PROGRESS ON THE
HYBRID VEHICLE TURBINE ENGINE TECHNOLOGY SUPPORT
(HVTE-TS) PROGRAM

George T. Sinnet, J. Mark French, Lance E. Groseclose
Allison Mobile Power Systems
Allison Engine Company
Indianapolis, IN

ABSTRACT

The purpose of the HVTE-TS program is to develop gas turbine engine technology in support of U.S. Department of Energy/automotive industry programs exploring the use of gas turbine generator sets in hybrid-electric automotive propulsion systems.

The primary objective is the development of four key technologies to be applied to advanced turbogenerators for hybrid vehicles:

- structural ceramic materials and processes
- low emissions combustion systems
- regenerators and seal systems
- insulation systems and processes.

The HVTE-TS program builds upon the significant technology base already established by the previous DoE/NASA Advanced Turbine Technology Applications Project (ATTAP).

HVTE-TS activities during 1996 included: ceramic component design, materials and component characterization, ceramic component process development and fabrication, ceramic component rig testing, and test-bed engine installation and setup. Progress has been made in the durability testing of various regenerator materials and components, as well as in the application of unique insulation systems. This paper highlights recent progress and current status of each of the four key technologies described above.

INTRODUCTION

Hybrid automotive propulsion systems utilizing battery powered electric drive systems with on-board power generators have become a current goal of development and demonstration efforts by the automotive industry and by DoE-funded development contracts. The HVTE-TS program has been structured to provide the necessary hybrid vehicle turbine engine technology support.

The current HVTE-TS program builds on the significant technology base established in ATTAP (Berenyi, 1994) to provide the key technologies described above. The HVTE-TS program utilizes the AGT-5 automotive gas turbine engine (to 150 kW for all-ceramic engine configuration) as the test-bed for ceramic component design verification/proof testing and ceramic assembly durability testing. In addition to AGT-5 based rigs, hybrid vehicle sized components (to 50 kW) were also tested in various other rigs to demonstrate performance and durability.

This paper summarizes the progress and accomplishments of the HVTE-TS program during 1996.

DISCUSSION

Structural Ceramic Materials and Processes

Ceramic component process development has been directed towards fabrication of structural ceramic components using near net-shape processes that are applicable to high volume production. Emphasis was placed on development and evaluation of components and technology required for support of the hybrid vehicle turbine engine, including the gasifier rotor, scroll, and combustor. Efforts have been focused on improvements in process yield, strength, shape processes that are applicable to high volume production.

Axial turbine rotor development has focused on the net-shape processing of silicon nitride (Si₃N₄) gasifier rotors. Pressure slip casting of SN253 Si₃N₄ rotors continues at Kyocera Industrial Ceramics, with hybrid molding of SN281 Si₃N₄ being the focus of the process development activities. AlliedSignal Ceramic Components (CC) is working on the development of gel casting of AS800 Si₃N₄ for rotor fabrication. The primary goals of the rotor...
development efforts are focused on increasing the reliability and producibility of ceramic rotors, addressing improvements in process definition and control, process yields, material strength characteristics, and fracture toughness/impact resistance. Gasifier turbine scroll development activities at Kyocera have continued to be directed towards slip casting of SN252 Si₃N₄ components. Both rectangular and circular cross-section scrolls are being produced. A novel scroll fabrication concept, adapted from techniques commonly used in the whiteware and metal casting industries, is also being developed. This approach offers the potential for significant improvements in cycle time and internal surface finish, and could be readily automated for high volume production. AlliedSignal is also working on the fabrication of thin-walled turbine engine components using gel casting with a removable internal core. Initial efforts are being directed towards development of a combustor body, with AS800 Si₃N₄ material being utilized for this application.

