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CERAMIC GAS TURBINE TECHNOLOGY DEVELOPMENT

BREAK

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ABSTRACT

Under the U.S. Dept. of Energy (DoE) funded Ceramic Turbine Engine Demonstration Project (CTEDP), AlliedSignal Engines is addressing remaining critical concerns slowing the commercialization of structural ceramics in gas turbine engines. These issues include demonstration of ceramic component reliability, readiness of ceramic suppliers to support ceramic production needs, and development of ceramic design technologies.

The AlliedSignal/Garrett Model 331-200[CT] auxiliary power unit (APU) is being used as a ceramics test bed engine. The first-stage turbine blades and nozzles were redesigned for ceramic materials, employing design methods developed during the earlier Dept. of Energy/National Aeronautics and Space Administration (DoE/NASA)-funded Advanced Gas Turbine (AGT) and Advanced Turbine Technology Applications (ATTAP) programs. The fabrication processes for these components provide the framework for demonstration of ceramic manufacturing process scale-up to the minimum level for commercial viability. Ceramic engine components have been fabricated and are now being evaluated in laboratory engine testing. This testing is helping to refine the component designs and focus the development of ceramic component technologies. Extended engine endurance testing and field testing in commercial aircraft is planned, to demonstrate ceramic component reliability.

Significant progress was made during 1996 in the ceramic component manufacturing scale-up activities. The CTEDP ceramics subcontractors, AlliedSignal Ceramic Components (Torrance, CA) and Kyocera Industrial Ceramics Corporation (Vancouver, WA) demonstrated increased capacity and improved yields of silicon nitride materials. Planned ceramic turbine nozzle manufacturing demonstrations were initiated by both companies.

Ceramic design technology was further refined in several areas. Work continued in defining boundary conditions for impact modeling of ceramic turbine engines, including completion of a three-dimensional trajectory analysis for combustor carbon particles in the engine flowpath. Contact rig tests and supporting analyses helped define the effectiveness of compliant layers in reducing ceramic turbine blade attachment contact stresses, and the results are aiding the evolution of more effective compliant layer configurations. This work supported evaluation of various ceramic turbine blade attachment designs in subelement and engine tests.

Thin-film strain gage technology for measuring vibratory levels at high temperatures was successfully applied on ceramic turbine blades. Ceramic materials were screened for susceptibility to cyclic hot corrosion fatigue at the conditions affecting turbine blades. Stress rupture testing in support of the proof test methodology development was completed.

Engine endurance tests with ceramic turbine nozzles accumulated over 482 additional hours of successful operation. Ceramic turbine blades were successfully demonstrated in over 190 hours of engine operation. This work brought the combined ceramic component engine test experience to over 1500 operating hours.

Work summarized in this paper was funded by the DoE Office of Transportation Technologies, as part of the Turbine Engine Technologies Program, and administered through Fiscal Year 1996 by the NASA Lewis Research Center, Cleveland, OH under Contract No. OEN3-335.

NOMENCLATURE

AE	AlliedSignal Engines (Phoenix, Arizona)
AGT	Advanced Gas Turbine
ANSYS	Finite Element Stress Modeling Computer Code
APU	Auxiliary Power Unit
ASME	American Society of Mechanical Engineers
AS-800	AlliedSignal Ceramic Components Silicon Nitride
ATTAP	Advanced Turbine Technology Applications Project
AZ	Arizona
BN	Boron Nitride
BU	Boston University (Boston, Massachusetts)
C	Celsius
CA	California
CC	AlliedSignal Ceramic Components (Torrance, California)
CFD	Computational Fluid Dynamics
CTEDP	Ceramic Turbine Engine Demonstration Project
CVD	Chemical Vapor Deposition
DARPA	U.S. Defense Advanced Research Projects Agency
DoE	U. S. Department of Energy
D.O.E.	Design Of Experiments
DYNA3D	Three-Dimensional Finite Element Computer Code

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EGT	Exhaust Gas Temperature
ERICA	AlliedSignal Ceramic Life Prediction Code
F	Fahrenheit
FEM	Finite Element Model
ft	Feet
HIP	Hot Isostatic Pressed
HS25	Haynes Alloy No. 25
kg	Kilograms
KICC	Kyocera Industrial Ceramics Corporation (Vancouver, Washington)
ksi	Thousands of Pounds Per Square Inch
Kt	Stress Concentration Factor
lb	Pounds
m	Meters
MA	Massachusetts
mm	Millimeters
MOD	Modification No.
MPa	MegaPascals
NASA	National Aeronautics and Space Administration
No.	Number
NT154	Norton Advanced Ceramics Pressure Slip Cast Silicon Nitride
OH	Ohio
ORNL	Oak Ridge National Laboratory (Oak Ridge, Tennessee)
ppm	Parts Per Million
Pt	Platinum
RAMPANT	Computational Fluid Dynamics Computer Code
RI	Rhode Island
sec	Seconds
SN-252	Kyocera Industrial Ceramics Company Silicon Nitride
SN-282	Kyocera Industrial Ceramics Company Silicon Nitride
SPC	Statistical Process Control
TN	Tennessee
UDRI	University of Dayton Research Institute (Dayton, Ohio)
URI	University of Rhode Island (Providence, Rhode Island)
U.S.	United States
WA	Washington State
μ	Coefficient of Friction
$\mu\epsilon$	Units Microstrain

INTRODUCTION

This paper summarizes progress during 1996 in the U.S. Dept. of Energy/National Aeronautics and Space Administration (DoE/NASA) sponsored 331-200[CT] Ceramic Turbine Engine Demonstration Program being conducted by AlliedSignal Engines, Phoenix, AZ, a unit of AlliedSignal Aerospace Company, in developing the needed technologies for ceramic gas turbine engines.

The Ceramic Turbine Engine Demonstration Project (CTEDP) is 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." The CTEDP program is authorized under DoE/NASA Contract DEN3-335 through the end of fiscal year 1996, with the NASA-Lewis Research Center (Cleveland, OH) providing program management and administration.

The thrust of the CTEDP/331-200[CT] 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.

As part of this overall effort, the CTEDP program will provide essential and substantial early field experience demonstrating the reliability and durability of ceramic components in modified, available, real engine applications, including manufacturing scaleup for competitive production. These efforts will lead to accelerated commercialization of advanced, high-temperature engines in hybrid vehicles and other applications. Additional efforts supported by this project include the DoE-sponsored Propulsion Systems Materials program, which has the objectives of improving the manufacturing processes for ceramic turbine engine components and demonstrating application of these processes in the production environment.

The 331-200[CT] ceramic engine test bed is based on the production AlliedSignal/Garrett Model 331-200[ER] auxiliary power unit (APU), with the first-stage turbine modified to incorporate ceramic nozzles and blades (Figure 1). This work will simultaneously 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, the 331-200[CT] Ceramic Turbine Engine Demonstration Project will effectively support the expansion of ceramics technology into automotive designs.

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

- Immature supporting technologies,
- Underdeveloped production capability, and
- Inadequate demonstration.

