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ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROJECT (ATTAP) 1994 ANNUAL REPORT

Engineering Staff of
AlliedSignal Engines, Phoenix, Arizona
A Unit of AlliedSignal Aerospace Company

June 1995

Prepared For:
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio 44135
Under Contract No. DEN3-335

For
U.S. DEPARTMENT OF ENERGY
Office of Transportation Technologies
Advanced Propulsion Division
Washington, DC 20585

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LIST OF ACRONYMS AND ABBREVIATIONS

<u>Abbreviation</u>	<u>Definition</u>
ACC	AlliedSignal Ceramic Components (Torrance, California)
AE	AlliedSignal Engines (Phoenix, Arizona)
AGT	Advanced Gas Turbine
APU	Auxiliary Power Unit
ASE	AlliedSignal Aerospace Systems and Equipment (Torrance, California)
ASME	American Society of Mechanical Engineers
AS-800	AlliedSignal Ceramic Components CIPped Silicon Nitride
atm	Atmosphere
ATTAP	Advanced Turbine Technology Applications Project
Ave.	Average
AZ	Arizona
BN	Boron Nitride
C	Celsius
CA	California
CCM	Contractors Coordination Meeting
CIP	Cold Isostatic Pressing
CMM	Coordinate Measuring Machine
CT	Connecticut
CVD	Chemical Vapor Deposited
deg	Degrees
DoE	Department Of Energy
DYNA3D	Particle Impact Analysis Computer Program
EBAR	Pressure Difference Ratio
EPACT	Energy Policy Act Of 1992
F	Fahrenheit
Fl	Florida
FPI	Fluorescent Penetrant Inspection
GE-CRC	General Electric Corporation Corporate Research Center (Schenectady, New York)
GN-10	AlliedSignal Ceramic Components Silicon Nitride
HIP	Hot Isostatic Pressing
hr	Hour
HS25	Haynes Alloy
HT	High Temperature
Hz	Hertz

LIST OF ACRONYMS AND ABBREVIATIONS (Contd.)

<u>Abbreviation</u>	<u>Definition</u>
ID	Inner Diameter
ITL	Inner Transition Liner
JTEVA	Journal Of Testing and Evaluation
kg	Kilogram
kHz	KiloHertz (Thousands of Cycles Per Second)
KICC	Kyocera Industrial Ceramics Corporation (Vancouver, Washington)
kPa	KiloPascal
ksi	Thousands of Pounds Per Square Inch
lb	Pounds
lb/hr	Pounds Per Hour
lb/sec	Pounds Per Second
LCF	Low Cycle Fatigue
Lubloc	Proprietary Antifriction Coating (EM Corporation, New Britain, Connecticut)
Max.	Maximum
MI	Michigan
min	Minute
mm	Millimeter
MPa	MegaPascal
N/A	Not Applicable
NAC	Norton Advanced Ceramics (East Granby, Connecticut)
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
No.	Number
NT154	Norton Advanced Ceramics HIPped Silicon Nitride
NT164	Norton Advanced Ceramics HIPped Silicon Nitride
OD	Outer Diameter
OH	Ohio
ORNL	Oak Ridge National Laboratories (Oak Ridge, Tennessee)
P/A	Bulk Stress
Pcs.	Pieces
PM	Powder Metal
pp.	Pages
ppm	Parts Per Million
PSC	Pressure Slip Casting
psi	Pounds Per Square Inch

LIST OF ACRONYMS AND ABBREVIATIONS (Contd.)

<u>Abbreviation</u>	<u>Definition</u>
rpm	Revolutions Per Minute
RT	Room Temperature
SAE	Society of Automotive Engineers
SCG	Subcritical Crack Growth
sec	Seconds
SiC	Silicon Carbide
Si ₃ N ₄	Silicon Nitride
SPC	Statistical Process Control
TBD	To Be Determined
TBS	To Be Supplied
TN	Tennessee
UDRI	University of Dayton Research Institute (Dayton, Ohio)
U.S.	United States
Vol.	Volume
WA	Washington State
3-D	Three Dimensional
μ	Coefficient of Friction, Mu

ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROJECT 1994 ANNUAL REPORT

1.0 SUMMARY

This report summarizes work performed by AlliedSignal Engines, Phoenix, Arizona, a unit of AlliedSignal Aerospace Company, during calendar year 1994, in development and demonstration of structural ceramics technology for automotive gas turbine engines. The work performed was sponsored by the U.S. Department of Energy (DoE) under National Aeronautics and Space Administration (NASA) Contract DEN3-335, Advanced Turbine Technology Applications Project (ATTAP). At the end of this reporting period, a contract modification was in process to change the name of the project to the "Ceramic Turbine Engine Demonstration Project", effective January, 1995. This new name more accurately reflects the new focus of the project, with emphasis on ceramic engine demonstration activities.

The objectives of this project are to provide essential and substantial early field experience demonstrating the reliability and durability of ceramic components in a modified, available gas turbine engine application; and to scale up and improve the manufacturing processes for ceramic turbine engine components and demonstrate the application of these processes in the production environment.

Simultaneously, this work will ready ceramic technology for the aircraft auxiliary power unit (APU) application, while gathering extensive laboratory and field experience, and will further develop and improve ceramic component design methods and fabrication techniques. In this way, the ATTAP/331-200[CT] program will effectively support expansion of ceramics technology into automotive engine designs.

The 1994 ATTAP activities emphasized demonstration and refinement of the ceramic turbine nozzles in the AlliedSignal/Garrett Model 331-200[CT] engine test bed in preparation for field testing; improvements in understanding the vibration characteristics of the ceramic turbine blades; improvements in critical ceramics technologies; and scale-up of the processes used to manufacture ceramic turbine components.

The following sections summarize the progress made during 1994 in each of the project activities.

1.1 Design

A second iteration of the 331-200[CT] ceramic turbine nozzle design (Mod 1) was completed, in response to difficulties experienced by the ceramic manufacturers in fabricating parts to the initial design (Mod 0) specifications. A third ceramic nozzle design iteration (Mod 2) was subsequently initiated, near the end of the calendar period, which incorporates changes to achieve further ceramic manufacturing benefits and to address improvements in the nozzle mounting system and metallic support structures. The combined benefits of the Mod 1 and Mod 2 ceramic nozzle design activities have resulted in a more robust ceramic turbine nozzle and metallic support structural system.

A second iteration of the 331-200[CT] ceramic turbine blade design (Mod 1) was initiated, responding to the results of blade vibration testing and additional work performed as part of the blade attachment technology activity.

1.2 Fabrication

Fabrication of ceramic turbine engine components was performed by subcontract vendors. Over 130 Mod 0 ceramic nozzles were fabricated and delivered by AlliedSignal Ceramic Components (Torrance, CA), and 69 Mod 0 ceramic blades were fabricated and delivered by Norton Advanced Ceramics (East Granby, CT). Inspections by AlliedSignal Engines showed these parts were of variable quality, which highlighted the need for common standards for inspection and quality of ceramic components.

Additional orders were placed for Mod 1 ceramic turbine nozzles from Kyocera Industrial Ceramics (Vancouver, WA). An existing order for Mod 0 ceramic nozzles from Norton Advanced Ceramics was changed to the Mod 1 specifications.

Subcontracts for ceramic component manufacturing scale-up activities were negotiated with Norton Advanced Ceramics and AlliedSignal Ceramic Components, and work was initiated.

1.3 Component Testing

Component testing activities accomplished during 1994 included vibration testing of the ceramic turbine blades and proof testing of ceramic blades and ceramic nozzles.

The 331-200[CT] ceramic turbine blade design was evaluated in vibration signature (acoustic "ring") tests, to characterize the restrained resonance modes. Airjet impingement spin testing was performed to identify resonant frequencies with the ceramic blades installed in the metallic turbine disk.

Overspeed spin testing was performed to proof test the ceramic turbine blades prior to engine testing. Each ceramic blade was individually spin tested, inducing stress levels 56 percent higher than the maximum predicted operational stresses in the blade neck area. All the ceramic blades for use in engine operational tests were proof tested prior to assembly into the engine test turbine rotor(s).

Proof tests performed on 82 Mod 0 ceramic turbine nozzles showed a 33-percent first-time failure rate. Retests of the 42 ceramic nozzles which had previously passed the proof testing, including those which survived the engine testing, showed a 100-percent "pass" rate, with no failures.

1.4 Ceramic Technologies

Refinement of critical ceramic design technologies continued during 1994. Significant progress was made in the Blade Attachment, Ceramic Oxidation/Corrosion, and Impact Resistant Design technology work.

1.4.1 Blade Attachment Technology

The results of a study of blade attachment interface properties indicated that attachment bearing stress was strongly influenced by the coefficient of friction (μ) in the interface and the contact angle. For the 331-200[CT] Mod 0 ceramic turbine blade, a preliminary analysis (ignoring the effects of elasticity in the turbine disk) predicted that the bearing stress increases by a factor of 5.8 as the coefficient of friction (μ) increases from 0.2 to 0.5.

