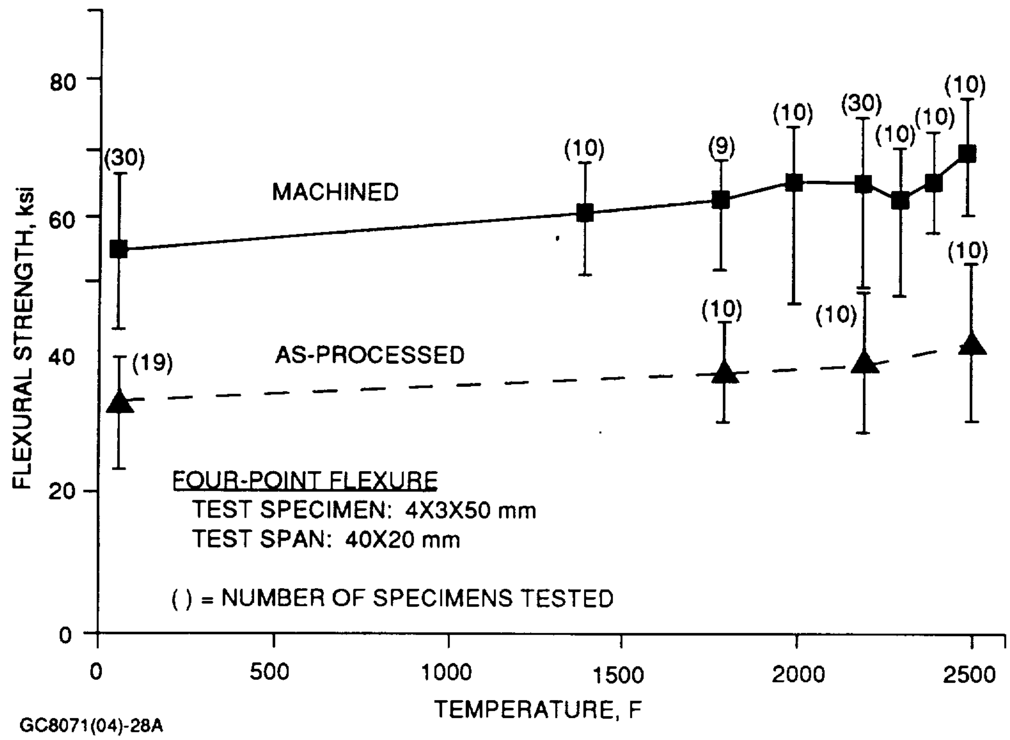

Figure 25. Norton/TRW NT230 Si-SiC As-Processed Surface Strength Is 40 Percent Lower Than Machined Surface Strength.

Machined NT230 specimen failures originated primarily from the surface. Some of the surface failures originated at sites with fluorescent penetrant inspection (FPI) indications. Noteworthy quantities of internal failure origins were also observed. For both surface and internal failure origins, the dominant fracture-originating flaws were pores and porous areas. In many instances, the pores were associated with pockets of silicon. Typical failure origins for machined NT230 are shown in Figures 26 and 27.

For as-processed NT230, all specimen failures originated from the as-processed surface. The fracture-originating flaws appear to be minor microstructure inhomogenieties at the as-processed surface (Figure 28), and are not sufficient to explain the 40-percent lower strength compared to machined NT230. If the reduced as-processed strength for NT230 is a residual stress effect, Norton/TRW annealing studies currently in progress may provide some strength recovery.

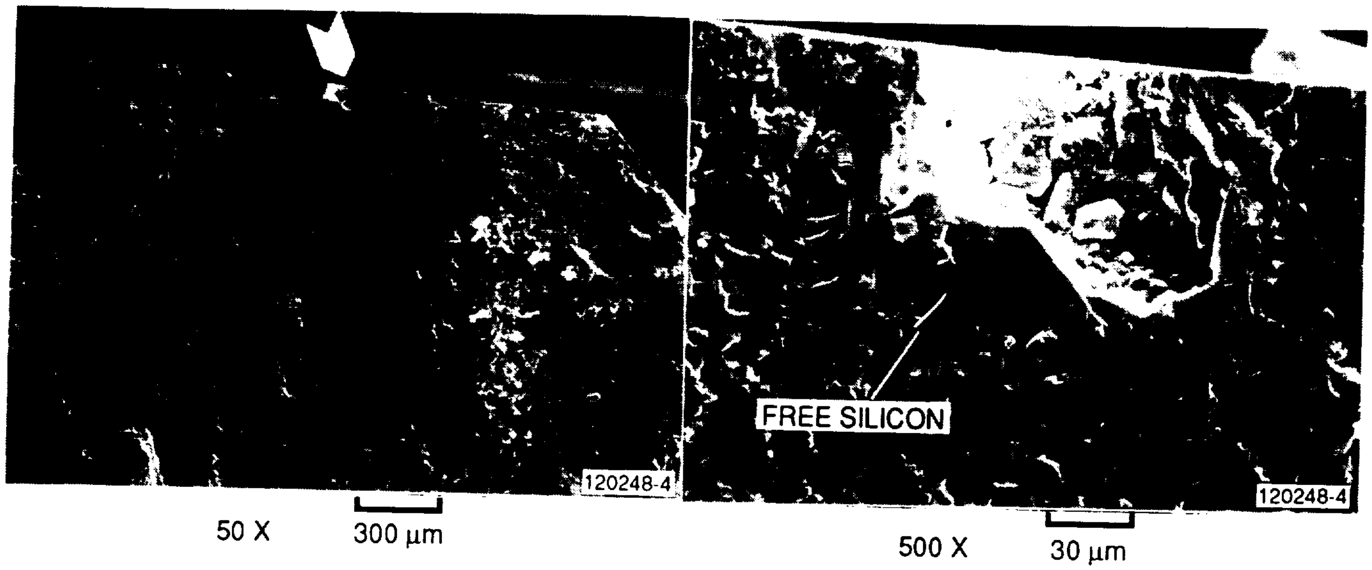

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Figure 26. NT230 Specimen Failure Originating at Surface Pore.

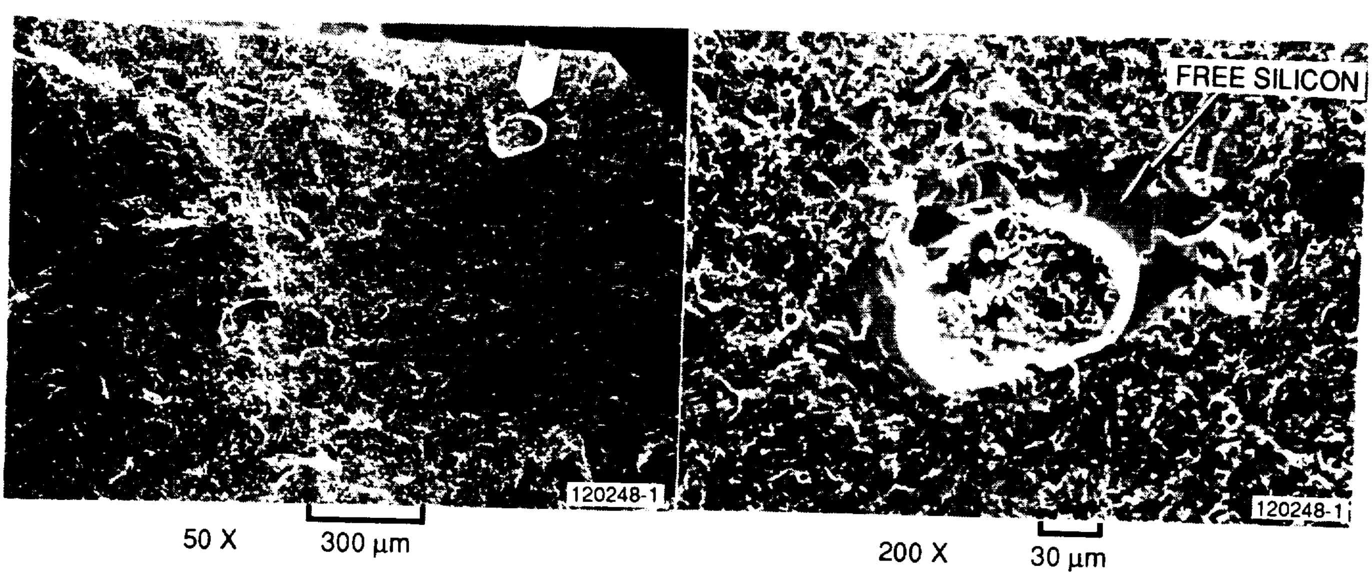

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Figure 27. NT230 Specimen Failure Originating at Internal Pore.

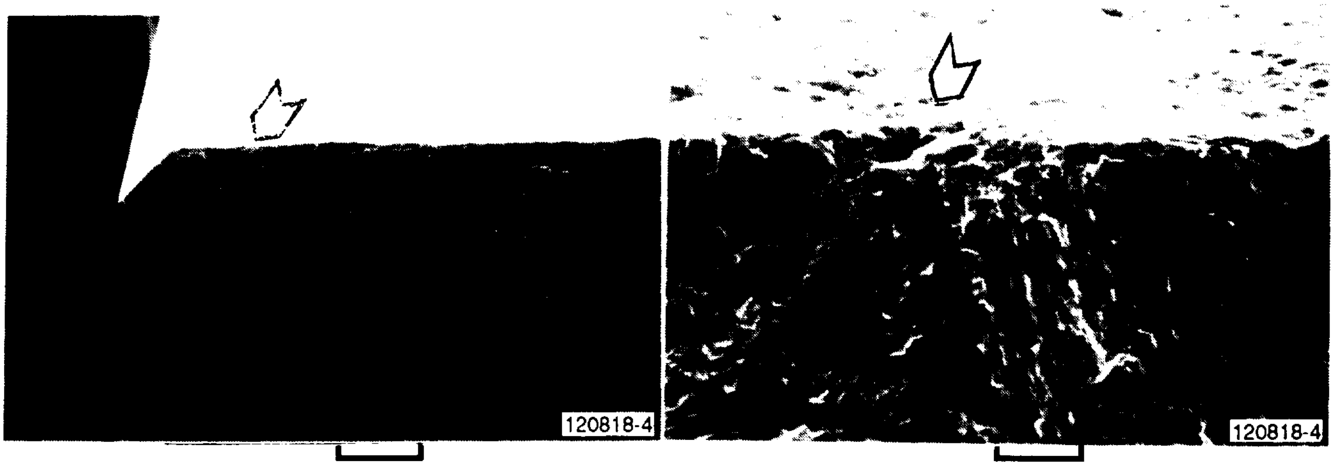

Figure 28. NT230 Specimen Failure Origin at As-Processed Surface Microstructure Anomaly.

Strength testing performed using large cross-section NT230 flexure bars successfully generated volume property data: 53 percent of the large specimens exhibited volume failures, compared to 20 percent for the smaller specimens. The fracture-originating flaws were the same as discussed above for the machined "B-size" specimens. The average strength for specimens with volume failure origins is 52.9 ksi, with a Weibull modulus of 12.3. The total average strength and Weibull modulus for all 30 large cross-section specimens was 50.3 ksi and 8.7, respectively.

5.1.1.3 NGK SN-88 Silicon Nitride Material Characterization

Flexural strength testing of machined NGK SN-88 specimens was performed. The results are summarized in Table 9. The flexural strength is plotted as a function of temperature in Figure 29. At room temperature, the average flexural strength was 114.2 ksi. SN-88 exhibited good strength retention at elevated temperature. The average flexural strength dropped gradually as a function of temperature to 91.8 ksi at 2400F, then exhibited some recovery to 102.8 ksi at 2600F. SN-88 exhibited good Weibull characteristics; the Weibull modulus was 21.5 at room temperature and 21.4 at 2200F. Fractography is in progress to identify the failure origin locations and fracture-originating flaw types.

TABLE 9. NGK SN-88 SILICON NITRIDE FLEXURAL STRENGTH TEST RESULTS

Material:	SN-88 Si_3N_4	**Date Received**:	03-91
Condition:	Machined		
Test:	4-Point Flexure	Test Specimen:	4 x 3 mm
		Test Spans:	40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent Surface Fractures	Percent Internal Fractures	Predominant Fracture Origins
Room Temperature	114.2	30	21.5	Fractography is in progress		
1400	104.4	10	--			
1800	101.3	10	--			
2000	97.9	10	--			
2200	94.4	30	21.4			
2300	93.2	10	--			
2400	91.8	10	--			
2500	99.9	10	--			
2600	102.8	10	--			

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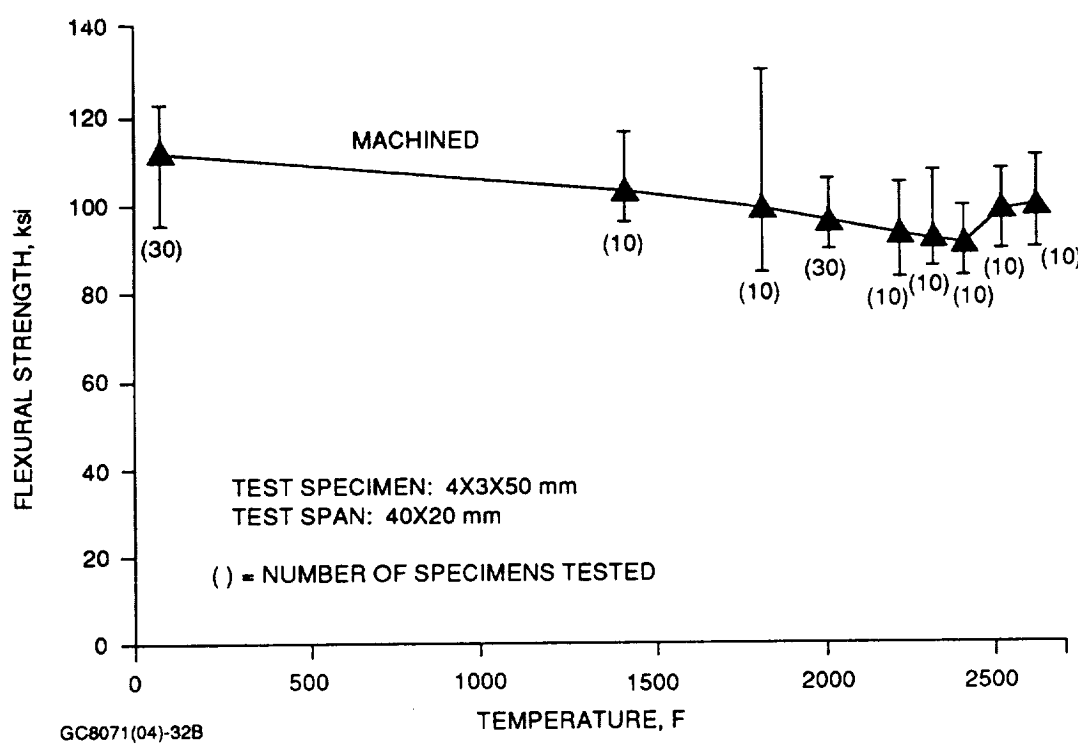

Figure 29. NGK SN-88 Exhibits Good Strength Retention at High Temperature.

5.1.1.4 Garrett Ceramic Components (GCC) GN-10 Material Characterization

Flexural strength was measured for GCC GN-10 silicon nitride produced with the fabrication process used for 1991 GN-10 rotor deliveries (Slip Revision 15/HIP Revision 8). Testing included "B-size" specimens with machined and as-processed test surfaces, and large flexure bars. Flexural stress rupture testing of machined and as-processed specimens is in progress.

Flexural strength test results for machined and as-processed GN-10 silicon nitride are summarized in Tables 10 and 11, respectively. The machined and as-processed surface strength properties are plotted as a function of temperature in Figure 30.

At room temperature, machined GN-10 flexural strength averaged 131.1 ksi, with a Weibull modulus of 8.4. The average strength decreased with increasing temperature from 131.9 ksi at 1400F to 68.5 ksi at 2500F. The GN-10 as-processed surface strength was approximately 50 percent of the machined surface strength. At room temperature, the GN-10 as-processed surface strength averaged 67.9 ksi, with a Weibull modulus of 14.2. The as-processed surface strength dropped gradually with increasing temperature to 39.2 ksi (average) at 2500F. At 2500F, slight nonlinearity of the load-deflection curves was noted in both machined and as-processed GN-10 strength tests, which suggests the onset of creep.

TABLE 10. GCC GN-10 FLEXURAL STRENGTH TEST RESULTS

<u>Material</u>: GN-10 Silicon Nitride — <u>Date Received</u>: 05-91
Condition: Machined
Test: 4-Point Flexure — Test Specimen: 4 x 3 mm
Test Spans: 40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent* Surface Fractures	Percent* Internal Fractures	Predominant Fracture Origins
Room Temperature	131.1	29	8.4	66	14	**Surface**
1400	131.9	10	--	50	40	Machined surface, chamfers,
1800	121.0	9	--	56	44	and carbon-iron inclusions.
2000	110.4	10	--	90	10	Slow crack growth at 2500F.
2200	99.4	30	28.3	80	7	
2300	94.3	10	--	90	10	**Internal**
2400	84.3	10	--	100	0	Carbon-iron inclusions and
2500	68.5	10	--	100	0	large grains

*Origins do not total 100 percent in all instances, since some were damaged or missing.

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TABLE 11. GCC GN-10 AS-PROCESSED SURFACE FLEXURAL STRENGTH

Material: GN-10 Silicon Nitride			**Date Received**: 05-91			
Condition: As-Processed						
Test: 4-Point Flexure			Test Specimen: 4 x 3 mm			
			Test Spans: 40 x 20 mm			
Test Temperature, F	**Average MOR, ksi**	**Specimen Quantity**	**Weibull Modulus**	**Percent Surface Fractures**	**Percent Internal Fractures**	**Predominant Fracture Origins**
Room Temperature	67.9	29	14.2	100	0	**Surface**
1800	52.9	5	--	100	0	Pits and porosity in as-processed surface. Slow crack growth at 2500F.
2200	48.8	5	--	100	0	
2500	39.2	5	--	100	0	

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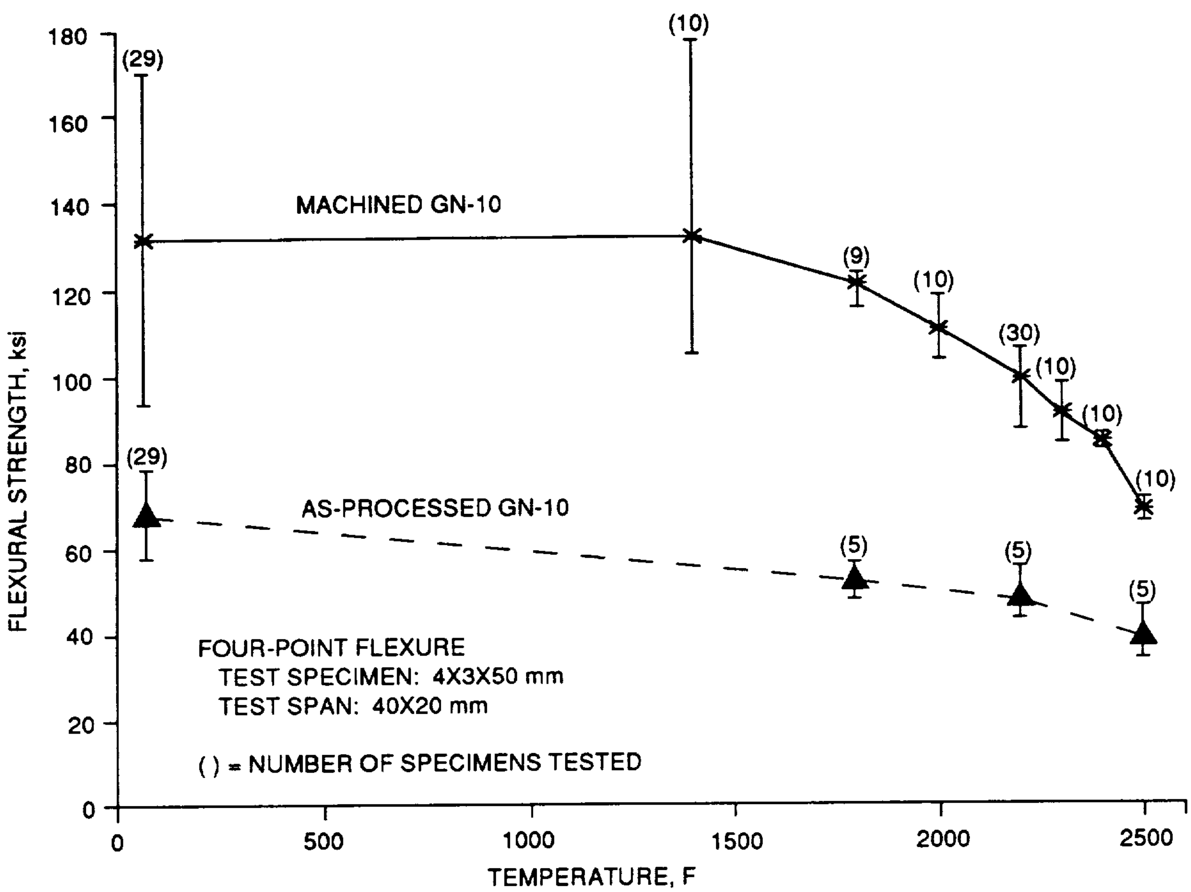

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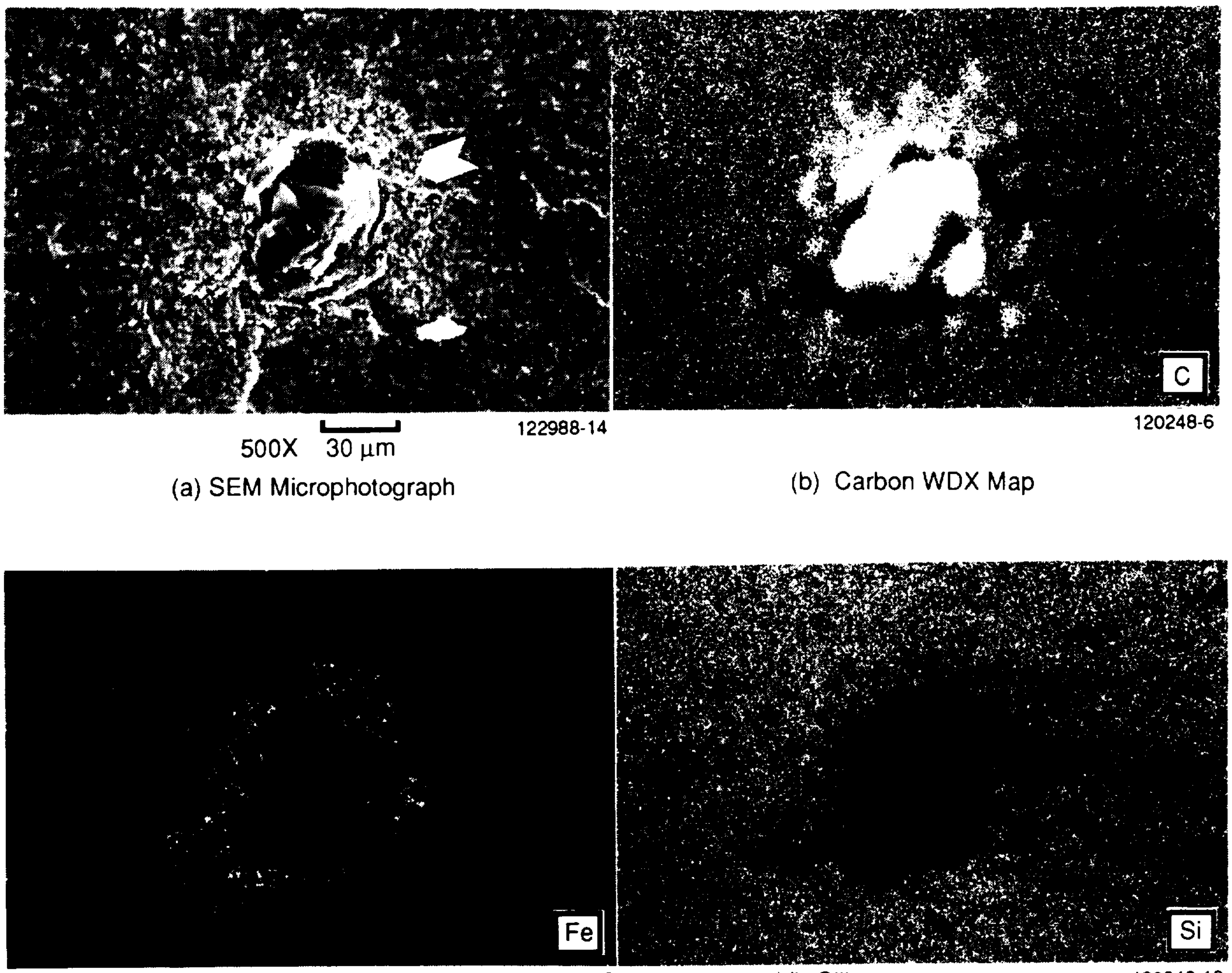
Figure 30. GCC GN-10 As-Processed Surface Strength Is Approximately 50 Percent of the Machined Surface Strength.

Machined GN-10 specimen failures originated predominantly at the tensile surface, though at the lower test temperatures, notable quantities of internal failures were also observed. Concentrations of iron were found at surface failure origins in a few instances, but no discernible defects were identified for most surface failures. Fracture-initiating flaws at internal failure origins were predominantly carbon particle inclusions with concentrations of iron in the surrounding matrix (Figure 31). Internal failures from areas of sintering aid concentration were also observed (Figure 32). For GN-10 tested at 2500F, all fracture surfaces showed evidence of slow crack growth.



500X 30 μm 122988-14 120248-6

(a) SEM Microphotograph (b) Carbon WDX Map

(c) Iron WDX Map 122988-16 (d) Silicon WDX Map 120248-12

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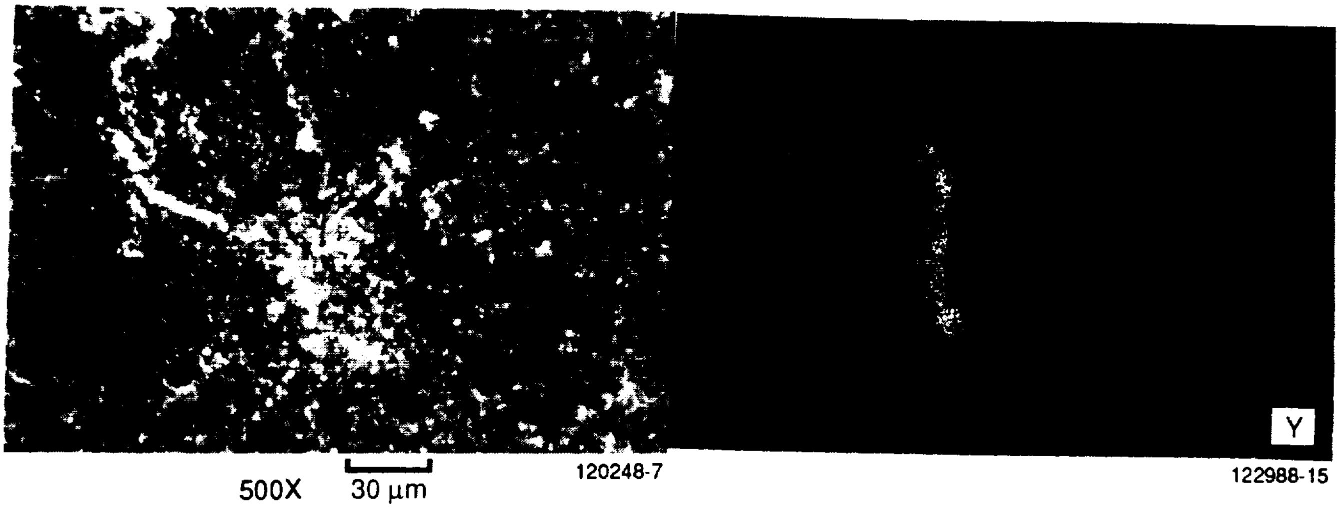
Figure 31. SEM Microphotograph (a) and WDX Element Maps (b)-(d) Show GCC GN-10 Fracture Originating Internal Flaws Occurred Predominantly at Carbon Particle Inclusions With Iron Concentrations in the Surrounding Matrix.



