DOE 0336-9F
EDR 18635

FINAL SUMMARY REPORT

Advanced Turbine Technology

ATTAP

Applications Project

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OST
Hybrid Vehicle Turbine Engine
HVTE-TS
Technology Support Project

Rolls-Royce Allison

P.O. Box 420

Indianapolis, Indiana 46206-0420

December 1998

Prepared for:

U.S. Department of Energy
Chicago Field Office

and

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Office of Transportation Technologies
Washington, D.C. 20585

under Contract DE-AC02-96EE50453
formerly Contract DEN 3-336

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Final Summary Report

Advanced Turbine Technology Applications Project (ATTAP)

Hybrid Vehicle Turbine Engine Technology Support Project (HVTE-TS)

Contract No. DE-AC02-96EE50453

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Rolls-Royce Allison P.O. Box 420 Indianapolis, Indiana 46206-0420

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FOREWORD

This final technical report summarizes Rolls-Royce Allison activities on the Advanced Turbine Technology Applications Project (ATTAP) and the Hybrid Vehicle Turbine Engine Technology Support (HVTE-TS) project. ATTAP was conducted from 1987 through 1993. In 1994, ATTAP activities were transferred to the HVTE-TS. The HVTE-TS project was conducted from 1994 through 1998.

ATTAP was sponsored by the U.S. Department of Energy (DoE), Conservation and Renewable Energy, Office of Transportation Technologies, Propulsion Systems, Advanced Propulsion Division. The work was performed under Contract DEN3-336 from the NASA Lewis Research Center (LeRC), Aeronautics Directorate, Propulsion Systems Division, Advanced Propulsion Applications Office, which provided project management and technical direction. Allison Gas Turbine Division of General Motors Corporation was prime contractor on ATTAP.

In 1993, Allison Gas Turbine Division became Allison Engine Company (now doing business as Rolls-Royce Allison) which assumed execution of the ATTAP contract. Concurrently, General Motors Corporation (GM) automotive gas turbine assets were transferred to the Allison Engine Company and relocated from the GM Technical Center in Warren, MI, to Rolls-Royce Allison in Indianapolis, IN.

The intent of the ATTAP project was to bring the automotive gas turbine engine to a technology state where commercialization decisions could be made for potential applications. Key to this goal was the development and demonstration of structural ceramic component technology as the critical high risk/high payoff element in this type of engine. Therefore, ceramic technology was the prime focus of ATTAP.

During the early 1990s, hybrid electric powered automotive propulsion systems became the focus of development and demonstration efforts by the U.S. auto industry and the Department of Energy. Thus in 1994, the original ATTAP technology focus was redirected to meet the needs of advanced gas turbine electric generator sets such as those under development in the Hybrid Electric Vehicle Program (HEV). At that time, ATTAP was restructured to provide hybrid

vehicle turbine engine technology support and the project was renamed HVTE-TS. The HVTE-TS project overall goal was to develop the key technologies required to support the use of gas turbine generator sets in hybrid-electric vehicles. In late 1996, the HVTE-TS focus was redirected to demonstrate ceramic component and ceramic engine operation maximizing use of existing ATTAP and HVTE-TS hardware.

In 1996, the administration of HVTE-TS was transferred from NASA LeRC to the Chicago Field Office of the DoE, and the contract number was changed from DEN 3-336 to DE-AC02-96EE50453.

Rolls-Royce Allison addressed both of the ATTAP and HVTE-TS projects with a team drawing upon:

- Rolls-Royce Allison's extensive ceramic design, analysis, and materials database and expertise. Previous automotive turbine development background including:
 - Substantial experience, design, and test capabilities
 - Automotive gas turbine technology and hardware
 - Test vehicle resources
- The infrastructure of expertise and resources in place in the American ceramics industry
- The working relationships between the ceramics industry and Rolls-Royce Allison
- The unique capabilities and resources at universities and national laboratories, such as:
 - High Temperature Materials Laboratory (HTML) at Oak Ridge National Laboratory (ORNL)
 - Argonne National Laboratory

In this arrangement, Rolls-Royce Allison served as prime contractor.

Major ceramics industry development subcontractors during HVTE-TS and ATTAP included Corning, Inc., Kyocera Industrial Ceramics Corporation, Schuller International, AlliedSignal Ceramic Components (ASCC), Carborundum Corporation, Norton Advanced Ceramics, GTE Laboratories (GTE), and Ceramics Process Systems (CPS).

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ABSTRACT

This final technical report was prepared by Rolls-Royce Allison summarizing the multiyear activities of the Advanced Turbine Technology Applications Project (ATTAP) and the Hybrid Vehicle Turbine Engine Technology Support (HVTE-TS) project.

The ATTAP program was initiated in October 1987 and continued through 1993 under sponsorship of the U.S. Department of Energy (DoE), Energy Conservation and Renewable Energy, Office of Transportation Technologies, Propulsion Systems, Advanced Propulsion Division. Until 1996, technical direction was provided by the NASA Lewis Research Center, Cleveland, Ohio. Subsequent technical direction was provided by DoE, Energy Efficiency and Renewable Energy, Office of Transportation Technologies, Washington, D.C., with contract management by the DoE Chicago Field Office.

ATTAP was intended to advance the technological readiness of the automotive ceramic gas turbine engine. The target application was the prime power unit coupled to conventional transmissions and powertrains.

During the early 1990s, hybrid electric powered automotive propulsion systems became the focus of development and demonstration efforts by the U.S. auto industry and the Department of Energy. Thus in 1994, the original ATTAP technology focus was redirected to meet the needs of advanced gas turbine electric generator sets. As a result, the program was restructured to provide the required hybrid vehicle turbine engine technology support and the project renamed HVTE-TS.

The overall objective of the combined ATTAP and HVTE-TS projects was to develop and demonstrate structural ceramic components that have the potential for competitive automotive engine life cycle cost and

for operating 3500 hr in an advanced high temperature turbine engine environment. Significant activities were also undertaken by engine manufacturers and ceramic companies in pursuit of these goals.

Accomplishments have included:

- Developed and implemented effective design process for turbine engine ceramic components
- Demonstrated and verified ceramic component operational capability, structural integrity and durability in a high temperature turbine engine environment
- Completed over 10,000 ceramic component test hours
- Achieved significant improvements to ceramic material processing techniques and fabrication technology with process yields improved fivefold and material strengths improved up to 100%
- Demonstrated high temperature advanced combustion systems capable of meeting current and proposed Federal and California Ultra Low Emissions Vehicle (ULEV) standards
- Developed and demonstrated regenerator core material, processing, and extrusion die technology in a production scale environment with the potential to meet system performance, efficiency, and cost goals for automotive application
- Increased actual "in engine" operation of structural ceramic components from mere minutes to hundreds of hours endurance
- Successfully demonstrated all-ceramic test-bed automotive turbine engine operation at rotor inlet temperatures in excess of the design target of 2500°F

SUMMARY

An executive summary is included at the beginning of each chapter of this report describing the task objectives, technical approach, accomplishments, results, progress, current status, and remaining work. These executive summaries are identified by a shaded background.

This final technical report was prepared by Rolls-Royce Allison summarizing the multi-year activities of the Advanced Turbine Technology Applications Project (ATTAP) and the Hybrid Vehicle Turbine Engine Technology Support (HVTE-TS) project.

ATTAP was initiated in October 1987 and continued through 1993. It was intended to advance the technological readiness of the automotive ceramic gas turbine engine for application as the prime power unit coupled to conventional transmissions and powertrains.

The ATTAP program primary focus was on specific gas turbine components as development and demonstration targets. These were:

- Ceramic gasifier turbine rotor, vanes, and scroll
- Ceramic regenerator system
- Thermal insulation

These components were identified as critical components because: (1) their functional success was critical to the viability of the ceramic automotive gas turbine engine and (2) each required further technological development to be proven reliable and durable in the automotive engine environment.

During the early 1990s, hybrid automotive propulsion systems, combining battery/electric drives with on-board power generators, became the focus of development and demonstration efforts by the U.S. auto industry and the Department of Energy. As a result, the original ATTAP technology focus was redirected in 1994 to include key technologies needed for advanced gas turbine electric generator sets. The application of the technology was redirected from a prime mover role to a hybrid propulsion system role, where the turbine power plant drives a high speed alternator for electrical power generation. The new program focus provided the required hybrid vehicle turbine engine technology support and the project was renamed HVTE-TS.

The purpose of the HVTE-TS project was to develop gas turbine engine technology in support of U.S. Department of Energy and automotive industry

programs exploring the use of gas turbine generator sets in hybrid-electric automotive propulsion systems.

With somewhat differing end applications, the overall goal of ATTAP and HVTE-TS was the same: to prove the performance and durability of structural ceramic components in the hot gas path of an automotive gas turbine engine. Of the several technologies (aerodynamics of small components, combustion systems, ceramic components and heat management) requiring development before such an engine becomes a commercial reality, structural ceramic components represented the greatest technical challenge and represented the prime focus of both programs.

Significant progress has been made toward reaching the overall program goals of both the ATTAP and HVTE-TS projects. Ceramic component technological readiness for application to an automotive environment has been demonstrated in automotive test-bed rigs and engines duplicating the program reference powertrain design for an advanced high temperature turbine engine. Figure 1 illustrates these program accomplishments which were identified as major contractual milestones. Goal achievements were verified by the following accomplishments:

- Defined, evaluated, and optimized a reference powertrain design (RPD) for an advanced high temperature automotive gas turbine engine
- Demonstrated and verified structural ceramic component operational capability, integrity, and durability in a high temperature turbine engine environment at RPD conditions:
 - 1000-hr ceramic gasifier rotor life
 - 100-hr cyclic durability of "all-ceramic" gasifier power section
 - 300-hr cyclic durability of "all-ceramic" gasifier power section
 - 550-hr cyclic durability of ceramic regenerator disks and seals
 - 10,000 ceramic component test hours
 - Gasifier turbine rotor tip rub survivability in test-bed environment

Figure 1. Major Technology Development Program Milestones

- Gasifier turbine rotor impact resistance and tolerance to foreign object damage in test-bed environment
- Structural integrity and performance of ceramic combustor systems
- Proved performance of injection-molded insulation for both simple and complex turbine engine components
- Increased actual "in engine" operation of structural ceramic components from minutes to hundreds of hours endurance
- Successfully demonstrated all-ceramic test-bed automotive turbine engine operation at rotor inlet temperatures in excess of 2500°F
- Implemented effective design process for turbine engine ceramic components
- Achieved significant improvements to ceramic material processing techniques and fabrication technology resulting in fivefold improvement in process yields and material strength improvements up to 100%
- Demonstrated advanced combustion systems capable of meeting current and proposed Federal and California ULEV emissions standards

- Developed and demonstrated regenerator core material, processing and extrusion die technology in a production scale environment with the potential to meet system performance, efficiency and cost goals for automotive application

The AGT-5 hot gasifier rig and test-bed engine test hours accumulated during the ATTAP and HVTE-TS projects are summarized in Table 1.

Table 1. AGT-5 Test-Bed Test Hours

	Test Hours
Engines	
• Durability, System Integration	547
• Ceramic Components Running	977
• Vehicle Running	651
Total Engine Hours	2175
Gasifier Turbine Hot-Test Rigs	
• Ceramic Components Running	2721
• Other Testing	210
Total Gasifier Rig Hours	2931
Total Test-Bed Activity	5106

The combined ATTAP and HVTE-TS projects represent major activities by DoE, by engine manufacturers, and by ceramic companies in pursuit of these goals. Outstanding progress and significant successes have been accomplished under these automotive turbine engine programs.

Technical challenges remain before the advanced automotive turbine engine, incorporating structural ceramic components, exhibits a competitive automotive engine life cycle cost and durability. Tasks significant to the development and demonstration of such engines capable of low-cost, high-volume production that have not been completed and should be considered as remaining work include:

Ceramic Component Technology:

Additional effort is required to refine, optimize and verify design methodologies and codes particularly in the areas of time dependent and ballistic impact analyses.

Material development activities need to be extended to provide ceramic materials with increased fracture toughness, creep resistance, temperature capability, and strength. Material property databases need to be expanded to provide more reliable input for design and analytic activities.

Ceramic machining and fabrication process development for high volume production will be required to establish process capabilities, component quality, and part cost.

Additional rig/engine testing of ceramic components is needed to establish performance, component life and metal to ceramic and ceramic to ceramic interface capability.

Regenerator System Development:

Additional effort is required to demonstrate ceramic regenerator and associated seal systems performance and durability in an automotive environment. Materials and processes development must be continued with emphasis on cost effective high volume production.

Combustion System Development:

Additional development and testing of advanced combustor systems will be required to verify performance and establish that emissions levels meet current and future federal and California ULEV standards.

Development of required combustor controls and integration of requirements into engine control systems are needed.

Insulation Development:

Additional material and process development are required to achieve higher temperature capability, reduced thermal conductivity, and address injection molding tooling needs.

Additional development and testing (including automated tooling) are needed to demonstrate injection-molded insulation processes on a pilot scale basis.

Long term injection-molded insulation durability and erosion testing in an automotive turbine engine environment are required.

Vehicle Performance And Durability Testing:

Continued testing of the advanced gas turbine engine is needed to demonstrate overall system performance and durability in an automotive environment.

PROGRAM HIGHLIGHTS, PROGRESS, AND STATUS

The ATTAP and HVTE-TS projects spanned 10 years from October 1987 through December 1998. During this period, significant accomplishments were achieved and outstanding progress made in the development of advanced gas turbine engine technologies for automotive application.

PROGRAM HIGHLIGHTS

Numerous program goals have been accomplished during the ATTAP and HVTE-TS projects. Major test highlights include:

- Completion of the original ATTAP proof of ceramic technology program goals:
 1. Achieved design gasifier rotor inlet temperature (RIT) of 2500°F at full gasifier speed (100% N1) during 1990 with a ceramic gasifier rotor followed by successful testing of a full ceramic gasifier stage
 2. Successfully completed a 100-hr cyclic durability test of an "all-ceramic" gasifier turbine stage including peak cycle conditions of 2500°F RIT and 100% N1 in 1991
 3. Successfully completed a 300-hr cyclic durability test of an "all-ceramic" gasifier turbine stage including peak cycle conditions of 2500°F RIT and 100% N1 in 1996
- Demonstration of engine operation with ceramic two-stage power turbine
- Demonstration of performance and structural integrity of two-piece ceramic combustor
- Successful demonstration of fully operational all-ceramic AGT-5 automotive gas turbine engine with 2500°F rotor inlet temperature
- Successful attainment of Tier 0 federal emissions levels over the EPA federal urban driving cycle on a chassis dynamometer with an AGT-5 automotive gas turbine engine using methanol fuel and installed in a test-bed vehicle
- Successful demonstration of a premixing/prevaporizing combustor capable of meeting California ULEV emissions standards on DF-1 fuel in an AGT-5 automotive gas turbine operated at steady-state conditions on an engine dynamometer

- Successful completion of a 550-hr cyclic durability test of one-piece extruded ceramic regenerator disks at their design inlet temperature of 1750°F
- Completion of salt/sulfur corrosion tests with ceramic regenerators

PROGRESS

ATTAP and HVTE-TS have addressed the key technologies to be applied to advanced automotive gas turbine engines. Significant progress has been achieved in each key area to address the critical issues for application of turbine engines in the automotive environment. Highlights are:

Structural Ceramic Materials and Processes

- Ceramic material strengths improved 50-100%
- Ceramic material process yields improved fivefold
- Successful rig/engine operation when incorporating ceramic components increased from minutes to hundreds of hours endurance
- Successful demonstration of fully operational all-ceramic AGT-5 automotive gas turbine engine with 2500°F rotor inlet temperature

Low Emissions Combustion Systems

- A metal diffusion flame combustor met federal emissions standards on methanol fuel in an AGT-5 automotive gas turbine. The test was conducted in the Camaro Z28 test-bed vehicle driven over the EPA federal urban driving cycle on a chassis dynamometer.
- A "poppet valve" premixing/prevaporizing combustor met California ULEV emissions standards on DF-1 fuel in an AGT-5 automotive gas turbine operated at steady-state conditions on an engine dynamometer.
- A two-piece ceramic combustor successfully completed proof testing verifying the structural integrity of the all-ceramic combustor.

Regenerator and Seal Systems

Regenerator core material, processing, and extrusion die technology has been developed and demonstrated in a production scale environment. Results show the potential of the regenerator system to meet system performance, efficiency, and cost goals for automotive application.

- A major result from the development program is a new lithium-aluminosilicate (LAS) disk material that can be produced at a much lower cost per pound and that meets regenerator strength requirements.
- Extrusion die technology development has enabled Corning to produce 9-in. diameter magnesium-aluminosilicate (MAS) and LAS disks with 5 mil thick cell walls at 1150 cells/in.²
- Cyclic testing demonstrated LAS material hot face strength is maintained throughout the regenerator 10,000 cycle design life.
- A combination of regenerator seal configurations has been identified as the optimum secondary sealing system.
- Screening tests conducted by Argonne National Laboratory (ANL) identified cold wearface and hot crossarm materials that have the potential to reduce the cost of the seal primary wearfaces by an order of magnitude.
- Low cost solutions to regenerator gear wear have been identified by ANL.
- An investigation of alternate techniques for attaching the drive gear to the regenerator ceramic core material was completed.

Insulation Systems and Processes

The application of protective thermal insulation to turbine engine structures has progressed from small batches of hand laid up simple surfaces to the development of a molding system capable of high performance injection molding of complex contours:

- Thermal cyclic durability testing demonstrated that the molded insulation components met performance goals.
- Material characterization of molded insulation has shown all criteria were met for density, erosion and surface hardness, and thermal conductivity.
- Injection-molded insulation components were successfully tested in engine, hot rig, and vehicular test-beds.

STATUS

ATTAP and HVTE-TS efforts have produced outstanding progress and significant successes by demonstrating the performance, durability, and reliability of structural ceramic components in an advanced high temperature automotive turbine engine environment.

Technical challenges remain before the advanced automotive turbine engine, incorporating structural ceramic components, exhibits a competitive automotive engine performance, life cycle cost, and durability.

Table 2 summarizes the combined efforts and current status of the ATTAP and HVTE-TS projects and identifies significant tasks remaining to develop and demonstrate an advanced high temperature turbine engine for automotive application.

Table 2. ATTAP/HVTE-TS Program Status and Remaining Tasks

Structural Ceramic Materials Development and Characterization			
	<u>1987 Baseline</u>	<u>Current Status</u>	<u>Goal</u>
● Flexural Strength - ksi @ 2500°F	60	80	100
● Weibull Modulus	8	20	25
● Fracture Toughness (ksi-in ^{1/2})	3	8	12
● Stress Rupture - Hrs @ 2500°F & 30 ksi	1	100	1000
● Process Yield - %	8	40	95
● Cost (Normalized to 1987)	1 @	0.0075 @	0.003 @
	10 units per year	1M units per year	1M units per year

Structural Ceramic Component Design	
<u>Current Status</u>	<u>Required</u>
● Effective Design Process for Turbine Engine Ceramic Components has been Developed and Implemented	● Development and Verification of Design Methodologies and Code (Emphasis on Time Dependent/Life and Ballistic Impact Analyses) ● Establishment of Reliable Material Property Databases for Design and Analytic Activities

Structural Ceramic Component Fabrication Processes	
<u>Current Status</u>	<u>Required</u>
● Improved Processing Techniques and Fabrication Technology - Material Strengths Improvements up to 100% - 5 Fold Improvement In Process Yields	● Material Development for Increased Fracture Toughness, Creep Resistance, Temperature Capability and Weibull Modulus ● Development of Semi-Automated Fabrication Techniques to Establish Process Capabilities, Quality Levels and Cost ● Development of High Volume Machining Processes to Improve Quality and Reduce Cost

Table 2 (continued). ATTAP/HVTE-TS Program Status and Remaining Tasks

Structural Ceramic Component Development	
<u>Current Status</u>	<u>Required</u>
<u>Ceramic Combustor:</u> <ul style="list-style-type: none"> ● Limited Operation with Two-Piece SiC Combustor on Test-Bed Engine ● Single Piece Si₃N₄ Combustor Designed/Fabricated but not yet Tested 	<u>Ceramic Combustor:</u> <ul style="list-style-type: none"> ● Extended Cyclic Durability Testing
<u>Ceramic Gasifier Turbine Inlet Scroll:</u> <ul style="list-style-type: none"> ● Over Five Different Scroll Configurations Engine/Rig Tested ● Baseline Scroll Completed 300-hr Cyclic Durability Rig Test ● Advanced Circular Cross-Section Scroll Fabricated & Awaiting Testing 	<u>Ceramic Gasifier Turbine Inlet Scroll:</u> <ul style="list-style-type: none"> ● Performance and Cyclic Durability Testing of Latest Designs & Configurations
<u>Ceramic Gasifier Turbine Rotor:</u> <ul style="list-style-type: none"> ● Five Different Rotor Designs & Materials Evaluated ● One Si₃N₄ Turbine Rotor Demonstrated 1000-hr Life ● Inlet Scroll/Turbine Rotor Completed 300-hr Cyclic Durability Rig Test ● Inlet Scroll/Turbine Rotor Completed "All-Ceramic" Test-Bed Engine Testing at over Design Temperatures ● Fourth Generation Improved Performance Turbine Rotor Designed & Fabricated 	<u>Ceramic Gasifier Turbine Rotor:</u> <ul style="list-style-type: none"> ● Extended Cyclic Durability Testing ● Performance and Cyclic Durability Testing
<u>Ceramic Power Turbine:</u> <ul style="list-style-type: none"> ● Two Stage Si₃N₄ Axial Turbine Rotor Completed "All-Ceramic" Test-Bed Engine Testing at up to 2500°F 	<u>Ceramic Power Turbine:</u> <ul style="list-style-type: none"> ● Extended Cyclic Durability Testing ● Refined & Re-Matched (Optimized) Aerodynamics ● Develop Ceramic 1st Stage Vane Assembly

Table 2 (continued). ATTAP/HVTE-TS Program Status and Remaining Tasks

Regenerator System Development	
<u>Current Status</u>	<u>Required</u>
<ul style="list-style-type: none"> ● Ceramic Disk Material Database Established ● Production Ready Extrusion Process Developed for Medium Size Disks ● Extruded LAS/MAS Disks Utilized in Rig & Engine Testing ● Alternative Seal Materials Selected & Characterized ● Prototype Seal System Designed and Tested ● Drive System Designed and Tested ● Completed 550-hr Cyclic Durability Rig Testing ● Completed Limited Chemical Durability Testing 	<ul style="list-style-type: none"> ● Additional Disk Material/Process Development ● High Temperature Seal Tribology ● System Cost Reduction (Seals, Disks, Drive) ● Performance Optimization (Leakage - Disk ΔP and ΔT) ● Long Term Durability Demonstration of: <ul style="list-style-type: none"> - Ceramic Disk Cyclic Life - Chemical Durability - Seal and Drive Systems Life
Injection-Moldable Insulation System	
<u>Current Status</u>	<u>Required</u>
<ul style="list-style-type: none"> ● Adhesion to Parent Metal & Erosion Resistance Quantified ● Thermal Characteristics Optimized ● Injection-Moldable Material, Process & Prototype Tooling Developed for Simple/Complex Shapes ● Completed 300-hr Cyclic Durability Rig Test ● Completed All-Ceramic Test-Bed Engine Test 	<ul style="list-style-type: none"> ● Material & Process Development for Higher Temperature Capability, Reduced Thermal Conductivity & Automated Tooling ● Demonstrate Injection Molding Process on Pilot Scale Basis ● Extended Durability and Erosion Testing ● Definition of Water/Oil/Fuel Soak Characteristics ● Identify Health Risks (If Any)

Table 2 (continued). ATTAP/HVTE-TS Program Status and Remaining Tasks

Low Emissions Combustion			
<u>1987 Baseline</u>		<u>Current Status</u>	<u>Goal</u>
● Diffusion Flame Combustor	● Standard AGT-5 Metal Combustor	● Multi-Fuel Capability Demonstrated	● Test-Bed Rig and Engine Development
● Premix/Prevaporization Metal Combustor	● Concept Conceived In 1990	● Demonstrated Potential to Meet ULEV Emissions Standards	● Transient ULEV Demonstration (Cold Start, Driving Cycle, Controls)
● Ceramic Combustor	● Run Time Measured In Minutes	● Successful Engine Operation up to RPD Temperature (2500°F) for over 10 hours	● Demonstrate Extended Durability and Low Emissions Combustion
Automotive Test-Bed Turbine Engine Development			
<u>Current Status</u>		<u>Required</u>	
● Demonstrated Reliability and Durability of the AGT-5 Test-Bed Engine		● Extended Test-Bed Engine Cyclic Durability Testing	
- 547 Engine Test Hours During System Integration & Durability Testing		● Vehicle Performance and Durability Testing	
- 977 Engine Test Hours with Ceramic Engine Components		● Limited Field Performance Evaluations	
- 651 Engine Test Hours In-Vehicle Test-Bed Operation		● Compressor and Turbine Aerodynamic Performance Development and Optimization for Automotive-Size Duty Cycle	
- 2721 Hot-Test Rig Hours Running Ceramic Components		● Development of High Volume Machining Processes to Improve Quality and Reduce Cost	
● All-Ceramic AGT-5 Test-Bed Engine Demonstration Test		● Engine, System and Ancillary Control Systems Design and Development	

INTRODUCTION

This is the final technical report prepared by Rolls-Royce Allison on the Advanced Turbine Technology Applications (ATTAP) project and the Hybrid Vehicle Turbine Engine Technology Support (HVTE-TS) project.

This report summarizes the multiyear effort of ATTAP which started in 1987 through the current HVTE-TS project which ended in 1998. This summary report does not include all detailed activities and accomplishments over this period. Instead the report presents an overview of major program goals, objectives, activities, and accomplishments. During the course of both the ATTAP and HVTE-TS, annual technical reports, design reports, technical society papers, and annual DoE Contractors Coordination Meeting presentations were prepared. These items are a source of additional detailed program information and are identified in Section 8, Bibliography.

ATTAP was conducted from 1987 through 1993. It was intended to advance the technological readiness of the automotive ceramic gas turbine engine. The target application was the prime power unit coupled to conventional transmissions and powertrains. In 1994, the ATTAP overall focus was redirected to an automotive hybrid propulsion system role, where the turbine power plant drives a high speed alternator for electrical power generation. At that time the project was renamed HVTE-TS.

The potential advantages of the automotive gas turbine include:

- Significantly increased fuel economy
- Ability to meet federal emission standards with untreated exhaust
- Ability to operate on a wide range of alternate fuels
- Inherently smooth, low vibration operation

Rolls-Royce Allison addressed the ATTAP and HVTE-TS projects with a team drawing upon:

- Rolls-Royce Allison's extensive ceramic design, analysis, and materials database and expertise. Previous automotive turbine development background including:
 - substantial design and test capabilities and experience
 - automotive gas turbine technology and hardware
 - test vehicle resources

- The infrastructure of expertise and resources in place in the American ceramics industry
- The working relationships between the ceramics industry and Rolls-Royce Allison
- The unique capabilities and resources at universities and national laboratories, such as:
 - High Temperature Materials Laboratory (HTML) at Oak Ridge National Laboratory (ORNL)
 - Argonne National Laboratory (ANL)

In this arrangement, Rolls-Royce Allison served as prime contractor.

Major ceramics industry development subcontractors during HVTE-TS and ATTAP included Corning, Inc., Kyocera Industrial Ceramics Corporation, Schuller International, AlliedSignal Ceramic Components (ASCC), Carborundum Corporation, Norton Advanced Ceramics, GTE Laboratories (GTE), and Ceramics Process Systems (CPS).

GOALS AND OBJECTIVES

The overall ATTAP project goal was to prove the design, performance, and life of structural ceramic components in the hot gas path of an automotive gas turbine engine. The ATTAP program aimed to develop and demonstrate the technology of structural ceramics that had the potential for competitive automotive engine life cycle cost and for operating for 3500 hr (automotive engine life) in a turbine engine environment at temperatures to 2500°F (1371°C).

The primary focus of ATTAP was on specific gas turbine components identified as development and demonstration targets. These were:

- Ceramic gasifier turbine rotor, vanes, and scrolls
- Ceramic regenerator system
- Thermal insulation

These components were identified as critical components because: (1) their functional success was critical to the viability of the ceramic automotive gas turbine engine and (2) each required further technological development to be proven reliable and durable in the automotive engine environment.

Project objectives were:

- To enhance the development of analytical tools for ceramic component design using the evolving ceramic properties database
- To establish improved processes for fabricating advanced ceramic components
- To develop improved procedures for testing ceramic components
- To evaluate ceramic component reliability and durability in an engine environment

During the early 1990s, hybrid automotive propulsion systems, combining battery/electric drives with on-board power generators, became the focus of development and demonstration efforts by the U.S. auto industry and the DoE. Gas turbine engines are very attractive in these hybrid systems based on their low emissions, multi-fuel capability, smooth low vibration operation and potential for high fuel economy.

As a result the focus of ATTAP was redirected, in 1994, and became the Hybrid Vehicle Turbine Engine Technology Support (HVTE-TS) Project, still under Contract DEN 3-336 with NASA LeRC providing management and technical direction.

The HVTE-TS project was structured to support the Hybrid Electric Vehicle (HEV) program, which included efforts initiated by ATTAP to develop ceramic components for an automotive gas turbine engine. Rolls-Royce Allison was a subcontractor to General Motors Corporation (GM) during the HEV project. Rolls-Royce Allison was contracted to design, develop, fabricate, and deliver gas turbine engine driven auxiliary power units (APUs), which were used in GM's Hybrid Propulsion System Development Program (Hybrid). Both the HEV and HVTE-TS projects draw on the significant technology base established by ATTAP. The HVTE-TS project focus was extended to make this technology applicable to the automotive gas turbine engines that form the basis of hybrid automotive propulsion systems consisting of combined batteries, electric drives, and on-board power generators.

HVTE-TS was focused on the development of four key technologies identified as critical to the success of an advanced high temperature automotive turbine engine:

- Structural ceramic materials and processes
- Low emissions combustion systems
- Regenerators and seal systems
- Insulation systems and processes

Figure 2. HVTE-TS Relationship to Hybrid Turbine APU Development Program

The relationship of HVTE-TS to the HEV project is depicted in Figure 2. Both the HEV and HVTE-TS projects draw upon the significant technology base established by ATTAP. As the key technologies were developed, the results of the technologies in materials, components, and manufacturing processes were to be incorporated into the hybrid projects at various milestone stages of the program. HEV overall focus, with the support from HVTE-TS, was to provide a solid basis for a commercialization decision within a reasonable time frame.

The final HVTE-TS project overall goal was to assemble and test an all-ceramic AGT-5 test-bed automotive turbine engine. The program was structured to maximize the use of existing ATTAP and HVTE-TS ceramic hardware recognizing that combining these components into a functional engine would result in aerodynamic mismatches and nonoptimum performance.

PROGRAM SCHEDULE AND CONTENT

Figure 3 shows the scheduled activities in the original ATTAP project. The program included design, process development and fabrication, rig and engine testing, and iterative development of selected key ceramic engine components.

Materials assessment occurred at initiation of ATTAP and resulted in the targeting of ceramic component technology goals and the identification of materials, processes, and manufacturers to address those goals. The materials assessment was updated in Year 3 and again in Year 5, at which time the state of the art was reassessed for each component and required technology improvements were defined. The identification

Figure 3. ATTAP Program Schedule

and evaluation of materials, processes, and manufacturers were ongoing, continuous activities in ATTAP, and promising candidates were integrated into the program as merited.

Test-bed engine development, shown as an intermittent activity during ATTAP, included efforts aimed at ensuring the availability and functionality of an automotive gas turbine engine test-bed for the high temperature ceramic components. Engine development was not a primary focus of ATTAP, but those activities recognized the need to continue the evolution of the engine in order to handle additional power and thermal loads.

The ATTAP test-bed engine is shown in Figure 4. This GM-developed engine, the AGT-5, is a two-shaft, regenerative configuration with axial-flow gasifier and power turbines. The AGT-5 was originally designed as a robust durable metal automotive prime power engine.

Figure 4. ATTAP AGT-5 Test-Bed Engine

A Reference Powertrain Design (RPD) that described an advanced automotive gas turbine powertrain system to meet the ATTAP project goals including performance, cost, and reliability design goals was completed. The RPD upgraded the AGT-5 from a 1900°F metal engine to a 2500°F ceramic test-bed engine. The ceramic engine RPD formed the basis for all subsequent turbine engine component design, analysis, fabrication, and test activities.