Compliant layers were investigated with respect to antifriction coatings in an effort to minimize contact stress in the ceramic blade attachment. This work confirmed that a pre-oxidized Haynes Alloy HS25 compliant layer retained its lubricious oxide coating more effectively than an un-oxidized HS25 compliant layer, with either boron nitride (BN) or Lubloc 7401 coatings.

Contact rig testing confirmed the strength reduction effects of rubbing contact of the metallic disk materials on the ceramic blade surfaces. This work is continuing, to characterize the level of damage with respect to load, stroke length, and temperature.

1.4.2 Impact Resistance Testing

Carbon particle impact tests were performed at the University of Dayton Research Institute (UDRI, Dayton, OH) in a continuing program, to characterize the impact resistance of the 331-200[CT] Mod 0 ceramic turbine blade. The impact tests were performed with 0.1 and 0.2 inch diameter carbon spheres (simulating particles from the combustor as are typically found in the turbine engine flowpath). The critical damage impact velocities found for the axial 331-200[CT] Mod 0 ceramic blade were compared with earlier ATTAP impact test data, taken on both the baseline mixed-flow radial ceramic turbine blade from the early AGT101 engine test bed and the later AGT101 mixed-flow blade design, which was optimized for impact resistance. The 331-200[CT] Mod 0 axial ceramic turbine blade was found to be more impact resistant than the AGT101 mixed-flow radial ceramic turbine blades.

1.4.3 Ceramic/Oxidation Corrosion Prevention

Several corrosion-resistant protective coatings for ceramic turbine components were evaluated. Chemical vapor deposited (CVD) zircon, CVD tantalum oxide, and plasma-sprayed Mullite were evaluated on silicon nitride flexure test bars following hot corrosion (salt-laden air) burner exposures for hundreds of hours. The condition of the test bars following the test exposures showed that all of the coatings evaluated were either consumed by corrosion, or delaminated from the silicon nitride substrate, allowing the substrate to corrode. Additional work is in process to develop a two-layer coating system to protect silicon nitride from hot corrosion from salt-laden air.

In further ongoing experiments to understand the ceramic hot corrosion mechanisms, silicon nitride tensile test specimens were exposed in a hot corrosion (burner rig) environment for various times and then tested in tensile stress rupture to determine if the resulting surface corrosion caused any reduction in the stress rupture life of the material. No significant reduction in stress rupture life was noted as a result of the pitting and material loss from the salt corrosion.

1.5 Engine Testing

An analysis was conducted to determine the cause of the failure that occurred during the ceramic turbine blade equipped engine test in November, 1993. The analysis inductively determined that a ceramic turbine blade had failed from vibration. This finding spurred a series of ceramic turbine blade component tests to characterize the restrained vibration resonance modes of the Mod 0 ceramic blade, and contributed to the design efforts for the Mod 1 ceramic blade attachment.

During 1994, Mod 0 ceramic nozzles were successfully operationally tested in the 331-200[CT] engine test bed for a total of 547 hours, accumulating over 600 starts. Out of 23 ceramic nozzles in the test, 2 nozzles experienced non-catastrophic airfoil damage.

2.0 INTRODUCTION

This report summarizes progress made in the ATTAP/331-200[CT] Ceramic Turbine Engine Demonstration Project during 1994 by AlliedSignal Engines, Phoenix, AZ, a unit of AlliedSignal Aerospace Company. The Advanced Turbine Technology Applications Project (ATTAP) is a continuation of activities sponsored by the U.S. Department of Energy (DoE) to develop an advanced ceramic gas turbine engine for hybrid vehicles, consistent with the U.S. Energy Policy Act of 1992 (EPACT). ATTAP is funded by the DoE Office of Transportation Technologies, as part of the Turbine Engine Technologies Program. The work is being performed under DoE/NASA Contract DEN 3-335, with the National Aeronautics and Space Administration (NASA) providing program management and administration. The NASA Project Manager is Mr. Thomas N. Strom, Advanced Propulsion Applications Office, NASA Lewis Research Center, Cleveland, OH, 44135-3191; telephone (216) 433-3408.

The present ATTAP/331-200[CT] program has been refocused on supporting ceramic turbine components for future automotive applications, by generating extensive operating experience in both laboratory engine testing and field operation. The program continues the development of ceramics technologies and design methods, and focuses fabrication development on a scale-up of demonstrated technologies to pilot production levels. The project utilizes a reliable test bed engine based on the existing production AlliedSignal/Garrett Model 331-200[ER] auxiliary power unit (APU) shown in Figure 1, which has proven capability for long-term endurance testing. The first-stage turbine of the 331-200[CT] test bed has been modified to incorporate ceramic nozzles and blades.

The 331-200[CT] ceramic technology test bed provides additional capability over the AGT101 test bed engine used in prior years of the Advanced Gas Turbine (AGT) and ATTAP programs. By virtue of its high reliability and potential for field testing, the 331-200[CT] test bed will enable the accumulation of very high operating times, while still exposing the ceramic components to many of the random failure modes that actually exist in production engine applications. In addition, designing and demonstrating ceramic components in this engine focuses on the mechanical aspects of integrating ceramics into gas turbines, which has been a principal barrier to the successful commercialization of ceramic turbine technology.

The relatively low average turbine inlet operating temperature of 1800F (988C) in the 331-200[CT] presents only a minor trade-off in effectiveness for evaluation of ceramic turbine components. Although this condition does not challenge the maximum temperature capability of the ceramic materials, other critical ceramic design aspects such as interface contact, impact resistance, vibration levels, and various fast fracture

failure modes present other, real challenges in this test bed and its field applications. In the future, commercial application of the ceramic technologies proven in this test bed will be able to successfully take maximum advantage of higher temperature capability of the ceramic materials, but only after the mechanical design issues are fully understood and resolved.

The thrust of the ATTAP/331-200[CT] program is to “bridge the gap” between structural ceramics in the laboratory and near-term commercial heat engine applications. This work will simultaneously ready ceramics technology for the aircraft APU application, while gathering extensive laboratory and field experience, and develop ceramic component design methods and fabrication techniques. The intent is to use this application as a stepping stone to transition ceramics technology into the automotive marketplace, where the benefits will have the greatest impact on reducing fuel consumption and gaseous emissions.

The overall ATTAP/331-200[CT] program plan provides an approach to resolve each of these issues. The discussions in the following sections of this report describe the progress to date in the various ATTAP activities and outline the go-forward plans to meet the program objectives.

G5349-1

94597-1

Figure 1. AlliedSignal/Garrett Model 331-200 APU Used As ATTAP Test Bed Engine Has Proven Capability For Long-Term Endurance Testing.

3.0 TURBINE STAGE DESIGN, PRELIMINARY MODELING AND ANALYSIS

ATTAP design activities during 1994 emphasized refinement of the 331-200[CT] ceramic turbine blades and nozzles to achieve additional robustness, from both the manufacturing and mechanical integrity perspectives. A nomenclature to distinguish between the various ceramic nozzle and blade design iterations has been established. The original designs for the ceramic nozzle and blade are referred to as the "Mod 0" designs. Subsequent design iterations will be identified by sequential numbers, such as Mod 1, Mod 2, etc. The "Mod 1" nozzle refers to the design generated in January, 1994 which incorporated more robust features and draft angles for proper casting tool removal. The "Mod 1" blade refers to the design currently in progress having more robust attachment geometry.

3.1 Mod 1 Ceramic Turbine Blade Preliminary Design

As a consequence of the two ceramic blade equipped engine test failures during 1993, which highlighted the extreme sensitivity of the Mod 0 blade to contact loading and vibration, a decision was made to initiate a second-generation design in order to make the blade attachment more robust. The design approach was to only modify the attachment portion of the blade. The Mod 0 airfoil was not changed for the Mod 1 blade design.

The new Mod 1 ceramic turbine blade attachment design in progress is shown conceptually in Figure 2. The Mod 1 ceramic blade design incorporates the following improvements:

- **45-Degree contact angle:** Reduces contact and shear stresses under certain transient thermal conditions, and also reduces relative motion in the contact interface under engine operating conditions, minimizing wear at the interfaces.
- **Thickened minimum attachment neck width:** Improves the attachment strength and ensures that by design, the airfoil will fail before the attachment under possible tip or impact overload conditions.
- **Shortened blade shank:** Raises blade resonant frequencies out of the range of excitation.

Table 1 shows a comparison of the Mod 1 blade design goals and actual values with those of the original (Mod 0) ceramic blade attachment. Significant changes from the Mod 0 design are in the attachment neck width (increased by 67 percent) and the contact surface angle (reduced from 60 to 45 degrees).

Mod 1 Ceramic Blade Attachment Design

G5349-2

Figure 2. Mod 1 Ceramic Turbine Blade Attachment Design Concept.

TABLE 1. COMPARISON OF 331-200[CT] CERAMIC TURBINE BLADE DESIGN FEATURES.

