THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

98-GT-392

STATUS OF THE EUROPEAN GAS TURBINE PROGRAM - AGATA

Rolf Gabrielsson, Robert Lundberg
Volvo Aero Corporation
Sweden

Patrick Avran
ONERA
France

ABSTRACT

The European Gas Turbine Program "AGATA" which started in 1993 now has reached its verification phase. The objective of the program is to develop three critical ceramic components aimed at a 60 kW turbogenerator in a hybrid electric vehicle - a catalytic combustor, a radial turbine wheel and a static heat exchanger. The AGATA partners represent car manufacturers as well as companies and research institutes in the turbine, catalyst and ceramic material fields in both France and Sweden. Each of the three ceramic components is validated separately during steady state and transient conditions in separate test rigs at ONERA, France, where the high pressure/temperature conditions can be achieved. A separate test rig for laser measurements downstream of the catalytic combustor is set up at Volvo Aero Turbines, Sweden.

The catalytic combustor design which includes preheater, premix duct and catalytic section operates at temperatures up to 1623 K. Due to this high temperature, the catalyst initially has undergone pilot tests including ageing, activity and strength tests. The premix duct flow field also has been evaluated by LDV measurements. The full scale combustion tests are ongoing.

The turbine wheel design is completed and the first wheels have been manufactured. FEM calculations have indicated that stress levels are below 300 MPa. The material used is a silicon nitride manufactured by AC Cerama (Grade CSN 101). Cold spin tests with complete wheels have started. Hot spin tests at TIT 1623 K will be performed in a modified turbo charger rig and are expected to start in February 1998.

The heat exchanger is of a high efficiency plate recuperator design using Cordierite material. Hot side inlet temperature is 1286 K . Therefore initial tests with test samples have been run to evaluate the thermomechanical properties at high temperatures. Tests are now proceeding with a ¼ scale recuperator prototype to evaluate performance at steady state conditions. Manufacturing of the full scale heat exchanger is now in progress.

INTRODUCTION

The European EUREKA Gas Turbine Program "AGATA" - Advanced Gas Turbine for Automobiles - has been running since January 1993 with the objective to develop three critical components for a 60 kW turbogenerator in a hybrid electric vehicle:

- Catalytic combustor
- Ceramic radial turbine wheel
- Ceramic static heat exchanger

Technical specifications for the gas turbine, excluding electric generator, are as flollows:

- Mechanical output:	60 kW
- Specific fuel consumption minimum:	200 g/kWh
- Turbine inlet temperature:	1623 K
- Max. pollution emission:	ULEV or similar European standards
- Fuel:	Diesel or alternative fuels

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition

The AGATA partners represent car manufacturers as well as companies and research institutes in the turbine, catalyst and ceramic material fields in both France and Sweden. Early progress on the AGATA program has been described in previous papers, refs 1-8.

SYSTEM CONDITIONS

As described previously in ref 5, steady state conditions at 298 K and 101.3 kPa inlet conditions have been calculated according to table 1.

Table 1. Engine steady state calculations at 298 K and 101.3 kPa.

Load %	SFC g/kWh	Thermal Efficiency %	Combustor Inlet Temp. K	Turbine Inlet Temp. K
100	200	42	1208	1623
50	211	39	1208	1518

The schedule for the cold start as shown in Fig. 1, is the critical condition for the ceramic parts, has been chosen in order to separate thermal and centrifugal mechanical stress. This is achieved by a start procedure where the turbine inlet temperature, TIT, is increased to the maximum 1623 K and the gas generator speed is accelerated to 80 %. The gas generator speed is held at 80 % for 60 s, allowing temperature gradients to even out. During hot start conditions there is, however, no limitation on the start cycle. In practice, the driving cycle for a recuperated gas turbine would normally only include one cold start per day because of heat storage in the recuperator. During the typical hot start, the acceleration to 100 % speed and max. power takes 9 s.