(a) SEM Microphotograph (b) Yttrium WDX Map

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Figure 32. SEM Microphotograph (a) and WDX Element Map (b) Show GCC GN-10 Internal Flaws Were Observed at Concentrations of Yttrium Sintering Aid.

All GN-10 as-processed specimen failures originated from the surface. The strength-limiting defects in the as-processed GN-10 surfaces are apparent from the surface topography, which consisted of a matrix of pits and porous regions 10 to 50 microns in diameter (Figure 33). A typical fracture origin at a surface pit with adjoining porosity is shown in Figure 34. Element mapping of the fracture surface showed the as-processed surface to be depleted of yttrium and strontium (sintering aid constituents) to a depth of 100 microns. For specimens tested at 2500F, all fracture surfaces showed evidence of slow crack growth.

Strength testing performed using large cross-section GN-10 flexure bars successfully generated volume property data: 67 percent of the large specimens exhibited volume failures, compared to 14 percent for the smaller specimens. The internal fracture-originating flaws were the same as discussed above for machined "B-size" specimens. The average strength for specimens with volume failure origins was 123.6 ksi, with a Weibull modulus of 12.3. The total average and Weibull modulus for all 30 specimens was similar: 121.9 ksi and 12.9, respectively.

5.1.1.5 Carborundum Co. Hexoloy SA Materials Characterization

The flexural strength and stress rupture testing of Carborundum Co. Hexoloy SA sintered alpha silicon carbide (SASC) was performed. All test material was produced using the fabrication process used for 1991 pilot combustor, transition duct, and combustor baffle deliveries (isopressing and green machining).

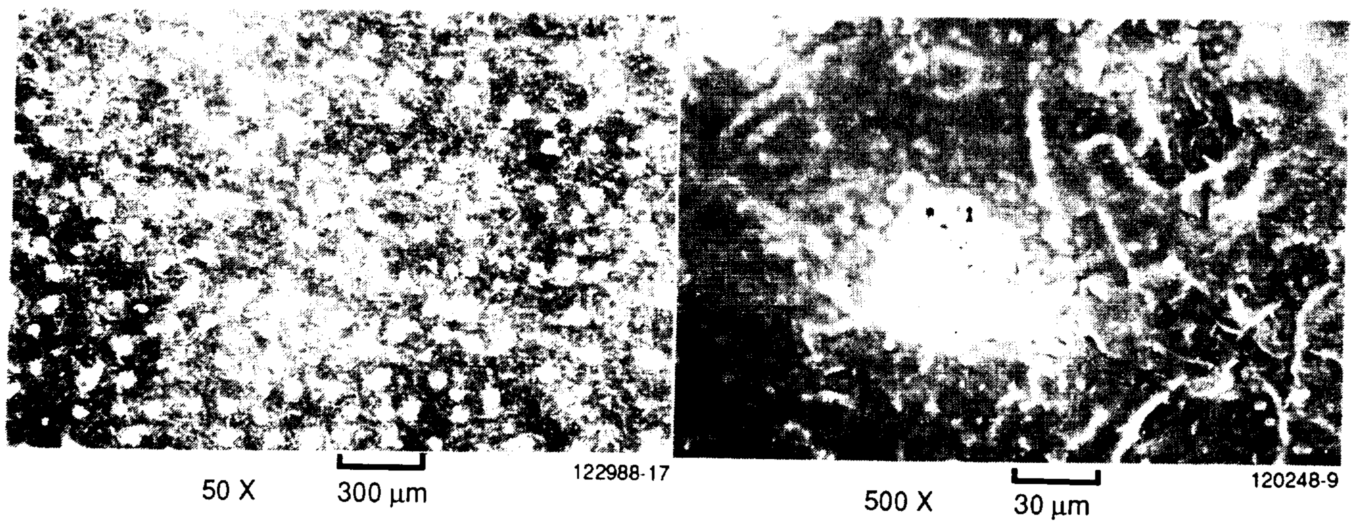

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Figure 33. **Surface Topography of GN-10 Specimen Consists of Pits and Porous Regions 10 to 50 Microns in Diameter.**

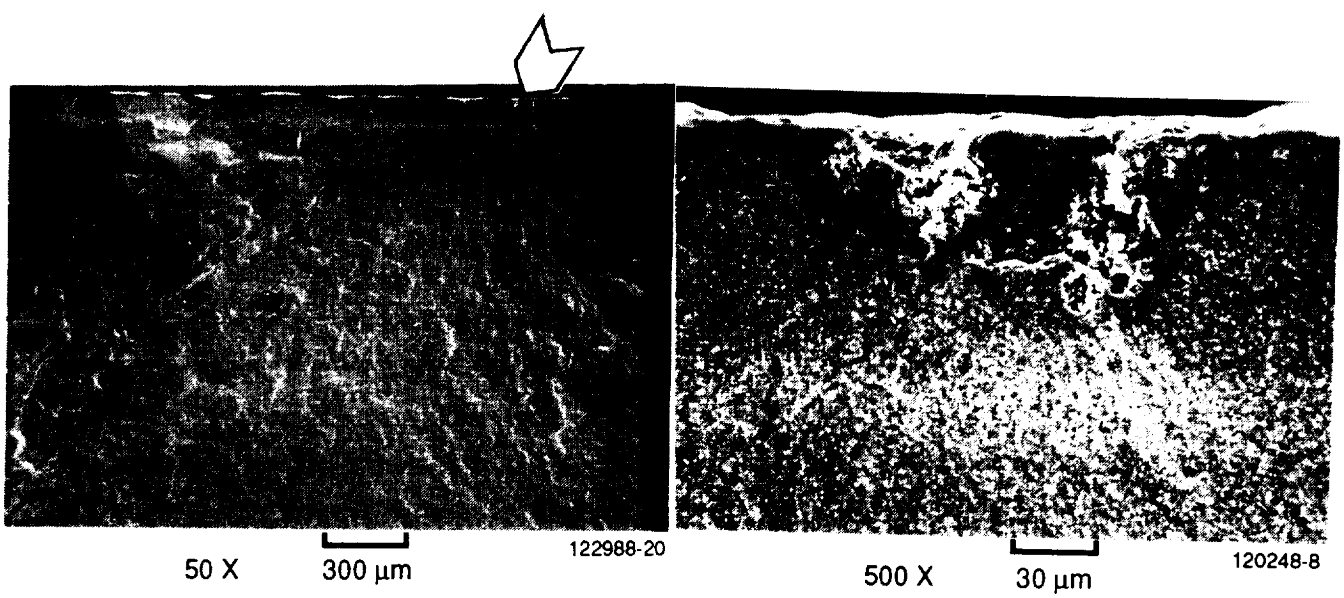

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Figure 34. **Typical GN-10 Fracture Origin at Pit With Adjoining Porosity (As-Processed Surface).**

Flexural strength test results for machined and as-processed Hexoloy SA silicon carbide are summarized in Tables 12 and 13, respectively. The machined and as-processed surface strength properties are plotted as a function of temperature in Figure 35.

Machined and as-processed surfaces exhibited similar flexural strength characteristics. At room temperature, the average flexural strength and Weibull modulus were 67.0 ksi and 15.4, respectively, for machined surfaces; and 63.8 ksi and 14.9, respectively, for as-processed surfaces. These strength levels were maintained up to 2600F for both surface conditions.

For both speciman conditions (machined and as-processed), the Hexoloy SA failures originated primarily from the tensile surface, although notable quantities of internal failure origins were also observed. Surface and internal failures for machined Hexoloy SA specimens originated from porosity (Figures 36 and 37). For as-processed surface Hexoloy SA, specimen failures originated mostly at anomalies in the as-processed surface (Figure 38). As-processed specimen failures from surface and internal porosity were also documented.

The 1991 Hexoloy SA flexural stress rupture test results are summarized in Figure 39. The current vintage of isopressed Hexoloy SA exhibits much improved stress rupture capabilities compared to 1985 vintage injection molded Hexoloy SA used in the AGT101 program.

5.1.1.6 Norton/TRW NT154 and Garrett Ceramic Components GN-10 Silicon Nitride Component Characterizations

The responsibilities for NT154 rotor and stator characterizations and GN-10 rotor characterizations have been assigned to the respective ATTAP ceramic subcontractors. A large amount of duplicated effort was identified in the area of component property verification testing. Since historical test data has shown good agreement between GAPD and ATTAP subcontractors, the duplication of effort was judged to be unwarranted. Norton/TRW Ceramics (NTC) and Garrett Ceramic Components (GCC) are now responsible for their own component cut-up and characterization testing. Test plans have been established and supplied to both firms. Following the characterization tests, the specimens are being forwarded to GAPD for fractography.

TABLE 12. CARBORUNDUM CO. ISOPRESSED HEXOLOY SA MACHINED SURFACE FLEXURAL STRENGTH TEST RESULTS

Material:	Hexoloy SA (Isopressed)	Date Received:	April 1991
Condition:	Machined and Annealed		
Test:	4-Point Flexure	Test Specimen:	4 x 3 mm
		Test Spans:	40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent* Surface Fractures	Percent* Internal Fractures	Predominant Fracture Origins
Room Temperature	67.0	29	15.4	45	41	Surface: Pores Internal: Pores
1400	69.4	10	--	60	40	
1800	68.1	10	--	70	30	
2000	70.8	9	--	89	0	
2200	68.0	29	10.2	76	17	
2300	67.7	10	--	50	30	
2400	68.0	10	--	50	40	
2500	72.0	10	--	60	30	
2600	71.2	10	--	80	20	

*Origins do not total 100 percent in all instances, since some were damaged or missing.

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TABLE 13. CARBORUNDUM CO. ISOPRESSED HEXOLOY SA AS-PROCESSED SURFACE FLEXURAL STRENGTH TEST RESULTS

Material:	Hexoloy SA (Isopressed)	Date Received:	April 1991
Condition:	As-Processed and Annealed		
Test:	4-Point Flexure	Test Specimen:	4 x 3 mm
		Test Spans:	40 x 20 mm

Test Temperature, F	Average MOR, ksi	Specimen Quantity	Weibull Modulus	Percent* Surface Fractures	Percent* Internal Fractures	Predominant Fracture Origins
Room Temperature	63.8	20	14.9	55	5	Surface: As-Processed Surface Anomalies and Pores Internal: Pores
1800	69.9	5	--	60	20	
2200	66.9	10	--	90	10	
2500	62.3	10	--	80	10	
2600	72.6	5	--	40	60	

*Origins do not total 100 percent in all instances, since some were damaged or missing.

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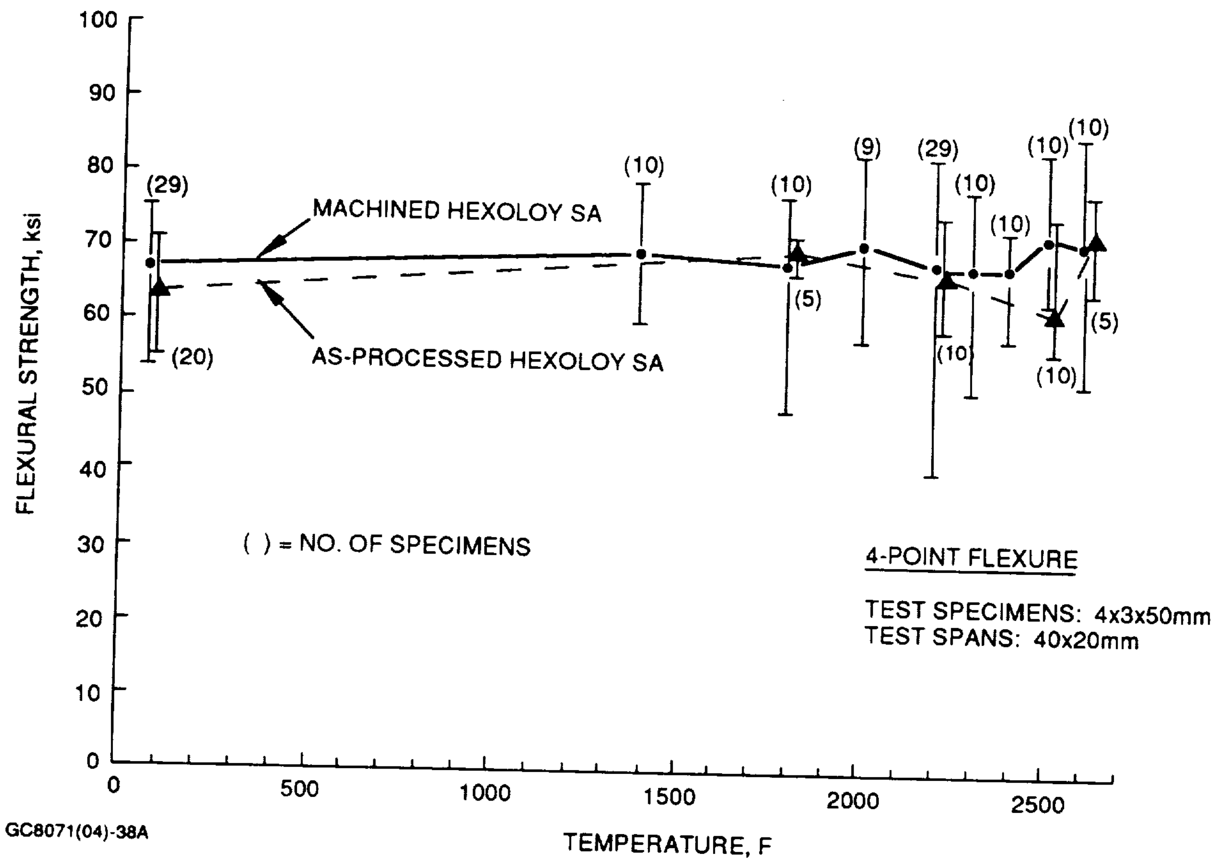

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Figure 35. Machined and As-Processed Carborundum Co. Hexoloy SA (Isopressed and Green Machined) Exhibit Similar Flexural Strength Characteristics.

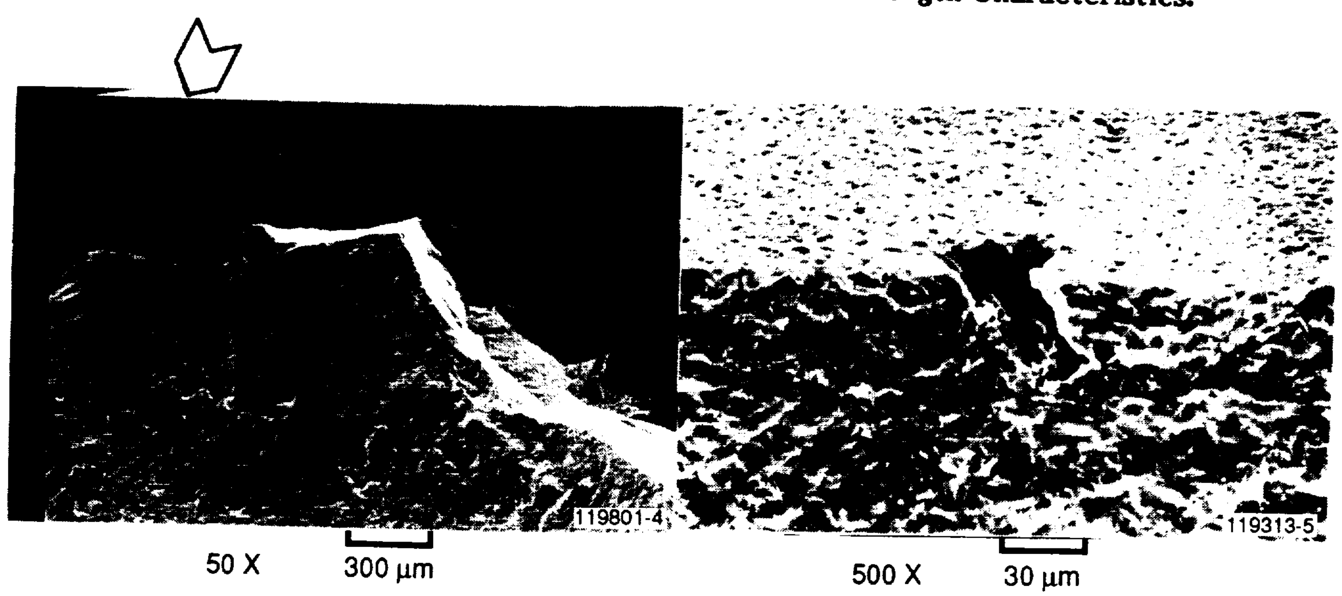

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Figure 36. Hexoloy SA SiC Machined Specimen Failure Originating From Surface Pore.

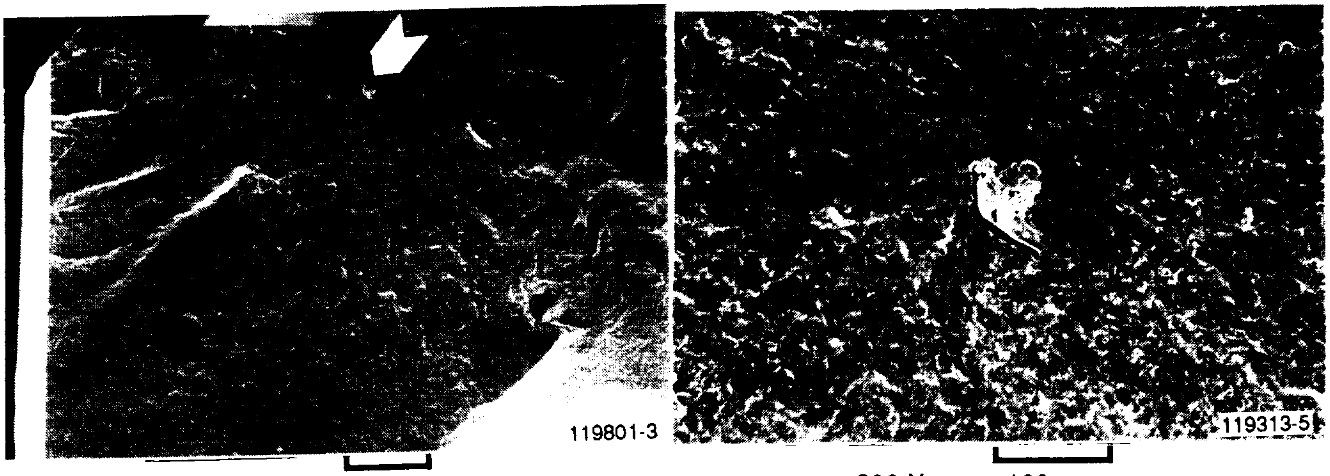

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Figure 37. Hexoloy SA SiC Machined Specimen Failure Originating From Internal Pore.

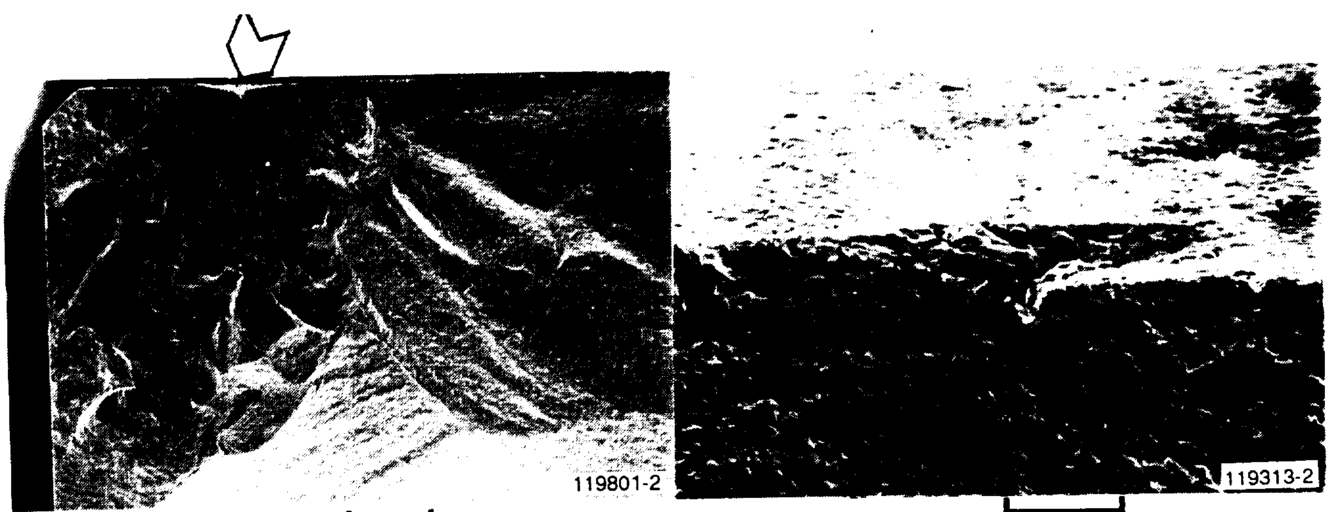

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Figure 38. As-Processed Hexoloy SA Specimen Failure Originating From Anomaly in Surface.

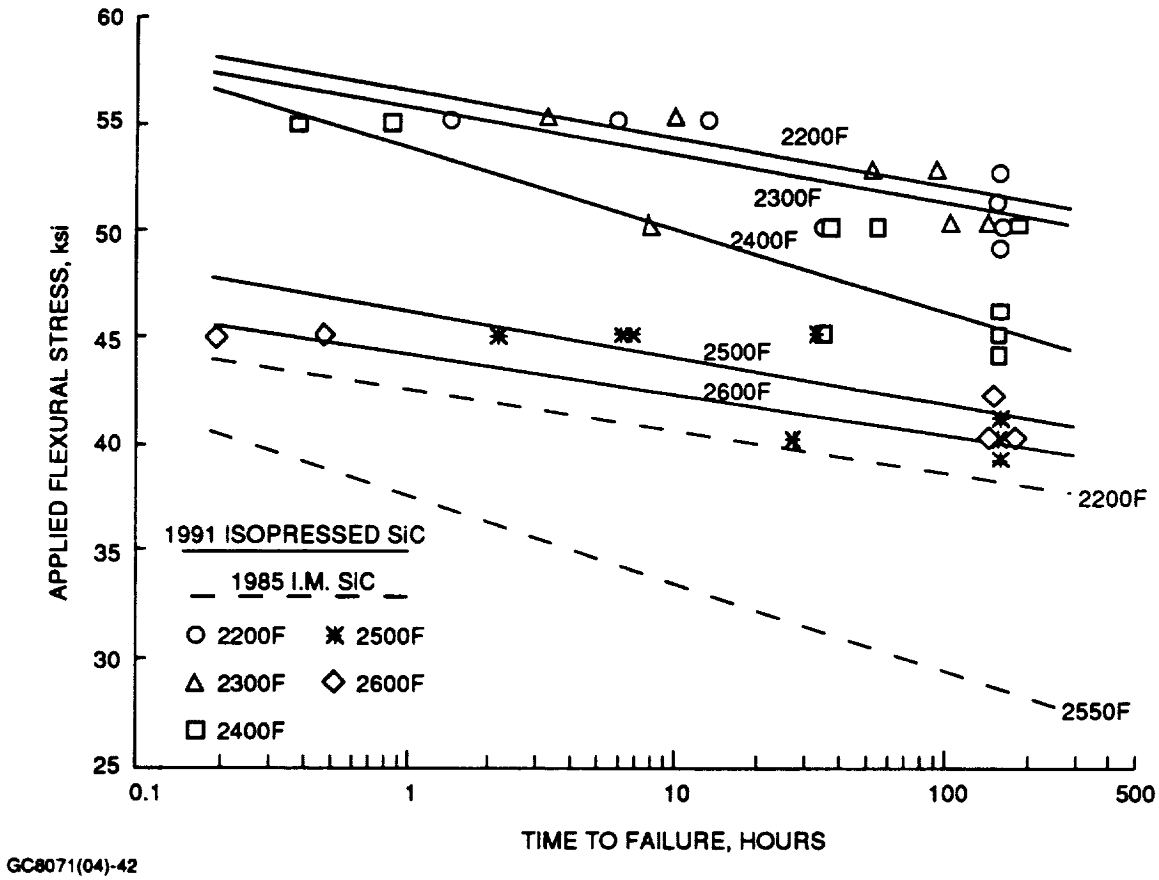

Figure 39. 1991 Vintage Isopressed Hexoloy SA Flexural Stress Rupture Test Results.

5.1.2 Nondestructive Evaluation (NDE)

During 1991, the ATTAP NDE effort was directed at inspection of test bars for the Materials Assessment and Materials Characterization Tasks, including Level 3 and 4 fluorescent penetrant inspection (FPI) of as-processed and machined test bars, respectively, and microfocus radiography at the 2-1T image quality level. Included under the Materials Assessment Task were inspections of Kyocera SC-221 beta silicon carbide (β-SiC), while the Materials Characterization Task included Norton/TRW Ceramics NT154 silicon nitride (Si_3N_4) and NT230 siliconized silicon carbide (Si-SiC), NGK SN-88 Si_3N_4, Garrett Ceramic Components GN-10 Si_3N_4, and Carborundum Company Hexoloy SA alpha SiC.

In general, any occurrence of NDE indications was rare. However, a void was detected in one NT230 test bar, which subsequently failed during flexural strength testing. In addition, the x-ray density of NGK SN-88 was observed to be considerably higher than other silicon nitrides, requiring a four-times greater exposure. All engine hardware was inspected using FPI and radiography prior to rig and engine testing. The lack of any significant number of rejected parts is indicative of the general high quality of ceramic hardware received.

Acoustic emissions (AE) monitoring of component rig testing was continued during 1991. Although it is not anticipated that a component failure can be avoided through detection of an acoustic event during testing, AE will provide early detection of component cracking and therefore has the potential to avoid secondary damage, by early termination of testing. An example occurred during operation of the 2500F screening rig. During the test, a turbine shroud cracked, which was detected by AE monitoring. Two separate series of AE events were detected (Figure 40), which confirmed the significance of discontinuities in the sensor readouts. In this case, the AE events influenced the decision to terminate the test and inspect the rig. The teardown revealed cracked components which had failed from thermal shock induced by inadvertent ducting of room temperature air onto the heated components.

5.2 Ceramic Component Fabrication

In recognition of the need to maintain a competitive position for domestic U.S. suppliers in critical ceramics 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 engine components is critical to the growth of ceramic applications. Under ATTAP, the U.S. suppliers are concentrating on fabrication technologies for the complex ceramic shapes needed for gas turbines. This forming technology must not sacrifice the temperature capability and the strength, reliability, and durability which make ceramic materials so desirable for engine applications.

Three U.S. subcontractors have been selected by GAPD to develop fabrication methods for high-quality ceramic engine components: Norton/TRW Ceramics (NTC), Garrett Ceramic Components (GCC), and The Carborundum Company (CBO). These suppliers have demonstrated the process and fabrication capabilities to produce ceramic components with material properties suitable for gas turbine use.