The overall CTEDP/331-200[CT] program plan provides the approach to resolve each of these issues. The following discussions describe the progress to date in the various project activities and outline the go-forward plans to meet the program objectives. This work was initiated in 1993 and the project progress through the end of 1995 has been reported by Easley, Smyth, and Rettler.[1,2,3]

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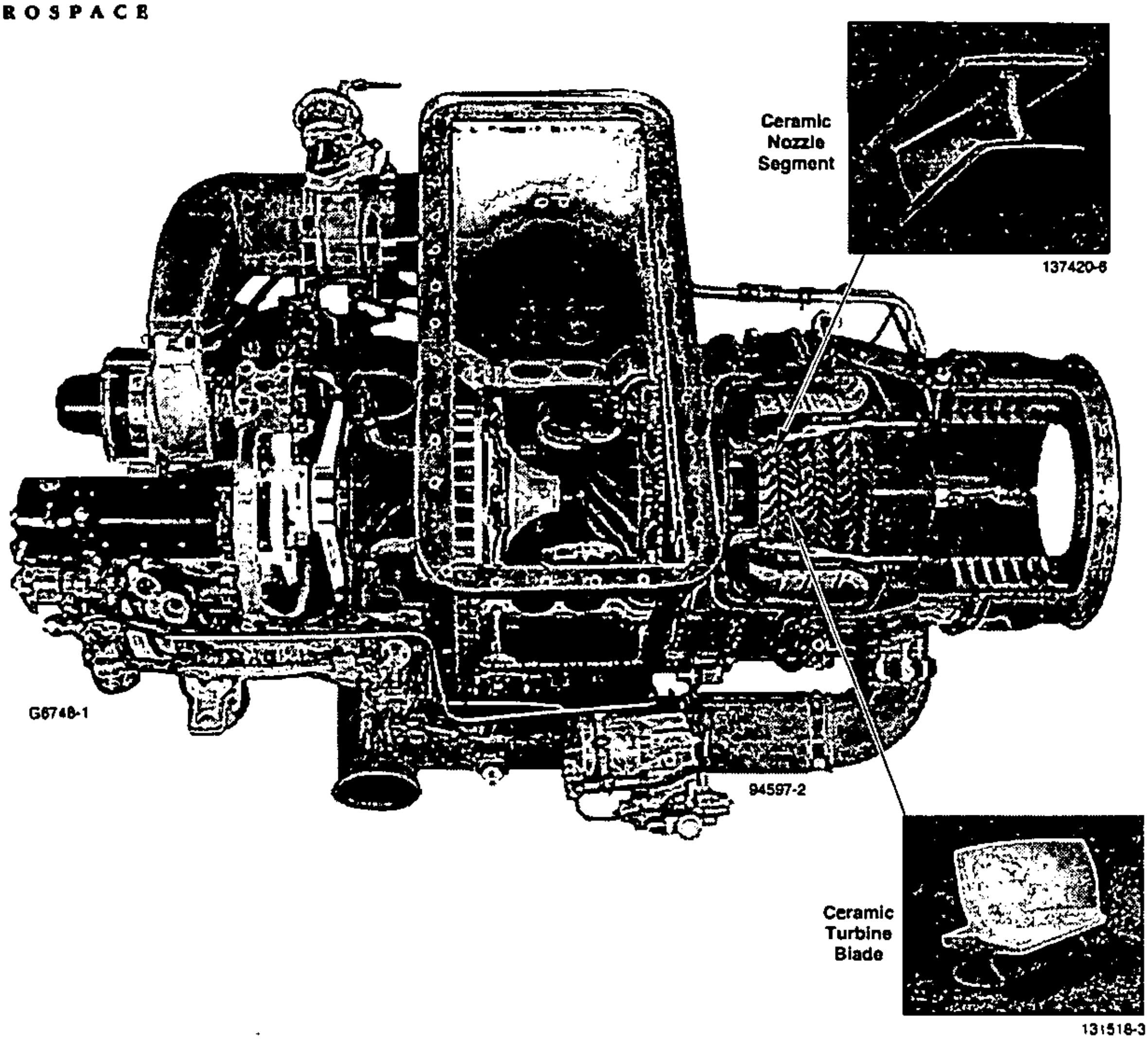

Fig. 1. Ceramic Turbine Engine Demonstration Test Bed Is Based On Proven AlliedSignal/Garrett Model 331-200 Auxiliary Power Unit, With Ceramic First-Stage Turbine Components.

TECHNOLOGY DEVELOPMENT

Ceramic technologies supported under the CTEDP/ 331-200[CT] Program during 1996 included:

- Impact design methods refinement
- Ceramic contact design methods development
- Thin-film instrumentation development
- Oxidation/corrosion characteristics of ceramic materials
- Ceramic proof testing methodology.

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 technolngies follows.

Impact Design Methods Development

The primary emphasis of this activity is to develop design methods capable of accurately predicting structural impact damage to ceramics from particles in the engine gas flowpath (combustor carbon). During the past year, significant progress has been made in efforts to predict trajectories of particles passing into the turbine hot section.

The 1996 plan was to enhance the impact analysis by refining the boundary conditions and to integrate the dynamic impact stress predictions from the DYNA3D code with mechanical and thermal stress predictions from the ANSYS code. These integrated results were then input into the ERICA life prediction code to perform a component probabilistic life assessment. The result of this project provides a tool for accurately assessing the design lifetime for ceramic components subjected to combined loading states.

A computational fluid dynamics (CFD) model produced with the RAMPANT code was used to predict carbon particle trajectories through the 331-200[CT] ceramic stator system, and to predict the resulting particle velocities and locations at the ceramic turbine blade leading edges for 0.05 to 0.30 inch diameter particles released at both static conditions and the average gas entrance velocity of 45 ft/sec (13.7 m/sec). Figure 2 shows a plot of computed particle velocities at the turbine leading edge versus particle size.

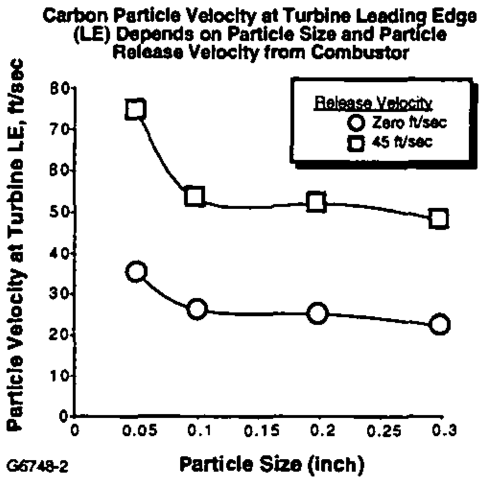

Fig. 2. Computed Particle Velocities At Turbine Blade Leading Edge Versus Particle Sizes.

The highest velocity predicted is approximately 75 ft/sec (22.9 m/sec) for a 0.05 inch (1.27 mm) diameter carbon particle with an initial release velocity of 45 ft/sec (13.7 m/sec). The predicted velocities for most of the particles ranged from 20 to 50 ft/sec (6.1 to 15.2 m/sec). These velocities are much lower than the free-stream air velocity of over 700 ft/sec (213 m/sec) and the maximum turbine blade tip velocity of 1600 ft/sec (488 m/sec).

Figure 3 shows a plot of predicted particle velocities versus the turbine flowpath radius. This figure shows that particles entering the turbine are more likely to impact near the tips of the blades.

Figure 4 shows predicted particle exit angles from the turbine stator system. This figure shows that there are two distinct paths followed by the exiting particles. Particles rebounding off the pressure side typically are predicted to have a high-angle exit path, while particles passing through the stator system without hitting a stator wall have a low-angle exit path.

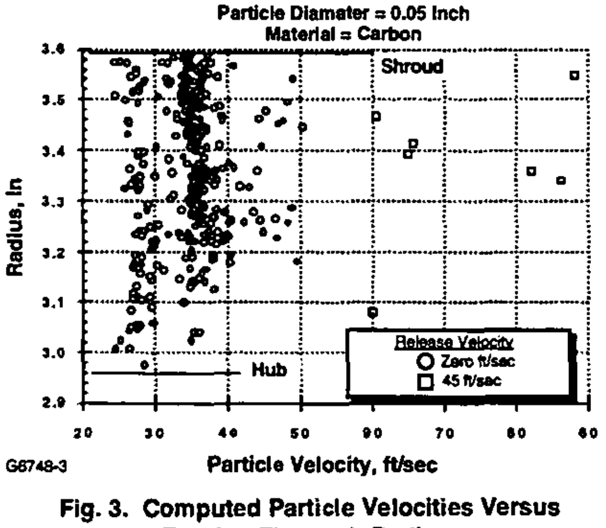

Fig. 3. Computed Particle Velocities Versus Turbine Flowpath Radius.