The original HVTE-TS project was structured into a four year program. The program continued the ATTAP development cycle of material assessment, fabrication, and test to advance ceramic technology for turbine engine application. Additional emphasis was placed on low emissions combustor development, regenerator system and associated seal systems development, and protective thermal insulation material and fabrication development. The original HVTE-TS scheduled activities are shown by Figure 5.

The RPD, as revised through the ATTAP, reflected then current ceramic technology and goals, and was carried through the HVTE-TS project. The initial Rolls-Royce Allison HEV program engines were intended to operate at lower temperatures than the original RPD goals. However, engine component technology development continued the original ATTAP 2500°F (1371°C) gasifier rotor inlet temperature goals to provide growth margins for future HEV configurations.

The AGT-5 test-bed turbine engine developed under the ATTAP project was selected as the HVTE-TS test-bed engine. This provided continuity to the established component databases and a proven flexible engine for evaluation of advances in ceramic component technology. The HVTE-TS test-bed engine is shown in Figure 6.

The Hybrid Electric Vehicle Program at Rolls-Royce Allison was discontinued in early 1996. The HVTE-TS technology development project was continued with the exception of the low emissions combustion task (due to funding limitations) and redefined to a final one-year effort aimed at demonstrating ceramic development status in 1997. The emissions and alternate fuels goals were considered achievable based on demonstrated GM experience. For example, the AGT-100 engine's (from the AGT project) combustion system has displayed laboratory steady-state emissions of oxides of nitrogen (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UHC) well within the Tier 0 Federal Emissions Standards using diesel fuel, jet fuel, and methanol. Although such systems have demonstrated

Figure 5. Original HVTE-TS Schedule (Time Phased to Hybrid Program Objectives)

Figure 6. HVTE-TS AGT-5 Test-Bed Engine

the potential for low emission/alternate fuel gas turbine combustion, significant additional effort was identified to achieve a fully functional system suitable for automotive applications.

Central to the logic of Rolls-Royce Allison's approach to ATTAP/HVTE-TS was the iterative component development cycle. The cycle (illustrated in Figure 7) includes the design/fabrication/characterization/rig test/

Figure 7. Ceramic Component Development Cycle

engine test sequence of activities. The development cycle reflects the anticipated improvements in ceramic materials and associated component processing technologies and the incorporation of laboratory characterization data and rig/engine test results into succeeding designs.

The initial design activity used the then-current monolithic ceramic technology in the design of the gasifier turbine stage of the AGT-5 engine for 2500°F (1371°C) RIT. The second design phase incorporated toughened monolithic materials in the same gasifier

stage components. The third phase incorporated advanced (e.g., from ORNL's Ceramic Technology for Advanced Heat Engines [CTAHE] project) materials and processes as they became available. Succeeding design phases included other necessary ceramic components in the high-temperature test-bed engine, notably power turbine flow-path pieces.

Component fabrication development included those process development activities by ceramic suppliers resulting in the fabrication of engine-usable and commercially viable components. Characterization involves the laboratory activities, at both Rolls-Royce Allison and outside suppliers, that measure and define the various properties and qualities of ceramic materials in test bar form or in actual components. Examples are microstructural evaluation and measurements of density, strength, oxidation resistance, toughness, etc. Included are development and application of nondestructive evaluation (NDE) techniques.

Component rig activities include the development of rigs for component verification and testing (e.g., hot gasifier turbine rigs) as well as the actual testing activities. Test-bed engine testing includes the test activities associated with test-bed engine development plus the verification and development testing of the ceramic components. Each component development cycle (Figure 7) begins with design, followed by component fabrication, characterization, rig testing, and finally engine testing. The rigorous development process is iterative between the users and the ceramic supplier community, and ensures developing an understanding of the behavior of components in service and in continuous identification of areas for improvement.

In late 1996, the HVTE-TS project was redirected into a one year program as shown in Figure 8 with the overall goal of demonstrating the operation of an all-ceramic AGT-5 test-bed engine.

Figure 8. 1997 HVTE-TS Program Schedule

KEY TECHNOLOGIES

During the ATTAP project, emphasis was placed on ceramic component technology development. The critical development components were selected because their functional success was critical to the viability of the ceramic automotive turbine engine, and each required further technological development to be reliable, durable, and cost effective in the automotive turbine engine. The components included:

- Gasifier turbine rotor
- Gasifier turbine vanes
- Gasifier turbine scroll
- Regenerator disks
- Thermal insulation

The HVTE-TS project was structured to develop advanced gas turbine engine technologies for use in generator sets for hybrid-electric automotive propulsion system. HVTE-TS used the ceramic technology base developed by ATTAP. Critical technologies to accomplish this goal were identified as follows:

- Structural ceramic materials and processes
- Low emissions combustion systems
- Regenerators and seal systems
- Insulation systems and processes

The HVTE-TS critical technologies are illustrated in Figure 9.

Figure 9. HVTE-TS Four Key Technologies

CONCLUSIONS

A key goal of the ATTAP and HVTE-TS projects was to prove the fabricability, performance and durability of structural ceramic components in the hot gas path of an automotive gas turbine engine. This goal has been accomplished. Ceramic component technological readiness for application to an automotive environment has been demonstrated in automotive test-bed rigs and engines duplicating the program reference powertrain design for an advanced high temperature turbine engine.

PROGRAM ACCOMPLISHMENTS

Goal 1: Develop and Enhance Ceramic Material and Component Analytical Tools

Accomplishment:

Developed and implemented an effective design process for turbine engine ceramic components implemented using an extensive ceramic properties database

Goal 2: Develop and Improve Processes for Advanced Ceramic Component Fabrication

Accomplishment:

Achieved significant improvements to ceramic material processing techniques and fabrication technology resulting in:

- Material strength improvements up to 100%
- Fivefold improvement in process yields

Goal 2: Evaluate Ceramic Component Reliability and Durability in an Automotive Engine Environment

Accomplishments:

- 1) Demonstrated, verified, and proved structural ceramic component operational capability, integrity, and durability in a high temperature turbine engine environment at RPD conditions:
 - Tip rub survivability
 - Improved impact resistance and tolerance to foreign object damage

- 1000-hr ceramic gasifier rotor life
- 100-hr cyclic durability of "all-ceramic" gasifier power section
- 300-hr cyclic durability of "all-ceramic" gasifier power section
- 550-hr cyclic durability of ceramic regenerator disks and seals
- Completed over 10,000 ceramic component test hours

- 2) Increased actual "in engine" operation of structural ceramic components from minutes to hundreds of hours endurance
- 3) Successfully demonstrated all-ceramic test-bed automotive turbine engine operation at rotor inlet temperatures in excess of 2500°F

Goal 4: Develop Advanced Combustors for High Temperature Automotive Turbine Engines and Meet Federal and ULEV Emissions Standards

Accomplishments:

- 1) Designed, fabricated, and successfully tested a two-piece ceramic combustor
- 2) Designed and fabricated a one-piece ceramic combustor
- 3) Demonstrated advanced combustion systems under steady-state operation which are projected to be capable of meeting current and proposed federal and California ULEV emissions standards

Goal 5: Develop Injection Moldable Thermal Insulation for High Temperature Automotive Environment

Accomplishments:

- 1) Established insulation injection molding process
- 2) Demonstrated insulation injection molding feasibility for simple and complex turbine engine flow path/housing components
- 3) Demonstrated injection-molded insulation durability and erosion resistance in engine environment

Goal 6: Design and Development of Regenerator and Seal System Materials and Processes for Use in An Advanced High Temperature Automotive Turbine Engine

Accomplishments:

- 1) Developed and demonstrated regenerator core material, processing and extrusion die technology in a production scale environment with the potential to meet system performance, efficiency and cost goals for automotive application
- 2) Successfully completed a 550-hr cyclic durability test of one-piece extruded ceramic regenerator disks at design inlet temperatures of 1750°F (954°C)
- 3) Completed salt/sulfur corrosion tests with ceramic regenerators
- 4) Developed a new LAS disk material which can be produced at a much lower cost per pound and which meets regenerator strength requirements
- 5) Developed extrusion die technology which has enabled Corning to produce 9-in. diameter MAS and LAS disks with 5 mil thick cell walls at 1150 cells/in²
- 6) Demonstrated LAS material hot face strength for the regenerator 10,000 cycle design life through cyclic testing
- 7) Identified a combination of regenerator seal configurations as the optimum secondary sealing system
- 8) Identified cold wearface and hot crossarm materials which have the potential to reduce the cost of the seal primary wearfaces by an order of magnitude through screening tests conducted by ANL
- 9) Identified low cost solutions to regenerator gear wear (by ANL)
- 10) Completed an investigation of alternate techniques for attaching the drive gear to the regenerator ceramic core material

REMAINING WORK

The ATTAP/HVTE-TS projects have addressed the key ceramic technologies to be applied to advanced automotive gas turbine engines and significant progress has been achieved.

However, the HVTE-TS project sponsorship by DoE ended in 1998 with the successful demonstration of an all-ceramic AGT-5 test-bed engine operating at RPD design rotor inlet temperatures up to 2500°F (1371°C). Technical challenges remain before the advanced automotive turbine engine, incorporating structural ceramic components, exhibits competitive automotive engine durability and life cycle cost. Tasks significant to the development and attainment of structural ceramic components capable of low-cost, high-volume production which have not been completed and should be considered as remaining work include:

- 1) Ceramic component technology:
 - Development and verification of design methodologies and codes, particularly in the areas of time dependent and ballistic impact analyses
 - Expansion of material property databases to supply suitable input for design and analytic activities
 - Additional material development activities to provide ceramic materials with further increased fracture toughness, creep resistance, temperature capability, and Weibull modulus
 - Development and verification of semi-automated component fabrication processes, involving relatively large production runs to establish process capabilities, component quality levels, and cost
 - Development and application of high volume ceramic machining processes to improve component quality and reduce final cost
 - Additional rig/engine testing of ceramic components to verify component life and metal/ceramic and ceramic/ceramic interface capability
- 2) Regenerator system development:
 - Continued materials and processes development focused on cost effective high volume production regenerator core fabrication
 - Regenerator material performance and durability verification in an automotive environment
 - Continued development of regenerator seal system optimization for performance and durability

3) Combustion system development:

- Continued development and test of advanced combustor systems designed to meet current and future federal and California Ultra Low Emissions Vehicle emissions standards
- Development of required combustor controls and integration of requirements into engine control systems
- Continued advanced combustor system performance and durability verification in an automotive environment

4) Insulation development:

- Additional material and process development to achieve higher temperature capability, reduced thermal conductivity and address injection molding tooling needs
- Additional development and testing (including automated tooling) to demonstrate injection-molded insulation processes on a pilot scale basis
- Long term injection-molded insulation durability and erosion testing in an automotive turbine engine environment

5) Vehicle performance and durability testing

6) Limited field performance evaluations

Additional technical challenges remain before the potential of an advanced gas turbine powered electric generator system for hybrid electric powered automotive propulsion systems can be realized. These include:

- 7) Compressor and turbine aerodynamic performance development and optimization for automotive size and duty cycle
- 8) Development and optimization of a turbine driven electrical power generation system
- 9) Development and optimization of automotive turbine engine, APU and vehicle electronic control systems
- 10) Cost reduction analysis and implementation to yield a marketplace competitive product

1. MATERIALS CHARACTERIZATION AND CERAMIC COMPONENT DEVELOPMENT

This section describes the ceramic material and component fabrication, characterization, and development activities that were a key focus of ATTAP and HVTE-TS. Brief descriptions of ceramic processing terms are presented in Appendix A. The ceramic materials subsection documents the results of characterization and qualification of ceramic materials and components developed for advanced automotive gas turbine engine applications, including the characterization of material properties (microstructure, density, fracture strength, and fracture toughness) on both test specimens and bars sectioned from components. The ceramic component fabrication subsection describes the ceramic component process development activities conducted at the selected ceramic suppliers for the Rolls-Royce Allison effort, including AlliedSignal Ceramic Components, Carborundum, Ceramic Process Systems, GTE Laboratories, Kyocera Industrial Ceramics, and Norton Advanced Ceramics.

1.1 Ceramic Material Characterization

1.1.1 Objective/Approach

The materials and component characterization efforts were focused on the testing and evaluation of candidate ceramic materials and components being developed for use in advanced automotive gas turbine engines. The primary objective of this task was to establish a database of appropriate material characteristics to support the design, analysis, development, and testing of hot section ceramic components. A secondary objective was to evaluate new candidate ceramic materials and suppliers and to assess which, if any, should be used in subsequent component development programs. The materials characterization activities were focused on microstructure, density, flexural strength, and fracture toughness evaluations of various ceramic materials. Fracture surface analysis was also conducted to determine the nature and location of strength-controlling flaws. In addition, tensile strength and time dependent strength characteristics were evaluated for select materials.

1.1.2 Accomplishments/Results

The ceramic materials and components evaluated during the ATTAP and HVTE-TS projects included:

- AC Cerama CSN101 Si_3N_4
- Alcoa beta-SiC

- AlliedSignal Ceramic Components GN-10 and AS800 Si_3N_4
- Carborundum sintered alpha and SX SiC
- Ceramic Process Systems CM200 and SRS201 sialon
- Dow Chemical C, D, and E Si_3N_4
- DuPont/Lanxide Alumina/SiC particulate
- Ethyl unsintered SiC
- GTE Laboratories AY6 and PY6 Si_3N_4
- Kyocera SC221 SiC; SN252, SN253, and SN281 Si_3N_4
- NGK Spark Plug EC-152 Si_3N_4
- Norton Advanced Ceramics NT230 and NT235 SiC; NT154 and NT164 Si_3N_4

A summary of the results of characterization of these materials is presented in Table 1-1. More detailed information (including fractography) may be found in the ATTAP and HVTE-TS annual reports. Figure 1-1 graphically shows material property improvements during the ATTAP and HVTE-TS programs.

1.2 Ceramic Component Development

1.2.1 Objective/Approach

This subsection details the ceramic component process development and fabrication at the component developers (AlliedSignal Ceramic Components, Carborundum, Ceramic Process Systems, GTE Laboratories, Kyocera Industrial Ceramics, and Norton Advanced Ceramics). The ceramic component process development activities were directed toward fabrication of structural ceramic components using near-net-shape processes that can be applicable to high volume, low cost production. Emphasis was placed on development and evaluation of components and technology required for the gasifier rotor, scroll, and combustor. Rolls-Royce Allison's approach to ceramic component technology focused on subcontracting process development to the domestic ceramic manufacturing community and working in an iterative development loop with those suppliers in areas of design, fabrication, characterization, and rig/engine testing data feedback. While basic ceramic materials development was not part of HVTE-TS, it did integrate material developments from DoE/Oak Ridge National Laboratory programs, supplier in-house activities, and other sources as they became available.

Table 1-1. Ceramic Materials Characterization by ATTAP/HVTE-TS Program

Manufacturer	Material	Fabrication Process	Surface Condition	Component	Date	Flexural Strength, ksi (MPa)				Weibull Modulus	Fracture Toughness ksi-in ^{1/2} (MPa-m ^{1/2})	Test Standard
						77 (25)	1832 (1000)	2192 (1150)	2282 (1250)	2500 (1370)		
Alcoa	Beta-SiC	CIP	Longitudinal Ground	Test Bars	1988	60.58 (417.7)			58.03 (400.1)	62.96 (434.1)	10.0	2.7 (3.0)
GCCD (ASCC)	GN-10 Silicon Nitride	CIP/HIP	Longitudinal Ground	Test Bars	1988	109.30 (753.62)	101.99 (703.2)	97.19 (670.1)	91.34 (629.8)	86.90 (599.2)	8.7	5.4 (5.9)
GTE Labs	AY6 Silicon Nitride	IM/HIP	Longitudinal Ground	Test Bars	1988	148.15 (1021.5)			80.40 (554.36)	87.50 (603.3)		
GTE Labs	PY6 Silicon Nitride	IM/HIP	Longitudinal Ground	Test Bars	1988	135.99 (937.7)	121.15 (835.3)		84.96 (585.8)	80.68 (556.3)		
Kyocera	SC221 SiC	CIP	Longitudinal Ground	Test Bars	1988	61.67 (425.2)	58.60 (404.1)	60.91 (420.0)	58.32 (402.1)	61.41 (423.4)	22.9	2.4 (2.6)
Kyocera	SN252 Silicon Nitride	Slip Cast	Longitudinal Ground	Rotor Bars - GT	1988	87.09 (600.5)	74.46 (513.0)		56.07 (386.6)			
GTE Labs	AY6 Silicon Nitride	IM/HIP	Longitudinal Ground	Test Bars	1989	162.69 (1121.8)	136.33 (940.0)	109.64 (756.0)	93.52 (644.8)		16.0	7.6 (8.4)
GTE Labs	AY6 Silicon Nitride	IM/HIP	As-Fired	Test Bars	1989	92.95 (640.9)	75.23 (518.7)	71.79 (495.0)	66.31 (457.2)		7.5	
GTE Labs	PY6 Silicon Nitride	IM/HIP	Longitudinal Ground	Test Bars	1989	140.01 (965.4)	119.95 (827.1)	98.41 (678.54)	91.73 (632.5)	86.04 (593.3)	11.5	5.8 (6.4)
GTE Labs	PY6 Silicon Nitride	IM/HIP	As-Fired	Test Bars	1989	117.12 (807.5)	79.80 (550.2)	75.28 (519.1)	76.34 (526.4)	73.98 (510.1)	7.9	
Kyocera	SN252 Silicon Nitride	Slip Cast	Longitudinal Ground	Test Bars	1989	91.97 (634.1)	78.10 (538.5)	75.42 (520.0)	75.17 (518.3)	73.67 (507.9)	16.7	
Kyocera	SN252 Silicon Nitride	Slip Cast	As-Fired	Test Bars	1989	73.76 (508.6)	66.64 (459.5)	62.41 (430.3)	60.86 (419.6)	77.20 (532.3)	17.7	
NGK Spark Plug	EC-152 Silicon Nitride	CIP	Longitudinal Ground	Test Bars	1989	153.69 (1059.7)	134.59 (928.0)		99.35 (685.0)	84.70 (584.0)	8.7	
CBO	Sintered Alpha-SiC	IM/HIP	Longitudinal Ground	Rotor Bars - GT	1989	73.17 (504.5)					11.4	
GCCD (ASCC)	GN-10 Silicon Nitride	CIP/HIP	Longitudinal Ground	Test Bars	1990	118.28 (814.5)			84.29 (581.2)		12.2	ASTM
Norton/TRW Ceramics	NT154 Silicon Nitride	Slip Cast/HIP	Longitudinal Ground	Test Bars	1990	155.24 (1070.4)	101.53 (700.1)	105.05 (724.3)	105.77 (729.3)	91.64 (631.9)	10.1	5.4 (5.9)
Norton/TRW Ceramics	NT154 Silicon Nitride	Slip Cast/HIP	As-Fired	Test Bars	1990	81.21 (559.9)	66.91 (461.3)	58.87 (405.9)	61.61 (424.8)	62.36 (430.0)	6.2	
Norton/TRW Ceramics	NT235 Siliconized SiC	Slip Cast	Longitudinal Ground	Test Bars	1990	42.82 (295.2)				36.63 (252.6)	16.9	
CBO	Hexoloy SX SiC	IM/HIP	Longitudinal Ground	Test Bars	1990	119.97 (827.2)	83.81 (577.9)	73.26 (505.1)	64.56 (445.1)	51.01 (351.7)		4.8 (5.3)
Ethyl	Unsintered SiC	CIP/HIP	Longitudinal Ground	Test Bars	1990	31.40 (216.5)	42.77 (294.9)		39.86 (274.8)	42.54 (293.3)	8.8	
Kyocera	SN252 Silicon Nitride	Hybrid Molded	Longitudinal Ground	Test Bars	1990	95.03 (655.2)	73.13 (504.2)		65.57 (452.1)	67.25 (463.7)	14.3	
GTE Labs	PY6 Silicon Nitride	IM/HIP	Longitudinal Ground	Rotor Bars - GT	1990	111.93 (771.8)	89.50 (617.1)		86.28 (594.9)	79.10 (545.4)		
CBO	Sintered Alpha-SiC	IM	Longitudinal Ground	Rotor Bars - GT	1990	54.78 (377.7)						
CBO	Sintered Alpha-SiC	IM/HIP	Longitudinal Ground	Rotor Bars - GT	1990	75.13 (518.0)						
CPS	CM200 SiAlON	Quickset IM	Longitudinal Ground	Vane Platform Bars	1990	100.76 (694.7)	76.48 (527.3)	70.80 (488.2)	63.87 (440.4)	55.76 (384.5)	8.6	ASTM
Norton/TRW Ceramics	NT230 Siliconized SiC	Slip Cast	Longitudinal Ground	Test Bars	1991	53.55 (369.2)	63.92 (440.7)	59.73 (411.8)	61.27 (422.5)	67.95 (468.5)	8.9	
CBO	Sintered Alpha-SiC	Slip Cast	Longitudinal Ground	Test Bars	1991	77.72 (535.9)				79.38 (547.3)	7.1	
CBO	Sintered Alpha-SiC	Slip Cast	As-Fired (Mold Surface)	Test Bars	1991	66.07 (455.5)					5.7	
CBO	Sintered Alpha-SiC	Slip Cast	As-Fired (Drain Surface)	Test Bars	1991	69.64 (480.2)						
Norton/TRW Ceramics	NT154 Silicon Nitride	Slip Cast/HIP	Longitudinal Ground	Rotor Bars - GT	1991	153.07 (1055.4)	90.16 (621.6)		84.86 (585.1)	69.64 (480.2)		
Kyocera	SN252 Silicon Nitride	Slip Cast	Longitudinal Ground	Rotor Bars - PT1	1991	103.41 (713.0)	81.24 (560.2)	78.15 (538.8)	71.89 (495.7)	71.84 (495.3)	19.1	
Kyocera	SN252 Silicon Nitride	Slip Cast	Longitudinal Ground	Rotor Bars - PT2	1991	161.33 (1112.3)	124.29 (856.9)	74.92 (516.6)	53.06 (365.8)			ASTM
Norton/TRW Ceramics	NT230 Siliconized SiC	Slip Cast	As-Fired (Mold Surface)	Test Bars	1992	26.92 (185.6)	41.87 (289.2)		31.39 (216.4)	32.90 (226.8)		
Norton/TRW Ceramics	NT230 Siliconized SiC	Slip Cast	As-Fired (Drain Surface)	Test Bars	1992	30.37 (209.4)	42.20 (291.0)		48.28 (332.9)	58.70 (404.7)		
Norton/TRW Ceramics	NT164 Silicon Nitride	Slip Cast	Longitudinal Ground	Test Bars	1992	130.76 (901.6)	90.67 (625.1)	91.57 (631.3)	84.79 (584.6)	82.21 (566.8)	14.6	5.3 (5.8)
Norton/TRW Ceramics	NT164 Silicon Nitride	Slip Cast	As-Fired	Test Bars	1992	82.23 (567.0)	77.10 (531.6)	81.29 (560.5)	72.60 (500.6)	70.18 (483.9)	10.8	
Dow Chemical	Silicon Nitride C	Hot Pressed	Longitudinal Ground	Test Bars	1992	116.63 (804.1)	69.80 (481.3)	74.77 (515.5)	80.83 (557.3)	71.20 (490.9)	16.0	7.6 (8.3)
Dow Chemical	Silicon Nitride D	CIP	Longitudinal Ground	Test Bars	1992	115.81 (798.5)	70.33 (484.9)	59.21 (408.2)	35.40 (244.1)	28.46 (196.2)	13.6	7.1 (7.8)
Dow Chemical	Silicon Nitride E	CIP/HIP	Longitudinal Ground	Test Bars	1992	104.55 (720.8)	102.1 (704.1)	104.63 (721.4)	101.33 (697.3)	69.72 (480.7)	10.2	7.1 (7.8)
DuPont/Lanxide	Alumina/SiC Particulate	DIMOX	Longitudinal Ground	Test Bars	1992	58.71 (404.8)	40.73 (280.8)	42.59 (293.7)	41.58 (286.7)	39.93 (275.3)	8.8	5.7 (6.3)
Norton Advanced Ceramics	NT230 Siliconized SiC	Pressure Slip Cast	Longitudinal Ground	Test Bars	1993	58.85 (405.8)	67.11 (462.7)	55.64 (383.6)	63.53 (438.0)	47.49 (327.4)	8.2	
Norton Advanced Ceramics	NT230 Siliconized SiC	Pressure Slip Cast	As-Fired	Test Bars	1993	40.69 (280.6)	45.01 (310.3)	30.41 (209.7)	24.31 (167.3)	42.29 (291.6)	9.2	
CPS	SRS201 SiAlON	Quickset IM	Longitudinal Ground	Test Bars	1993	109.28 (753.5)	91.48 (630.7)	97.83 (674.5)	80.23 (553.2)	55.21 (380.7)	8.0	
CPS	SRS201 SiAlON	Quickset IM	As-Fired	Test Bars	1993	56.09 (386.7)	60.63 (418.0)	58.96 (406.5)	56.30 (388.2)	41.98 (289.4)	14.1	
CPS	SRS201 SiAlON	Quickset IM	Longitudinal Ground	Rotor Bars - GT	1994	100.93 (695.9)	84.93 (585.6)	87.36 (602.3)	72.68 (501.1)	56.76 (391.3)	17.8	
ASCC	AS800 Silicon Nitride	Slip Cast	Longitudinal Ground	Test Bars	1994	105.60 (728.1)	93.73 (646.2)	90.73 (625.6)	88.98 (613.5)	83.79 (577.7)	28.4	
ASCC	AS800 Silicon Nitride	Slip Cast	As-Fired	Test Bars	1994	97.16 (669.9)	90.20 (621.9)	84.32 (581.4)	81.86 (564.4)	69.75 (480.9)	12.8	
Kyocera	SN253 Silicon Nitride	Slip Cast	Longitudinal Ground	Rotor Bars - GT	1995	113.17 (780.3)	112.61 (776.4)	100.05 (689.8)	99.39 (685.3)	83.12 (573.1)	13.5	
Kyocera	SN253 Silicon Nitride	Slip Cast	As-Fired	Test Bars	1995	81.55 (562.3)	79.23 (546.3)	82.24 (567.0)	83.61 (576.5)	66.35 (457.5)	18.5	
Kyocera	SN281 Silicon Nitride	Hybrid Molded	Longitudinal Ground	Rotor Bars - GT	1996	108.58 (756.0)	133.58 (918.1)	117.53 (804.5)	91.45 (613.4)	87.46 (777.9)	8.6	6.2 (6.8)
Kyocera	SN281 Silicon Nitride	Hybrid Molded	As-Fired	Test Bars	1996	87.96 (782.4)	88.60 (788.1)	89.11 (792.6)	76.94 (684.4)	69.41 (617.4)	12.9	
AC Cerama	CSN101 Silicon Nitride	CIP/HIP	Longitudinal Ground	Test Bars	1996	140.40 (968.0)	107.64 (742.1)	100.20 (690.8)	104.69 (721.8)	85.40 (588.8)	15.0	5.1 (5.6)
ASCC	AS800 Silicon Nitride	Gelcast	Longitudinal Ground	Test Bars	1996	106.34 (733.2)	99.18 (683.8)	85.00 (586.0)	79.04 (545.0)	75.42 (520.0)	16.1	7.6 (8.4)
ASCC	AS800 Silicon Nitride	Gelcast	As-Fired	Test Bars	1997	85.87 (592.0)	88.13 (607.6)	83.29 (574.3)	71.48 (492.8)	60.14 (414.6)	25.0	ASTM

AGT - Four-point bending, 1/4-point loading, inner span 0.75" (19.05 mm), outer span 1.50" (38.1 mm), test specimen 0.25" x 0.125" x 2.0" (6.35 mm x 3.18 mm x 50.8 mm)

ASTM - (ASTM C-1161) Four-point bending, 1/4-point loading, inner span 0.787" (20.0 mm), outer span 1.57" (40.0 mm), test specimen 0.157" x 0.118" x 1.969" (4.0 mm x 3.0 mm x 50.0 mm)

Figure 1-1. Ceramic Structural Materials Property Improvements and Requirements

1.2.2 Accomplishments/Results

- **AlliedSignal Ceramic Components** - Component development activities were focused on pressure slipcast/gelcast silicon nitride gasifier turbine rotors (GN-10 and AS800) and gelcast combustor bodies. Three proof spin tested rotors and one machined combustor body were delivered to Rolls-Royce Allison.
- **Carborundum** - Component activities were directed toward injection molded sintered alpha-SiC gasifier turbine rotors and slipcast scroll assemblies and combustor bodies. Process yields increased from 10% to 45% for the rotors and from 5% to 50% for scroll bodies. Strengths for sintered alpha SiC increased from 50 ksi (345 MPa) to 86 ksi (593 MPa).
- **Ceramic Process Systems** - Development efforts were focused on the fabrication of sialon gasifier turbine rotors using the Quickset injection molding process. Significant increases in material strength and component processing were achieved.
- **GTE Laboratories** - Component development efforts focused on the fabrication of injection molded gasifier turbine rotors using PY6 silicon nitride. Increases in strength and fracture toughness were realized using both microstructural modifications and SiC whisker reinforcement.
- **Kyocera Industrial Ceramics** - Development efforts were focused on the fabrication of gasifier and power turbine rotors, scrolls, (rectangular and circular cross section) and combustor liners. Hybrid molding process development was conducted for SN281 silicon nitride rotors.
- **Norton Advanced Ceramics** - Gasifier turbine rotors fabricated by pressure slip

casting of NT154/164 silicon nitride and slipcast NT230 siliconized SiC turbine scrolls were the focus of Norton's ceramic component development activities. Automated high pressure slipcasting was developed for fabrication of SiC scrolls. Nineteen proof spin tested rotors and six machined scrolls were received and evaluated.

1.3 Remaining Technical Challenges

Tasks significant to the development and attainment of structural ceramic components capable of low-cost, high-volume production which have not been completed and should be considered as remaining work include:

- Development and verification of design methodologies and codes, particularly in the areas of time dependent and ballistic impact analyses.
- Expansion of material property databases to supply suitable input for design and analytic activities.
- Additional material development activities to provide ceramic materials with increased fracture toughness, creep resistance, temperature capability, and Weibull modulus.
- Development and verification of semi-automated component fabrication processes, involving relatively large production runs to establish process capabilities, component quality levels, and cost.
- Development and application of high volume ceramic machining processes to improve component quality and reduce final cost.
- Additional rig/engine testing of ceramic components to establish component life and metal/ceramic and ceramic/ceramic interface capability.

1.4 AlliedSignal Ceramic Components

1.4.1 Objective/Approach

A development program was conducted with AlliedSignal Ceramic Components (CC) to demonstrate gelcasting as a viable production method for manufacturing turbine components. The material used was AS800 silicon nitride, a high temperature in-situ reinforced microstructure material. Fabrication processes for axial turbine rotors and combustor bodies were developed.

1.4.2 Accomplishments/Results

- Gelcasting of AS800 Si_3N_4 turbine rotors demonstrated.
- Three of four rotors passed 80,000 rpm proof spin test.
- Gelcasting process developed for fabrication of thin-wall castings.
- Two combustor bodies processed and machined.

1.4.3 Discussion

The goal of the rotor development effort was the fabrication of gelcast AS800 Si_3N_4 gasifier turbine rotors for evaluation at Rolls-Royce Allison. Activities in this area began in 1995, with numerous delays encountered in rotor fabrication, primarily due to casting defects. Early rotor forming efforts were directed toward spin casting, where the mold rotates on a turntable as it is filled with AS800 gel slip. While spin casting had been demonstrated as a viable wheel forming technique in other molds, no defect-free gelcast wheels were produced in the AGT-5 mold. The common defects were voids, cracked airfoils, and cracked shafts. The cause of most defects was attributed to leakage in the mold.

Transfer press experiments were conducted in early 1996. This process applied a clamping pressure to the mold to eliminate slip leakage. However the results were poor. The clamping pressure proved ineffective for containing the gel slip in the mold. The AS800 gel slip, which consists of water, submicron particle size powders, and polymerization chemicals, was forced into the spaces between mold sections during transfer press casting. After gelation, the AS800 gel slip acted as an adhesive in the tight spaces between mold sections, making mold disassembly difficult and increasing the incidence of cracked airfoils. Furthermore, pressurization of the slip did not force all the air from the mold cavity and large voids were observed in all of the

castings. Subsequent rotor forming efforts were focused on spin casting.

The AGT-5 gelcasting process was mapped in detail. The process map provided a launching point for the failure mode effect analysis (FMEA). The FMEA was applied to each step in the spin casting process, with the most critical process inputs identified as those which (1) control the strength of the gelled part and (2) could affect the occurrence of voids. Experiments were designed accordingly.