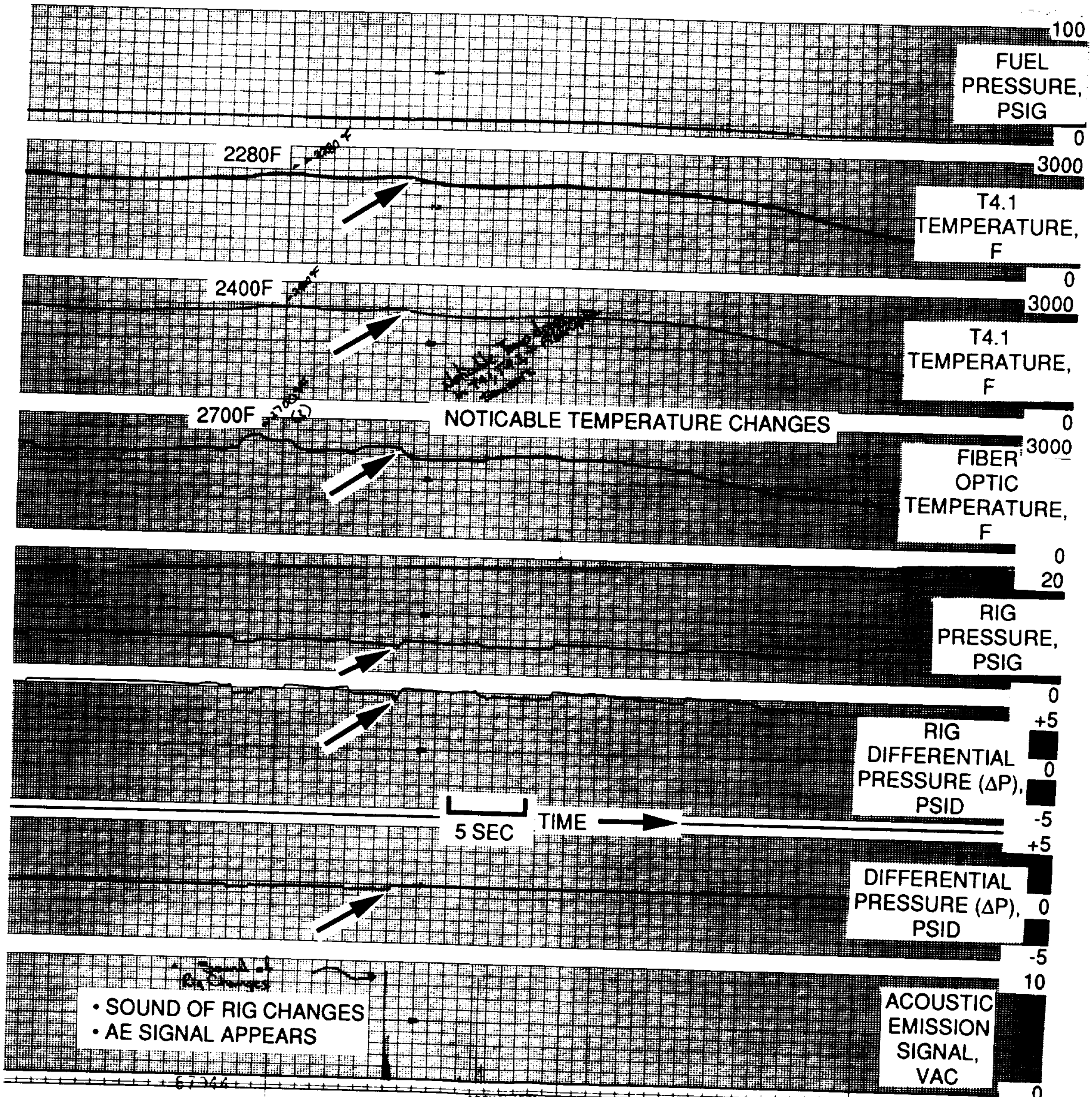

Figure 40. Acoustic Emission Events Were Detected During a 2500F Rig Test.

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Activities of the three ATTAP ceramic component subcontractors are detailed in the Appendices to this report. A brief synopsis of activities is presented in the following paragraphs.

5.2.1 Norton/TRW Ceramics (NTC)

Norton/TRW identified and corrected a problem with metallic inclusions introduced into the NT154 silicon nitride powder during agglomeration. Agglomeration of the powder is currently necessary for the retention of adequate properties throughout the thick rotor section. A steel part in the agglomerator equipment was replaced with a silicon nitride piece, after which material properties comparable to nonagglomerated NT154 were demonstrated.

Other NTC activities during 1991 included completion of experiments in hot isostatic pressing (HIP) control, as-fired surface optimization, and rotor casting optimization.

Fabrication of silicon nitride rotors of the new design was begun during 1991, after receipt of a new steel pattern for the ATTAP impact-resistant rotor. Molds made from this pattern were subsequently used to cast NT154 silicon nitride rotors, and the first pieces were delivered to GAPD in late 1991. Predelivery operations included dimensional and NDE inspections, and proof spin tests up to 15 percent overspeed.

Fabrication of silicon nitride stators in the impact-resistant configuration also received high priority at NTC. To provide commonality of the ceramic rotor and stator processing, agglomerated NT154 powder was also used in preparation of the AGT101 stators. Once GAPD submitted the final design to NTC in the spring of 1991, NTC selected a vendor capable of machining the highly complex stator segment geometry into an oversized pattern (to allow for shrinkage during densification). Molds based on the oversized pattern were then used to cast the NT154 stator segments. The casting gate, previously placed at the vane leading edge, was relocated to the sidewall, permitting the gate to be fully machined away, while leaving the complex airfoil shape intact as a cast feature. Better material flow and improved consistency in the airfoil shape resulted. First castings were machined in late 1991 and delivered by year's end.

5.2.2 Garrett Ceramic Components (GCC)

In 1991, GCC concentrated on fabrication of the GN-10 silicon nitride ATTAP impact-resistant rotor, including completion of experiments to optimize GN-10 as-HIPped surface and high-temperature material properties. Increased emphasis on hardware deliveries showed a shift from process development activities to actual hardware fabrication. Initial rotors produced by GCC from the early plastic stereolithographic (SLA) rotor pattern (defined from electronic CADAM design files supplied by GAPD) were slightly deficient in stock at the hub and journal. The journal size was corrected by mold modifications, following an unsuccessful attempt to compensate through alterations in the casting conditions.

In late fall 1991, GCC successfully spin tested to burst several ceramic impact-resistant rotors, including several from molds formed with the SLA pattern, and others from the final "hard" metal pattern. The SLA process employs a laser to scan and harden liquid plastic material to form a mold, saving time in initial evaluation of the design, but produces a pattern having slight ridges in the surface. No reduction in burst speed was seen for the ceramic rotors with surface ridges, cast from the SLA pattern. The burst test results are given in Table 14. Analysis by GAPD of the predicted failure speed for ceramic rotors under cold spin conditions correlated well with the test data (Figure 41), assuming that the failures originated from surface flaws.

5.2.3 The Carborundum Company (CBO)

CBO worked on fabrication and delivery of three critical ceramic ATTAP engine components during 1991, and successfully delivered static structure components well ahead of the test schedule, paced by the rotor and stator component deliveries. The fabrication process selected by CBO -- isopressing and green machining of Hexoloy SA silicon carbide -- is well established, although the geometries of the ATTAP components and the stringent quality requirements presented challenges.

CBO delivered transition ducts, combustor baffles, and pilot combustor supports to GAPD during 1991. Although some minor dimensional discrepancies were noted, the overall appearance and quality of the components were good, as verified by NDE inspection. Strength evaluations of material billets coprocessed with the parts through the various fabrication stages (raw powder qualification, isopressing, sintering, and annealing or heat treatment) confirmed that the strength and Weibull modulus target values of 50 ksi and 7.5, respectively, were being met in all cases.

TABLE 14. GCC ATTAP CERAMIC ROTOR SPIN TEST DATA

Rotor Description	Measured Burst Speed, rpm
Hard Tool, Solid Shaft	113,400
Hard Tool, Solid Shaft	112,800
Hard Tool, Solid Shaft	113,900
SLA* Tool, Solid Shaft	114,100
SLA* Tool, Solid Shaft	119,000
Hard Tool, Hollow Shaft	102,500

*Sterolithographic process plastic mold pattern

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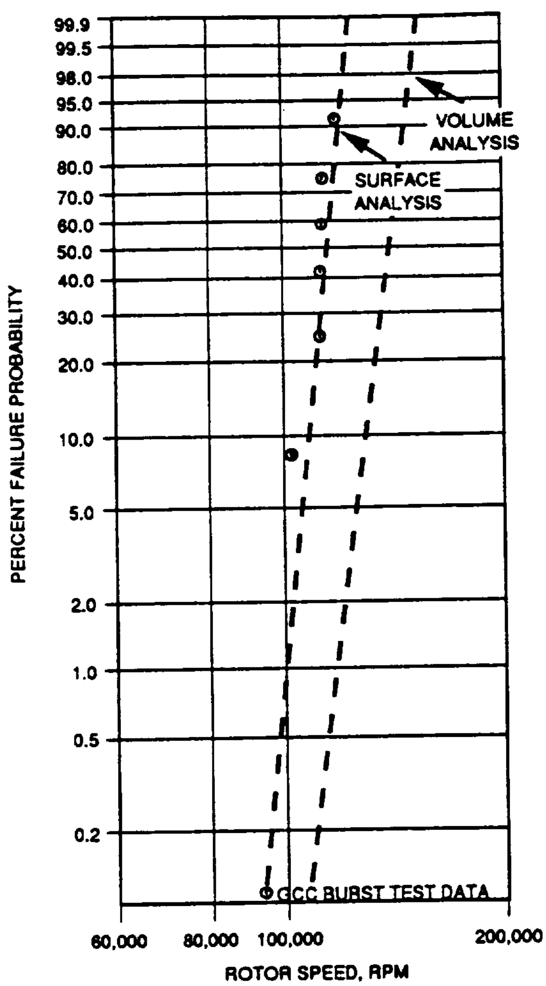

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Figure 41. **Failure Predictions for Ceramic Rotor Agreed Well With Spin Test Data, Assuming Surface Flaw Origination.**

5.3 Ceramic Component Preparation

New ceramic hardware received was processed through an inspection loop consisting of visual, dimensional, fluorescent penetrant (FPI), and radiographic inspections as necessary. Certain items were also subjected to proof testing, discussed in Section 6.4.

Some ceramic hardware machining was necessary, to correct certain dimensional features or otherwise alter the parts to meet test requirements. Selected ceramic items were sent to outside machining vendors to develop alternate out-of-house machining sources.

6.0 COMPONENT RIG TESTING

6.1 Hot Spin Pit Design and Fabrication

The objective of this effort is to use data generated from test specimens to formulate methods of analytically predicting ceramic component life, and to apply these methods to successfully predict the life of ceramic disks of like material, spin tested under room temperature and heated conditions.

The spin tests are necessary to acquire biaxial stress field data to demonstrate successful life prediction under more than just a uniaxial state of stress (as generated in ordinary test specimens). Such spin testing at high rotational speeds is normally accomplished in a near-complete vacuum to eliminate viscous drag effects which limit the speed and affect stability of the spinning member. However, spin testing silicon nitride (Si_3N_4) specimens in a near-complete vacuum for prolonged time periods (more than one hour) can cause dissociation of the Si_3N_4 test material; thus, spin testing under atmospheric conditions is indicated.

During 1991, a design of a double loose attachment configuration for the interface between the ceramic spin disk and drive motor was initiated. The new attachment design was tested to determine if it would provide stable rotor dynamics. A titanium disk was spin tested in air at room temperature to simulate the rotor system. All test points were successfully accomplished. Further development of cold and hot attachment designs will address arbor manufacturability and arbor/spin disk assembly concerns.

Preparations were initiated for a test planned to characterize the temperature gradient in the ceramic spin disks during hot spin testing. A ceramic spin disk will be instrumented with five thermocouples at varying depths and radial locations. Ultrasonic and laser drilling studies were conducted to determine which process would be most feasible to produce instrumentation holes in the required size and depths. Laser drilling was determined to be inadequate; holes of only 0.045-inch depth were produced, compared to the required 0.500-inch depth. The ultrasonic drilling study proved successful; five satisfactory instrumentation holes were ultrasonically drilled in a ceramic spin disk.

Tests were performed to qualify the heating capability of the heated spin pit design. A post-test inspection of the heating system hardware revealed insulation degradation had occurred, possibly due to inadequate heating element spacing. The heated spin pit design was revised to include smaller diameter heating elements, providing more uniform heating. A second series of tests was conducted to evaluate the revised design; the spin pit reached the 2500F test temperature after 45 minutes of heating, and posttest inspection revealed little insulation degradation, indicating the redesign was acceptable.

6.2 Combustor Rig Testing

Combustor rig testing continued in 1991 to validate fuel nozzle and ceramic pilot combustor designs and to select the final configuration for use in AGT101 test bed engine durability tests. This series of tests was designed to evaluate improvements to prevent carbon formation in the combustor, eliminating a possible source of ceramic turbine damage. In earlier tests, utilizing the stepped ceramic pilot combustor and a simplex (single-point) fuel nozzle, soot was deposited on the nozzle face, resulting from excess fuel dripping from the nozzle. To alleviate this problem, an airwipe feature was added to the nozzle, utilizing the combustor pressure drop to force air across the face of the nozzle and wipe excess fuel away.

Combustor rig tests of the modified simplex fuel nozzle with airwipe and both the stepped-diameter and constant-diameter ceramic combustor designs indicated clean operation with DF-2 diesel fuel during simulated idle, cruise, and maximum power engine operating conditions (Figure 42). Additional tests of the combustor configurations were successfully accomplished in the AGT101 metal test bed engine.

6.3 Regenerator Rig Testing

Regenerator rig testing is being conducted to evaluate new component designs prior to implementation into the AGT101 engine test bed and to assess regenerator system durability and performance. The regenerator rig build configuration utilizes the metallic and ceramic structures of the AGT101 ceramic engine, except for replacement of the rotating group with an adjustable ceramic valve (Figure 43). During 1991 testing, two new ceramic component designs were validated, the regenerator core pocket was instrumented to determine system deflections, and the regenerator seal system was tested for durability.

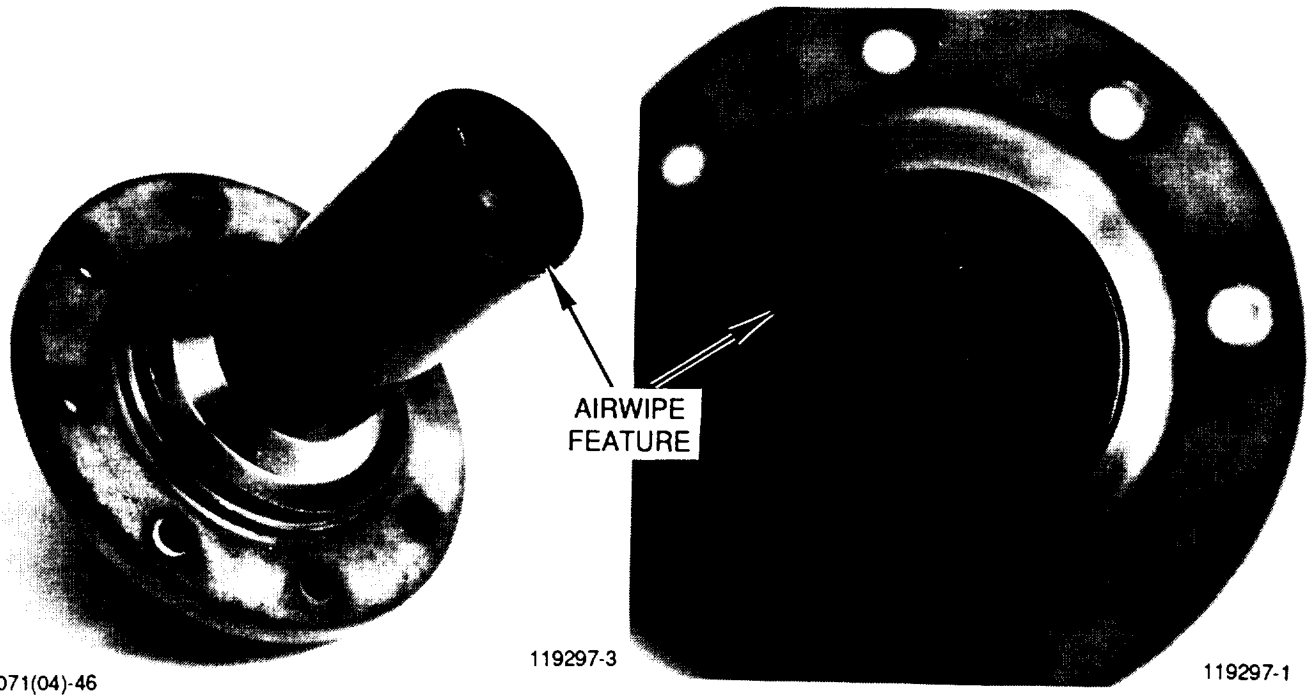

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Figure 42. Fuel Nozzle Airwipe Feature Eliminated Sooting.

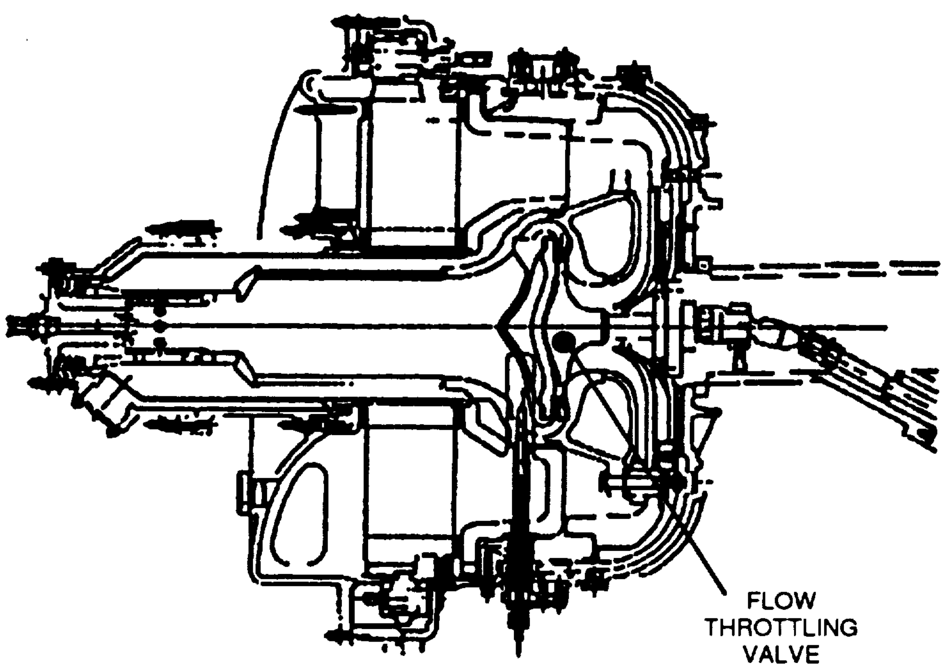

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Figure 43. ATTAP Hot Regenerator Test Rig Incorporates a Ceramic Valve Replacing the Rotating Group.

The new component designs verified were the flow separator housing (FSH) rocker support system and the diffuser support seal system (refer to Sections 3.4.3 and 3.4.4, respectively).

In other testing, the regenerator system was instrumented in an attempt to determine regenerator core displacement and tilt. This data is required for revisions to the component designs to reduce the deflections and lessen system torques. Capacitance-type clearance probes were used to define movement of the metallic regenerator seals. The hot and cold seals were instrumented (Figure 44). Data was collected at temperatures of 1200F, 1500F, and 1800F, and pressures of 10, 25, and 40 psig, corresponding to various engine operating conditions. Analysis of the data shows regenerator core displacement and core tilt occurs throughout operation (Figure 45). Maximum deflection measured was 0.028 inch at the outer periphery of the low-pressure side of the hot seal at maximum rig test conditions. Analysis of the core position data resulted in the design of a regenerator core antitilt roller which will be tested early in 1992.

A regenerator rig test was performed to determine the durability of the ceramic-coated metallic hot seal. The hot seal tested combined the baseline coating configuration with a new mechanical design allowing for thermal expansion (Figure 7). The seal shoe tested employed a serrated Haynes 230 (nickel-base alloy) substrate coated with the ATTAP baseline seal coating configuration (Figure 8). The goal of the durability test was 100 hours of operation at the maximum regenerator inlet temperature (RIT) of 1800F.

Cross sectional metallographic analysis specimens were taken from the crossarm portion of the ceramic-coated hot seal shoe after completion of 100 hours testing at 1800F RIT. Both the regenerator core side (rubbing seal surface) and the flow separator housing (FSH) side of the seal shoe were coated (Figure 7). Metallographic analysis of the regenerator seal shoe crossarm revealed severe oxidation of the metallic bond coating and the substrate, and mechanical damage and wear of the ceramic wearface coating. Typical microstructures of the core side and the FSH side seal coatings are illustrated in Figure 9. Substrate attack up to 0.04 inch (1.0 mm) depth was measured. Additionally, the ceramic coating wear during the 100-hour rig test was estimated to be approximately 0.020 inch (0.5 mm).

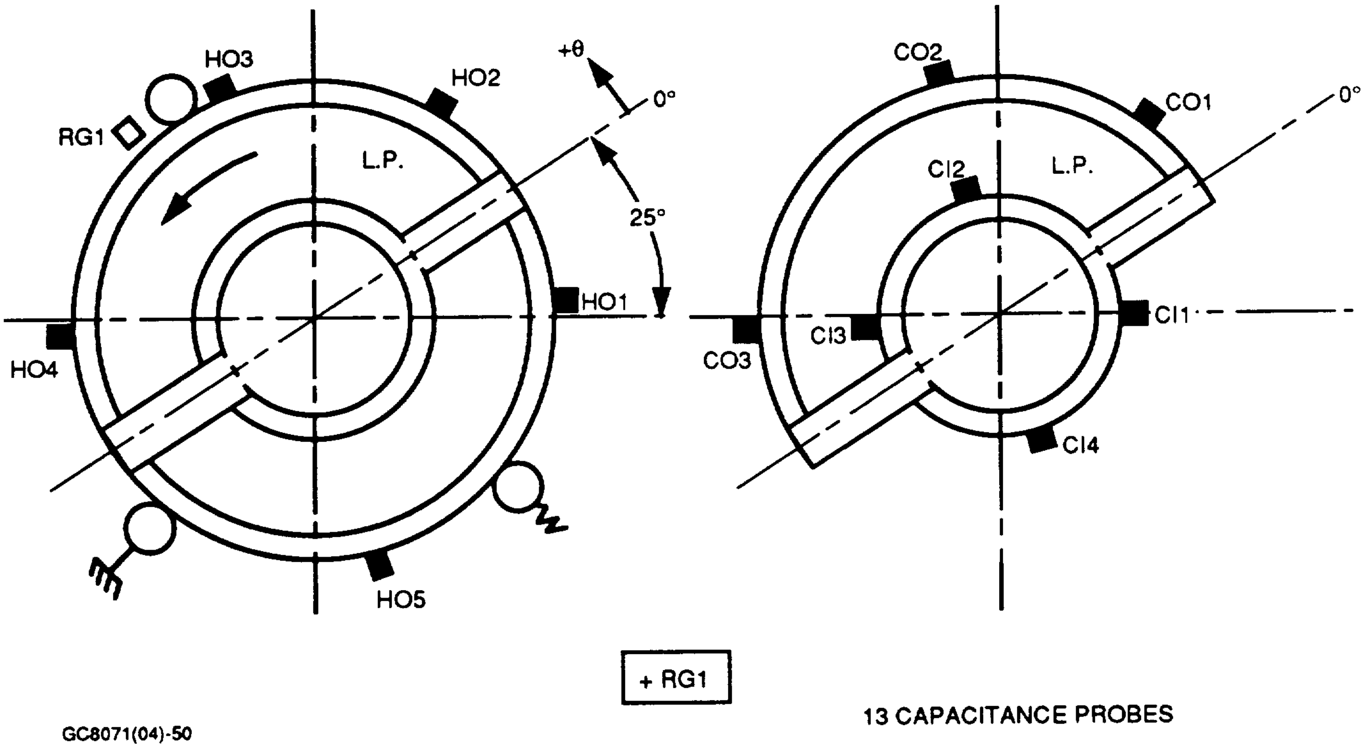

Figure 44. Probe Positions Were Selected to Determine Regenerator Core Displacement.

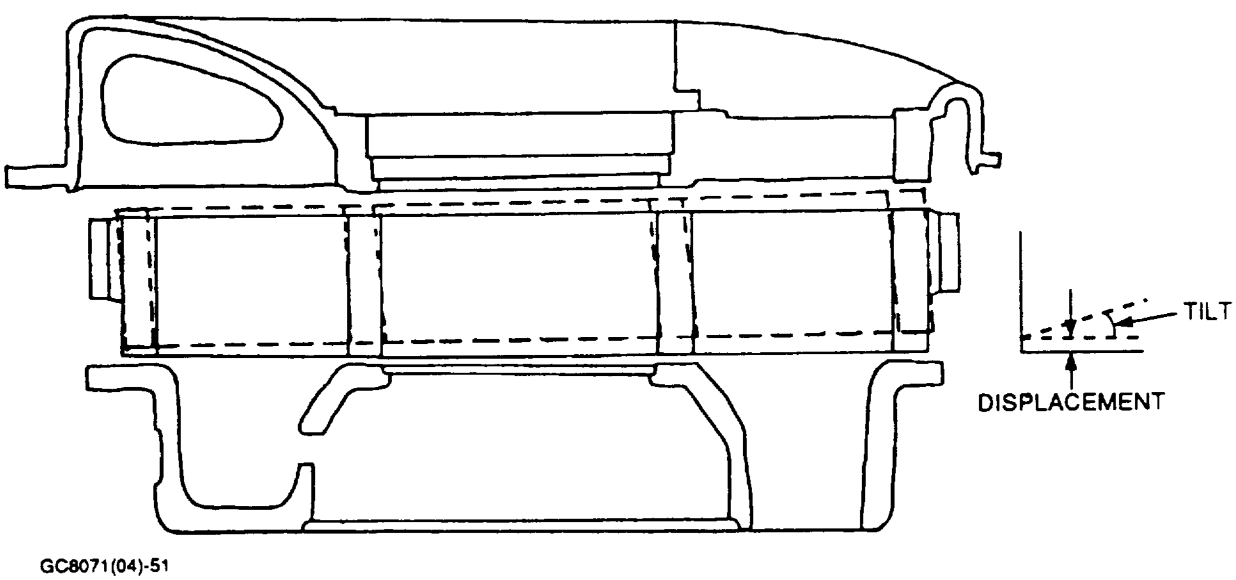

Figure 45. Regenerator Core Displacement and Tilt Was Measured During Operation.

The seal substrate was visually inspected after every 25 hours of testing. The last 25 hours of testing appear to have contributed the greatest amount of chemical breakdown of the coating. The Series 1 coating configuration (refer to section 3.4.1) is planned for evaluation early in 1992 during a 100-hour rig test to address the baseline coating problems encountered during regenerator rig testing. The high wear rate for the baseline seal ceramic wearface coating remains a concern.

6.4 Structural Proof Testing

NDE techniques required to assure high reliability of ceramic components have not yet been fully identified or developed and it remains necessary to perform component proof tests to qualify ceramic hardware for use in the ATTAP test bed engine. These tests generally simulate a worst-case stress condition with a 25 percent overstress margin. Information from these proof tests, when combined with results of prior NDE testing, can be valuable in determining critical flaw characteristics and will aid in establishing specifications for ceramic components.

6.4.1 Flow Separator Housing

A flow separator housing (FSH) was mechanically screened before use in the FSH multiple support test rig. A 65 psig pressure load was applied to the high-pressure side of the FSH, and the load test was repeated three times. The FSH successfully completed the load tests.

6.5 1371C (2500F) Test Rig

The 2500F test rig subjects selected ceramic hardware to high temperatures for extended periods of time, simulating the 100-hour durability test, and assessing the durability of ceramic stators and other components. During the first test run in 1991, the 2500F test rig (Figure 46) was successfully operated for 10 hours at 2200F. This test at reduced temperature evaluated the rig performance prior to operation at full temperature and successfully demonstrated the capability of the ceramic components under test to withstand the temperature requirements for the first ceramic engine test.

