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CERAMIC GAS TURBINE TECHNOLOGY DEVELOPMENT

M. L. Easley and J. R. Smyth
AlliedSignal Engines
AlliedSignal Aerospace Company
Phoenix, Arizona

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ABSTRACT

AlliedSignal Engines is addressing critical concerns slowing the commercialization of structural ceramics in gas turbine engines. These issues include ceramic component reliability, commitment of ceramic suppliers to support production needs, and refinement of ceramic design technologies.

The stated goals of the current program are to develop and demonstrate structural ceramic technology that has the potential for extended operation in a gas turbine environment by incorporation in an auxiliary power unit (APU) to support automotive gas turbine development. AlliedSignal Engines changed the ATTAP ceramic engine test bed from the AGT101 automotive engine to the 331-200[CT] APU. The 331-200[CT] first-stage turbine nozzle segments and blades were redesigned using ceramic materials, employing design methods developed during the earlier DOE/NASA-funded Advanced Gas Turbine (AGT) and the ATTAP programs.

The ceramic design technologies under development in the present program include design methods for improved resistance to impact and contact damage, assessment of the effects of oxidation and corrosion on ceramic component life, and assessment of the effectiveness of nondestructive evaluation (NDE) and proof testing methods to reliably identify ceramic parts having critical flaws. AlliedSignal made progress in these activities during 1993 ATTAP efforts.

Ceramic parts for the 331-200[CT] engine have been fabricated and evaluated in component tests, to verify the design characteristics and assure structural integrity prior to full-up engine testing. Engine testing is currently underway.

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NOMENCLATURE

AGT	Advanced Gas Turbine
APU	Auxiliary Power Unit
ASR&T	AlliedSignal Research and Technology
atm	Atmosphere
ATTAP	Advanced Turbine Technology Applications Project
C	Celsius
Ca	Calcium
DARPA	Defense Advanced Research Projects Agency
deg	Degrees
DOE	Department of Energy
EBAR	Pressure Difference Ratio
F	Fahrenheit
GN-10	AlliedSignal Ceramic Components Silicon Nitride
Hz	Hertz
IDZDYNA	Computer Code
in	Inch
kg	Kilograms
ksi	Thousands of Pounds Per Square Inch
lbm	Pounds Mass
kPa	KiloPascals
Mg	Magnesium
min	Minutes
MPa	MegaPascals
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NT154	Norton Advanced Ceramics Pressure Slip Cast Silicon Nitride
ORNL	Oak Ridge National Laboratory
P	Pressure
P_{static}	Static Pressure
P_{tinlet}	Turbine Inlet Pressure
pH	Log Hydrogen Ion Concentration (Acidity or Alkalinity)
POD	Probability of Detection
ppm	Parts Per Million (Mass)
psia	Pounds Per Square Inch Absolute
rpm	Revolutions Per Minute
sec	Second
TIR	Total Indicated Reading
T_{max}	Maximum Temperature

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UDRI	University of Dayton Research Institute, Dayton, Ohio
U.S.	United States
s	Sigma, Stress
s_{max}	Maximum Stress

INTRODUCTION

The Advanced Turbine Technology Applications Project (ATTAP) is a continuation of activities sponsored by the U.S. Department of Energy (DOE) to develop the technology for an improved automobile propulsion system under Title III of U.S. Public Law 95-238, "Automotive Propulsion Research and Development Act of 1978". ATTAP is authorized under DOE/NASA Contract DEN 3-335, with the National Aeronautics and Space Administration (NASA) providing management and administration. This paper summarizes the progress of the ATTAP/331-200 Ceramic Demonstration Program conducted during 1993 by AlliedSignal Engines (formerly Garrett Auxiliary Power Division), a unit of AlliedSignal Aerospace Company, in developing the needed technologies for a ceramic gas turbine engine.

The thrust of the ATTAP/331-200 program is to "bridge the gap" between ceramics in the laboratory and near-term commercial heat engine applications. The intent is to use this application as a stepping stone to transition the technology into the automotive marketplace where its benefits can have the greatest impact on reducing fuel consumption and gaseous emissions. The project goal is to develop and demonstrate structural ceramic component technology in an auxiliary power unit (APU), so that the technology can be evaluated in an existing commercial gas turbine application. Simultaneously, this work will ready ceramic technology for the aircraft APU application, while gathering extensive laboratory and field experience, and develop ceramic component design methods and fabrication techniques. In this way, ATTAP/331-200 will effectively support the expansion of ceramics technology into automotive designs.

This strategy will augment the maturation of ceramics technology by developing the infrastructure and engineering disciplines within the technology to overcome those barriers which prevent its commercialization. Currently, the principal barriers to the commercialization of ceramics are seen as:

- Immature supporting technologies
- Underdeveloped production capability
- Inadequate demonstration

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

BACKGROUND

The present ATTAP/331-200 program is following a natural progression based on its predecessors. The focus is on near-term production capability, drawing heavily on "lessons learned" from the problems and successes on the previously-completed ceramics development and demonstration programs.

The **DARPA/Navy Ceramic Gas Turbine Engine Demonstration Program** (1976 to 1981)[1] and the USAF **Ceramic Components For Turbine Engines Program** (1979 to 1982)[2] provided the foundation for the modem ATTAP/331-200 program. These programs utilized a test bed of similar design to the AlliedSignal/Garrett production Model GTCP331-200 gas turbine APU. Significant progress was successfully achieved in demonstration of ceramic axial inserted turbine blades, as well as initial exploration of ceramic design technologies, including contact failure and particle impact damage resistance, and component life prediction.

The DOE/NASA **Advanced Gas Turbine - AGT101 Engine Program** (1980 to 1987)[3] pursued several high-risk technologies, including ceramics for future automobile engine applications. The AGT101 Program succeeded in simultaneously demonstrating many related advanced engine technologies, and identified the most critical areas in ceramic engine technology needing further development.

The DOE/NASA **Advanced Turbine Technology Applications Project - ATTAP/AGT101 Program** (1987 to 1992)[4], emphasized the development of critical ceramics technologies, using the AGT101 automotive test bed. Significant progress was made in the ATTAP/AGT101 Program toward successful impact-resistant ceramic turbine designs and ceramic component processing. However, the AGT101 engine proved to be inadequate as a test bed for the advanced ceramic technologies. This was because the AGT101 was designed as a demonstrator for several high-risk technologies, including the high-temperature ceramic regenerator, low-emission ceramic combustor, low-friction gas bearings, all-ceramic hot section structures, and impact-resistant ceramic turbine. As such, AGT101 reliability as a turbine test bed was not adequate for long-term endurance testing and evaluation.

The present DOE/NASA **ATTAP/331-200 Ceramic Engine Demonstration Program**[4] continues refinement of ceramics technologies and design methods, and focuses fabrication development on a scaleup of demonstrated technologies to pilot-production levels. To adequately demonstrate ceramic technology, over 6000 hours of endurance testing is planned, utilizing a reliable test bed based on the AlliedSignal/Garrett Model 331-200 APU (Figure 1). The 331-200 APU is a fully-developed gas turbine with current production applications in the Boeing 757 and 767 aircraft, which has higher capability for successfully accomplishing long-term endurance testing.