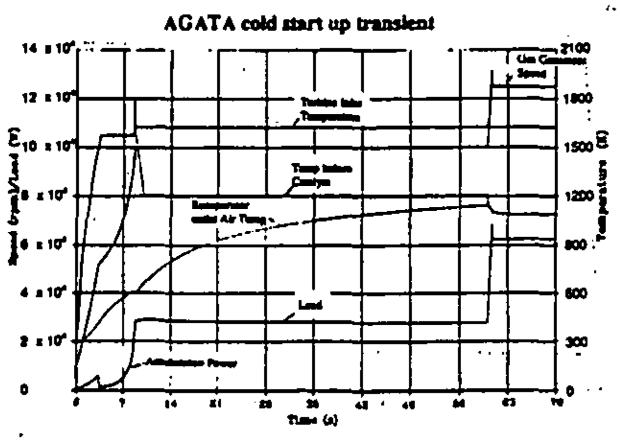


Figure 1. Cold start transient

CATALYTIC COMBUSTOR

The catalytic combustor section is shown in Fig. 2. At full load conditions, the temperature in the catalytic section is increased from inlet 1208 K to the exhaust 1623 K. Therefore all structural components in the hot section are made of ceramic materials.

The catalytic combustor includes the following components

- Preheater, to be operated only during the start-up period of 60 seconds and then by-passed for all other engine conditions.
- Premix duct based on a LPP concept with a venturi configuration which has been optimized in order to obtain a good velocity profile at the inlet to the catalytic section. Fuel is injected upstream of the venturi minimum section with injectors angled relative to the air flow. Mixing is achieved with an inlet radial/axial turbulence generator in the venturi inlet. The aerodynamic function of the mixing zone and the premix duct has been evaluated in water tunnel tests. These tests have shown that a nonseparated flow pattern in the venturi and into the first substrate can be achieved. Flow visualization is shown in Fig.3.
- Catalytic reactor, Fig. 4, with catalyst substrates made of ceramic honeycomb of an extruded oxide ceramic material inside the catalytic section envelope made of silicon nitride material.
- Afterburner cone, Fig. 4, for exhaust gases, designed for high strength thermal shock resistance and for operations at 1623 K is made of silicon nitride material.

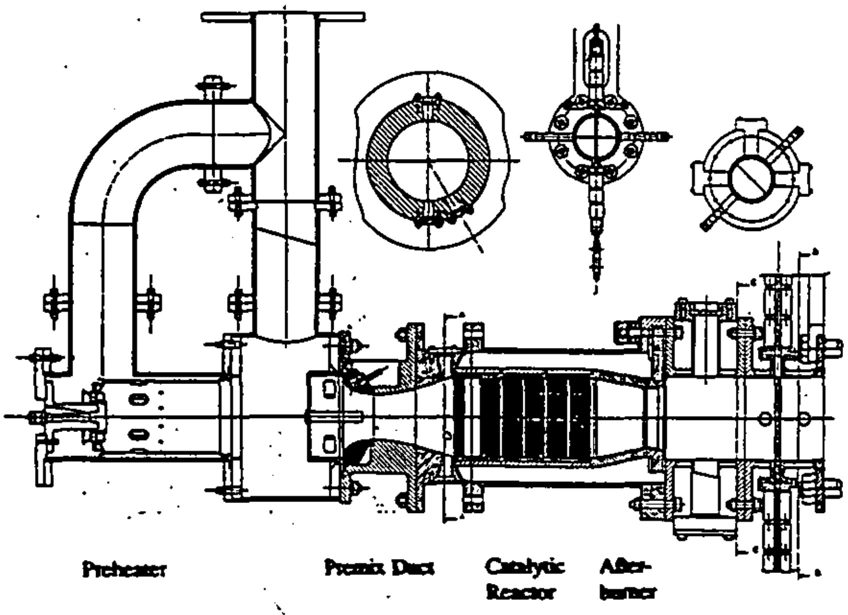
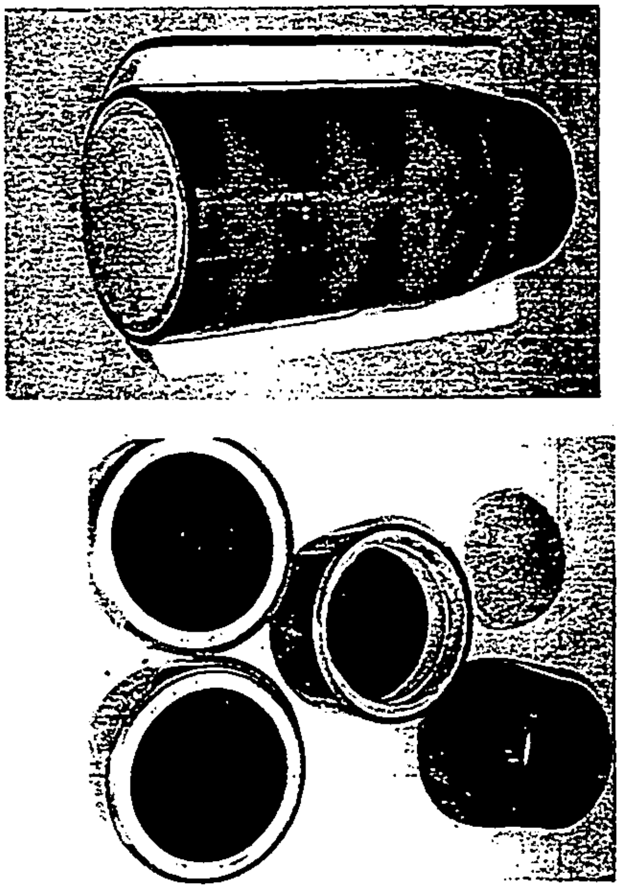