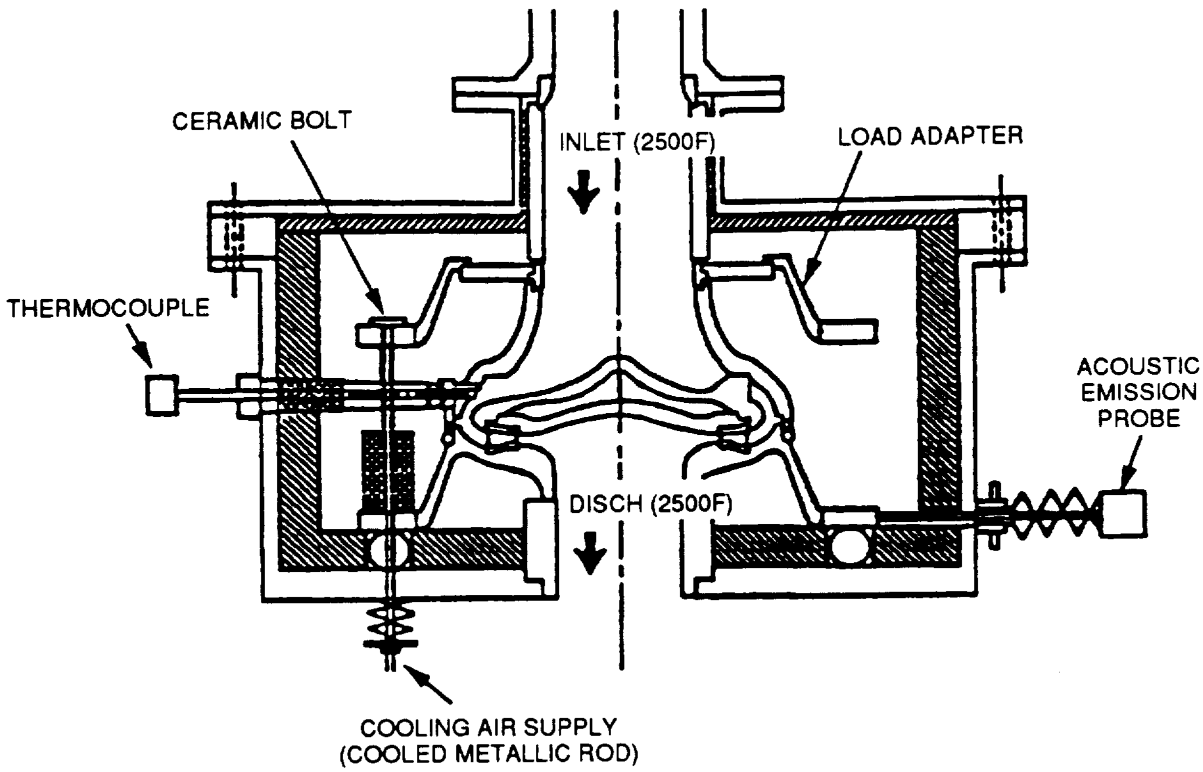

Figure 46. The 2500F Test Rig Exposes Ceramic Hardware to High Temperature While Stacked in an Engine Configuration.

Following the initial 10-hour test at reduced temperature, 3.5 hours of testing was accomplished at 2500F, evaluating the following materials:

- o NT154 Silicon Nitride - Stators
- o SASC Sintered Alpha Silicon Carbide - Transition Duct and Baffle
- o SN-251 Silicon Nitride - Stators, Turbine Shroud, Wave Spring, Back Shroud
- o SN-250 Silicon Nitride - Stators

This testing provided information concerning oxidation, sticking, and the behavior of interfaces between a variety of ceramic materials exposed to the combustor discharge. Following this test, all of the hardware was in good condition, except for the SN-250 stators, which suffered heavy oxidation.

A Conax Buffalo high-temperature fiber optic sensor is being evaluated in the 2500F test rig. The sensor performed well during testing; the probe exhibited no damage upon rig disassembly.

Following 3.5 hours at 2500F, the rig was shut down due to failure of a metallic bolt. No ceramic hardware damage occurred. Correction of the failure included adding insulation and increasing the rig cooling air to prevent a recurrence.

Acoustic emission (AE) monitoring was conducted during this test, and no events were recorded.

The next rig test attempt was aborted prior to stabilization at 2500F. Leakage of rig cooling air onto the turbine shroud induced a fracture. A review meeting was held to determine possible corrective actions. The test rig was subsequently modified to correct the condition, and is ready for continued testing.

6.6 Turbine Stage Aerodynamic Test Rig

During 1991, fabrication of the turbine stage aerodynamic test rig was completed. Testing was postponed until 1992, to accommodate manpower loading requirements.

7.0 ENGINE TEST BED TRIALS

Engine test goals successfully accomplished in 1991 included elimination of the compressor surge seen in previous metal AGT101 engine tests, final debugging of the electronic control unit (ECU) during transient and steady-state operation, demonstration of AGT101 test bed improvements, and demonstration of ceramic engine durability. An all-ceramic radial turbine AGT101 engine successfully ran at maximum design operating conditions of regenerator inlet temperature (RIT) = 1800F and turbine speed = 90,000 rpm.

Four AGT101 engine builds were accomplished and successfully tested during 1991; the test results are listed in Table 15. Total engine test hours during the ATTAP program are summarized in Table 16.

TABLE 15. 1991 ATTAP ENGINE BUILDS AND TEST RESULTS

Build Number	S/N	Configuration	Operating Hours	Starts
51	001	All Metal	28.80	69
52	001	Metal With Ceramic Rotor	0.93	6
19	002C	All Ceramic	7.30	57
20	002C	All Ceramic	6.00	21

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TABLE 16. ATTAP ENGINE TEST STATUS

Configuration	Builds	Starts	Operating Hours
Metal	5	97	38.4
Metal With Ceramic Rotor	3	7	1.7
All Ceramic	2	78	13.3

8071(04)-15

7.1 Metal Engine Testing

The primary goal for the metal AGT101 engine test (Build No. 51) was to diagnose the cause of the compressor surge seen in earlier testing and to debug operation of the new ECU. Instrumentation was added to the turbine nozzle for the tests, and together with a pretest nozzle calibration conducted in the GAPD flow facility, the cause of the compressor surge was successfully determined.

The compressor surge was identified as being caused by excessive swirl introduced into the core airflow of the stepped pilot combustor; this caused the turbine nozzle to "choke", creating backpressure which induced the compressor to surge. The pressure changes across the engine also placed undue cyclic stress on the regenerator core, causing the core to fail at several radial locations.

Installing a 1600F diffusion flame combustor on the Build 51 engine temporarily eliminated the surge problem, permitting successful debugging of the new ECU. ECU fuel gain adjustments now provide stable engine operation during transient accelerations and steady-state conditions. Fuel schedule adjustments have also been made, to permit hot reignition and satisfactory hot and cold automatic starts of the metal AGT101 engine.

Build 52 of the metal AGT101 radial engine incorporated a ceramic SN-84 silicon nitride turbine rotor and a modified stepped pilot combustor. The primary purpose of the test was to evaluate the modified combustor configuration for elimination of surge, to determine if the modified combustor would be adequate for use in the all-ceramic radial engine, and to evaluate operation of the new simplex (single-point) fuel nozzle scheme. The modified stepped pilot combustor featured a reworked swirler section, with air inlet swirl angle changed from 30 degrees to zero.

The Build 52 engine successfully operated at speeds up to 80,000 rpm with no indication of surge. Aerodynamic test data indicated a surge margin of 7 to 8 percent exists between satisfactory engine operation and the compressor surge line. The new simplex fuel nozzle also operated successfully, with satisfactory lightoff and acceleration. The modified stepped pilot combustor and simplex fuel nozzle were selected for use in the later all-ceramic AGT101 radial engine.

The Build 52 engine test was terminated prematurely, due to failure of three of the four high-temperature (Wayne Kerr type) proximity probes. These probes provide an indication of the turbine rotating group vibration level for monitoring of proper engine operation. Shorting of the probes was attributed to the routing scheme for the probe cables, which permitted exposure of the cables to hot gases, damaging the insulation. The cable routing will be changed on future engine builds to eliminate this problem.

7.2 All-Ceramic Engine Testing

The purpose of the S/N 002C all-ceramic radial AGT101 engine test (Build 19) was to demonstrate the test bed improvements incorporated into the AGT101 engine (Figure 47) and to demonstrate the durability of the AGT101 engine at full operating conditions. The engine accumulated over 7 hours running time at speeds up to 90,000 rpm. During this testing a maximum turbine inlet temperature (TIT) of 2200F was measured.

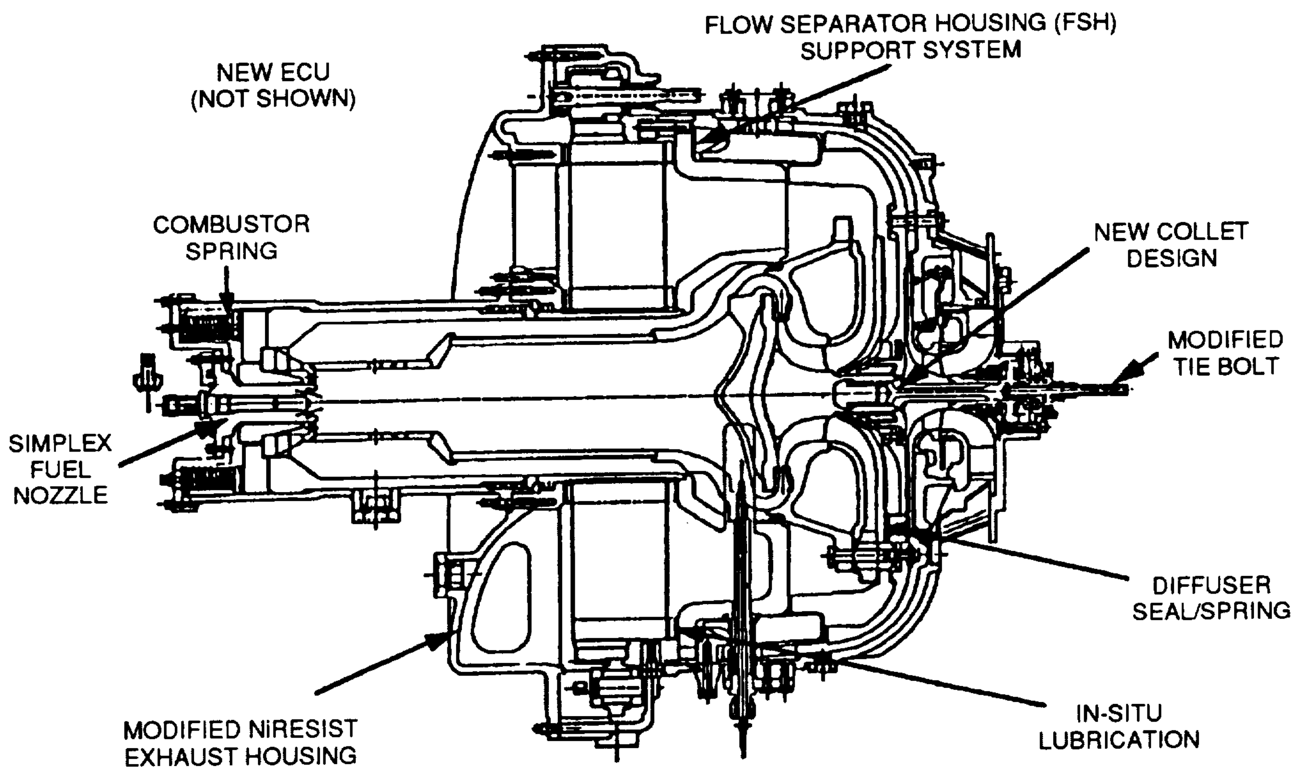

Figure 47. AGT101 Test Bed Improvements Were Successfully Verified in Engine Testing.

The planned 10-hour durability test was terminated prematurely, due to the loss of all four of the Wayne Kerr vibration probe signals. Teardown of the engine revealed high-temperature damage to the vibration probe leads, in a different location than the earlier failure during the metal engine testing. The probe lead routing was modified, and provisions were made to monitor the temperature of the leads and provide cooling air as required to maintain the lead temperature at a safe level.

The engine teardown revealed no failed ceramic engine components, including the NGK SN-84 silicon nitride turbine rotor and Kyocera SN-251 silicon nitride turbine shroud. The new flow separator support system, the diffuser support system, and the combustor insulation all performed satisfactorily. Only a minor turbine and compressor shroud rub were found during disassembly, attributed to a bore misalignment of the engine housing and compressor backshroud. The matched set of components was realigned and dowel pinned for the next engine test.

Build 20 (S/N 002C) of the all-ceramic radial AGT101 engine was tested to evaluate the remaining test bed improvements at elevated engine test conditions and demonstrate engine durability at maximum operating conditions of 90,000 rpm, regenerator inlet temperature (RIT) of 1800F, and turbine inlet temperature (TIT) of 2500F. To this end, Build 20 employed a Kyocera SN-251 silicon nitride fully-bladed radial turbine rotor and a Carborundum Co. Hexoloy SA silicon carbide combustor baffle.

The Build 20 engine successfully operated at a maximum measured TIT of 2379F at 80,000 rpm and RIT of 1800F. Secondary test goals for Build 20 were verification of variable inlet guide vane (VIGV) operation at speeds up to 70,000 rpm and final adjustment of ECU fuel control gains permitting operation of the engine over the full speed and power ranges. These goals were also successfully accomplished.

The ECU fuel gains and other operating parameters were successfully adjusted to provide stable engine operation from 55,000 to 90,000 rpm, under both VIGV and dynamometer engine loads. It was later recognized that further ECU adjustments to the maximum fuel schedule would have permitted a higher TIT to be achieved at 90,000 rpm. Subsequently, modifications to the slope of the fuel schedule curve were incorporated to provide additional fuel at the higher engine speeds.

Teardown of the Build 20 engine revealed no damage to any of the ceramic components. A slight rub indication between the regenerator core and shield was found to be caused by an oversized OD on the regenerator shield, which was remachined to correct the condition.

7.3 Engine Test Summary

During 1991, all planned engine test bed goals were successfully achieved. Compressor surge was eliminated, proper ECU operation was verified over all engine operating conditions, design improvements to the AGT101 test bed were demonstrated at maximum engine operating conditions, and an all-ceramic AGT101 radial engine successfully demonstrated durability at maximum operating conditions. No ceramic component failures occurred during engine testing. These accomplishments position the ATTAP program for continued successful testing during 1992.

8.0 PROJECT MANAGEMENT AND REPORTING

The ATTAP Milestone Schedule is shown in Figure 2. Milestone 4, Initiation of Component Testing to Full Design Conditions, has slipped beyond December 1991, due to later than anticipated deliveries of engine-candidate ceramic hardware. Ceramic component deliveries were made in late 1991.

GAPD issued six Bi-Monthly Technical Progress Reports during 1991 and conducted five Bi-Monthly Review Meetings with NASA/DOE.

GAPD personnel attended the "Twenty-Ninth Automotive Technology Development Contractors' Coordination Meeting" in Dearborn, Michigan, October 28 - November 1, 1991 and made a presentation reporting on ATTAP accomplishments over the past year: "ATTAP/AGT101 Ceramic Gas Turbine Technology Development" (GAPD Report No. 31-10187). At the Dearborn meeting, an additional presentation was made on the following ATTAP support program: "Life Prediction Methodology for Ceramic Components of Advanced Heat Engines" (GAPD Report No. 31-10186). These presentations will be published by the Society of Automotive Engineers (SAE) in the Proceedings of the Dearborn meeting. GAPD personnel made an additional presentation on the ATTAP effort in June, 1991 at the 36th International Gas Turbine and Aeroengine Congress and Exposition, in Orlando, Florida, sponsored by the American Society of Mechanical Engineers (ASME).

A book chapter summarizing the development of ceramics technology for gas turbine engines, in particular the DOE-sponsored AGT and ATTAP programs, was prepared by Dr. J.R. Smyth of GAPD and published by ASTM International, Materials Park, Ohio in Ceramics and Glasses, Engineered Materials Handbook Volume 4, pp. 995-1002, S.J. Schneider, Technical Chairman (ISBN 0-87170-282-7; GAPD Report No. 31-9571).

APPENDIX I

ANNUAL TECHNICAL PROGRESS REPORT
NORTON/TRW CERAMICS COMPANY

ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROJECT
COMPONENT DEVELOPMENT PROGRAM

ANNUAL TECHNICAL PROGRESS REPORT

for the period
January 1, 1991 through December 31, 1991

Work Performed Under GAPD Purchase Order Nos.
P11776307, P1772578, P1772588, P1772598, and P1772606.

Submitted By:
NORTON/TRW CERAMICS
Northboro, MA 01532-1545

Tony Taglialavore
Principal Project Engineer

Report Date: March 5, 1992

Prepared For:
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Phoenix, AZ 85034

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Norton/TRW Ceramics (NTC) completed its fourth-year effort of the ATTAP. Process and component development work continued for the AGT101 rotor and stator. Work during the year focused on development of component specific fabrication operations for engine quality hardware. From precision casting masters, NTC successfully produced, proof tested and delivered engine quality rotors and stators to GAPD. A summary of significant accomplishments for the year is given below.

- NT154 Silicon Nitride (Si_3N_4) - Characterization of NT154 continued during the year. A significant data-base of critical mechanical properties for this material exists both at NTC, GAPD, other engine builders and a number of independent laboratories. Flexural strength, fracture toughness, static and dynamic fatigue, creep, and thermal property information are available for engine design and analyses. Overall, properties for this material continue to exceed program specifications.

- NT164 Silicon Nitride - Through its experience with NT154, NTC has been able to develop a new highly creep resistant Si_3N_4. Designated NT164, this material has approximately four times the creep life of NT154 at 1370°C. This evolutionary achievement was realized by a slight change in overall composition, and by selective post-HIP heat-treatments. NT164's microstructure has no amorphous grain boundary phases. Because of this, NT164 has significantly higher hot strength ($\approx$690 MPa at 1370°C), and slightly higher fracture toughness ($\approx$6.4 $MPa \cdot m^{1/2}$) when compared with NT154.

- NT230 Siliconized Silicon Carbide (Si·SiC) - A new generation siliconized silicon-carbide (Si·SiC) was developed and introduced. Designated NT230, NTC is using this material to produce transition ducts for GAPD under a parts-supply contract. This material has approximately double the strength of existing Si·SiC compositions. At elevated temperatures (up to 1370°C), its strength is nearly equivalent to NT154.

- Casting System Development - In an effort to simplify the NT154 process, and as a prerequisite to aqueous based component casting, work was directed at developing water milling of NT154 powders. Substitution of water for alcohol in the current process was seen as necessary to improve product quality and reduced cost. An experimental matrix was planned and conducted using standard pilot level equipment. From water milled powders, casting trials were conducted for rotors, stators, tensile rods and test tile. Physical and mechanical properties were acquired on tile components. Casting techniques and properties were found to be equivalent with or superior to the current alcohol-based process. Pending the successful completion of additional limited trials in 1992, this process will be adopted.

- AGT101 Rotor Production - After completion of a limited amount of component specific casting development, hard tooling for the AGT101 rotor was ordered, process steps were firmly established and documented, and inspection plans implemented. Laboratory pressure casting was utilized for casting trials and the production of hardware. Impact-tolerant AGT101 rotors were successfully cast, densified, characterized, spin-tested and delivered to GAPD. Mechanical properties for these components met program requirements, and were comparable to data acquired from co-processed test-tile. A total of six components were spin tested. All exceeded the proof speed of 105 KRPM. Four components were delivered to GAPD. The remaining two were purposefully spun to failure. They failed at speeds of 126.6 and 118.9 KRPM, or 141% and 132% of maximum engine design speed, (i.e., ≈90 KRPM). Engine testing of this hardware by GAPD is planned in 1992. At the close of the year, NTC performed a comprehensive review of the entire rotor fabrication process. Corrective action was identified and has become part of NTC's 1992 Technical Work Plan. Improved rotor quality and yields are expected upon its implementation.

- AGT101 Stator Production - Following the receipt of a final stator design in early 1991, NTC ordered a precision casting master. Machining stock along with an allowance for isotropic shrinkage were applied to the design. After further casting trials and the completion of machining development activities, production of engine quality stators was initiated. Upon production of an initial set of components, NTC found that these parts did not meet print tolerances. An investigation revealed that the components exhibited anisotropic shrinkage. Consequently, print tolerances for the outside dimensions of the platforms were achieved because of the added machining stock; while the airflow passage was found to be restricted by ≈0.51mm. Following a discussion of this problem with GAPD, and with their approval, NTC continued production of the component. Production yields for this part were low due to a persistent green crack which occurred on the trailing edge of the vane next to one of the platform cleats. Despite this fact, NTC was able to prepare and deliver 24 engine quality parts. Mechanical properties for this hardware were evaluated and found to exceed ATTAP specifications. Data were consistent with rotors. An additional number of potentially acceptable components were also identified. Pending a joint review of these parts by NTC and GAPD personnel, a number of these components are to be delivered early in 1992. At the close of 1991, NTC performed a comprehensive review of the entire stator fabrication process. Corrective action was identified and has become part of NTC's 1992 Technical Work Plan. Part of this plan calls for the construction of new stator tooling, and improved mold design and casting procedures. Better quality stators and higher yields are expected upon implementation.

- HIP Development - NTC continues to perform a limited amount of long-term stress rupture testing for experiments which were initiated in 1990. Completion of this effort is expected in 1992.

- Process Engineering, NDE Development And Quality Assurance - Documentation of the NT154 process and component specific operations is complete. Revisions of these, as necessary, will be conducted for future hardware sets. Microfocus X-Ray Radiography (MFXR) and Fluorescent Dye Penetrant Inspection (FPI) are routinely conducted on all components. NTC's Quality System was audited by GAPD and found to be in conformance with their internal requirements.

- Deliverables - In addition to delivering 4 engine quality rotors and 24 engine quality stators, NTC also supplied 100 "as-processed" flexural test specimens and 43 tensile rods.

Continued effort in each of the above areas is scheduled for the 1992 program year. Work will again focus on component specific problems for the rotor and stator. Additional engine quality hardware sets will be prepared and delivered.

INTRODUCTION

Commercialization of advanced structural ceramics requires development of reliable component manufacturing processes. The Advanced Turbine Technology Applications Project (ATTAP) addresses this requirement. The ATTAP is a DOE-sponsored, 5-year ceramic component development program which utilizes the AGT101 gas-turbine engine as a functional test-bed. The goals of this program include: (1) The development and demonstration of reliable ceramic fabrication processes; (2) Production of the required ceramic components; and (3) Evaluation of these components in actual engine tests.

As a participant in ATTAP, and subcontractor to Garrett Auxiliary Power Division (GAPD) of Allied Signal Aerospace Company, Norton/TRW Ceramics (NTC) is developing ceramic fabrication processes for the AGT101 rotor and stator. NTC's effort centers on the development of controlled manufacturing processes for each component. NTC has performed work in accordance with GAPD's overall ATTAP program schedule. Based on GAPD's requirements, NTC has been responsive in the development of an annual detailed Technical Work Plan. During 1991, a Work Plan was prepared, and later revised due to budgetary restrictions. The revised plan is shown in Figure 48. This plan describes NTC's 1991 efforts for all major tasks and sub-tasks. Work performed during the year and summarized in this report fall within the following tasks: (1) Design and Cost Analysis; (2) Forming Methods; (3) Process Engineering; (4) NDE; (5) Quality Assurance; (6) Deliverables; and (7) Project Management. The report comprises a summary of NTC's activities for the fourth year of the ATTAP.

DESIGN AND COST ANALYSIS

Design - NTC has developed two principal materials for use in fabricating components under the ATTAP. They include NT154 Silicon Nitride (Si_3N_4), and NT230 Siliconized Silicon-Carbide (Si·SiC). NT154 is a 4% Y_2O_3-doped composition densified by hot isostatic pressing (HIP). HIPping is accomplished using glass encapsulation techniques. Assessment and characterization of this material has been conducted both at NTC, GAPD, and by other engine builders, or independent laboratories.[1-4] It continues to be one of the materials of choice for a number of DOE-sponsored heat-engine programs including the two major ATTAP contracts with GAPD and Allison Gas Turbine Division of General Motors Corporation. The material is also utilized in the ORNL/GAPD Life Prediction Methodology contract.* A fabrication flow chart and updated physical, thermal and mechanical properties for NT154 are given in Figure 49 and Table 17, respectively. NT154 possesses excellent flexural fast-fracture behavior up to 1370°C, accompanied by an acceptable Weibull Modulus. Failure origins have been associated with surface related machining flaws or internal impurities. Reported tensile strengths under fast-loading conditions parallel flexural tests. For tensile tests, principal failure origins were volume inclusions--generally identified as iron impurities. Under slow-loading conditions at elevated temperatures, creep and slow crack growth behavior have been characterized.[1-2,5]. NT154 exhibits creep through a cavity nucleation and growth mechanism. Failure occurs via cavity link-up. In comparison with other advanced materials, excellent durability has been noted; and NT154 remains as one of the

* Life Prediction Methodology For Ceramic Components Of Advanced Heat Engines, ORNL Contract No. 86X-SC674C.

Figure 48 - NTC's 1991 Technical Work Plan

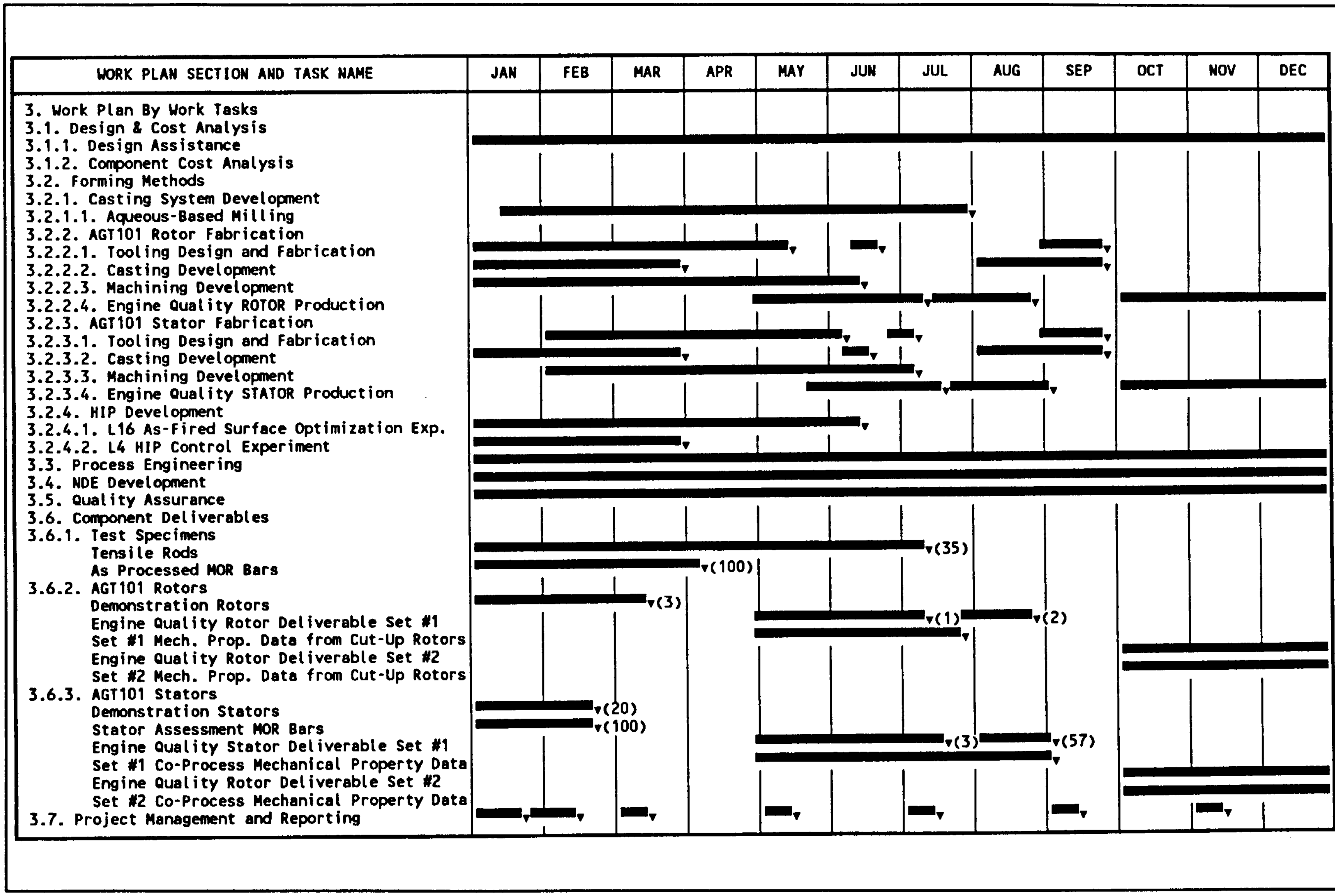


Figure 49
NT154 Process Flow-Chart

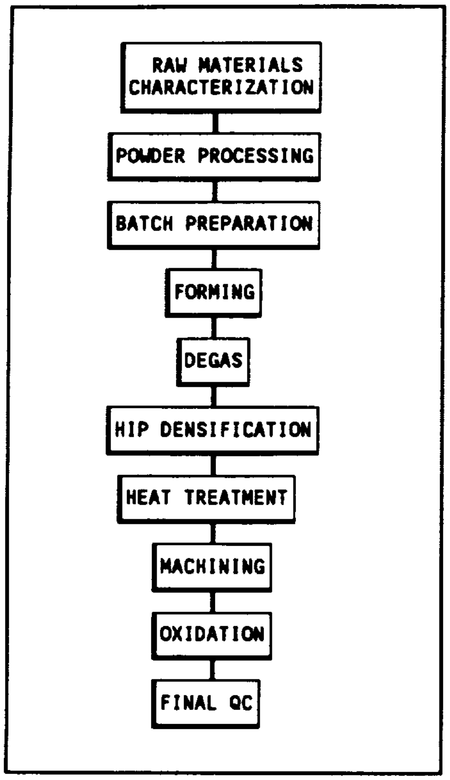


Table 17
Properties of NT154 Si_3N_4

Properties	Values
1. Density (g/cc)	3.232 ± 0.004
2. Elastic Modulus (GPa)	310 - 320
3. Shear Modulus (GPa)	126
4. Poisson's Ratio	0.273
5. Hardness (Kg/mm^2)	1620
6. Thermal Expansion Coefficient	3.93 x 10^{-6}/°C
7. Thermal Conductivity (W/m°K)	
(25°C)	37.6
(900°C)	20.7
(1400°C)	15.8
8. 22°C Mechanical Properties	
Average Flexural Strength (MPa)	890 - 960
Characteristic Strength (MPa)	≈980
Weibull Modulus	8 - 19
Fracture Toughness (MPa·m^{½})	4.7 - 7.5*
Tensile Strength (MPa)	700 - 920**
9. 1370°C Mechanical Properties	
Average Flexural Strength (MPa)	520 - 650
Characteristic Strength (MPa)	≈600
Weibull Modulus	11.4
Fracture Toughness (1200-1400°C MPa·m^{½})	4.1 - 13*
Tensile Strength (MPa)	240 - 520***
10. 1260°C Tensile Creep Rate (300 MPa)	1.9 x 10^{-8}
11. 1370°C Tensile Creep Rate (200 MPa)	8.7 x 10^{-7}

* Chevron Notch or Controlled Flaw Methods; NT154 exhibits R-Curve Behavior. Higher values are for crack extensions of ≤ 1 mm; (NTC and UDRI Data).
** Includes CIP and Cast Samples, (UDRI and ORNL Data).
*** Loading Rate Dependent, (UDRI and ORNL Data).

foremost high-temperature ceramic materials available today.