The progress of the current DOE ATTAP initiative toward commercialization of ceramic engine technology may be visualized with the chart in Figure 2. This curve, based on cumulative experience in engine demonstration test hours and quantity of ceramic engine components achieved from 1980 to present and projected through 1997, shows the geometric trend in ceramics technology improvement. Figure 2 shows that ceramic engine technology is on the threshold of exploitation. The ATTAP/331-200 Program will enable near-term commercialization in low volume, premium gas turbine applications such as airborne APUs, paving the way toward eventual production of ceramics for automotive gas turbines.

TECHNOLOGY DEVELOPMENT

Ceramic technologies supported under the ATTAP/331-200 Program in 1993 included:

- Impact design methods refinement
- Contact design methods refinement
- Ceramic blade attachment technology

[1] DARPA/Navy Contract No. N00024-76-C-5352

[2] USAF Contract No. 33615-77-C-5171

[3] DOE/NASA Contract No. DEN3-167

[4] DOE/NASA Contract No. DEN3-335

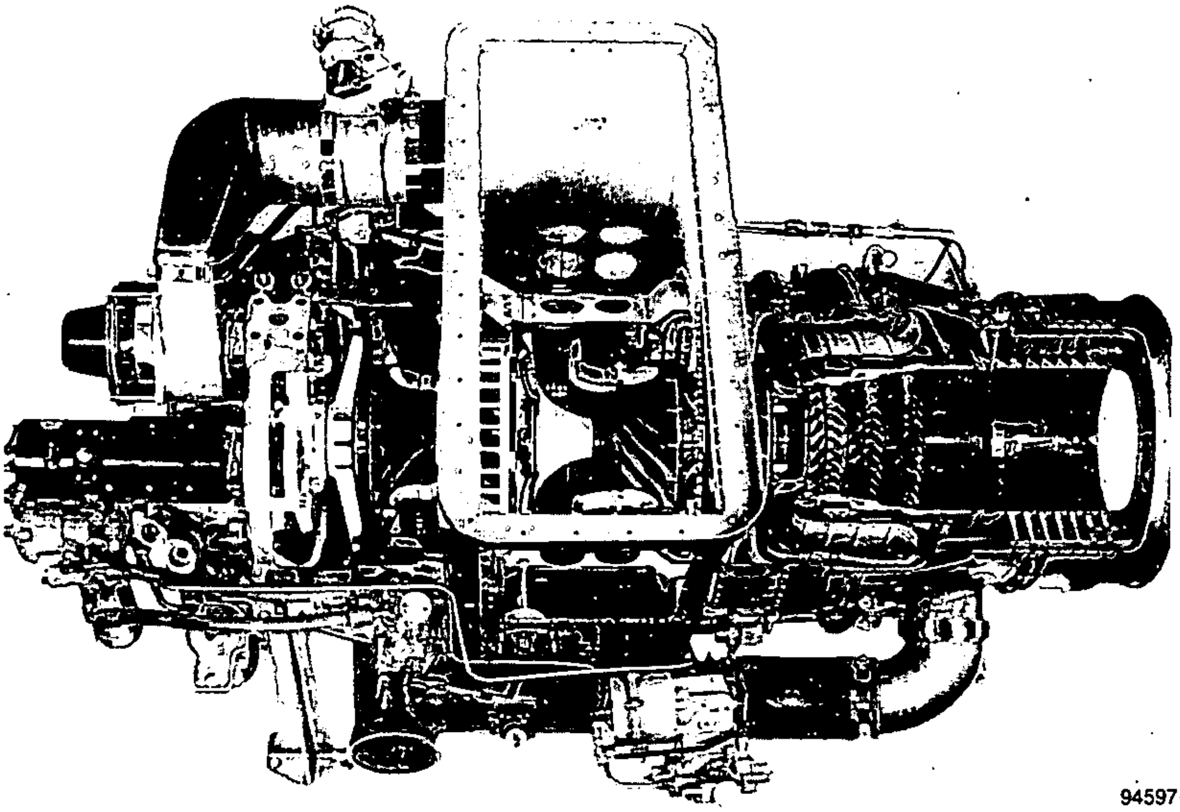

FIGURE 1. ATTAP CERAMIC DEMONSTRATION TEST BED IS BASED ON AlliedSignal PRODUCTION MODEL 331-200 APU

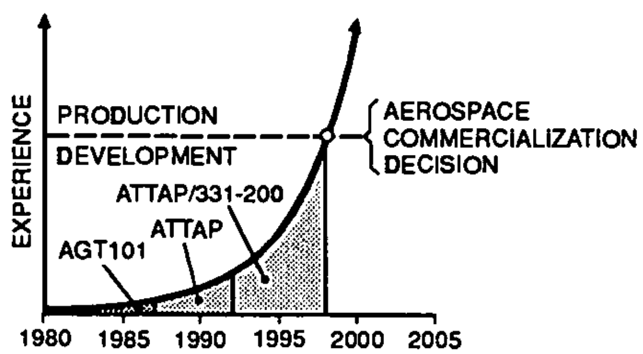

FIGURE 2. ATTAP TARGETS SOLUTIONS FOR EARLY CERAMICS COMMERCIALIZATION.

- Oxidation/corrosion characteristics of ceramic materials
- Reliability of nondestructive evaluation (NDE) methods

All of these technologies were identified as critical to the success of ceramics in commercial gas turbine applications. A description and discussion of the progress in each of these technologies follows.

Impact Design Methods Development

Development of a method capable of accurately predicting structural impact damage for any ceramic component from carbon particles (combustor carbon) is the end goal of this activity, which will result in design guidelines for impact-resistant, axial ceramic turbine blades. In 1993, reduction of the subelement impact test results from the ATTAP/AGT101 program was completed. Trial impact simulations for comparison were conducted using the resulting IDZDYNA code. This model will be transferred to workers at the Livermore Research and Engineering Company, Livermore, CA for addition of a carbon pulverization model to finalize the simulation code.

Contact Design Methods Refinement

The goal of this activity is to develop design tools to predict strength and life for ceramic/ceramic and ceramic/metal interfaces under gas turbine engine operating conditions. A contact test rig (Figure 3) for evaluation of ceramic contact interfaces of various configurations was designed and fabricated. This test rig was set up and tested to resolve operational issues and to evaluate contact damage in ceramic specimens. Specimen rig tests are currently being conducted and the test data will be compared with the results of contact stress analyses.

Future work will develop preliminary guidelines for ceramic contact interface design, further evaluate subelement contact test specimen designs, and test the subelements to validate the contact failure model.