Feature	Unit	Mod 0	Mod 1	Design Goal
Geometric Features				
Blade Neck Width	inch	0.15	0.25	0.22 (Minimum)
Disk Neck Width	inch	0.166	0.12	N/A
Contact Angle	deg	60	45	45
Contact Length	inch	0.15	0.068	N/A
Broach Angle	deg	20	11	N/A
Blade Bottom Surface	---	Flat	Round	N/A
Blade Stresses				
Bearing Stress	ksi	24.3	36.5	<50
Neck P/A Stress	ksi	17.7	9.3	<20
3-D Peak Stress	ksi	39.8	43.7	<50
Shear Stress	ksi	8.7	11.0	--
Disk Stresses And LCF Life				
Neck P/A Stress	ksi	48.1	45.3	<70
3-D Peak Stress	ksi	155.0	121.6	N/A
Shear Stress	ksi	6.9	13.0	N/A
LCF Life	cycles	64,000	>20,000	>20,000
Vibration Frequencies				
Mode 1	Hz	16,049	24,375	25,873
Mode 2	Hz	31,201	37,213	--
LCF = Low Cycle Fatigue. N/A = Not Applicable. P/A = Bulk Stress.				

3.2 Ceramic Nozzle Design and Analysis

3.2.1 Mod 1 Ceramic Nozzle

Fabrication difficulties resulting in poor yields and high costs highlighted the need to improve the Mod 0 ceramic nozzle design for better fabricability. Problems with respect to casting fill, demolding, and extreme fragility of the greenware made fabrication of the Mod 0 nozzle design unfeasible, using the pressure slip casting (PSC) process. Nozzle redesign activity was initiated in late 1993 and completed in early 1994, resolving these issues.

The Mod 1 ceramic nozzle design features are shown in Figure 3. The Mod 1 ceramic nozzle attachment to the metallic structures remained basically the same as on the Mod 0 nozzle, except an inner diameter (ID) seal added to help reduce hot air leakage. The major changes from the Mod 0 design consist of the following:

- Thickened endwalls (platforms)
- Thickened airfoils
- Increased radius airfoil fillets
- Endwall draft.

The redesigned (Mod 1) ceramic nozzle airfoil was thickened using the same velocity diagrams predicted for the production 331-200 metallic nozzle and the 331-200[CT] Mod 0 ceramic designs. The Mod 1 vanes were designed to yield the correct throat size without a need to restagger the vanes. The viscous 3-D aerodynamic loading values are shown in Figure 4 at the midchord for both the Mod 0 (initial design) and the Mod 1 airfoils. The loading values are favorable for both designs.

The full-vane passage losses are also similar for the two ceramic designs. The distributions of exit kinetic energy loss coefficient (without fillets) are compared in Figure 5. However, the addition of fillets between the airfoil and endwalls would significantly increase the losses, as shown in Figure 6, where the mass-averaged kinetic energy loss coefficient is 0.0568 for the Mod 1 vane with fillets, and 0.0453 without fillets. The total effect on overall turbine stage performance is estimated to be a decrease in efficiency of 0.16 points.

G5349-3

Figure 3. Mod 1 Ceramic Turbine Nozzle Design Enhances Producibility And Durability.

Figure 4. Mod 0 and Mod 1 Ceramic Nozzle 3-D Dawes Viscous Aerodynamic Loads (At Midchord).

The stresses in the Mod 1 nozzle were also calculated, exposing an additional benefit of the redesign activity. The data in Table 2 compares the critical stresses in the Mod 0 and Mod 1 ceramic nozzles. It is significant to note that the bulk temperature, normal start transient stresses in the Mod 1 nozzle are only 7 ksi, compared to 45 ksi in the Mod 0 nozzle design. When the effect of possible "hot spots" occurring during a starting transient are considered, the peak stress for the Mod 1 nozzle increases to 17 ksi. The hot-spot transient stress was not calculated for the Mod 0 design, but is expected to be significantly higher than the value previously noted for the bulk temperature calculation.

Figure 5. Mod 0 and Mod 1 Ceramic Nozzle Exit Loss Coefficients (Without Fillets).

Figure 6. Mod 1 Ceramic Nozzle Exit Loss Coefficients (With Fillets).

TABLE 2. MOD 0/MOD 1 CERAMIC NOZZLE STRESS COMPARISON.

Location	Peak Transient Stress, ksi		Peak Steady-State Stress, ksi	
	Mod 0	Mod 1	Mod 0	Mod 1
Airfoil Leading Edge	44	8	24	5
Airfoil Trailing Edge	41	16	20	8
Post Fillet	---	10	---	4

3.2.2 Mod 2 Ceramic Nozzle and Support Structure

The Mod 2 ceramic nozzle design activity addresses only the attachment design and the supporting structures surrounding the ceramic nozzle assembly. This work was initiated as a result of an assessment of the potential of the 331-200[CT] ceramic nozzle assembly for successful field testing, and addressed the following aspects:

- Make the ID and OD seals more robust
- Simplify and reduce the parts count for the surrounding metallic structures
- Provide for retention of both platforms in the event of ceramic nozzle damage.

The preliminary Mod 2 ceramic nozzle design is shown in Figure 7. The Mod 2 design deletes the mounting post and uses axial loading for the ceramic-to-metal interface and nozzle positioning, and has thicker platforms than the Mod 1 design. The Mod 2 nozzle design was optimized by simplifying the configuration of the metallic support structures, and enhancing the manufacturability and durability of the ceramic nozzle segments. This design is expected to have lower manufacturing costs than either the Mod 0 or Mod 1 configurations.

**Current Post-Style
Stator Segment
(Mod 1)**

G5349-7

**Proposed Reduced-Cost
Stator Segment
(Mod 2)**

**Figure 7. Mod 1 (Left) And Preliminary Mod 2 (Right) Ceramic Turbine Nozzle Designs
Share Common Airfoil And Gas Path Geometries.**

4.0 COMPONENT FABRICATION

4.1 Ceramic Component Fabrication

Fabrication of ceramic turbine engine components was performed by subcontract vendors. Over 130 Mod 0 ceramic nozzles were fabricated and delivered by AlliedSignal Ceramic Components (Torrance, CA), and 69 Mod 0 ceramic blades were fabricated and delivered by Norton Advanced Ceramics (East Granby, CT). Inspections by AlliedSignal Engines showed these parts were of variable quality, and their manufacture highlighted the need for common standards for inspection and quality of ceramic components.

Additional orders were placed for Mod 1 ceramic turbine nozzles from Kyocera Industrial Ceramics (Vancouver, WA). An order for Mod 0 ceramic nozzles from Norton Advanced Ceramics was changed to the Mod 1 specifications. The status of the ATTAP/331-200[CT] ceramic components received or on order at the end of the 1994 calendar year is given in Table 3.

TABLE 3. 331-200[CT] CERAMIC COMPONENTS ORDER STATUS (AS OF 12/31/94).

Item	Source	Quantity Accepted	Quantity Remaining	Status or Scheduled Delivery	Remarks
Mod 0 Nozzles	ACC	107	0	Complete	Low surface strength of co-processed specimens; platform dimensions out of tolerance.
Mod 0 Nozzles	ACC	33	0	Complete	Low properties; rig evaluation only.
Mod 0 Nozzles	ACC	10	0	Complete	Low properties; rig evaluation only.
Mod 1 Nozzles	NAC	0	30	05/15/95	Delayed by process problems.
Mod 1 Nozzles	NAC	0	70	(TBD)	Delayed by process problems.
Mod 1 Nozzles	KICC	0	50	04/14/95	Delayed.
Mod 0 Blades	NAC	8	0	Complete	Ordered for rig test only.
Mod 0 Blades	NAC	122	0	Complete	Dimensions out of tolerance.
Mod 1 Blades	KICC	0	70	(TBD)	Being requoted to new specifications.
Mod 1 Blades	CC	0	70	(TBD)	In quote.
ACC = AlliedSignal Ceramic Components KICC = Kyocera Industrial Ceramics Corp. NAC = Norton Advanced Ceramics (TBD) = To Be Determined.					

Significant challenges during the 1994 program year concerned the dimensional and material specification compliance of the ceramic components delivered. As noted in Table 3, several batches of components were delivered which did not meet all of the requirements specified; some of these were accepted so that critical engine or rig testing could be supported. In each case, acceptance was based on the specific defect(s) with respect to mechanical integrity, and whether the part could be reworked or qualified through proof testing. The AlliedSignal Engines (AE) Ceramic Supplier Strategy Team, a cross-functional team serving several programs, worked closely with each of the ceramic suppliers to resolve these issues, and aided the design teams in specifying requirements for ceramic components as well as resolving issues regarding drawing and specification interpretation.

Many of the problems encountered were the result of ceramic component process variability, which will be improved as a byproduct of the manufacturing scale-up and demonstration work. However, a significant number of problems were the result of differences in print and specification interpretation, and different dimensional inspection methods that were in use. As a result of this work the importance of working closely with each of the prospective ceramic supplier(s) during the ceramic component design phase was reinforced. The problems may be resolved by seeking agreement on drawing tolerances and datum structures. In addition, it was determined that for the sophisticated geometries of ceramic gas turbine blades, coordinate measuring machine (CMM) data has not been found to be sufficiently reliable. Inspection using a projection optical comparator with 50X Mylar drawings was found to be the most reliable method for these components.