NTC utilized the experience in processing NT154 to make several alternations within the material itself in an effort to improve properties. Recent research has focused on slight changes to the glass phase composition, along with adjustments to selected heat-treatment schedules. These modifications resulted in an improved version of NT154, which NTC has designated NT164. NT164 has slightly better room-temperature properties, particularly fracture toughness. However, significant improvements are noted in high-temperature strength and creep resistance. Typical NT164 properties are presented in Table 18. These data were generated by NTC and ORNL. A comparison of the creep behavior of both NT154 and NT164 are shown in Figure 50. NT164 has four times the expected creep life of NT154 at 1370°C. NT164 derives its enhanced high temperature strength and creep resistance from the fact that it has no amorphous grain boundaries. As demonstrated by the TEM photographs of Figure 51, the intergranular glassy phase present in NT154 is fully crystallized in NT164. NTC continues to increase its data base on NT164, and will be introducing this material to engine builders during 1992. It is conceivable that further improvements to NT164 can be achieved by selective process development work, similar to efforts performed under the ATTAP for NT154.

Table 18
Properties of NT164 Si_3N_4

Properties	Values
1. Density (g/cc)	3.190 ± 0.004
2. 22°C Flexural Strength (MPa)	910 ± 90
3. 22°C Weibull Modulus	17
4. 22°C Fracture Toughness ($MPa \cdot m^{1/2}$)	6.4 ± 0.1
5. 1370°C Flexural Strength (MPa)	689 ± 28
6. 1400°C Flexural Strength (MPa)	648 ± 41
7. 1425°C Flexural Strength (MPa)	607 ± 28
8. 1450°C Flexural Strength (MPa)	510 ± 21
9. 1500°C Flexural Strength (MPa)	394 ± 21
10. 1260°C Tensile Creep Rate (300 MPa)	2.2×10^{-9}
11. 1370°C Tensile Creep Rate (200 MPa)	1.0×10^{-8}

Density, Flexural Strength, Weibull Modulus And Fracture Toughness Data Were From Pressure Cast Samples, (5 - 20 Data Points Each). Fracture Toughness Was Evaluated Using Controlled Flaw Methods. Tensile Creep Values Determined For CIP Tensile Rods Using ORNL Design And Data.

Figure 50
Creep Behavior Of NT154 And NT164 Si_3N_4 At 1370°C

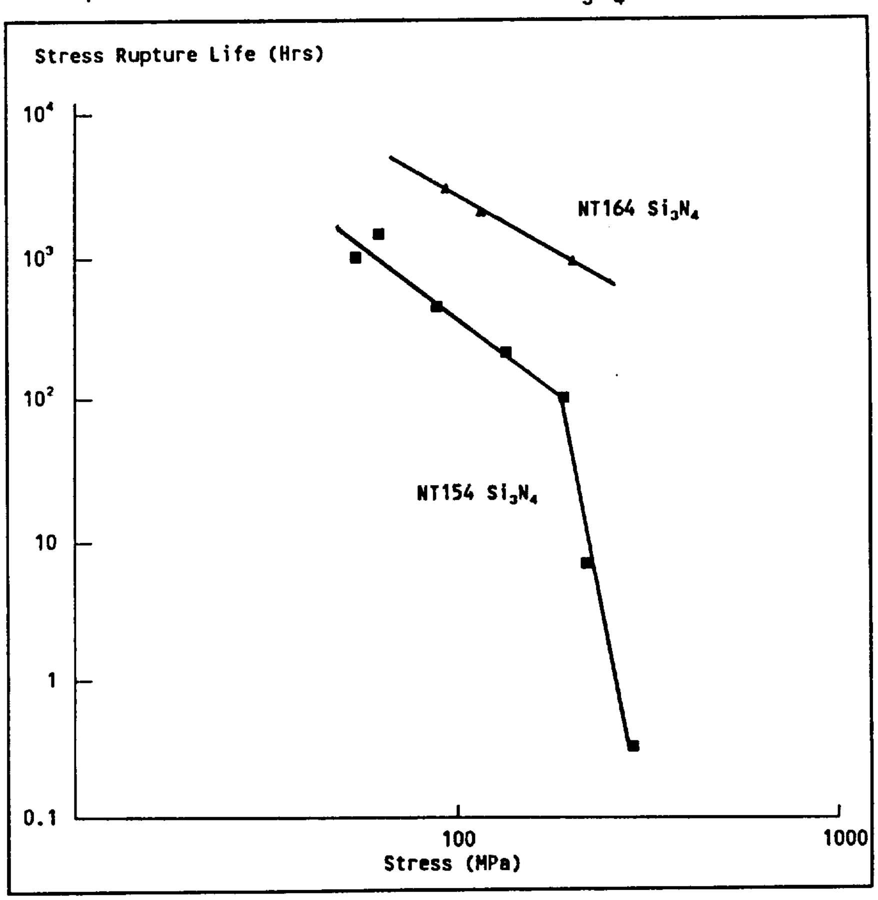
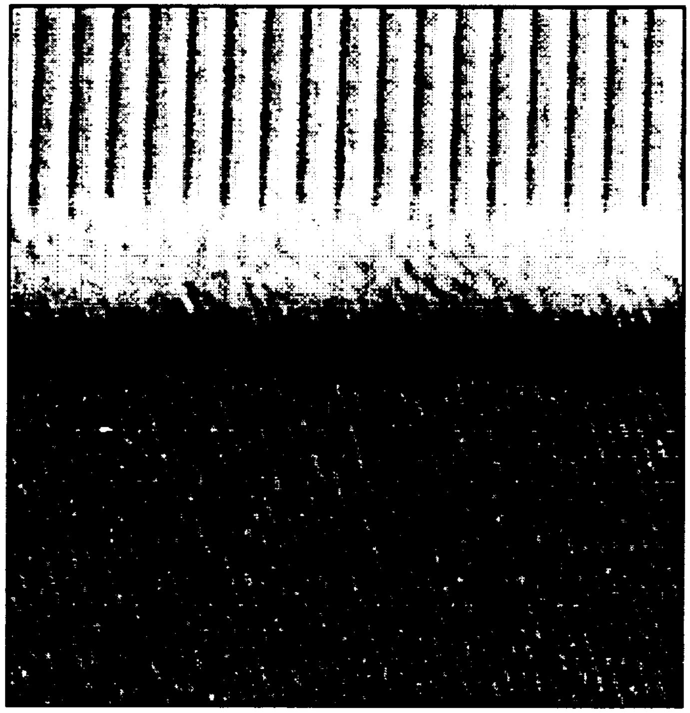
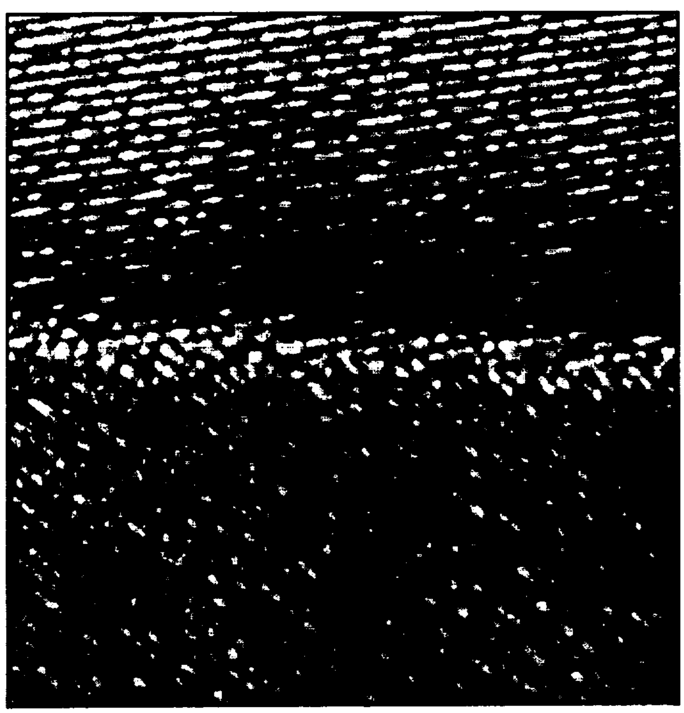


Figure 51
TEM Photographs Of NT154 And NT164 Si_3N_4

TEM of NT154
Grain Boundary



TEM Of NT164
Grain Boundary



NT164 SHOWS NO AMORPHOUS GRAIN-BOUNDARIES

During 1990-91, NTC completed an IR&D development program on improving Norton's siliconized silicon carbide (Si·SiC). NTC investigated Si·SiC because of its potential as a static-structural material within advanced gas turbine engines. Initial studies utilized an existing Si·SiC, designated NT235. This material has been previously examined for heat-engine applications [6-7], and is commonly known under a Norton designation as NC430, or *Crystar*™.[8-9] These products are densified, reaction-sintered silicon carbides featuring a bimodal distribution of silicon carbide grains and metallic silicon. Compositionally, they contain between 5 and 15% silicon, along with extremely low levels of trace impurities. NTC's efforts were directed at improving the mechanical behavior of these Si·SiC composites. By modification of the grain size distribution, and through selective changes to the fabrication process (Figure 52), NTC was able to essentially double the strength of existing Si·SiC compositions. A new material resulted from this effort--designated NT230. Typical material properties for NT230 are shown in Table 19. This material is an ideal candidate for static structural components within the engine at temperatures below about 1400°C. Siliconized silicon carbides, and NT230 in particular, exhibit an interesting behavior. Strengths at elevated temperatures (up to 1370°C) are higher than room temperature values. Improvements have been attributed to increases in fracture toughness associated with localized flaw blunting.[10] Above about 1400°C, reductions in strength are noted due to the softening and melting of the silicon phase. This material is an ideal candidate for static structural components within the engine at temperatures below about 1400°C. Due to the fact that the material exhibits little or no shrinkage upon densification, complex large components such as scrolls, combustors, shrouds and transition ducts

Figure 52
NT230 Process Flow Chart

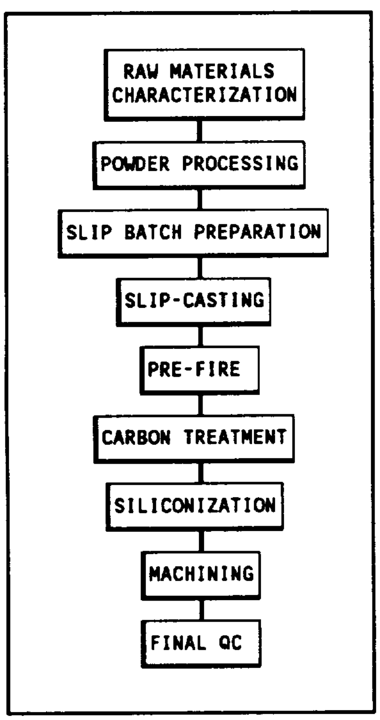


Table 19
Properties of NT230 Si·SiC

Properties	Values
1. Density (g/cc)	3.05
2. Elastic Modulus (GPa)	395
3. Shear Modulus (GPa)	165
4. Poisson's Ratio	0.17
5. Hardness (Kg/mm^2)	≈1620
6. Thermal Expansion Coefficient	$4.7 \times 10^{-6}/°C$
7. Thermal Conductivity (W/m°K)	
(25°C)	≈135
(1000°C)	36
8. Flexural Strength	
(25°C)	410
(1260°C)	540
(1370°C)	500
Weibull Modulus	8-10
9. Fracture Toughness ($MPa \cdot m^{1/2}$)	
(25°C)	3.2*
(25°C)	3.2**
(1370°C)	8.1*
(1370°C)	5.5**

* Controlled Flaw Method at 25°C and 1370°C, respectively.
** Single Edge Pre-cracked Beam Method at 25°C and 1370°C, respectively, ORNL Data.

can be readily produced to near final size. Also, because NT230 utilizes low cost raw materials and excludes HIP as the densification step, total material and processing costs remain relatively low in comparison with NT154 or NT164 Si_3N_4. NTC is utilizing NT230 for the production of ATTAP transition ducts for GAPD under a fixed-price parts-supply type contract.

Cost Analysis - NTC performed no formal cost analyses work during the year. A cost analysis task for the NT154 process is scheduled as part of the ATTAP during 1992.

FORMING METHODS

In accordance with NTC's 1991 Work Plan, sub-tasks within Forming Methods include: (1) Casting System Development; (2) AGT101 Rotor Fabrication; (3) AGT101 Stator Fabrication; and (4) HIP Development.

Casting System Development - During 1990, NTC completed experimental efforts on two concepts in casting development: (1) PEEP Casting (Pressure-assisted Endothermic Extraction Process); and (2) WEEP Casting (Water Endothermic Extraction Process). Upon completion of this work, the PEEP process was chosen for the production of components. Yet within the PEEP process itself, two conceptual variations were identified. As shown in Figure 53, PEEP methods involve either: (1) Agglomeration and calcination of alcohol milled raw materials; or (2) Aqueous milling and controlled flocculation of the same materials. NTC has found that the agglomeration step within the process is necessary for the production of crack free rotors; although stators have been produced exclusive of agglomerated powders. (Cross-sectional thickness appears to account for the need to use agglomeration methods for rotors.) Yet, for consistency, NTC has standardized on the use of agglomerated materials. Standard procedures have been written for the agglomeration process and statistical process control (SPC) methods implemented. However, NTC personnel were concerned that impurities associated with the agglomeration operation itself, and the number of required process steps could lead to higher product variability. Therefore, as part of its 1991 Technical Plan, NTC worked to develop aqueous-based milling to substitute for the current alcohol milling process. Aqueous-based milling reduces the number of process steps; but more importantly, it is a prerequisite to the use of controlled flocculation methods--which could be a part of future ATTAP efforts.

NTC conducted a simplified experiment to replicate alcohol milling operations using water as the fluid medium. The experiment involved four milling trials using a production size mill. Solids loading, media to powder ratio, dispersant content, and milling time were varied. Experimental tests included the determination of viscosity, pH, powder chemistry, particle size, and surface area. After completion of the first three trials, conditions were identified which replicated alcohol based powders in every measurable attribute. Using selected conditions, a single 20 kg qualification lot was then prepared. The resulting powder was agglomerated, calcined, and used in comparative casting trials for test-tile and components. The pressure casting behavior of the material was demonstrated to be equivalent to the standard NT154 process. Tile, tensile rods, AGT101 rotors and stators were all successfully cast. All components were processed through the presintering step without loss. From this point, only tile components were HIPed and crystallized. These parts were machined into test bars, oxidized and assessed for mechanical properties. Results of these tests are given in Table 20. As compared to typical alcohol-milled NT154, the aqueous-milled material is equivalent or better at all temperatures. Tensile rods have been fabricated from the water-milled powder. As of year-end they are being processed through machining, oxidation and testing. Tensile fast fracture and stress rupture testing will be conducted using these rods. Provided successful results are obtained, the water milling process will become fully qualified, based on mechanical properties, for use in the fabrication of deliverable rotor and stator components. Upon qualification, the pre-sintered rotors and stators (fabricated earlier in the year) will be densified to obtain shrinkage information. Pending joint approval between NTC and GAPD of this process change, this improvement will be used for engine quality components during 1992 and beyond.

AGT101 Rotor Fabrication - As part of NTC's 1991 Technical Work Plan, each set of deliverable rotors were produced from defined and qualified processes. Iterations, as necessary, were performed prior to component production. They mainly involved work in the following three sub-tasks: (1) Tooling Design and Fabrication; (2) Casting Development; and (3) Machining Development. These tasks were directed at defining features and achieving dimensional tolerance. Once these various parameters were set, rotors were produced under identical fixed processes.

Tooling Design and Fabrication - From work performed in 1990 using stereolithographic patterns, NTC optimized basic casting tooling and mold designs. Demonstration hardware was prepared early in 1991, and subsequently delivered to GAPD. This demonstration hardware served to define final shrinkage for engine quality components. An oversized stainless steel casting pattern of the rotor was fabricated and delivered to NTC in April. Inspection results confirmed dimensional conformance to NTC's pattern design specifications including the application of an isotropic shrink factor, and the addition of machin-

Figure 53
NT154 Process Flow Diagram

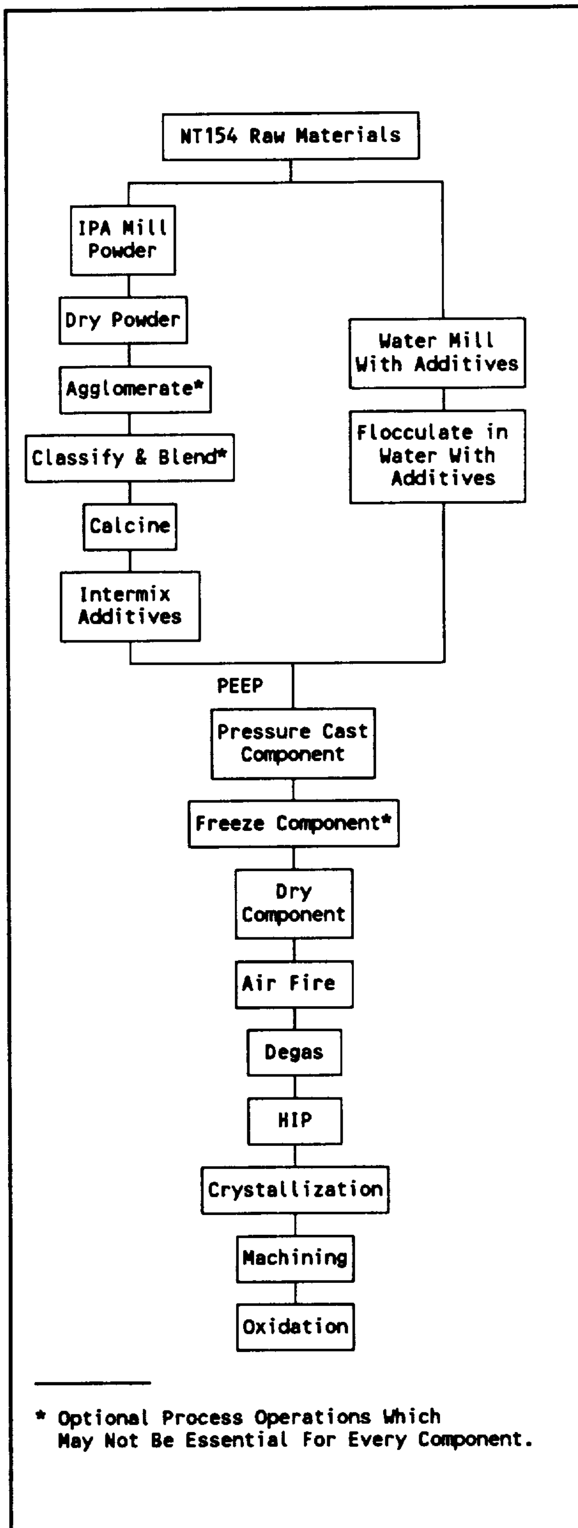


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Table 20
Aqueous-Milled NT154 Mechanical Properties

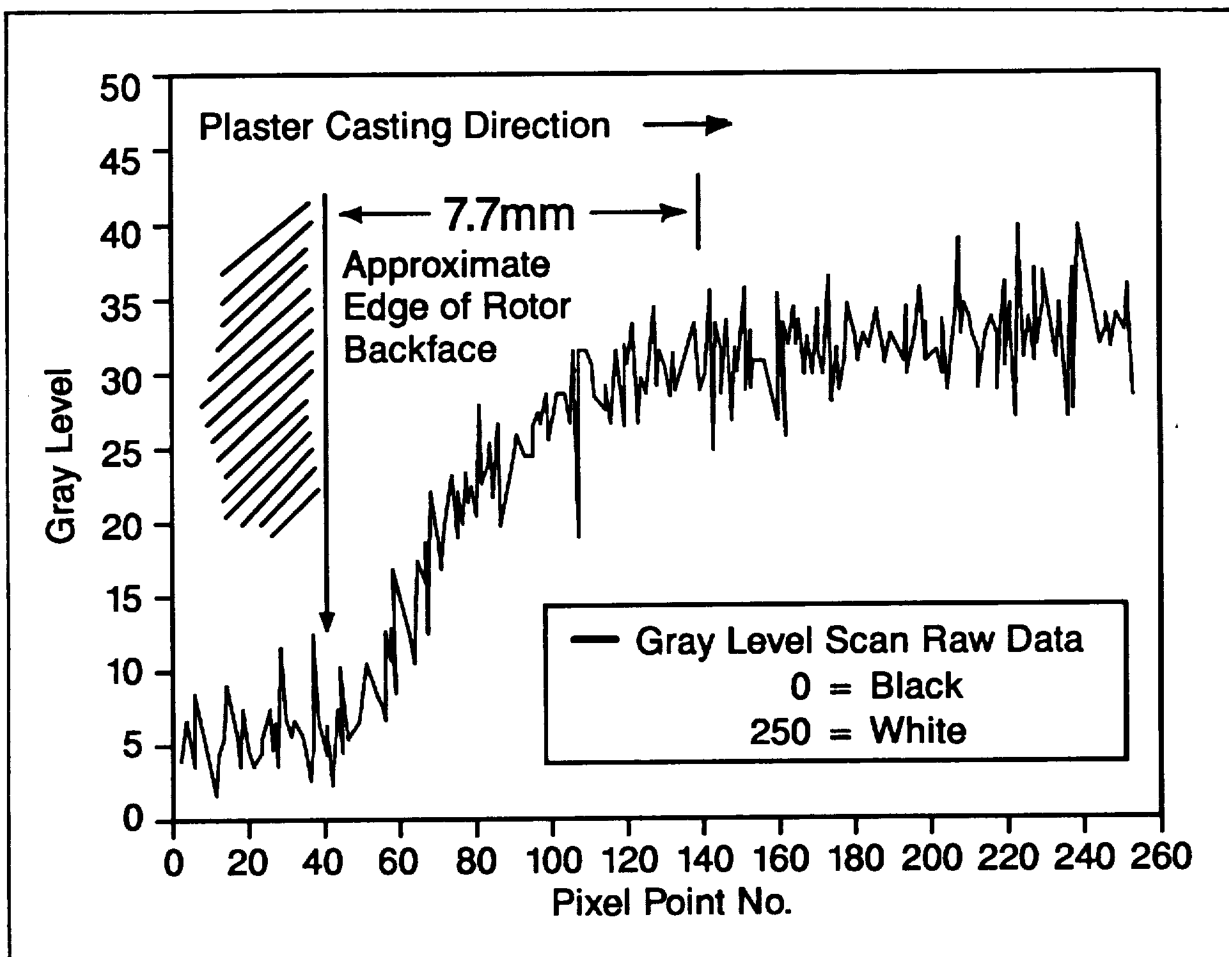
Property	Typical Alcohol-Milled Pressure Cast NT154	Aqueous-Milled Pressure Cast NT154
I. Fracture Toughness ($MPa{\cdot}m^{1/2}$)	5.5 ± 0.1 (5)	6.2 ± 0.1 (5)
II. Flexural Strength (MPa)		
22°C	862 ± 172 (20)	1000 ± 69 (30)
1260 °C	690 ± 21 (5)	682 ± 28 (5)
1370 °C	607 ± 21 (5)	648 ± 28 (20)
1400 °C	600 ± 35 (5)	641 ± 14 (5)
1425 °C	503 ± 21 (5)	572 ± 28 (5)
1450 °C	420 ± 14 (5)	503 ± 14 (5)
1500 °C	317 ± 41 (5)	296 ± 14 (5)
III. Stress Rupture		
1370°C and 300 MPa	100% (8)*	100% (8)*
1370°C and 325 MPa	50% (4)	-
1370°C and 350 MPa	50% (4)	-
1370°C and 400 MPa	25% (4)	-

Numbers in parentheses represent the quantity of specimens tested.
* Survival rate on testing to ≥ 150 hours.

ing stock on the rotor backface and shaft diameter. Scaled (shrink factor removed) 10X plots of actual L and Z section dimensional contours were prepared by NTC's tooling vendor. These plots were checked against 10X mylars of the nominal L and Z section contours provided by GAPD. Results showed minor dimensional deviations in the L and Z section mylars, but tolerances were within acceptable limits for rotor fabrication. NTC then utilized this steel pattern to prepare a number of plaster/plastic casting molds for engine quality rotor production.