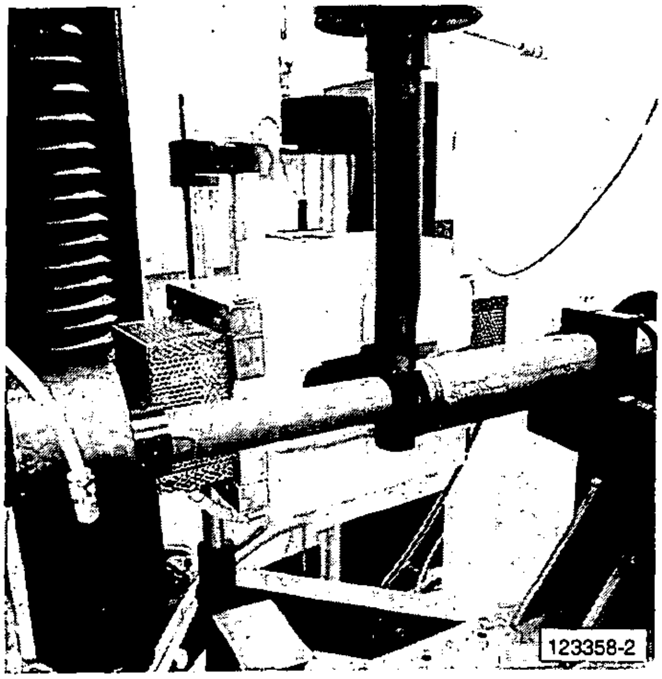

FIGURE 3. CONTACT TEST RIG WILL BE USED TO EVALUATE VARIOUS CERAMIC INTERFACE CONFIGURATIONS

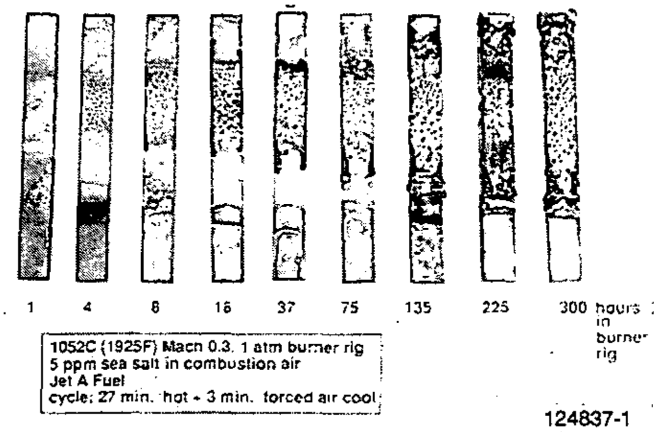

FIGURE 4. CONDITION OF CERAMIC OXIDATION TEST SPECIMENS AFTER EXPOSURE IN HOT BURNER ENVIRONMENT.

Blade Attachment Technology

The goal of this activity is to provide the best, most cost-effective design solutions for robust ceramic axial inserted blade attachments for production gas turbines. In 1993, this activity focused on the development of basic design data relevant to the conditions within the ceramic inserted blade attachment. This work included assessment of compliant layers, surface topography and tolerance effects, and surface strength with respect to machining direction.

A test matrix was defined and test specimens were purchased for evaluation of these design elements using the Contact Test Rig.

Ceramic Oxidation/Corrosion

An environmental life model is being developed that will be capable of accurately predicting the influence of engine operating design conditions and mission usage on the strength of silicon nitride turbine blades and vanes in a production gas turbine engine. This activity complements related ceramics research activities conducted by AlliedSignal Engines.[5]

During 1993, burner rig testing was performed on specimens of Norton Advanced Ceramics NT154 silicon nitride, one of the ceramic materials selected for ATTAP/331-200[CT] components. Figure 4 shows the typical glassy surface condition of the NT154 specimens after burner rig exposure. Following exposure, room temperature strength test data was acquired on the specimens. The data was then reduced to establish the oxidation and corrosion regimes for NT154 in air laden with sea salt.

Figure 5 summarizes the test results, showing the time-temperature relationship necessary to reduce the room temperature strength of NT154 by approximately 50 percent in the test environment of hot combustion air laden with 5 parts per million (ppm) sea salt.

These results also indicate that above 1550F (843C), NT154 silicon nitride exhibits rapid strength degradation in the hot, salt-laden burner test environment, largely due to pitting and surface roughening from sodium sulfate salts and (pH)-basic corrosion, forming sodium-rich silicates. While these tests were performed on NT154, the current understanding of the corrosion mechanism indicates that other types of silicon nitride based ceramics will also suffer similar degradation.

This information will be incorporated into an environmental life model for NT154 and integrated with the life methodology being developed by AlliedSignal Engines under the ongoing DOE/ORNL Ceramic Life Prediction program.[6] Meanwhile, ATTAP work is continuing, to develop and evaluate protective coatings for silicon nitride components exposed to corrosive environments.

Nondestructive Evaluation (NDE) Technology

This ATTAP activity complements a similar activity funded by DOE/ORNL to establish the probability of detection of flaws of various sizes in ceramic components.[6] The ATTAP-funded activity will focus on establishing the probability of detection (POD) for internal flaws. This activity will ultimately establish production requirements for NDE to assure acceptable component quality, demonstrate whether NDE reliability and cost improvements are necessary and provide quantitative data for tradeoff comparisons with proof testing for assurance of component quality.

[5] T.E. Strangman and D.S. Fox, "Strength Retention of NT154 Silicon Nitride Exposed to High-Temperature Oxidation and Hot Corrosion Environments," presented at the 184th Meeting of the Electrochemical Society, New Orleans, LA October 12, 1993; AlliedSignal Engines Report No. 31-11623.

[6] DOE/ORNL Contract No. 86X-SC674C, "Life Prediction Methodology for Ceramic Components of Advanced Heat Engines"; J. Cuccio, AlliedSignal Engines, Principal Investigator.