Figure 2. Catalytic combustor with exhaust measurment section.



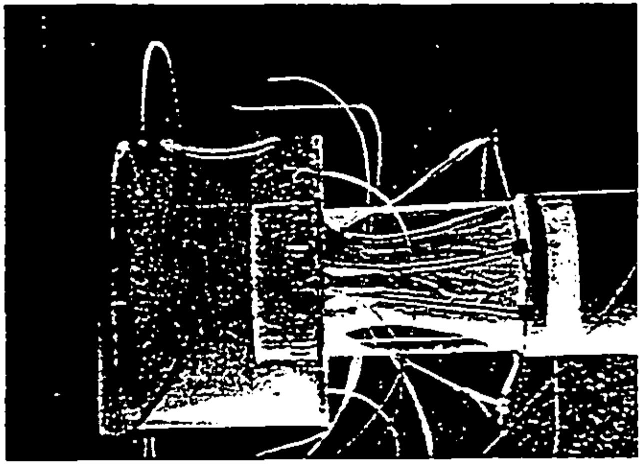


Figure 3. Mixing zone and Premix Duct flow visualization

Figure 4. Catalytic and afterburner sections
a. Assembled
b. Separate components

The combustor validation during steady state and transient conditions is performed in a test rig at ONERA, France, where the high pressure/temperature conditions can be achieved. The test rig, which was earlier described in ref. 7, is shown in Fig. 5.

The full scale combustor verification is ongoing. The preheater operation during the cold transient condition is essential for the catalytic combustor operation.

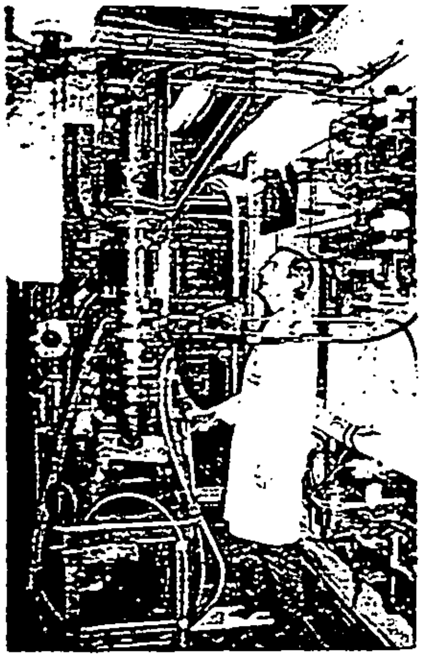


Figure 5. Catalytic combustor test rig.