**Kyocera Industrial Ceramics.** Kyocera is pursuing the fabrication and development of Si₃N₄ gasifier turbine rotors. Initial activities at Kyocera have been directed towards the fabrication of SN253 Si₃N₄ 20-bladed rotors using pressure slip casting to support ceramic component proof/durability testing with the AGT-5 engine. A rapid prototyped rotor master pattern fabricated using stereolithography was utilized for making the plaster molds, reducing the cycle time by 2-4 weeks. A total of 30 rotors have been cast, with an overall process yield of 60% (for engine quality hardware) observed for the most recent casting lots. Three rotors were proof spin tested to 120% design speed and were delivered to Allison. One of these rotors was successfully run in a hot gasifier rig for 300 hours of cyclic durability testing at temperatures to 2500°F (1370°C) [See Ceramic Durability Hot Rig Testing section]. Recent efforts have focused on the development of hybrid molding for rotor fabrication. This process (used in Japan by Kyocera for turbocharger rotor production) utilizes hard tooling for improved dimensional conformance and reduced cycle time. The material being utilized is SN281 Si₃N₄, an improved Si₃N₄ material with excellent elevated temperature strength and time dependent properties. The strength characteristics of the silicon nitride materials being developed in HVTE-TS are summarized in Table 1.Kyocera SN252 and SN253 silicon nitride materials are quite similar in thermal and mechanical properties, with the SN252 Si₃N₄ being utilized for thin-walled drain cast structures (scrolls and combustors) and SN 253 Si₃N₄ used for solid cast components (rotors and vanes).

Hard mold tooling was designed and procured. Development of appropriate process parameters is ongoing. Eight forming lots have been processed, with slip viscosity, mold filling and demolding being the focus of current efforts. Complete mold filling is now routinely obtained; however, molding knit lines and internal cracking remain challenges. Recent molding lots have attained a 75% yield of acceptable quality green rotors, which are continuing through processing to evaluate the effects of dewaxing and densification on the rotors. The Kyocera rotor is shown in Fig. 1.

Kyocera is also working on the development of a gasifier turbine inlet scroll, as shown in Fig. 2. The primary approach being utilized is pressure slip casting of SN252 Si₃N₄. Four scrolls with rectangular cross-sections were delivered to Allison in 1996, with one of the scrolls successfully achieving 300 hours of cyclic rig testing at gas temperatures to 2500°F (1370°C).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Strength, MPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kyocera</td>
</tr>
<tr>
<td>25°C (77°F)</td>
<td>SN253</td>
</tr>
<tr>
<td>1000°C (1832°F)</td>
<td>SN281</td>
</tr>
<tr>
<td>1150°C (2102°F)</td>
<td>AS800</td>
</tr>
<tr>
<td>1250°C (2282°F)</td>
<td>SN253</td>
</tr>
<tr>
<td>1370°C (2500°F)</td>
<td>SN252</td>
</tr>
</tbody>
</table>

**Figure 1.** Slip Cast SN 253 Silicon Nitride Gasifier Rotor by Kyocera

**Figure 2.** Si₃N₄ Inlet Scroll by Kyocera

Recent efforts have focused on the fabrication of circular cross-section scrolls, which have improved aerodynamic performance. A rapid prototyped stereolithographic pattern was produced directly from the 3-D CAD file and used for fabrication of the plaster mold sections. Major improvements in scroll processing have been realized, with green yields increasing to 80% acceptable parts in the latest casting runs (versus <10% in the early castings). Sintered scrolls are currently being finish machined with an anticipated
delivery schedule of early 1997. In conjunction with the conventional slip casting approaches being used for making components to support rig/engine test evaluation, Kyocera is developing a novel scroll fabrication concept adapted from techniques commonly used in the whiteware and metal casting industries. This fabrication method uses the same slip system and material as that used for hybrid molding and offers the potential for significant improvements in cycle time and internal surface finish, and could be automated for high volume production.

**AlliedSignal Ceramic Components.** Axial turbine rotor activities at AlliedSignal Ceramic Components have focused on the development and demonstration of gel casting as a viable manufacturing process for component production. The gel casting process was originally developed at Oak Ridge National Laboratory and was licensed to AlliedSignal for further development. Gel casting offers numerous process benefits, including low green packing density gradients, significantly higher green strength, and reduced process cycle time relative to conventional pressure slip casting. The use of metal tooling results in greatly improved surface finish and dimensional control. The AS800 material is an in-situ reinforced Si$_3$N$_4$ with a highly acicular microstructure. This material has excellent fracture toughness [7.7 ksi-in$^{1/2}$ (55 MPa-m$^{1/2}$)] with a high Weibull modulus (28.4 for slip cast, 16.1 for gel cast material) and good creep resistance. In addition, the high thermal conductivity results in improved thermal shock resistance relative to conventional hot isostatic pressed silicon nitride materials.