4.2 Ceramic Component Manufacturing Scale-Up and Demonstration

Subcontracts were in place with AlliedSignal Ceramic Components (ACC) and Norton Advanced Ceramics (NAC) for a demonstration of fabrication capability for gas turbine components in production quantities. Work under these subcontracts was initiated in 1993 and was scheduled to continue through 1996.

The goal of this program is to scale up existing, laboratory/prototype processes for the fabrication of ceramic turbine components to a production level capability of 500 parts per month. These processes will be demonstrated by the production at a rate of at least 100 parts per month of ceramic turbine components which meet all of the requirements of the aerospace production release blueprints and specifications.

In parallel with this demonstration, production yields and costs will be monitored and improved in order to demonstrate that ceramic turbine components are cost effective for incorporation in commercial aerospace products. Overall program goals for the multi-year ceramic manufacturing scale-up program are summarized in Table 4.

TABLE 4. OVERALL (1996) CERAMIC MANUFACTURING SCALE-UP GOALS.

Item	Units	Goals	
		Component - Subcontractor	
		Nozzles - ACC	Blades - NAC
Overall Yield	percent	75%	66%
Capacity (Individual Process Capability)	parts/month	500	500
Capacity (Demonstrated over 6-month period)	parts/month	100	100
ACC = AlliedSignal Ceramic Components. NAC = Norton Advanced Ceramics			

The work performed by each of the participating subcontractors is summarized in the following paragraphs.

4.2.1 AlliedSignal Ceramic Components

Scale-up work at AlliedSignal Ceramic Components (ACC) was initiated in November, 1993. This work focused on the demonstrated ACC baseline process for fabrication of 331-200[CT] ceramic turbine nozzles, consisting of pre-sintering a slip cast blank, machining two nozzle shapes from each blank, hot isostatic pressing (HIPping) the nozzles to full density, and final machining of critical features. The 1994 ACC Work Plan was established, focused on achieving the milestones listed in Table 5.

Much of the work performed in addressing these milestones was part of the same demonstration, starting with the same starting powder batch and ending with some number of finished ceramic nozzles. In general, the goals for increasing the capacity for each of the process steps were achieved. However, individual process step yields did not meet expectations.

The major barriers to achieving the overall goals for total process yield and part cost were identified as platform distortion during HIPping, and the rejection of several parts due to low-density X-ray indications in the airfoil/platform fillet. The low-density indications were actually the result of surface defects in the fillets from the pre-sinter machining process. Follow-on work was applied to improving the pre-sinter machining

process to eliminate these defects. The problem with platform warpage seemed to be largely inherent in the HIPping process. ACC recommended changing the ceramic material from GN-10 silicon nitride, which requires HIP densification, to AS-800 silicon nitride, which is gas pressure sintered. In addition to the expected benefits of lower warpage and fewer surface defects with AS-800, this material offered improved as-processed surface properties and lower processing cost compared to GN-10.

TABLE 5. ALLIEDSIGNAL CERAMIC COMPONENTS 1994 MILESTONES.

Milestone	Status	Comments
65 Nozzle Blanks Per Slip Batch	Accomplished	---
30 Percent Reduction In Pre-Sinter Machining Costs	Accomplished	---
Identify Key Process Controls For SPC	Accomplished	---
60 Percent More Nozzles Per HIP Run	Accomplished	---
90 Percent HIP Furnace Yield	Not Achieved	70 Percent yield demonstrated
50 Percent Yield For Platform Profile	Not Achieved	None met platform profile requirements
80 Microinch (Maximum) Surface Roughness	Not Achieved	91 Maximum, 72 average in sample of 34 pieces
25 Percent Cycle Time Reduction	Accomplished	---
35 Percent Part Cost Reduction	Not Achieved	21 Percent reduction realized
25 Percent Total Process Yield	Not Achieved	Parts did not meet platform tolerances

4.2.2 Norton Advanced Ceramics

As a subcontractor to AlliedSignal Engines, Norton Advanced Ceramics (NAC) was developing the production process for NT164 silicon nitride 331-200[CT] ceramic turbine blades. The objective of this effort was to scale-up the current prototype process for 331-200[CT] ceramic blades to achieve the improvements in quality levels, delivery times, and parts cost required for volume production of aerospace components.

Work was being performed by NAC to demonstrate improvements in capacity, yield, process cycle time, and cost. Work in 1994 was aimed at developing casting tooling amenable to a semiautomated pressure slip casting (PSC) technique, casting parameter optimization, and a demonstration of production of slip-cast

blades. Also on the NAC near-term agenda were tasks to define optimized machine tooling and inspection tooling for ceramic turbine blades.

The status of the 1994 NAC milestones is summarized in Table 6. A summary discussing progress from the initiation of this activity through October, 1994 follows. Capacity scale-up was successful for the process steps required prior to casting. However, in order to achieve the remaining milestones listed, additional work was required with respect to robust mold design and machining and inspection processes.

TABLE 6. NORTON ADVANCED CERAMICS 1994 MILESTONES.

Milestone	Status	Comments
Continuous Heat Treatment of Raw Materials	Accomplished	---
2X Scale-Up of NT164 Powder Batch Size	Accomplished	---
3X Scale-Up of NT164 Slip Batch Size	Accomplished	---
Dense Casting Inspection Yield of 55 Percent	Not Achieved	Results not reported*
Production Capacity of 100 Blades per Month	Not Achieved	Results not reported*
Total Process Yield of 44 Percent	Not Achieved	Results not reported*
20 Percent Reduction in Unit Variable Cost	Not Achieved	Results not reported*
Complete Process Control Plan	Not Achieved	Results not reported*
* See text.		

Experiments were conducted by NAC to develop a unidirectional approach to casting ceramic turbine blades using a semiautomated slip casting process. This work, which investigated various powder formulations, slip solids content values, and mold designs, generated a set of ten blades which were subsequently HIP densified and inspected in accordance with the surface quality requirements of the blade drawing. The result of this experiment was a casting process that produced improved surface quality, with fewer large pits (> 0.005 inch diameter).

"Lessons learned" from past procurement of ceramic hardware indicated that improved control was needed for the machining process, and better understanding of the inspection requirements and methods for ceramic turbine blades was also needed. To this end, the datum structure for the drawings describing the turbine blade were reviewed, with the focus on augmenting the finish grinding process. Practices for fixturing the work as well as alternate casting datum targets were identified to facilitate the improved grinding processes.

Control charts were updated for each process input and output variable. Data generated under ceramic blade and nozzle parts buy orders have been included on the control charts. A process control plan was being developed for the 331-200[CT] ceramic turbine blade.

At the end of 1994, consideration was given to redirecting the NAC subcontract effort, to concentrate on improvement of the baseline ceramic component production process by incorporation of closed-loop process (CLP) NT164 silicon nitride. As a result, as indicated in Table 6, the status of progress against several planned 1994 milestones was not reported.

5.0 COMPONENT TESTING

5.1 Ceramic Turbine Blade Component Testing

In response to the failures that occurred during operational tests of the ceramic blade equipped 331-200[CT] engine test bed during late 1993, component testing was performed to characterize the vibration modes of the ceramic turbine blade. This work supported an overall effort to understand the response of ceramic turbine blades in the engine environment and to prepare for a go-forward decision on the direction of ceramic turbine blade development. The 1994 Ceramic Blade Component Test Plan was established to confirm the resonant frequencies of the 331-200[CT] Mod 0 ceramic blade in both the static and dynamic conditions, and to prepare the hardware for a strain gage equipped engine operational test, originally planned for late in the year. However, as a result of problems experienced in mounting the required high-temperature strain gages onto the ceramic turbine blades, the planned engine testing was postponed until 1995.

5.1.1 Ceramic Blade and Rotor Proof Testing

During the 1994 reporting period, 69 Mod 0 ceramic turbine blades were received. These blades were individually spin proof tested in the whirlpit to 50,000 rpm, which imposes peak stresses in the blade attachment neck that are approximately 156 percent of the maximum predicted stress in that area during operation. All of the ceramic blades successfully passed this test

5.1.1.1 Mod 0 Blade Vibration Testing

Tests were conducted in an effort to characterize the resonant characteristics of the Mod 0 ceramic turbine blades, and to determine the integrity of the ceramic blades in a severe vibration environment. Mod 0 331-200[CT] ceramic turbine blades were instrumented with conventional (low-temperature) strain gages and evaluated on a vibration test (shaker table) apparatus, shown in Figure 8. In this testing, the ceramic turbine blade under test was mounted on a broach block and instrumented with strain gages to measure the blade response to driving frequencies up to 50,000 Hz. Excited by white noise, the Mod 0 ceramic blade natural frequency modes were found at 14,460 and 30,720 Hz.

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Figure 8. Vibration Test Setup Used To Characterize Mod 0 Ceramic Turbine Blade Static Resonance.

A vibration test procedure was then established, to determine the relative amount of energy required to cause the failure of a ceramic turbine blade at resonance. First, a production metallic 331-200 APU turbine blade was vibrated at resonance until failure occurred, and then a similar test was attempted with a Mod 0 ceramic blade. The energy levels for each blade type were then to be compared, to evaluate the relative vibration tolerance. Unfortunately, a vibration shaker table with sufficient power at 14,500 Hz to break the ceramic blade could not be located, so this test effort was suspended.

