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# AGATA: A EUROPEAN CERAMIC GAS TURBINE FOR HYBRID VEHICLES

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## ABSTRACT

The European EUREKA project EU 209 or AGATA - Advanced Gas Turbine for Automobiles is a program dedicated to the development of three critical ceramic components; *i.* catalytic combustor, *ii.* radial turbine wheel, *iii.* static heat exchanger, designed for a 60 kW turbogenerator for a hybrid electric vehicle. The objective is to develop and test the three components as a full scale feasibility study with an industrial perspective. The AGATA partners represent car manufacturers as well as companies and research institutes in the turbine, catalyst and ceramic material fields in France and Sweden.

## INTRODUCTION

The AGATA project as defined in 1987 was initially dedicated to a 100 kW gas turbine for a conventional car power train. A gas turbine as a turbogenerator in a hybrid electric vehicle offers additional advantages for the automotive application (Koslowski) (Volvo) and in 1992 the AGATA program was re-oriented in this direction. There is also an interest in small turbogenerators in the turbine industry for application as high efficiency, clean aeronautical auxiliary power units (APUs). The AGATA program will concentrate on three components of great importance for obtaining low emissions and high efficiency:

- ceramic catalytic combustor
- ceramic radial turbine wheel
- ceramic heat exchanger

These three components will be designed, developed, manufactured and tested separately in a full scale feasibility study. A conceptual AGATA gas turbine indicating the three critical components studied is shown in figure 1. The re-oriented AGATA project started early 1993 and will run for 4 years until the end of 1996, with a total budget of 120 MFF.

## AGATA OBJECTIVES

The objectives of the AGATA project are to develop and test the above mentioned three critical components as a full scale feasibility study with the following technical specification:

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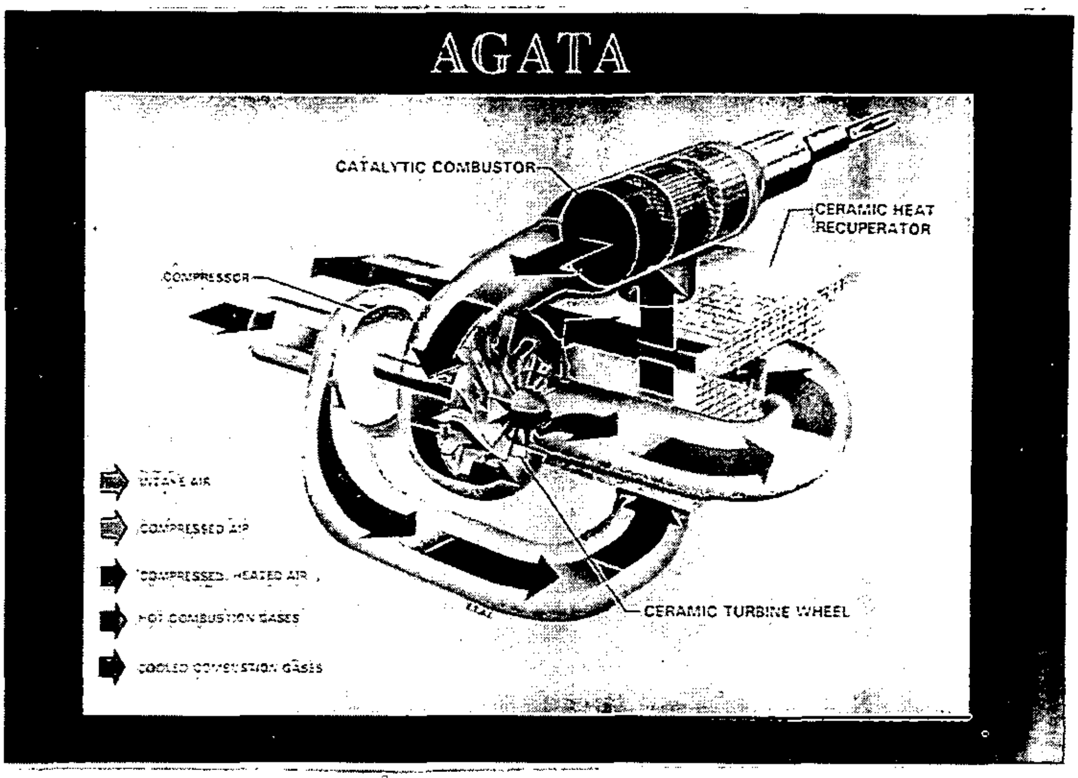


Figure 1. The AGATA gas turbine with the three critical components, ceramic catalytic combustor, ceramic radial turbine wheel and ceramic heat exchanger, indicated.

- Mechanical output 60 kW
- Specific fuel consumption 200 g/kWh
- Turbine inlet temperature 1350°C
- Max. pollutant emissions ULEV or similar European standard
- Fuel Diesel or alternative fuel
- Applicable to hybrid electric vehicles

The pollutant emissions and fuel economy are the prime concerns of the project. The catalytic combustor promotes clean, complete combustion at very lean air/fuel mixtures resulting in extremely low $NO_X$ emissions. Together with a ceramic turbine wheel permitting a high turbine inlet temperature and a high efficiency heat exchanger this will yield very moderate specific fuel consumption. In a hybrid electric vehicle application the turbogenerator system will mostly operate at constant, high load and the operating conditions can therefore be optimised with regard to emission and fuel consumption objectives.