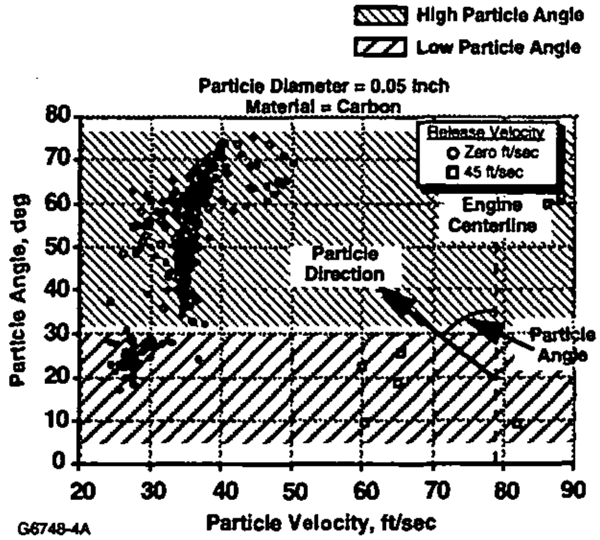

Fig. 4. CFD Analysis Indicates Particles Follow Two Distinct Paths Exiting The Turbine Stators.

These analysis results will be used in refining the structural design of ceramic turbine blades and to define the boundary conditions for planned rotating impact tests.

Ceramic Contact Methods Development

The goal of this activity is to achieve better understanding of ceramic contact conditions and to develop methods of predicting contact stresses, to provide effective design solutions for robust, axial inserted ceramic blade attachments for production gas turbines. These design solutions necessarily require a thorough understanding of the blade attachment contact stresses, the compliant layer behavior, and the controlling environmental and geometric factors. The major focus of this activity has been on gathering and evaluating data from tests performed on the contact and subelement test rigs. The contact test rig has been described by Easley and Smyth (1996).[3]

The major emphasis of the contact methods technology program in 1996 was to identify a suitable near-term complaint layer system for ceramic blade engine testing, and also to identify a viable long-term (10,000 hours/10,000 cycles) compliant layer system. A boron nitride (BN)-lubricated platinum/Haynes Alloy HS25 (Pt/HS25) compliant layer system was chosen for the initial ceramic blade engine testing. This baseline system was successfully demonstrated in earlier testing (1976-81) under U.S. military funding.[4] This system exhibits low coefficient of friction (μ) characteristics at elevated temperatures, but has not proven to be sufficiently durable for long-term use. An optimum long-term compliant layer system has yet to be identified.

A contact rig test matrix was developed to effectively screen candidate compliant layer materials. Figure 5 shows the results of a typical room-temperature screening test for the HS25 compliant layer.

The initial value of μ for the HS25 layer was quite low; however, μ increased dramatically after only a few cycles. This phenomena was observed for many different compliant layer materials tested at room temperature. Figure 6 shows the results of a 1200F (649C) screening test for HS25 using the lubricated dual compliant layer system. The dual compliant layer system exhibited very low μ up to 100 cycles, when the Pt layer became perforated from wear. Figure 6 also shows that for HS25, μ remains remarkably stable at elevated temperature, in contrast to the room-temperature test results. This data confirms that the HS25 lubricated dual-layer system is an effective short-term solution, supporting its selection for use in initial ceramic blade engine testing.

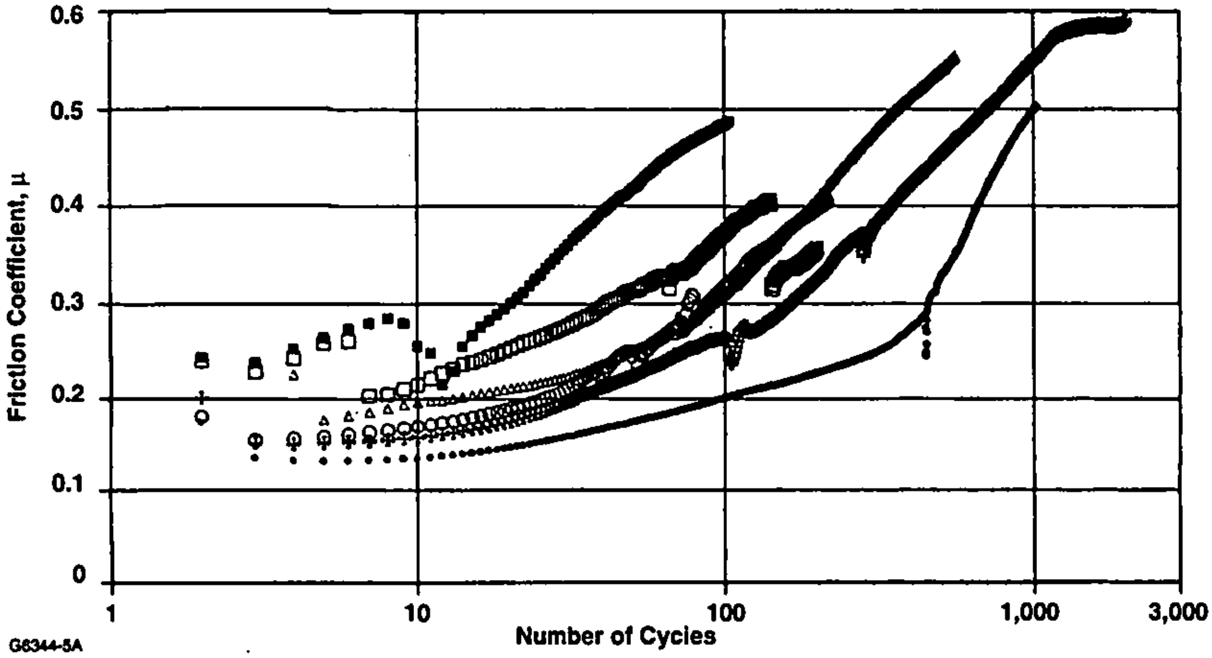

Fig. 5. Room Temperature Screening Test Results Show HS25 Compliant Layer Has Low Short-Term Coefficient Of Friction.

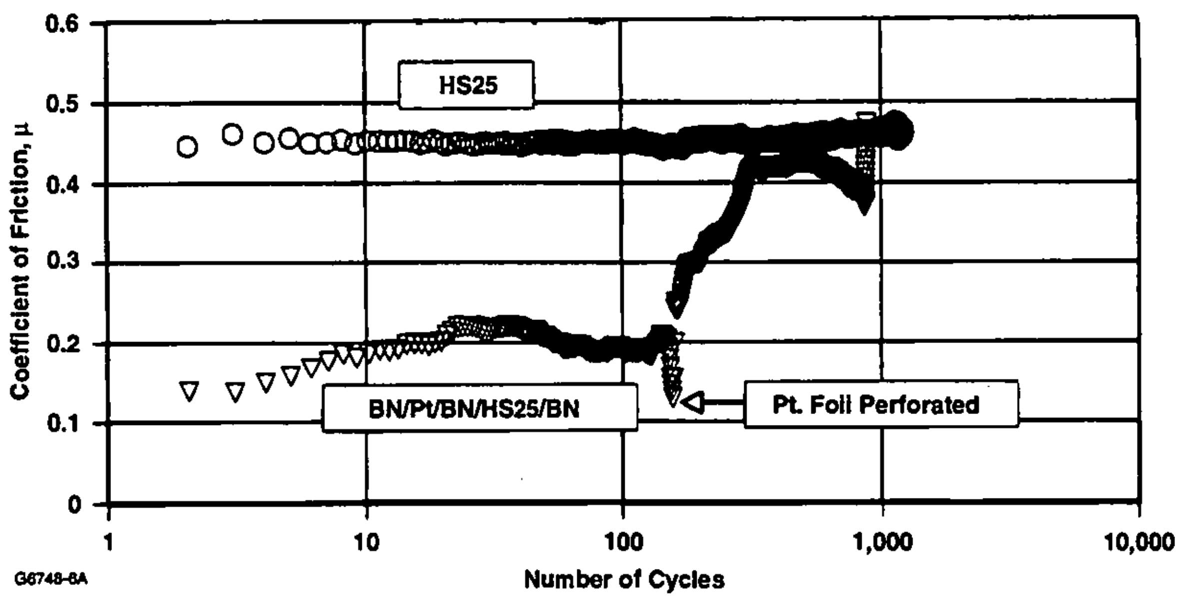

Fig. 6. High Temperature (1200F/649C) Screening Test Results Confirm Lubricated Dual Compliant Layer System Is Effective For Initial Ceramic Blade Engine Testing.