A total of 17 rotors were cast, with 4 of the rotors having the potential for testing despite the presence of voids and cracked airfoils because the voids were small and/or located in low stress areas. Three of the rotors subsequently passed proof spin testing to the goal of 80,000 rpm. The remaining rotor burst at a speed of 78,600 rpm. The gelcast AS800 rotor is shown in Figure 1-2.

Figure 1-2. AlliedSignal Ceramic Components
Gelcast AS800 Silicon Nitride
Gasifier Turbine Rotor

Combustor development was conducted under the HVTE-TS program with casting trials conducted on a component with similar size, shape, and wall thickness as the combustor body. The prototypes were used to develop effective drying and sintering cycles. The first prototype castings cracked severely during the drying cycle.

Adjustments were made to correct the alignment and wall thickness issues, but cracking still occurred during drying using the standard cycle. Experimental drying cycles were used in the humidity dryers. Reductions in cracking resulted from the experimental cycles but none of the combustors were crack-free. These findings pointed to the inhibition layer as the primary cause of cracking. The inhibition layer on the interior of the prototype combustors penetrated approximately 0.020 in. (0.5 mm) into the wall thickness. As experiments to develop an effective drying cycle for combustors continued, casting methods that would reduce or eliminate the inhibition layer were investigated. The most effective method found to prevent an inhibition layer was to apply a barrier coating to the wax core before gelcasting. The first combustor that was gelcast with the coated core was fully dried, crack-free, using an extended drying cycle.

A combustor, shown in Figure 1-3, was delivered to Rolls-Royce Allison at the conclusion of the program.

Figure 1-3. CC Gelcast Combustor Body

1.5 Carborundum

1.5.1 Objective/Approach

The ceramic component development efforts conducted by the Carborundum Company (CBO) consisted of three major tasks: SiC rotor processing, slipcast scroll processing, and ceramic/ceramic joining. Sintered alpha-SiC material was used for all component fabrication, with the rotors being injection molded and the scrolls fabricated by slipcasting.

1.5.2 Accomplishment/Results

- Process parameters were established and optimized for the fabrication of 15-blade gasifier turbine rotors.
- Improved processing resulted in substantial improvements in the strength of sintered alpha-SiC from a baseline of 50 ksi (345 MPa) to 86 ksi (593 MPa).
- Slipcast scroll assemblies were successfully fabricated and delivered to Rolls-Royce Allison.

1.5.3 Discussion

The rotor processing activities were directed toward the establishment of processing parameters for the injection molding of sintered alpha-SiC gasifier turbine axial rotors. To determine the effects of variables in the injection molding process and to optimize the final engine configuration gasifier turbine rotor injection molding tool, activities were conducted on finite element modeling of the injection molding process.

A statistically designed molding matrix was conducted using a bladeless axial rotor injection molding tool to determine the molding variable values required to reduce knit lines on the surface of the rotor hub. Five rotors were molded at each condition, with the last three parts processed through sintering. The rotors were evaluated for flow lines, density, and dimensional accuracy (hub diameter). Statistical analysis of the rotor molding test matrix was conducted and process variables were established for rotor molding.

A hot isostatic pressing (HIP) test matrix was also conducted to reduce density variations and improve material strength. These results were substantiated in terms of mechanical properties, with the average flexural strength for as-sintered rotors of 54.6 ksi (376.5 MPa) increasing to 81.4 ksi (561.3 MPa) after HIP.

The 15-bladed engine configuration gasifier turbine rotor injection molding tool was received in February 1989. Over 100 rotors were molded, with a 70% yield

of acceptable rotors. A total of 16 rotors were processed through HIP processing, with 15 acceptable quality rotors received. A total of 11 rotors were proof spin tested, with two rotors successfully passing the proof spin speed of 80,000 rpm. The remaining nine rotors burst at speeds between 31,000 and 79,900 rpm, with an average burst speed of 66,900 rpm. The rotor activity at CBO was discontinued in 1990 because the alpha-SiC material did not possess the mechanical properties required to meet the transient loading conditions of the gasifier rotor.

The objectives of the slipcasting development task involved improvement of the properties of the sintered alpha-SiC slipcast components based on processing variables and fabrication of slipcast scrolls to be evaluated in rig and engine test activities. The slip development activities focused on the fundamentals of each processing step with the goal of improving casting yields and structural integrity by decreasing microstructural and macrostructural flaws. All development work was conducted using an alpha-SiC aqueous slip with a bimodal particle size distribution.

The slip development efforts were concentrated on powder beneficiation to remove unwanted ionic species, dispersion improvements through adjustments in chemical levels to increase the state of dispersion, and binder additions to improve the plasticity and handling strength of the green cast parts. A number of statistically designed experiments were conducted to determine the influence of various material and processing variables (dispersant type and level, slurry pH, binder type and level, and ionic conductivity) as they affect the final slip quality.

Based on these results, a final scroll casting process was established for component fabrication. The optimal plaster mold for the scroll was a four-piece mold with a disposable insert for the combustor inlet throat region. This configuration was the best for demolding and provided the highest casting yield. A change to the demolding procedure was an important factor. The disposable insert was removed from the cast part while it was still somewhat wet to minimize crack-producing stresses in the throat area. The scroll model, cast, and sintered scrolls are shown in Figure 1-4.

Significant increases in sintered density and mechanical strength were realized in the slipcast sintered alpha-SiC material. The sintered densities of slipcast scrolls increased from 0.108 lb/in.³ (3.00 g/cc) to 0.112 lb/in.³ (3.11 g/cc) from 1987 to 1990. Strength was improved from 51.5 ksi (355 MPa) to 67.8 ksi (467.5 MPa).

Figure 1-4. Carbtorundum Scroll Model (Top), Green Part (Middle), and Sintered Part (Bottom)

A total of four sintered alpha-SiC scroll assemblies were successfully cast, sintered, machined, and delivered to Rolls-Royce Allison for test evaluation.

1.6 Ceramics Process Systems

1.6.1 Objective/Approach

A development program was conducted with Ceramics Process Systems Corporation (CPS) to fabricate gasifier turbine rotors using SRS201 sialon material. Quickset injection molding was selected as the fabrication process for the 26-bladed rotor configuration. The rotor program consisted of three major phases, including injection molding tool fabrication, rotor processing development, and deliverable rotor fabrication.

1.6.2 Accomplishments/Results

- Design and fabrication of both 20- and 26-bladed rotor tools for Quickset injection molding were completed.
- Injection molded gasifier turbine rotors with good surface quality and material strength characteristics were successfully fabricated.
- Dimensional accuracy of Quickset molded rotors was excellent.

1.6.3 Discussion

The ceramic component development activities at CPS focused on the application of Quickset injection molding to sialon axial turbine rotors. The Quickset injection molding process uses a low pressure aqueous-based system with a colloidal solidification mechanism that does not utilize a binder system. As a result of binderless processing, CPS Quickset molded ceramic materials have demonstrated isotropic shrinkages with excellent dimensional tolerances and as-molded surface finish. In addition, overall processing time is significantly reduced over conventional thermoplastic binder injection molding processes.

Over 200 rotors were Quickset injection molded with a new gasifier rotor tool. The external quality of the SRS201 sialon rotors (shown in Figure 1-5) was significantly improved using the new molding tool.

In particular, the flow textures were significantly reduced by tailoring injection rate profile and the molding parameters. It was observed that the injection profile required tight control to minimize flow textures that were introduced at points in the mold cavity where the slip sharply changed speed or direction and where injection fronts converged.

Figure 1-5. CPS Quickset Injection Molded SRS-201 Sialon Gasifier Turbine Rotors

Approximately 40 of the RPD 20-blade rotors were processed through sintering. The measured as-processed surface finish was 28 μ -inches (0.7 μ m). Real time microfocus X-radiography revealed no internal flaws in the rotors, which had an average density of 0.117 lb/in.³ (3.245 g/cc), 99.5% of theoretical density. The dimensional characteristics of the rotors were excellent, with tolerances of ± 0.004 in. (0.10 mm) on the rotor hub surface. The mechanical strength characteristics of the rotor material demonstrated significant improvement, increasing from a baseline strength of 80 ksi (552 MPa) for a machined surface in 1990 to a strength of 119 ksi (820 MPa) with a Weibull modulus of 13.1 in 1993. Rotors with the as-processed surface also demonstrated substantial increases in strength, going from 54 ksi (372 MPa) to 80 ksi (552 MPa). One of the rotors was subjected to cold spin proof testing. Rotor failure occurred at a speed of 67,580 rpm, prior to the target proof spin speed of 80,000 rpm. Inspection of the rotor fragments revealed that fracture initiated from the top hub surface near the base of the airfoil leading edge. Failure of the rotor from this region at a speed lower than the proof spin level was not unexpected. Difficulties encountered in the translation of the 3-D rotor coordinates to the injection molding tool resulted in a blade fillet radius in which the airfoil leading edge transition to the rotor hub was much smaller than designed, resulting in excessively high mechanical stresses in spin testing.

1.7 GTE Laboratories

1.7.1 Objective/Approach

The ceramic component development activities at GTE Laboratories were focused on three main objectives: the development of PY6 silicon nitride fabrication technology for axial gasifier turbine rotors and vanes, the improvement of monolithic Si₃N₄ toughness using microstructural modifications, and the development of toughened PY6 Si₃N₄ using SiC whisker reinforcement.

1.7.2 Accomplishments/Results

- Tooling procured and process established for injection molding of PY6 Si₃N₄ gasifier turbine rotors
- 20 PY6 Si₃N₄ rotors delivered to Rolls-Royce Allison for evaluation
- SiC whisker reinforced PY6 Si₃N₄ characterized and rotors injection molded

1.7.3 Discussion

The rotor shapemaking development efforts have been focused on the establishment of injection molding and process parameters for PY6 Si_3N_4 gasifier turbine rotors which were glass encapsulated HIP processed. The PY6 Si_3N_4 composition is a more refractory version of GTE's Si_3N_4 material, replacing the prior AY6 material. As a result of a change to Ube Si_3N_4 powder from the prior GTE SN502 powder, the cracking tendency of large cross-section parts, such as the rotor, during the binder removal step increased significantly. The cracking was most commonly observed at the junction of the rotor shaft and hub. Initial activities were directed toward the refinement of an alternate injection molding procedure utilizing small additions of a binder removal aid. This procedure was developed during GTE in-house research and demonstrated potential for greatly improving resistance to crack formation during binder removal without compromising final mechanical properties. Subsequent rotors fabricated with this additive were observed to be consistently free of typical binder removal cracks although they did have a slightly rougher surface texture. Material strength evaluation on specimens sectioned from HIP processed rotors indicated that the burnout aid did not result in degradation, with a strength of 112.5 ksi (775.7 MPa) at room temperature, 98.6 ksi (679.8 MPa) at 2192°F (1200°C), and 82.8 ksi (570.9 MPa) at 2500°F (1371°C).

Concurrent with the binder-related activities, the injection molding tool was modified to improve the molding characteristics for fabrication of the deliverable rotors. These changes included: increasing the airfoil fillet radius to the value on the drawing, revising the tool to achieve a cavity vacuum of 10 in. (254 mm) of mercury, tightening the blade inserts against the scroll plate to minimize stresses during mold opening, and adding extra machining stock in the shaft and hub surface. Initial molding trials with the modified tool were successful. The cavity evacuation capability resulted in the elimination of surface blisters on the molded parts and binder removed parts did not exhibit cracking at the shaft/hub interface.

The tooling changes did not resolve the problem with fold lines on the rotor backface. Although these fold lines are present in an area with generous grinding stock, they frequently open up during HIP processing and allow HIP glass penetration into regions deeper than the allowable machining depth. These fold lines result from the freezing of the material first injected into the mold cavity. Also, since mold release is applied at the entrance of the sprue cavity, the freezing material

carries along some of the mold release, which then becomes entrapped as the cooling material folds back upon itself. The use of a "permanent" mold release agent good for 20-40 moldings was instituted. The surface quality of parts molded using this release agent was significantly better than prior pieces with respect to flow indications, but the occurrence of knit lines on the rotor hub face opposite the shaft was not completely eliminated.

A total of 20 PY6 Si_3N_4 gasifier turbine rotors were received from GTE Laboratories for evaluation. A total of eight rotors were subjected to room temperature proof spin testing. All eight of the rotors burst prior to achieving the proof speed of 80,000 rpm, with an average burst speed of 67,700 rpm. A high speed photograph of one of the rotors at the moment of burst (66,800 rpm) is shown in Figure 1-6. The failure origin was on the forward face of the rotor hub and was identified as a small surface flaw, probably the result of machining damage.

The objective of the toughened monolithic silicon nitride activity was to identify process conditions for increasing the fracture toughness of PY6 Si_3N_4 . The basic mechanism for achieving improved fracture toughness involved microstructural modifications, specifically focusing on increasing the average grain size. By increasing the grain size of Si_3N_4 , resistance to crack growth should increase because the crack is deflected more by propagation around the grains.

Figure 1-6. GTE Laboratories PY6 Si_3N_4 Gasifier Turbine Rotor at Moment of Burst (66,800 rpm)

To study the effect of different densification times, pressures, and temperatures on microstructure and material properties, a test matrix of the HIP process was conducted. Scanning electron microscope (SEM) examination revealed different microstructures resulting from each of the HIP cycles, indicating that sufficient flexibility exists in the process variability to warrant a study of toughness adjustment via process modifications. However, no significant differences in fracture toughness were observed. Compared to the baseline hot pressed PY6 Si_3N_4 , the HIP processed material showed higher room temperature strength but lower retention of strength at elevated temperatures. The hot pressed material retained 60-70% of the room temperature strength at 2552°F (1400°C) while the HIP processed material retained approximately 50% of the room temperature strength. Microstructural examination revealed a significantly larger average grain size (5X) in the hot pressed material compared to the HIP processed material.

For all the combinations of the various process parameters evaluated, it is apparent that the indentation fracture toughness for the PY6 Si_3N_4 material composition is limited to approximately 4.9 $\text{ksi-in}^{1/2}$ (5.4 $\text{MPa-m}^{1/2}$). This is a 20% improvement over the baseline toughness of PY6 Si_3N_4 ; however, it indicates that, unlike hot pressed PY6, HIP processed PY6 does not follow the simple model which shows that fracture toughness increases with grain size.

The objective of the toughened composite rotor task was to evaluate the densification kinetics, material properties, and fabricability of PY6 Si_3N_4 containing 30 volume percent (v/o) SiC whiskers. Improvements in fracture toughness, strength, and creep resistance were demonstrated in a prior ORNL Ceramic Technology for Advanced Heat Engines (CTAHE) project for additions of SiC whiskers in an AY6 Si_3N_4 matrix. At 30 v/o whisker loading, a 40% increase in fracture toughness and a 25% increase in fracture strength were observed. However, whisker reinforcement also decreased the densification rate of the composite material by limiting particle rearrangement. A dust containment/collection system for working with SiC whisker-containing powders was developed and tested at GTE and found to be more than adequate for protection of the operator and the environment. Several thick cross-section test samples of PY6 with 30 v/o SiC whiskers were successfully injection molded. Two of these samples were processed through binder removal and HIP. Both samples were over 99% theoretical density after HIP and exhibited only slight distortion during densification. Test specimens sectioned from the sample pieces had an average room temperature strength of 117 ksi (807

MPa) and an average strength of 80 ksi (552 MPa) obtained at a test temperature of 2552°F (1400°C). The fracture toughness of the whisker reinforced material measured 5.3 $\text{ksi-in}^{1/2}$ (5.8 $\text{MPa-m}^{1/2}$) as determined using the controlled surface flaw technique.

A larger batch of PY6 Si_3N_4 + 30 v/o SiC whisker material was then compounded for preliminary gasifier rotor fabrication trials. A total of 12 rotors were injection molded. The material filled the mold easily, but the molded parts tended to show more flow lines and were not as well packed as rotors made using monolithic PY6. Two of the rotors were processed through binder removal. Both rotors showed numerous cracks on the outside contour of the rotor shaft after binder removal, but appeared acceptable in the hub and airfoil sections. One rotor was densified by HIP processing. The rotor densified fully, but showed considerable airfoil distortion, as shown in Figure 1-7, presumably due to preferential whisker alignment during the injection molding step.

Figure 1-7. Injection Molded and HIP Processed GTE AGT-5 Rotors Made Using Monolithic PY6 Si_3N_4 (left) and PY6 Si_3N_4 + 30 v/o SiC Whiskers (Right)

1.8 Kyocera Industrial Ceramics

1.8.1 Objective/Approach

The objective of Kyocera Industrial Ceramics Corporation's (KICC) ceramic component development effort was focused on delivery of AGT-5 gasifier turbine rotors, turbine scrolls, and combustor liners to support engine testing, and development and

demonstration of manufacturing technologies applicable to low cost, high volume production.

Deliveries were to be accomplished by fabricating components from sintered silicon nitride using the following processes and materials:

- Rotors by slipcasting SN253 silicon nitride
- Scrolls by drain casting SN252 silicon nitride
- Combustor liners by drain casting SN282 silicon nitride

Manufacturing technologies were to be advanced in the following areas:

- Development of a fabrication process for circular cross-section turbine scrolls
- Application of Kyocera's Hybrid Molding process to SN281 turbine rotors

1.8.2 Accomplishments/Results

Deliveries:

- Five SN253 20-bladed AGT-5 gasifier rotors passed NDE and spin proof test requirements and were delivered.
- Four SN252 rectangular scrolls were delivered.
- Three SN252 circular cross-section scrolls were delivered.
- Four SN282 combustor liners were delivered.

Process Development:

- Drain casting and sintering processes for rectangular scrolls were successfully transitioned to two circular scroll designs.
- Polycarbonate patterns were successfully used in the mold fabrication process for the circular scrolls, shortening the tool development process.
- SN281 AGT-5 20-bladed gasifier turbine rotors were successfully formed using Kyocera's hybrid molding processes.

1.8.3 Discussion

Although the Kyocera Corporation in Japan had previously provided SN252 AGT-5 gasifier rotors under the previous AGT program, the aim of this effort was to provide rotors from Kyocera's Vancouver, WA facility using Kyocera's newer SN253 material. SN253 is a hot isostatic pressed (HIP) material, with higher strength than SN252, thus a better selection for a

turbine rotor. Kyocera's production proven hybrid molding process is the preferred method of rotor forming; however, rotor deliveries would have been delayed during the lead time required for mold procurement and process development. Thus, to expedite delivery of rotors to Rolls-Royce Allison, rotors were formed by solid slipcasting. Rotors were cast to near net shape to provide as-processed blades and minimal machining of the hub, shaft, and blade tips. Figure 1-8 illustrates the rotor in the as-HIP processed condition.

Subsequent spin proof testing of the completed rotors confirmed their integrity. Figure 1-9 illustrates a rotor photographed at the 80,000 rpm proof speed by high speed electronic recording. The recording system is also configured to record rotor burst occurrences, although no SN253 AGT-5 rotor bursts occurred in proof testing. Five rotors were completed and delivered.

Figure 1-8. Kyocera Slipcast SN253 AGT-5 20-Bladed Rotor (as-HIP Processed)

Figure 1-9. Rotor S/N 5-5 Captured at the 80,000 rpm Proof Speed

The objective of the hybrid molding development effort was to apply the hybrid molding process to the fabrication of SN281 gasifier rotors. The SN281 and SN282 family of silicon nitride is Kyocera's newest, developmental material for high temperature gas turbine applications. The SN282 is suitable for many static turbine parts, whereas the HIP processed SN281 is preferred for rotors or blades. Both materials exhibit superior high temperature creep and oxidation resistance.

This program task required the development of the forming, drying, and dewaxing parameters to achieve complete mold fill without defects. This optimization was accomplished through die design and fabrication, and the performance of multiple forming cycle iterations.

KICC performed the initial die design, procured the die, and initiated forming cycle iterations. Because SN281 was a new composition to hybrid molding, with different viscosity characteristics than prior hybrid molded material, several iterations were required to determine the slip preparation and mold filling parameters needed to achieve complete mold fill. These efforts were successful, as illustrated in Figure 1-10. However, subsequent drying and dewaxing of the rotors revealed the presence of cracking in the rotor hubs. Resolution of this problem via improvements of the forming and drying cycles was not achieved prior to the end of the contract.

The scroll fabrication efforts were directed to producing rectangular and circular cross-section configuration scrolls. The terms "rectangular" and "circular" refer to the shape of the flow path cross section.

Figure 1-10. Kyocera Hybrid Molded AGT-5 Rotor Processed Through Partial Densification

Although the circular cross-section geometry is preferred for aerodynamic performance, this design was considered more vulnerable to sintering distortion than the rectangular version. Thus, the initial efforts focused on the rectangular design to expedite component delivery.

AGT-5 rectangular cross-section scrolls were fabricated in one piece by drain casting from the SN252 composition. The gas inlet, outlet, and mounting surfaces were machined, but the majority of the part surfaces remained in the as-fired condition. No proof testing was performed on this part due to the difficulty in simulating the in-use thermally induced stress states. Parts were qualified via certification of co-processed test material, and fluorescent penetrant inspection (FPI) and radiographic inspections.

The desire for thin, uniform, void-free walls in this complex shape presented the initial processing challenge. Prevention of air entrapment during the casting process was key to successful fabrication, as the complex shape provided many locations for bubbles to lodge. Additionally, the thin walls were susceptible to collapsing during the casting process, and distortion during sintering. Finally, the overall complexity of the part, in conjunction with tight tolerances and the importance of the relative positions of the gas inlet, outlet, and support features, presented grinding set-up and dimensional inspection challenges.

These challenges were addressed by using a well controlled and understood slip, multiple-piece plaster molds, iteratively improved casting and draining techniques, and special fixtures for supporting the part in sintering and final grinding. Initially, yield was low (<20%), however, iterative improvements resulted in a yield of over 75%. Processing results from eight casting lots confirmed the attainment of the thin, uniform wall thickness from lot-to-lot, with total thickness variations of less than 0.020 in. (0.5 mm).

Only the gas inlet, outlet, and mounting surfaces of the part were ground. A successfully cast and machined part is illustrated in Figure 1-11. Four rectangular cross-section scrolls were completed and delivered.

In parallel with the fabrication of the rectangular cross-section scroll, KICC also developed the processes needed to fabricate scrolls of the circular configuration. With the support of Rolls-Royce Allison, KICC utilized polycarbonate mold patterns fabricated by selective laser sintering rapid prototyping. Patterns were provided to KICC by Rolls-Royce Allison based on component design data and shrinkage factors. The

Figure 1-11. Kyocera SN252 AGT-5 Rectangular Cross-Section Scroll

patterns were used to fabricate casting molds and provided a significant reduction in design-to-mold fabrication effort.

Scrolls were successfully cast and sintered, as shown in Figure 1-12. Two fully machined AGT-5 scrolls were delivered to Rolls-Royce Allison for rig testing.

Combustor liners were fabricated by drain casting SN282 material. Undersized dilution and cooling holes were green machined in the castings. After sintering, the holes and combustor liner inlet and outlet ports were all final ground. These parts were fabricated rather late in the program, after the drain casting methods for SN282 had matured, thus the combustor fabrication was completed in one processing lot. Four parts were completed and delivered. A finished combustor liner is illustrated in Figure 1-13.

Figure 1-12. Kyocera Cast and Sintered AGT-5 Circular Cross-Section Scroll

Figure 1-13. Kyocera SN282 Drain Cast Combustor Liner

1.9 Norton/TRW Ceramics

1.9.1 Objective/Approach

The ceramic component development efforts at Norton Advanced Ceramics (NAC) were directed towards two AGT-5 components: the gasifier turbine rotor and the turbine scroll. The turbine rotor activity focused on pressure slipcasting of NT154 and NT164 silicon nitride for both the 20- and 26-bladed gasifier turbine rotor configurations. The scroll development efforts addressed pressure slipcasting of NT230 siliconized silicon carbide. Development and optimization of the automated high pressure casting process was also conducted.

1.9.2 Accomplishments/Results

- Process parameters were established for processing of 20- and 26-bladed configuration gasifier turbine rotors.
- Nineteen rotors successfully passed proof spin test and were delivered to Rolls-Royce Allison for shaft assembly/engine testing.
- Six NT230 siliconized SiC turbine scrolls finish machined and delivered to Rolls-Royce Allison.
- Scroll casting trials on Dorst high pressure casting machine were successfully conducted.

1.9.3 Discussion

The initial development activities at NAC for the gasifier turbine rotor focused on the establishment of casting process parameters and optimization of the

NT154 Si_3N_4 slip system. Work was performed using a combination of exploratory screening experiments, including a Taguchi L8 experiment investigating mold design, drying conditions, powder treatment, and powder blend. Mold design was found to be the most significant factor for elimination of cracks in the rotor casting process. The removal of mold inserts between the blades proved to be a difficult problem to overcome. A large number of blade insert materials and insert coatings to aid release were screened. Limited success resulted from applying a release agent.

Upon verification of the proper shrinkage factor, a master pattern for the 20-bladed rotor configuration was procured and casting molds fabricated. Engine quality rotors were successfully cast after several mold iterations, according to the rotor process flow chart shown in Figure 1-14. A total of 12 pressure slipcast NT154 Si_3N_4 rotors were densified, finish machined, inspected, and proof spin tested. Seven of the rotors attained the proof spin speed of 80,000 rpm and were forwarded to Rolls-Royce Allison for assembly to metal shaft for subsequent rig/engine test evaluation.

Following the activities on the 20-blade NT154 rotors, efforts were transitioned to fabrication of 20-blade NT164 rotors. The NT164 Si_3N_4 is a more refractory material with superior elevated temperature strength and stress rupture properties. Drawing heavily on the experience gained in the NT154 rotor activities, 19 NT164 rotors were cast. Of these, 15 passed visual inspection and were dried, presintered, passed X-ray inspection, and were HIP densified. Five of the rotors were sent to spin testing, with all five achieving the proof spin speed goal of 80,000 rpm.

Efforts were also conducted on fabrication of NT154 26-blade configuration rotors, which had improved aerodynamic performance. A stainless steel casting pattern was fabricated and casting molds identical to those used for the 20-blade rotor castings prepared. Following initial casting activities to identify dimensional accuracy and casting behavior, fabrication of 26-blade engine rotors was conducted. A total of 34 rotors were cast in this effort, with 18 rotors passing postcasting inspection and were dried, presintered, inspected, and qualified for densification. Ten acceptable quality rotors were successfully machined and subsequently spin tested, with 8 of the rotors attaining the design proof speed of 80,000 rpm.

The development and fabrication of AGT-5 scrolls was also addressed at NAC. Two major tasks were automated pressure slipcasting development and scroll fabrication for rig/engine test activities. The material selected for this effort was NT230 SiC, a reaction sintered SiC with a bimodal distribution of silicon carbide grains in a matrix of metallic silicon. Compositionally, NT230 SiC contains approximately 10% silicon, along with extremely low levels of trace impurities. By modification of the grain size distribution and selective changes to the fabrication process, NAC was able to essentially double the strength of existing siliconized SiC compositions. The material is also ideally suited for scroll fabrication due to the minimal shrinkage (1-2%) upon densification.

The automated pressure slipcasting task was directed at development of semi-automatic forming procedures for scroll components as a means of reducing costs at high volume production levels. NAC selected pressure slipcasting as the preferred forming method for scrolls and acquired a Dorst semi-automatic pressure casting machine and porous plastic mold technology.

Optimization of the slip formulation was directed toward development and characterization of various slip additives. The additives were evaluated regarding their improvement in the strength and fracture toughness of as-cast components. For the slips with additives, the wet green strength of as-cast scrolls was significantly greater than standard mix NT230 components. The additive appears to enhance the Weibull modulus of NT230 SiC with a marginal increase in fracture toughness with no impact on strength. Based on the positive results from the scroll casting trials, the NT230 slip formulation for casting scrolls on the Dorst equipment was fixed using the casting additive.

Norton activities also included development and characterization of various porous plastic mold

Figure 1-14. Norton Advanced Ceramics Process Flow Chart for Rotor Pressure Slipcasting

materials, plastic formulations, and mold fabrication processing conditions. The Dorst/Laufen porous plastic mold material was selected for development and testing efforts.

Two porous plastic scroll body mold design iterations were evaluated on the Dorst casting machine. The first iteration design was a seven-piece mold utilizing a four-stage demolding cycle, shown in Figure 1-15.

Figure 1-15. Norton Turbine Scroll Mold on Dorst Automated Pressure Slipcasting Machine

Concurrent with the slip and plastic mold development activities, NAC conducted work on fabrication of NT230 AGT-5 scrolls to satisfy rig/engine test requirements. A first iteration porous plaster mold was designed and fabricated utilizing six mold segments and two endcaps with internal cores. The initial scroll castings cracked during demolding due to several mold segments that were observed to lock up on the casting. This problem was eliminated in subsequent trials after the casting pattern and setup boards were modified to incorporate additional draft angles. A total of five batches of AGT-5 scrolls were cast following the casting development efforts. The overall casting yield of acceptable quality parts was 78%. A total of four finish machined scrolls were delivered to Rolls-Royce Allison to support rig and engine testing and evaluation.

2. CERAMIC COMPONENTS

This section presents an overall summary of the ceramic component design, analysis, development, and test activities associated with both the ATTAP and HVTE-TS projects. These activities were conducted during 1987 through 1998. Additional detailed discussion of the ceramic component activities is available in the annual reports, design reports, and technical papers listed in Section 8, Bibliography.

There is a background of over 30 years of R&D of ceramics in gas turbine engines. Successful short-term operation of engines with ceramic components—combustors, vanes, blades, rotors, and various other components—has been demonstrated. Sophisticated analysis methods have been coupled with statistical characterization of material properties for a probabilistic approach in the design of these ceramic components.

Structural ceramics offer the potential for significant improvement in gas turbine engine performance. The Small Engine Components Technology Studies^{1*} (SECTS) show that the use of ceramic holds more promise than any other single technology improvement. The U.S. Government, through various agencies, has provided funding/support to pursue this potential. For defense-related uses, the funding agency for many projects has been the Defense Advanced Research Projects Agency (DARPA).

Concentrated work on the application of ceramics to civil transportation engines began in 1976 with a Heavy Duty Gas Turbine Engine (HDGTE) study followed in 1978 by the Ceramic Application in Turbine Engines (CATE) program,² and in 1979 by the Advanced Gas Turbine (AGT) program. The ATTAP and HVTE-TS programs followed the AGT program and continued the development of structural ceramic components for turbine engines. These development programs for non-military use were sponsored by the DoE Office of Transportation Systems, later Office of Transportation Technologies.

The test-bed engine utilized in the ATTAP and HVTE-TS programs was the AGT-5, an engine designed as a primary power source for automotive application. The engine, which incorporates three axial flow turbine stages, was rated at about 200 hp (150 kW) at 2500°F (1371°C) turbine inlet temperature when ceramic hot section components are utilized.

* References are identified in Section 9.

2.1 Objective/Approach

The objective of this task was to design, develop, and demonstrate the technology of structural ceramics that have the potential for competitive automotive engine performance, life cycle cost, and reliability. All design activities included thermal and structural analyses utilizing 2-D and/or 3-D finite element modeling (FEM). Probability of survival (POS) was calculated for all ceramic components and compared to design goals assigned to each component. Design configurations were revised when required to achieve design POS. Extensive interaction with ceramic vendors took place during the design process to ensure successful fabrication of the ceramic components.

Specific project objectives included:

- Design an all ceramic gasifier turbine assembly capable of operating at reference powertrain design (RPD) (2500°F [1371°C]) conditions.
- Design a hybrid ceramic/metallic gasifier turbine assembly to operate at intermediate temperature (2200°F [1204°C]). This allowed testing of ceramic gasifier turbine rotors with a hybrid ceramic/metallic gasifier turbine static structure.
- Design (aerodynamic and structural) a power turbine assembly that would allow operation of the ceramic gasifier turbine components at RPD operating conditions in an engine environment.

2.2 Accomplishments/Results

Significant results were achieved with ceramic component design and development during the ATTAP/HVTE-TS programs. These efforts culminated in components that performed as designed in proof, rig, and engine tests. Activities that led to these accomplishments include:

- Established design guidelines, engine cycle parameters, reliability goals, and mechanical specifications for RPD AGT-5 test-bed engine.
- Completed design, thermal and stress analyses for several gasifier turbine static structure assemblies. This included evaluation of alternate material systems and configuration revisions to accommodate different methods of component fabrication. Design goal POS was achieved with silicon carbide and/or silicon nitride materials for each component.