During the first 9 seconds the preheater is increasing the turbine inlet temperature to 1573 K. At a time of 9 seconds, the preheater temperature is reduced to the catalytic combustor inlet running temperature of 1208 K and main fuel is introduced. Temperature profiles at the preheater exit as measured from gas analysis are flat as shown in Fig. 6. The temperature profile at 38 seconds is also shown. At this stage of the cold start, the recuperator temperature is increasing and therefore the temperature rise over the preheater is limited to 141°, see to Fig. 1.

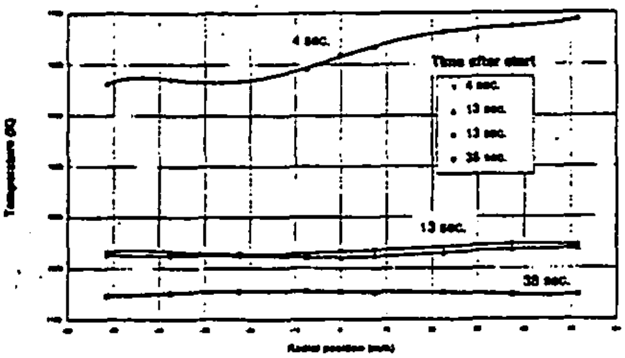


Figure 6. Preheater exhaust temperature profile during the cold start transient condition .

As was earlier pointed out in ref. 5, in order to obtain high hetero/homogenous combustion efficiency with low emission values it is important to create an even velocity profile at the catalytic section inlet. Extensive LDV measurements in the venturi premix duct outlet were therefore carried out using the test set up shown in Fig. 7. These tests, which were run at cold conditions at the design point same Reynolds no, show a very symmetric and even velocity profile at all circumferential angles in the duct outlet. The velocity profile with mean velocity of 11.66 m/s, Fig. 8, corresponds to a mean velocity of 28 m/s at design point conditions. The measured RMS values, 30-35 % of the mean velocity, also showed that a high turbulence level exists in the venturi. This will enhance the mixing and fuel vaporization process.

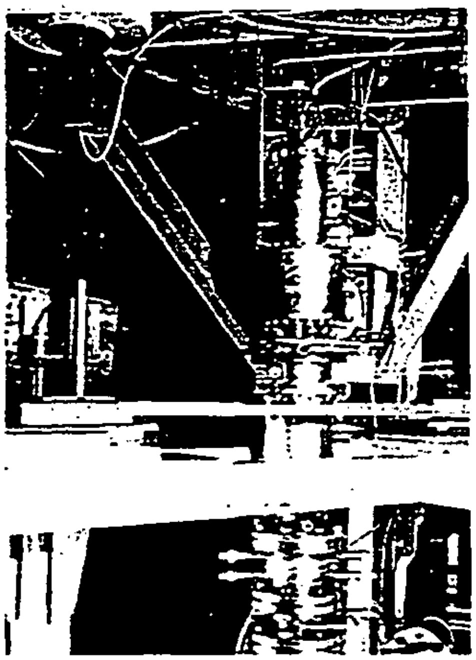


Figure 7. LDV test set up in the Premix Duct outlet

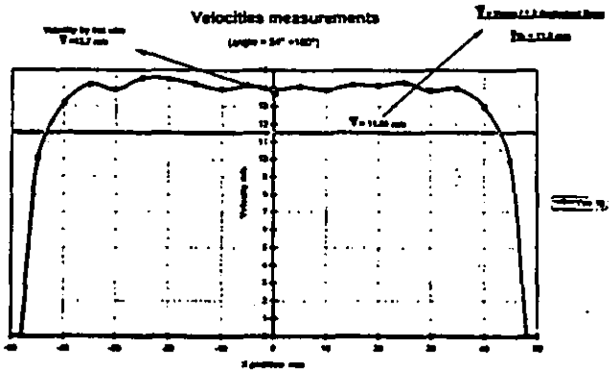


Figure 8. LDV measurements in the venturi premix duct outlet

The catalytic section of 100 mm diameter as shown in Fig. 4 is built up in sections with:

1. A first inactive SiC substrate with a thickness of 12.5 mm as a monolithic guard for the residual droplets from the premixer during transient or low temperature operations.
2. A catalytic section with 5 segments of 25 mm thickness. Based on the results from a screening process, the catalytic section materials for the first full-scale prototype were chosen..The active material is palladium based. An oxide ceramic developed by Ceramiques & Composites was chosen for the substrate. This material exhibits a significantly higher melting point than cordierite, although lacking its extremely good thermal shock resistance. The catalytic section outer rings are manufactured in SiC-whisker reinforced Si_3N_4 by Aerospatiale using uniaxial hot pressing.
3. The afterburner cone is manufactured by AC Cerama in the same Si_3N_4-grade (CSN 101) as the turbine wheel. This component is manufactured at the prototype scale by cold isostatic pressing, followed by green machining, glass encapsulation and HIP. In a future larger production volume such a piece could be formed by injection moulding. The outer and inner surfaces of this component will is used with as-HIPed surface finish. Only the contact surfaces are machined after HIP.

The full scale combustion tests are ongoing for the design points from idle to full load as well as transient conditions. After the first test campaign, the combustor was dismantled, inspection of the separate components showed that two out of five catalyst segments had single cracks but the segments were contained. Fig.4. These tests which were run at temperatures 200°C below the design condition have shown very good emission characteristics with $NO_x < 1$ ppm at 15 % O_2.

A special test set up for CARS laser diagnostics in the combustor outlet is being set up. Temperature and oxygen maps measured by CARS will be correlated with emissions maps. Combustor tests will be finalized by the end of February 1998.

CERAMIC TURBINE WHEEL

The turbine wheel design is completed and the first wheels, as well as some bladeless spin discs have been manufactured by AC Cerama AB. The wheels are made by injection moulding followed by Hot Isostatic Pressing (HIP). The material chosen is the Si_3N_4 grade CSN 101 containing 3 % Y_2O_3 sintering additive. This material has undergone an extensive evaluation of mechanical properties as described in ref 9. Good oxidation resistance as well as a balance of high strength and toughness at room temperature coupled with adequate creep resistance at 1473 - 1623 K make the CSN 101 Si_3N_4 material a good choice for gas turbine components. The material development and properties are reported in a separate paper, ref 9. A straight blade design has been selected. The target wheel efficiency is 86%. In a wheel efficiency test 84% efficiency was measured using a final design wheel.

FEM calculations have indicated that stress levels which occur during cold start are below 300 MPa. The first HIPed wheels have been delivered and are now being balanced and cold spin proof tested. So far one wheel has survived the initial 60 000 rpm proof test.

The ceramic wheels are inspected using cone beam X-ray inspection system developed by CEA/LETI especially for inspection of the AGATA wheels, ref 9. The wheel is joined to the metallic shaft using a brazing technique developed by CEA/Cerem. An interlayer material of intermediate thermal expansion is used to reduce the residual stresses caused by brazing. Hot spin tests at TIT 1623 K and 125000 rpm will be performed in a modified turbo charger rig at ONERA and are expected to start in February 1998.