A metal rotor mold optimized for gel casting AGT-5 axial turbine rotors was designed and fabricated and is being used for rotor process development and component fabrication. Initial gel casting trials resulted in the formation of small voids in the shaft and hub region due to inadequate surface finish and fitting of the mold. Subsequent processing after rework of the tool have resulted in rotors, shown in Fig. 3, with greatly reduced defects and minimal blade breakage. These rotors are currently being processed with an anticipated delivery in early 1997. AlliedSignal is also working on the fabrication of thin-walled turbine engine components using a modified gel casting process. A removable core is used to define and generate the internal features. Initial efforts are being directed towards development of a combustor body, as shown in Fig. 4, with AS800 Si$_3$N$_4$ the material being utilized for this application. The combustors have been sintered to full density and are currently being finish machined, with delivery anticipated in late 1996.

![Figure 3. Si$_3$N$_4$ Gasifier Rotor by AlliedSignal](image1)

**Figure 4. Si$_3$N$_4$ Combustor by AlliedSignal**

**Ceramic Durability Hot Rig Testing.** A major effort of the ATTAP/HVTE-TS programs has been structural ceramic component testing to validate durability, performance and compatibility with automotive/hybrid vehicle gas turbine engine requirements. The test program employs a hot gasifier rig as the test-bed. The rig is a complete gasifier from the AGT-5 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 large diameter regenerator disks. The hot gasifier rig can incorporate various combinations of ceramic and metal hot section components.

Rig testing has focused on an all-ceramic gasifier section (complete gasifier stage including static and rotating structures). Major ceramic components of this section include the inlet scroll assembly (which incorporates the rotor blade track shroud and mounting flange) and a gasifier turbine rotor. The gasifier section ceramic components along with the AGT-5 magnesium-aluminosilicate (MAS) ceramic regenerator disks and ceramic coated hot seal crossarms are shown in Fig 5.

![Figure 5. Hot Gasifier Durability Test Rig Ceramic Components](image2)

Prior years’ rig testing of an all-ceramic gasifier section resulted in significant milestones achieved, including: (1) Operation at maximum design conditions of 2500°F (1371°C) gasifier rotor inlet
temperature at 100% gasifier speed and (2) successful completion of a 100-hour cyclic durability test with peak cycle conditions of 2500°F (1371°C) gasifier rotor inlet temperature at 100% gasifier speed (Haley, 1992 and Berenyi, 1994).

Recent Allison activities have included refurbishing of test facilities and associated hardware to accommodate the needs of the HVTE-TS program. This effort included rig enhancements directed at ceramic component testing. A newly designed scroll/gasifier rotor mounting system was incorporated. The ceramic scroll is positioned with respect to the assembly centerline using a crosskey system which is piloted from the gasifier rotor housing. This design allows the ceramic rotor and scroll to move as a single unit. The rig was also fitted with a special sight tube with quartz window to permit observation of the gasifier turbine rotor exit during operation. This sight tube also incorporates an exhaust port (secondary exhaust) to allow diversion of hot gas flow from the rotor overboard of the rig. Ceramic rotor stability and bearing life were enhanced with the addition of a patented Allison oil squeeze film damper design to both the compressor and turbine bearings to ensure proper damping and to limit oil flow requirements. A high energy ignition system and compatible ignitor were incorporated into the rig for reliable starting. Figure 6 shows the hot gasifier rig installed in Allison test cell 892.