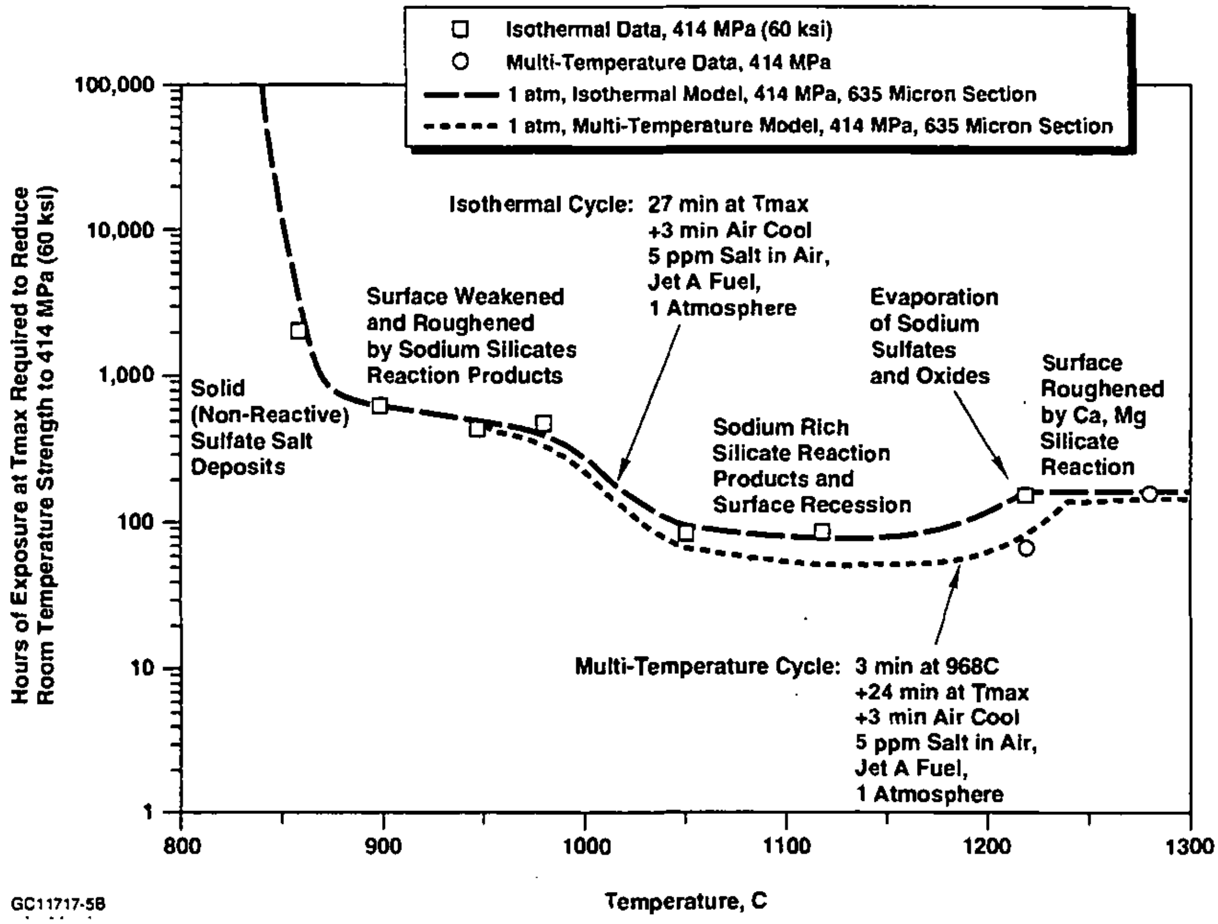

FIGURE 5. REACTION WITH SULFATE SALT DEPOSITS FROM INGESTED SEA SALT AND FUEL CONTAMINANTS REDUCES THE STRENGTH OF NT154 SILICON NITRIDE

Silicon nitride turbine blades and vanes have been procured from various sources to establish typical volume flaw characteristics for actual parts. This information will be used in the design and fabrication of seeded defect specimens for later work. Under this activity, work was also initiated with researchers at the University of Dayton Research Institute (UDRI) in Dayton, Ohio to develop statistical methods for the internal flaw detection reliability study.

CERAMIC COMPONENTS QUANTITY FABRICATION DEMONSTRATION

The purpose of this activity is to develop the capability of the domestic U.S. ceramic engine component suppliers to provide quality components in sufficient quantities to support scaleup to engine production. This will effectively move the component fabrication processes out of the laboratory and into an environment where components of consistent high quality can be made economically.

Scheduled to begin in late 1993 and continue through 1996, this work will focus on the suppliers of the ATTAP/331-200[CT] ceramic turbine blades and nozzle segments. These manufacturers will be challenged to improve their demonstrated fabrication processes and develop methods and procedures to achieve the quantity production goal. By the end of 1996, each of the manufacturers will have built a pilot facility and demonstrated production of over 100 parts per month, on a continuous basis for several months.

ENGINE DEMONSTRATIONS

The ATTAP/331-200 engine demonstration activities included redesign and modification of the Model 331-200 APU into the ATTAP ceramic test bed. Within the 331-200[CT] test bed, the first axial turbine stage was redesigned to incorporate ceramic turbine nozzle segments and inserted ceramic blades. This activity included detailed design of the ceramic components and modified metallic support structures, test hardware fabrication, component testing to verify the component performance characteristics, and engine demonstration testing. These tasks are summarized in the sections following.

Turbine Design

The existing production, all-metallic 331-200 APU first-stage turbine assembly was redesigned to incorporate ceramic nozzle segments and inserted ceramic blades. The design guidelines recognized that the redesigned components will be used in a later field evaluation program, in which ceramic-equipped engines replace production all-metallic engines; thus, the ceramic-equipped engines must be aerodynamically similar to the metallic engines. In addition, to maintain the reliability of the test bed, modifications to the metallic engine supporting structures were minimized. The design cycle conditions for the ceramic turbine stage are listed in Table 1.

TABLE 1. 331-200[CT] CERAMIC TURBINE DESIGN CYCLE CONDITIONS

Parameter	Units	Value
Corrected Flow	lbm/sec	1.556
	(kg/sec)	(0.7058)
Corrected Speed	rpm	19,993
Physical Speed	rpm	41,731
Pressure Ratio	--	8.741
Efficiency	percent	85.7
Inlet Total Temperature	F	1800
	(C)	(982)
Inlet Total Pressure	psia	129.8
	(kPa)	(895)

The ceramic turbine nozzle segments and blades were designed with principal consideration given to component producibility, while also satisfying structural integrity and aerodynamic performance requirements.

The ceramic nozzle assembly (Figure 6) has 23 segmented ceramic vanes (Figure 7). For simplicity, the ceramic vane count was reduced to 23, from 29 vanes on the all-metallic engine. Nozzle surface geometry was kept as simple as possible to favor manufacturing, a result of concurrent engineering with the close collaboration of the ceramic nozzle manufacturer.

Nozzle stresses predicted for transient operation during normal engine startup (summarized in Figure 8) peaked at 33 ksi (228 MPa) at the nozzle trailing edge, nine seconds into the startup cycle, which was within the capability of the selected AlliedSignal Ceramic Components GN-10 silicon nitride material.

An attempt was made to maintain the aerodynamic performance of the ceramic nozzles at the level of the original all-metallic design. The nozzle aerodynamic loadings were high, due to the low number of vanes and the envelope limitations, giving rise to concerns regarding increased losses due to flow separation on the suction side of the vanes. However, both inviscid and viscous analyses of the nozzle loadings (shown in Figure 9 for the midspan section) indicated acceptable suction side diffusion.

The number of ceramic blades in the redesigned first-stage turbine wheel (Figure 10) was reduced to 28 blades from 36 in the original all-metallic engine. This permitted an increase in the size of the ceramic blades (Figure 11), thickening the blade sections for better fabricability, and increasing the room available for a low-stress blade attachment scheme.