Casting Development - During 1990, extensive process development was performed for AGT101 rotors. This included work on slip preparation, casting techniques for agglomerated powders, mold design and engineering, component fabrication practice, and optimization of bulk and as-fired surface properties. Preferred conditions were selected from these various studies and demonstration hardware were initiated into production using stereolithographic masters as patterns. During casting of some of this hardware, NTC experienced cracking of blade and hub features. NTC believed that part of this cracking problem was associated with minor green density gradients which develop during the casting process. Based on our understanding of the mechanism of cast layer buildup, a lower green density is expected in initial cast layers adjacent to porous mold surfaces. This occurs because the rate of particle deposition in these regions is very high. Consequently, individual particles are constrained from rearrangement. NTC has attempted to determine the existence of density gradients, but previous experiments using standard immersion wax measurement techniques proved inconclusive. Microfocus x-ray radiography (MFXR) was also investigated as a potential technique for characterizing this problem. To demonstrate the validity of MFXR methods, an AGT101 rotor was presintered, sectioned to a slice thickness of approximately 6.4mm, and surface ground flat and parallel. This rotor slice was characterized by MFXR at 1X magnification. A line-scan through the axial center of the rotor slice was then performed on the developed MFXR negative using a film digitizer. Film densities were quantified for 575 pixel points over a gray level range of 0 (black) to 250 (white). A graph of gray level versus consecutive pixel point number is shown in Figure 54. The data show increasing gray levels starting from the rotor backface, (which was the mold drawing surface), to approximately 7.7 mm into the casting. The increase in gray level corresponds to an increase in green density. This result therefore confirms the existence of a density gradient in the near-surface region, and its presence is consistent with high initial casting rates predicted from theory. Characterization of relative green density gradients using MFXR and film digitization appears to be a valid technique, but quantifying absolute green density values will require further study. It was estimated that the change in density between the surface and bulk ranged between one and three percent. A green density gradient is undesirable because it can lead to the development of surface tensile stresses upon drying. If these stresses are higher than the intrinsic green strength, a crack

Figure 54
Gray Level Line Scan Of A MFXR Film From An AGT101 Rotor Section



will develop during drying beginning at the surface and proceeding towards the center of the rotor shaft. For components which possess cracks, this type is the most common. To mitigate this problem a reduction of the initial casting rate is needed. Using plaster molds, the initial casting rate is determined by the suction pressure of the mold along with applied line pressure. Since all of NTC's 1991 components were cast using plaster molds, procedural adjustments in applied line pressure were performed to minimize gradients. Ultimately, this problem can be solved through the use of porous plastic molds and automated equipment. Porous plastic materials will not exhibit suction pressure, and the use of automated equipment will allow the application of a programmed pressure profile. Control over the pressure profile is a key element in suppressing density gradients. Work on these techniques is part of NTC's 1992 effort.

Using preferred casting conditions, NTC proceeded to fabricate a number of demonstration rotors using a fixed process. Approximately 10 components were prepared. A number of these were retained for machining development. A second group was reserved for cut-up and mechanical property assessment, and three parts were delivered to GAPD in March as demonstration of the process. A summary of flexural properties for these components is reported in Table 21. Stress rupture results are shown in Table 22. Values are consistent with ATTAP specifications and prior data. With the delivery of this hardware, NTC fixed and fully documented the casting and densification process to be used in the production of engine quality components.

Machining Development - In accordance with NTC's technical plan, NTC developed machining practice for both green and dense components. Green machining development focused on fabrication of the internal attachment feature of the rotor shaft. Efforts included performing limited machining tests, defining detailed standardized process operations, and production of a first article which met all dimensional requirements. Work was successfully completed using demonstration hardware.

For dense machining, effort focused on component specific machining issues. These included methods for grinding the rotor back face, ID and OD of the shaft and blade edges. NTC developed the necessary fixturing and CNC programming to perform this work; then proceeded to verify their correctness by machining a phenolic resin model of the AGT101 rotor. After several minor iterations in tooling and CNC programs, a fixturing method and machining approach were selected. A dense first-article rotor was then ground to confirm corrective action. Machining of this component was conducted in less than 10 hours total cycle time, including set-up, inner and outer surfaces of the shaft, blade edges and backface. Upon inspection, some minor dimensional deviations were noted and corrective action

Table 21
Flexural Properties Of
AGT101 Demonstration Rotors

I. K_{IC} (MPa·m^{½})	4.9 ± 0.10 (3)*
II. Flexural Strength	
Temperature (°C)	(MPa)
21	841 ± 110 (30)*
1093	655 ± 43 (5)
1204	586 ± 97 (5)
1260	607 ± 55 (5)
1316	552 ± 34 (5)
1370	538 ± 21 (5)

* Number in parentheses represent samples tested at each temperature.

Table 22
Stress Rupture Life (Hrs) For AGT101 Demonstration Rotors

	Temperature (°C) and Load (MPa) Conditions							
	1204	1204	1260	1260	1316	1316	1370	1370
Test Bar ID No.	350	400	350	400	200	250	200	250
579-872-1	163.7							
579-872-2	150.5							
579-872-3	150.5							
579-872-4		5.5*						
579-872-5		150.7						
579-872-6			163.6					
579-872-7			8.6*					
579-872-8			154.7					
579-872-9			6.7*					
579-872-10				163.7				
579-872-11					163.7			
579-872-12					163.7			
579-872-13					164.6			
579-872-14						164.6		
579-872-15						154.2		
579-872-16							163.7	
579-872-17							163.7	
579-872-18							164.6	
579-872-19								26.2*
579-872-20								0.6*

* Premature Failure.
Test bars were 3mm x 4mm x 50mm; Outer span = 40mm; Inner span = 20 mm.

was taken to eliminate these problems for the engine quality rotors. Sufficient information was obtained to consider the machining process to be qualified for use in the production of engine quality components. The process was therefore fixed and documented.

Engine Quality Rotor Production - Efforts during the year focused on fabrication of NTC's first set of deliverable hardware. Additional sets are due in 1992. Following developmental activities, NTC completed all pre-engineering tasks necessary for production. These included finalization of drawings and tooling requirements, defining and documenting detailed process operations, developing a proof spin test procedure, and an overall component inspection plan. All engineering work was completed and implemented prior to the beginning of rotor fabrication. NTC investigated and selected subcontractors for balancing, spin-testing and coordinate measuring machine (CMM) inspection. A total of twenty-four rotors were cast under the fixed process. Eight of these were rejected due to casting defects. An additional seven were rejected after furnacing operations, or due to handling defects and minor blade cracks. Two were cut-up to generate mechanical property information. The remaining seven were successfully machined, balanced and oxidized. After completion of these operations, one additional part was rejected due to a fluorescent dye penetrant indication. Four of the remaining components were successfully spin-tested to 105 KRPM and delivered to GAPD. The remaining two rotors were purposefully spin-tested to failure in order to determine failure location and speed limit. These parts failed at

Table 23
NT154 Si_3N_4 AGT101 Engine Quality Rotors

Rotor Identification No.	December 31, 1991 Status
632-950	Passed 105 KRPM Proof; Delivered To GAPD 10/4/91
646-953	Passed 105 KRPM Proof; Delivered To GAPD 10/30/91
650-953	Passed 105 KRPM Proof; Delivered to GAPD 10/30/91
654-952	Post-Balance Rejected by NTC Due to FPI Indication
654-953	Passed 105 KRPM Proof; Delivered to GAPD 11/25/91
653-950	Purposefully Burst Test; Failure at 126.6 KRPM
657-953	Purposefully Burst Test; Failure at 118.9 KRPM

126.6 and 118.9 KRPM, or 141% and 132% of full engine design speed (i.e., 90 KRPM). Table 23 summarizes the status of the seven engine quality rotors fabricated during 1991. A photograph of two of these components is presented in Figure 55. Mechanical property data from cut-up rotors and co-processed tile are presented in Table 24. These values clearly exceed ATTAP specifications, and are typical of the current fixed, alcohol milling process.

After completion of all activities associated with the delivery of this hardware, NTC performed a complete review of the fixed process utilized in the production of these components. Issues requiring improvement were identified and a corrective action plan was formulated. Its implementation is part of NTC's 1992 Work Plan. Efforts will be directed at improving the quality and yields for deliverables in 1992.

AGT101 Stator Fabrication - In a similar fashion to the rotor fabrication task, each set of deliverable stators during 1991 were produced from a defined and qualified process. Iterations, as necessary were performed prior to component fabrication; and were performed in the following sub-tasks: (1) Tooling Design and Fabrication; (2) Casting Development; and (3) Machining Development. Following the completion of these required activities, engine quality stators were fabricated using a fixed documented process.

Tooling Design and Fabrication - During 1990, NTC performed a number of casting trials utilizing a stereolithographic master as the casting pattern. This work served to define most issues related to plaster mold design, gate location, and other casting parameters. During early 1991,

Figure 55
NT154 Si_3N_4 AGT101 Rotors

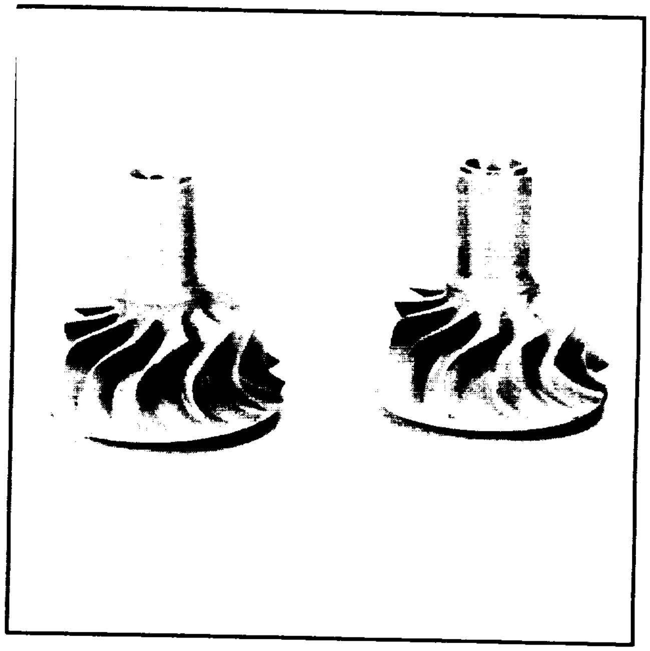


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Table 24
Mechanical Properties For AGT101 Rotors And Co-Processed Tile

Mechanical Property	Rotor Cut-Ups	Co-Process Tile
I. K_{IC} (MPa·m$^{1/2}$)	5.2 ± 0.1 (6)	5.4 ± 0.2 (12)
II. Flexural Strength (MPa)		
22°C	935 ± 111 (40)	828 ± 84 (86)
1204°C	667 ± 71 (9)	-
1260°C	669 ± 35 (15)	-
1315°C	643 ± 26 (9)	-
1370°C	580 ± 46 (9)	609 ± 47 (53)
II. Stress Rupture Life*		
1370°C/300 MPa	N/A	[3 of 4]
1260°C/375 MPa	[4 of 4]	N/A
1260°C/414 MPa	[4 of 4]	N/A

Numbers in parentheses represent the quantity of specimens tested
* Number to survive without failure to >150 hours

the stator mold design was further refined by changing the gate location from the air-foil to the outer platform surface, and by incorporating platform protrusions in accordance with a design revision from GAPD. Final prints for the stator were received from GAPD in early 1991. NTC then ordered a metal casting pattern from a selected subcontractor. This pattern incorporated an isotropic shrinkage factor in addition to machining stock on platforms, slash angles, OD and ID surfaces. The pattern was received and inspected early in June. A minor amount of re-work was identified to achieve correct feature and tolerance. This was accomplished, and the pattern was re-delivered by the end of June. A number of casting molds were then fabricated to verify the achievement of geometry and tolerance. Casting trials were conducted as part of the Casting Development sub-task. Following minor modifications, additional molds were prepared for the Component Production sub-task. NTC utilized this pattern and its molds for the preparation and delivery of engine quality stators in 1991. Upon completion of the production sub-task, NTC performed a comprehensive review of the entire stator fabrication operation. As part of this review, it was determined that a new pattern should be ordered for use in the producing the second set of deliverables due in 1992. Utilizing the experience gained during the first deliverable set, the design of the second generation pattern incorporates features which NTC expects will greatly improve castability and overall process yields. One of the problems with the first generation design was the use of an isotropic shrinkage factor. In actual practice, it was found that the stator exhibits anisotropic shrinkage. Platform to platform shrinkage was larger than chord length shrinkage. NTC attempted to account for this difference by adding additional machining stock to the outside of the platforms; but underestimated the shrinkage effect on the inside of the platforms. The resulting stators were produced with proper features and tolerance on the outside but a narrower flow passage of ≈0.51mm. Consequently, the second generation pattern accounts for this bi-directional shrinkage, and should produce dimensionally correct components. Delivery of the second generation pattern is expected in early 1992.

Casting Development - Efforts performed during 1990 using a stereolithographic master served to define the basic stator mold design and casting process. From this technology, NTC was able to produce and deliver a set of 20 demonstration stators to GAPD in February. Mechanical properties for these parts were evaluated from co-processed tile.

Results for flexural strength and stress rupture are presented in Table 25 and Table 26, respectively. These data exceed ATTAP specifications and are consistent with prior values generated from the casting process. These trials served to refine NTC's mold design and casting procedures. Following the delivery of these demonstration components, the casting process was fixed and documented for the production run-off of engine hardware. After receipt of the production casting master, molds were prepared and a limited production run-off initiated. At this point it was discovered that the anisotropic shrinkage of the stator resulted in dimensional deviations on the inside of the platform which could not be corrected without construction of a new master. In addition, due to the protrusions on the platforms and other persistent casting defects, component yields were lower than anticipated. Nevertheless, after discussion with GAPD personnel, NTC elected to proceed with production of these components. After the first set of engine quality deliverables were completed, NTC performed a comprehensive review of the entire casting process and developed a corrective action plan. This plan, which includes changes to the pattern and modifications of specific casting procedures, has become part of NTC's 1992 technical effort.

Machining Development - Due to the complexity of the stator and to ensure the timeliness of component deliveries, NTC initiated parallel machining development with two shops in 1991. Fixture design, fabrication, and machining trials were conducted internally using NTC's own shop and resources. In addition, an external vendor was also contracted to perform this work. Machining development was completed by both organizations. Due to the stator casting being narrow by ≈0.5mm within the platforms, NTC proposed and received approval from GAPD to move the positions of datum E_1 and E_2 by ≈0.13mm and ≈0.25mm, respectively. These slight changes were necessary in order to finish grind and clean-up the external features of the stator. With these adjustments, a first article component was delivered by NTC's external vendor in October. NTC performed CMM inspection on this part and found that all machined surfaces met print requirements. The component was forwarded to GAPD for their review. Shortly after this accomplishment,

Table 25
Flexural Properties For AGT101 Demonstration Stators

Temperature (°C)	Flexural Strength (MPa)	Weibull Modulus	Fracture Toughness ($MPa\cdot m^{1/2}$)
21	848 ± 83 (63)*	12.2	5.65 ± 0.14 (20)
1093	648 ± 41 (5)	-	-
1204	641 ± 21 (5)	-	-
1260	572 ± 55 (31)	11.7	-
1316	600 ± 23 (5)	-	-
1370	544 ± 48 (31)	12.4	-

* Number in parentheses represent samples tested at each temperature.

Table 26
Stress Rupture Life (Hrs) For AGT101 Demonstration Stators

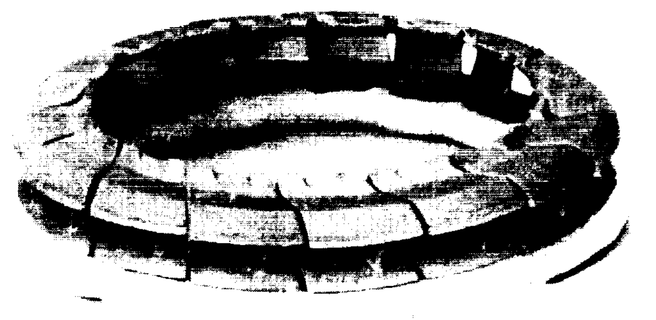
	Temperature (°C) and Load (MPa) Conditions							
Test Bar ID No.	1204 350	1204 400	1260 350	1260 400	1316 200	1316 250	1370 200	1370 250
558-1	163.5							
556-2	163.5							
558-3	153.7							
556-4		153.7						
558-5		163.7						
558-1			163.5					
558-2			163.5					
558-3			153.7					
556-4				153.7				
556-5				163.6				
558-1					168.3			
556-2					168.3			
558-3					163.8			
556-4						163.8		
558-5						160.7		
556-1							160.8	
558-2							160.8	
556-3							160.8	
556-31								166.4
556-32								166.4
556-33								163.3
556-34								163.3
556-35								164.2

Test bars were 3mm x 4mm x 50mm; Outer span = 40mm; Inner span = 20 mm.

NTC's internal shop completed its machining development efforts and produced four first article stators. These components were subjected to CMM inspection and found to meet all print tolerances for external features as well. Although NTC's internal machining process was qualified and determined to be capable of producing dimensionally correct components, NTC elected to delay further efforts with its own shop in favor of completion of the job by the external vendor. This decision was based principally on timeliness of delivery.

Engine Quality Stator Production - Based on the initial limited success of NTC's developmental activities, production of engine quality stators was initiated. A total of 323 components were cast. Of these, only 108 were qualified for densification. Following HIPing, 74 were determined to be acceptable for finish machining. A photograph of this hardware prior to machining is shown in Figure 56. A very small, yet persistent trailing edge crack which wrapped around one of the outer platform cleats resulted in the large amount of rejected components. This crack was difficult to detect during post-casting visual inspection; but was easier to identify after the presinter operation using MFXR techniques. However, a significant number of parts (≈38) possessed HIP healed versions of this same crack after densification. Liquid dye penetrant inspection was able to effectively sort out the remaining acceptable components. After an extensive review of the casting process, NTC believes this crack occurred during de-molding. It resulted from stress generated by the difficult release of the outer platform cleat. Release is expected to improve via changes to the casting pattern, mold design, and mold separation procedures. Appropriate corrective action has become part of NTC's 1992 Technical Plan.

Figure 56
AGT101 Stator Ring Set



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From the acceptable dense castings, a total of 61 were machined during the year using NTC's external grinding vendor. Twenty-four (24) of these parts were received and passed final inspection without exception. These components were delivered to GAPD in December. Mechanical properties from co-processed tile are given in Table 27. Data for this hardware exceed ATTAP specifications, and are consistent with the NT154 casting process. As of the close of the year, an additional 13 parts were being machined for inspection and delivery in January. Delivery of these 13 components along with the inspection and delivery of the balance of the 61 parts machined previously were delayed pending an on-site review of each part by GAPD personnel. Subsequent to review and approval by GAPD, it is expected that a significant number additional stators will be delivered to GAPD in early 1992. This will complete all of NTC's stator deliverables for the first engine quality group of components. Effective in January 1992, NTC will implement all planned corrective action for these components to improve quality and yield for the second batch of hardware due later in 1992.

Table 27
Mechanical Properties For AGT101 Stators From Co-Processed Tile

Mechanical Property	Co-Processed Tile
I. K_{IC} (MPa·m^{½})	5.82 ± 0.15 (3)
II. Flexural Strength (MPa)	
22°C	882 ± 117 (20)
1204°C	675 ± 21 (5)
1260°C	669 ± 21 (5)
1315°C	593 ± 28 (5)
1370°C	565 ± 28 (5)
II. Stress Rupture Life*	
1260°C/414 MPa	-
1370°C/276 MPa	2 of 3
1370°C/310 MPa	3 of 3

Numbers in parentheses represent the quantity of specimens tested
* Number to survive without failure to >150 hours

HIP Development - In accordance with NTC's 1991 Technical Plan, this effort was divided into two sub-tasks: (1) As-Fired Surface Optimization; and (2) HIP Control.

As-Fired Surface Optimization - During the first two and one-half years of the ATTAP, the character of

NT154 "as-fired" surfaces was demonstrated to be influenced by many different process steps. Powder processing, degas, HIP, sandblasting, crystallization, and oxidation were all shown to individually affect the character of "as-fired" surfaces. Understanding the interactive nature of these various process steps was perceived by NTC as a key to the maximization of both physical and mechanical properties. A Taguchi L16 optimization experiment was therefore designed and initiated in the third quarter of 1990 to understand the interactive nature of each process step in controlling as-fired surface qualities. Most of the work for this experiment was completed in 1990. A limited amount of additional stress-rupture results were acquired in 1991; but further testing is still planned. These tests are long in duration (+100 hours), at intermediate to high temperatures (1260°C - 1370°C), and moderate to high stresses (200 to 400 MPa). Data acquired during 1991 have not materially changed the conclusions of the experiment as reported in the 1990 Annual Technical Report. However, testing and reporting of results from this experiment will continue into 1992 under a low level of effort and priority.

HIP Control - Also during the first few years of the ATTAP, it was recognized that NT154 material variation was caused mostly by variations associated with the HIP densification process. HIP variability was divided into three major categories: (1) Component Cross Section; (2) HIP Location; and (3) Run-To-Run Reproducibility. As part of NTC's 1990 Work Plan, an L4 HIP Control Experiment was designed and conducted. The experiment was completed during 1990 and the majority of the data collected and analyzed. Only a limited number of additional stress-rupture tests were conducted in 1991. The results from these tests did not materially affect the conclusions of the experiment as reported in the 1990 Annual Technical Report. The experiment is considered complete. Optimum conditions, as reported previously have been selected and implemented.

PROCESS ENGINEERING

Work during 1991 was performed in accordance with NTC's Technical Work Plan. The original plan, submitted in January, 1991, was revised due to funding limitations. The revised plan was developed and forwarded to GAPD in May 1991. As part of component specific fabrication issues, corrective action plans were developed for both the rotor and stator by year end. These have become part of NTC's 1992 Technical Plan.

NDE DEVELOPMENT

NTC's efforts in NDE development using microfocus X-ray radiography (MFXR) were completed during the first two program years. An assessment of seeded defects was conducted, and specific inspection protocols were developed and documented. NTC determined that MFXR was an effective tool for the characterization of forming defects of relatively large size (>25 micron): but was ineffective in assuring ultimate component quality. NTC now routinely utilizes MFXR for component forming development and inspection activities. During 1991, modifications to MFXR procedures, defining protocols for both green state and dense state characterization, were completed. Changes were made to account for: (1) Recent component design revisions; (2) Pass/fail criteria; and (3) Additional exposures to improve inspection coverage. These modifications were implemented, and are now part of NTC's overall production and inspection plans for rotors and stators.

In addition to MFXR development, NTC intended to perform work on Fluorescent Dye Penetrant Development as part of its 1991 Work Plan. However, by mutual agreement between NTC and GAPD, this work has been delayed into the 1992 program year.

QUALITY ASSURANCE

In accordance with the 1991 Work Plan, NTC continued efforts in developing a quality assurance system. Effort was conducted within the following sub-tasks: (1) Measurement Techniques and Standards Development; (2) Process Documentation; and (3) SPC Development and Implementation.

Measurement Techniques/Standards Development - MFXR procedures were modified and incorporated into NTC Quality System as described in the NDE Development section above. During the year, NTC's Quality System was audited by GAPD personnel and found to be in conformance with GAPD's internal requirements and MIL-STD-4562.

Process Documentation - During the year, complete process documentation was implemented for the fabrication and inspection of engine quality rotors and stators. As a result of formal reviews of these processes, revisions are expected per identified corrective action plans. These revision will be conducted in 1992.

SPC Development and Implementation - As of the close of 1992, SPC is now formally in place for the following NT154 process operations: (1) Raw materials; (2) Powder processing; (3) Agglomeration; (4) Calcination; (5) Slip batch preparation; (6) Forming; (7) Degas; and (8) HIP. SPC has been discontinued for both Post-HIP Crystallization and Post Machining Oxidation steps because these processes were shown to be consistent and adequately controlled via equipment monitoring. Job-specific SPC is also performed in connection with the above work station SPC as necessary. Parameters monitored by SPC are reviewed on an ongoing basis, and are dropped if they are found to be ineffective in correlating to product or process performance.

DELIVERABLES

According to the 1991 Work Plan, deliverables were divided into three sub-categories: (1) Test Specimens; (2) AGT101 Rotors; (3) AGT101 Stators.

Test Specimens - During the year, NTC delivered 100 "as-processed" flexural specimens and 43 tensile rods. These components were delivered in April and August, respectively. For the tensile rods, only 35 were required; but due to higher than expected yields, NTC delivered 43 rods. Mechanical property data for these two sets of deliverables are shown in Table 28.

AGT101 Rotors - During the year, production of the first set of engine quality rotors was completed. Of the three required components, four were delivered, An additional two engine candidates were purposefully spin-tested to failure. Both exceeded minimum spin-test requirements. A discussion of this hardware is contained earlier within this report.

AGT101 Stators - During the year, production of the first sets of engine quality stators was

Table 28
Mechanical Properties Of NT154 Test Bars
And Tensile Rods

I. As Processed Test Bars	Values
Bulk Ground Surfaces	
22°C Flexural Strength (MPa)	854 ± 117 (30)
1370°C Flexural Strength (MPa)	597 ± 34 (20)
Stress Rupture Life	4 of 4*
As Processed Surfaces	
22°C Flexural Strength (MPa)	517 ± 69 (9)
1370°C Flexural Strength (MPa)	448 ± 103 (9)

II. Tensile Rods	Values
Co-Processed Flexural Test Bars	
Fracture Toughness ($MPa \cdot m^{1/2}$)	5.62 ± 0.10 (15)
22°C Flexural Strength (MPa)	976 ± 152 (30)
1370°C Flexural Strength (MPa)	642 ± 145 (10)
Tensile Rods	
22°C Tensile Strength (MPa)	765 ± 152 (4)
1370°C Tensile Strength (MPa)	414 ± 41 (3)

* Conditions - 1370°C, 250 MPa, ≥ 150 hrs.
Number in parentheses are tests conducted at each condition.

completed. By year end, a total of 24 stators were delivered to GAPD. Delivery of additional hardware was delayed until January 1992, pending an on-site review of components by GAPD personnel. After this review, acceptable components from the remaining balance will be forwarded to GAPD.

PROJECT MANAGEMENT

As part of the 1991 Project Management effort, NTC and GAPD participated in weekly or bi-weekly technical conference phone calls. Bi-monthly technical reports were submitted to GAPD. In addition, on-site visits at both locations occurred periodically throughout the year. NTC attended the DOE Contractor's Coordination Meeting in Dearborn MI during October 28-31, 1991, and presented a summary of its developmental efforts.

SUMMARY AND CONCLUSIONS

NTC completed its fourth-year effort of the ATTAP. Work during the year focused on development of component specific fabrication operations for engine quality hardware. NTC successfully produced, proof tested and delivered engine quality rotors and stators to GAPD. A summary of accomplishments is given below.

- NT154 Silicon Nitride (Si_3N_4) - Characterization of NT154 continued during the year. A significant data-base of critical mechanical properties for this material now exists both at NTC, GAPD, other engine builders and a number of independent laboratories. Flexural strength, fracture toughness, static and dynamic fatigue, creep, and thermal property information are available for engine design and analyses. Overall, properties for this material continue to exceed program specifications.

- NT164 Silicon Nitride - Through its experience with NT154, NTC has been able to develop a new highly creep resistant Si_3N_4. Designated NT164, this material has approximately four times the creep life of NT154 at 1370°C. This evolutionary achievement was realized by a slight change in overall composition, and by selective post-HIP heat-treatments. NT164's microstructure has no amorphous grain boundary phases. Because of this, NT164 has significantly higher hot strength (≈690 MPa at 1370°C), and slightly higher fracture toughness (≈6.4 MPa·m$^{1/2}$) when compared with NT154.

- NT230 Siliconized Silicon Carbide (Si·SiC) - A new generation of siliconized silicon-carbide (Si·SiC) was developed and introduced. Designated NT230, NTC is using this material to produce transition ducts for GAPD under a parts-supply contract. This material has approximately double the strength of existing Si·SiC compositions. At elevated temperatures (up to 1370°C), its strength is nearly equivalent to NT154.

- Casting System Development - In an effort to simplify the NT154 process, and as a prerequisite to aqueous based component casting, water milling of NT154 powders was developed. An experimental matrix was planned and conducted using standard pilot level equipment. From water milled powders, casting trials were performed for rotors, stators, tensile rods and test tile. Physical and mechanical properties were acquired on tile components. Casting techniques and properties were found to be equivalent with or superior to the current alcohol-based process. Pending the successful completion of additional limited trials in 1992, this process will be adopted as standard practice.

- AGT101 Rotor Production - After completion of a limited amount of component specific casting development, hard tooling for the AGT101 rotor was ordered, process steps were firmly established and documented, and inspection plans implemented. Laboratory pressure casting was utilized for casting trials and the production of hardware. Impact-tolerant AGT101 rotors were successfully cast, densified, characterized, spin-tested and delivered to GAPD. Mechanical properties for these components met program requirements, and were comparable to data acquired from co-processed test-tile. A total of six components were spin tested. All exceeded the proof speed of 105 KRPM. Four components were delivered to GAPD. The remaining two were purposefully spun to failure. They failed at speeds of 126.6 and 118.9 KRPM, or 141% and 132% of maximum engine design speed, (i.e., ≈90 KRPM). Engine testing of this hardware by GAPD is planned in 1992. At the close of the year, NTC performed a comprehensive review of the entire rotor fabrication process. Corrective action was identified and has become part of NTC's 1992 Technical Work Plan. Improved rotor quality and yields are expected upon its implementation.