Preliminary ceramic blade attachment subelement tests were completed in 1996. The ceramic subelements and grippers are designed to simulate actual engine disk and ceramic blade attachment deflection and load distribution characteristics.

These tests were performed to verify rig operation, test loads, and the subelement gripper design. Figure 7 shows the typical ceramic blade attachment subelement instrumented test setup.

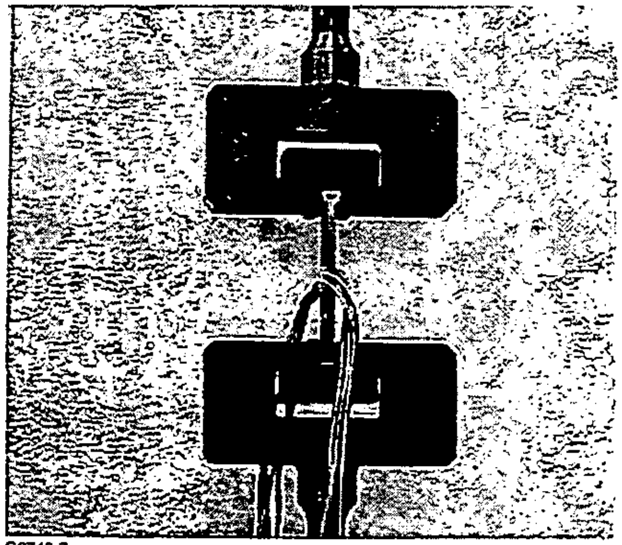

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Fig. 7. Ceramic Blade Attachment Subelement Tests Were Initiated.

Thin-Film Instrumentation Development

Technology for chemical vapor deposition (CVD) methods to apply thin-film strain gages and thermocouples on silicon nitride gas turbine components has been developed and demonstrated in this project. These efforts are the result of work performed in AlliedSignal Engines laboratories, subcontract work by the University of Rhode Island (URI, Providence, RI), and collaboration with the NASA-Lewis Engineering Research Center (Cleveland, OH). The strain gage fabrication efforts used photomasking and sequential deposition methods to apply gage elements to the ceramic turbine blade airfoil surfaces and to attach the required leadfilms to the blade root area.

In subcontract development activities, URI has concluded planned testing of palladium/chrome dynamic strain gage systems on AS-800 silicon nitride constant-strain beam specimens. This testing supported development of application methods for a chrome overcoat layer, from which a native chromium oxide protective scale may be grown. The purpose of the protective scale is to reduce the thin-film strain gage element signal drift and variability.

Under in-house fabrication efforts, AlliedSignal Engines has successfully deposited and fabricated thin-film palladium/chrome dynamic strain gages on SN-252 and AS-800 silicon nitride turbine blades. Similar gages were deposited on ceramic constant-strain test beams were tested for 10 million cycles at 1700F (927C) and 1000$\mu\epsilon$ strain without failure.

In addition, a method to produce the necessary hardwire lead attachments to the ceramic blade gage elements was developed and successfully demonstrated on sample ceramic blade root specimens. This technique has been selected for use on the strain gage leadwire transitions for ceramic blades to be used in upcoming engine tests.

Oxidation/Corrosion Technology Development

The susceptibility of silicon nitride ceramics to high-temperature oxidation and corrosion is being investigated, and methods of protecting ceramic materials in the gas turbine combustion environment are being evaluated. Uncoated AS-800 specimens have been concurrently evaluated with uncoated baseline NT154 silicon nitride specimens for up to 300 hours in jet-fuel burner rig test cycles with exposures at 1052C (1927F) for 27 minutes plus air cooling for 3 minutes with 5 ppm sea salt added to the combustion air. These materials are also being evaluated in multi-temperature burner rig test cycles with exposures at 968C (1775F) for 3 minutes and 1218C (2224F) for 24 minutes plus air cooling for 3 minutes, again with 5 ppm salt added to the air. Visual inspection following the exposures indicated that the AS-800 and NT154 specimens are attacked at comparable rates in these hot corrosion environments.

In collaborative work with Dr. V. Sarin and M. Auger of Boston University (BU, Boston, MA) with funding from the DoE Oak Ridge National Laboratories, experimentally produced corrosion-resisting chemical vapor deposited (CVD) mullite coatings on NT154 specimens have been evaluated at AlliedSignal Engines. One of the CVD mullite coating formulations appears to provide significant protection in cyclic burner rig tests at 1050C (1922F). BU is conducting a post-test analysis of the exposed specimens. A second set of specimens with improved CVD mullite microstructures is being prepared by BU for additional burner screening tests.

Ceramic Proof Test Methods

This activity, in collaboration with the ongoing DoE-sponsored Phase II Life Prediction Methodology For Ceramic Components of Advanced Heat Engines Program, is being performed by AlliedSignal Engines and managed by the DoE Oak Ridge National Laboratories (DoE-ORNL, Oak Ridge, TN). This work will establish the reliability of proof testing of ceramic components with respect to volume flaws.

Tests of ceramic tensile specimens have been conducted to determine the effect of room-temperature proof testing on elevated-temperature fast fracture and time-dependent failure modes for volume-distributed flaws. The goal is to determine if proof testing affects the component integrity. The test specimens have been divided into two groups: one group initially received proof testing, with test criteria selected to fail 30 percent of the specimens; the other group has not been proof tested.

Tensile stress-rupture testing of previously proof tested NT154 specimens has been completed at DoE-ORNL by Dr. K. Liu. These specimens were tensile proof tested at room temperature at a stress level of 75 ksi (517 MPa). The test data is currently under review.

CERAMIC COMPONENTS QUANTITY FABRICATION DEMONSTRATION

The goal of this project is to scale up existing, laboratory/prototype fabrication processes for ceramic turbine nozzles to a production level capability of 500 parts/month by the ceramic component manufacturing subcontractors. This process will be demonstrated by the production of ceramic turbine components at a rate of at least 100 parts/month 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 low-volume applications such as aerospace gas turbine engines. This level of ceramic manufacturing technology development is an essential step toward eventual production of ceramic components for large-volume automotive applications.

Initiated in late 1993 and scheduled to continue through 1997, this subcontract work is focusing on the suppliers of the 331-200[CT] ceramic components for the Ceramic Turbine Engine Demonstration Program. AlliedSignal Ceramic Components (CC, Torrance, CA), and Kyocera Industrial Ceramics Company (KICC, Vancouver, WA) participated in this activity during 1996. At the conclusion of the manufacturing scaleup and demonstration subcontract activity, each of the participating manufacturers will have achieved the goals listed in Table 1.

Table 1. Ceramic Component Manufacturing Scaleup Goals.