The blade attachment scheme is further illustrated in an exploded view in Figure 12. This design utilizes a single-tang dovetail with a thin foil of compliant metal to distribute the compressive loads between the ceramic blade dovetails and the metallic turbine disk. Each blade assembly is held in place axially with a conventional metallic bent tab.

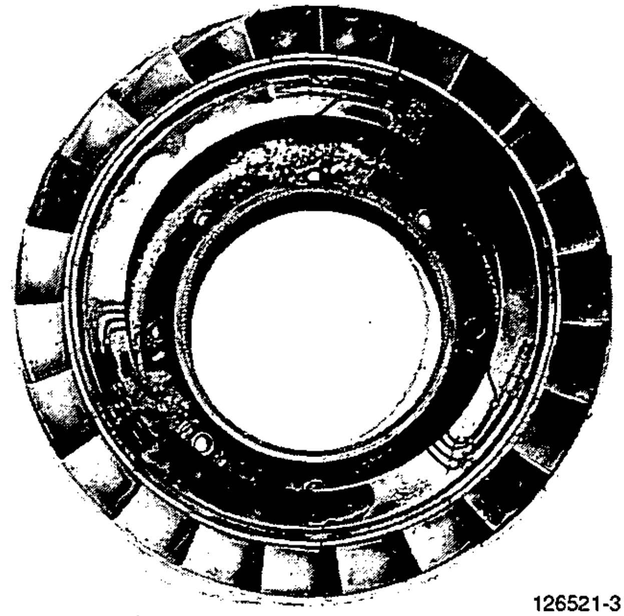

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FIGURE 6. ATTAP 331-200[CT] CERAMIC NOZZLE ASSEMBLY HAS 23 SEGMENTS

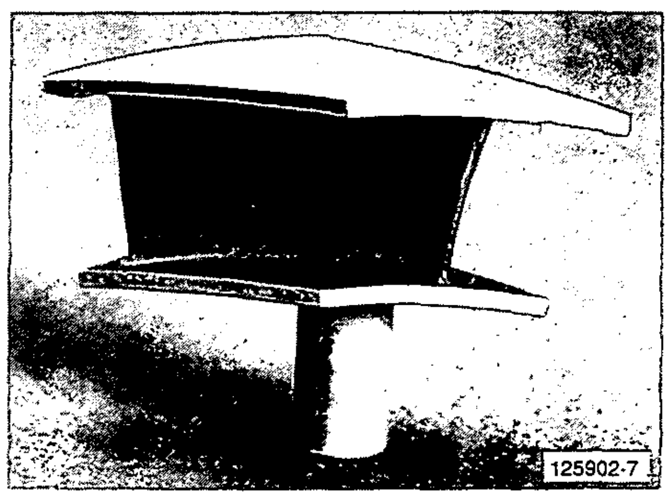

FIGURE 7. ATTAP 331-200[CT] CERAMIC NOZZLE SEGMENT

Figure 13 shows the predicted principal stress isopleths within the ceramic blade at maximum speed, compared with the corresponding thermal contour lines. Peak stress of 43 ksi (296 MPa) occurs on the surface in the dovetail region near the edge of the contact zone. A life prediction analysis was also performed on the ceramic blade, and the results indicated the probability of survival was better than 99 percent, with 95 percent confidence for 20,000 hours life with 20,000 cycles.

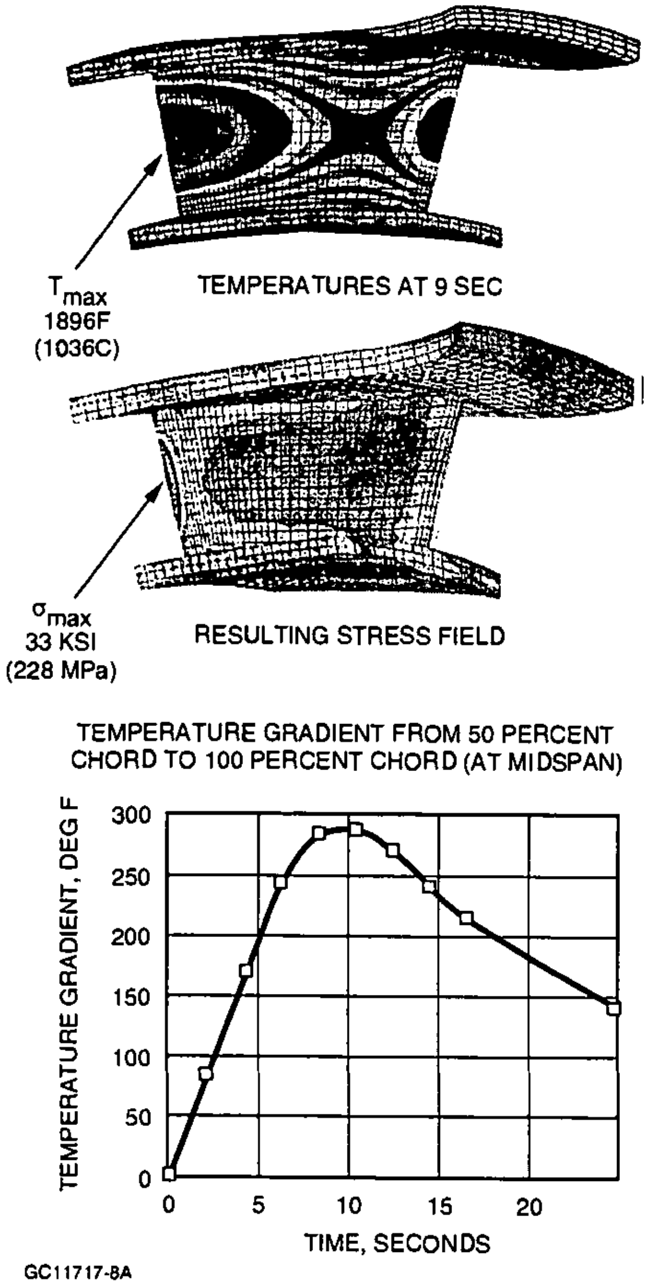

FIGURE 8. PREDICTED STRESSES FOR TRANSIENT (STARTUP) OPERATION PEAK AT 33 KSI (228 MPA) ON TRAILING EDGE OF CERAMIC NOZZLE

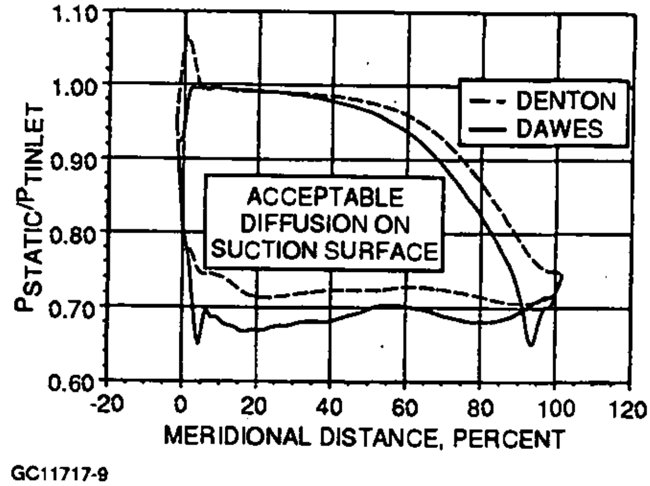

FIGURE 9. 331-200[CT] CERAMIC NOZZLE MIDSPAN INVISCID AND VISCOUS LOADING ANALYSES SHOW ACCEPTABLE AERODYNAMIC PERFORMANCE WILL BE MAINTAINED