- AGT101 Stator Production - Following the receipt of a final stator design in early 1991, NTC ordered a metal casting tooling. Machining stock along with an isotropic shrinkage factor were applied to the design. After completing a number of casting trials and machining development, production of the stator was initiated. However, initial components exhibited anisotropic shrinkage. Consequently, due to the presence of external machining stock, print tolerances for the outside dimensions of the platforms could be achieved; while the air-flow passage was found to be restricted by ≈0.51mm.

Following discussion of this problem with GAPD, and with their approval, NTC continued production of the component. Production yields for this part were low due to a persistent crack which occurred on the trailing edge of the vane next to one of the platform cleats. Despite this fact, NTC was able to prepare and deliver 24 engine quality parts. Mechanical properties for this hardware were evaluated and found to exceed ATTAP specifications. Data were consistent with rotors. An additional number of potentially acceptable components were identified. Pending a joint review of these parts by NTC and GAPD personnel, acceptable components are to be delivered early in 1992. At the close of 1991, NTC performed a comprehensive review of the entire stator fabrication process. Corrective action was identified and has become part of NTC's 1992 Technical Work Plan. Part of this plan calls for the construction of a new stator tooling, improved mold design and casting procedures. Better quality and yields are expected upon its implementation.

- HIP Development - NTC continues to perform a limited amount of long-term stress rupture testing for experiments which were initiated in 1990. Completion of this effort is expected in 1992.

- Process Engineering, NDE Development And Quality Assurance - Documentation of the NT154 process and component specific operations is complete. Revisions of these, as necessary, will be conducted for future hardware sets. Microfocus X-Ray Radiography (MFXR) and Fluorescent Dye Penetrant Inspection (FPI) are routinely conducted on all components. NTC's Quality System was audited by GAPD and found to be in conformance with their internal requirements.

- Deliverables - In addition to delivering 4 engine quality rotors and 24 engine quality stators, NTC also supplied 100 "as-processed" flexural test specimens and 43 tensile rods.

Continued effort in each of the above areas is scheduled for the 1992 program year. Work will again focus on component specific problems for the rotor and stator. Additional engine quality hardware sets will be prepared and delivered.

ACKNOWLEDGEMENT

Work accomplished during the 1991 program year represents the combined efforts of a number of individuals. The following principal engineers are gratefully recognized for their key contributions: R. L. Yeckley--Materials Development; M. G. Bingham and J. R. Blackmore--Machining Development; L. D. Lynch--Design and Drafting; and E. Bright--NDE and Quality Assurance. Additionally, G. Janulewicz, D. Moylan, J. Gulcius, G. Manoogian, B. McGeary, D. Karsberg, S. FitzGerald, and L. Russell are acknowledged and appreciated for detailed performance of the technical plan. The Characterization and Analysis Groups of Norton Company are acknowledged for their work in chemical analysis, x-ray diffraction, microfocus x-ray characterization, mechanical property testing, and electron microscopy. A. M. Schiavitti-Smith, E. M. MacKinnon, R. T. Foy, and S. Manago are appreciated for cost analysis and accounting services. Special thanks go to Dr. R. R. Wills who constructively reviewed program objectives, plans, and reports; and to J. M. Garwood for government contract administration review and support. T. J. Woods is gratefully acknowledged for contributions in technical, financial and program management. J. Smyth, D. Carruthers, J. Schienle, J. Minter, and B. Morey of GAPD are acknowledged and thanked for technical guidance, analyses, program direction and support. Finally, appreciation is expressed to Norton Company, TRW, GAPD, NASA and DOE for financial support.

NOMENCLATURE

ATTAP - Advanced Turbine Technology Applications Project.
CIP - Cold Isostatic-Pressing.
CMM - Coordinate Measuring Machine.
DOE - Department Of Energy.
FPI - Fluorescent Dye Penetrant Inspection.
GAPD - Garrett Auxiliary Power Division, Allied Signal Aerospace Company.
HIP - Hot isostatic Pressing.
MFXR - Microfocus X-Ray Radiography.
MOR - Modulus of Rupture
NASA - National Aeronautics And Space Administration.
NT154 & NT164 Si_3N_4 - HIPped Silicon Nitride.
NT230, NT235 and NC430 Si-SiC - Siliconized Silicon Carbides.
NTC - Norton/TRW Ceramics.
ORNL - Oak Ridge National Laboratory.
PEEP - Pressure-assisted Endothermic Extraction Process.
SPC - Statistical Process Control.
UDRI - University Of Dayton Research Institute.
WEEP - Water Endothermic Extraction Process.

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APPENDIX II

ANNUAL TECHNICAL PROGRESS REPORT
CARBORUNDUM COMPANY

CARBORUNDUM

ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROJECT (ATTAP)

Contract DEN3-335
Subcontract K71-2331780

ENGINE COMPONENT FABRICATION

ANNUAL TECHNICAL PROGRESS REPORT
NO. 2

January/December 1991

Submitted By:
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Date: ____________

Approved By: Harry A. Lawler — Date: FEB. 14, 1992

Prepared For:
Garrett Auxiliary Power Division
Allied-Signal Aerospace Company
Phoenix, Arizona

Introduction

This report, prepared by The Carborundum Company, represents the second annual progress report submitted under the ceramic component fabrication contract. This subcontract is part of the U.S. Department of Energy-sponsored and NASA-administered 5-year contract DEN3-335. The prime contractor is Garrett Auxiliary Power Division--Advanced Turbine Technology Applications Project (ATTAP) with Dr. Jay Smyth as Project Manager. Work reported herein covers the period of January through December 1991.

The objective of this program was to fabricate and deliver by March 31, 1991, five engine-quality sets of three different Hexoloy SA Silicon Carbide components. In accomplishing this, Carborundum was to establish dimensional tolerance capabilities of the isopressing/green machining process to provide the basis for meeting the anticipated GAPD requirement for nine additional sets to be delivered through 1992. This requirement for additional identical components disappeared in the later part of 1991.

The three Hexoloy SA SiC components required were as follows:

Dwg. No. PA361290-1	Pilot Combustor Support
Dwg. No. R45315	Combustor Baffle
Dwg. No. R45319	Transition Duct

The processing parameters and capabilities had been well established for non-engine components. However, the stringent dimensional and NDE specifications along with the very limited time frame available made it imperative that very close control be exercised at every processing step. The specifications as stated in the Proposed Workplan Revision 2, dated February 5, 1991, are defined in Appendix 1.

Carborundum developed a work plan which required material qualification at each process step in order to minimize risk and ensure that material or processing problems were identified as soon as possible and corrected.

The following tasks were established:

Task I. Qualify Premix
Task II. Qualify Isopressed Billets
Task III. Green Machine and Sinter Components
Task IV. Finish Machine and Anneal Components
Task V. Program Management

The progress made during this reporting period and leading to the completion of the letter subcontract is summarized below:

Task I. Qualify Premix

This task which was completed in the previous reporting period included the fabrication of 2 1/2" x 2 1/2" x 3/8" plates from isopressed billets formed from the same Powder Lot D90040 used for the fabrication of the engine components. The plates were subsequently sintered and machined into size B MOR test bars.

Test results shown in Table 1 exceeded the minimum requirement of >50 ksi MOR and >7.5 Weibull Modulus.

Task II. Qualify Isopressed Billets

This task was essentially completed in the previous reporting period. Billets in three different sizes were isopressed from Powder Lot D90040 for the different sized components. Plates were sliced from these billets adjacent to the blanks for the components. The plates for the transition duct and combustor baffle qualification were sintered, machined into MOR bars, and tested. The MOR and Weibull Moduli results shown in Table 29 exceeded the specifications.

When GAPD revised the plan to shift the final qualification testing (20 MOR bars) from Carborundum to GAPD, it was mutually decided to verify that no significant differences would be found as a result of different procedures and/or test facilities. Ten additional sample bars from the baffle billet qualification group, therefore, were forwarded to and tested by GAPD. The resulting test values shown in Table 29 are in very close agreement with those generated in the Carborundum characterization laboratory.

Because the combustor support drawing was available and green machining could be immediately initiated, the combustor support billet qualification was waived. Instead, the test specimen plates were sintered with the green machined components for both the sintered and machined/annealed qualification specimens. The results will be discussed in Tasks III and IV for 1991.

These activities completed Task II.

Task III. Green Machine and Sinter Components

The completion of green machining and sintering of the combustor supports (including six replacements) was described in the No. 1 Annual Report for 1990. The green vs. as-sintered dimensions are shown in Table 30.

The initiation of ten replacement baffles and qualifiers was also discussed in the No. 1 Annual Report. These were green machined, sintered, and inspected. Eight were then forwarded to Therm, Inc., for further dimensional inspection and coordinate measurement of the flow path contours.

The 5X Mylars generated by Therm, Inc., on two baffles and forwarded to GAPD for review verified that sufficient stock was available to obtain the final machined dimensions where required, and the as-sintered flow path surfaces were within specification. The green vs. as-sintered dimensions are shown in Table 31.

Sintered baffle qualification test specimens were processed and tested. Results are shown in Table 29.

The transition ducts along with qualification specimens were also completed through green machining and sintering. Six were approved by QC; however, the ID of the large end had no machining stock, and it was questionable if final dimensions could be met. Therm plotted the flow path surfaces on two of the six using Coordinate Measurement equipment and referenced on the large ID dimensions. It appeared that the six components were candidates for finish machining, and Therm agreed to confirm this on each component as they were set up in the machining fixtures.

The 5X Mylars of the two transition ducts were forwarded to GAPD, and the qualification specimens were tested. The green vs. as-sintered dimensions are shown in Table 32, and the MOR results as shown in Table 29 are in good agreement with all of those generated through the sintering process.

Task IV. Finish Machine and Anneal Components

After correcting the machining fixture which resulted in damage to almost all of the first group of combustor supports, Therm machined the replacement components. The chipping problem was no longer evident and all passed FPI and X-ray inspection.

On dimensional inspection, however, the .176"-182" diameter holes (18 per component) were found to be oversize by .001" to .006". This issue was discussed with GAPD, after which Carborundum was advised that the deviations would not affect performance.

The finish-machined combustors and qualification specimens were annealed. The five components identified below along with twenty (20) test specimens were delivered to GAPD on March 28, 1991

Serial No. 100-331-29-1
Serial No. 100-331-29-2
Serial No. 100-331-29-13
Serial No. 100-331-29-14
Serial No. 100-331-29-17

Ten test specimens were retained and tested by Carborundum. The results shown in Table 29 are consistent with previous values.

Analytical Inspection Reports were prepared for each component and provided to GAPD.

Transition Ducts

Three transition ducts were finished initially by Therm, Inc. The first, No. 100-331-37-9, was inspected, annealed, and shipped to GAPD on March 28, 1991 along with twenty (20) qualification specimens. Ten specimens were retained and tested by Carborundum. The data was added to the Material Qualification Summary (Table 29).

A second transition duct, No. 100-331-37-3, was completed and shipped to GAPD on April 10, 1991.

The third transition duct, No. 100-331-37-2, deviated from specifications in that two of the three thermocouple holes were displaced downstream by .001"-.002" due to an error in machining. In addition, breakout of the ultrasonic tool used to machine these holes caused chips on the inside flow path surface. This was the first transition duct machined, and corrective action subsequently taken resulted in the two acceptable components discussed previously. At a later date GAPD agreed to accept this component if needed but advised Carborundum to maintain it in inventory pending disposition of the others which were in process.

Three additional transition ducts plus one without the air diverter (No. 100-331-37-11) ordered on a separate Purchase Order No. P233490 were completed by Therm. Two identified below were inspected, annealed, and shipped to GAPD on June 28, 1991.

Serial No. 100-300-37-6
Serial No. 100-300-37-8

The transition duct without the air diverter also met specifications and was shipped on June 28.

Shortly after receiving the above components, GAPD advised Carborundum to delete the annealing operation. The oxide layer developed on the surface was found to inhibit identification of possible surface defects via fluorescent penetrant inspection.

Carborundum was also advised to fair the surface of the internal flow path between tolerance zones on the last deliverable transition duct, No. 100-331-37-2, which was in finished inventory. The green machining setup procedure had resulted in a slight step between zones which was identified on the previously delivered components.

Therm completed the rework on this last transition duct after which it was inspected and shipped to GAPD on July 24, 1991.

A complete set of Development Analytical Inspection Reports was also provided.

Baffles

Six baffles at Therm, Inc., were machined except for the fin contours. The process selected for the fins was ultrasonic machining with several tool configurations starting at rough shaping and completing with a close tolerance finishing tool.

This process proved to be very difficult, and machining rates were significantly lower than anticipated. In addition, it was found that insufficient machining stock had been provided in the fillets along the sides of the fin base. As a result, the maximum fillet possible with a slight change in the air-foil profile was only .060"-.080" vs. the .26" R specified.

GAPD authorized this revision, and the first baffle (No. 100-331-40-1) was completed, inspected, and annealed by Carborundum and shipped to GAPD on May 31, 1991. It was accompanied by twenty (20) qualification test specimens.

Once again Carborundum verified the strength and Weibull Modulus by breaking ten (10) similar test bars. The results are included in Table 29.

The next two baffles machined were broken while ultrasonically machining the fins. Machining was subsequently suspended while the cause was identified and corrective action taken. Minor procedural revisions were made, and the final two baffles were successfully completed. After undergoing inspection by Carborundum, the following two baffles were shipped--unannealed--to GAPD on September 27, 1992:

No. 100-331-40-2
No. 100-331-40-3

On September 11 GAPD advised Carborundum to delete the last two deliverable baffles from the workplan. In addition, Carborundum was requested to quote on two replacement baffles to be processed via CNC green machining including the final fin configurations. It is anticipated that this procedure will result in much higher yields and reduced machining costs; however, the tolerances would have to be broadened.

Development Analytical Inspection Reports for the baffles were also provided to GAPD.

Additional deliverables included fracture analysis reports on all of the test specimens tested by Carborundum and the remains of the fractured bars. Also provided were tables which stated the dimensional tolerance performance on each component (Tables 33, 34, and 35) and recommended process revisions which would facilitate fabrication of future component requirements.

Representative samples of each of the final components are shown in Figure 57.

Appendix 1
Specification for Sets 1 - 5

Material:

- o MOR >50 ksi
- o m >7.5 (maximum likelihood method)

Dimensional Tolerances:

- o Machined to drawing tolerances specified with the exception of as-sintered flow path surfaces.
- o Carborundum shall exert its best efforts to achieve the objectives +/-0.5% dimensional tolerances on as-sintered flow path surfaces (except where designated as a critical surface). Please note the +/-0.5% objective is on a best-efforts basis, and the formal dimensional tolerances capability will not exceed +/-1.0%. The machining vendor selected by Carborundum cannot machine the following surfaces:

  Baffle - exterior surfaces between the fins
  Transition Duct - exterior surface of the air diverter

  When the letter subcontract was issued, Carborundum could not identify any other machining vendor with this capability; therefore, the first five sets were to be supplied with the above surfaces as-sintered and not machined.

NDE:

- o X-Ray Maximum allowable indication 1% of thickness or 0.010", whichever is larger in high-stress regions (to be identified by GAPD). In high-stress regions no indications by the procedure described below.
- o FPI No defects >.005" on as-fired surfaces in high-stress regions (to be identified by GAPD). Maximum allowable defect on machined surfaces 1% of thickness or 0.010", whichever is larger.

  Subsequent finishing to remove surface defects which do not meet this criteria will be performed subject to approval by Garrett.

Procedures:

X-ray inspection will be performed using a Magnaflux M-100 Unit located in Niagara Falls. Procedures shall be mutually agreed to by Carborundum and Garrett and shall include both part orientations and the number of views. The zero degree point will be identified by Carborundum and shall be used to determine the part orientation during inspections at both locations. Radiograph quality shall be measured in accordance with MIL-STD-453 to a 1-1T quality level, and duplicate films will be processed at Carborundum. Fluorescent Penetrant Inspection shall be accomplished using a high-sensitivity, postemulsifiable penetrant and lipophyllic emulsifer. Parts are to be evaluated prior to and after application of nonaqueous wet developer.

Specifications on subsequent sets of deliverables shall be developed iteratively during the course of fabricating the first five (5) sets.

TABLE 29. MATERIAL QUALIFICATION SUMMARY

Qualification Sample	MOR MPa	MOR (ksi)	s MPa	s (ksi)	m (Maximum Likelihood)
• SA SiC Powder	453	(65.7)	37	(5.3)	15.7
• Billet Qualifiers					
- Combustor Baffle	458	(66.4)	41	(6.0)	14.2
	476	(69.1)*	--	--	13.6*
- Transition Duct	443	(64.3)	52	(7.5)	8.5
- Combustor Support	--	--	--	--	--
• Sintd. Comp. Qualifiers					
- Combustor Baffle	450	(65.2)	36	(5.2)	15.0
- Transition Duct	445	(64.6)	44	(6.4)	11.7
- Combustor Support	477	(69.2)	41	(5.9)	12.4
• Machd./Anld. Comp. Qual.					
- Combustor Baffle	457	(66.3)	39	(5.7)	16.5
- Transition Duct	478	(69.3)	26	(3.8)	21.1
- Combustor Support	465	(67.5)	36	(5.2)	13.5

*Garrett Data

TABLE 30. COMBUSTOR SUPPORT DIMENSIONAL TOLERANCE CONFORMANCE

	Major OD	Minor OD	Major ID	Minor ID	Overall Height
±3σ as % of Green	0.1	0.3	0.5	1.0	0.6
±3σ as % of Sintered	0.4	0.4	0.4	1.0	0.3

Note: 6σ = Process capability. Carborundum typically quotes ±0.5% as isopress/green machine tolerance capability

TABLE 31. COMBUSTOR BAFFLE DIMENSIONAL TOLERANCE CONFORMANCE

	Major OD	Major ID	Wall Thickness	Top Thickness	Overall Height
$\pm3\sigma$ as % of Green	0.5	0.3	3.7	4.9	0.4
$\pm3\sigma$ as % of Sintered	0.6	0.3	4.5	4.5	0.5

Note: 6σ = Process capability. Carborundum typically quotes ±0.5% as isopress/green machine tolerance capability

TABLE 32. TRANSITION DUCT DIMENSIONAL TOLERANCE CONFORMANCE

	Major OD	Minor OD	Major ID	Minor ID	Overall Height
±3σ as % of Green	0.3	0.1	0.4	0.4	0.1
±3σ as % of Sintered	0.4	0.1	0.3	0.3	0.3

Note: 6σ = Process capability. Carborundum typically quotes ±0.5% as isopress/green machine tolerance capability

TABLE 33. GAPD ATTAP COMBUSTOR SUPPORT DIMENSIONAL RELATIONSHIPS

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Feature	(B) Major O.D.	Minor O.D.	Major I.D.	Minor I.D.	Overall Height
Nominal Dimension	3.888	2.850	2.360	1.490	1.752
Measured Dimension (includes grind stock)					
n	12	12	12	10	12
$\bar{X}$	3.943"	2.896	2.340	1.464	1.813
σ	.005	.004	.003	.005	.002
3σ	.015	.012	.009	.015	.006
$\pm 3\sigma$ as % nominal	±0.4%	±0.4%	±0.4%	±1.0%	0.3%

GREEN

Feature	(B) Major O.D.	Minor O.D.	Major I.D.	Minor I.D.	Overall Height
Nominal Dimension	4.740	3.488	2.803	1.755	2.172
Measured Dimension					
n	12	12	12	10	12
$\bar{X}$	4.752	3.487	2.801	1.748	2.181
σ	.001	.003	.005	.006	.004
3σ	.003	.009	.015	.018	.012
$\pm 3\sigma$ as % nominal	±0.1%	±0.3%	±0.5%	±1.0%	±0.6%

TABLE 34. GAPD ATTAP REPLACEMENT BAFFLES DIMENSIONAL RELATIONSHIPS

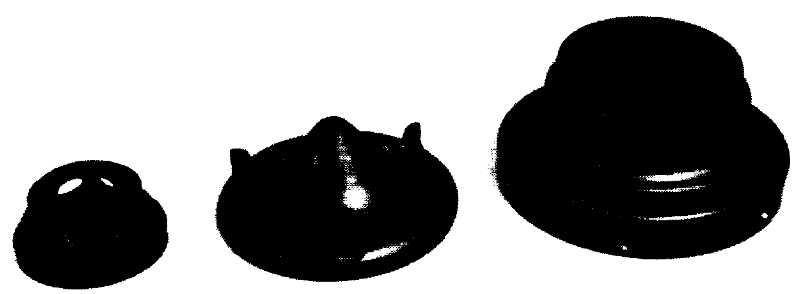
Sintered Feature	Major O.D. E	Major I.D. B	Wall Thickness	Top Thickness	Overall Height
nominal dimension	6.307	5.919	.200	.200	2.779
measured dimension (includes grind stock)					
n	10	10	10	10	10
$\overline{X}$	6.378	5.852	.201	.200	2.807
σ	.012	.005	.008	.003	.005
3σ	.036	.015	.009	.009	.015
$\pm 3\sigma$ as % nominal	0.6	0.3	4.5	4.5	0.5

Green Feature	Major O.D. E	Major I.D. B	Wall Thickness	Top Thickness	Overall Height
nominal dimension	7.605	7.055	.246	.246	3.410
measured dimension					
n	11	11	11	11	11
$\overline{X}$	7.682	7.052	.247	.244	3.417
σ	.012	.008	.003	.004	.004
3σ	.036	.024	.009	.012	.012
$\pm 3\sigma$ as % nominal	0.5	0.3	3.7	4.9	0.4

TABLE 35. GAPD ATTAP TRANSITION DUCTS DIMENSIONAL RELATIONSHIPS

Sintered Feature	Minor O.D.	Major O.D. B	Minor I.D.	Major I.D. E	Overall Height
nominal dimension	4.776	7.720	3.977	7.078	3.531
measured dimension (includes grind stock)					
n	7	7	7	7	7
$\overline{X}$	4.785	7.838	3.977	7.085	3.624
σ	.006	.002	.004	.008	.003
3σ	.018	.004	.012	.024	.009
$\pm$ 3σ as % nominal	0.4	0.1	0.3	0.3	0.3

Green Feature	Minor O.D.	Major O.D. B	Minor I.D.	Major I.D. E	Overall Height
nominal dimension	5.762	9.437	4.796	8.540	4.378
measured dimension (includes grind stock)					
n	10	10	10	10	10
$\overline{X}$	5.759	9.435	4.774	8.521	4.384
σ	.005	.002	.007	.011	.002
3σ	.015	.006	.021	.033	.006
$\pm$ 3σ as % nominal	0.3	0.1	0.4	0.4	0.1



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(A) (B) (C)

FIGURE 57. MACHINED AND ANNEALED ENGINE COMPONENTS

(A) PILOT COMBUSTOR SUPPORT
(B) COMBUSTOR BAFFLE
(C) TRANSITION DUCT

APPENDIX III

ANNUAL TECHNICAL PROGRESS REPORT
GARRETT CERAMIC COMPONENTS DIVISION

ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROJECT

GARRETT CERAMIC COMPONENTS
1991 ANNUAL TECHNICAL PROGRESS REPORT
FOR GARRETT AUXILIARY POWER DIVISION

I. INTRODUCTION

The objective of this 48 month technical effort is to develop a fabrication process with the potential for low-cost, mass production of AGT101 turbine rotors using GN-10 silicon nitride. Pressure slip casting will be the primary fabrication approach. Materials and components will be extensively characterized and NDE methods developed and evaluated for improved process control and material/component qualification. In Task A, fabrication of the AGT101 rotor using GN-10 silicon nitride and pressure slip casting will be developed. In Task C, GN-10 test specimens and NDE seeded defect standards will be fabricated by pressure slip casting.

II. SUMMARY OF PROGRAM EFFORTS PRIOR TO 1991

TASK A. FABRICATION OF AGT101 ROTORS BY PRESSURE SLIP CASTING

SUBTASK A.A FABRICATION OF ROTORS AND PLATES USING BASELINE SLIP AND FORMING PROCESS

The goal of Subtask A.A was to evaluate the capability of the GN-10 slip preparation, rotor and plate forming, and densification processes on resultant component shape forming capability and mechanical properties. Subtask A.A was begun at the beginning of the program (July 1988) and completed in 1989. Evaluation of the baseline forming and densification processes resulted in the identification of areas in need of improvement.

SUBTASK A.B SLIP CAST ROTOR PROCESS DEVELOPMENT 1

The goal of Subtask A.B was to take the problems identified in Subtask A.A and investigate their elimination using iterative process development, and designed experiments, where appropriate. Subtask A.B was begun in early 1989. GN-10 slip properties were improved, specifically degree of dispersion and stability time, resulting in slip revision #15, which allowed slip casting of defect-free AGT101 rotors. Subtask A.B ended in early 1990 with the delivery of four as-HIPed AGT101 radial rotors to Garrett Auxiliary Power Division. The rotors were fabricated using revision #15 slip and the revision #1 HIP process (HIPed at ASEA).

SUBTASK A.C SLIP CAST ROTOR DEVELOPMENT 2

Subtask A.C addressed further reproducibility and improvement of the fabrication of the radial AGT101 rotor focusing on both net-shape development and material property improvements and was initiated in January 1990. In April 1990, densification of GN-10 Si_3N_4 material using the ASEA glass-encapsulation HIP process was initiated in-house. Refinement of the in-house HIP process resulted in HIP revision #8 and the resulting GN-10 Si_3N_4 mechanical properties were equivalent or better than any previous slipcast GN-10 material HIPed at ASEA. Subtask A.C was completed in October 1990 with the delivery to Garrett Auxiliary Power Division of two radial-design AGT101 rotors. The rotors were utilized for spin balancing and spin-to-burst evaluation (with just the shaft outside diameter machined). Due to a small shaft-hub misalignment in the original mold fabrication tool, the radial-design rotors required extensive stock removal for spin balancing. The first rotor burst at approximately 80,000 rpm, suspected to be due to the size of the balancing groove that needed to be machined into the part. The second rotor burst at 114,000 rpm, within 1% of the required proof test spin speed for deliverable rotors.

SUBTASK A.D IMPACT-RESISTANT DESIGN ROTOR DEVELOPMENT

This subtask was initiated in January 1990 to develop the fabrication of the impact-resistant design (IRT) AGT101 rotor, building on the GN-10 silicon nitride pressure slip casting process developed for the radial-design radial shaped AGT101 rotor. Due to rotor and mold design changes, the impact-resistant design rotor mold hard tool delivery was delayed until late November 1990.

In order to evaluate the castability of the impact-resistant design rotor shape before the hard tool was delivered, a stereolithographically generated plastic pattern impact-resistant design rotor was provided to Garrett Ceramic Components by Garrett Auxiliary Power Division to fabricate slip casting molds for rotor casting evaluations. The only significant difference between the mold developed from the stereolithographic pattern and the hard tool being built was that the stereo pattern has approximately 0.003" ridges on its surface due to the limited surface detail resolution of the stereolithographic process. Casting of the prototype impact-resistant design rotors was very successful. Two prototype impact-resistant-design AGT101 rotors were provided to Garrett Auxiliary Power Division for evaluation in January 1991.

The hard tooling for the impact-resistant design rotors was received in late November 1990. Pressure slip casting of hardtool derived rotors was begun in mid-December 1990.