Item	Goal
Individual Process Capability	500 Parts/Month
Overall Yield	75 Percent
Demonstrated Overall Process Capacity	100 Parts/Month
Cost	< $300 Per Part

Subcontractor Activities – CC

The 1996 efforts by CC included: establishing a baseline fixed process for the manufacture of ceramic turbine nozzles from AS-800 silicon nitride; implementation of short-run statistical process control (SPC); and process cost reduction efforts.

Figure 8 shows the various processing stages of a ceramic nozzle. The process begins with slip-casting of nozzle blanks, which are presintered to impart proper minimum strength for handling and machining. The blanks are then single-point machined (purposely oversized, to allow for shrinkage during densifying) with a numerically-controlled computer aided machining (CAM) process. The oversize, presinter machined nozzle forms are theo densified (sintered). After sintering, the functional interface surfaces are ground to final size. The gas path surfaces remain in the as-sintered state, with no grinding. Inspections are performed at each stage to ensure proper control of the processes.

By defining a fixed process and developing formal procedures for any changes to the nozzle manufacturing processes, CC is able to ensure consistent properties from one batch to the next, instilling confidence in the users that the ceramic parts will reflect design integrity. SPC methods have been implemented to ensure the fixed rocess remains under control and to identify any unstable manufacturing process phases needing remedial effort.

CC's approach to cost reduction started with the first fabrication process, by maximizing batch size. 1996 efforts were successful in maximizing ceramic slip utilization by combining slip batches and the use of more efficient mold tooling for casting. A secondary benefit seen is reduced presinter machining time, due to less stock removal required on the redesigned blanks from the new mold. Cost modeling of the baseline process identified presinter machining as a significant cost driver. A Design of Experiments (D.O.E.) approach has been initiated to address this challenge.

In the meantime, CC has initiated the ceramic component produc-tion demonstration phase. For purposes of initial demonstration, a manufacturing process capable of supporting production of 500 parts/month will be developed, but only a minimum quantity of parts will be produced. Initial deliveries of 25 nozzles each month are planned for the first two months, and thereafter the monthly quantity will be increased up to 100 parts per month for the first half of 1997. Thereafter, ceramic turbine nozzles will be produced and delivered at the rate of 100 parts/month throughout the first half of 1997.

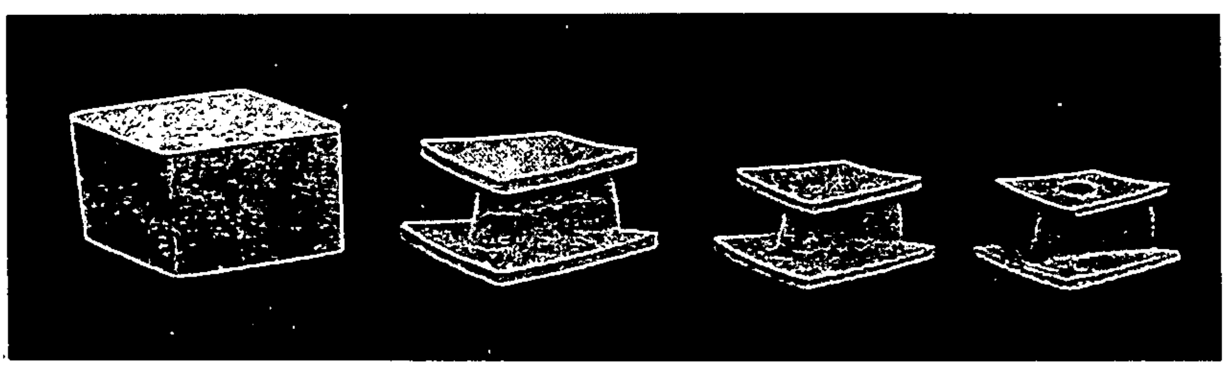

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Fig. 8. Manufacturing Steps For Ceramic Turbine Nozzles. (L to R) (a) Molded Blank; (b) Presinter Machined Blank; (c) Densified Blank; (d) Nozzle After Final Grinding. (CC Photo).

Subcontractor Activities – KICC

The 1996 efforts by KICC primarily focused on the optimization of fabrication processes to achieve economical production of ceramic components in moderate production quantities. The fixed process in use by KICC utilizes a proprietary hybrid molding method to form the nozzle shapes. These parts are then gas pressure sintered to achieve full density. After densification, the functional interfaces of the ceramic nozzles are ground to final dimensions. As with the process used by CC, the gas path surfaces remain in the as-sintered state, with no additional grinding following densification.

The initial focus of this work addressed ceramic nozzle fabrication using SN-252 silicon nitride. KICC successfully demonstrated yields of 82 percent through the sintering phase. Only a few of these parts were processed to completion.

At the request of AlliedSignal, a material change was initiated at midyear, to SN-282 silicon nitride. This change required new fixed process parameters and new mold tooling, to accommodate the different shrinkage of SN-282.

Cost Models

The cost models for 331-200[CT] ceramic nozzle manufacturing were updated, based on results obtained in recent parts processing. Cost analyses were performed for the processes as they existed in mid-1996, and as they are expected to be in mid-1997. Figure 9 shows the relative unit costs for each step in the KICC ceramic nozzle manufacturing process. The figure clearly shows that grinding and final dimensional inspection costs are the largest components of the part cost. These results indicate the need for a more detailed analysis of and improvements in the grinding and inspection processes. KICC has initiated development of improved machine tools and inspection processes to reduce these costs.

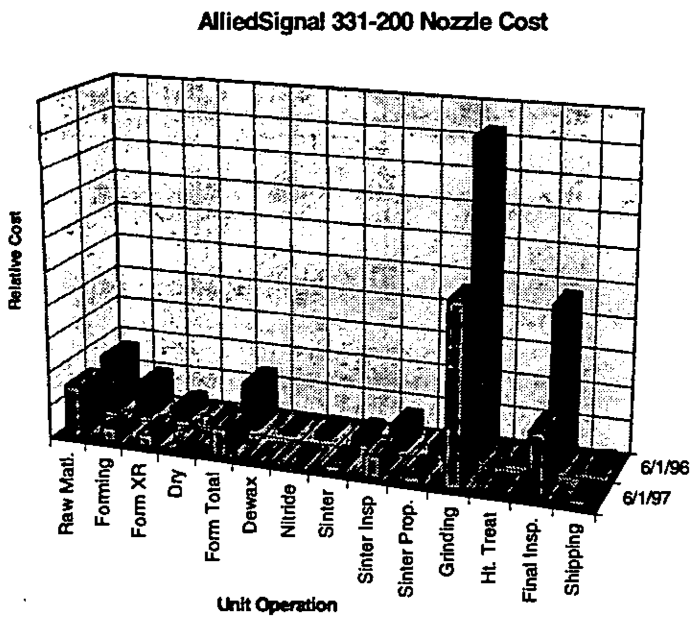

Fig. 9. KICC Cost Model For Ceramic Turbine Nozzles.

ENGINE DEMONSTRATIONS

Demonstration of engine operation with ceramic turbine nozzles and blades has served as the validation activity for the ceramic design methods and the integrity of the actual ceramic components. Initial engine testing activities have provided the environment for development and refinement of the ceramic component systems. Planned field testing and ongoing engine endurance testing will be used to establish the reliability of the ceramic components, in both simulated and actual gas turbine operating service conditions.

Significant progress has been made during the past year. Performance and endurance tests of the MOD 2 ceramic nozzles accumulated over 482 engine operating hours. The CTEDP program also reached a significant milestone by accumulating over 190 hours of partial-speed engine testing with the MOD 1 ceramic turbine blades. These tasks are summarized in the sections below.

MOD 2 Ceramic Nozzle Engine Testing

MOD 2 design ceramic nozzles made of AS-800 silicon nitride provided by AlliedSignal Ceramic Components (CC) were proof tested and then evaluated in engine testing for performance and durability. A summary of the ceramic nozzle performance test results is shown graphically in Figure 10. These results indicate that the MOD 2 and MOD 1 ceramic nozzle assemblies exhibit very similar performance characteristics in the engine. Both of these nozzle designs represent improvement over the MOD 0 ceramic nozzle with respect to engine performance, but the performance values still fall short of the baseline metallic nozzle equipped engine.