Figure 6. Hot Gasifier Ceramic Durability Test Rig

A major contractual milestone of the HVTE-TS program scheduled for 1996 was to complete a 300-hour cyclic durability test of an all-ceramic gasifier section. The objective of the 300-hour test was to demonstrate durability performance of key technology components of the automotive gas turbine (AGT) including:

- Ceramic Gasifier Scroll Assembly
- Ceramic Gasifier Turbine Rotor
- Ceramic Regenerator Cores
- Regenerator Crossarm Hot Seal Materials
- Injection Molded Insulation

The ceramic inlet scroll assembly was fabricated from silicon nitride by Kyocera Industrial Ceramics. The ceramic gasifier turbine is a 20-bladed silicon nitride axial flow rotor also fabricated by Kyocera. The regenerator cores were extruded MAS ceramic pasted disks. 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. The left crossarm was NiO/CaF₂ plasma sprayed onto an 1-625 substrate. The right crossarm was 1-112 (ZnO/SnO₂/CaF₂) plasma sprayed onto an 1-625 substrate. This arrangement allowed simultaneous evaluation of two alternative crossarm coatings. The AGT-5 engine housing was injection molded with insulation as were the gasifier housing and combustor cover.

Prior ceramic component durability test schedules have simulated the 1992 Reference Powertrain Design based on the Combined Federal Driving Cycle. The schedule duration was 55 minutes and included 19 accelerations, 24 decelerations, 9 engine starts/stops and a 9 minute soakback period. Three hundred repetitions of this durability cycle simulated 3500 operating hours (10 year automotive engine life) in a prime power turbine engine environment at temperatures to 2500°F (1371°C). Recent emphasis has shifted the automotive gas turbine engine environment from prime power to auxiliary power for hybrid vehicles utilizing battery powered electric drive systems. Therefore the ceramic component durability test schedule has been modified to simulate an accelerated life test based on the cyclic operating modes of a typical hybrid vehicle turbine engine environment. The schedule is one hour in duration and includes 20 accelerations and 24 decelerations. It also includes a 9 minute soakback at the end. Execution of a complete schedule is one durability cycle. The maximum rotor speed of the cycle is 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 in order to increase the severity of the ceramic component environment yet remain within the limitations of rig hot section metallic components.

Gasifier rotor inlet temperature control is accomplished by conditioning rig inlet air temperature, compressor bleed, exhaust cavity cooling air pressure 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.

Rig operational control is provided by a new custom designed and programmed digital controller. A personal computer (PC) is interfaced to the digital controller permitting manual (keyboard or mouse) and/or automatic control of rig operation. During automatic operation, the rig control PC commands the digital controller based on a predefined durability test schedule.

The test cell incorporates instrumentation to measure rig speed, pressures, temperatures, vibration, air and fuel flow, etc. Real-time data acquisition and reduction are accomplished by three PC's. The PC's convert measured data to engineering parameters, perform checks to ensure safe rig operation, log data to disk for permanent record and provide real-time graphic display of rig operation, status and performance. RIT is calculated rather than measured due to the difficulty of positioning thermocouples directly into the ceramic inlet 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 metallic inlet scroll with rotor...
inlet thermocouples installed) demonstrated excellent correlation between measured and calculated RIT.

First rig testing of an all-ceramic gasifier section was initiated in April 1996. Figure 7 shows rig performance during a 100% gasifier speed durability cycle with a 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.

The gasifier assembly was rebuilt with new ceramic components. It was installed in a backup AGT-5 engine housing which had been refurbished with new injection molded insulation. The rebuild also included new ceramic regenerator disks (and seals) and new combustor components. A standard metallic AGT-5 Lamilloy combustor dome was used instead of the TVG dome.

Testing on the second buildup of the all-ceramic gasifier section was initiated in July 1996. The first durability cycle was completed after 1.5 hours 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).

Figure 7. Ceramic Durability Rig Operating to Full Rated Speed and Temperature

- Rig performance at 12 hours into the durability test is shown in Fig. 8. During execution of this 92% speed durability schedule, a maximum RIT of 2449°F (1339°C) was reached with a maximum regenerator inlet temperature of 1947°F (1064°C).

Figure 8. Ceramic Durability Rig Performance (12 Hours)

Rig performance at 54 hours into the durability test is shown in Fig. 9. During execution of this 90% speed durability schedule, a maximum RIT of 2443°F (1339°C) was reached with a maximum regenerator inlet temperature of 1947°F (1064°C).