- Completed design and analyses of 15-, 20-, and 26-bladed ceramic gasifier turbine rotors. Design goal POS was achieved with several silicon nitride material systems and methods of fabrication. Analyses showed that silicon carbide rotors would not survive the transient start-up/acceleration cycle described in the analyses. Engine test of one silicon carbide rotor confirmed that result when the rotor failed during its initial start-up cycle. Several rotor design configurations were evaluated in an effort to improve POS. No acceptable solution was found. Silicon carbide material characteristics (high modulus of elasticity, relatively high coefficient of thermal expansion, and low strength when compared to silicon nitride) combine to yield these results.
- Completed design and analyses of ceramic first- and second-stage rotors for the power turbine. Design goal POS was achieved with a developed silicon nitride material for the first-stage rotor. A new higher strength, lower temperature capability silicon nitride material was utilized in the second-stage rotor to obtain design goal POS. Both rotors were successfully tested in the engine.
- General Motors began developing a ceramic turbine rotor/metallic shaft attachment scheme prior to the ATTAP program. This design activity continued during ATTAP and included adaptation of the design concept to the power turbine rotors. Additional analyses were performed and a precise assembly procedure for the power turbine rotors was defined. This joint concept was utilized in all ceramic gasifier and power turbine rotor assemblies tested. The attachment(s) performed satisfactorily when the joint operating temperature did not exceed design limits (about 1000°F [538°C]).
- Completed design and analyses of hybrid ceramic/metallic power turbine static structure. The static structure incorporated a ceramic blade tip shroud ring over each turbine rotor and an air-cooled metallic first-stage nozzle assembly. This static structure was tested with the ceramic power turbine rotors in a complete engine assembly.

2.3 Progress/Status/Remaining Work

Progress during the ATTAP/HVTE-TS programs and work remaining to be accomplished is reported in two categories: (1) activity specific to the AGT-5 test-bed hot rig and engine, and (2) activity applicable to the development of structural ceramic components for engines of the same general size. Such development could lead to the application of ceramic components in larger engines.

ATTAP AGT-5 Test-Bed Hot Rig and Engine

- Good performance relative to foreign object damage (FOD) resistance and survivability in hot rig and engine environments has been achieved with the 15- and 20-blade silicon nitride gasifier turbine rotors. Many hours of operation have been accumulated on the 20-blade rotors, demonstrating that blades with 0.028 in. (0.71 mm) trailing edge thickness have acceptable resistance to FOD. Successful short time proof testing of one 26-blade rotor with a blade trailing edge thickness of 0.022 in. (0.56 mm) was accomplished during the program.
- One ceramic two-stage power turbine rotor assembly was tested in the AGT-5 engine. After several hours of testing, a failure occurred that destroyed the rotor assembly. While a failure scenario was not established, the power turbine failure probably was secondary to a failure upstream in the engine.

Structural Ceramics for Automotive Gas Turbine Engines

- Ceramic integrally bladed rotors, individual vane airfoils, blade tip shroud rings, vane platforms, and seal rings were produced with high dimensional accuracy during the ATTAP/HVTE-TS programs. Ceramic gasifier turbine scroll bodies and combustor bodies were produced with some dimensional deviations, mostly on their interior surfaces. In general, all these components were fabricated in one piece (no joints). An exception was reaction bonded silicon carbide scroll bodies, some of which incorporated joints that performed satisfactorily. Unsatisfactory performance was the norm with any silicon nitride component incorporating a joint. RPD engine design goal life could not be achieved without a ceramic or air-cooled metallic first-stage power turbine vane. An air-cooled metallic vane was not feasible because of performance penalties and cost. The ceramic

power turbine vane design incorporated vanes encased in outer and inner shroud rings. Such a part would be very difficult if not impossible to fabricate in one piece. Even if fabricated successfully, survival in an engine environment would be questionable. Joint technology, which would allow fabrication of this silicon nitride component into individual vane segments to be later joined together, was not developed during this program.

- The aerodynamic performance of the ceramic advanced concept design gasifier turbine scroll was inconsistent, sample to sample, because of dimensional deviations of interior surfaces of the components. This was the result of forming the scroll's exterior surface in a mold and having an inconsistent wall thickness.

Remaining Work

Additional testing of "on hand" ceramic components in a developed test-bed engine would enhance the success of future ceramic component development programs. This effort would include:

- Several 26-blade gasifier turbine rotors remain in inventory. These rotors should be exposed to extended durability testing to determine if the thinner trailing edge will survive in the engine environment. Turbine performance would be enhanced if the 0.022 in. (0.56 mm) trailing edge thickness could be adapted to the 20 (or fewer) blade rotor design.

- Several first- and second-stage power turbine rotors remain available for test. The blades on each of these rotors have a trailing edge thickness of 0.026 in. (0.66 mm). Additional testing of these rotors would provide valuable data regarding performance of these rotors in an engine environment in general and especially blade trailing edge thickness versus tolerance to foreign object damage.
- Several advanced design high quality ceramic static structure components remain available for test including gasifier turbine scroll assemblies and combustor bodies. (Ceramic combustor design and test efforts are reported in other sections of this report.)

Remaining work associated with the design and development of structural ceramic components would include:

- Ceramic-ceramic joint technology should be developed to enhance ceramic component design for application to advanced turbine engines.
- Improved gasifier scroll aerodynamic performance is obtainable using a multi-piece design where the interior surfaces are accurately molded and positioned relative to each other. Such a component could be held together by mechanical attachment or joined during fabrication from the joining technology developed above.
- A ceramic first-stage power turbine inlet vane set should be designed and developed.

2.4 Ceramic Component Design

2.4.1 Design Methodology

The inherent characteristics of ceramic materials differ sufficiently from metallic structural materials to require special attention at all phases of the design effort. In most cases, specifically different practices are necessary.

The need for change in design practice is not a new phenomenon to gas turbine engine experience. Materials use has continually progressed to lower ductility levels through the incorporation of high-strength steel alloys, superalloys, and high-strength titanium. The necessary changes in design methodology have addressed refined criteria definitions, improved fatigue characterization through finite element modeling and combined loading conditions, use of fracture mechanics technology, and application of probability and/or reliability practices. The advent of

structural ceramic materials, therefore, represents a logical extension of these changes in the design disciplines required for gas turbine components.

Probabilistic (as opposed to deterministic) design analysis is required for each ceramic turbine component. Finite element models, either two or three dimensional, are generally required to adequately calculate the temperature and stress distributions necessary for assessing component reliability (probability of survival) at critical operating conditions. In the Rolls-Royce Allison ATTAP program, the engine utilized as a test-bed for ceramic component development was designed to be a primary power source for an automobile. A primary power source must operate over a broad range of power settings and have a very rapid response to changes in power level demand. Normally, for this type of engine, the critical operating condition occurs during rapid transient engine operation, either an acceleration from low to high power

or a rapid deceleration from high to low power. Thermal stresses, due to temperature gradients within the components, are most severe during this period. Input data for the design analysis are derived from the engine duty cycle, material characteristics, reliability requirements, and proof-test definition.

A schematic diagram of the ceramic component design/analysis process is shown in Figure 2-1. Thermal, aerodynamic, and mechanical loads for steady-state and transient operation in both test rig and engine environments must be considered. Proof-test requirements are determined for each component. Proof-test failures can be predicted and correlated with component operational reliability. The material properties necessary for these analyses are continually being updated through material testing. In addition, new advanced materials that improve component reliability and/or improve engine performance by permitting operation at higher engine cycle temperatures are periodically introduced. Also, component data obtained from test rig and engine tests have been fed back through the analytic models for correlation of the analytic techniques. This feedback provides improved analytic predictive capability for evaluation of subsequent geometric configurations and/or the impact of changes in environmental conditions.

The development of design requirements and a conceptual design were two of the initial efforts undertaken when designing the ceramic engine components. For the ATTAP program, the overall

engine design requirements that impact durability of ceramic (and metallic) components were as follows:

- Duty cycle, 100,000 miles (160,000 kilometers) durability of which 55,000 miles (88,000 kilometers) is on an urban cycle and the remainder (45,000 miles [72,000 kilometers]) is on highway operation
- 3,500 hr life
- 12,000 starts
- 33,600 low cycle fatigue (LCF) cycles
- Gasifier turbine peak inlet temperature 2500°F (1371°C)
- Rotor containment at maximum burst speeds
- Meet automotive environmental, maneuver, and attitude requirements
- Reliability goals have less than 0.25 major engine system failure in 100,000 miles (160,000 kilometers) of operation
- Impact of automotive fabrication processes on design configuration of components

Other requirements such as aerodynamic performance, cost, and emissions goals were important but did not directly impact the probability of survival of the ceramic components.

In the context of ceramic design methodology, operating conditions are those that define worst case conditions to which the component might be exposed in service. The maximum power steady state engine operating condition is one such condition to be analyzed. Transient operating conditions, such as a cold start-up to maximum power or a rapid reduction in power, are examples of other conditions to be considered. In real life service, an automotive engine might be started and accelerated to high power in a few seconds in an emergency or at the whim of an aggressive driver. In ATTAP, analysis showed that for the regenerative automotive turbine engine, rapid deceleration was not as severe as a cold start-up because of the heat stored in the regenerator(s). In a nonregenerative turbine engine, a rapid reduction in power might produce very high stresses in hot section components. A thorough understanding of the conditions (including time at condition) under which the engine and ceramic components will operate in service is necessary so that appropriate "design" operating conditions can be defined for analysis purposes.

Analysis of proof test(s) performed on ceramic components must also be completed to (1) validate the

Figure 2-1. Ceramic Component Development Cycle

test as an appropriate screening tool for inspecting parts and (2) to ensure that the proof test does not create unrealistically high stresses in the component.

For ATTAP, the turbine rotor components were analyzed for (1) cold spin conditions (proof test), (2) maximum power steady state, and (3) a very rapid cold start to idle to maximum power transient. The latter condition resulted in the lowest probability of survival (POS) for the turbine rotor. For the ceramic combustor body, the least POS was computed for the maximum power steady state condition.

The overall engine specification establishes the reliability goal for the complete engine assembly. In ATTAP, that goal was that three of four engines would reach 100,000 miles (160,000 kilometers) (3500 hr.) without a major engine failure. To determine the reliability goal(s) for the ceramic components, the engine assembly was examined to determine the total number of failure sites for all components (metallic and ceramic). For the ATTAP test-bed engine (AGT-5), that total was about 500 sites. Thus, the design (POS) for each failure site was $(0.75)^{1/500} = 0.999425$. If a turbine rotor with 20 blades contained 42 failure sites, its overall required POS would be $(0.999425)^{42} = 0.97612$. This POS was the design goal for the 20-blade gasifier turbine rotor(s) in the ATTAP program. The POS goal for other ceramic components was determined in a like manner with each component having a unique goal determined by the number of failure sites in that component. Since the analysis utilized was for fast fracture, it was implied that component failure might occur at first start-up at the same rate as at the end of engine life. Clearly this was not acceptable. However, actual assembly line reliability requirements are closely held data and were not available to this program. Additionally, long term material strength/stress rupture data were not available to enable a comparison of POS for low and high time parts. The design POS of a component can be significantly enhanced by utilizing an appropriate proof test during component manufacture.

The method(s) of component fabrication must be considered during the design process because it may effect: (1) the material characteristics (strength, etc.), (2) the configuration of the part (volume or shape, minimum or maximum material thickness), (3) the dimensional accuracy of the part, and (4) the amount of finish machining required.

2.4.2 Design Analysis

The inherent characteristics of ceramic materials are sufficiently different from metallic structural materials to require special attention at all phases of the design process. Probabilistic analysis is utilized for each ceramic turbine component. Finite element models, two or three dimensional (in the case of a turbine rotor design, both), are generally required to adequately calculate the temperature, deflection, and stress distributions necessary for assessing component reliability. Analyses are conducted at operating conditions considered to be most severe for each component. In the primary power source engine utilized in ATTAP, the minimum calculated POS for ceramic components usually occurred during a severe start-up to maximum power transient. The POS was calculated based on Weibull's weakest-link theory as described in Reference 3. An analysis program that calculates deflections and stress distributions (such as CARES described in Reference 4) can be utilized to determine the POS for ceramic components. For the analysis, input data are derived from the engine duty cycle, material characteristics, reliability requirements, and proof test definition.

An example of the thermal analysis results for a three-dimensional model of a ceramic turbine rotor is shown in Figure 2-2. Examples of three-dimensional stress analysis results for a ceramic rotor and airfoil are shown in Figures 2-3 and 2-4.

Figure 2-2. Calculated Thermal Gradient Utilizing Three-Dimensional Turbine Rotor Model

Figure 2-3. Calculated Maximum Principal Stress Distribution Utilizing Three-Dimensional Turbine Rotor Model

Figure 2-4. Calculated Maximum Principal Stress Distribution in Turbine Rotor Blade, Opposite Side of Blade Shown in Figure 2-3.

The stress field distributions in the ceramic component are utilized to calculate the POS of the component. This calculation requires material characteristic strength data. Should the calculated POS be lower than the design requirement, adjustments are made to the component design to reduce stress or improve material strength characteristics by improved surface finish or heat treatment.

To execute the design analysis, an extensive material database is required for each material evaluated. Materials vary in characteristics with different

fabrication and machining methods. Two parameter Weibull characterization of the materials is utilized in the probability analysis.

Analyses were conducted with fast fracture material strength data. Long-term strength data was not available and, therefore, were not used in a systematic analysis of ceramic component life.

2.4.3 Gasifier Turbine Rotor Design

The approach to the design of the integral blade/disk ceramic turbine rotor is an iterative process involving the following parameters:

- Operating temperature and speed
- Aerodynamic performance
- Blade configuration suitable for manufacture
- Blade trailing edge thickness/blockage/no. of blades/ FOD
- Blade natural frequency
- Rotor material selection
- Rotor disk natural frequency (26-blade rotors)
- Rotor attachment configuration
- Probability of survival/worst case condition(s)

The first gasifier rotor designed for ATTAP incorporated 15 blades. The aerodynamic design of the airfoil was revised to be appropriate to the ATTAP RPD engine cycle conditions (2500°F [1371°C] RIT). This rotor had very robust blades and required additional axial length in the turbine gas path.

A 20-blade gasifier rotor design was fabricated by several vendors in a variety of silicon nitride materials. Very positive test results were obtained with several of the 20-blade rotors. One rotor accumulated over 1000 hr of testing and was retired in good condition. Another 20-blade rotor completed a 300-hr endurance test during which it was exposed to many, many start-ups, accelerations, decelerations, short cruise periods, and shutdowns. This same rotor was later utilized in additional test programs.

Significant increases in strength and fracture toughness of the silicon nitride materials occurred during the period of and following the completion of the 20-blade rotor design and fabrication. Fabrication processes were also being improved during this period resulting in high quality rotors. The success of the 20-blade rotor, demonstrating that a blade trailing edge thickness of 0.028 in. could survive in an engine environment, led to the final gasifier turbine rotor design in the ATTAP program. This final rotor design, with 26 blades, had an

airfoil trailing edge thickness of 0.022 in. (0.56 mm). As before, the airfoil design was scaled from the 15 and 20-blade designs and has the same aerodynamic blockage, but with 23% less total blade load on the rotor disk and a 30% increase in aspect ratio when compared to the 20-blade rotor. The choice of 0.022 in. (0.56 mm) thickness for this rotor design, as opposed to 0.024 in. (0.61 mm), was made in an effort to determine the minimum allowable trailing edge thickness with regard to FOD in the engine environment. An additional consideration was that both ATTAP AGT-5 ceramic power turbine rotors were designed with 0.026 in. (0.66 mm) thick blade trailing edges. (The power turbine rotors were designed prior to the 26-blade gasifier turbine rotor.)

Rotors with 26 blades were fabricated by three vendors in three different silicon nitride materials: CM200, NT154, and SN252. While the blade airfoil designs were the same for all the 26-blade rotors, the rotor disk designs were tailored to the strength characteristics of each material. The NT154 and SN252 rotor disks were essentially identical while the CM200 disk was thicker (reflecting the lower strength of CM200) as shown in Figure 2-5. Analysis of the 26-blade rotor designs included the calculation of disk natural frequencies as well as blade natural frequencies. Each 26-blade rotor design satisfied Rolls-Royce Allison turbine rotor dynamic criteria. The natural frequencies of the thicker (more rigid) 15- and 20-blade rotor disks were higher than those of the 26-blade rotors and were not a concern in this engine design.

Figure 2-5. Comparison of Optimum Disk Shapes for Different Silicon Nitride Materials

2.4.4 Power Turbine Rotor Design

As for the gasifier turbine rotor, the approach to the design of the integral blade/disk ceramic power turbine rotors was an iterative process involving the following parameters:

- Operating temperature and speed
- Aerodynamic performance
- Blade configuration suitable for manufacture
- Blade trailing edge thickness/blockage/number of blades/ FOD
- Blade natural frequency
- Rotor material selection
- Rotor attachment configuration
- Probability of survival/worst case condition(s)

The design output power of the power turbine in the ATTAP test-bed engine was about 1.75 times that of the power turbine in the all-metallic baseline engine. This was made possible by the increased rotor inlet gas temperature (from about 1650°F [900°C] to about 2150°F [1177°C]), the increased expansion ratio across the power turbine stages (from about 1.9 to about 2.4), and an increase in gas flow rate. Clearly the first-stage rotor of the power turbine must be of ceramic material because of the gas temperature.

A study was conducted to determine if the second-stage rotor could remain metallic to reduce the design complexity of the power turbine rotor assembly. Preliminary stress calculations performed on the proposed metal second-stage rotor design showed it to have insufficient life at "RPD" conditions. Hence the second-stage rotor also would be ceramic. A major concern in making the second-stage rotor of ceramic material was that the rotor likely would have a bore through the center of the disk for assembly purposes. Rotor disk stress is increased significantly when a hole exists in the disk.

Three different power turbine aerodynamic designs were evaluated. A design incorporating a conventional first-stage vane was chosen for the ATTAP test-bed engine because of better predicted performance. Ideally, the first-stage vane should be of ceramic material because of the gas temperature.

Establishing the rotor blade trailing edge thickness was a major element of the power turbine aerodynamic design. A blade trailing edge thickness of 0.026 in. (0.66 mm) was chosen following the successful test experience with 0.028 in. (0.71 mm) trailing edge thickness on gasifier turbine rotors and a desire to extend ceramic blade technology a moderate amount.

Power turbine rotor speed was another major design element to be determined. Preliminary calculations showed the maximum allowable speed of the ceramic power turbine rotor to be about 62,000 rpm. A design speed of 57,000 rpm was chosen to satisfy aerodynamic design criteria at full power and to also have good off design performance at cruise power (reduced rotor speed).

These two design parameters combined with Rolls-Royce Allison turbine aerodynamic design practice established the ATTAP ceramic power turbine design. The ceramic first-stage rotor has 28 blades surrounding a solid rotor disk with an integral hollow stub shaft to which a metallic shaft is attached. The ceramic second-stage rotor has 26 blades surrounding a rotor disk with a center bore. The gas path hub (inside) diameters of the two rotors are nearly identical, with the first-stage rotor slightly larger. The hub diameters were sized to provide a smooth gas path into the turbine exhaust gas duct that surrounds the insulation blanket on the power turbine bearing housing. Figure 2-6 shows a cross section of the two-stage power turbine rotor assembly.

The power turbine first-stage rotor was made of Kyocera's SN252 silicon nitride material, the same material as was used for the gasifier turbine rotor. The rotor is similar to the gasifier turbine rotor in configuration, but larger and with the stub shaft extended in length. Finite element analyses showed the rotor to exceed design goal POS (0.9853) at maximum power were steady-state and at the worst case condition during a start-up transient. The maximum power steady-state temperature profile (Figure 2-7) displays the effect of the long ceramic shaft. It functions as a heat-dam which creates a steep temperature gradient at the base of the shaft and reduces the thermal gradients in the rotor disk. A maximum principal stress of 27.7 ksi (191 MPa) was calculated for the first-stage rotor

during steady-state operation with a corresponding POS of 0.9996. (see Figure 2-7). The temperature profile for the lowest POS during the start-up transient is shown in Figure 2-8. It occurs 36 seconds after the cold start is initiated. In this case, temperature gradients are higher in the web region of the rotor than in the base of the shaft. The maximum principal stress (see Figure 2-8) produced by this temperature pattern is 40.6 ksi (280 MPa), and the POS is 0.9918.

The operating temperature of the power turbine second-stage rotor is lower than that of the first-stage rotor, but the stresses are higher because of greater blade mass and the presence of the large bore in the center of the disk.

Temperature and stress distributions and POS for the second-stage rotor operating at maximum power steady-state condition are shown in Figure 2-9, and for the worst case transient condition in Figure 2-10. The power turbine second-stage rotors were fabricated of SN235 silicon nitride material.

Good performance had been demonstrated with the gasifier turbine rotor ceramic to metal shaft attachment scheme. That attachment scheme was duplicated in the design of the power turbine rotor/shaft joints with the diameter of the joints adjusted to facilitate the power turbine rotor assembly requirements (see Figure 2-6).

2.4.5 Gasifier Turbine Static Structure - Scrolls

ATTAP AGT-5 engine cycle conditions require that the collector/scroll component that joins the combustor to the gasifier turbine be designed to accommodate 2500°F (1371°C) gas at about 5 atmospheres pressure. This component also provides a close fitting shroud over the gasifier turbine rotor blade tips. Guidelines established to facilitate ceramic static structure design were the following:

- Minimize heat transfer from ceramic components to connecting (metal) engine structure (minimizes thermal stress in ceramic components).
- Minimize constraints on ceramic components to allow free relative movement during engine operation.
- Maintain maximum control of shroud-to-rotor concentricity.
- Minimize radial flanges in ceramic components that would be subject to radial thermal gradients.
- Establish assembly procedure that minimizes exposure of ceramic components to accidental damage during engine assembly.
- Interact with ceramic vendor to ensure successful fabrication of components.

Figure 2-6. Cross-Section View of Two-Stage Power Turbine Rotor Assembly

Figure 2-7. Temperature and Maximum Principal Stress Distributions in First-Stage Power Turbine Rotor at Maximum Power Steady State Condition

Figure 2-8. Temperature and Maximum Principal Stress Distributions in First-Stage Power Turbine Rotor for Lowest POS During Start-Up Transient

Figure 2-9. Temperature and Maximum Principal Stress Distributions in Second-Stage Power Turbine Rotor at Maximum Power Steady State Condition

Figure 2-10. Second-Stage Power Turbine Operating at Worst Case Transient Condition

The configuration of the ceramic components was restricted by the then current fabrication technologies. Figure 2-11 shows an initial gasifier turbine scroll design concept. Consultation with a candidate vendor revealed that forming the "T" section at the inside diameter of the part would be very difficult with the vendor's slip cast process. The design concept was revised to eliminate the "T" feature and make the part in two pieces which would be held together mechanically. This design concept is shown in Figure 2-12.

The simple vane platform configuration could be fabricated by die pressing or by machining a billet. The two-piece concept became even more attractive when analyses showed that a scroll fabricated of silicon carbide (as shown in Figure 2-11) would not survive,

Figure 2-11. One-Piece Scroll Configuration with 'T' Section Mount Flange

Figure 2-12. Two-Piece Scroll/Vane Platform Design Configuration

whereas if configured as shown in Figure 2-12, it would survive. The two-piece design reduced the thermally induced stress in the flange region of the scroll to an acceptable level. Scroll components were fabricated of silicon carbide and silicon nitride materials. Vane platform components were fabricated of several silicon nitride material systems. Fourteen individual ceramic vanes were included in this assembly. They were inserted through slots in the scroll body and positioned in vane shaped pockets in the vane platform. A vane retaining ring detail that incorporates an air seal ring groove retains the individual vanes in this scroll assembly as shown in Figure 2-13.

The vane retaining rings were fabricated of silicon carbide and silicon nitride materials and were used on scrolls of the same material to maintain proper fit of the ring on the scroll at operating temperature. A compliant layer made of Nextel™ fiber was wrapped around the scroll, over the outer end of the vanes, to seal the cavity above the vanes and dampen vibration of the vanes. The vane retaining ring covers the compliant layer. The compliant layer is shown cross-hatched in Figure 2-14. Several samples of this gasifier turbine static structure design were tested during the ATTAP program. The design of the nozzle vanes used in this assembly is discussed in a following section.

A study was conducted to evaluate alternate ceramic material systems as candidate materials for the gasifier turbine static structure. One material system was aluminum titanate/alumina. This material has lower strength than silicon carbide and a low thermal expansion characteristic similar to that of the ceramic materials used in regenerator disks. Analyses showed a scroll fabricated of aluminum titanate/alumina would

Figure 2-13. Gasifier Turbine Scroll Design

* Nextel is a trademark of 3M.

Figure 2-14. Gasifier Turbine Ceramic Assembly

have a very low probability of survival (POS) due to the combination of low material strength and high stresses concentrated around the vane slots. If the vane slots did not exist in the scroll, the POS exceeded design goal at maximum power operating condition and improved to about 0.5 during the startup transient cycle.

To further investigate a scroll design without vane slots, the design configuration shown in Figure 2-15 was modeled and analyzed with several material systems.

Figure 2-15. Modified Scroll Design for Use with One-Piece Integral Vane Platform

This design configuration was attractive because (1) it permitted the use of an expanded number of materials for the scroll, and (2) the overall cost of the scroll assembly was potentially reduced because the individual vanes, vane slots, and vane pockets were eliminated and replaced by a one-piece platform with integral vanes. The analysis included a study to determine what minimum clearance could be maintained between the vane tips and surrounding scroll for various material combinations. A clearance as small as 0.002 in. (0.05 mm) was possible when both the scroll and the vane platform were fabricated of silicon nitride. An advanced concept design scroll with even greater cost reduction potential was developed.

The features that make the advanced concept scroll design attractive include:

- One-piece construction, excluding the mount flange detail
- Integrated seal ring groove
- Low stress in scroll body allowing broad choice of materials for scroll body
- Mount system thermally isolating scroll body from metallic engine structure

The mount system utilized with this scroll assembly is shown in cross section in Figure 2-16.

The separate ceramic mount ring was made of silicon nitride to withstand the relatively high stress in the part caused by the thermal gradient in the part. The mount

Figure 2-16. Advanced Concept Design Scroll Mount System (Separate Scroll and Mount Ring)

ring cross-keyed to the scroll body and also to the metallic engine structure to accommodate relative thermal growth of the components and still maintain concentricity between the scroll blade tip shroud and the turbine rotor blade tips. The crosskey features on the mount ring are shown in Figure 2-17. Insulating elements were included in the mount assembly to impede heat flow from the scroll body to the engine structure. Figure 2-16 also shows the integral seal ring groove on the outside of the shroud portion of the scroll body. The calculated POS for all the ceramic components in this turbine static structure assembly exceeded design requirements. Significant interaction with the fabricating vendor took place during the design activity to ensure successful fabrication of the scroll and its associated parts. The scroll body components initially produced were made of NT230 siliconized silicon carbide.

Advanced concept design scroll components subsequently were fabricated of SN252 silicon nitride material by Kyocera. Kyocera's then current drain cast technology allowed for the forming of a "T" configuration mounting flange similar to that shown in Figure 2-11. The use of high strength silicon nitride material for the scroll component allowed for the mount flange to be integral with the scroll body. This would not be possible with silicon carbide material because of too high thermally induced stresses.

The integral flange feature simplified fabrication of the scroll component by eliminating (machining) the cross-key features that locate the separate mount flange in the scroll body. The crosskey features that locate the mount flange to the metallic engine structure remain as described in the previous paragraph. However, Kyocera preferred that the cross section of the flow path through the scroll be rectangular rather than

circular as in the silicon carbide scroll described previously. The "flat" sided scroll was easier to support during the sintering process. This decreased distortion in the part during the sintering process. (The wall thickness of the silicon nitride scroll was less than that of the similar silicon carbide scroll. Hence the silicon nitride scroll was less rigid in the green state.) The scroll design was modified to accommodate this fabrication requirement. Several samples of the silicon nitride rectangular cross-section scroll were fabricated and rig and engine tested with good results (including the successful 300-hr cyclic endurance test).

The rectangular cross section in the scroll causes increased pressure loss compared to one with a circular cross section. Therefore development of scrolls with circular cross-section flow paths was initiated. Late in the HVTE-TS program silicon nitride advanced concept design scrolls with a circular cross section were successfully fabricated. This was made possible through continued development of the vendor's drain cast process and advanced methods of supporting the part during the sintering process. These components were not received in time to be included in rig or engine tests.

2.4.6 Ceramic Gasifier Turbine Vane Design

The first ceramic gasifier turbine static structure (scroll/nozzle assembly) designed for the ATTAP program incorporated 14 individual vane details. Each vane was inserted through a slot in the scroll body and positioned in a pocket in the vane platform detail as shown in Figure 2-14. The vanes were retained by a ceramic retaining ring that fits over the scroll body. Radial looseness of the vanes was minimized by wrapping Nextel™ ceramic fiber material over the tips of the vanes with enough thickness so the ceramic fiber wrap was squeezed inside the vane retaining ring as shown (cross hatched) in Figure 2-14. The transition portion of the scroll body induces initial whirl into the turbine gas ahead of the vanes. The vanes turn the gas an additional 30 deg or so to direct the flow to the gasifier turbine rotor. The vanes were relatively flat (straight) and fewer in number (14) than in a turbine without a scroll type inlet transition.

The initial thermal and stress analysis conducted with the FEM model shown in Figure 2-18 assumed gas flow with a uniform temperature and velocity profile impinging on the vanes. Both alpha silicon carbide and PY6 silicon nitride materials were evaluated. The calculated POS for silicon carbide vanes exceeded design requirements. The PY6 vanes met design goal POS only if the material strength characteristics were

Figure 2-17. View of Advanced Concept Design Scroll and Separate Mount Ring

Figure 2-18. Three-Dimensional Finite Element Model for Ceramic Gasifier Turbine Vane

adjusted to have higher "machined" strength along the trailing edge of the vane. It was planned to use vanes with "as cast" surface finish. Utilizing machined strength properties implied that the as cast surface along the trailing edge had to be polished to remove the rough surface texture. Vanes fabricated of both materials were obtained for test.

The PY6 vanes exhibited cracks at the trailing edge after exposure to cyclic endurance testing. Material examination revealed the cracks were caused by high stress rather than material defects. This suggested that the boundary conditions utilized in the design analyses were not representative of the actual engine operating environment. Data describing the temperature/velocity profile entering the vane row were not available for this engine combustor/turbine assembly. This was the reason for using a uniform profile in the design analyses. Turbine engine combustor systems often exhibit nonuniform exit temperature and/or velocity profiles. Nonuniform temperature profile can be caused by uneven fuel distribution, cooling air distribution in the combustor, and leakage between the combustor outlet and the turbine nozzle assembly.

To evaluate the effect of a radial and tangential temperature profile on the POS of the ceramic vanes, an analytical profile was developed from other engine experience for maximum power turbine inlet condition and also an over-temperature condition such as exists during an acceleration. An over-temperature condition was not evaluated in the original design analysis.

Calculations were made using the more severe temperature profiles to determine the minimum POS for vanes made of the two materials previously evaluated and two additional silicon nitride materials, NT154 and SN252. Maximum material temperature in the vane occurs during maximum power operating condition. However, the maximum thermal gradient in the vane occurs during an acceleration with momentary over temperature. The highest stress occurs in the vane when the largest thermal gradient exists. The calculated POS for the three silicon nitride materials exceeded 0.99 for the worst case temperature profile. This was very close to the design goal POS assigned to the vane. The POS calculated for the silicon carbide vane was reduced to 0.80, too low to be considered viable for test if the more severe temperature pattern was present in the engine. To ensure an adequate number of silicon nitride vanes were available for test, additional vanes made of NT154 and SN252 were procured but not tested. The silicon carbide vanes were not engine tested because of the low predicted POS.

2.4.7 Ceramic First-Stage Power Turbine Vane Design

Operation of the ATTAP AGT-5 test bed engine at rated power exposes the power turbine first-stage vane to a gas temperature of 2150°F (1177°C). Uncooled metallic vanes would have a very short life under these conditions. A solution to this entailed the redesign of the power turbine static structure to incorporate a ceramic first-stage vane. The proposed ceramic vane design (Figure 2-19) was monolithic silicon nitride incorporating integral hub and tip platforms that extend to form the interstage turbine duct. The integral tip platform was cross-keyed at the trailing edge using a mount pin common with the first-stage power turbine rotor shroud. A compliant layer positions the vane and shroud ring axially against the aft turbine case at assembly. The ceramic vane configuration was analyzed using a 2-D axisymmetric FEM. The analyses utilized SN252 as the vane material and included calculation of temperatures, stresses, and POS for maximum power operation and a cold start-up transient. While calculated POS in the 2-D analysis exceeded design goals for the vane and shroud ring, the large thermal gradients shown to exist in the components

Figure 2-19. Ceramic First-Stage Power Turbine Vane Design Configuration

during transient operation were of concern. To determine more precisely the stress field at the vane/platform interfaces, a 3-D analysis would have been required but was not completed. Design of the ceramic power turbine vane was suspended for the following reasons:

- Program direction de-emphasized development of the power turbine components during the first several years of the ATTAP program. (Major program emphasis was toward development of ceramic gasifier turbine components in the hot rig. The hot rig did not employ a power turbine assembly.)
- Fabrication of the one-piece vane/platform(s) component would be high risk, involving complicated tooling.
- Then current joining technology did not allow fabrication of the vane in multiple pieces joined together during or after the sintering process.
- Short-term engine operation was possible with the metallic vane assembly.