The cause of the performance shortfall with respect to the baseline metallic nozzles is a slight mismatch between the ceramic turbine nozzles and the production metallic blades used in the engine tests. The ceramic nozzles were designed to be used with the ceramic turbine blades. Despite the shortfall seen in the performance tests, the ceramic nozzle equipped 331-200[CT] APU is still judged to have adequate performance for field tests, planned to begin in 1997.

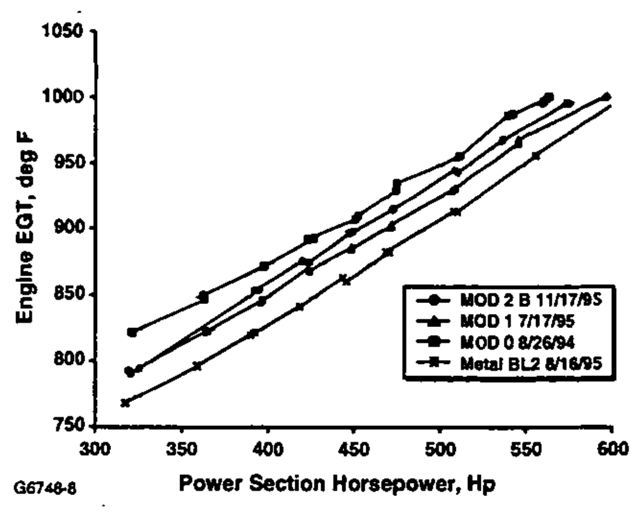

Fig. 10. 331-200[CT] Ceramic Nozzle Engine Performance Test Results.

Engine endurance testing resumed with tests of the MOD 2 ceramic nozzle design. Over 482 operating hours and 1283 test cycles were accumulated during 1996. Table 2 summarizes the engine operating hours and test cycles accumulated to date on the MOD 0, MOD 1, and MOD 2 ceramic nozzle designs.

Table 2. 331-200[CT] Ceramic Nozzle Engine Testing Summary.

Nozzle Type	Test Time, Hours	Starts
MOD 0	897.6	2481
MOD 1	9.8	22
MOD 2	482.5	1283
Totals	1389.9	3786

MOD 1 Ceramic Turbine Blade Engine Testing

Partial-speed engine tests with MOD 1 ceramic turbine blades made of SN-252 and AS-800 silicon nitride were completed during 1996. The ceramic blades accumulated a total of 191 operating hours and 340 operating test cycles at 68-percent speed. Table 3 summarizes the MOD 1 ceramic turbine blade engine testing during 1996. These results were accumulated using five engine builds and three different test cycles. The engine test cycles are shown schematically in Figure 11.

Table 3. 331-200[CT] MOD 1 Ceramic Turbine Blade Partial-Speed Engine Test Summary.

Blade Material	Test Cycle	Test Time, Hours	Starts
SN-252	Continuous	10	3
SN-252	Hot Restart	25	25
SN-252	Cold Start	100	200
AS-800	Cold Start	56	112
	Totals	191	340

The Continuous Cycle, in which the engine operates at steady-state condition for the entire test duration, is considered the least severe cycle with respect to both the ceramic blades and the compliant layer system. The Hot Restart Cycle is considered to be more severe than the Continuous Cycle, because this cycle adds engine speed changes in addition to the period of steady-state operation. The Cold Restart Cycle is the most severe test, because in addition to operating time, it adds significant temperature changes along with speed changes to the ceramic blade, metal rotor disk, and compliant layers.

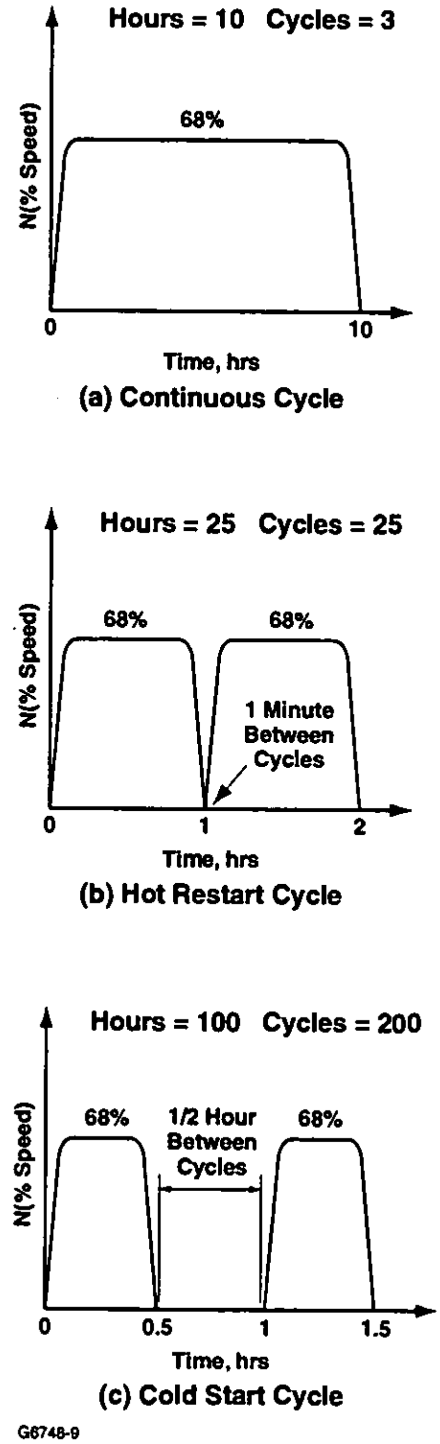

Fig. 11. 331-200[CT] Ceramic Turbine Blade Engine Performance Test Cycles.

These part-speed engine tests utilized the 0.005 inch (0.127 mm) thick platinum (Pt) and 0.002 inch (0.051 mm) thick HS25 dual compliant layer system lubricated with boron nitride (BN). The ceramic blades were installed with the compliant layers sandwiched between the blades and the metallic turbine rotor disk slots.

During engine disassembly for inspection after completion of each test phase, the ceramic blades and compliant layers were removed from the rotor for evaluation. Following inspection, the ceramic blades and compliant layers were then reassembled for further testing. The compliant layers did not exhibit any significant signs of wear until after a total of 75 hours and 125 test cycles of engine operation had been accumulated. The photomicrograph shown in Figure 12 shows a cross section through the compliant layers after 125 hours of operational testing. The arrow indicates an area where an accumulation of BN lubricant between the compliant layers caused displacement of the soft Pt layer. This result helped demonstrate that the HS25 lubricated dual-layer system is an effective short-term solution (up to 100 hours operation) for use in ceramic blade engine testing.