SUBTASK C.C FABRICATION OF SLIP CAST DEFECT SEEDED BILLETS FOR NDE DEVELOPMENT

Garrett Ceramic Components fabricated GN-10 seeded defect specimens (containing both controlled size iron inclusions and voids) for evaluation of X-Ray radiographic and ultrasonic NDE detection capabilities. Seeded defect sizes ranged from 25 μm to 500 μm in diameter. The specimens were inspected at each intermediate processing step nondestructively and then the results quantified using destructive cut-up and characterization. The three processing steps evaluated were green (dried after slip casting, calcined (presintered), and HIPed (fully densified). Destructive characterization of the calcined specimens revealed smallest detectable voids as 0.002" diameter and 0.002" diameter for iron inclusions. Using nondestructive techniques, the smallest detectable voids 0.003" diameter using realtime fluoroscopy at 10X magnification and 0.002" diameter using film radiography at 1X magnification. The smallest detectable iron inclusion using either realtime or film radiographic techniques was 0.002". The remaining calcined specimens were then HIPed at Garrett Ceramic Components and characterized by realtime and film microfocus X-ray, then delivered to Garrett Auxiliary Power Division for evaluation.

III. 1991 PROGRAM EFFORTS

SUBTASK A.D IMPACT-RESISTANT DESIGN ROTOR DEVELOPMENT

Development efforts over the past 12 months have focussed on fabrication development of the modified design AGT101 rotor - the impact resistant turbine. Fabrication development of the AGT101 IRT rotor using hard tooling derived molds began in January 1991. Initial fabricated rotors indicated defects in the tooling and casting process that needed to be eliminated. The hard tooling and mold assemblies were modified, and the casting and drying procedures slightly modified to eliminate all defects. Defect-free rotors were slip cast starting in May 1991. All densified engine candidate rotors were submitted for final machining in early August 1991.

Six IRT design rotors were spun-to-burst to evaluate rotor material and property performance and capability of meeting proof-spin testing requirements. Two rotors were stereolithographic derived, while four were fabricated from hard tooling. The hard tooling derived rotors had backfaces and shaft outside diameters fully machined (three rotors had solid shafts while one had a simple bisque-machined pilot hole) while the two stereolithographic derived rotors had solid shafts with only the shaft outside diameters machined. The balanced rotors ready for spin-to-burst testing are shown in Figure 58. Both stereolithographic rotors and the three solid shaft hard tool derived rotors burst at speeds between 111,250 rpm and 119,800 rpm, above the required proof speed. An analysis of predicted rotor room temperature spin performance was conducted by

Garrett Auxiliary Power Division using GN-10 as-processed surface and machined flexure test bars. The analysis results (shown in Figure 59) correlate well with as-processed surface stregths, which would indicate that the rotors fail at the as-processed surfaces, which exist only on the blade surfaces and on the hub surfaces in between the blades. Finite element analysis of rotor stress distributions indicates that the maximum as-processed surface stress is on the hub surface near blade roots.

Machining of the deliverable rotors was completed in November 1991. The rotor used for machining procedure setup is shown in Figure 60 completely machined. Garrett Auxiliary Power Division decided to balance and proof spin the rotors in-house, because of discrepancies in balancing results previously obtained (on both ceramic and metal rotors) at the rotor balancing and spin testing company being used. The five engine candidate rotors were delivered to Garrett Auxiliary Power Division in December 1991. They will balance the rotors, followed by a heat treatment at Garrett Ceramic Components. The rotors will then be proof spun-test at 105,000 rpm at Garrett Auxiliary Power Division. Two of the rotors will be burst test to verify performance.

The current slip and HIP process revision GN-10 Si_3N_4 that has been used for the first set of deliverable IRT rotors has been extensively characterized over the past year. Mechanical properties including tensile fast fracture, flexure and tensile fractography results, slow crack growth threshold determination, and stress-rupture resistance have been evaluated. The reliability and strength distribution of current process GN-10 is shown in Figure 61 and the corresponding fractography results in Figure 62. The majority of failures are due to small carbon inclusions generated during the slip preparation process. The tensile strength (measured on buttonhead cylindrical design specimens) is presented in Figure 63, where it is compared with the corresponding flexural strength. The majority of tensile failures are also carbon inclusions and sintering aid agglomerates. Slip casting processing improvements are focussing on elimination of these defects.

As-HIPed surface strengths, compared with machined surface strength, as a function of temperature are presented in Figure 64. The as-HIPed strengths are about 40% less and the fractography results for room temperature failures (Figure 65) indicate surface pits as the most numerous failure origin. The reason for the strength drop with as-HIPed surfaces is still being determined but is expected to be one or a combination of four causes (that may change with test temperature):

1) Surface Roughness (Topography)
2) Structural Phases at Surface
3) Chemical Composition at Surface
4) Microstructure at Surface

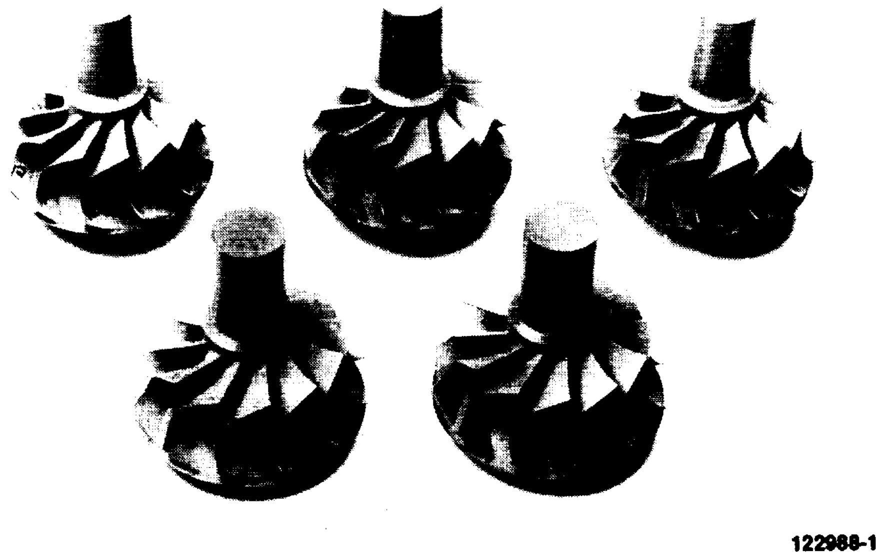
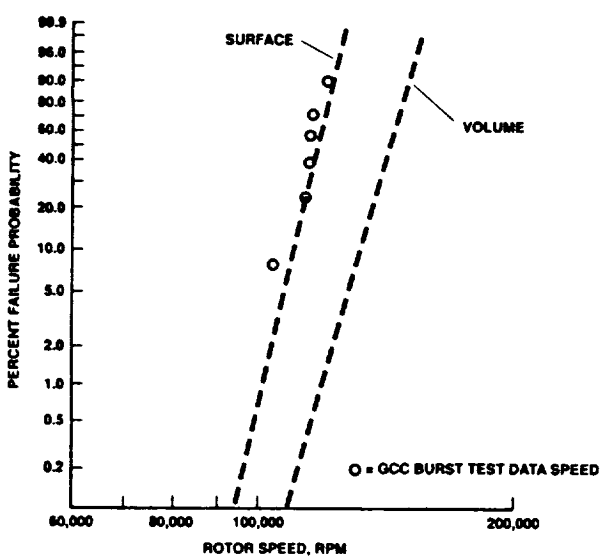


Figure 58. Balanced and Partially Machined AGT101 Rotors Utilized for Spin-To-Burst Tests.



ROTOR DESCRIPTION	MEASURED BURST SPEED, RPM
HARD TOOL, SOLID SHAFT	113,400
HARD TOOL, SOLID SHAFT	112,800
HARD TOOL, SOLID SHAFT	113,900
SLA* TOOL, SOLID SHAFT	114,100
SLA* TOOL, SOLID SHAFT	119,000
HARD TOOL, HOLLOW SHAFT	102,500

* SLA = STEREOLITHOGRAPHIC

- ATTAP IMPACT-RESISTANT ROTOR

Figure 59. Comparison of Rotor Burst Test Results and Predicted Performance Based on As-Processed and Machined Flexure Data for GN-10.

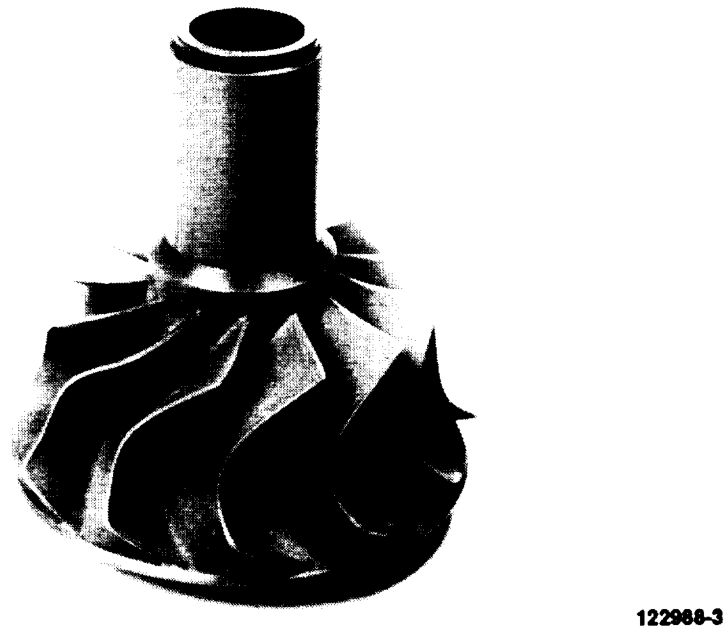


Figure 60. Fully Machined AGT101 Impact Resistant Design Rotor of GN-10 Si_3N_4.

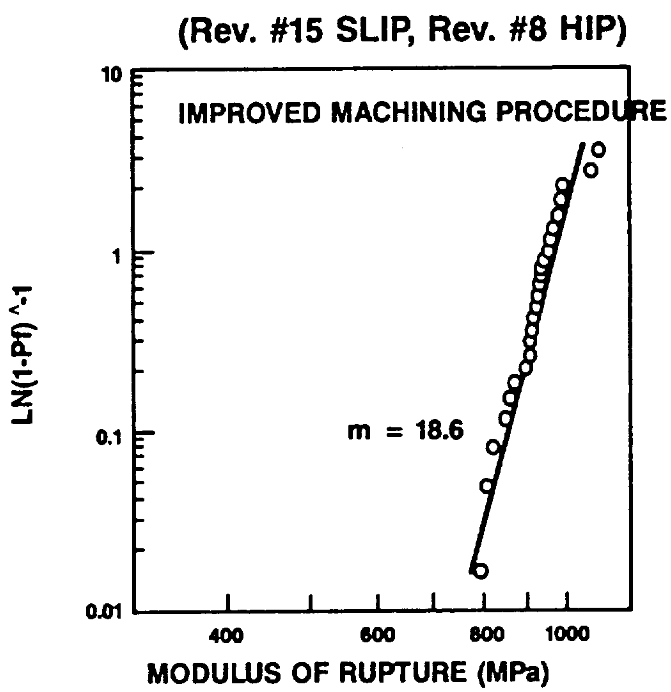


Figure 61. Reliability and Strength Distribution of Current Process Slip Cast GN-10.

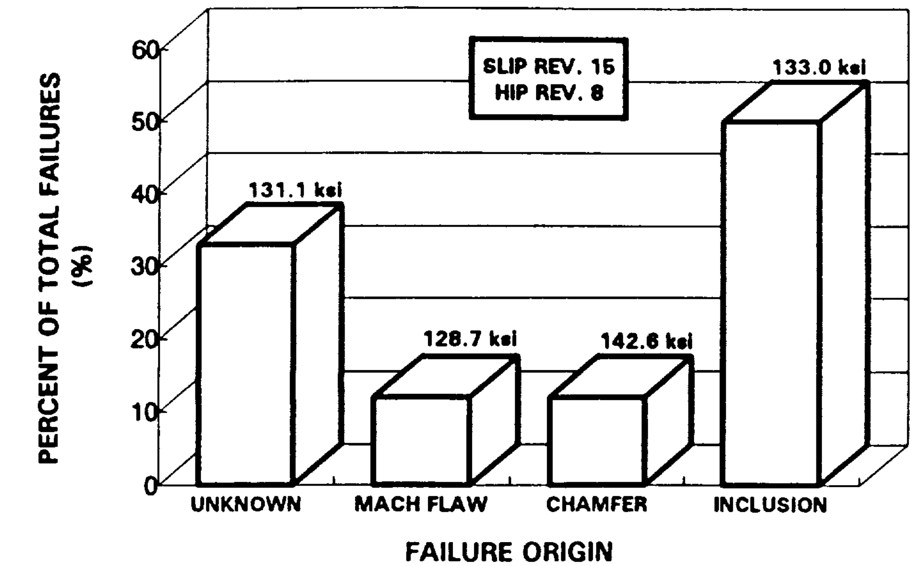


Figure 62. Fractographic Results of GN-10 Material Results Presented in Figure 61.

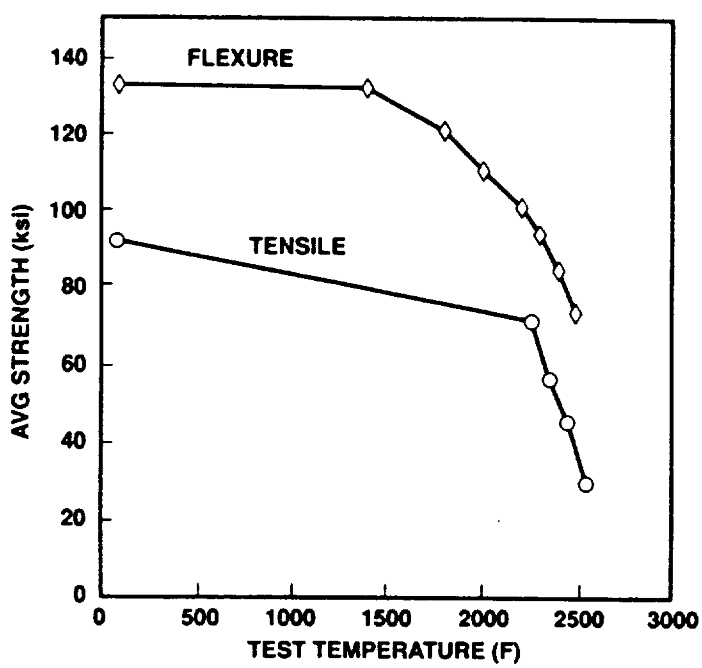


Figure 63. Comparison of GN-10 Tensile and Flexural Strength.

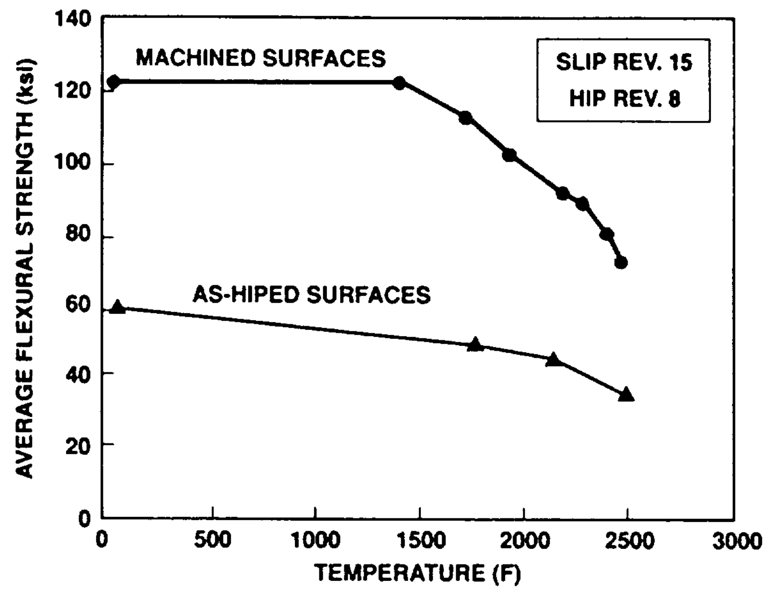


Figure 64. Comparison of As-HIPed Surface and Machined Surface Flexural Strengths.

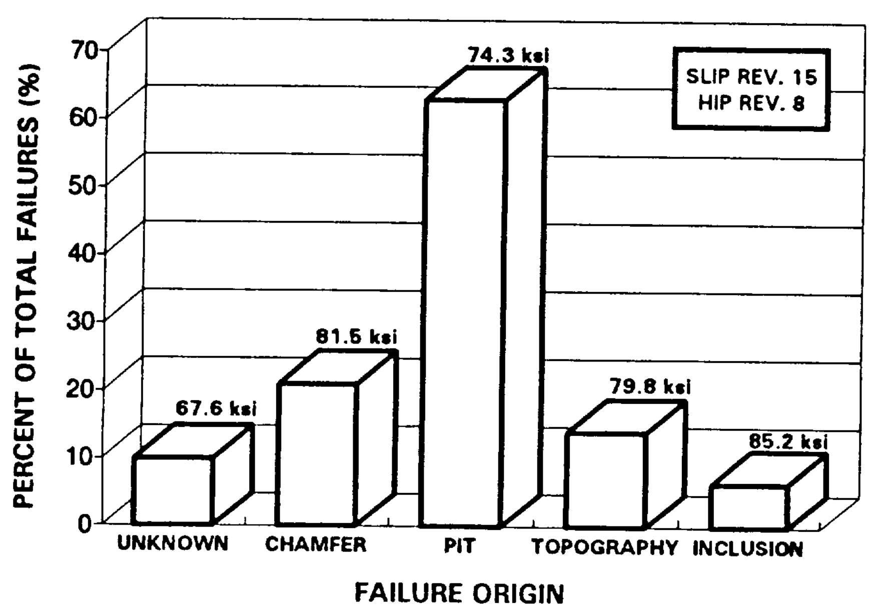


Figure 65. Fractographic Analysis of As-HIPed Surface Test Specimens at Room Temperature.

Machining orientation is also seen to have a significant effect on room temperature strength. In tests conducted on transverse (as related to testing orientation) machined flexure bars, the as-machined strength drops about 50% when transverse machined, but the strength can be restored to the parallel machined level by oxidative heat treatment (Figure 66).

High temperature static properties have also been evaluated. Figure 67 shows the current stress-rupture testing results. The desired program goal of 100 hours life at 2200^{O}F and 70 ksi load is almost achieved (currently about 80 hours average life achievable) but further refinement is needed to achieve the goal. Interrupted static fatigue tests were also conducted to determine the slow crack growth threshold as a function of temperature. GN-10 test specimens were held at a range of applied loads for 4 hours, then loaded to failure. Slow crack growth was detected by observing failures during the static loading, or lower strengths in test bars after the static load. Figure 68a shows an example test result for the determination of slow crack growth initiation at a specific temperature while Figure 68b summarizes GN-10 results and failure mechanisms (fast fracture versus slow crack growth) as a function of applied stress level temperature.

Work is ongoing to further improve the properties and forming process reproducibility of GN-10 Si_3N_4 for the second set of deliverable rotors, due in July, 1992. The focus of improvements are:

1) As-Processed Surface Strength
2) Stress-Rupture Resistance
3) Tensile Strength

In addition, rotor machining and dimensional conformance is being refined.

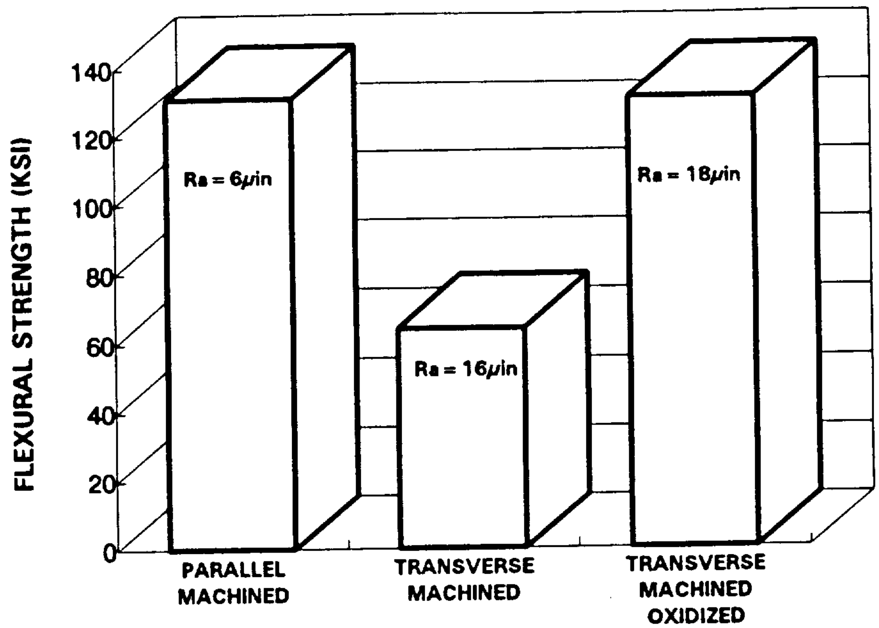


Figure 66. Room Temperature Strength Results of Transverse Machining of Flexure Test Bars.

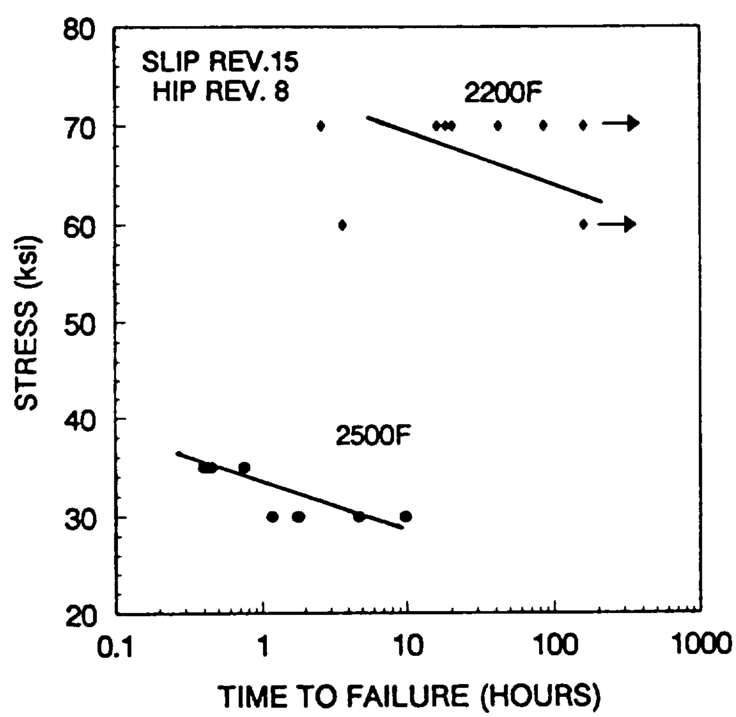


Figure 67. Current Stress-Rupture Properties of Slip Cast GN-10 Si_3N_4.

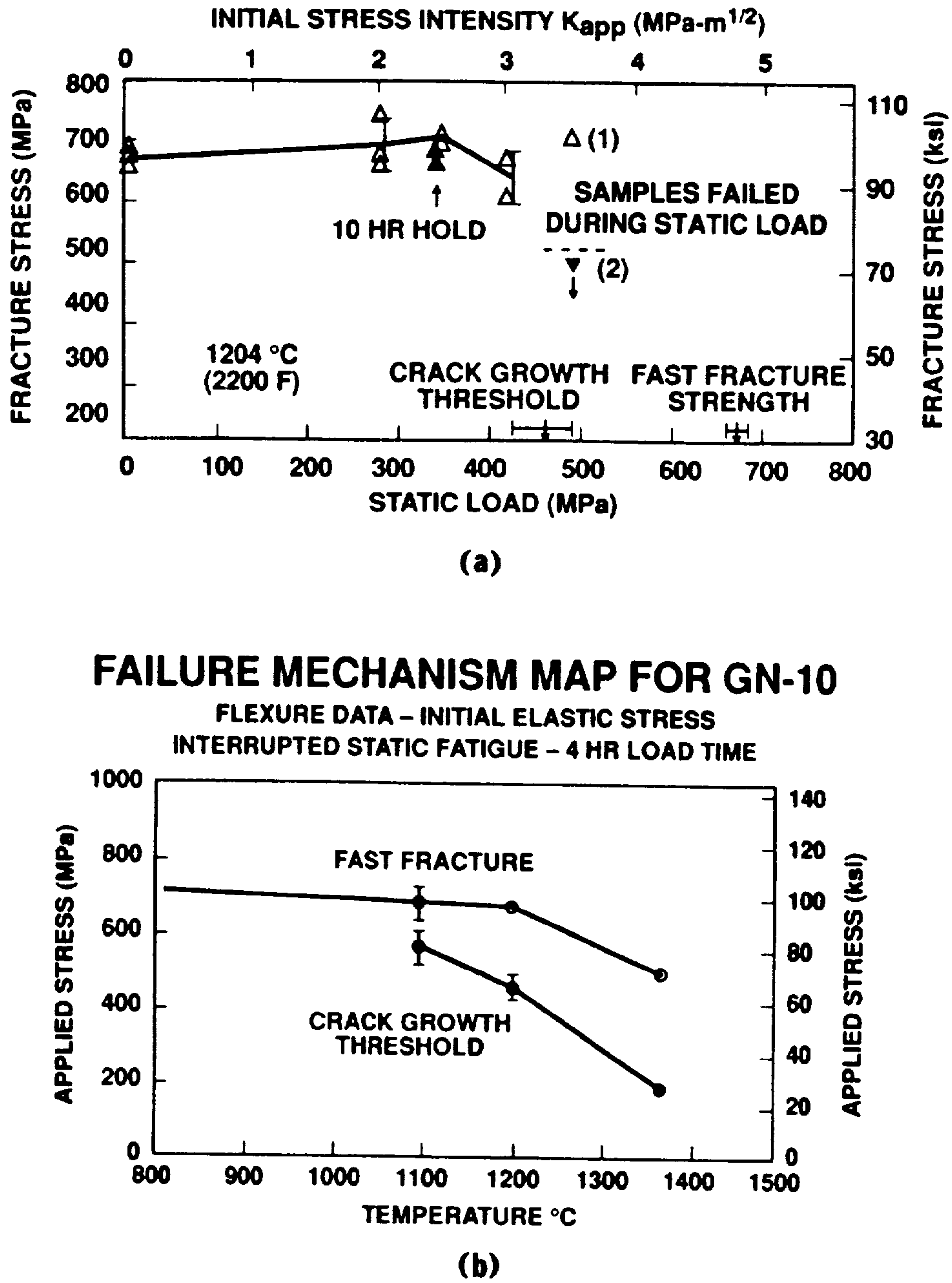


Figure 68. Slow Crack Growth Threshold is Determined by Interrupted Static Fatigue Tests (a) and Resulting Failure Mechanism Map (b).

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15. Supplementary Notes

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16. Abstract

This report is the fourth in a series of Annual Technical Summary Reports for the Advanced Turbine Technology Applications Project (ATTAP), authorized under NASA Contract DEN3-335 and sponsored by the U.S. Department of Energy. The report was prepared by Garrett Auxiliary Power Division (GAPD), a unit of Allied-Signal Aerospace Company. The report includes information provided by Garrett Ceramic Components (GCC), the Norton/TRW Ceramics Company (NTC), and the Carborundum Company, all subcontractors to GAPD on the ATTAP. The project is administered by Mr. Thomas Strom, Project Manager, NASA-Lewis Research Center, Cleveland, OH. This report covers plans and progress on ceramics development for commercial automotive applications over the period January 1 through December 31, 1991.

Project effort conducted under this contract is part of the DOE Gas Turbine Highway Vehicle System program. This program is directed to provide the U.S. automotive industry the high-risk, long-range technology necessary to produce gas turbine engines for automobiles with reduced fuel consumption, reduced environmental impact, and a decreased reliance on scarce materials and resources. The program is oriented toward developing the high-risk technology of ceramic structural component design and fabrication, such that industry can carry this technology forward to production in the 1990s. The ATTAP test bed engine, carried over from the previous AGT101 project, is being used for verification testing of the durability of next-generation ceramic components, and their suitability for service at Reference Powertrain Design conditions.

This document reports the technical effort conducted by GAPD and the ATTAP subcontractors during the fourth year of the project. Topics covered include ceramic processing definition and refinement, design improvements to the ATTAP test bed engine and test rigs and the methodology development of ceramic impact and fracture mechanisms. Appendices include reports by ATTAP subcontractors in the development of silicon nitride and silicon carbide families of materials and processes.

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