When testing of the power turbine components was initiated late in the HVTE-TS program, the metallic first-stage vane assembly was modified to incorporate air cooling of the vane shroud rings. This reduced the operating temperature of the metallic vane

approximately 50°F (28°C), ensuring successful short-term operation. Fabrication of a ceramic power turbine first stage vane was not initiated during the ATTAP or HVTE-TS programs.

2.4.8 Ceramic Blade Tip Shroud Ring Design

A ceramic rotor blade tip shroud must be used in conjunction with a ceramic rotor to maintain close blade tip-to-shroud ring clearance during engine operation. In an ATTAP size engine, a metallic tip shroud ring will grow 0.030 to 0.035 in. (0.76 to 0.89 mm) more radially than a silicon nitride rotor, resulting in a blade tip clearance of 0.030 to 0.035 in. (0.76 to 0.89 mm) plus the cold build clearance, with consequent poor turbine performance. Ideal blade tip operating clearance would be 0.004 to 0.012 in. (0.10 to 0.30 mm). Analyses of the ceramic blade tip shroud rings utilized in the AGT-5 test bed engine show the (hot) operating blade tip-to-shroud clearance(s) to be within 0.002 in. (0.05 mm) of the "cold" clearance at assembly.

Three ceramic blade tip shroud rings were designed and fabricated for the ATTAP program, one for the gasifier turbine and one for each stage of the power turbine. The ceramic gasifier turbine shroud ring was utilized to maintain close blade tip-to-shroud clearance when a ceramic rotor was tested with a metallic gasifier turbine scroll/nozzle assembly. Figure 2-20 shows one of the hybrid metal/ceramic gasifier turbine assemblies utilized to test ceramic gasifier turbine rotors. (Ceramic gasifier turbine scroll/nozzle assemblies included a blade tip shroud ring as an integral part of the scroll.) The ceramic shroud rings for the power turbine were identical in design to the gasifier turbine shroud ring except for diameter; the power turbine rings were

Figure 2-20. Hybrid Metal/Ceramic Gasifier Turbine Hot Flow Path Components

Figure 2-21. AGT-5 Ceramic Power Turbine General Arrangement

larger in diameter to match their respective power turbine rotors. Figure 2-21 shows the ceramic power turbine shroud rings assembled in the supporting metallic power turbine static structure.

All the ceramic shroud rings were about 0.100 in. (2.54 mm) thick to minimize thermally induced stress in the ring. Three local tabs, spaced equally around the outside of the ring, have slots that engage round pins (three) assembled in the supporting metallic structure. This crosskey mount arrangement allows unconstrained movement (thermal expansion) of the ceramic shroud with respect to the metallic static structure. (The ceramic gasifier turbine shroud ring shown in Figure 2-20 has six slotted tabs instead of three. Only three engaged pins at a time. The second set of three slotted tabs allowed continued use of the ring if tab slots in the other set of three became damaged. The power turbine shroud rings did not incorporate this feature.)

Analyses of the ceramic shroud ring designs for the gasifier and power turbine show the rings to function at very low stress levels (less than 5 ksi [34.5 MPa]) during all modes of engine operation. This translates to a very high POS with the rings fabricated of Kyocera's SN251 or SN252 silicon nitride materials.

2.5 Turbine Rotor Cold Proof Spin Tests

All ceramic turbine rotors (gasifier and power turbine) produced in the ATTAP program as engine test candidates were exposed to a cold proof spin test by the fabricating vendor prior to delivery to Rolls-Royce Allison. Successful completion of the proof test demonstrated that in each sample tested no material flaw existed that reduced the material strength to a value less than the local stress existing during the proof test. The stress distribution existing in the rotor(s) during cold proof testing was different from the stress distribution(s) that exist during various engine operating conditions. The proof test speed was selected so that as much of the material mass in the rotor was exposed to stress levels at or near operating stress levels without inducing excessive local stress in other regions of the rotor. The proof test speed for the gasifier turbine rotors (all design versions) was 80,000 rpm. The test speed for the first-stage power turbine rotor was 83,500 rpm; and for the second-stage power turbine rotor, 81,500 rpm. The proof tests were conducted at room temperature in an evacuated chamber. The designated test speed was maintained for 30 seconds. One test facility utilized for proof tests was equipped with a photographic system that would photograph a rotor burst should one occur.

The ceramic turbine rotors were fabricated with slightly extended blade tips to (1) ensure successful forming of the blades, and (2) allow adjustment of turbine flow capacity through adjustment of the rotor blade tip diameter. To improve the initial balance of rotors being prepared for proof testing, the blade tips were machined to a diameter slightly larger than required for engine testing. The rotors were then assembled to a quill shaft unique to the spin test facility and the rotor/shaft assembly was balanced by removing material from the ceramic rotor and metallic shaft as necessary. Early spin test failures were determined to have occurred because of improper material removal from the ceramic rotor disks during the balance procedure. To eliminate this risk, the spin test quill shaft was modified to allow balancing the assembly without machining the ceramic component. Subsequent spin tests produced an accurate assessment of rotor material quality.

3. HOT GASIFIER RIG TESTING

This section presents an overall summary of the hot gasifier rig test program activities associated with both the ATTAP and HVTE-TS projects. The test activities were conducted during the period from 1987 through 1997. Additional detailed discussion of the hot gasifier rig development and test effort is available in the annual reports and technical papers listed in Section 8, Bibliography.

Hot gasifier rig testing to demonstrate and verify hot gas path component reliability and durability were key project objectives under ATTAP. The HVTE-TS project continued with these goals and conducted ceramic component proof and durability tests of structural ceramic components. The rig test data were used in the development and verification of ceramic design methodology.

The hot gasifier rig is a complete gas generator section from the AGT-5 automotive gas turbine engine (without power turbine or output gearbox). The rig duplicates real engine conditions without the added complexity and cost of a complete engine test. It is a regenerative rig incorporating two large diameter regenerator disks. The hot gasifier rig can incorporate various combinations of ceramic and metal hot section components.

The ATTAP hot rig test program was conducted at the General Motors Technical Center. During 1994, the ATTAP rig and engine hardware, instrumentation, and data systems were transferred to Rolls-Royce Allison in Indianapolis and, coincidentally, the overall project was renamed HVTE-TS. Setup and checkout of test facilities at Rolls-Royce Allison occurred during the last months of 1994 and most of 1995. During 1996, hot rig testing was resumed at Rolls-Royce Allison with primary focus on ceramic hot gasifier section durability testing. The hot rig testing during 1997 consisted of ceramic component screen and proof testing.

3.1 Objective/Approach

The objective of hot gasifier rig testing was to screen/proof test and simultaneously evaluate critical gas turbine engine structural ceramic components identified for technology development: ceramic gasifier turbine rotor, ceramic gasifier scroll assembly, ceramic regenerator and hot seals, combustor system, and injection-molded insulation. The gasifier rig test program was structured to address the performance and durability development of these components as required

for the application of gas turbine engines to the automotive/hybrid vehicle environment.

3.2 Accomplishments/Results

Outstanding accomplishments were achieved by the ATTAP and HVTE-TS hot gasifier rig test programs. These successes have provided significant advances to the key technologies required for the application of gas turbine engines to automotive/hybrid vehicles. Specific accomplishments include:

- **Ceramic Gasifier Power Section**

- Demonstrated design RPD temperature of 2500°F (1371°C) rotor inlet temperature (RIT) at full gasifier (100% N1) speed
- Completed a 100-hr cyclic durability test of an "all-ceramic" gasifier power section, including peak conditions of 2500°F (1371°C) RIT and 100% N1
- Completed 1000-hr durability test of a 20-bladed silicon nitride gasifier rotor
- Completed a 300-hr cyclic durability test of an "all-ceramic" gasifier power section, including peak conditions of 2500°F (1371°C) RIT and 100% N1. Major ceramic components (SN252 silicon nitride inlet scroll assembly and SN253 silicon nitride gasifier turbine rotor) showed no physical or structural damage after test.

- **Regenerators.** Two pasted MAS ceramic regenerator disks completed the 300-hr cyclic durability test of an "all-ceramic" gasifier power section, with only minimal surface pitting and cracking. Both disks were available for continued use at test end. Peak regenerator inlet temperature was 2001°F (1094°C) with an average maximum run temperature of 1680°F (916°C).

- **Insulation Systems.** A total of 300 hr of cyclic durability testing were completed by the hot gasifier rig with injection-molded insulation including both simple (gasifier housing and combustor cover) and complex (AGT-5 engine housing) shapes.

- **Ceramic Combustor.** A two-piece ceramic combustor successfully completed proof testing verifying the structural integrity of the all-ceramic combustor.

3.3 Progress/Status/Remaining Work

Hot gasifier rig testing of ceramic turbine engine components has accomplished significant progress over the time span of the ATTAP and HVTE-TS projects. The ATTAP program provided for the development of an upgraded high temperature gasifier rig that has allowed screen, proof and durability testing of advanced turbine engine components. The ATTAP and HVTE-TS gasifier rig test programs have been instrumental in achieving program project goals of demonstrating and proving structural ceramic component performance and durability in an automotive turbine engine environment.

Hot gasifier rig testing was terminated after DoE sponsorship of the HVTE-TS ended in 1998.

Several advanced design ceramic engine components remain untested and unproven. These components include a single piece ceramic combustor, an advanced design circular cross-section gasifier scroll, 26-bladed gasifier rotor designs, improved regenerator cores, advanced regenerator hot seals, etc. These advanced technology components offer the potential of significantly improved ceramic turbine engine performance.

3.4 Hot Gasifier Rig Tests

Two hot gasifier rigs were utilized during ATTAP. Both rigs comprised a complete gasifier power section from the AGT-5 engine (without power turbine or output gearbox). The primary objective of this activity was to develop necessary test procedures and to conduct rig testing of the ceramic components. A secondary objective was to conduct tests of nonceramic hardware/systems related to the evolution of the AGT-5 engine into a high temperature test-bed. One of the ATTAP hot gasifier rigs is shown in Figure 3-1.

Over the time span of the ATTAP project, numerous hot gasifier rig tests were completed. These tests included:

- Screening and proof testing of both metallic and ceramic combustor designs and configurations
- Screening and proof testing of various design ceramic gasifier rotors fabricated from candidate materials by two suppliers

Figure 3-1. ATTAP Hot Gasifier Rig

- Screening and proof testing of ceramic gasifier rotor inlet scroll systems
- Cyclic durability testing of ceramic gasifier power sections
- Long term ceramic gasifier rotor durability testing

With the transfer of ATTAP/HVTE-TS program responsibilities to Rolls-Royce Allison in Indianapolis, facilities were refurbished and set up to accommodate program testing requirements. During 1995, the AGT-5 test hardware and auxiliary test equipment were installed in the test cell. Procurement, fabrication, and installation of test cell mechanical, electrical, and instrumentation systems were completed. Figure 3-2 shows the hot gasifier rig installed in a Rolls-Royce Allison test cell.

The hot gasifier rig was fitted with a special sight tube with quartz window to permit observation of the gasifier turbine rotor exit during operation. This sight tube also incorporated an exhaust port (secondary exhaust) to allow diversion of hot gas flow from the rotor overboard of the rig to help limit regenerator inlet temperature.

Figure 3-2. HVTE-TS Hot Gasifier Rig

HVTE-TS hot gasifier rig testing focused on an "all-ceramic" gasifier power section. The "all-ceramic" gasifier section consisted of a ceramic inlet scroll assembly with integral ceramic rotor shroud and a ceramic gasifier turbine rotor. Specifically, the hot gasifier rig was used to proof test and evaluate durability and performance of structural ceramic components (combustors, gasifier turbine components, and regenerators) and related engine systems prior to introduction into the test-bed engine.

At the beginning of the ATTAP program, ceramic technology verification was structured into three major demonstrations utilizing the hot gasifier rig test bed:

- Demonstration of structural ceramic components operating at design RPD temperature of 2500°F (1371°C) rotor inlet temperature (RIT) at full gasifier (100% N1) speed
- 100-hr cyclic durability test of an "all-ceramic" gasifier power section, including peak cycle conditions of design RPD values (2500°F [1371°C] RIT and 100% N1)
- 300-hr cyclic durability test of an "all-ceramic" gasifier power section, including peak cycle conditions of design RPD values (2500°F [1371°C] RIT and 100% N1)

3.4.1 Rig Tests at Full RPD Conditions

Ceramic component screening and proof testing was deemed a requirement before introduction into the test-bed engine. The hot gasifier test rig allowed verification of ceramic component structural integrity at full RPD conditions closely replicating engine operation.

One of the goals of ATTAP was to demonstrate and verify ceramic component performance and durability. The ceramic gasifier power section contained the most critical of these engine components. The hot gasifier tests produced verification of ceramic component durability and capability to sustain multiple stressful conditions in service and still maintain overall structural integrity. One ceramic gasifier section assembly was successfully operated up to RPD conditions, sustained tip rubs, foreign object damage, and still was fully operational at the end of 1000 hr of testing.

The gasifier section was built using a 20 blade-design rotor of Kyocera's SN252 silicon nitride material. The ceramic gasifier section components are shown in Figure 3-3. During the first 34 hr of operation, the rotor sustained fracture damage to 13 of the 20 airfoils (minor chips in the blade leading edge tips). The rotor

Figure 3-3. ATTAP Ceramic Gasifier Stage

was inspected, found to have no additional damage and returned to test. At 348 hr into the test history of the rotor, a ceramic shroud band was introduced for rotor tip clearance control at hot running conditions. After 7.5 hr of operation, the ceramic shroud fractured and rubbed the rotor at an operating condition of 87% gasifier speed and 2340°F (1282°C) RIT.

The rotor was returned to service and run to full RPD conditions of 100% gasifier speed and 2543°F (1395°C). This hot rig test run successfully completed the first key ATTAP contractual milestone.

At 430 hr, an emergency rig shutdown occurred at 86% gasifier speed and 2372°F (1300°C) RIT due to rig over temperature and high vibration conditions. Inspection revealed a large piece of hard carbon was lodged between the rotor airfoils. This is shown in Figure 3-4. The carbon was removed and the rotor returned to service.

While operating at 100% gasifier speed and 2192°F (1200°C) RIT, the rig experienced a compressor failure at 556 hr. Teardown inspection revealed a bent gasifier shaft, a broken ceramic shroud, and evidence of another rotor/shroud rub. The rotor sustained no additional damage. After the attached metal shaft was straightened, the rotor was returned to test.

Figure 3-4. Ceramic Gasifier Rotor at 430 hr with Hard Carbon in Flow Passage

Routine inspection at 874 hr revealed chipping on the trailing edge airfoil/rim of the rotor. After minimal blending, the rotor was returned to test with peak durability cycle conditions set at 100% speed and 1904°F (1040°C) due to combustor limitations.

The 20-bladed silicon nitride gasifier rotor was retired in serviceable condition at 1000.7 hr total test time, of which 507 hr were on the durability cycle. The 1000-hr gasifier rotor is shown in Figure 3-5. The capability of this rotor to sustain multiple distress conditions in service and maintain overall structural integrity shows the advancement in ceramic materials and processing technology and verified the validity of such components in turbine engine service.

a) Leading Edges

b) Trailing Edges

Figure 3-5. Ceramic Gasifier Rotor at 1000-hr Total Test Time

3.4.2 100-hr Cyclic Durability Test

One of the major milestones established at the beginning of ATTAP was to demonstrate high temperature capability and 100-hr durability of ceramic static and rotating components. This milestone was attained in 1991.

The initial ATTAP ceramic component durability test schedule was designed to subject the automotive gas turbine to conditions considered extreme compared to the most severe expected field use. The schedule duration was 60 minutes and included 19 accelerations to design RPD speed, 24 decelerations, 9 engine starts/stops, and a 9-minute soakback period. Engines subjected to 1000 hr of testing using this accelerated schedule experience wear and operational characteristics comparable to 100,000 miles of typical automotive operation.

The "all-ceramic" gasifier section contained the components listed in Table 3-1. It was tested using a ceramic combustor (Carborundum α -SiC, S/N FX79402). The combustor had 0.25 in. (6.25 mm) thick walls, although the design thickness was 0.16 in. (4 mm) thick walls. After starting the rig twice and running for 0.6 hr to a peak condition of 1688°F (920°C) at 100% speed, inspection revealed the combustor had cracked into three segments (Figure 3-6). No damage occurred to the other ceramic components.

Table 3-1. Ceramic Components in 100-hr Durability Test

Component	Part Number	Serial Number	Supplier	Material
Scroll	5-80553	1-1	Kyocera	SN252 Si3N4
Vane Platform	5-80561	2-1	Kyocera	SN252 Si3N4
Vanes	5-80552	-	GTE	PY6 Si3N4
Vane Retaining Ring	5-80560	1-1	Kyocera	SN252 Si3N4
Rotor (15 Blade)	5-66946	5K12	Kyocera	SN252 Si3N4

Figure 3-6. Failed One-Piece Ceramic Combustor

The damaged combustor was replaced with a porous metal Lamilloy® combustor assembly. An inspection at 41 hr revealed no damage to the ceramic components, however, the combustor was replaced because the platinum rod containing the burner thermocouples had yielded.

The 100-hr durability test continued using a modified durability schedule (as shown in Figure 3-7) limited to three accelerations to full speed and temperature per each 1-hr cycle due to concerns about the metal combustor durability under high temperature operation.

The "all-ceramic" gasifier test began in May 1991 and the 100-hr ceramic component durability milestone was completed in December 1991. A summary of the durability test includes:

- Inspection revealed three cracks around the scroll vane slots, one small surface crack in the scroll shroud and two cracked nozzle vanes.
- The distressed ceramic components maintained overall structural integrity.

Figure 3-7. ATTAP Durability Test Cycle for Automotive Gas Turbine

* Lamilloy is a register trademark of Allison Engine Company, Inc.

- The scroll and rotor assembly was deemed available for continued usage.
- The ceramic gasifier rotor peak operating conditions were 2525°F (1385°C) at 101% N1.
- A total of 880 rig starts were completed and 95.8 durability cycle hours were completed during the 100-hr durability test.

3.4.3 300-hr Cyclic Durability Test

During the ATTAP program, several hot rig tests were conducted to address the second major program milestone; a 300-hr cyclic durability test of an "all-ceramic" gasifier power section. The two most successful ATTAP tests are described below: 196-hr duration and 267-hr duration. It should be noted that none of the failures to reach the 300-hr milestone were initiated by basic ceramic material or component problems. Test hours have been limited ceramic/metallic interfaces and positioning, tolerancing and thermal growth characteristics.

The "all-ceramic" gasifier assembly that had completed the 100-hr durability test was reassembled (only the two cracked vanes were replaced with new ones) and durability schedule testing resumed with the target being 300 hr of durability testing.

At 116 hr total test time, the gasifier assembly was removed from the rig for a complete inspection. Although one vane suffered new cracking, no crack growth or new crack growths were observed in the scroll. The newly cracked vane was not replaced and the assembly continued durability testing to 132 total test hours, when it was again removed from the rig for complete inspection. No new cracks or crack growth were observed in the scroll, but two vanes had developed new cracks and six new chips were found on the rotor leading edge blade tips. The rotor chips were blended out and the rotor balanced. One of the cracked vanes was replaced. The "all-ceramic" gasifier testing was continued using the durability schedule. At a total test time of 196.5 hr, an automatic rig shutdown occurred. The ceramic components were found to be destroyed. In summary:

- Ceramic scroll accumulated 186 total durability cycle hours (of which 90 were run with cracks).
- The ceramic gasifier rotor peak operating conditions were 2571°F (1411°C) at 100% N1.
- A total of 1706 rig starts were completed and 186 durability cycle hours were completed during the 196.5-hr durability test.
- Ceramic gasifier components were destroyed from undeterminable cause

The HVTE-TS project continued the goals established during the ATTAP program. Thus, one of the major HVTE-TS contractual milestones was to complete a 300-hr cyclic durability test of an "all-ceramic" gasifier section. The objective of the test was to demonstrate durability performance of key technology components of the automotive gas turbine including:

- Ceramic gasifier scroll assembly
- Ceramic gasifier turbine rotor
- Ceramic regenerator cores
- Regenerator crossarm hot seal materials
- Injection-molded insulation

The HVTE-TS project emphasis shifted the automotive gas turbine engine environment from prime power to auxiliary power for hybrid vehicles utilizing electric drive systems. Therefore the ceramic component durability test schedule was modified to simulate an accelerated life test based on the cyclic operating modes of a typical hybrid vehicle turbine engine environment. The schedule was 1 hr in duration and included 20 accelerations and 24 decelerations. It also included a 9 minute soakback at the end. Execution of a complete schedule was one durability cycle. The maximum rotor speed of the cycle was 90% rated speed, corresponding to a rotor inlet temperature (RIT) of 2100°F (1149°C). Variations of this basic cyclic durability schedule (gasifier turbine rotor operation to 100% rated speed and RIT to 2500°F [1371°C]) were used during the test program to increase the severity of the ceramic component environment yet remain within the temperature limitations of rig hot section metallic components.

First HVTE-TS rig testing of an "all-ceramic" gasifier section was initiated in April 1996. Figure 3-8 shows rig operation during a 100% gasifier speed durability cycle with a maximum RIT of 2507°F (1375°C). A total of 29.9 test hours was accumulated on the initial ceramic section build before a hardware failure occurred on May 14, 1996. The ceramic rotor and scroll were destroyed along with severe damage to other components. Failure analyses have concluded that sections of the metallic thermal variable geometry (TVG) combustor dome melted and deposited molten metal between the ceramic turbine rotor and its blade track causing failure of the rotor. The rotor failure then resulted in subsequent ceramic scroll assembly failure and damage to other components.

Figure 3-8. Ceramic Durability Rig Operating to Full Rated Speed and Temperature

The gasifier assembly was rebuilt with new ceramic components. It was installed in S/N 14 hot rig housing which had been refurbished with new injection-molded insulation. The ceramic inlet scroll assembly was fabricated from SN252 silicon nitride (Figure 3-9). The ceramic gasifier turbine was a 20-bladed axial flow rotor fabricated from SN253 silicon nitride (Figure 3-10). A newly designed mounting system was incorporated (see Section 2, Ceramic Components) to position the ceramic scroll with respect to the assembly centerline using a crosskey system that is piloted from the gasifier rotor housing. This design maintains concentricity of the turbine rotor and scroll more precisely than previous designs. Ceramic rotor stability and bearing life were enhanced with the addition of a patented Rolls-Royce Allison oil squeeze film damper design to both the compressor and turbine bearings to ensure proper damping and to limit oil flow requirements.

Figure 3-9. SN252 Silicon Nitride Inlet Scroll

Figure 3-10. SN253 Silicon Nitride 20-Bladed Gasifier Rotor

Extruded magnesium-aluminosilicate (MAS) ceramic pasted regenerator disks (Figure 3-11) were used. The cores were fabricated by pasting rectangular extruded MAS segments together and then machining the assembly to form a disk of the proper diameter.

Two different regenerator crossarm hot seal materials were used: NiO/CaF₂ plasma sprayed onto an I-625 substrate and I-112 (ZnO/SnO₂/CaF₂) plasma sprayed onto an I-625 substrate. Specific usage and performance are discussed below. The plasma sprayed crossarms are shown in Figure 3-12 (NiO/CaF₂ plasma sprayed arm at top of photograph). Additional discussion on regenerator system development is presented in Section 7, Regenerator System Development.

Figure 3-11. AGT-5 MAS Pasted Regenerator Core

Figure 3-12. AGT-5 Regenerator Hot Seal Plasma Sprayed Crossarms

Hot rig components injection-molded with insulation included the gasifier housing, AGT-5 engine housing and combustor cover. These components are shown in Figures 3-13 and 3-14. (See Section 6.0, Insulation System Development for details).

During test programs incorporating ceramic gasifier turbine inlet scrolls, RIT is calculated rather than measured due to the difficulty of positioning thermocouples directly into the scroll. The equation for calculated RIT is based on a curve fit to temperature rise curves for diesel fuel. Inputs to the curve fit are combustor inlet temperature and combustor fuel/air ratio. Ceramic gasifier rotor proof testing (using a

Figure 3-13. AGT-5 Injection-Molded Insulation Components

Figure 3-14. AGT-5 Engine Housing with Injection-Molded Insulation

metallic inlet scroll with rotor inlet thermocouples installed) demonstrated excellent correlation between measured and calculated RIT.

Gasifier rotor inlet temperature control is accomplished by conditioning rig inlet air temperature, compressor bleed, exhaust cavity cooling air, and secondary exhaust duct flow. The regenerator disk inlet temperature is a function of rotor exit temperature with exhaust cavity cooling air pressure and secondary exhaust duct flow levels providing auxiliary means to control disk inlet temperature.

The second 300-hr durability test of an "all-ceramic" gasifier section was initiated in July 1996. The first durability cycle was completed after 1.5 hr of testing. The cycle was based on a 90% speed schedule and achieved a maximum RIT of 2143°F (1173°C) with a maximum regenerator inlet temperature of 1745°F (952°C).

Rig performance at 12 hr into the durability test is shown in Figure 3-15. During execution of this 92% speed durability schedule, a maximum RIT of 2449°F (1343°C) was reached with a maximum regenerator inlet temperature of 1929°F (1054°C).

Figure 3-16 is a photograph of the ceramic gasifier rotor operating at RPD design conditions (100% rated gasifier rotor speed) as viewed through the rig sight tube quartz window.

Figure 3-15. Ceramic Durability Rig Performance (12 hr)

Figure 3-16. Ceramic Gasifier Rotor as Viewed from Sight Tube

Scheduled rig inspections were conducted every 50 hr of testing. These inspections were primarily to evaluate gasifier section ceramic component condition including structural integrity and rotor blade tip clearance. No problems associated with the "all-ceramic" section were discovered during these inspections. A total of 14 non-scheduled rig inspections were made to correct assorted rig nonceramic operational problems.

At 64 hr into the durability test, the left regenerator hot seal crossarm (NiO/CaF₂ plasma sprayed) was replaced with a crossarm having the I-112 (ZnO/SnO₂/CaF₂) plasma sprayed coating. The original NiO/CaF₂ coated arm did not develop a full contact wear pattern and was judged to be a potential source of leakage. At 123 hr, a major repair of the engine housing injection-molded insulation was performed. Several areas on the left and right hot side suffered insulation debonding from the metal housing and had broken away. The remaining insulation was trimmed and fixtures made to injection mold repair the affected areas. A part of the fixture was designed to be left in place to provide a blast shield from the high velocity rotor exhaust gases.

The 300-hr durability test of the "all-ceramic" gasifier section was successfully completed during November 1996. Rig performance at 300-hr of cyclic durability testing is shown in Figure 3-17. During execution of this 96% speed durability schedule, a maximum RIT of 2130°F (1165°C) was reached with a maximum regenerator inlet temperature of 1663°F (906°C).

Figure 3-17. Ceramic Durability Rig Performance (300 hr)

Figure 3-18 shows rig speed, rotor inlet temperature, and regenerator disk inlet temperature maximum values for the entire 300-hr durability test.

The majority of the runs prior to 215 test hours were executed using a durability schedule more severe than the base schedule (90% rated gasifier rotor speed at RIT of 2100°F [1149°C]). After 215 test hours, rig operation was controlled to maintain RIT near the base schedule of 2100°F (1149°C).

Results of the 300-hr durability test can be summarized as follows:

- The ceramic scroll assembly showed no evidence of physical or structural problems.

Figure 3-18. Maximum Operating Environment of the "All-Ceramic" Gasifier Section

- The ceramic gasifier turbine rotor showed no physical or structural problems.
- The "all-ceramic" gasifier section completed the durability test without teardown.
- Maximum RIT of 2497°F (1369°C) was reached. RIT exceeded 2400°F (1316°C) 12 times. RIT was above 2100°F (1149°C) for almost 10 hr.
- A total of 392 successful ceramic rig starts were executed.
- A total of 238 automatic 1-hr durability test schedules were executed with gasifier rotor speeds to 101%.
- The MAS ceramic regenerator disks had minimal surface breakdown and cracking. The maximum measured regenerator inlet temperature was 2001°F (1094°C).
- Cold side engine housing injection-molded insulation had minimal debonding from the metal housing. After repair, the hot side engine housing insulation completed over 177 hours of durability testing without additional problems.
- The I-112 (ZnO/SnO₂/CaF₂) coated regenerator right hot seal crossarm had minimal degradation in seal surface function. The left crossarm (NiO/CaF₂ plasma sprayed) was replaced with an I-112 coated crossarm at 64-hr testing and completed the remaining test hours.

Figure 3-19 shows the gasifier section components, regenerator disks, and hot seal crossarms after completing the 300-hr durability test. Teardown

Figure 3-19. AGT-5 Hot Gasifier Rig Components after 300-hr Durability Test

inspection and measurements showed all components were in excellent condition. The ceramic inlet scroll assembly and ceramic gasifier rotor (Figure 3-20) were in excellent condition with microscopic inspection showing no evidence of physical or structural damage.

Post-test inspection of other rig components revealed no major problems. The gasifier housing injection-molded insulation was cracked and debonded close to the hot section as shown in Figure 3-21. However, it remained in place and was fully operational throughout the 300-hr test. The injection-molded combustor cover showed no evidence of damage. Figure 3-22 shows the regenerator disks after test. Only minimal surface breakdown and cracking were observed. The AGT-5 engine housing injection-molded insulation after test is shown in Figure 3-23. The hot side injection-molded insulation was in excellent shape with only minor areas of delamination or debonding from the housing. Cold side insulation was also in excellent condition with only two areas of debonding from the housing. Both hot seal crossarms showed excellent wear patterns and durability. The crossarms are shown in Figure 3-24. The right crossarm is on the top in the photograph and was subject to 236 hr of testing. The left crossarm completed the 300-hr durability test.

Figure 3-20. Ceramic Gasifier Rotor After 300-hr Durability Test

Figure 3-21. Injection-Molded Insulation on Gasifier Housing after 300-hr Durability Test

Figure 3-22. MAS Pasted Regenerator Disks after 300-hr Durability Test

Figure 3-23. AGT-5 Engine Housing Injection-Molded Insulation after 300-hr Durability Test

Figure 3-24. Ceramic Coated Hot Seal Crossarms After 300-hr Durability Test

3.4.4 Ceramic Combustor Test

Proof testing of the two-piece all-ceramic combustor was completed in the AGT-5 hot gasifier rig. The combustor assembly consisted of a silicon carbide body, silicon carbide dome, metallic fuel nozzle/air swirler assembly, and metallic dome/body support structure. The combustor body was fabricated from an existing single piece silicon carbide combustor, which was produced by Carborundum Corporation. The dome was machined from a second single piece silicon carbide combustor (also produced by Carborundum Corp.) to

mate with the modified body. The dome design provides for a metallic fuel nozzle/air swirler assembly and standard fuel ignitor.

A total of 6 successful rig starts were executed with a total run time in excess of 1 hr. The last run reached a maximum gasifier turbine speed of 98% design speed with a corresponding combustor inlet temperature of 1600°F (871°C) and a calculated rotor inlet temperature of 2552°F (1400°C). Figure 3-25 shows rig performance during the run.

Thermocouples located on the inside face of the fuel nozzle shroud and combustor support structure reached temperatures of 2010°F (1099°C) and 1601°F (872°C), respectively. The thermal paint stripes that had been applied axially to both the body and the dome indicated that temperatures above 2500°F (1371°C) were reached in the reaction zone.

Heat transfer models of the combustor predict the inner wall differential temperatures to be more than 100°F (56°C) higher than the outer wall. Based on this prediction, the ceramic inner wall temperature at this operating condition reached temperatures above 2600°F (1427°C). This is consistent with heat transfer predictions of a maximum combustor body temperature of 2691°F (1477°C) and maximum combustor dome temperature of 2638°F (1448°C) at 100% rated speed.

After completion of the run, the combustor was removed from the rig for inspection. Both the combustor dome and body and associated metal hardware were in excellent condition. The two-piece ceramic combustor after test is shown in Figure 3-26.

Figure 3-25. Ceramic Combustor Proof Test Data

Figure 3-26. Ceramic Combustor after Proof Test

The AGT-5 engine and hot gasifier rig have been the test-beds employed to demonstrate hot section ceramic component compatibility with the automotive turbine engine operating environment. Early efforts were conducted by the ATTAP project. The HVTE-TS program extended the technology database established by the ATTAP program. Tables 3-2 and 3-3 summarize this extensive ceramic gasifier inlet scroll and rotor database. Table 3-4 presents the first entry in the database established for ceramic power turbine rotors and ceramic combustors.