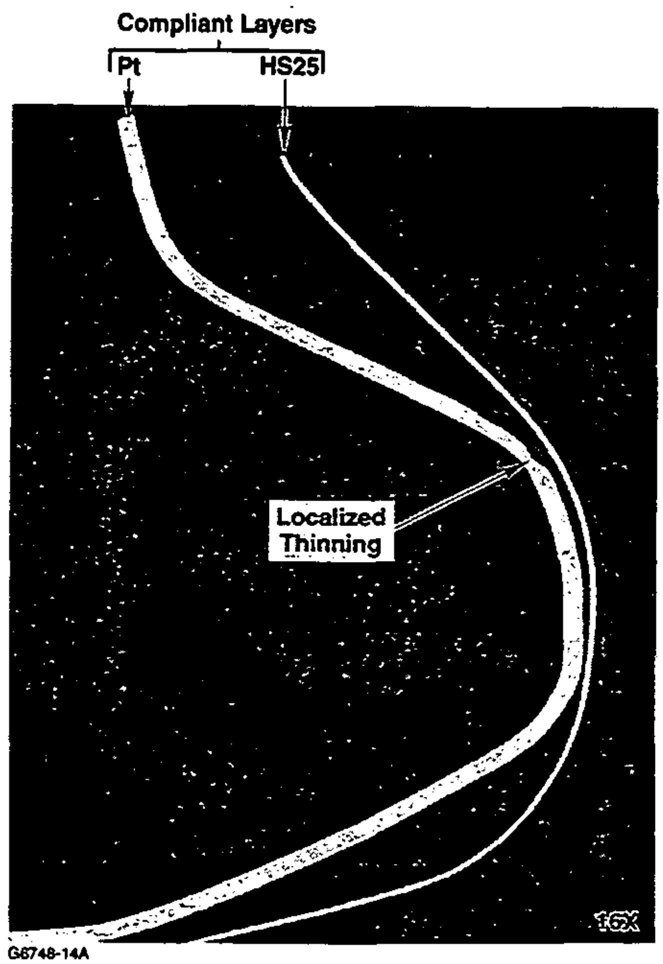

Fig. 12. Cross-Section Through Compliant Layers Following 125 Hours Of Operational Testing.

The possibility of a coupled blade/disk vibratory mode occurring at or near 100-percent engine operating speed has delayed the planned full-speed ceramic blade engine testing until the thin-film high-temperature strain gages are available. At that time, an engine test will be performed with strain gage equipped ceramic blades to evaluate the vibratory strain environment over the entire engine speed operating envelope, before proceeding with planned ceramic blade engine endurance testing.

MOD 1 Ceramic Turbine Blade Development

Ceramic turbine blade development is focused on enhancing the overall robustness of the 331-200[CT] first-stage inserted axial turbine blades. In 1996, the primary emphasis of this effort was on spin proof testing of the MOD 0 and MOD 1 ceramic blades and analytical evaluation of blade attachment stresses.

Ceramic Blade Spin Testing. A total of 20 MOD 1 and 13 MOD 0 ceramic turbine blades were spin tested to failure in the AlliedSignal spin pit facilities. These tests were designed to evaluate the effects of the compliant layer materials and lubrication, and the blade geometry on blade failure speeds. The spin pit was modified to include a ring of ballistic gelatin around the spinning rotor disk, allowing successful capture of the ceramic turbine blade fragments for later material analysis.

The spin test results are shown in Table 4, listing the blade types, test conditions (compliant layer system), burst speed, ceramic material Weibull slope value, and number of test articles. The small number of tests for each configuration limits the statistical conclusions that may be drawn. However, there was an obvious trend in the data which should be noted. The addition of boron nitride (BN) lubrication to the baseline HS25 compliant layer system resulted in a moderate increase in failure speed for both the MOD 0 and MOD 1 blades. The characteristic failure speed increased 7.3 percent for the MOD 0 blades and 8.0 percent for the MOD 1 blades when lubrication was added.

One other notable finding is that the failure initiation sites on ceramic blades in spin-to-burst tests using the unlubricated baseline HS25 compliant layer system were located at the top edge of the blade attachment contact zone; whereas the initiation sites for blades with the BN-lubricated compliant layer system were above the contact plane, near the minimum neck area of the blade. It should be noted that the location of the analytically-predicted peak blade stresses for both blade designs is in the blade minimum neck area.

Evaluation of Ceramic Turbine Blade Attachment Stresses. Finite element model (FEM) analyses were performed on both the MOD 0 and MOD 1 ceramic turbine blade configurations, including the frictional boundary conditions at the ceramic-to-metallic interfaces along the attachment contact plane (see Figure 13). The coefficient of friction (μ) was varied from a value of zero to 0.6 for most of the analysis cases. The analysis conditions included cold rotation, a simulated start transient, and a simulated unload transient.The results of these analyses, shown in Table 5, indicate that the MOD 1 ceramic blade stresses are predicted to increase dramatically with increasing μ for these conditions.

Table 4. Summary Of 331-200[CT] Ceramic Turbine Blade Compliant Layer Spin Pit Burst Test Results.

Blade Type	Blade Material	Compliant Layer	Burst Speed, rpm			Weibull Slope, m	No. Blades Tested
			Low	High	Typical		
MOD 0	NT154	Baseline HS25	52,600	71,300	64,054	5.30	5
MOD 0	NT154	HS25 + BN	65,700	70,600	68,777	21.40	5
MOD 0	NT154	(None)	63,600	65,100	64,611	56.50	3
MOD 1	AS-800	Baseline HS25	50,000	61,400	59,293	10.00	5
MOD 1	AS-800	HS25 + BN	61,400	65,300	64,054	28.60	5
MOD 1	SN-252	HS25 + BN	55,300	65,500	62,500	9.80	5
MOD 1	SN-252	HS25 + Pt + BN	58,500	66,500	64,000	13.30	5

BN = Boron Nitride
HS25 = Haynes Alloy 25
Pt = Platinum.

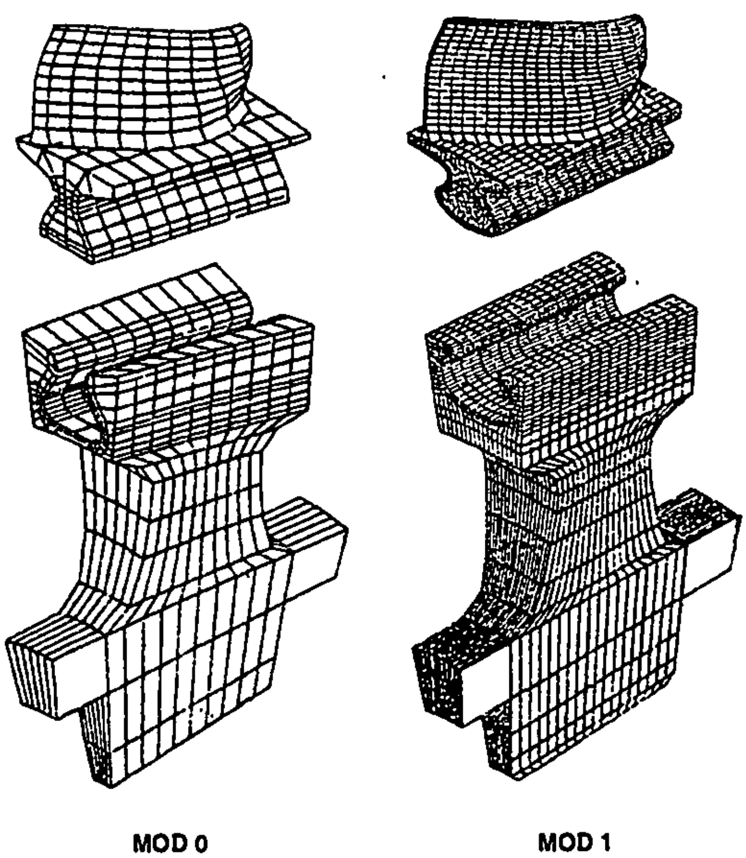

Fig. 13. Finite Element Models Used For Ceramic Blade Attachment Frictional Analyses.

Table 5. Summary of Ceramic Blade Attachment Frictional Analysis Results.

Coefficient Of Friction (μ)	Predicted Blade Stress, ksi					
	Cold Rotation		Simulated Start Transient		Simulated Shutdown Transient	
	MOD 0 Blade	MOD 1 Blade	MOD 0 Blade	MOD 1 Blade	MOD 0 Blade	MOD 1 Blade
0.00	39.8	41.1	40.2	41.1	40.2	41.1
0.03	38.8	41.1	---	---	---	---
0.30	38.3	48.8	37.9	4.5	44.9	42.5
0.60	38.8	64.4	---	---	50.1	46.6

Closer study of these results indicates that the high stress concentration (Kt = 3.5) of the MOD 1 ceramic blade fillet may be the reason for this sensitivity.