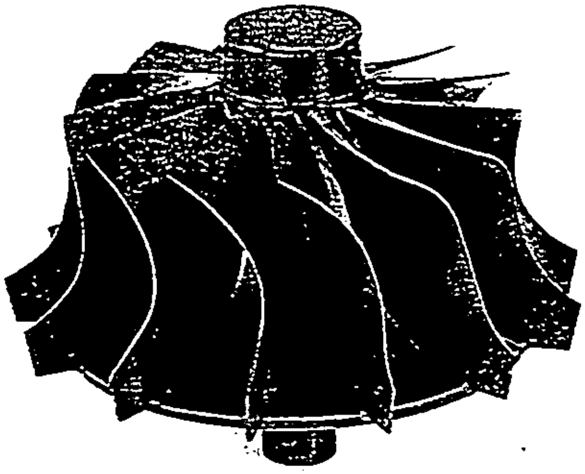


Figure 9. HIPed Si_3N_4 wheel delivered by AC Cerama

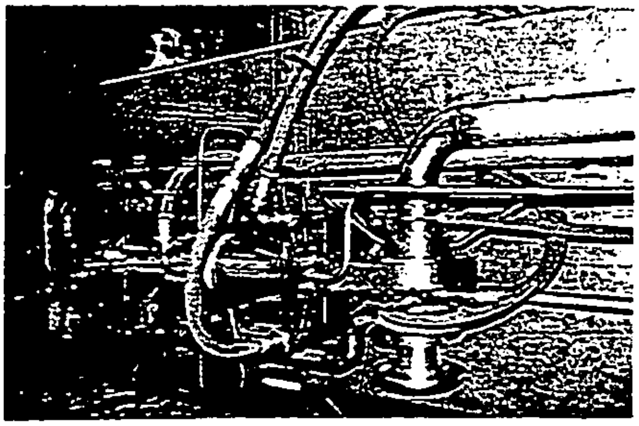


Figure 10. Hot spin rig at ONERA.

HEAT EXCHANGER

The fixed geometry heat exchanger/recuperator is a counter flow design. The heat exchanger conditions are specified according to Table 2.

Table 2. Heat exchanger conditions

Cold side	Inlet temperature	483 K
	Inlet pressure	0.397 MPa
	Air mass flow	260 g/s
Hot side	Inlet temperature	1286 K
	Inlet pressure	0.110 MPa
	Air mass flow	264 g/s

The matrix, Fig. 11, is manufactured by Ceramic & Composites by extrusion. The concept is based on stacking undulating layers separated by thin flat sheets. The thickness of the wavy layers are 0.2 mm and the flat sheets 0.3 mm with the channel heights on the gas side 3 mm and air side 2 mm.

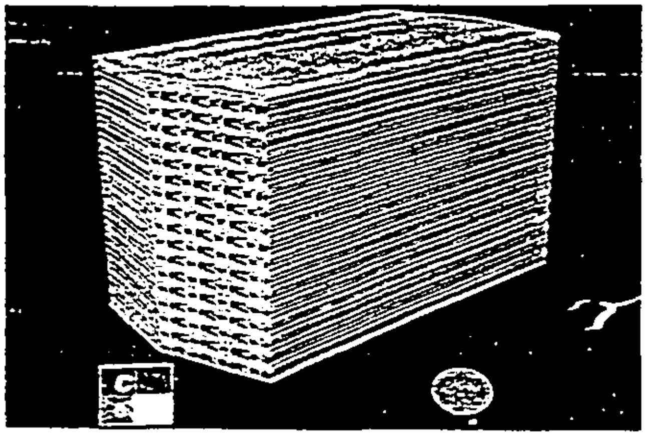


Fig. 11. Cordierite heat exchanger in scale 1:4 with length scale 1:1

The bonding properties of the cordierite heat exchanger plates have been evaluated during transient start and shut down cycling at temperatures up to 1300 K. These transient tests have been run with 50x50x50 mm test samples in a test rig, Fig 12. The test series have shown that the bonding between the individual elements appeared to be very resistant to transient thermal stresses, although some microcracks were found in the air sealing bars at the edges of the samples.

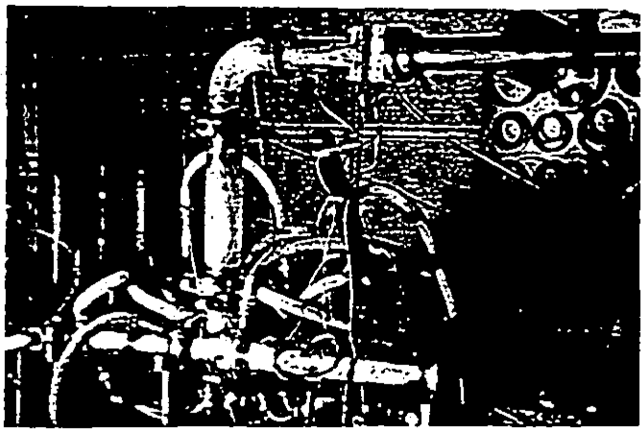


Fig. 12. Test rig for heat exchanger samples transient tests.