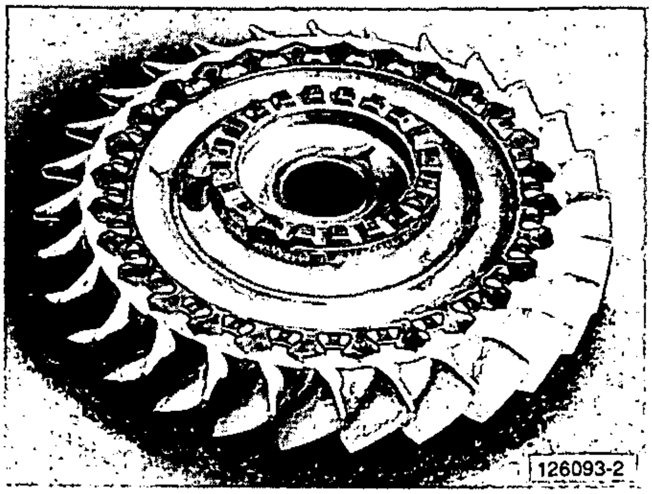

FIGURE 10. 331-200[CT] TURBINE WHEEL HAS 28 CERAMIC BLADES

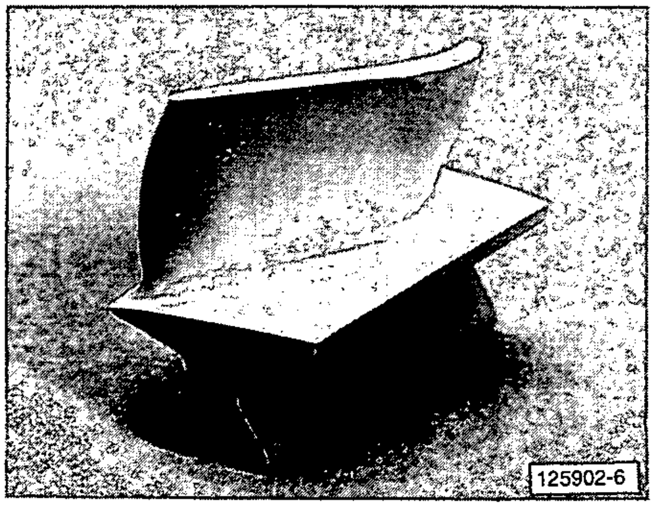

FIGURE 11. 331-200[CT] CERAMIC TURBINE BLADE EMPLOYS DOVETAIL ATTACHMENT SCHEME

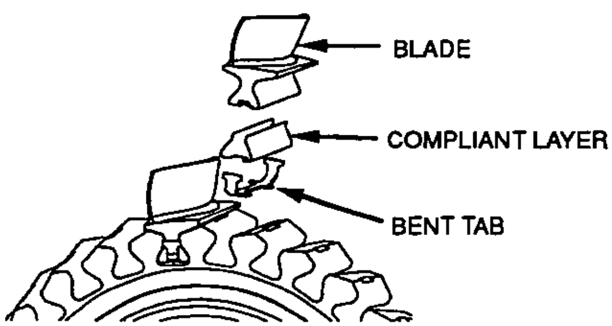

FIGURE 12. 331-200[CT] CERAMIC BLADE ATTACHMENT SCHEME EMPLOYS A COMPLIANT LAYER WITH A CONVENTIONAL METAL BENT TAB RETAINER

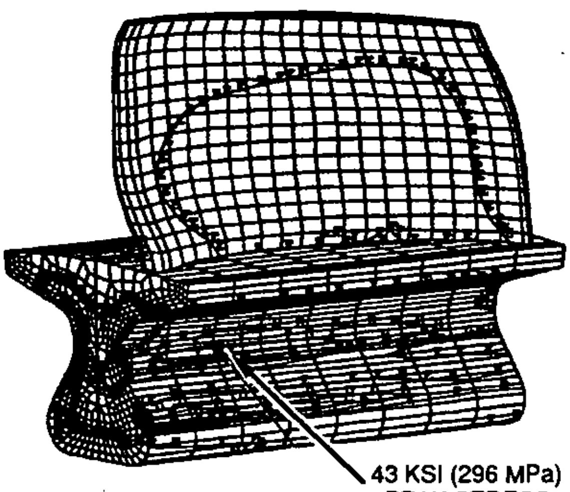

FIGURE 13. PREDICTED PEAK STRESS OF 43 KSI (296 MPA) OCCURS ON DOVETAIL SURFACE OF 331-200[CT] CERAMIC BLADE

While it is felt that the ceramic-equipped 331-200[CT] engine will meet its performance goals, aerodynamic performance of the ceramic blade may have been lessened, in favor of improved fabricability and mechanical integrity. Aerodynamic loading increased as a result of the reduced blade count and simultaneous restriction of the blade envelope. Figure 14 shows the predicted distribution of kinetic energy loss coefficient (EBAR) along the length of the ceramic blade from hub (zero percent span) to shroud (blade tip = 100 percent span). Note that the largest loss distribution occurs over the last 20 percent of the blade, near the blade tip. Engine performance will be monitored closely during testing, and a further turbine redesign for increased performance will be considered if necessary.

Ceramic Hardware Fabrication

Ceramic components for the 331-200[CT] engine were procured from two domestic U.S. sources: Norton Advanced Ceramics in Northboro, MA, and AlliedSignal Ceramic Components in Torrance, CA. Unlike previous ATTAP ceramic parts purchases, which were conducted on a "Best Efforts" basis, these procurements were fixed-price/quantity parts-buy type purchases with quality requirements similar to those that would be required in production. Also differing from previous ATTAP practices, each of the component designs were "concurrently engineered" in collaboration with the ceramics suppliers. Through this activity, the suppliers and AlliedSignal Engines were able to develop ceramic parts geometries which not only meet functional requirements, but are also fully producible. All of the drawing dimensional tolerances and specifications were mutually understood and agreed upon before any ceramic parts were fabricated.