Table 3-2. Ceramic Scroll Database

Supplier	Scroll Type	Scroll S/N	Scroll Material	Cumulative Total per Component (hours)	Peak Rotor Inlet Temperature °C (°F)
Kyocera	Advanced	34-2	SN252	304.7	1504 (2740)
Kyocera	Advanced	11-2	SN252	29.9	1375 (2507)
Kyocera	Advanced	0000	SN252	9.1	1400 (2552)
Kyocera	Standard	KX61234	SN252	0.3	1150 (2102)
Norton	Advanced	KX244-18	NT230	26.4	1150 (2102)
Norton	Advanced	KX61227	NT230	50.8	1150 (2102)
Norton	Advanced	KX61314	NT230	4.3	1150 (2102)
Norton	Advanced	KX61200	NT230	1.1	1327 (2420)
Kyocera	Advanced	KX59815	SN252	267.7	1380 (2515)
Norton	Standard	KX59008	NT230	1.5	1050 (1920)
Kyocera	Standard	S-2	SN252	13.5	1380 (2515)
Kyocera	Standard	0001-1	SN252	196.5	1385 (2525)
Norton	Standard	KX56721	NT230	8.9	1350 (2460)
Kyocera	Advanced	KX55599	SN252	1.1	930 (1706)
Kyocera	Advanced	KX55836	SN252	5.2	1406 (2563)
Kyocera	Advanced	S-1	SN252	7.2	1401 (2554)
Cumulative Total				928.2	

Table 3-3. Ceramic Rotor Database

Supplier	Rotor S/N	No. of Blades	Rotor Material	Cumulative Total per Component (hours)	Peak Speed %	Peak Rotor Inlet Temperature °C (°F)
Kyocera	4-2	20	SN253	313.8	101	1504 (2740)
Kyocera	3-3	20	SN253	29.9	100	1375 (2507)
Kyocera	KX00023	26	SN253	0.1	65	1111 (2032)
Norton	1538-75	20	NT154	35.5	90	1150 (2102)
Norton	1541-88	20	NT154	12.3	95	1150 (2102)
Norton	130X-2	20	NT164	62.6	95	1150 (2102)
Norton	122X-1	20	NT164	15.9	95	1206 (2192)
Kyocera	5K9	15	SN252	12.6	97	1327 (2421)
Kyocera	5K21	20	SN252	279.8	100	1380 (2515)
Norton	6F	20	NT154	12.0	100	1180 (2155)
Kyocera	5K27	20	SN252	0.5	100	1115 (2040)
Kyocera	5K23	20	SN252	13.1	100	1150 (2100)
Kyocera	5K13	15	SN252	22.4	100	1380 (2515)
Kyocera	5K12	15	SN252	229.0	101	1385 (2552)
Norton	5S	20	NT154	224.7	100	1350 (2460)
Kyocera	5K26	20	SN252	22.7	100	1408 (2566)
Kyocera	5K10	15	SN252	0.8	90	1277 (2331)
Carborundum	FX78527	15	a-SiC	0.0	40	N/A
Kyocera	5K22	20	SN252	1000.7	98	1395 (2543)
Kyocera	5K25	20	SN252	3.9	90	1160 (2120)
Kyocera	5K24	20	SN252	7.9	101	1150 (2102)
Kyocera	5K8	15	SN251	365.0	100	1150 (2102)
Cumulative Total				2665.2		

Table 3-4. Ceramic Power Turbine and Combustor Database

Supplier	Component Type	Component S/N	Component Material	Total per Component (hours)
Kyocera	1st Power Stage Turbine	KX55140	SN252	7.9
Kyocera	2nd Power Stage Turbine	KX58424	SN252	7.9
Carborundum	Combustor Body	FX 79409	a SiC	4.95
Carborundum	Combustor Dome	FX 79405	a SiC	4.95

4. TEST-BED ENGINE TESTING

This section presents an overall summary of the engine test program activities associated with both the ATTAP and HVTE-TS projects. The test activities were conducted during the period from 1987 through 1998. Additional detailed discussion of the test-bed engine development and test effort is available in the annual reports and technical papers listed in Section 8, Bibliography.

Engine testing to demonstrate and verify hot gas path component reliability and durability were a key focus of and included as project objectives under ATTAP. The primary goal of the HVTE-TS engine test program was to demonstrate the operation of an all-ceramic test-bed engine. Engine testing was key to the development of ceramic hot flow-path components, verification of ceramic design methodology, advanced combustor emissions development testing, and testing of injection-molded insulation components.

The ATTAP test-bed engine was the GM-developed AGT-5 automotive gas turbine engine. The ATTAP project upgraded the AGT-5 from a 1900°F (1038°C) metal engine to a 2500°F (1371°C) ceramic test-bed engine. This ceramic test-bed engine formed the basis for all subsequent turbine engine component design, analysis, fabrication and test activities.

The HVTE-TS program continued to employ the AGT-5 test-bed turbine engine developed under ATTAP. This provided continuity to the established component databases and a proven flexible engine for evaluation of advances in ceramic component technology.

The ATTAP engine test program was conducted at the General Motors Technical Center. During 1994, the ATTAP rig and engine hardware, instrumentation, and data systems were transferred to Rolls-Royce Allison in Indianapolis. Setup and checkout of test facilities at Rolls-Royce Allison occurred during the last months of 1994 and most of 1995. During 1996, testing at Rolls-Royce Allison focused on ceramic hot gasifier section durability testing in the AGT-5 hot gasifier rig. AGT-5 engine testing resumed at Rolls-Royce Allison during 1997.

4.1 Objective/Approach

The overall goal of test-bed engine testing was to verify advancements in ceramic component technology. The

test programs were structured to address the development of key technologies required for the application of gas turbine engines to the automotive/hybrid vehicle environment.

The ATTAP engine test objective was to evaluate ceramic component reliability and durability in an engine environment.

The HVTE-TS engine test objectives were to demonstrate ceramic component structural integrity and the operation of an all-ceramic AGT-5 test-bed engine.

Engine testing provides for the evaluation of all critical turbine engine components identified for technology development: ceramic gasifier turbine rotor; ceramic gasifier scroll assembly; ceramic power turbine stage; ceramic regenerator and hot seals; combustor system; and injection-molded insulation.

4.2 Accomplishments/Results

Outstanding accomplishments were achieved by ATTAP and HVTE-TS engine test programs. These successes demonstrated and verified the significant advances to the key technologies required for the application of gas turbine engines to automotive/hybrid vehicles. Specific accomplishments included:

- Upgraded the baseline AGT-5 metal component automotive turbine engine to a high temperature structural ceramic component test-bed engine
- Successfully demonstrated fully operational all-ceramic AGT-5 automotive gas turbine test-bed engine with 2500°F (1371°C) gasifier rotor inlet temperature
- Demonstrated limited reliability and durability of the AGT-5 high temperature test-bed engine
- Completed 547 engine test hours during system integration and durability running
- Completed 977 engine test hours with ceramic engine components
- Completed ceramic gasifier, ceramic power turbine stage, and ceramic combustor proof testing during engine operation

4.3 Progress/Status/Remaining Work

The ATTAP and HVTE-TS programs provided for the development of an upgraded high temperature automotive ceramic turbine engine which has demonstrated limited reliability and durability during dynamometer testing of advanced turbine engine components. The HVTE-TS program built on the ATTAP results to demonstrate the successful operation of an all-ceramic AGT-5 automotive ceramic engine.

Engine development and testing were concluded after the HVTE-TS program ended in 1998.

Several advanced design ceramic engine components remain untested. In addition, HVTE-TS engine testing highlighted engine modifications needed to eliminate gas flow-path mismatch. The combination of advanced design components and engine modifications offer the potential of significantly improved ceramic test-bed engine performance.

4.4 Test-Bed Engine Testing

A primary goal of the ATTAP program was the demonstration of structural integrity of turbine engine ceramic components. Therefore it was necessary to select a development engine test-bed capable of accommodating a variety of component designs and configurations. A reference powertrain design (RPD) was completed at the start of the ATTAP program to ensure the selected turbine engine test-bed had the potential to fulfill the goals related to DoE's sponsorship of automotive gas turbine technologies. The RPD was based on a high temperature derivative of the existing General Motors AGT-5 automotive turbine engine. This engine was originally developed by the General Motors Advanced Engineering Staff as a prime power all-metal automotive gas turbine engine (AGT-5). The RPD upgraded the AGT-5 engine to include structural ceramic components with a gasifier rotor inlet temperature of 2500°F (1371°C) at design conditions. The AGT-5 is a two-shaft turbine engine with a single-stage centrifugal compressor, single-stage axial gasifier turbine, two-stage axial power turbine, twin regenerator heat recovery system, a single can type combustor, and a reduction gearbox as shown in Figure 4-1.

Figure 4-1. AGT-5 Automotive Gas Turbine Engine

This RPD was a preliminary engineering design of a powertrain system that integrated vehicle and turbine engine characteristics to provide a system with the potential for meeting performance, cost, and reliability goals. The RPD design objectives were:

- 30% improved fuel economy over the reference vehicle with a contemporary, spark-ignition engine over the Federal Driving Cycle
- Emission levels consistent with proposed federal levels for automotive powerplants
- Ability to use a variety of alternate fuels
- Minimum use of strategic materials
- Reliability and life comparable with current powertrains
- Competitive initial and life cycle costs with conventional powered vehicles
- Competitive vehicle drivability and performance with the reference vehicle
- Noise and safety characteristics that meet federal standards

While the AGT-5 initially brought a running, workable, automotive powertrain system to the ATTAP program, more engine development was needed to ensure full power 2500°F (1371°C) RPD capability. Test-bed engine design and development activities included engine mechanical design, combustor design, gasifier and power turbine flow-path design and mechanical layout, and engine systems integration efforts aimed at upgrading the AGT-5 metal engine to a durable 2500°F (1371°C) structural ceramic component test-bed engine. Also, the engine output gearbox was redesigned to meet increased power output requirements of the all-ceramic turbine engine. The resulting turbine engine arrangement represented the best configuration, within the existing confines of the AGT-5 engine envelope, to meet performance and durability goals. The RPD included detailed aerodynamic designs of the engine cold and hot flow-paths to provide a basis for upgraded engine component development and fabrication.

A durability test schedule was designed to subject the ceramic automotive gas turbine engine components to conditions considered extreme compared to the most severe expected field use. Each hour of the durability cycle contains 19 accelerations, 24 decelerations, 9 engine starts/stops and a 9-minute soakback. The cycle is intended to compress 3500 hr of vehicular engine operation on the Federal Driving Cycle into 1000 hr of engine dynamometer testing. Engines subjected to 1000 hr of testing using this accelerated schedule experience wear and operational characteristics comparable to 100,000 miles of typical automotive operation.

During the ATTAP program the AGT-5 engine has accumulated over 1300 hr of engine dynamometer operation of which more than 500 hr have been on the durability cycle shown in Figure 4-2.

Engine dynamometer testing is a cost-effective means to evaluate turbine engine performance. These tests provide high temperature durability verification and evaluation of ceramic hot flow-path components and engine insulation. This testing supported the ceramic redesign process and evaluated advanced component materials and configurations.

In-vehicle engine testing was also conducted during the ATTAP program to provide a real-world automotive environment to assess ceramic component performance and/or durability design criteria unique to vehicular gas turbine operation. More than 600 hr of vehicular running have been accumulated toward evolving and verifying the AGT-5 powertrain in preparation for ceramic component verification.

Figure 4-2. Gas Turbine Durability Test Cycle

Engine development and testing were completed to verify improvements in ceramic component technology required to achieve the performance and durability goals of the ATTAP program. The test program addressed all areas associated with upgrading the AGT-5 metal engine to a durable 2500°F (1371°C) structural ceramic component test-bed engine with the development of automotive gas turbine engine. These included:

- Performance and durability tests of the AGT-5 baseline metal engine and ceramic component engines
- Verification testing of engine components and assemblies upgraded by the RPD process including compressors and diffusers, combustors, gasifier and power turbine assemblies, regenerator and seal systems, output gearbox, and thermal insulation systems
- Verification testing of upgraded engine accessories including starter motor, fuel pump and motor, and control systems

Engine testing was performed to determine the desirable parameters for ceramic component operation. These included assessing the best available compressor diffuser geometry, best air intake geometry, and best impeller tip clearance for overall engine efficiency and surge-free operation. Engine tests were also performed to compare the effect of different regenerator disk designs and seals on engine performance.

Engine tests were conducted to evaluate critical turbine engine components identified for technology development: ceramic gasifier turbine rotor; ceramic gasifier scroll assembly; ceramic regenerator and hot seals; combustor system; and injection-molded insulation. The engine test program also included the design, development, and fabrication of engine components and systems to ensure the test-bed engines were compatible with and capable of operating at the power and temperature levels associated with advanced ceramic technology components.

Engine testing was also conducted to support the ATTAP low emissions combustor development. Additional discussion of combustor development and testing is discussed in Section 5, Combustion Development. Vehicle emission testing included a Camaro Z28 outfitted with an AGT-5 test-bed engine. The car was driven over the EPA urban driving cycle on a chassis dynamometer at the General Motors Technical Center.

Dynamometer engine testing of advanced design combustors in the AGT-5 test-bed engine was also completed. Emissions measurements were taken at steady-state conditions at various gasifier speeds. The range of conditions tested were based on the EPA automotive emissions driving cycle. Test results showed the combustor could be operated to meet California ULEV standards under steady-state conditions. The lean stability of the combustor was excellent. However, the combustor was susceptible to flashback and fuel ignition was not reliable with an automotive spark ignitor. During engine tests it was difficult to determine whether flashback was caused by combustor or compressor instability.

The HVTE-TS engine test program was conducted at Rolls-Royce Allison during 1997 and 1998. It used the AGT-5 automotive gas turbine engine as the test-bed for ceramic component evaluation providing continuity from the ATTAP test program. The engine test program included the following goals:

- Set up an operational high temperature ceramic AGT-5 engine test-bed at Rolls-Royce Allison
- Demonstrate engine ceramic component structural integrity from proof testing
- Establish baseline AGT-5 metal engine performance
- Demonstrate all-ceramic AGT-5 automotive gas turbine engine operation

It should be noted that the AGT-5 engine was used as the test-bed to develop and verify ceramic component technology. The test-bed AGT-5 engine and/or its components were not optimally designed as performance hardware. Rather the components available to assemble an all-ceramic engine were the result of parts produced to evaluate materials and fabrication and producibility techniques. These parts therefore were known to be deficient aerodynamically and their combination into a full engine assembly would result in mismatches between components. In spite of this and with the knowledge that the current HVTE-TS program was ending, it was concluded that an all-ceramic engine test would provide a significant and major milestone that focused the years of development effort undertaken by the combined ATTAP and HVTE-TS programs into a single task to demonstrate the technological readiness of structural ceramic turbine engine components.

One of the HVTE-TS program milestones was to complete the setup of the ATTAP engine test-bed at Rolls-Royce Allison. This included a dynamometer, fuel and inlet air system, air ducting, oil lubrication system, engine controller and instrumentation,

accessory systems, and data acquisition systems. The engine dynamometer test rig was completed in June 1997 as shown in Figure 4-3.

Figure 4-4 is a close-up view of the AGT-5 test-bed engine installed on the dynamometer rig.

To accomplish the HVTE-TS test program goals in an extremely aggressive time schedule, a matrix of six engine configurations for test was defined as shown in Figure 4-5. The initial engine test consisted of an all-metal configuration of the AGT-5 engine with the objective of dynamometer stand checkout and verification of baseline engine performance. The next three engine configurations contained selected ceramic hot flow assemblies to verify component structural integrity. The fifth engine configuration represented the initial ceramic engine to be assembled and successfully operated under the combined efforts of both

Figure 4-3. Engine Dynamometer Test Rig

Figure 4-4. AGT-5 Test-Bed Engine

Figure 4-5. HVTE-TS Engine Test Matrix

the ATTAP and HVTE-TS programs. The sixth engine configuration was an all-ceramic hot gas flow-path AGT-5 engine including combustor, gasifier power section, and two-stage power turbine.

The basic AGT-5 power turbine ceramic components were designed during the ATTAP program. These components were only minimally tested in prior years due to inability to control blade tip clearances and power turbine shaft dynamics. Therefore, ceramic power turbine testing under the ATTAP was delayed until the ceramic gasifier stage structural integrity was proven. The robustness of the ceramic gasifier stage was demonstrated in 1996 by the HVTE-TS program with the successful completion of the third major ATTAP goal—a 300 hr cyclic durability test of an “all-ceramic” gasifier power section.

Prior testing under the ATTAP program had indicated the need to control and minimize operating clearances between the power turbines and static engine structures for maximum engine efficiency. To accomplish this, an improved mount system was developed under the HVTE-TS program for the power turbine static structure assembly. The new mount system maintains a more precise relationship between the power turbine rotor assembly and the power turbine static structure. It also prevents thermal or mechanical distortion of the engine housing from influencing power turbine rotor blade tip clearance.

The power turbine bearing system was also redesigned. The new design provides for enhanced ceramic rotor stability and bearing life with the addition of a patented

Rolls-Royce Allison oil squeeze film damper design to the turbine bearings to ensure proper damping. The power turbine analysis and design activities are discussed in Section 2.4.4, Power Turbine Rotor Design.

Prior to testing the redesigned ceramic power turbine section and bearing system in the engine, the shaft dynamics were verified in a spin rig. Figure 4-6 is a photograph of the spin rig installed on the dynamometer test rig.

The power turbine was driven to 90% design speed (maximum spin rig capability). The power turbine critical speed was predicted to occur at 67% rated speed with no further shaft modes in or near the operating range. Rig vibration response data verified the predictions. Rig clearance probe data showed the bearing and squeeze film damper system centers the power turbine rotor as shaft speed increases.

Test results indicate the ceramic power turbine shaft dynamics should not constrain ceramic engine operational limits.

Baseline Metal Engine Test

Prior to initiating an all-ceramic engine performance test, the entire test stand, controls, instrumentation, and data logging system were checked out by installing an all-metal AGT-5 engine, and generating an overall performance map within the temperature limitations of the metal hardware. Figure 4-7 illustrates the performance characteristics of this baseline metal engine.

Figure 4-6. Power Turbine Shaft Dynamics Spin Rig

Figure 4-7. Baseline AGT-5 Metal Engine Performance

Ceramic Gasifier Proof Test

After completion of the baseline tests, the original metal gasifier assembly was removed, and the ceramic gasifier assembly from the 1996, 300 hr durability test was installed in combination with the original metal power turbine components and a Lamilloy metal combustor. This situation created a mismatch between the temperature and flow capacities of the gasifier and power turbine, but it did allow the generation of a performance map with higher turbine inlet temperatures than before. Figure 4-8 is an operating map of this combination ceramic/metallic engine operating at higher temperatures.

Extrapolation of the demonstrated trends clearly shows that the targets projected for this system appear to be well within reach when turbine inlet temperature is extended to 2500°F (1371°C).

26-Bladed Rotor Proof Test

This proof test utilized an advanced design 26-bladed gasifier rotor in a metallic gasifier test section along with a metallic combustor and metal power turbine. This test showed the 26-bladed ceramic rotor was structurally sound. However, engine operation suggested severe aerodynamic mismatch between the

Figure 4-8. AGT-5 Ceramic/Metallic Engine Operating Map

engine stages. It was decided to employ the 300 hr 20-bladed gasifier rotor for the all-ceramic engine build.

Ceramic Power Turbine Proof Test

The final proof test involved the all-ceramic two-stage power turbine coupled with a metal gasifier stage and metal combustor. The test showed structural or rotor stability concerns should not inhibit the engine operating envelope.

AGT-5 Ceramic Test-Bed Engine Predictions

The performance of the AGT-5 engine incorporating existing ceramic components was predicted using the Rolls-Royce Allison turbine engine performance analysis program. Performance design limitations of individual components were used as input to the analysis. The resulting predictions reflect as-built ceramic engine performance and not the performance that would be anticipated from a ceramic engine with performance optimized components.

AGT-5 Ceramic Test-Bed Engine Tests

The final HVTE-TS program goal was to demonstrate the operation of an all-ceramic AGT-5 test-bed engine.

The ceramic engine was assembled using the ceramic gasifier power section and ceramic regenerator disks which had completed the "all-ceramic" gasifier power

section 300 hr cyclic durability test. The remaining ceramic components were qualified during either hot gasifier rig or engine proof tests.

The initial ceramic engine build employed the standard AGT-5 metallic combustor. After successful engine operation with this configuration, the second ceramic engine configuration replaced the metal combustor with a two-piece ceramic combustor. This all-ceramic engine configuration included:

- Carborundum silicon carbide combustor dome
- Carborundum silicon carbide combustor body
- Kyocera SN252 silicon nitride gasifier inlet scroll assembly
- Kyocera SN252 silicon nitride gasifier rotor
- Kyocera SN252 silicon nitride first-stage power turbine rotor
- Kyocera SN235 silicon nitride second-stage power turbine rotor
- NGK pasted MAS regenerator cores
- Injection-molded insulation housings and cover

These components represent the key technology areas identified by ATTAP and addressed by the HVTE-TS

program. The ceramic and insulated components are shown in Figure 4-9.

Initial testing of the AGT-5 ceramic test-bed engine was completed with the ceramic gasifier section, two-stage ceramic power turbine, and a standard metal combustor. These tests revealed compressor surge was the limiting factor in engine operation. The surge was related to component aerodynamic mismatch which also resulted in elevated engine operating temperatures.

To rectify this problem, several engine modifications were undertaken. These included reworking the compressor diffuser to reduce its throat area, modification of the first-stage power turbine vane set to increase throat area, and improvements to the gas flow path between the gasifier section and power turbine vane set. After several iterations to complete these changes, the compressor surge was overcome. The improvements in gas flow path resulted in engine operating temperatures (combustor, gasifier rotor, etc.) being reduced approximately 200 to 400°F when compared to previous ceramic engine builds. However, the engine temperature levels were still elevated over predicted temperatures and still a result of inherent component mismatch.

At this point, an all-ceramic AGT-5 engine configuration was built including two-piece ceramic

Figure 4-9. AGT-5 Ceramic Test-Bed Engine Key Technology Components

combustor, "all-ceramic" gasifier section, and ceramic two-stage power turbine. Ceramic engine performance data were measured from 60 to 92% gasifier turbine speed. At 92% gasifier turbine speed, the engine developed 72.6 hp with a peak RIT of 2661°F (1461°C). The elevated operating temperature beyond the desired goal of 2500°F (1371°C) was a result of stage aerodynamic mismatch. Compressor surge was not encountered. At this juncture in the ceramic engine test program, the HVTE-TS program was technically complete.

During additional Rolls-Royce Allison engine testing initiated to measure engine exhaust emissions, it was decided to extend the ceramic engine performance mapping to a higher operating speed with an expected rotor inlet temperature that probably would exceed design levels. It was believed the engine ceramic hardware would withstand brief transient excursions to RIT levels around 2700°F (1482°C). At 95% gasifier turbine speed, a peak measured horsepower of 91.3 (68.1 kW) was obtained. Peak gasifier rotor inlet temperature of 2740°F (1504°C) was recorded. Engine operation was normal after this high temperature excursion. During subsequent engine operation to continue exhaust emissions measurements, an engine failure occurred wherein the hot gas path ceramic components (with the exception of the ceramic combustor) were destroyed. Subsequent failure analysis did not reveal the cause of the failure.

Table 4-1 summarizes the test-bed ceramic engine operating points. The AGT-5 ceramic engine maximum power performance is shown in Figure 4-10. Performance data for these operating conditions are shown graphically in Figure 4-11.

Table 4-1. Ceramic Engine Performance Matrix

Output Shaft Speed (RPM)	Gasifier Turbine Speed - % Rated (% Rated)	Gasifier Turbine Speed - % Rated							
		60	65	70	75	80	85	90	95
1500	42	x	x	x		x		x	
2000	55	x		x	x	x	x	x	x
2500	70	x		x		x		x	
3000	83			x		x			x
3600	100					x			
		(Observed)							
Maximum RIT (deg.F)		2045	-	2043	-	2372	2404	2672	2661
Maximum HP		10.5	12.6	22.8	24.3	42.5	52.1	72.0	91.3

Figure 4-10. Maximum Power Performance

Figure 4-11. AGT-5 Ceramic Engine Performance

Ceramic engine testing to acquire these performance data completed the goals of the HVTE-TS engine test program.

The combined hot gasifier rig and engine test-bed rig activity completed under the ATTAP and HVTE-TS programs is shown in Table 4-2.

Table 4-2. Engine and Gasifier Rig Testing

	<u>Test Hours</u>
Engines	
• Durability, System Integration	547
• Ceramic Components Running	977
• Vehicle Running	651
Total Engine Hours	2175
Gasifier Turbine Hot-Test Rigs	
• Ceramic Components Running	2721
• Other Testing	210
Total Gasifier Rig Hours	2931
Total Test-Bed Activity	5106

Conclusion of the HVTE-TS program left several advanced design ceramic components untested. These include one-piece ceramic combustors, circular cross-section advanced gasifier rotor inlet scrolls, improved design 26-bladed ceramic gasifier rotors and reduced leakage regenerator seals. These components are shown in Figure 4-12.

In addition, HVTE-TS engine testing highlighted engine modifications needed to eliminate gas flow-path mismatch. The combination of advanced design components and engine modifications offer the potential of significantly improved ceramic test-bed engine performance.

**Single Piece
Combustor**

**Circular Cross-Section
Gasifier Inlet Scroll Assembly**

**26-Bladed
Gasifier Rotor**

**Improved
Regenerator System**

Figure 4-12. On-Hand Advanced Technology Ceramic Engine Components Remaining To Be Tested

5. COMBUSTION DEVELOPMENT

5.1 Objective/Approach

There were three major combustion development objectives during the ATTAP/HVTE-TS programs:

- Develop a ceramic combustor that will enable sustained operation of AGT-5 test-bed engines and hot gasifier rigs at RPD temperature levels, i.e. 2500°F (1371°C) rotor inlet temperature.
- Develop a short-term emissions objective to meet federal automotive emissions standards while maintaining carbon-free operation when burning methanol fuel.
- Develop a long-term emissions objective to meet California Ultra Low Emissions Vehicle (ULEV) emissions standards when burning diesel fuel. The objective must be met without exhaust gas after-treatment and while maintaining carbon-free operation.

Although the ATTAP/HVTE-TS programs spanned a period from 1987 to 1998, there was no combustion development effort from 1994 to 1996 due to program funding limitations.

5.2 Accomplishments/Results

All three major objectives of the combustion development effort were met during the ATTAP/HVTE-TS programs:

- A two-piece ceramic diffusion flame combustor capable of sustained operation at 2500°F (1371°C) rotor inlet temperature was designed, fabricated, and tested.
- Near the end of the HVTE-TS program, a thin-walled one-piece silicon nitride ceramic combustor was designed and fabricated, but has not been tested.
- A solid wall metal diffusion flame combustor met Tier 0 federal emissions standards of 1.0 gm/mi NO_x, 3.4 gm/mi CO, and 0.41 gm/mi HC on methanol fuel in an original "all-metal" AGT-5 automotive gas turbine. The test was conducted in a Camaro Z28 test-bed vehicle driven over the EPA federal urban driving cycle on a chassis dynamometer.

- A metal poppet-valve premixing/prevaporizing combustor with two ceramic components was tested on DF-1 fuel in an AGT-5 automotive gas turbine operated on an engine dynamometer. Emissions were measured at steady-state conditions that, if integrated over the urban driving cycle, met California ULEV emissions standards.

5.3 Progress/Status/Remaining Work

At the beginning of the ATTAP program, the baseline metal AGT-5 combustor was not capable of sustained operation at the 2500°F (1371°C) rotor inlet temperature required by the RPD cycle. Durability testing of ceramic turbine components at this elevated temperature was hindered by the need for frequent replacement of the metal combustor. By the end of the HVTE-TS program, a ceramic two-piece combustor capable of sustained operation at 2500°F (1371°C) was available for hot section development testing. A less complicated one-piece version of the combustor was fabricated, but not tested before the program ended.

At the beginning of the ATTAP program, the AGT-5 gas turbine could not meet Tier 0 federal emissions standards in effect at the time on either distillate or methanol fuel. Minor modifications were then made to the baseline metal diffusion flame combustor which enabled it to successfully pass vehicle emissions testing over the EPA driving cycle on methanol fuel. To reduce carbon monoxide and hydrocarbon emissions, cooling air was removed from the combustor walls. For such a design to provide acceptable durability, the combustor should be ceramic rather than metal.

At the beginning of the ATTAP program AGT-5 NO_x emissions on diesel fuel were an order of magnitude higher than the California ULEV standard. A poppet-valve premixing/prevaporizing combustor that successfully met ULEV levels for NO_x, CO, and HC at steady-state conditions on DF-1 fuel was designed and tested. Design modifications were identified to address ignition and durability problems encountered during testing, but the redesigned parts were not implemented. Also, integration of the combustor variable geometry with the engine controls was not completed.

Tasks significant to the development and attainment of a low emissions ceramic turbine engine combustion

system that have not been completed and should be considered as remaining work include:

- Engine test of the one-piece ceramic combustor
- Fabrication and test of a ceramic version of the solid wall combustor
- Fabrication and test of the redesigned poppet-valve combustor and integration of variable geometry control with the engine control system

5.4 Ceramic Combustor Development

The baseline combustor for the AGT-5 gas turbine was a metal combustor designed for use with metal turbine components and the corresponding metal engine operating temperatures. Metal combustors were used initially for gasifier testing of ceramic turbine components; however, expected combustor durability problems were encountered at the 2500°F (1371°C) RIT of the ceramic engine operating cycle. These problems are described in the next subsection, 300-hr Ceramic Durability Test. An ATTAP/HVTE-TS objective was established to develop ceramic combustors capable of long term operation at turbine inlet temperatures of 2500°F (1371°C). Ceramic combustors were designed for use with both the baseline and advanced concept turbine scrolls.

The Carborundum alpha silicon carbide combustor for the baseline scroll is shown in Figure 5-1. Mechanical design of this combustor is described in Sections 2.1.1 of the 1988 and 1989 ATTAP Annual Reports. The initial lot of these combustors was fabricated with an out-of-specification wall thickness of 0.246 in. (6.25 mm) due to vendor tooling and shrinkage difficulties. This led to increased stress and failure of the part when engine tested. Failure analysis is described in Sections 2.1.1 and 3.1.3 of the 1991 ATTAP Annual Report. The second lot of combustors was held to the proper 0.158 in. (4 mm) wall thickness, but also failed when engine tested due to subsurface pores. The failure analysis appears in Section 3.1.3 of the 1992 ATTAP Annual Report.

Figure 5-1. Carborundum Alpha Silicon Carbide Ceramic Combustor for Use with Baseline Turbine Scroll

Ceramic combustors for use with advanced concept scrolls were supplied by Norton and Carborundum. The Norton combustor, Figure 5-2, was NT230 siliconized silicon carbide and the Carborundum combustor was alpha silicon carbide. Heat transfer and stress analysis for these combustors appear in Section 2.1.1 of the 1991 ATTAP Annual Report.

Ultimately, the ceramic combustor which performed successfully in an AGT-5 engine equipped with a fully ceramic hot section and operated over the ceramic engine cycle was a hybrid combustor formed from the dome of the combustor shown in Figure 5-1 and the body of the combustor shown in Figure 5-2. This is described in additional detail in subsection 5.4.2, Two-Piece All-Ceramic Combustor.

Figure 5-2. Norton Siliconized Silicon Carbide Ceramic Combustor for Use with Advanced Concept Scroll

5.4.1 300 Hr "All-Ceramic" Gasifier Section Durability Test

A standard AGT-5 porous metal Lamilloy diffusion flame combustor was used during the 300-hr durability test since a proven ceramic combustor design was yet to be demonstrated. The primary factor limiting the metal combustor life was sagging of the combustor dome at the support pin which supports the combustor body. Some cracking was also observed between thumbnail scoops on the dome. Figure 5-3 shows a Lamilloy combustor used during the 300-hr cyclic durability test. Due to limitations in the Lamilloy dome when operating at very high burner inlet temperature (1600°F), the combustor was inspected frequently and domes were replaced at approximately 50-hr intervals.

A second motivation for pursuing a ceramic combustor was the belief that any low emission combustor for a regenerative gas turbine would ultimately be ceramic due to better durability and reduced carbon monoxide and unburned hydrocarbon emissions by eliminating wall cooling.