5.1.1.2 Airjet Impingement Vibration Testing

Airjet impingement spin tests were completed, to confirm the first and second ceramic turbine blade resonant frequencies under the dynamic conditions of disk rotation, and to determine the relative vibration energy detectable at the blade surface versus the disk post. The test results indicated that the strain levels indicated at the disk post for the first vibration mode were 75 percent of the value measured at the blade surface, and for the second mode the disk post strain levels were 10 percent of the blade surface strain levels. The vibration frequencies measured for both modes compared closely with predicted values, and also with the values measured on each blade separately in a modal test. Table 7 indicates the measured and predicted vibration values.

TABLE 7. COMPARISON OF MEASURED AND PREDICTED MOD 0 CERAMIC BLADE VIBRATION FREQUENCIES.

Mode	Predicted Value, Hz	Measured Values, Hz	
		Individual - Modal Test	Airjet Test
1	16,000	14,200	14,300
2	30,000	30,500	30,600

5.2 Ceramic Nozzle Component Testing

5.2.1 Mod 0 Ceramic Nozzle Proof Testing

Proof testing was performed on a total of 82 new Mod 0 ceramic turbine nozzles received from AlliedSignal Ceramic Components (ACC), made from slip-cast GN-10 silicon nitride blanks. This test, described more completely in the 1993 ATTAP Annual Report (Ref. 1), exposed each ceramic nozzle individually in a hot gas flow test rig to the following temperature excursion cycle: a rapid temperature increase from 100F to 2450F (38C to 1343C), held at 2450F (1343C) for eight seconds, and then rapidly cooled to less than 200F (93C). Twenty-seven nozzles (33 percent of the total) failed the test, due to cracking of the airfoils. Figure 9 shows a typical ceramic nozzle airfoil crack following the proof testing, highlighted by fluorescent dye penetrant inspection (FPI) techniques.

Note that the crack initiated at the leading edge of the airfoil and propagated only partially along the chord of the airfoil before stopping. All the failures noted in this batch of Mod 0 ceramic nozzles were similar, though in some nozzles, the fracture had initiated at the leading edge, and in the remainder, fractures had initiated at the trailing edge and propagated in the opposite direction.

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Figure 9. Typical Crack Found In Proof-Tested Mod 0 Ceramic Nozzle Airfoil, Highlighted With Fluorescent Dye Penetrant Inspection (FPI).

This high nozzle failure rate may be explained by a comparison of results from the proof tests with results from the as-processed flexure strength testing performed on material billets co-processed with the ceramic nozzles. The flexure test data indicated that the co-processed billet material specimens often did not meet the minimum requirements of the GN-10 silicon nitride material specification, and the billets that did pass only met the minimum requirements.

Figure 10 shows a Weibull plot of the flexure test data from the co-processed ceramic billets. At the 33-percent probability of failure level, the plot indicates a flexure strength of 61.6 ksi. This value is approximately midway in the range (56 to 67 ksi) of stresses induced during the ceramic nozzle proof test cycle.

Figure 10. Weibull Plot Of Flexure Test Data From Co-Processed GN-10 Billets.

5.2.2 Mod 1 Ceramic Nozzle Proof Test Fixture

A test fixture redesign to permit proof testing of the Mod 1 ceramic nozzles was completed. The new proof test fixture incorporated modified flowpath and nozzle seat geometry, as well as an improved nozzle retention system that eliminates flow leakage around the test article and out of the rig. Figure 11 shows a cross section of the redesigned ceramic nozzle proof test fixture, showing the improved nozzle retention system, platform insulation, and nozzle removal tool features.

Figure 11. Cross Section Of Redesigned Ceramic Nozzle Proof Test Fixture, Showing Improvements.

5.2.3 Post-Endurance Test Ceramic Nozzle Proof Testing

Proof tests were performed to determine whether any ceramic nozzles had experienced deterioration following the 243-hour ceramic nozzle equipped engine endurance test. In June, 1994 two sets of ceramic nozzles, including the 21 surviving Mod 0 ceramic nozzles from the engine endurance testing, plus a control set of 21 Mod 0 ceramic nozzles from inventory (that had been previously proof tested but were not engine tested), were retested in the nozzle proof test rig at the conditions developed for ceramic nozzle acceptance testing.

Following this additional proof testing, inspections were performed employing both visual examination and fluorescent penetrant inspection (FPI) methods to detect any cracks. No cracks were found on any of the re-proof tested parts. This result confirmed that the fast fracture properties of the GN-10 ceramic nozzles had not significantly deteriorated during the 243-hour engine endurance testing.

5.2.4 Nozzle Assembly Flow Testing

The assembly of Mod 0, cold isostatic pressed (CIPped) ceramic nozzles used in the 100-hour engine endurance testing was tested to determine its flow capacity and secondary flow losses. The measured nozzle flow capacity, adjusted for the test conditions and secondary flow differences, matched the 331-200[CT] engine operational requirements. The secondary flow losses were found to be 5.7 percent of the total corrected flow. The largest component of this loss (3.7 percent) was due to leakage beneath the inner diameter (ID) platform. The new (Mod 1) nozzle assembly installation had an ID platform seal incorporated into its design, which would help to improve the flow performance.

An assembly of GN-10 Mod 0 slip-cast ceramic nozzles was also flow tested, for comparison with the GN-10 Mod 0 CIPped nozzle assembly used in the 100-hour engine testing. The test results indicated the slip-cast nozzle assembly flow capacity was consistent with the results from the CIPped nozzle assembly. Minor differences in the airfoil and endwall geometry due to the profile tolerances caused minor variations in the measured flow characteristics. Table 8 shows a comparison of the measured choked flow rates for the slip-cast ceramic, CIPped ceramic, and baseline metallic nozzle assemblies.

TABLE 8. MEASURED FLOW RATES OF 331-200 APU TURBINE NOZZLE ASSEMBLIES.

Assembly Type	Choked Flow Rate, lb/sec
CIPped GN-10 Ceramic Nozzles	1.70
Metal Nozzles (Baseline)	1.73
Slip-Cast GN-10 Ceramic Nozzles	1.75

6.0 CERAMIC TECHNOLOGIES AND METHODS

Refinement of several ceramics technologies, critical to the success and cost-effectiveness of the 331-200[CT] axial ceramic turbine stage, are being addressed in the ATTAP program. These included:

- Methods for predicting the reliability benefits of proof testing
- Options for ceramic turbine blade attachment
- Characterization and modeling of silicon nitride (Si_3N_4) oxidation and hot corrosion
- Methods to predict impact damage
- Development of alternative ceramic nozzle proof testing techniques.

The progress during 1994 for these activities is summarized in the following sections.

6.1 Ceramic Proof Testing Methodology Development

This technology refinement activity complements similar work being conducted by AlliedSignal Engines under the Dept. of Energy Oak Ridge National Laboratories (DoE-ORNL) Ceramic Life Prediction Methodology Phase II Program. The ATTAP efforts are specifically tasked with determining the methods for predicting the reliability of proof testing methods with respect to volume flaws in ceramic components. This activity includes the development of analytical methods for projecting the effects of proof testing and validating these methods with a series of tests. This work was augmented by a subcontract with the General Electric Corporate Research Center (GE-CRC) in Schenectady, NY for the participation of Dr. C. Johnson and Dr. W. Tucker, noted experts in this field.

6.1.1 Ceramic Specimen Proof Testing

During 1994, a test matrix for development of ceramic proof testing methodology for volumetrically-distributed failure modes was generated. The test matrix is listed in Table 9. The test matrix included tensile fast fracture, subcritical crack growth (SCG), and stress rupture tests, encompassing the fast fracture and time-dependent failure modes. The intent of the test matrix was to proof test each set of specimens at room temperature and at a predetermined mechanical tensile stress level at which approximately one-third of the specimens would fail. The remaining specimens would then be tested at high temperature in the three failure modes. The results of the tests will be used to develop methodology defining the effects of proof testing on volumetric failure modes.

TABLE 9. VOLUME PROOF METHODS TEST MATRIX.

Failure Mode	No. Of Specimens	Test Conditions	
		Proof Test	Fracture Test
Fast Fracture	40	RT	HT
Slow Crack Growth	40	RT	HT
Stress Rupture	40	RT	HT
HT = High Temperature. RT = Room Temperature.			

NT154 silicon nitride tensile stress rupture test specimens were received, dimensionally inspected, and X-rayed to detect any existing internal flaws and inclusions. Work was initiated to define the required load for the mechanical proof test. These specimens will be tested and the data will be shared with the ongoing DoE-ORNL-sponsored Phase II Ceramic Life Prediction Program.

6.1.2 Reliability Methods Development

A principal effort in this program will be to develop confidence limit prediction methodology for time-dependent failure modes of ceramic components. Methods developed by Margeson and Cooper (Ref. 2) will be used to determine the strength distribution of the proof-tested specimens. These methods will be used to make comparisons before and after proof testing, to determine if the specimens belong to the same failure population. Most importantly, the results will be used to determine the life prediction interval in which the specimens may fail, to verify the accuracy of the prediction methodology.