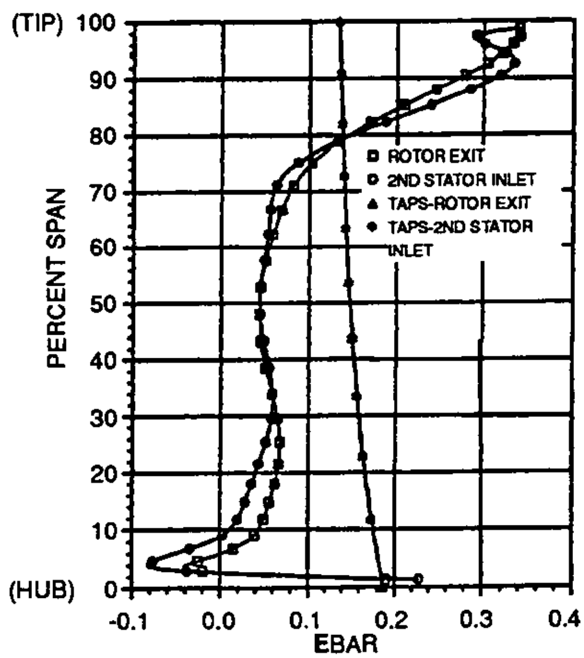

FIGURE 14. KINETIC ENERGY LOSS COEFFICIENT (EBAR) DISTRIBUTION NEAR 331-200[CT] CERAMIC BLADE TIP (100 PERCENT SPAN) ATTRIBUTED TO TIP LEAKAGE FLOW

Norton Advanced Ceramics fabricated the ceramic turbine blades from NT154 silicon nitride. These parts were made using a pressure slip cast process, in which the blades were cast to near-net shape, with final grinding required only on the blade attachment dovetails and the blade tips.

AlliedSignal Ceramic Components fabricated the ceramic turbine nozzle segments from GN-10 silicon nitride. These parts were made by either cold isostatic pressing or pressure slip casting cylindrical blanks, then green machining to near-net shape, densifying the nozzles, and then final grinding the critical surfaces of the parts.

Fabrication of these parts offered significant challenges to both suppliers, and several design, specification, and fabrication issues were identified which will be addressed in future work.

Component quality was a major issue in both procurements. The blueprint specifications required not only dimensional compliance, but also compliance with material defect specifications, and fixed process specifications. The burden of certifying component quality was placed on the suppliers, subject to audit by AlliedSignal Engines.

Both suppliers experienced problems in various degrees in meeting the production quality requirements. Several of these problems, such as dimensional deviation of machined surfaces, incorrect specification interpretation, and misplaced parts markings, were not unexpected, and were correctable with improvements in the production-level quality systems for aerospace parts at these suppliers.

Significant problems in the control of as-processed surface quality and dimensional control of as-processed surfaces were also common, typically resulting in poor production yields. Since these problems seemed to be characteristic of the ceramic fabrication processes, additional refinement will be required in these areas before these processes will be ready for regular production of precision aerospace components.

Component Testing

Tests were performed on the ceramic components after receipt by AlliedSignal Engines, to verify critical design aspects and the mechanical integrity of the manufactured components. The ceramic blades were spin proof tested and characterized for vibration, and the ceramic nozzle segments were thermally proof tested.

During the ceramic blade proof tests, a total of 60 blades were spin tested at up to 50,000 rpm in an evacuated whirl pit. This test imposed stresses in the blade attachment that were 44 percent higher than predicted for engine operation. Only two blades failed during the proof tests, both during the same run; neither blade failed from internal defects. One of the blades failed due to silicon carbide grit which contaminated the blade attachment contact zone, and the other blade was damaged from impact with debris from the first blade.

The source of the silicon carbide grit was traced to a hand finishing operation prior to assembly of the ceramic blade into the spin test rotor. A grit particle was deposited on the blade dovetail during hand finishing and was not removed completely during the cleaning operation prior to assembly. The cleaning operation has been improved, and the problem has not recurred.

Two ceramic blades were also tested in an airjet spin test, to verify the blade resonant frequencies. This test was also conducted in the whirl pit, equipped with a ring of air nozzles directed into the path of the whirling blades to simulate the nozzle-passing conditions in the engine. The blades were instrumented with strain gages, to measure the vibration response of the blades to the excitation from the impinging air jets. During the tests, the blade strain levels were monitored as the rotor decelerated from various speeds. Peak responses indicated the blade resonant frequencies, and the strain ratios between various locations on the blades identified the resonant mode(s). The Campbell diagram in Figure 15 compares the airjet test results with analytically-predicted values and the critical engine speed harmonics. Note that the measured first resonant mode was higher than the predicted value, but does not intersect the critical 23/rev and 31/rev engine speed harmonics. This result indicates a reduced risk of troublesome blade vibrations possibly occurring during engine testing.

The ceramic nozzle segments were proof tested in a thermal shock rig, shown schematically in Figure 16. This test rig was designed to expose a single ceramic nozzle to thermal transients from room temperature up to 2600F (1427C) in less than two seconds, and has the capability to impose stress levels 25 percent higher than the predicted peak transient stress value during engine operation. At the time of this writing, 35 nozzles had been tested in the rig proof cycle and all had successfully passed.

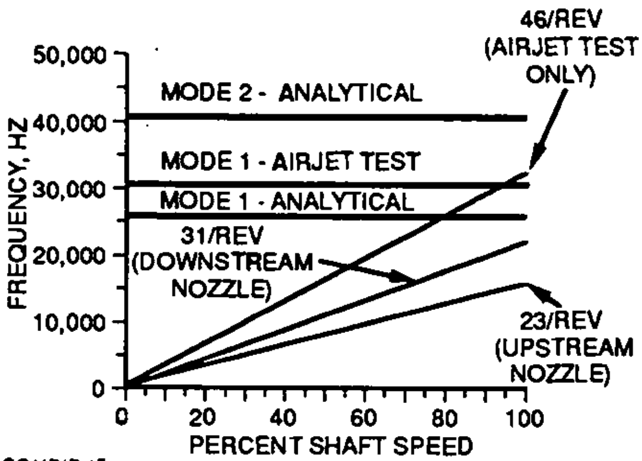

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FIGURE 15. CAMPBELL DIAGRAM OF AIRJET SPIN TEST RESULTS SHOWS 331-200[CT] CERAMIC-BLADED ROTOR HAS ACCEPTABLE VIBRATORY RESPONSE

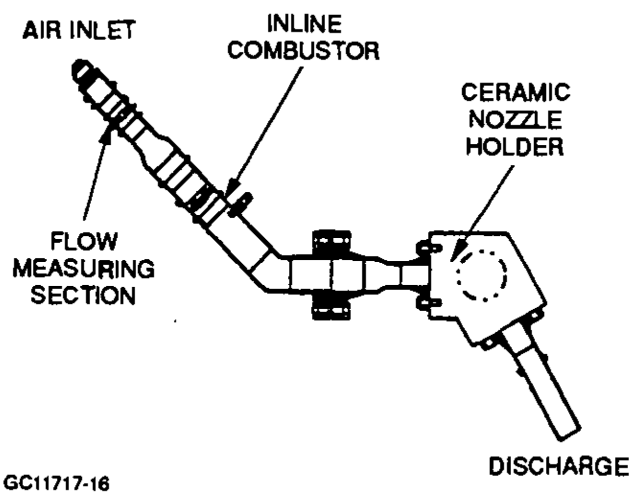

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FIGURE 16. CERAMIC NOZZLE SEGMENTS WERE INDIVIDUALLY PROOF TESTED IN A THERMAL SHOCK RIG

Engine Testing

Two production Model 331-200 APU engines were converted to the 331-200[CT] configuration for use as test beds; one engine for evaluating the ceramic nozzles with metallic blades, and the other for evaluating the ceramic blades with metallic nozzles. Using separate test beds reduces the test risks and enhances data collection for each ceramic component set.