Figure 9. Ceramic Durability Rig Performance (54 Hours)

Rig performance at 150 hours into the durability test is shown in Fig. 10. During execution of this 96% speed durability schedule, a maximum RIT of 2270°F (1243°C) was reached with a maximum regenerator inlet temperature of 1744°F (951°C).
Figure 10. Ceramic Durability Rig Performance (150 Hours)

Figure 11 is a photograph of the ceramic gasifier rotor at 100% rated gasifier rotor speed as viewed through the rig sight tube quartz window.

Figure 11. Ceramic Gasifier Rotor as Viewed from Sight Tube

Scheduled rig inspections were conducted every 50 hours 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 rig operational problems. These inspections were non-ceramic component related. At 64 hours into the durability test, the left regenerator hot seal crossarm (Ni/CaF2 plasma sprayed) was replaced with a crossarm having the 1-112 (ZnO/SnO2/CaF2) plasma sprayed coating. The original Ni/CaF2 coated arm did not develop a full contact wear pattern and was judged to be a potential source of leakage. At 123 hours, a major repair of the engine housing injection molded insulation was completed. 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.

Other development issues addressed included the metallic combustor system (3 domes and 1 body replaced due to thermal stress), hot section molded insulation repair, regenerator disk leaf seal repair, engine housing leaf seal platform repair, instrumentation system repair, rig digital controller software modifications and rig controller hardware replacement.

The 300-hour durability test of build 2 of the all-ceramic gasifier section was successfully completed during November 1996. Rig performance at 300 hours of cyclic durability testing is shown in Fig. 12. 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 12. Ceramic Durability Rig Performance (300 Hours)

Figure 13 shows rig speed, rotor inlet temperature and regenerator disk inlet temperature maximum values for each test run of the 300-hour 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-hour durability test can be summarized as follows:

- The ceramic inlet scroll assembly showed no evidence of physical or structural problems.
- The ceramic gasifier turbine rotor showed no evidence of 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 hours.
• A total of 392 successful ceramic rig starts were executed.
• A total of 238 automatic 1-hour 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 1-112 (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 1-112 coated crossarm at 64 hours testing and completed the remaining test hours.

Figure 13. Maximum Operating Environment of the All-Ceramic Gasifier Section

Figure 14 shows the gasifier section components, regenerator disks and hot seal crossarms after completing the 300-hour durability test. Teardown inspection and measurements showed all components to be in excellent condition. The ceramic inlet scroll assembly and ceramic gasifier rotor (Fig. 15) were in excellent condition with microscopic inspection showing no evidence of no 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 Fig. 16. However, it remained in place and was fully operational throughout the 300-hour test. The injection molded combustor cover showed no evidence of damage. Figure 17 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 Fig. 18. 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 left crossarm can be seen in Fig. 18.

Figure 14. AGT-5 Hot Gasifier Rig Components After 300-hour Durability Test

Figure 15. Ceramic Gasifier Rotor After 300-hour Durability Test

Figure 16. Injection Molded Insulation on Gasifier Housing After 300-hour Durability Test
Low Emissions Combustion Systems

Potential advantages of gas turbine generator sets for automotive application include increased fuel economy, ability to meet current and future emission standards without exhaust gas treatment, and ability to operate on various alternate fuels. One of the key elements to achieving these potentials is the combustor system. Additional development is required to extend current technology using lean premixed prevaporized combustor systems and demonstrate compliance with automotive emission requirements. This effort includes optimizing combustor system design for alternate fuel tolerance, combustion stability, cold and hot starts, steady-state and transient emissions levels below future California ultra-low emission vehicle (ULEV) requirements, reliability and cost.

The low emissions combustion effort is focused on lean premixed prevaporized combustor designs having the potential to operate at sub-ULEV levels. These requirements are shown graphically in Fig. 19. With this approach, the premixed fuel/air mixture is burned at a relatively lean mixture and consequently lower flame temperatures. Because NOx formation is predominately controlled by temperature, NOx levels will be substantially lower than in stoichiometric diffusion flame combustors. Incorporating ceramics in the design also lowers emission levels by reducing quenching of carbon monoxide and hydrocarbon oxidation reactions near the combustor walls.