During the design phase, a number of matrix configurations were evaluated. Essential parameters for automotive applications are volume and weight. Depending on heat exehanger hydraulic diameter and geometry, the matrix volume necessary to fulfill the AGATA specification has been varied from 10 - 67 liters as shown in Table 3.

Table 3. Heat exchanger matrix volume

Design	Channel dimension Gas/Air H x W mm	Matrix volume liter
1	3 / 2 x 0.6	26
2	1.8 / 1.2 x 0.6	20
3	5 / 3 x 1	67
4	3 / 2 x 1	50
5	1 / 1 x 3	37
6	1 / 1 x 0.6	23
7	0.6 / 0.6 x 0.6	10

For manufacturing reasons, it was decided to choose configuration no 1 to be tested in the AGATA program. This heat exchanger configuration also has been evaluated for SiC material. The volume decreases to 17 litres and the weight to 18 kg. The thermal properties of cordierite, however, lead to lower thermal stresses which makes cordierite the preferred choice despite the higher strength and smaller volume of SiC. When including the ceramic inlet, outlet and sealing sections, the volume for this configuration increases to appr. 40 litres with a weight of 35 kg when manufactured in cordierite material. The total volume and weight including inlet/outlet zones and casing is about 55 litres and 50 kg.

The most critical aspect of the recuperator design is the connection of the outlet and inlet ducts to the ceramic matrix to ensure sealing of the air and gas circuits. This sealing has been solved by springloading the air inlet and outlet sections, Fig 13. The ¼ scale heat exchanger hardware is shown in Fig 14 with the inlet/outlet sections dismantled, Fig. 14a, and installed in the test rig, Fig 14b.