The dual-test-bed strategy paid off during the first engine test on the ceramic blades. Approximately 86 seconds into the first engine start, at 33,600 rpm, the engine suffered a failure. Subsequent disassembly, inspection, and analysis identified a number of possible causes; however, contact failure at the blade attachment was the most likely mode. The posttest inspections verified that the contact surfaces of the broached slots in the turbine disk were flat to 0.001 inch TIR, but witness marks on the contact surfaces indicated that the compliant layer did not effectively spread the contact loads over the surfaces.

Corrective actions were identified and implemented, with respect to this and other potential failure causes. This activity includes improved inspections of both the blades and the metallic turbine disks, and revised manufacturing processes to improve flatness in the blade attachment, to ensure proper load transfer.

The first engine test of the ceramic turbine nozzles was successful. This engine operated for 10.1 hours without failure, over the full range of engine operating conditions. Included in this test was a start with immediate loading to maximum power, inducing a 2470F (1354C) temperature spike within four seconds after light off, which represents an extreme thermal stress condition in the nozzle segments. Figure 17 shows a photograph of the ceramic nozzle assembly after test completion. All of the nozzle segments were intact and in good condition.

Engine testing will continue to move forward in 1993 with accelerated mission testing of the ceramic nozzles and blades, in separate engines.

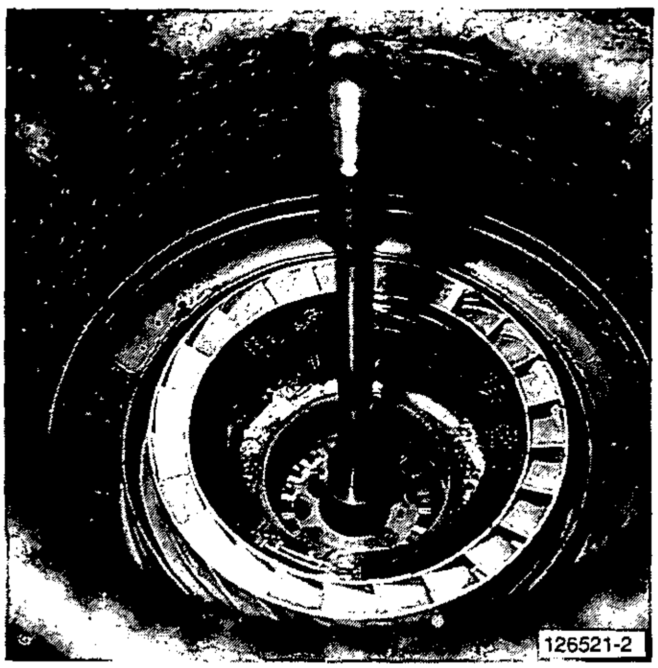

FIGURE 17. CERAMIC NOZZLE ASSEMBLY SUCCESSFULLY COMPLETED FIRST 331-200[CT] ENGINE TEST

Future Work

Engine demonstration testing is planned to continue through 1994, accumulating up to 1000 hours of test time on the ceramic nozzles and blades. This activity will focus on verifying the integrity of the ceramic component designs. Certification test activities will begin in 1995, to qualify the ceramic-equipped 331-200[CT] engine for installation on commercial aircraft for field evaluations, planned to begin in 1996. Extended endurance testing will also begin in 1996, accumulating over 6000 hours of operating experience by program end in 1997.

SUMMARY AND CONCLUSIONS

During 1993, the ATTAP program was refocused to more effectively address the critical issues surrounding the commercialization of ceramics. The current program addresses ceramic reliability, reliability demonstration, ceramic design technology refinement, and cost-effective component fabrication. Utilizing the AlliedSignal/Garrett Model 331-200[CT] auxiliary power unit as a test bed/demonstrator, the program will provide the supporting experience, design methodologies, and fabrication capability necessary for limited commercialization of ceramics in aeronautical applications, and provide a solid technological foundation supporting automotive ceramic heat engine applications.

Technical activity through 1993 emphasized the design, fabrication, and integrity demonstration of a ceramic first-stage turbine nozzle and inserted ceramic turbine blade. These components were designed to meet the commercial life goals of 20,000 hours or 20,000 cycles for stress rupture and fast fracture failure modes with 99 percent probability of survival and 95 percent confidence.

Both ceramic components were made of silicon nitride. The ceramic nozzles were fabricated by AlliedSignal Ceramic Components using their GN-10 material. The ceramic blades were fabricated by Norton Advanced Ceramics using their NT154 material. Both suppliers experienced difficulties in meeting the stringent quality requirements of the production procurement specifications; despite this, both suppliers were able to provide acceptable ceramic parts for test rig and engine evaluations.

To ensure adequate component integrity, proof tests were devised for the ceramic turbine nozzles and ceramic turbine blades. A thermal shock test rig was designed and fabricated to expose the nozzles to a peak stress level exceeding 125 percent of the maximum design stress for normal engine operation. The ceramic turbine blades were proof tested in a spin test, which induced stresses exceeding 144 percent of the design maximum at the blade neck. Prior to engine testing, each of the ceramic components passed their respective proof tests.

The ceramic nozzles and blades were independently evaluated in two separate engine tests. One test engine was equipped with ceramic nozzles and metallic blades; the other, with ceramic blades and metallic nozzles. The ceramic-nozzle-equipped engine accumulated 10 hours of test operation without distress to the ceramic nozzles. However, the engine equipped with ceramic blades failed during the first start attempt. The problem was traced to insufficient contact in the load bearing surfaces at the ceramic blade/metal disk attachment. Corrective actions were identified and initiated to ensure that contact loads in the attachment bearing surfaces are nominal. Engine test activities on the ceramic turbine nozzles and blades will continue through the remainder of 1993 and into 1994.

The ATTAP/331-200 program has the mission of augmenting the development of ceramic technology in support of automotive gas turbine development. To achieve this goal, the program has a plan to enhance the ceramic technologies required to support the design of gas turbine ceramic components, to refine and scaleup the production capability of domestic U.S. ceramic component manufacturers, and to demonstrate the capability of the ceramic components, first in laboratory tests and then in extensive field trials. The engine demonstrations and field evaluations will not only gather the experience required to verify the improvements in ceramic design technology and component fabrication, but will also give feedback of new data to help improve these capabilities on a continuous basis.