5.4.2 Two-Piece All-Ceramic Combustor

A two-piece ceramic combustor was designed by modifying two different ceramic combustors from the previously mentioned ceramic combustor efforts. The first of these was a slip cast sintered alpha silicon carbide combustor designed to be used with a metallic thermal variable geometry (TVG) dome. (The TVG concept utilizes a bimetallic strip to ensure a rich mixture for reliable ignition during cold starts. When hot, the strips deflect away from the dome and allow air to be inducted into the primary zone for leaner combustion resulting in reduced carbon build-up and lower NO_x emissions. See Section 1.4.2 of the 1989 ATTAP Annual Report for more details.) Nominal wall thickness was 0.157 in. (3.99 mm). A portion of this combustor (made by Carborundum and similar

Figure 5-3. Lamilloy Combustor Dome After Operation in the AGT-5 Hot Gasifier Rig During 300-Hr Cyclic Durability Test

to the Norton combustor shown in Figure 5-2) was used to form the combustor body, transition, and outlet. A second combustor (made by Carborundum and similar to the combustor shown in Figure 5-1), which was designed for a baseline scroll, was used for the combustor dome. This design incorporated a large swirler around an air assist fuel nozzle. The fuel nozzle was similar to those used in the Lamilloy combustors. Nominal wall thickness was 0.236 in. (5.99 mm).

The two-piece all-ceramic combustor uses desirable features from both combustors. The thinner wall ceramic piece forming the combustor body would have lower thermally induced stress while the ceramic dome incorporated a large swirler. The dilution and primary holes already existing in the combustor body were enlarged to maintain the same pressure drop as the Lamilloy combustor. The resulting combustor configuration is shown in Figure 5-4.

A two-dimensional axisymmetric heat transfer analysis was performed to predict maximum steady-state temperatures. These temperatures were used as input for a stress analysis. The predicted temperatures and probability of survival (POS) for the ceramic combustor dome at maximum power steady-state conditions are shown in Figure 5-5.

Figure 5-4. Initial Configuration of Two-Piece All-Ceramic Combustor

Figure 5-5. Maximum Power Predicted Steady-State Temperature and Probability of Survival

Predicted maximum temperatures were 2691°F (1477°C) and 2638°F (1448°C) for the combustor body and dome respectively. The results were consistent with previous analysis of earlier ceramic combustors. The proposed metal support had predicted temperatures higher than the normal long term usage limit for Hastelloy X and consequently was modified. In addition, the POS was low in the dome region where the ceramic forms a neck. Consequently, this inlet transition around the dome swirler was reduced. The final configuration is shown in Figure 5-6.

Proof testing of the two-piece all-ceramic combustor was performed in the AGT-5 hot gasifier rig to minimize risk to downstream hardware. The outer walls of the ceramic were painted with temperature indicating paints. Paints that indicate 2000, 2100, 2200, 2300, 2400, and 2500°F were used. The combustor lit on the second start attempt after increasing the fuel schedule and fuel nozzle immersion depth. During this run, rig operation was limited to 70% gasifier speed. After about 16 minutes, the rig was shut down. At this

Figure 5-6. Final Configuration of Two-Piece All-Ceramic Combustor with Modified Combustor Support

point, the combustor was removed and inspected. No damage was found on the ceramics and a maximum temperature on the dome was 2000°F (1093°C). Due to unsteady fuel delivery, a second fuel nozzle body was fabricated from a standard fuel nozzle body.

The final phase of the ceramic combustor proof test was to operate the rig at rotor inlet design temperature of 2500°F (1371°C). Gasifier speed was increased in intervals to 60, 70, 80, and 90% of rated speed. After a short hold, rotor speed was dropped to 60% and the engine shut down. Another start was executed and a maximum gasifier turbine speed of 98% of design speed was reached, corresponding to a combustor inlet temperature of 1600°F (871°C) and a calculated rotor inlet temperature of 2552°F (1400°C). Thermocouples located on the inside face of the fuel nozzle shroud and combustor support structure reached a maximum temperature of 2010°F (1099°C) and 1601°F (872°C), respectively. The thermal paint stripes that had been applied axially to both the body and dome indicated a maximum temperature higher than 2500°F (1371°C) was reached in the combustor reaction zone. The heat transfer analysis predicted that the inner wall temperature was more than 100°F higher than the outer wall. Based on this prediction, the ceramic inner wall temperature at this operating condition reached temperatures higher than 2600°F (1427°C), which was

consistent with the maximum combustor body temperature of 2691°F (1477°C) and maximum combustor dome temperature of 2638°F (1448°C). In total, four starts were completed in approximately 2 hr of operation.

Following successful testing of the two-piece combustor, a one-piece ceramic combustor incorporating the major features of the two-piece combustor was designed, analyzed, and fabricated. The one-piece combustor made by Kyocera from SN282 silicon nitride is illustrated in Figure 5-7. The one-piece combustor had not been tested by the time the HVTE-TS program was concluded.

Figure 5-7. One-Piece SN282 Silicon Nitride Ceramic Combustor with Metallic Support and Zirconia Insulator Ring

5.5 Federal Automotive Emissions Standards

Figure 5-8 shows the metal baseline AGT-5 diffusion flame combustor. This combustor was not designed with any particular regard for emissions. The combustor primary zone is slightly fuel rich at the maximum power design point yielding excellent flame stability but correspondingly high rates of NO_x formation. NO_x emissions when burning distillate fuels such as DF-1 or Jet-A were nearly three times

Figure 5-8. Baseline AGT-5 Diffusion Flame Combustor

the federal standard of 1.0 gram per mile. This was measured with the AGT-5 engine installed in the Camaro Z28 test-bed vehicle and driven over the federal urban driving cycle on a chassis dynamometer. Carbon monoxide and hydrocarbon emissions were within the federal limits of 3.4 gm/mi and 0.41 gm/mi, respectively.

When the baseline vehicle was tested with methanol fuel, which has a much lower flame temperature, emissions results were opposite to those obtained with distillate fuel. NO_x emissions were just below the federal standard, but carbon monoxide was two to three times the standard and hydrocarbon was an order of magnitude too high. An ATTAP program objective was established to meet federal standards simultaneously for all three emissions species on methanol fuel by making minor modifications to the baseline diffusion flame combustor. This was to be accomplished without the benefit of exhaust gas cleanup. Therefore, the challenge was to reduce carbon monoxide and hydrocarbon emissions significantly when burning methanol fuel without adversely affecting NO_x. A description of the early portions of this effort appears in Sections 1.4.2 of the 1989 and 1990 ATTAP Annual Reports.

The modified diffusion flame solid wall combustor which met federal emissions standards is shown in Figure 5-9. There are two differences with respect to the baseline combustor. An additional row of air admission holes (intermediate zone) was added and cooling air was removed from the combustor walls.

Figure 5-9. Modified AGT-5 Diffusion Flame Solid Wall Combustor Which Met Federal Emissions Standards

Ordinarily, the function of an intermediate zone in a combustor is to allow carbon monoxide to approach equilibrium at some intermediate temperature prior to quenching in the dilution zone. However, in this case an intermediate zone was added to penetrate some air to the combustor centerline to quench NO_x formation just downstream of the primary zone.

The walls of the baseline combustor are fabricated from Lamilloy, a laminated, porous, transpiration cooled sheet structure. Transpiration cooling is an extremely effective means of cooling combustor walls. However, carbon monoxide and unburned hydrocarbon emissions typically result from the quenching of burnout of these species in the relatively cool film of air along the combustor walls. In the modified combustor, Lamilloy was replaced with solid sheet metal to increase wall temperature and minimize the quenching of carbon monoxide and unburned hydrocarbon burnout reactions near the combustor walls.

The modified combustor was installed in an AGT-5 engine, which in turn was installed in the Camaro Z28 automotive gas turbine test-bed vehicle. The car was then driven over the EPA urban driving cycle on a chassis dynamometer at the General Motors Technical Center. This cycle includes a cold start. The fuel was M85 which is a mixture of 85% methanol and 15% gasoline by volume. A small amount of gasoline is commonly added to methanol to improve cold weather starting performance and to make the flame visible for safety reasons.

Alcohols and aldehydes may be present in the exhaust when methanol is burned. These species are not captured by the standard hydrocarbon measurement using a flame ionization detector (FID). Alcohols and aldehydes were collected in gas impingers, measured by chromatograph, and the results added to the hydrocarbon measurement. Therefore, the reported hydrocarbon emissions for the methanol test are actually total organics.

Table 5-1 compares emissions results obtained with the baseline combustor burning distillate fuel and the modified combustor burning methanol fuel to Tier 0 federal emissions standards. As shown in this table, the baseline combustor exceeded the federal NO_x standard by a factor of 2.8, whereas the modified combustor successfully achieved the program goal of meeting all three federal emissions standards when burning methanol.

Table 5-1. Emissions Levels of Diffusion Flame Combustors Compared to Tier 0 Federal Standards

	HC (gm/mi)	CO (gm/mi)	NO_x (gm/mi)
Tier 0 Federal Standard	0.41	3.4	1.0
Baseline Combustor with Distillate Fuel	0.18	2.3	2.8
Modified Combustor with Methanol Fuel	0.23	2.0	0.9

5.6 Premixing/Prevaporizing Combustors

Conventional gas turbine combustors operate in the diffusion flame mode. Evaporation of fuel, mixing of fuel and air, and chemical reaction all occur simultaneously. The chemical reactions proceed at near stoichiometric equivalence ratios resulting in very high local flame temperatures within the combustor primary zone. Hydrocarbon (HC) and carbon monoxide (CO) emissions are characteristically low; however, formation rates of oxides of nitrogen (NO_x) are high in this mode of operation. To meet future automotive NO_x standards, e.g., California ULEV of 0.2 gm/mi, a different approach, premixed combustion is required.

In premixing combustors the evaporation and mixing processes are separated from the chemical reaction process. Air may take either of two paths through the combustor. Primary (combustion) air enters a fuel preparation zone where fuel is added. Evaporation of

fuel and mixing of fuel and air take place in this region before the mixture flows into a reaction (combustion) zone. Hot combustion products then pass through a dilution zone before exiting the combustor. Air can alternatively take a second path entering the dilution zone directly, bypassing the fuel preparation and reaction zones. With this arrangement fuel evaporates and mixes with an excess of air in a separate chamber before chemical reaction takes place at well below the stoichiometric equivalence ratio. Peak flame temperatures are thus reduced and, therefore, the rate of NO_x formation is greatly reduced.

Unlike diffusion flame combustors, premixing combustors are operated properly only over a narrow range of fuel/air ratios. If the fuel/air ratio is too high, NO_x formation rates increase dramatically. If the fuel/air ratio is too low, HC and CO emissions increase dramatically and eventually a point is reached where the combustor will blow out. Premixing combustors generally have some form of variable geometry to shift the airflow distribution in the combustor to maintain the fuel/air ratio in the reaction zone within acceptable limits over the entire operating range of the engine.

One objective of the ATTAP/HVTE-TS Combustion Systems Development effort was to meet 1997 California ULEV automotive emissions standards (0.2 gm/mi NO_x , 1.7 gm/mi CO, 0.04 gm/mi HC) on diesel fuel. A premixing/prevaporizing combustor is required to achieve this goal. Three combustor concepts were designed; the indexing-head combustor, the sliding-pad combustor, and the poppet-valve combustor. The names are derived from the form of variable geometry employed in each case. Of the three concepts, the poppet-valve combustor was selected for fabrication and engine test.

Indexing-Head Combustor

The indexing-head combustor, Figure 5-10, derives its name from the rotatable cover that controls the airflow split between two concentric paths. The inner path contains the fuel preparation and reaction zones. The outer annular path channels dilution air around the reaction zone for mixing with combustion products just prior to entering the turbine scroll. The indexing-head covers two rows of rectangular slots that open and close as the head indexes. As combustion airflow is increased, dilution airflow is decreased. Total airflow remains constant.

Upon entering the fuel preparation zone, combustion air mixes with the fuel spray. To achieve ultra-low NO_x operation, the fuel preparation zone must provide

Figure 5-10. Indexing-Head Low Emissions Premixing/Prevaporizing Combustor

sufficient residence time for vaporization of the fuel and thorough mixing of the fuel and combustion air. Although residence time is beneficial for evaporation and mixing, excessive residence time within this region may result in autoignition. This must be avoided as it can cause increased NO_x emissions and possibly damage the combustor.

Flame stabilization in the indexing-head combustor is accomplished via a bluff body stabilizer. Premixed fuel and air flow around this dome shaped obstruction that separates the fuel preparation and reaction zones. Hot combustion products recirculate behind this bluff body and continuously ignite the incoming fresh mixture. Since the overall fuel/air ratio varies considerably over the operating envelope of the engine, variable geometry is required to maintain fuel/air ratios and flame temperatures in the reaction zone within a narrow enough window that will ensure both low CO and NO_x emissions. Carbon formation is precluded by the lean premixing approach. The ceramic inner liner surrounding the reaction zone is uncooled except for external convection to the dilution air passing around it. Additional description of the design of the indexing-head combustor appears in Section 1.4.2 in each of the 1989 and 1990 ATTAP Annual Reports.

Sliding-Pad Combustor

The sliding-pad combustor shown in Figure 5-11 performs the same functions as the indexing-head combustor described previously. Variable geometry is employed to control the airflow split between the reaction and dilution zones and maintain a narrow range of fuel/air ratios in the reaction zone. The form of variable geometry is a derivative of that used in the

Figure 5-11. Sliding-Pad Low Emissions Premixing/Prevaporizing Combustor

AGT-100 combustor developed under an earlier DoE/NASA contract, DEN 3-168. Pads that slide axially on the outside surface of the combustor cover and uncover openings in both the fuel preparation and dilution zones. As the flow area of one path is increased, the flow area of the other is decreased. As opposed to the indexing-head combustor, which is predominantly ceramic, the sliding-pad combustor is entirely metal.

Poppet-Valve Combustor

Air enters the poppet-valve combustor, Figure 5-12, through two paths. One path is an annular passage between the combustor inner and outer liners that provides convective cooling of the inner liner. This path leads to the fuel preparation zone where fuel is sprayed into the air by the main nozzle; evaporation of fuel and mixing of fuel and air take place in this region. The mixture then passes around the poppet-valve and enters the reaction zone, where combustion takes place. Recirculation of combustion products downstream of the valve stabilizes the flame. Hot combustion products then pass through the dilution zone before exiting the combustor. Air can alternatively take the second path, entering the dilution zone directly through holes in the combustor inner liner and bypassing the fuel preparation and reaction zones.

The poppet-valve combustor contains two ceramic parts supplied by Norton Advanced Ceramics, an NT154 silicon nitride valve and an NT230 silicon carbide valve seat. Remaining combustor parts are metal.

TE94-1405

Figure 5-12. Poppet-Valve Low Emissions Premixing/Prevaporizing Combustor

Axial movement of the poppet-valve regulates the open area between the valve and valve seat controlling the flow of air to the reaction zone. Fuel/air ratio and flame temperature in the reaction zone are controlled in this manner. This approach is different from the indexing-head and sliding-pad combustors in that flow area is controlled in only one of the two combustor air flow paths. As a result, the poppet-valve combustor has a smaller range of control of the combustor airflow split and a larger variation in combustor pressure loss over the operating range than do the other combustor concepts. However, the advantage of the poppet-valve design is a less complicated, more reliable variable geometry that is less likely to bind in hot operation.

Light-off is accomplished by a start nozzle positioned on the axis of the valve. The combustor operates in the diffusion flame mode until the engine reaches idle speed, at which time fuel is transferred from the start to the main nozzle. The start nozzle is then purged with air that continues to flow during operation at temperature for cooling. The start nozzle is a pressure atomizer, whereas the main nozzle is a continuous air assist atomizer. Additional description of the design of the poppet-valve combustor appears in Section 1.4.2 in each of the 1991 and 1992 ATTAP Annual Reports.

Fuel Nozzle Test

Screening tests of poppet-valve combustor prototype fuel nozzles were conducted by the fuel nozzle supplier. The main fuel nozzle must produce an annular spray since the shaft of the poppet-valve passes through the center of the nozzle. Two concepts were tested: one with a full annular exit slot, the other with a ring of discrete holes. The discrete hole design yielded a more uniform circumferential spray pattern, so this design

TE94-1409

(a) Baseline Design As-Tested

(b) Extended Valve Seat Design

(c) Final Enhanced Backside Cooling Design

Figure 5-15. Schematic of Redesigned Poppet-Valve Combustor

carbide valve seat reached temperatures high enough to induce the silicon to effuse from ceramic. Based on these observations, a redesign was completed to enhance the thermal survivability of the inner liner and ceramic valve seat without altering the low emissions capability of the poppet-valve combustor.

A computational fluid dynamics simulation of the baseline poppet-valve combustor indicated that flow impingement occurred on the inner liner at the location just downstream of the ceramic valve seat. To reduce the heat transfer coefficient at this location, the valve seat contour was extended to gradually turn the flow and minimize direct flow impingement. The baseline and extended valve seat designs are shown in Figure 5-15a,b. Flow simulations indicated that this geometry change should produce the desired change in the flow

structure and consequently should lower the local heat transfer coefficient and wall temperature.

A heat transfer analysis of both the extended and baseline ceramic valve seat designs was performed at the operating conditions associated with the peak power point in the federal urban driving cycle for a metal engine. Steady-state temperatures for this operating point are shown in Figure 5-16. Peak temperatures were predicted to be 2433°F (1334°C) and 2459°F (1348°C) for the baseline and extended valve seat designs, respectively. Stress analyses indicated that steady-state peak stresses were less than 15 ksi (103 MPa) for both designs. Since the baseline concept was observed to reach unacceptable temperatures during testing, the proposed extended valve seat, which was predicted to achieve even higher temperatures, was considered an unacceptable modification.

In both the baseline and extended valve seat designs the ceramic valve seat had minimal backside cooling and consequently was cooled mainly through conduction and radiation. An alternative approach was to use significantly more backside cooling in this region. This was accomplished by reducing the length of the

(a) Baseline Design

** Legend **	
ID	°F
A	2500
B	2400
C	2300
D	2200
E	2100
F	2000
G	1900
H	1800
I	1700
J	1600
K	1500
L	1400
M	1300
N	1200
O	1100

(b) Extended Valve Seat Design

Figure 5-16. Predicted Steady-State Temperatures for the Baseline and Extended Valve Seat Designs

ceramic valve seat and necking the inner liner to meet the top of the valve seat (see Figure 5-15c). The combustor flow path was maintained as closely as possible to the extended valve seat design to avoid flow impingement on the inner liner. The reduction in the length of the valve seat was estimated to reduce valve seat tip temperatures by at least 250°F (139°C).

Drawings were completed for the modified poppet-valve combustor design, however, hardware was never procured and tested due to limitations in funding. Additional description of the poppet-valve combustor redesign and plans for integration of combustor variable geometry with the engine controls appear in Sections 1.4.2 and 1.4.4 of the 1993-1994 ATTAP/ HVTE-TS Annual Report.

6. INSULATION DEVELOPMENT

6.1 Objective/Approach

The objective of the thermal insulation development program was to develop an injection-moldable insulation capable of low-cost, high-volume production for application to automotive gas turbine components. The approach selected was to modify the insulation material system for improved injection-molding properties while developing the injection-molding process for both simple and complex engine components. In addition, associated developmental items were addressed including: insulation/metal hardware bondability, erosion resistance and non-hazardous nonrespirable materials. Efforts by General Motors Corporation, Rolls-Royce Allison, and Schuller International (formerly Manville Corp.) supported this development.

6.2 Accomplishments/Results

Development efforts under the ATTAP and HVTE-TS programs have significantly advanced the state of the art as related to injection-molded insulation thermal performance, surface erosion resistance, application to complex shapes, mass production potential, and cost/performance trade-offs.

Results of the development program include:

- Successfully demonstrated insulation injection-molding feasibility for both simple and complex turbine engine components
- Material characterization of molded insulation has shown all criteria were met for density, erosion and surface hardness, and thermal conductivity
- Thermal cyclic durability testing demonstrated that the molded insulation components met performance goals
- Injection-molded insulation thermal cyclic durability and erosion resistance has been demonstrated during limited testing

- Injection-molded insulation components have been successfully used in hot rig, engine and vehicular test-beds

6.3 Progress/Status/Remaining Work

The application of protective thermal insulation to turbine engine structures has progressed from small batches of hand laid up simple surfaces to the development of a system capable of high performance injection-molding of complex contours:

- Prototype injection-molding hardware system was developed
- Insulation injection-molding process has been established
- Injection-molding system was developed and demonstrated in pilot line trials which applied insulation to the complex interior shape of an automotive turbine engine housing

Tasks significant to the development and attainment of an injection-moldable insulation capable of low-cost, high-volume production which have not been completed and should be considered as remaining work include:

- Long term durability and erosion testing
- Insulation system resistance to water, fuel and oil
- Evaluation and definition of potential health hazards of the insulation materials (if any)
- Additional material and process development to achieve higher temperature capability, reduce thermal conductivity and address injection-molding tooling needs
- The demonstrated ability to successfully injection-mold insulation on a pilot basis remains in its infancy. Additional testing and development are required.
- Automated tooling placement and retraction needs to be addressed before the economies of scale can be realized

6.4 Materials Development

The higher cycle temperatures permitted by the all-ceramic engine flow path mandated an advanced insulation system capable of withstanding these higher temperatures and be mass producible and cost effective.

Several approaches to injection-molding were evaluated with parallel development of insulation material

suitable for injection. Early attempts at injection with material developed for hand lay-up applications proved to be unsatisfactory. Generic problems in this approach were failure to adequately fill the mold cavities, poor bonding to the part being insulated, and substandard surface finish. Additionally, variations in insulation density due to the application process and material mix had to be overcome to meet thermal performance goals.

Material development focused on fiber length, ratios of binder liquids to fibers, mixing times, water content, handling, and storage. Suitability for injection of the various samples was determined by trial injections on simple shaped engine parts. The AGT-5 gasifier housing and burner cover were used for this purpose. Additionally, square samples were injected for use in the thermal cyclic durability rig and other samples for thermal conductivity testing.

Processing of raw fiber revealed an optimum level of fiber treatment. The optimal level balanced the quality of surface finish with material density and drying shrinkage along with moldability. A nondimensional indicator was used to signify the processing level of the fiber. The fiber processing level (FPL) relates to the degree of fiber cleaning prior to incorporation in the insulation mixture. At higher processing levels, the insulation surface finish improved on the cured part but with higher shrinkage due to the insulation drying cycle.

Table 6-1 illustrates the effects of fiber processing levels on average drying shrinkage deviations. The higher fiber processing levels indicate progressively shorter fiber lengths as a result of longer processing time and greater agitation. As the fiber processing level increased, the texture of the wet insulation became smoother but the drying shrinkage increased. The best balance of wet insulation smoothness and low drying shrinkage was at a FPL of 600 and 57% fiber content.

Table 6-1. Fiber Processing Level Drying Shrinkage Deviation

Fiber Processing Level	Average Drying Deviation (in.)
500	0.054
600	0.042
675	0.097
750	0.060
1000	0.076
1250	0.136
1500	0.167
1500 (10% less water)	0.139
1500 (10% less water, more fiber)	0.121
1500/200 (80%/20%)	0.087

Concurrent with the fiber processing study was exploration of various binder mixtures and content. At the onset of this program no fiber/binder combination met all of the parameters of moldability, surface finish, and shelf life. Early efforts resulted in some criteria being met at the expense of others. Initial mixtures produced poor mold release characteristics but acceptable shrinkage.

Subsequent development led to improved mixtures and fiber processing. The resultant wet insulation compound possessed the required combination of characteristics of moldability, shelf life in the as mixed state, surface finish, bonding to parent parts, shrinkage, and thermal/erosion performance.

These developments occurred over a four year period at the Schuller International laboratory and in parallel with the mold tooling design activities at General Motors and Rolls-Royce Allison.

Figure 6-1 shows the results of thermal conductivity testing of various mixture samples in a temperature calorimeter at temperatures up to 2100°F (1149°C). No significant differences were noted between mixtures ranging from 18 lb/ft³ (288 kg/m³) to 23 lb/ft³ (368 kg/m³) in density.

Figure 6-1. Injection-Molded Insulation Thermal Conductivity

The mixture of 22 lb/cu ft (352 kg/cu.m) was selected as the preferred insulation compound because it met all criteria for insulating properties, erosion resistance, moldability, and cost consideration.

6.5 Processes

At the start of the program no injection-molding systems existed to utilize the unique properties of the selected insulation compound in a high volume, low cost, mass producible manner. The major problems were releasing the finished part from the mold, adhesion to the metal part, and injectability of the insulation. Additionally, the injection equipment required development to allow injection of the high viscosity insulation mixture.

A year long development effort resulted in injection equipment suitable for laboratory scale trials of the insulation mixtures. A series of hydraulic and pneumatic cylinders were employed as injection equipment. Schuller International worked closely with the design team at the General Motors Technical Center to design and fabricate this equipment. Both Schuller and General Motors conducted insulation injection experiments. The Aeroquip Corporation was contracted to provide pilot line scaled equipment and conduct injection tests on engine parts provided by General Motors. One lot of 24 AGT-5 gasifier housings was loaned to Aeroquip for this purpose.

Several mold release compounds were evaluated. These compounds were already in service as release agents used in other molding processes. None of the existing release agents proved suitable for the combination of molds, insulation mixture and injection pressures required. The high bonding agents required for the insulation to adhere well to the parts being insulated also bonded "too well" to the molds being used.

Three approaches to modifying the molds were tried: (a) highly polished mold surfaces, (b) Teflon-coated molds, and (c) a sacrificial mold liner. Highly polished mold surfaces proved to be expensive to produce and had less than satisfactory results. Various mold release agents were tried on the polished surfaces but they didn't work reliably with the insulation compounds.

The molds were then Teflon coated with similar results. Polyethylene liners that closely mimicked the mold surfaces were then tried with some degree of success. The liners allowed the mold to part from the injected part without adhering to the mold. The liner was then peeled from the wet insulation surfaces and discarded. While this method provided satisfactory results for simple-shaped parts it was not practicable nor

economical for the complex shapes of the engine housing. The design of the molds and inserts for the engine housing was done at General Motors and the resultant hardware sent to Schuller for further development.

Schuller used the multipiece mold system to develop a unique process that finally allowed the molds to release from the engine housing while leaving the insulation intact. The molds were modified to incorporate a ring mesh coat similar to ancient chain mail armor or a modern day "shark suit". The ring meshed molds were then covered with Spandex cloth that served the same function as the polyethylene liners. The Spandex was permanently attached to the mold and allowed the molds to be separated from the engine housing, with the Spandex peeling away from the wet insulation. The ring mesh that was between the mold and the Spandex allowed air and water to pass through space between the rings of the mesh and the mold. This was a very significant development in molding technology that permitted further work toward a high volume, low cost insulation injection. Figures 6-2 and 6-3 show complex and simple engine components with injection-molded insulation.

Figure 6-2. Injection-Molded Insulation in AGT-5 Engine Housing

Figure 6-3. Gasifier Housing and Combustor Cover Treated with Injection-Molded Insulation

The next generation of mold development was to cast the features of the ring mesh directly to the mold surface. This eliminated the ring mesh and resulted in a simple, two-piece mold. Experiments with the two-piece mold were conducted at Schuller Labs with very good results. Three engine housings were insulated with generation 1 and 2 molds and were placed under engine operational tests at Rolls-Royce Allison.

6.6 Evaluation Tests

One of the engine housings was built as a gasifier test rig to evaluate gas producing modules that utilized high temperature ceramic components. This engine rig operated at temperatures in excess of 2500°F (1371°C) and allowed cyclic testing of the hardware and insulation. Three hundred hours of cyclic testing were completed on this housing at elevated temperatures with no significant degradation of insulation performance. The insulated engine housing after the 300-hr test is shown in Figure 6-4. The gasifier housing injection-molded insulation (Figure 6-5) was cracked and debonded close to the hot section. However, it remained in place and was fully operational throughout the 300-hr test. The injection-molded combustor cover insulation (Figure 6-6) showed no evidence of damage.

Figure 6-4. AGT-5 Engine Housing after 300-hr Cyclic Durability Test

Figure 6-5. AGT-5 Gasifier Housing After 300-hr Cyclic Durability Test

Figure 6-6. AGT-5 Combustor Cover after 300-hr Cyclic Durability Test

A second engine housing was built up as a metal flow path engine and installed in a vehicle for over the road testing of the insulation under actual driving conditions. The testing allowed evaluation of the overall durability of the insulation system, road shock and load, and noise intrusion into the vehicle. The tests were conducted over a three month period and compiled over 60 vehicle run hours. The test was halted after a failure of an older generation turbine component. The engine was disassembled and the insulation was inspected. No failure of the insulation was found or any surface erosion evident. This was the first "real world" testing of the insulation system.

The third engine housing was built as the all-ceramic flow path engine and placed under test. While not specifically tested for insulation characteristics, this did prove that the insulation performed as required at transient internal engine temperatures above 2500°F (1371°C). No significant cracking or erosion was found upon inspection.

Flat test samples were molded onto a 12-in. square plate for thermal cyclic durability testing. The samples were molded using the same generation of technology as the engine parts. The thermal cyclic durability rig was fabricated by Schuller and testing conducted in their laboratory. The burner rig is shown in Figures 6-7 and 6-8.

Figure 6-7. Thermal Cyclic Durability and Erosion Burner Rig

Figure 6-8. Insulation Sample Installed in Durability and Erosion Burner Rig

The rig had the capability to impinge the sample with burner flame at over 1800°F (982°C) and at a gas velocity of 250 ft/sec (76.2 m/sec). These parameters represented the expected engine maximum power operating point. The cycle of the rig was to blast the test sample with the flame for 15 seconds per minute for 10,500 cycles. The test cycle is shown in Figure 6-9.

The first sample tested was of hand lay-up mixture. This sample debonded early in the test and cyclic testing was stopped. Modifications were made to the sample holder to obtain additional temperature readings on the cold side of the test sample.

The next test was an injection-molded sample with an FPL of 500. A total of 10,500 cycles was completed on this sample with no obvious distress to the insulation. The center portion of the sample was darkened slightly by the flame impinging on an area of about 3 in. (76 mm) in diameter. The insulation remained firmly attached to the sample holder throughout the test.

Figure 6-9. Insulation Thermal Cycle Schedule

Cyclic testing of improved injection-molded material (FPL of 200) was started with the insulation hot side temperature at 1800°F (982°C) and the temperature was increased 100°F (56°C) after every 1000 cycles. A maximum temperature of 2400°F (1316°C) was reached and held for 1000 cycles. Evidence of small cracks in the area of flame impingement appeared but no signs of failure of the insulation were obvious.

Injection-molded engine components were also subjected to thermal cyclic durability testing in the Schuller test rig. Figures 6-10 and 6-11 show the insulated AGT-5 gasifier housing undergoing cyclic testing with insulation hot side temperatures over 1800°F (982°C) and at a gas velocity of 250 ft/sec (76.2 m/sec). These tests showed the injection-molded engine parts had bondability, durability, and erosion resistance characteristics suitable for application in the AGT-5 ceramic engine environment.

Figure 6-10. Injection-Molded Gasifier Installed in Thermal Cyclic Durability and Erosion Burner Rig

Figure 6-11. Injection-Molded Gasifier Housing under Test Thermal Cyclic Durability and Erosion Burner Rig

7. REGENERATOR SYSTEM DEVELOPMENT

Fuel economy requirements of gas turbine engines for application to automotive environments dictate highly effective exhaust heat recovery systems to minimize fuel consumption. The Rolls-Royce Allison approach for exhaust heat recovery is to employ a rotating regenerator system. The regenerator and associated seal systems are key elements that were identified for development for application to automotive turbine engines.

Activities associated with the regenerator and seal system development were conducted in-house and with partners including Corning Incorporated and Argonne National Laboratory (ANL).

In 1991, Corning initiated a major multiyear ceramic regenerator development program. Activities included regenerator disk material selection, material optimization, and fabrication process development. Corning goals included the development of low cost, high cell count extruded ceramic regenerator disks compatible with automotive turbine engine operating environment and durability requirements.

ANL provided materials support for the regenerator system. Program goals included the identification and development of low friction, low wear materials for regenerator hot seal crossarms, and techniques for drive gear reduced friction and wear.

7.1 Objective/Approach

The primary objective of the task was to develop an efficient and cost effective regenerator system compatible with high volume manufacturing. The regenerator system development efforts were focused on materials and processes development, component design, testing, and evaluation of candidate materials and systems for use in an advanced high temperature automotive turbine engine.

7.2 Accomplishments/Results

Substantial progress was made in all areas of the regenerator system development including:

- Materials, processes, and extrusion die technology has been developed and demonstrated in a production scale environment demonstrating the potential of automated ceramic regenerator

disk production which meets both technical and cost targets for automotive application.