The simulated cold rotation MOD 1 blade analysis results agree well with the spin burst test data reported in a previous section. The burst test data shows the characteristic failure speed increased 8 percent (for a 17-percent increase in blade stress) with the addition of lubrication (hence lower μ) to the HS25 compliant layer system.

The analysis also indicated that the MOD 0 ceramic blade stresses were relatively insensitive for increasing μ for the cold rotation and simulated start transient cases. This portion of the analysis was not confirmed by the spin-to-burst failure test results. The MOD 0 ceramic blades burst at higher speeds than the MOD 1 blades, validating the prediction of higher stresses in the MOD 1 design. However, the MOD 0 blades also exhibited the same degree of sensitivity to changes in friction. Bursts occurred at even higher speeds in the spin tests when BN lubricant was used on the ceramic blade attachments.

Contact rig testing shows that the value of μ is 0.25 to 0.30 for unlubricated HS25 and 0.10 for lubricated HS25. The cold rotation analysis predicts that the MOD 1 blade stresses will increase 18 percent when μ increases from 0.03 to 0.30. The MOD 0 blade burst test data shows a similar increase in characteristic failure speed; however, the MOD 0 analysis does not predict any significant increase in blade stresses.

Conclusions – Ceramic Turbine Design Philosophy

Ceramic turbine design philosophies are now being formed that advocate peak design stresses in inserted blades be set much lower than in the present designs. The driver for this approach is the realization that ceramic materials are more sensitive to the restraint conditions in the blade attachment than for conventional inserted metallic blades. Technology is being developed to improve the compliant layers for inserted ceramic blades; but the sense is that the combined effects of thermal stresses, inertial loads, friction, and contact stresses are not well enough understood at present to achieve successful ceramic turbine designs using the same margins assumed with metallic blades.

To this end, activity has been initiated to identify alternate ceramic turbine blade concepts, and to initiate a MOD 2 ceramic turbine design, based on the most promising candidates.

FUTURE WORK

CTEDP program activity is planned to continue into 1998 with preparation of ceramic component technology for commercialization. The schedule shown in Figure 14 summarizes the overall activities from program inception through 1998.

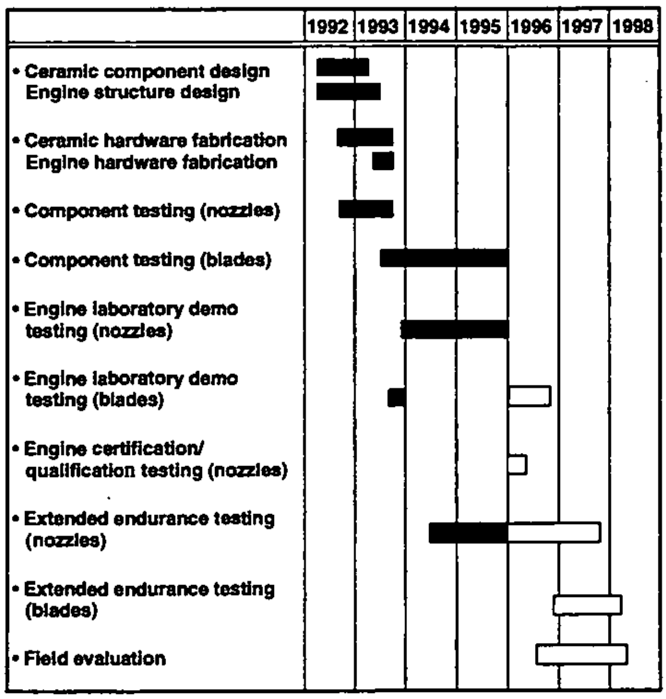

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Fig. 14. 331-200[CT] Ceramic Turbine Engine Demonstration Program Overall Schedule.

The following future activities are planned:

- MOD 2 ceramic turbine nozzle development and qualification testing
- Continuation of endurance tests with MOD 2 ceramic nozzles
- Initiation of field testing with MOD 2 ceramic nozzles
- Continuation of MOD 1 ceramic turbine blade engine testing
- Initiation of endurance tests with MOD 1 ceramic turbine blades
- Design and procurement of MOD 2 ceramic turbine design.

SUMMARY AND CONCLUSIONS

The Dept. of Energy-sponsored 331-200[CT] Ceramic Turbine Engine Demonstration Project is planned to continue into 1998, with the mission of advancing ceramic gas turbine component technology towards commercialization. This will be accomplished by enhancing critical ceramic design technologies, scaling up and demonstrating production-level ceramic component manufacturing capability of domestic U.S. ceramics manufacturers, and demonstrating ceramic engine component durability and reliability in extensive laboratory and field engine tests.

During 1996, the design technologies for ceramic turbine blades were further advanced with completion of the ceramic turbine particle impact trajectory analysis. Investigations into the contact stress environment of the ceramic axial turbine blade attachment confirmed the importance of compliant coatings to reduce friction and minimize contact stresses. Spin-to-burst testing quantified the inherent strength of the ceramic materials and the MOD 1 ceramic turbine blade design. Finite element model (FEM) analyses revealed the magnitude of the peak stresses due to frictional effects in the MOD 0 and MOD 1 ceramic turbine blades.

In the ceramic component manufacturing scaleup and demonstration activities, subcontractors AlliedSignal Ceramic Components and Kyocera Industrial Ceramics Corporation completed the work necessary to justify a change to new ceramic materials and production processes that were more amenable to quantity production and improved quality.

Successful engine testing with the MOD 2 ceramic nozzles and MOD 1 ceramic blades were completed. The MOD 2 ceramic nozzles accumulated over 482 hours of engine testing and 1283 test cycles. The MOD 1 blades accumulated over 191 operating hours and 340 test cycles of partial-speed engine testing.

Engine testing with ceramic nozzles is planned to continue, with the objective of validating the performance and integrity of the MOD 2 ceramic nozzle design, and qualifying the 331-200[CT] ceramic nozzles for initiation of field testing, planned to begin in 1997. Full-speed engine testing with ceramic turbine blades is planned to continue, with the objective of validating the integrity of the blades and the compliant layer system. Engine endurance testing of the ceramic turbine blades is planned to begin in early 1997.

The 331-200[CT] Ceramic Turbine Engine Demonstration Project has the vision of augmenting the development of ceramic technology in support of automotive gas turbine development. To achieve this goal, the program plan is to continue to enhance the ceramic technologies required to support the design of gas turbine ceramic components, to refine and scale up the production capability of domestic U.S. ceramic component manufacturers, and to demonstrate the capabilities of the ceramic components, first in laboratory field tests and then in extensive field trials.

The engine demonstration testing and field evaluations will provide the experience required to verify the improvements in ceramic design technology and component fabrication.

REFERENCES

1. M.L. Easley and J.R. Smyth, "Ceramic Gas Turbine Technnlogy Development," ASME Paper 94-GT-485, American Society of Mechanical Engineers, 1994.
2. M.W. Rettler, M.L. Easley, and J.R. Smyth, "Ceramic Gas Turbine Technology Development," ASME Paper 95-GT-207, American Society of Mechanical Engineers, 1995.
3. M.L. Easley and J.R. Smyth, "Ceramic Gas Turbine Technology Development," ASME Paper 96-GT-367, American Society of Mechanical Engineers, 1996.
4. David W. Richerson and Keith M. Johansen, "Ceramic Gas Turbine Engine Demonstration Program Final Report, January 1976 to May 1981, Contract No. N00024-76-C-5352." DARPA Order No. 3155, Garrett Report No. 21-4410, Garrett Turbine Engine Co., Phoenix, AZ, May, 1982.