During 1996, a combustion rig was designed, procured and installation begun (see Fig. 20). This rig will be used to screen and develop low emissions combustor designs. It is capable of operation at burner inlet temperatures representative of ceramic gas turbine engines. The rig design incorporates interchangeable spools to permit testing of different size (gas turbine generators for hybrid vehicles or AGT-5 test-bed engine) combustors. Initial testing will concentrate on a ceramic two stage lean premixed combustor. The rig incorporates a turbine scroll assembly and combustor cover to replicate the flow path of an actual engine. Combustor rig testing will allow parametric variation of operating conditions to evaluate exhaust emissions, flashback, autoignition, flame stability and thermal/mechanical design. Once combustors have been successfully proof-tested in the rig, transient phenomena such as cold/hot start and transient emissions will be evaluated in an engine when possible. Testing of both lean premixed hybrid engine-sized and ceramic AGT-5 combustor hardware is planned.
Regenerators And Seal Systems

Fuel economy requirements of hybrid vehicle gas turbine generators dictate exhaust heat recovery systems to minimize fuel consumption. The Allison approach for exhaust heat recovery is to employ a rotating regenerator system. The regenerator and associated seal systems are key elements which are being developed for application to hybrid vehicle turbine engines.

Activities associated with the regenerators and their seal systems are being conducted in-house at Allison and with partners including Coming Incorporated and Argonne National Laboratory (ANL). Coming is pursuing regenerator disk material and fabrication process development. ANL is providing support on regenerator seal development. Progress and accomplishments during 1996 are discussed below.

Coming Regenerator Effort. Recent focus has been on regenerator disk overall cost reduction to levels acceptable for automotive use.

Coming has concentrated their materials development and testing on their two most developed materials: magnesium-aluminosilicate (MAS) and lithium-aluminosilicate (LAS).

The relation between thermal expansion and strength of solid extruded rods as shown in Fig. 21 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 Fig. 21 which would lead to 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 at Allison become available.

LAS materials work in 1995 and 1996 concentrated on reducing the 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 (Holleran, 1995).

Previous 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, Coming 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/cm$^2$ (62-78 cells/cm$^2$) with wall thickness of 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 regenerators. This translates to cell counts on the order of 1000-1500 cells/cm$^2$ (155-233 cells/cm$^2$) and wall thickness of 0.004-0.005 in. (0.102-0.127 mm) respectively. Stretching current die technologies based on the catalytic converter extrusions, Coming has provided Allison with regenerator cores having 1100 cells/cm$^2$ (171 cells/cm$^2$) and 0.006 in. (0.152 mm) thick walls in MAS material. Novel die development work underway in support of Coming’s catalyst business will provide strength improvements to the die, enhancing the capability for single piece extrusion of hybrid vehicle size cores (Day, 1996).

Allison Regenerator Effort. Allison has concentrated recent design and fabrication efforts on a regenerator system sized for engines to 67 horsepower (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 horsepower (75-150 kW) sized 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 Fig. 22, was incorporated with reduced part count and cost.

Regenerator disk design has concentrated on the hub area to reduce cost and to incorporate features made possible by extrusion. The latest design incorporates a recent Coming development, namely an extruded hub. Previous designs had used a cast hub which was separately fired, machined on its outside diameter, and then joined to a separately fired, pre-machined matrix core in a third firing cycle using a cement which had to be matched for the thermal expansion of 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 pre-machining or cement joint required. Figure 23 shows a green extruded hub and one that has been installed and fired into a piece of disk matrix.

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 cross.
arm. This maximized the unblocked open frontal area of the disk available for heat transfer.

A critical aspect of the regenerator system is the design of the seals. Two major requirements, cost and performance, drove the most recent regenerator design towards the most cost effective and production compatible features. The seal system consists of the primary seal wearface directly contacting the rotating disk and a secondary seal leaf system bridging between the engine block 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. Leakage through the regenerator seals directly impacts turbine engine performance since these leaks are losses directly overboard from the compressor discharge.

The secondary seal can be designed in one of three basic configurations. Figure 24 illustrates the three concepts that were evaluated for this application. The L-seal was chosen as the inboard secondary seal in the latest design.