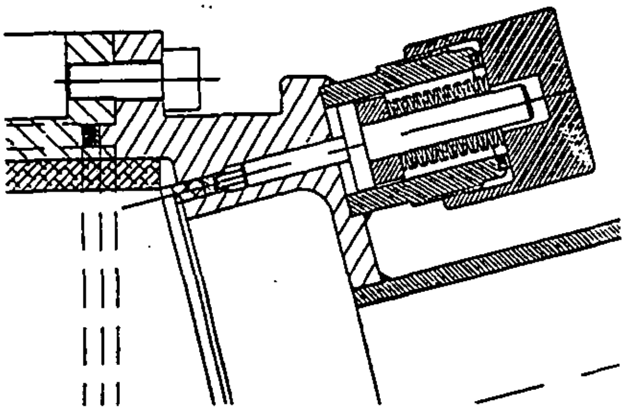


Fig. 13. Heat exchanger air inlet/outlet sealing section

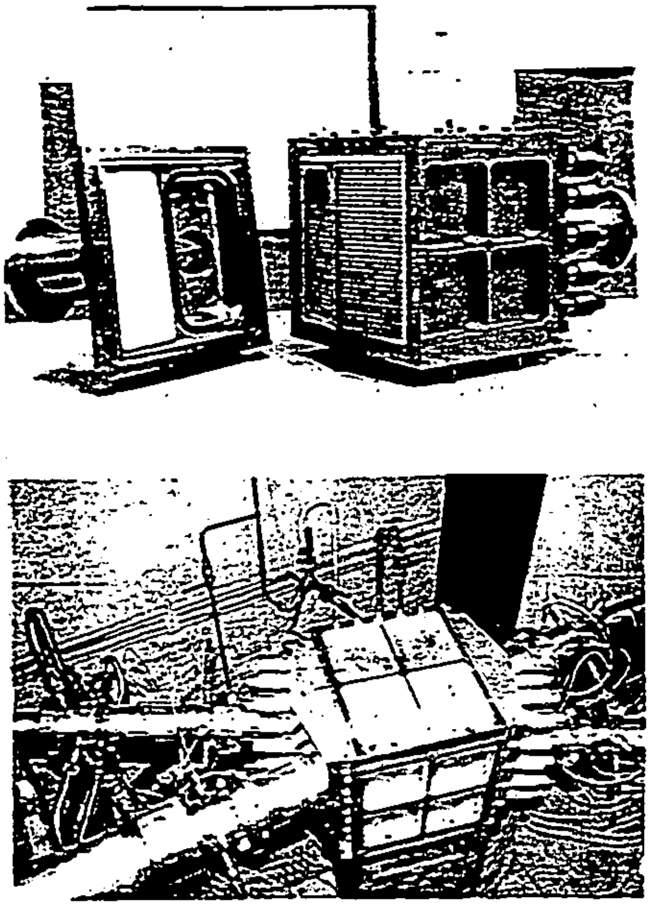


Fig 14. Heat exchanger hardware
a. Dismantled inlet/outlet section
b. Installed in the test rig

The quarter scale heat exchanger is now tested in the test rig at ONERA and the manufacturing of the full scale cordierite heat exchanger is ongoing.

CONCLUSIONS

The European Gas Turbine Program "AGATA" which started 1993 now has reached its verification phase.

- Test rigs for steady state and transient tests are commissioned

Catalytic combustor

- The full scale combustion rig tests up to the operating temperature of 1623 K are ongoing.

Ceramic Turbine Wheel

- First ceramic turbine wheels have been manufactured by injection molding and Hot Isostatic Pressing (HIP)
- Cold spin tests are ongoing
- Hot spin tests at TIT 1623 K will start in Feb. 1998

Heat Exchanger

- Tests are ongoing with ¼ scale prototype
- Manufacturing of full scale heat exchanger in progress

ACKNOWLEDGEMENTS

The authors would like to thank the AGATA partners (AC Cerama AB and Volvo Aero Corporation in Sweden, Aerospatiale, AlliedSignal Catal. Environ. (ACE), AlliedSignal Turbo SA, CEA/Cerem, Céramiques & Composites, GRETH, IFP, ONERA, Peugeot SA and Renault, France, for their contribution to the technical reports and the French Ministry of Research, (MESR), and NUTEK, (Sweden) for their sponsorship

REFERENCES

1. Larker, H.T, Adlerborn, J.E, Lundberg, R: "HIPed Silicon Nitride Wheel Development" 5th Int Symp on Ceramic Materials and Components for Engines, Shanghai, China 1994.

2. Lundberg, R: "AGATA - A European Ceramic Gas Turbine for Hybrid Vehicles", ASME paper 94-GT-8, 1994

3. Lundberg, R, Gabrielsson, R: "Progress on the AGATA Project - A European Ceramic Gas Turbine for Hybrid Vehicles" ASME paper 95-GT-446, 1995

4. Lundberg, R, Gabrielsson, R, Adlerborn, J: "Development of Silicon Nitride Components for AGATA - A European Gas Turbine for Hybrid Vehieles", Proc. Int. Gas Turbine Congress, Yokohama, Japan, Oct. 22-27, 1995.

5. Gabrielsson, R, Holmqvist, G: "Progress on the European Gas Turbine Program - AGATA" ASME paper 96-GT-362, 1996

6. Lundberg, R, Adlerborn, J: "Silicon Nitride Components for AGATA - A European Gas Turbine for Hybrid Vehicles", ASME-paper 96-GT-287, 1996

7. Avran, P, Leclair, A, Payen, G: "Test Benches for Ceramic Components for Automobile Gas Turbines" ASME-paper 97-GT-69, 1997

8. Lundberg, R, "HIPed Silicon Nitride Components for AGATA - A European Gas Turbine for Hybride Vehicles" ASME paper 97-GT-322, 1997

9. Lundberg, R, Garguet-Duport, L., "HIPed Silicon Nitride Components for AGATA - Properties and Non-Destructive Testing" ASME Turbo Expo 1998