Work with Drs. Tucker and Johnson of GE-CRC during 1994 focused on determining the effects of proof testing on isotropic flaw populations, specifically concentrating on generating the equations to characterize the effects of proof testing on flaw density and flaw orientation. This activity will continue in an effort to develop a cohesive approach.

6.2 Ceramic Blade Attachment

This technology activity is examining the characteristics of highly-loaded ceramic-to-metal interfaces, and developing tools to facilitate successful designs. The focus application for the technology is the attachment for an axially-inserted-type ceramic turbine blade. Tests in support of this technology refinement are being performed in the ATTAP Contact Test Rig developed earlier in the program, shown in Figure 12, and in the AlliedSignal Engines Turbine Rotor Whirlpit Test facility, shown in Figure 13.

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Figure 12. Ceramic Blade Attachment Specimen Testing Is Being Performed Using The Existing ATTAP Contact Test Rig.

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Figure 13. Ceramic Turbine Blades Are Qualified For Engine Testing In Whirlpit Test Rig.

During 1994, evaluations were performed in the Contact Test Rig to characterize the coefficient of friction between the ceramic turbine blade and metallic compliant layer materials, and to investigate the effects of highly-loaded ceramic contact on the retained strength of the ceramic material. Spin pit testing was also performed to assess the durability of various antifriction coatings on the ceramic blade attachment compliant layer. This work is described below.

6.2.1 Interface Friction Evaluation

The ATTAP Contact Test Rig was used in a screening experiment to evaluate the coefficient of friction (μ) between NT154 silicon nitride (the 331-200[CT] ceramic turbine blade material) and Haynes Alloy HS25 (the compliant layer material) over the range of temperatures and loads that typically occur in an inserted axial turbine blade attachment. The test data indicated that μ varied from 0.2 to 0.4. To understand the effects of this friction variation on the stresses in a typical blade attachment, an analysis was performed using the geometry of the 331-200[CT] Mod 0 ceramic turbine blade.

Figure 14 shows the predicted effects of increasing coefficient of friction (μ) on the inserted turbine blade attachment contact stress. The preliminary range of values for μ , determined from the contact rig screening tests, is also indicated. This preliminary analysis, ignoring the contribution of elasticity in the blade and disk, showed that the blade contact bearing stress would increase dramatically with increasing coefficient of friction. This effect would be characterized by an inserted turbine blade "sticking" in the attachment during a decreasing turbine inlet temperature transient while still rotating at design speed, and could cause contact-type fracture of a ceramic blade. This effect is potentially mitigated by the disk elasticity and the initial stress states, for which a more detailed three-dimensional (3-D) analysis (planned for late 1995) is needed to more accurately predict. Possible approaches to avoid this type of problem include reducing the interface friction and/or altering the contact angle in the blade attachment.

Figure 14. Increased Coefficient Of Friction, μ , Results In Increased Blade Attachment Contact Stress.

6.2.2 Antifriction Coatings Evaluation

Two candidate antifriction coatings have been identified for potential use with the compliant layer to control ceramic blade attachment contact bearing stress. Both of these coatings, boron nitride (BN), and Lubloc 7401 (a proprietary coating supplied by EM Corporation, New Britain, CT), have previously been successfully used by another AlliedSignal Aerospace business unit, AlliedSignal Aerospace Systems and Equipment (ASE), as friction-reducing surface treatments. During 1994, AlliedSignal Engines performed a matrix of tests in the ATTAP Contact Test Rig, and later in the spin pit, to evaluate several test coatings and their effectiveness. The systems evaluated were:

- Pre-oxidized Haynes Alloy HS25 compliant layer
- HS25 with Lubloc 7401
- HS25 with Boron Nitride.

Room temperature tests were completed with static loading of the various antifriction coatings for use between the ceramic blades and the metal turbine disk dovetail slots. However, the test results did not clearly identify a superior antifriction coating for the planned ceramic blade equipped engine endurance testing.

The preliminary test results showed a "plowing" effect occurred, in which the antifriction coating was pushed ahead of the test indenter, creating bare spots between the indenter and the compliant layer, which increased the coefficient of friction (μ) at the interface. This behavior persisted despite the fact that a very large radius indenter was used, which more closely simulated the plane-on-plane contact of the actual ceramic blades and metallic turbine disk. The result in each case was a very low friction coefficient during the first cycle, which then increased with each successive cycle, ultimately to unacceptably high levels. Concern was expressed whether the conditions in the ATTAP Contact Test Rig were too harsh, since in an actual blade attachment, the lubricant would be "trapped". However, a review of the damage characteristics seen in metallic blade attachments showed many similarities, leading to the conclusion that the contact rig testing was representative of the conditions within an actual operational blade attachment.

Spin pit tests were also performed, in which antifriction treated compliant layers were installed with Mod 0 331-200[CT] ceramic turbine blades in a metallic test rotor and spun at speeds up to the maximum engine operating speed (40,400 rpm) for 100 cycles. The first series of tests were performed at room temperature, followed by further cyclic testing at 1300F.

The boron nitride (BN) coated compliant layers and the Lubloc 7401 coated specimens showed coating wearthrough and subsequent metal transfer to the ceramic blade upon completion of the room temperature spin tests. The pre-oxidized HS25 specimens completed this testing without wearthrough of the oxide coating.

Cyclic spin tests at 1300F were also conducted with the three candidate antifriction coatings. The results were similar to the room temperature testing, except that the ceramic blade with the Lubloc 7401 coated compliant layer was found to be firmly "stuck" in the metallic rotor disk following the test, and the ceramic blade fractured due to excessive contact when attempts were made to remove it from the disk.

It was concluded that the current coating system using pre-oxidized HS25 was the most effective of those evaluated for retention of lubricity after several load cycles. However, there is still concern about longevity of the HS25 coating, on the basis of the room temperature contact rig test results.

6.2.3 Effects Of Contact On Material Strength

Ceramic specimen testing in the ATTAP Contact Test Rig identified the damage thresholds for combined normal and shear loading at room temperature. Figure 15 shows how the normal/tangential loads affected the retained flexure strength of the NT154 silicon nitride flexure specimens. In this test, the specimens were evaluated with indentors having two different surface radii and with varying pinch loads up to 2000 lbs. After the contact rig testing was completed, the specimens were flexure tested in four-point loading to determine the retained strength. The maximum tangential load was the result of interface friction. The data suggests that the threshold tangential load will vary as a function of the indenter radius.

The results of additional contact rig tests showed that a large relative displacement of the loaded indenter produced surface damage in the ceramic test specimens and greatly reduced the overall strength of the ceramic specimen. Tests using smaller displacements and higher temperatures are planned to continue into 1995 as this phenomenon is investigated further.

Figure 15. Threshold For Contact Damage Was Determined For NT154 Ceramic On Powder Metal (PM) Astroloy.

6.3 Ceramic Oxidation and Hot Corrosion

6.3.1 Protective Coatings Evaluations

Several chemical vapor deposited (CVD) and plasma-sprayed coatings were evaluated in exposure tests conducted in the AlliedSignal Engines environmental burner test rig. These tests were performed to determine if these coatings offered adequate protection of silicon nitride (Si_3N_4) against the effects of the hot corrosive atmosphere that could exist in a gas turbine engine operating in humid, salt-laden air conditions, such as might exist near the seacoast or in the wintertime, when northern roads are salted to prevent ice buildup. To make the comparisons meaningful, the following methodology was observed: flexure tests were performed on both coated and uncoated silicon nitride test specimens prior to exposure, to verify that all the

specimens had comparable strengths. Then the coated and uncoated specimens were exposed for 100 hours in a 1925F (1052C) burner rig hot corrosion environment with 2 to 5 parts per million (ppm) sea salt in the combustion air. Following the exposure, the specimens were loaded to failure in four-point flexure to assess the effects of the hot corrosion environment on the specimen strength.

During 1994, two coatings were tested by AlliedSignal Engines:

- CVD zircon, 3 microns thick on an NT164 silicon nitride substrate, supplied by AlliedSignal Research and Technology (Morristown, NJ)
- CVD tantalum oxide, 3 microns thick on an NT154 silicon nitride substrate, supplied by the Dept. Of Energy Oak Ridge National Laboratory (DoE-ORNL) (Oak Ridge, TN).

Neither of these two CVD coatings was found to adequately protect the silicon nitride substrates from the strength-reducing effects of salt corrosion in the environmental test rig. Comparable reductions in flexure strength were reported for both the coated and uncoated specimens following exposure. Post-exposure scanning electron microscopy (SEM) evaluations confirmed that the CVD coatings had been completely consumed by corrosion.

Other screening tests were conducted by the NASA-Lewis Research Center on ceramic specimens with plasma-sprayed Mullite coatings. Test conditions were exposure at 1832F (1000C), with 2 ppm sea salt at 5 atmospheres pressure for 40 hours. The test results indicated that the plasma-sprayed Mullite coatings were protective on silicon carbide (SiC) substrates, but showed cracks on silicon nitride (Si_3N_4) specimens. Further evaluation tests of the plasma-sprayed Mullite coating were postponed, until development of an improved coating system is completed.