In order 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

The finger springs are shown in Fig. 25. The canted coil spring was proposed as an alternate design (See Fig. 26). Large deflections (to 45% of the initial spring height) can be accommodated by this spring permitting an overall compact design. The spring is easily installed and can be manufactured in a variety of high temperature materials.

A single disk hot flow performance rig was designed and fabricated to test the hybrid-size regenerator system design in a controlled environment where performance 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 27 shows the disk test section of the completed operational rig installed in a test cell, as well as, an overall plan view of the rig. The rig operates at simulated steady-state engine conditions, with electrically heated inlet air and gas side inlet air heated by a gas-fired burner.
Orifices upstream and downstream of the high pressure half of the disk measure airflow. The difference between these flows is regenerator system leakage. 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. A torque meter is used to measure disk drive torque to permit evaluation of seal wearface materials 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.

A gasifier rig (incorporating twin regenerator disks) for regenerator durability testing is operational at Allison (See Fig 28). The rig fulfills two purposes:

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

During 1996, a pair of MAS material extruded disks completed 500 hours of steady state durability testing at 1750°F (954°C) regenerator hot side inlet temperature. The rig was operated at two conditions of interest for regenerator testing: a high temperature / low pressure condition with a regenerator hot side inlet temperature of 1750°F (954°C), combined with an air side inlet pressure of 6.0 psig (41.3 kPa); and a low temperature / high pressure condition with a regenerator hot side inlet temperature of 1550°F (843°C) and air side inlet pressure of 32.5 psig (224.1 kPa). One of the disks is shown in Fig. 29. These disks have also completed 50 hours of steady state testing at the low temperature / high pressure condition.

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 (1.5 x 2.5 x 3
in. (38.1 x 63.5 x 76.2 mm) sample size. After testing, the regenerator material is analyzed to determine hot face strength loss.

Figure 28. Small Regenerator Gasifier Test Rig

The samples were exposed to cycles that represent expected operating transients including initial startup. The start-up accelerations were the most severe, with a rapid step from ambient to 1900°F (1039°C), held for several seconds, and followed by a rapid decrease to 1350°F (732°C). The rig cycled from 1350°F (732°C) to 2090°F (1143°C) [ten percent was added to the 1900°F (1039°C) peak to account for burner pattern] and back to 1350°F (732°C) every 15 seconds.

Figure 29. Extruded MAS Disk After 500 Hour Test In Small Regenerator Gasifier Rig

Samples of both MAS and LAS extruded material were evaluated for various numbers of temperature cycles. Figure 30 presents some results and shows how the samples are sliced at six axial stations through the disk from hot to cold face. Each slice is cut into three modulus of rupture (MOR) test bars and strength data obtained. All data shown is 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. Testing with cycles to lower peak temperatures is underway to determine an acceptable use limit for MAS.

Figure 30. Modulus Of Rupture For Disk Samples Exposed In The Cyclic Thermal Rig

Argonne National Laboratory. A significant part of the total cost of the regenerator is attributable to the seal system. 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) is conducting a seal materials screening and development program to support 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)] are being pursued. The low temperature materials requirement can be further subdivided into a 750°F (400°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 cross arm.

ANL has evaluated more than 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-hour 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 Allison's standard carbon/graphite material which exhibits friction coefficients below 0.2, and wear below 4x10^-4 in/hr (10^-4 m/hr). One polyimide material, one carbon-carbon, and one alternate carbon/graphite material have shown friction and wear performance equal to or better than the baseline material. The carbon/graphite and polyimide are being subjected to longer duration testing (150+ hours) to better...
assess their capability.