- An improved LAS ceramic regenerator material with reduced fabrication costs was developed by Corning.
- More than 110 hr of chemical compatibility testing confirmed LAS regenerator material has sufficient salt and sulfur corrosion resistance to meet automotive exposure and life requirements.
- An improved MAS microcracked material was developed that meets the cyclic hot face life requirement at regenerator inlet temperatures below approximately 1750°F (954°C).
- Large face area one-piece extrusions of MAS ceramic regenerator disks were fabricated and delivered by Corning.
- Large face area one-piece extrusions of LAS ceramic regenerator disks were fabricated and delivered by Corning.
- More than 300 hr of hot rig testing with pasted MAS ceramic regenerator disks were completed at Rolls-Royce Allison.
- A 500-hr cyclic durability test of one-piece extruded MAS ceramic disks with regenerator inlet temperatures to 1750°F (954°C) was successfully completed at Rolls-Royce Allison.
- Regenerator seal material development, tribology studies, and testing were completed at Argonne Labs.

7.3 Progress/Status /Remaining Work

Substantial progress was made in all areas of the regenerator both in terms of reducing cost and improving performance.

- A major result from the development program is a new LAS disk material that can be produced at a much lower cost per pound and meets regenerator strength requirements
- Extrusion die technology development has enabled Corning to produce 9-in. diameter MAS and LAS disks with 5 mil thick cell walls at 1150 cells/in.²

- Cyclic testing demonstrated LAS material hot face strength is maintained throughout the regenerator 10,000 cycle design life.
- A combination of regenerator seal configurations has been identified as the optimum secondary sealing system. Time has prevented demonstrating seal system performance.
- Screening tests conducted by ANL identified two cold wearface and one hot crossarm materials which have the potential to reduce the cost of the seal primary wear faces by an order of magnitude.
- Low cost solutions to regenerator gear wear have been identified by ANL.
- An investigation of alternate techniques for attaching the drive gear to the regenerator ceramic core material was completed.

Tasks significant to the development and attainment of regenerator systems capable of low-cost, high-

volume production that have not been completed and should be considered as remaining work include:

- Continued ceramic extrusion die development work to enhance the capability for single piece extrusion of large diameter regenerator cores
- Continued regenerator core material development to improve material properties
- Performance and durability testing of candidate hot seal materials employing full scale regenerator cross arms
- Evaluation of proposed low cost solutions for regenerator gear wear
- Rig testing to evaluate performance and durability of candidate hot and cold seal configurations
- Long term friction and wear testing of crossarm seal materials
- Long term performance and durability testing of optimum regenerator system configuration in an automotive environment

7.4 Regenerator System Development and Test

7.4.1 Corning Regenerator Material and Process Development

Corning Incorporated activities included regenerator disk material and fabrication process development. Corning focus has been on regenerator disk overall cost reduction to levels acceptable for automotive use.

The regenerator disk material and manufacturing technique are key aspects of the cost and capability of the regenerator system. Previous Rolls-Royce Allison regenerator systems have incorporated different materials (ceramic and metallic) and their associated manufacturing techniques. Ceramics were selected as the automotive engine regenerator core material because of their high temperature and low thermal expansion characteristics. Corning Inc. has been in the forefront of ceramic core materials and manufacturing

research and has been an integral part of the automotive gas turbine development programs.

During the ATTAP and HVTE-TS programs, different candidate ceramic core materials were investigated. Five of these materials and their initial characteristics are shown in Table 7-1.

Only initial screening tests were completed on the last two materials, MAT (mullite aluminum titanate) and NZP (zirconium phosphate), because the remaining materials offered more potential. Based on the AS material characteristics, process improvements were explored to reduce cost but no viable processes were identified. Therefore, the development program efforts were directed toward magnesium-aluminosilicate (MAS) and lithium-aluminosilicate (LAS) materials.

MAS is in mass production for catalytic converter substrates and has matured over the years to a relatively

Table 7-1. Candidate Ceramic Regenerator Core Materials

Material	Strengths	Weaknesses	Research Focus	Relative \$
MAS	Low Cost, Chemical Resistance	Low Strength, High Expansion	Composition	1
LAS	Low Expansion, Good Strength	Chemical Resistance, Cost	Composition / Process	10
AS	High Strength & Temperature Capability	High Cost	Process	100
MAT	Very High Temperature Capability	High Cost, Many Unknowns	Composition / Process	>100
NZP	Expected Good Material Properties	Undeveloped Material, Cost	Composition / Process	>100

low cost material. However, the requirements for a regenerator disk are different than the catalytic converter substrate, and therefore development was directed at improving strength and reducing thermal expansion.

The majority of material development efforts was focused on LAS. The most significant improvement to LAS was made by reducing the amount of high cost glass used as the raw material ingredient. Previous LAS was made from 100% glass. Reducing glass content significantly lowers processing cost. However, material properties are also altered. Therefore development efforts focused on adjusting the compositions with low glass composition while maintaining adequate material properties. This effort was successful in reducing the cost ratio between LAS and MAS from 10:1 to approximately 2:1. The chemical durability of LAS with respect to sodium was improved, but the durability with respect to sulfur was decreased. Thus the net effect was the chemical durability of this new LAS was projected to be in the marginal to acceptable range.

The relation between thermal expansion and strength of solid extruded rods as shown in Figure 7-1 provides a capsule representation of MAS and LAS material development. The low expansion of MAS is largely due to controlled microcracking. It is theorized that when the microcracks are highly stressed by cycling to elevated temperatures, they grow and result in strength loss. It was thought that MAS with reduced microcracks would result in a material with slightly higher expansion and higher strength than that of the MAS-2 point in Figure 7-1. This effect should result in a better retained strength after thermal cycling and shock.

When evaluated using a slow thermal cycling test, MAS materials formulated in 1995 with less microcracking did show a significant improvement as demonstrated by less change in length after slow cycling tests. However, when evaluated using a rapid cycling thermal shock test, the retained strength was no better than MAS-2. Additional development of MAS materials was put on hold until after extruded disks with long time exposure in engine tests became available.

LAS materials development has included efforts to reduce material cost and firing shrinkage (which results in distortion and cracking). LAS is currently a glass-based material (MAS is 100% mineral-based) which involves more pre-extrusion processing and a higher extrusion pressure than MAS, resulting in higher processing cost. LAS-3 development involved adding mineral content to the extrusion batch to decrease cost, improve extrudability, and reduce firing shrinkage to acceptable levels. The LAS-4 material is a progression from LAS-3 obtained by optimizing sintering and firing cycles.

Early ceramic regenerator cores for gas turbine engines were fabricated by a wrapping process. This process is not cost effective for high-volume production. Independently of the regenerator effort, Corning has demonstrated that extrusion of MAS cellular structures for automotive catalytic converters is a feasible production process. Current extruded converter substrates have 400 to 500 cells/in.² (62-78 cells/cm²) with wall thickness to 0.0065 in. (0.165 mm). Thermal efficiency targets for regenerative gas turbine engines dictate high heat transfer surface area and low pressure drop for rotary regenerators. This translates to cell counts on the order of 1000-1500 cells/in.² (155-233 cells/cm²) and wall thickness of 0.004-0.005 in. (0.102-0.127 mm) respectively. Extending current die technologies based on the catalytic converter extrusions, Corning has provided Rolls-Royce Allison with regenerator cores having 1100 cells/in.² (171 cells/cm²) and 0.006 in. (0.152 mm) thick walls in MAS material.

In summary, LAS has better material strength and temperature properties while MAS offers a cost savings over LAS. Material selection for an application will be based on various factors such as maximum temperature, cost, chemical durability, etc.

Figure 7-1. Corning MAS and LAS Materials Development

7.4.2 Rolls-Royce Allison Regenerator Design, Fabrication, and Test

Rolls-Royce Allison has concentrated design and fabrication efforts on a regenerator system sized for engines up to 67 hp (50 kW) intended for hybrid vehicle use. Test activities have involved both this size hardware as well as larger hardware used in the 100-200 hp (75-150 kW) AGT-5 engine. The hybrid-size engine utilizes a 1:1 air-to-exhaust area ratio. This concept, along with a narrow constant section seal arm, as shown in Figure 7-2, was incorporated to reduce part count and cost.

Regenerator System Design

Rolls-Royce Allison regenerator disk design has concentrated on the hub area to reduce cost and to incorporate features made possible by extrusion. The latest design incorporates an extruded hub developed by Corning. Previous designs had used a cast hub which was separately fired and machined on its outside diameter. The hub was then joined to a separately fired, premachined matrix core in a third firing cycle using a cement that was matched in thermal expansion to the individual parts. The extruded hub is pressed into a separately extruded disk matrix while both are still in the "green" as-extruded state. The assembly then goes through a single firing with no premachining or cement joint required. Figure 7-3 shows a green extruded hub and one that has been installed and fired into a piece of disk matrix versus the cast and cemented hub.

Previously, the outside diameter of the disk hub was driven by the matrix production process. The diameter of the wrapping mandrel or the extrusion die center support rod dictated the hub diameter. The center bearing was redesigned so that it and the disk hub would be covered by the narrower, constant width seal crossarm. This maximized the unblocked open frontal area of the disk available for heat transfer. The hub

Figure 7-2. Regenerator System for Hybrid-Size System

Figure 7-3. Green Extruded Hub and Extruded Hub Fired into Disk Matrix versus Cast and Cemented Hub

redesign transferred all of the retention features for the center bearing from the disk hub to the more easily machineable metallic mounting spindle. The pressed-in hub is extruded with a single constant diameter through-hole which is finished machined after firing with one constant diameter boring operation.

The pressed-in extruded hub has undergone static-load testing successfully withstanding approximately eight times the expected radial forces and forty times the expected axial forces.

A critical aspect of the regenerator system is the design of the seals. A schematic view of the original regenerator seal system is shown in Figure 7-4.

Figure 7-4. Regenerator Seal Concept

The seal system consists of the primary seal wearface directly contacting the rotating disk and a secondary seal leaf system bridging between the engine housing or cover and the primary seal platform. The secondary seal allows the primary seal to move axially to compensate for wear, disk out-of-flatness, or misalignment. Leaks through the regenerator seals significantly impact turbine engine performance since these leaks are losses directly overboard from the compressor discharge. The early seals consisted of monolithic carbon-graphite material for the cold seal and the hot side rims. Metal leaves were used for the secondary seals attached to the engine housing. This seal system design was not adaptable to mass production due to the number of parts that had to be assembled into the engine housing as separate pieces. In addition, it was determined that thermal gradients through the seal leaf resulted in low cycle fatigue cracks and excessive leakage. These two factors were the major reason improved regenerator seal designs were investigated during the ATTAP and HVTE-TS projects.

The secondary seal can be designed in one of three basic configurations. Figure 7-5 illustrates the three concepts that were evaluated for this application. The L-seal was chosen as the inboard secondary seal in the latest design.

For the seal system to work properly, it must be preloaded axially to ensure the sealing surfaces remain in contact with the regenerator disk. The L-seal requires a separate member to load the L simultaneously against both the seal platform and the inside of the housing seal groove. This flexible element must be able to apply a uniform load along the entire L and should be able to provide a nearly constant force over the full required axial travel range. Several alternative approaches to load the L-seal were designed. Two of the designs were fabricated and tested:

- Finger spring mimicking the axial loading action of the attached or reversed leaf design
- Commercially available continuous canted coil spring

Figure 7-5. Secondary L-Seal

The finger springs are shown in Figure 7-6. The canted coil spring was proposed as an alternate design (see Figure 7-7). Large deflections (to 45% of the initial spring height) can be accommodated by canted coil spring permitting an overall compact design. It is easily installed and can be manufactured in a variety of high temperature materials.

Regenerator System Test Rigs

In addition to the core development work at Corning, Rolls-Royce Allison also conducted extensive development testing on regenerator disks and seals.

A gasifier rig (incorporating twin regenerator disks) for regenerator durability testing was set up at Rolls-Royce Allison (see Figure 7-8) for regenerator core testing. This rig serves two purposes:

- Exposes regenerator disks to thermal gradients and pressures similar to those expected in the developmental engines
- Exposes regenerator disks to NaCl salt typical of seashore and winter driving environments as well as low sulfur diesel fuels (to check chemical stability of the disk material)

Figure 7-6. Finger Spring

Figure 7-7. Canted Coil Spring

Figure 7-8. Small Regenerator Gasifier Test Rig

As a part of the ATTAP and HVTE-TS projects, a single disk hot flow performance rig was also designed and fabricated to test the hybrid-size regenerator system design in a controlled environment where perform-

ance parameters can be evaluated in detail. The primary purpose of this rig is to measure regenerator system leakage. The rig accepts a single disk and its mating seals from the hybrid-size engine. Figure 7-9 is an overall plan view of the rig.

Figure 7-10 shows the disk test section of the single disk rig installed in a test cell. The rig operates at simulated steady-state engine conditions, with electrically heated inlet air simulating compressor discharge air and gas side inlet air heated by a gas-fired burner simulating turbine exhaust gas.

Orifices upstream and downstream of the high pressure half of the disk are used in measuring airflow. The difference between these air mass flows is regenerator system leakage plus disk carryover. Extensive pressure and temperature instrumentation at the inlet and exit of both the air and gas halves of the disk provide data to calculate pressure drop and disk thermal effectiveness and to assess flow distribution.

Figure 7-9. Plan View of Single Disk Hot Flow Regenerator Rig

Figure 7-10. Single Disk Hot Flow Regenerator Rig

A torque meter is used to measure disk drive torque to permit evaluation of seal wearface materials friction and clamping forces. In addition to measuring disk and seal performance parameters under controlled, high temperature conditions, the rig can evaluate mechanical design integrity with short-term durability tests. Rig control is provided by a dedicated computer system for consistent operation. The computer system also provides enhanced data acquisition, reduction, storage, and retrieval.

Regenerator Core Testing

MAS extruded disks have completed 550 hr of steady-state durability testing. During these tests, the rig was operated at two inlet flow conditions of interest. In the first series of tests, the regenerator hot side inlet temperature was maintained at 1750°F (954°C) and a

low pressure condition for 500 hr. One of the disks from these tests is shown in Figure 7-11. These disks have also completed 50 hr of steady-state testing at the low temperature/high pressure condition.

Chemical compatibility testing of regenerator core material was conducted in the small gasifier rig using two extruded LAS disks. The fuel for this test had salt and sulfur added to it to simulate approximately 5100 hr of engine operation in an environment combining the average airborne salt concentrations measured on a seashore with the sulfur concentration of 0.05% sulfur fuel. Damage rate assumptions are based on previous Corning experience with LAS material. The test program had completed 110 hr of running at the termination of the HVTE-TS program.

These tests verified the expected deformations of LAS materials with exposure to these chemicals. Figure 7-12 illustrates one of these cases. Although deformed, the disks remained operational and are available for more extensive testing.

In addition to the full rotating disk testing, regenerator disk material samples have been exposed to simulated engine acceleration temperature spikes using a gas-fired cyclic thermal rig. After testing, the regenerator material was analyzed to determine hot face strength loss.

The samples were exposed to cycles that represent expected operating transients including initial start-up. The start-up accelerations were the most severe, with a rapid step in "exhaust gas" temperature from ambient to 1900°F (1039°C), held for several seconds, and followed by a rapid decrease to 1350°F (732°C). The rig was then cycled from 1350°F (732°C) to 2090°F

Figure 7-11. Extruded MAS Disk After 500 hr Test in Small Regenerator Gasifier Rig

Figure 7-12. Regenerator Surface Profile after Salt and Chemical Durability Test

(1143°C) (10% was added to the 1900°F [1039°C] peak to account for burner pattern) and back to 1350°F (732°C) every 15 seconds.

Samples of both MAS and LAS extruded material were evaluated for various numbers of temperature cycles. Figure 7-13 presents some results and shows how the samples were sliced at six axial stations through the disk from hot to cold face. Each slice was cut into three modulus of rupture (MOR) test bars and strength data obtained. All data shown were from samples tested to the 2090°F (1143°C) peak temperature. While this test indicates LAS is useful to 2090°F (1143°C), MAS retains almost no strength when cycled to this temperature.

Regenerator Seal Testing

A thermal survey test of the regenerator system was completed using the single disk rig. The survey used thermal paint on all of the seal wearfaces and secondary leaf seals. Thermal paint records a maximum temperature and provides a good indication of thermal gradients, but provides no information regarding temperature change rate or history. The intent of this testing was to obtain temperatures for a given operating point and to guide the future placement of thermocouples that would provide a complete picture of temperature history.

Figure 7-13. Modulus of Rupture for Disk Samples Exposed in the Cyclic Thermal Rig

Figure 7-14 shows results for the hot side wearface and secondary seal operating at the maximum power point of a typical hybrid turbine engine operating cycle with an average regenerator hot side inlet temperature of 1718°F (937°C). The maximum regenerator seal component temperature was 1425°F (774°C) at the center of the crossarm of the hot side seal wearface. The hot wearface rim seals reached a maximum of 975°F (524°C).

A maximum temperature of 1200°F (649°C) was recorded on the hot side secondary seals. Although not shown in the figure, a maximum temperature of just over 700°F (371°C) was recorded on both the cold side wearface and secondary seal.

Figure 7-14. Thermal Paint Pattern on Inboard (Hot Side) Regenerator Seal Wearface and Leaf at Maximum Power Condition

Additional lower inlet temperature operating points were also run to provide data on how the temperature field changed with regenerator inlet temperature.

The L-seal design represented an improvement in reduced seal leakage over the conventional leaf seal design. L-seal performance has been demonstrated in rig and engine tests. Problem areas identified with the L-seal included leakage at the corner, leakage at the overlap joint, and insufficient axial travel to accommodate seal wear and the stack up of axial tolerances.

While the L-seal was an improvement over the attached or reverse leaf seal designs, it was not easily adaptable to "drop-in" assembly. In addition, better sealing could be obtained if the seal could be made as a single piece and could be used between parallel planes. A metal bellows satisfies these requirements, but cost is prohibitive.

Rolls-Royce Allison conducted finite element modeling studies to define a single piece alternative seal concept to both the bellows and L-seal. These results were then transferred to EG&G Sealol, Inc., who further developed the concept. The result was a unique D-shaped metal seal with a V cross section (the V-seal). Volume flow through the exhaust side of the disk is greater than the air side. This results in an unbalanced pressure load on the regenerator that during operation tends to force it against the regenerator disk cover. This cold side secondary seal runs bottomed against the cover. Thus the secondary seal on this side needs only limited axial travel capacity, within the range of the V-seal.

Flow fixture test results for the V-seal (Figure 7-15) demonstrated the seal leaked at a rate less than 50% of the L-seal. In addition it is cost effective in automotive quantities. It is also a "drop-in" seal compatible with assembly line installation. The V-seal was incorporated into the design for the hybrid engine and retrofitted into the smaller engine housings.

Unlike the attached and reverse leaf seals, the L-seal must be preloaded against the groove and the seal platform with a separate mechanical spring. This assures that the seal is initially in contact with its mating surfaces. With the L initially in contact, differential air pressure will force the seal against its mating surfaces, actually decreasing leakage. This will only occur if the sealing faces are initially contacting. Initially a helically wrapped metal strip was used to accomplish this function. This arrangement only allowed approximately 0.010 in. (0.25 mm) of axial travel before becoming coil bound and locking up. Rolls-Royce Allison tried

Figure 7-15. V-Seal Test Results

replacing the metal coil with a finger spring. This provided sufficient axial travel, but proved extremely difficult to manufacture and install.

The finger spring was replaced with a patented canted coil spring manufactured by Bal Seal, Inc. The coil spring met technical and cost requirements for this part. This is a helical spring, but the coils are canted with respect to the axial centerline of the spring. The spring is manufactured in a variety of materials, sizes, and spring rates. Because of the unique geometry of the spring, the force deflection curve is not linear. The finger and canted coil springs are contrasted in Figures 7-6 and 7-7.

The canted coil spring requires that the bottom of the seal groove be sloped to allow the spring to simultaneously rotate and cant as it deflects axially so as to provide a simultaneous preload in both the radial and axial directions. Following the manufacturers recommendations resulted in extremely high axial loads and yielding of the spring. A small test fixture was used to conduct load/deflection tests where groove width as well as the contour of the bottom of the groove was varied. Results showed the manufacturer's groove width recommendation was adequate, but the bottom of the groove should be sloped in a direction opposite the manufacturer's recommendation. Figure 7-16 summarizes the results of a number of these tests.

The design goal was to obtain a system that would provide approximately 50 lb (22.7 kg) load at maximum deflection. The 107VLB-INC spring and the groove insert with the 30-deg slope were selected. The non-linear force deflection characteristic is shown in the figure as well as the lower loading produced by changing inset orientation.

Figure 7-16. Deflection Curves for Spring/Insert Combinations

7.4.3 Argonne National Laboratory

A significant part of the total cost of the regenerator is attributable to the seal system. Rolls-Royce Allison has used high temperature carbon/graphite, and plasma sprayed coatings (primarily nickel oxide/calcium fluoride applied over a metal substrate) for the regenerator disk primary seal. Most of the cost for these seal parts is incurred in the processing of these materials into finished parts. In addition to lower cost processing, better friction and wear performance are also goals.

Argonne National Laboratory (ANL) conducted a seal materials screening and development program in support of Rolls-Royce Allison's overall regenerator development effort. Two main tasks—development of low temperature lubricious materials (to 1200°F [648°C]) and development of high temperature lubricious coatings or materials (to 1800°F [982°C])—were pursued. The low temperature materials requirement can be further subdivided into a 750°F (399°C) thermal requirement for the regenerator cold side, and to 1200°F (648°C) for the hot side seal rims, while the 1800°F (982°C) capable materials are for use on the hot side crossarm.

ANL evaluated over 45 candidate low temperature materials, including 6 different types of carbon/graphite, more than 12 different types of carbon-carbon, 3 different types of advanced high temperature polyimides, and various other materials. These materials were subjected to a 7-hr screening test in which temperature was stepped up in four 55°C

increments (99°F step) from starting to maximum temperature and then stepped back down while friction drive torque was measured. Most of these materials were unsuitable, being rejected for high wear, high friction, or both. The baseline for comparison for this test was Rolls-Royce Allison's standard carbon/graphite material which exhibited friction coefficients below 0.2, and wear below 4×10^{-8} in./hr (10^{-9} m/hr). One polyimide material, one carbon-carbon, and one alternate carbon/graphite material showed friction and wear performance equal to or better than the baseline material. The carbon/graphite and polyimide materials should be subjected to longer duration testing (150+ hr) to better assess their capability.

The high temperature coatings effort was directed toward finding a replacement for nickel oxide-calcium fluoride. The goals were to reduce cost, friction, wear, and environmental impact. This work was conducted on a high temperature friction and wear rig capable of temperatures to 1800°F (982°C). Plasma spray was used to apply the candidate wear face coatings to the wear buttons. High cell density MAS, LAS, and AS disks (both wrapped and extruded) were provided by Corning (Figure 7-17) to support this testing.

Several metal oxides in various combinations were evaluated in this test rig. Coatings in which nickel oxide forms the major constituent with calcium fluoride, barium titanate, magnesium oxide, and strontium fluoride in various combinations as minor constituents were tested. A second group of coatings that contained various mixtures of zinc oxide, tin oxide, calcium fluoride, strontium fluoride, and magnesium oxide were also tested. The last group consisted of modifications

of commercially available coatings such as NASA's PS300 series coatings, and Tribolite. The most promising coating found was a mixture of magnesium oxide, zinc oxide, and calcium fluoride, which exhibited friction coefficients as low as 0.2 at 1800°F (982°C). Future programs should include long-term friction and wear testing, and compatibility testing with the substrate and disk materials.

The Rolls-Royce Allison rotating ceramic regenerator cores are driven by a rim drive gear system. The ANL effort also included testing of potential low cost coatings for the drive gear teeth that would eliminate wear. ANL conducted screening tests on a pin-on-slider tester at room temperature and 446°F (230°C). Several materials were evaluated including electroless nickel coatings with silicon carbide, electroless nickel with Teflon, Diamond Black® (boron nitride), ion nitrided parts, bare H13, diamond like carbon, tungsten carbide (baseline), and 6 different kinds of high temperature grease. Potential coatings were initially tested running against themselves. Several tests were conducted using various combinations of the more promising coatings and greases. Friction and wear results from this program are presented in Figures 7-18 and 7-19, respectively. Diamond-like carbon running either against itself or bare H13 was the best coating tested. It provided lower friction than the baseline tungsten carbide and had similar wear. Krytox grease was the best grease tested.

The attachment of the metallic rim drive gear to the ceramic regenerator core is an area requiring further development. Their large thermal expansion differences coupled with high temperatures requires a unique bonding material. The most successful cost effective solution has been to use room temperature vulcanizing (RTV) rubber. However, RTV has a temperature limitation at or near normal regenerator operating temperature levels. Published recommendations for the high temperature "red" RTV are continuous operating maximum temperature of 500°F (260°C) and an intermittent maximum temperature of 600°F (316°C). Predicted maximum temperatures of the regenerator ring gear mounting surface are 550 to 650°F (288 to 343°C), depending on the disk design and the engine operating conditions.

Figure 7-17. High Cell Density Regenerator Disks

Figure 7-18. Friction Results from ANL Screening Tests

Figure 7-19. Wear Results from ANL Screening Tests

Failure of the RTV joint results in the ring drive gear becoming debonded from the ceramic core. This has occurred during testing for various reasons, including high seal torque, poor gear meshes, and excessive operating temperature. The RTV bonding design does not require special geometry or close tolerances on the outer diameter of the disk. Since the cost of the disk is a large percentage of the total regenerator system cost, a design change that would increase the cost of the disk, i.e., add special features, was not considered. Therefore only design changes that maintained the current disk outer diameter were considered. This included

modifying the geometry of the metallic ring which attaches to the disk through the bonding RTV if required.

A simple test was devised to test RTV and alternative materials at temperature. A search was completed to find alternate adhesives that offered higher temperature capability with the same or better adhesion strength. The search identified a high temperature epoxy, a very high temperature ceramic adhesive, and some alternative RTVs. These materials were tested in a tensile test machine at room temperature and at a temperature of 600°F (316°C). A force on the bonded-

on metal strips was applied until failure of the adhesive bond occurred.

Four alternative materials were tested. The alternative bonding material candidates (a high temperature epoxy and a ceramic cement) failed before the samples were installed in the tensile test machine. The high temperature epoxy required curing in an oven, and upon cool down the epoxy tore the top layer off of the ceramic matrix (the wash coat/ceramic matrix bond broke). The second bonding candidate also experienced a premature failure. The cement/ceramic bond broke at room temperature when the samples were handled.

Two types of RTV were tested. A GE Silicon "RTV-106" (red RTV), which is the current baseline bonding material used on disks, and a Permatex "Ultra Copper RTV". These were tested at room temperature and at 600°F (316°C). One sample of each material was tested at each of the temperatures. The results are shown

in Figure 7-20, with the force being the force applied to one bonding bead (the Hybrid designed disk that was tested in the single disk rig has 30 beads circumferentially spaced around each disk).

RTV-106 demonstrated surprising elongation at room temperature and relatively good strength. At 600°F (316°C), the RTV-106 retained only 7.1% of its original strength. The Ultra copper RTV had reasonable strength at room temperature but was not able to support a load at 600°F (316°C). These tests demonstrated that a drastic strength reduction occurs at high temperatures and the strength is marginal.

As demonstrated on the various rigs and test engines, RTV is capable of bonding the drive gear to the regenerator disk under limited temperature exposure conditions. No suitable bonding material replacement for RTV was identified from these studies. Future programs should pursue the rim drive gear/ceramic core attachment evaluation initiated here.

Figure 7-20. RTV Force versus Deflection

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Appendix A

Ceramic Component Processing Descriptions

Ceramic Component Processing Descriptions

- Cold Isostatic Pressing: (CIP)** A forming process in which ceramic powders are mixed with a small amount of binder and compacted by uniform pressing in all directions. This process is limited to relatively simple shapes and often requires subsequent green machining.
- Drain Casting:** A form of the slipcasting process in which the liquid slip is allowed to set in the mold for a set period of time, forming a hollow green body with a desired wall thickness.
- Gelcasting:** A near-net-shape forming process with ceramic particles suspended in a liquid with the addition of a monomer based material. This monomer is converted to a polymer in a thermal process, resulting in a green body with excellent strength characteristics, which can be green machined.
- Hot Isostatic Pressing: (HIP)** A densification process using uniform omnidirectional pressure (typically applied using an inert gas) at elevated temperature to enhance densification and interparticle bonding. Glass encapsulation of the porous green ceramic body is required during the HIPing process.
- Hybrid Molding:** A Kyocera proprietary forming process utilizing a ceramic suspension which is injected under low pressure into a metallic mold.
- Injection Molding:** A near-net-shape forming process in which ceramic particles are mixed with a thermoplastic binder system and injected into a metallic mold under relatively high pressure. The binder is then removed in a thermal process to result in a green ceramic body.
- Pressure Slipcasting:** A form of the slipcasting process in which the slip is pressurized to increase the casting rate.
- Sintering:** A process which utilizes high temperature to drive interparticle bonding of compacted ceramic bodies resulting in formation of a dense part. Pressure is often used for silicon nitride ceramics (usually using nitrogen gas) to aid in densification and prevent disassociation of the silicon nitride.
- Slipcasting:** A near-net-shape forming process with ceramic particles suspended in a liquid (usually water) that is poured into a porous plaster or plastic mold. The water is filtered through the mold wall leaving a hollow or solid green body of ceramic.
- Solid Casting:** A form of the slipcasting process in which an excess amount of liquid slip is present in the mold, resulting in the formation of a solid green body.

Appendix B

Glossary/Abbreviations/Acronyms

Glossary/Abbreviations/Acronyms

AC	AC Cerama
AEC	Allison Engine Company
AGT	automotive gas turbine/Advanced Gas Turbine
AGT-5	automotive gas turbine test-bed rig or engine
AMMRC	Army Materials and Mechanics Research Center
AMPS	Allison Mobile Power Systems
ANL	Argonne National Laboratory
APU	auxiliary power unit
AS	aluminosilicate
ASCC	AlliedSignal Ceramic Components
ATTAP	Advanced Turbine Technology Applications Project
CARES	Ceramics Analysis and Reliability Evaluation of Structures
CATE	Ceramic Applications in Turbine Engines
CBO	Carborundum Corporation
CC	Allied Signal Ceramic Components
CIP	Cold Isostatic Pressing
cm	centimeter
CO	carbon monoxide
CPS	Ceramic Process Systems
CTAHE	Ceramic Technology for Advanced Heat Engines
cu	cubic
DARPA	Defense Advanced Research Projects Agency
DIMOX	directed metal oxidation
E	Young's modulus
EPA	Environmental Protection Agency
DoE	Department of Energy
EPRI	Electric Power Research Institute
FEM	finite element modeling
FMEA	failure mode effect analysis
FOD	foreign object damage
FPI	fluorescent penetrant inspection
FPL	fiber processing level
ft	feet
g/cm ³	grams per cubic centimeter
GCCD	Garrett Ceramic Components Division
gm	gram
GM	General Motors Corporation
GTE	GTE Laboratories Inc
HC	hydrocarbon
HDGTE	Heavy Duty Gas Turbine Engine
HEV	Hybrid Electric Vehicle

HIP	hot isostatic pressing
HP	horsepower
HTML	High Temperature Materials Laboratory
HVTE-TS	Hybrid Vehicle Turbine Engine Technology Support
IM	Injection Molding
in.	inch
kg	kilogram
KICC	Kyocera Industrial Ceramics Corporation
ksi	kilopounds per square inch
kW	kilowatt
LAS	lithium-aluminosilicate
lb	pound
LeRC	Lewis Research Center
m	meter
MAS	magnesium-aluminosilicate
mi	mile
mm	millimeter
MOR	modulus of rupture
MPa	MegaPascal
mpg	miles per gallon
NAC	Norton Advanced Ceramics
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NGK	NGK Spark Plug
NO _x	oxides of nitrogen
N1	gasifier rotor speed
ORNL	Oak Ridge National Laboratory
POS	probability of survival
R&D	research and development
RIT	gasifier rotor inlet temperature
RPD	reference powertrain design
rpm	revolutions per minute
S/N	serial number
sec	second
SECTS	Small Engine Components Technology Studies
SEM	scanning electron microscope
SFC	specific fuel consumption
Sialon	Ceramic Process Systems silicon nitride
SiC	silicon carbide
TVG	thermal variable geometry
ULEV	Ultra Low Emissions Vehicle Standard
v/o	volume percent

2-D two dimensional
3-D three dimensional

°C degrees Celsius
°F degrees Fahrenheit

α coefficient of thermal expansion
 ν Poisson Ratio