As a result of discussions between NASA-Lewis, AlliedSignal Engines, and DoE-ORNL, testing of a two-layer coating system was proposed. This coating would be composed of a tantalum oxide bond coating with a corrosion-resistant Mullite surface layer. The thermal expansion characteristics of equiaxed tantalum oxide closely match silicon nitride, potentially minimizing any cracking. This system was designed to take advantage of the salt resistance of Mullite and resolve the cracking problems noted previously on silicon nitride substrates. Specimens will be fabricated and screened in the NASA pressurized burner rigs.

6.3.2 Effects Of Hot Corrosion On Ceramic Tensile Stress Rupture Strength

Burner rig hot corrosion testing of NT154 silicon nitride tensile stress-rupture specimens was initiated in August, 1994. Following completion of exposures to hot corrosion, the specimens were evaluated for stress-rupture life.

Short-exposure tests were conducted in the AlliedSignal Engines hot corrosion burner test rig to determine if silicon nitride rupture life was reduced by the presence of glassy silicate reaction products. Twenty NT154 tensile stress-rupture specimens were exposed to the burner rig hot corrosion environment at 1890F (1032C) with 5 ppm salt for 30 hours. This exposure resulted in formation of a glassy surface layer without a significant reduction in specimen cross-sectional area.

Many of the NT154 specimens failed anomalously after very short times in the high-temperature tensile stress rupture test at 1204C (2200F) at stresses ranging from 42 to 54 ksi. All of these premature stress-rupture test failures were found to be the result of large internal inclusions in the NT154 test specimens, and were unrelated to the hot corrosion environment exposure.

The few NT154 specimens exposed in the burner rig that did not fail prematurely from large internal inclusions showed stress rupture lives typical of the NT154 material used in previous testing. It was concluded that the short-term exposure to the hot corrosion environment did not significantly reduce the stress rupture life of NT154 silicon nitride.

6.3.3 Environmental Life Model

Pressurized burner rig test data from the NASA-Lewis Research Center has been analyzed with the environmental life model developed in this program. This model estimates the strength reduction of silicon nitride ceramics based on surface recession and pitting, as a function of the concentration of sea salt, time, and the thermodynamic conditions during exposure. The model was calibrated with the results from atmospheric burner rig test data collected by AlliedSignal Engines. The calibrated model predictions were in excellent agreement with the experimental results for pressures in the 1 to 5 atmospheres range and vaporized sea salt ingestion levels of 2 to 10 parts per million (ppm) weight in the combustion air.

In support of the planned field operational test of ceramic turbine nozzles in the 331-200 APU, the hot corrosion life model was used to estimate the strength retention of 331-200[CT] ceramic NT154 blades and

vanes for the Boeing 767 APU installation operating on a severe route structure, featuring high salt ingestion APU operating conditions. The estimates used typical meteorological and salt/air concentrations for Miami (FL) International Airport. Experience factors for routes based on AlliedSignal Engines metallic turbine component corrosion data were used to establish the salt vapor concentration in the engine hot section, based on the ambient salt particulate concentration. The analysis showed that the predicted strength retention would be acceptable for the 331-200[CT] APU on the Boeing 767 routes. However, these results also indicated that more advanced ceramic turbine engines, operating with airfoil temperatures of 1000C to 1200C (1832F to 2192F), might have reduced durability in a high salt ingestion environment. Additional analysis is planned, to evaluate the potential strength reduction of silicon nitride ceramic materials in automotive gas turbines operating in high salt environments.

6.4 Impact Design Methods Development

The objectives of the ceramic impact resistance design technology work are to: 1) Improve the accuracy of the impact design methods by incorporating a material model simulating carbon pulverization during impact, and 2) Verify (through impact testing) the functional relationship between axial inserted blade design variables and impact resistance (impact failure velocity) to guide ceramic blade design efforts.

6.4.1 Carbon Pulverization Model

Verification of the projectile pulverization model was completed for the previously-developed DYNA3D particle impact analysis computer code, and the carbon particle pulverization model has been incorporated in the DYNA3D source code. Impact simulation test runs with the updated DYNA3D code, using previous 1992 data from impact tests performed on ATTAP/AGT101 ceramic radial mixed-flow turbine blade segments, showed good correlation with the test data for the first oscillation of the impact event, in which the highest strains occurred.

6.4.2 Impact Testing

Testing was performed to further validate the DYNA3D particle impact code with ceramic axial turbine blade geometry. In this work, 331-200[CT] ceramic turbine blades were used in impact tests at the University of Dayton Research Institute (UDRI) in Dayton, OH. The ceramic blades were impacted with 0.1 and 0.2 inch diameter spheres machined from seal grade graphite and "combustor carbon" removed from actual gas turbine engine combustors. Some of the testing was conducted with blades instrumented with strain gages. The data from this test series is shown as a function of blade geometry vs. critical speed in

Figure 16. Note that the 331-200[CT] Mod 0 ceramic axial turbine blade was found to be capable of surviving higher velocity impacts than the earlier AGT101 radial mixed-flow ceramic blade design. Since the AGT101 mixed-flow turbine wheel successfully completed over 50 hours of testing and endured several particle impacts without failure, it could be expected that the 331-200[CT] Mod 0 ceramic airfoil will be at least as durable in engine testing.

During 1994, the carbon pulverization material model was successfully incorporated into the DYNA3D particle impact model source code. Data from this testing will be compared with the results of DYNA3D simulations of the impact events during 1995.

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Figure 16. 331-200[CT] Mod 0 Thin, Axial Inserted Ceramic Turbine Blade Is More Impact Resistant Than AGT101 Mixed-Flow, Radial Ceramic Blade.

6.5 Ceramic Nozzle Proof Testing Techniques

This activity was initiated to develop potential proof testing techniques and associated test rig designs to ensure quality in development and production ceramic components. Four distinct categories were identified to rate the various proof testing methods: accuracy, versatility, production capability, and flexibility. Three proof testing techniques were then selected and were evaluated against the five major sources of ceramic nozzle stresses (in order of priority): trailing edge radial stress, trailing edge ID and OD fillet stress, attachment stress, trailing edge bending stress, and leading edge radial stress.

It was determined that separate thermal impingement and mechanical bending tests would satisfy all of the proof testing requirements. Table 10 summarizes the important ceramic nozzle stresses and the proposed proof testing techniques selected.

TABLE 10. PROPOSED CERAMIC NOZZLE PROOF TESTING TECHNIQUES.

Priority	Critical Stress	Proposed Proof Test Technique
1	Trailing Edge Radial	Thermal Impingement Rig
2	Trailing Edge ID/OD Fillets	Mechanical Test Rig
3	Attachment (Bending, Contact)	Mechanical Test Rigs
4	Trailing Edge Bending	Thermal Impingement Rig
5	Leading Edge Radial	Thermal Impingement Rig

Designs for the thermal (flame) impingement test rig, attachment test rigs, and cantilever test rig were initiated. These prototype proof test rigs incorporated features addressing both thermal and mechanical stresses, to ensure overall ceramic nozzle integrity. Some proof rig hardware fabrication was initiated.

7.0 ENGINE TESTING

7.1 Ceramic Nozzle Engine Testing

Ceramic nozzle engine testing conducted during 1994 evaluated the long-term durability of the Mod 0 ceramic nozzle and assessed the performance potential of the 331-200[CT] design. A total of 519 test hours and 1380 cycles were accumulated in two ceramic nozzle equipped engine endurance tests.

7.1.1 Mod 0 Ceramic Nozzle Engine Performance Assessment

The Mod 0 ceramic nozzle equipped 331-200[CT] engine was tested and compared with the performance of the standard production metallic nozzle equipped 331-200[ER] APU. For an accurate comparison, the engine performance was checked in the test cell and then analytically corrected to standard conditions. These checks were performed on the ceramic nozzle equipped engine before and during each of the endurance test runs. The test results are summarized in Table 11, comparing the values for the 331-200[CT] equipped with Mod 0 ceramic nozzles versus the production metallic nozzle equipped 331-200[ER] APU:

TABLE 11. PERFORMANCE COMPARISON OF 331-200 APU EQUIPPED WITH MOD 0 CERAMIC NOZZLES VERSUS PRODUCTION METALLIC NOZZLES.

Parameter	Measured Value Change (With Ceramic Nozzles)
Turbine Discharge Temperature	50F to 60F Higher
Fuel Flow	18 to 20 lb/hr (5 to 7 percent) Higher
Power Section Compressor Discharge Pressure	3 to 4 psi Lower
Power Section Compressor Discharge Temperature	7F Higher
Nozzle Inlet Temperature	30F to 40F Higher

The relative lower overall performance of the 331-200[CT] engine equipped with the Mod 0 ceramic nozzles was attributed to a combination of overboard air leakage through the test engine instrumentation ports, and to gas leakage around the ceramic nozzles at the OD and ID seal locations. Neither problem seriously affected the engine operation or the results of the endurance testing with respect to the integrity of the ceramic nozzles. However, the performance of the 331-200[CT] with the ceramic nozzles will have to be corrected up to the baseline production 331-200 APU levels, in order to make meaningful performance comparisons in the planned field testing.