The high temperature coatings work is directed at a replacement for nickel oxide / calcium fluoride. Again the goals are lower cost, friction, and wear than the baseline. This work is being conducted on a high temperature friction and wear rig capable of temperatures to 1800°F (982°C). Plasma spray is currently being used to apply the candidate wear face coatings to the wear buttons. High cell density MAS, LAS and AS disks both wrapped and extruded, have been supplied by Coming to support this testing. Several metal oxides in various combinations have been 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 have been tested. A second group consists of coatings which contain various mixtures of zinc oxide, tin oxide, calcium fluoride, strontium fluoride and magnesium oxide. The last group consists of modifications of commercially available coatings such as NASA's PS300 series coatings, and Tribolite. The most promising coating to date is a mixture of magnesium oxide, zinc oxide, and calcium fluoride which has exhibited friction coefficients as low as 0.2 at 1800°F (982°C). Future plans include long term friction and wear testing, and compatibility testing with the substrate and disk materials.

Insulation Systems And Processes

The development and demonstration of high temperature insulation materials and forming processes is a key technology area required for successful implementation of advanced gas turbine engines. Schuller International has developed a high temperature insulation system, consisting of Cerachrome Al2O3-SiO2-Cr2O3 ceramic refractory fibers embedded in a two part binder system comprised of both organic and inorganic components. The fibers and binder system have been optimized to allow the insulation mix to be injection molded in place using conventional low pressure injection molding equipment. This composition has excellent (very low) thermal conductivity (1.8 Btu-in/hr-ft2°F (0.260 W/m°K) at 200°F (1093°C)) and low density (22 lbs/ft³ (3.53 g/cm³)). Prototype injection molding tooling has been procured and the molding system modified to provide improved mold fill-out, mold release, and surface finish. Numerous components (See Ceramic Durability Hot Rig Testing section) have been injection molded with several hundred hours of successful rig durability testing at gas temperatures to 2500°F (1371°C) demonstrated. In addition to the molding system development, other issues being addressed include: development of insulation materials with lower thermal conductivity, improving insulation/metal component bondability, and increasing erosion resistance/thermal cyclic durability. A natural gas fired burner rig has been developed at Schuller and is being utilized to evaluate the cyclic durability and erosion resistance of various insulation systems. The burner rig is capable of exposing the insulation to temperatures of 2372°F (1300°C) with an impingement velocity of 250 ft/sec (98.4 m/sec) at angles ranging from 45 to 90 degrees. Testing the molded insulation for 10,000 thermal cycles resulted in no evidence of erosion and only minor shallow surface cracking of the insulation.

SUMMARY

Significant accomplishments in the development of key technologies for application to advanced turbogenerators for hybrid vehicles during the 1996 HVTE-TS program included:

- A 300-hour cyclic durability test of an all-ceramic gasifier section was successfully completed. Major ceramic components (SN252 silicon nitride inlet scroll assembly and SN253 silicon nitride gasifier turbine rotor, both fabricated by Kyocera) showed no physical or structural damage after test.
- Over 300 hours of hot rig testing with pasted MAS ceramic regenerator disks were completed.
- Over 300 hours of hot rig testing with injection molded insulation including both simple (gasifier housing and combustor cover) and complex (AGT-5 engine housing) shapes were completed.
- A 500-hour cyclic durability test of one piece extruded MAS ceramic disks with regenerator inlet temperatures to 1750°F (954°C) was successfully completed.
- Low emissions combustor test rig was designed, procured and installation begun.
- Thin-walled AS800 silicon nitride ceramic combustor was successfully gel cast by AlliedSignal.
- SN281 silicon nitride technology gasifier rotors are being processed by Kyocera.
- Large face area one piece extrusions of LAS ceramic regenerator disks are in process at Coming.
- Regenerator seal material development, tribology studies and testing are in process at Argonne Labs.
- 10,000+ cycles of durability testing were completed on injected insulation samples at 1800°F (982°C) at Schuller.

All goals and objectives of the 1996 HVTE-TS program were achieved including a major program milestone of a 300-hour cyclic durability test of an all-ceramic gasifier section. These successes have provided significant advances to the key technologies required for the application of gas turbine engines to hybrid vehicles.

ACKNOWLEDGMENTS

The authors would like to thank those Allison individuals and members of the vendor support team who contributed to the success of the HVTE-TS program during the past year. Special recognition should go to the Allison HVTET-S Project Team without whose efforts the accomplishments during 1996 would not have been possible, as well as to the U.S. Department of Energy for continuing sponsorship of the project.

REFERENCES