7.1.2 Mod 0 Ceramic Nozzle Engine Endurance Testing

By the end of 1994, a total of 629 hours of engine test experience was accumulated with the Mod 0 ceramic turbine nozzle design. The high-time ceramic nozzles had accumulated 511 hours operation in testing. Two endurance tests of the 331-200[CT] engine equipped with Mod 0 ceramic nozzles (with metal turbine blades) were conducted during 1994. This engine endurance testing consisted of accelerated durability test cycles representing an operating time acceleration factor of three, based on the typical operating time for a production 331-200 APU. During the accelerated-cycle testing, the engine was programmed to complete 3 starts per hour of run time, with 20 percent of the operating time spent at maximum power/load. The engine was forced-air cooled between each start by blowing ambient temperature air into the inlet. Figure 17 shows a photograph of the engine endurance test set up.

The first ceramic nozzle engine endurance test during 1994 accumulated 243 hours of operation and 621 cycles. The second test (in progress at the end of the reporting period) had accumulated an additional 275 hours and 779 test cycles by the end of 1994, as part of a 500-hour endurance test which continued into 1995.

Post-test inspection of the ceramic nozzle assembly after the first test revealed cracks in the trailing edge on 2 of the 23 ceramic nozzle segments. The cracks in both of the damaged nozzle segments were determined to be induced by thermal stress, and had initiated from the trailing edge surface and only propagated halfway through the vane. In the subsequent planned 500-hour engine endurance test, the two cracked ceramic nozzle segments were replaced in the engine build with new parts that had successfully passed the proof test.

Other problems noted following the 200-hour endurance test were cracks in the metallic inner transition liner (ITL) and deterioration of the OD seal. Analysis of the ITL indicated that the cracks had resulted from a faulty weld. The ITL was redesigned and modified with a thicker ID extension to reduce the sensitivity to thermal and vibration-induced cracking. No changes were made to the OD seal. It was determined that the OD seal would benefit from the ITL modifications, and that the OD seal durability was sufficient for continuation of near-term testing. Long-term seal durability is being addressed as part of the Mod 2 ceramic nozzle design.

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Figure 17. Ceramic Nozzle Engine Endurance Test Setup Includes Blower For Forced-Air Cooling Between Cycles.

7.2 Ceramic Turbine Blade Engine Testing

7.2.1 Ceramic Turbine Blade / Metal Nozzle Engine Testing

An operational test of a 331-200 engine equipped with ceramic turbine blades and standard metallic nozzles was scheduled later in the year, following the completion of planned ceramic turbine blade component evaluations. This test was planned to incorporate instrumented ceramic blades, in an effort to measure the blade vibratory response in the 331-200[CT] engine. However, due to problems involving mounting of the high-temperature strain gages on the ceramic blades, this test was postponed until 1995.

7.2.2 Ceramic Turbine Blade Equipped Engine Test Failure Investigation

A failure analysis was conducted to determine the cause of the failure that occurred in November, 1993 during the second operational test of a 331-200[CT] engine equipped with ceramic turbine blades. The initial findings were that a ceramic blade in the first-stage turbine failed from vibration, and that fragments from the first failed ceramic blade initiated a cascade of impact events with the remaining ceramic blades in the first-stage turbine wheel assembly, which subsequently damaged the entire turbine. Consistent with the features of this engine failure was the postulated fracture of a single ceramic turbine blade from overstress, or the existence of a flaw which had not been screened during the proof testing and nondestructive evaluation (NDE) which all the ceramic blades used in the engine build had received prior to the engine testing. This finding spurred a series of ceramic turbine blade component tests to characterize the restrained vibration resonance modes of the Mod 0 ceramic blade (refer to sections 5.1.1.1 and 5.1.1.2), and contributed to the design efforts for the Mod 1 ceramic blade attachment (refer to section 3.1).

These conclusions from the failure analysis were supported by an extensive failure investigation, which eliminated such causes as damage resulting from contact or impact, gross material defects, and mechanical rubs as the modes of ceramic blade fracture. In addition, a "footprint" of a turbine blade impact, shown in Figure 18, was found on the damaged turbine shroud. This imprint implied a single blade had fractured well below the blade tip, and with the tip intact, was flung outward against the shroud, causing the imprint. This type of failure could be caused by either an overload condition, or a first mode blade vibration resonance. Since each of the blades had been individually proof spin tested to 144 percent of the maximum static operating loads prior to assembly of the test engine, an overload failure condition was determined to be less likely than the vibration failure mode.

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Figure 18. Indentation In The Shape Of A Blade Tip Was Noted On First-Stage Turbine Shroud Following Ceramic Blade Equipped Engine Test Failure (November, 1993).

8.0 PROGRAM MANAGEMENT

8.1 Project Technical Progress

Because of the unsuccessful ceramic blade equipped engine tests that occurred during 1993, the ATTAP/331-200[CT] Ceramic Turbine Engine Demonstration program has been restructured by AlliedSignal Engines, with Dept. Of Energy and NASA concurrence. Ceramic nozzle and ceramic blade development progressed along two separate paths through 1994.

The ceramic nozzle efforts continued with development testing to validate the 331-200[CT] ceramic nozzle and associated metallic structural component designs. The ceramic blade efforts concentrated on component testing to develop a solid technical understanding of why the ceramic blade equipped engine tests were unsuccessful. Along with the ceramic nozzle and ceramic blade efforts, AlliedSignal Engines continued enhancement and validation of several critical technologies that support the incorporation of ceramics in gas turbine engines. The ATTAP/331-200[CT] project completed the year having achieved the majority of the planned milestones for ceramic nozzle development and demonstration, with continued endurance testing and ceramic nozzle design evolution.

As the year ended, the Mod 0 ceramic nozzle engine endurance test was at the midpoint of the planned 500-hour cyclic endurance testing, having accumulated 275.5 hours of operation. Twenty-one of the ceramic nozzles in this engine build had accumulated an additional 244 hours of test hours in the previous 200-hour engine endurance test, for a total of 519 hours on the ceramic nozzles from that engine set. This testing provided insight into the effectiveness of the ceramic nozzle proof testing and highlighted necessary design considerations for the 331-200[CT] ceramic nozzle system.

Work on a Mod 2 ceramic nozzle design was initiated, to further reduce the component production costs and improve the installation of the ceramic nozzles in the 331-200[CT] engine structure. This work will enable AlliedSignal Engines to continue the planned 1995 efforts to qualify and field test the ceramic nozzles. The ceramic nozzle manufacturing scale-up activity will also benefit from the low-cost Mod 2 design.

Ceramic Mod 0 turbine blades were characterized for vibration response in several component tests. This work set the stage for the planned engine testing (now set for 1995) of the Mod 0 ceramic turbine blades equipped with strain gages to provide information on the vibration environment within the engine during operation.

The Mod 1 ceramic turbine blade robust redesign has been completed. It is anticipated that testing of the Mod 1 blade design will begin in 1995.

8.2 Project Schedule

The overall, multi-year 331-200[CT] Ceramic Turbine Engine Demonstration Project schedule is shown in Figure 19. This chart compares the currently-scheduled activities with the original plan established upon initiation of the project in 1993. The chart shows that despite delays in ceramic nozzle fabrication and component testing, the ceramic nozzle field testing will be delayed only three months into 1996. However, due to other difficulties encountered in ceramic blade development, completion of the ceramic turbine blade equipped engine field testing is projected to be delayed until early 1999, more than a one-year slippage from the original plan.

8.3 Administrative Activities

During 1994, the following administrative activities were completed:

- Six Bimonthly Technical Narratives were published
- Four Bimonthly Planning Meeting were held at AlliedSignal Engines, Phoenix, AZ, and one at NASA-Lewis Research Center, Cleveland, OH
- The 1994-1997 proposal/cost estimate was submitted to NASA
- The Ceramic Manufacturing Scale-Up and Demonstration tasks were initiated at the subcontractors, AlliedSignal Ceramic Components (Torrance, CA) and Norton Advanced Ceramics (E. Granby, CT)
- The 1993 ATTAP Annual Report was published
- A technical paper on 1993 ATTAP activities was presented by AlliedSignal Engines personnel on June 13, 1994 at the Turbo Expo '94 Conference sponsored by the American Society of Mechanical Engineers (ASME) in The Hague, Netherlands
- A Component Manufacturing Progress Review was held on July 14, 1994 at Norton Advanced Ceramics in East Granby, CT
- The Abstract and Preprints of the presentation for the annual DoE-sponsored Contractors Coordination Meeting (CCM) were submitted for review
- Presentations were made at the DoE-sponsored CCM conference in Dearborn, MI by personnel from AlliedSignal Engines, AlliedSignal Ceramic Components, and Norton Advanced Ceramics on work performed under the ATTAP/331-200[CT] Ceramic Turbine Engine Demonstration Project

- A technical paper on 1993 progress was drafted and submitted for review for publication by the American Society of Mechanical Engineers (ASME).

ATTAP/331-200[CT] Overall Program Schedule

Figure 19. ATTAP/331-200[CT] Ceramic Turbine Engine Demonstration Project Schedule.

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