## AGATA PARTNERS

The AGATA partners are companies and research institutes from France and Sweden:

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|---|---|---|
| AC Cerama | (S, company) | ceramics |
| Aerospatiale | (F, company) | ceramics |
| Allied Signal Automotive Catalysts (ASAC) | (F, company) | catalysts |
| Allied Signal Turbo | (F, company) | turbines |
| CEA/Cerem | (F, research lab) | ceramics materials |
| Céramiques & Composites | (F, company) | ceramics |
| Institut Français du Petrole | (F, research lab) | combustion catalysts |
| ONERA | (F, research lab) | turbines combustion |

| | | |
|---|---|---|
| Peugeot SA | (F, company) | automobile |
| Renault | (F, company) | automobile |
| Volvo Flygmotor | (S, company) | turbines ceramics |

## CERAMIC CATALYTIC COMBUSTOR

This sub-project is operated with the following partners;

- Aerospatiale
- AC Cerama
- Allied Signal Automotive Catalysts
- Allied Signal Turbo
- Institut Français du Petrole
- ONERA
- Peugeot SA
- Renault (Co-pilot)
- Volvo Flygmotor (Pilot)

Today's best technology for low $NO_x$ emission combustors for small gas turbines is based on the Lean Pre-mixed Pre-vaporised (LPP) concept. To reach even more lean air/fuel mixtures and lower combustion temperatures further decreasing thermal $NO_x$ emissions a catalytic combustor is an attractive alternative. The field of high temperature catalysts for catalytic combustion has been recently reviewed by Zwinkels et al. In the re-oriented AGATA project the catalytic combustor concept will be developed. Some features of the AGATA catalytic combustor will be discussed here.

The catalytic combustor configuration includes a start-up preheater. The fuel preparation mixture system takes advantage of LPP combustor technology making the catalytic combustor a logical evolution of the developed LPP technology. The technical program is focused on ceramic structural parts as well as catalytic combustion. All ceramic parts will operate uncooled at 1350°C. The main ceramic parts are catalyst section envelope, catalyst honeycomb substrate and afterburner. The catalyst section envelope and afterburner are manufactured at Aerospatiale and AC Cerama using high strength, thermal shock resistant high performance ceramics with a proven potential for long term use at 1350°C. The catalyst honeycomb substrate will also have to be capable of operation at 1350°C. The substrate used for automotive exhaust catalysts is a ceramic honeycomb structure made of extruded cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$). Cordierite has a melting point of ~1450°C, which makes operation at 1350°C questionable. Other ceramic honeycomb substrates with better high temperature properties are at the moment being studied within the AGATA project with promising results. The task of finding the right catalyst with high activity, low light-up temperature and good thermal stability is also well under way. A low light-up temperature is desirable in order to minimise pre-heater $NO_x$ by making it possible to use the pre-heater only for a very short time.

At the moment ceramic component hardware has already been manufactured, promising ceramic substrates and catalyst are being screened and extensive design and modelling work has been carried out. Later in the project a full scale catalytic combustor will be tested under realistic gas turbine conditions. Both transient and steady state conditions will be part of the testing. At this stage optical laser diagnostics will be employed to verify emissions.

## CERAMIC RADIAL TURBINE WHEEL

The partners in the turbine wheel sub-project are:

- AC Cerama
- Allied Signal Turbo
- Céramiques & Composites
- CEA/Cerem
- ONERA
- Peugeot SA
- Renault (Pilot)
- Volvo Flygmotor (Co-pilot)

This sub-project is focused on establishing a fruitful relationship between designers and ceramic manufacturers with impact both on the design work and on the material development. To design and manufacture a ceramic turbine wheel capable of operation at a high rotational speed and a turbine inlet temperature of 1350°C this designer-manufacturer interaction is of greatest importance. Two different design approaches with different load coefficients leading to different tip speeds are currently being studied. Also two different ceramic processing techniques are being evaluated. $Si_3N_4$ is the material of choice for both processing techniques.

AC Cerama is developing a method of combining two green forming techniques with their proprietary glass encapsulation - hot isostatic pressing (HIP) technique (Larker). The hub section of the wheel is formed by cold isostatic pressing while the blade-ring is injection moulded. After binder burn-out the hub and blade-ring are green-joined, glass encapsulated and HIPed. The advantage of this technique is that binder burn-out is much easier and quicker for two smaller pieces then for a one-piece injection moulded turbine wheel. The advantage of glass encapsulated HIPing is that virtually all pores and internal cracks are eliminated as defects. So far a 4-point bending strength of 955 MPa (average) at room temperature with a Weibull modulus of $m = 24$ has been found for this material. Testing of HIP-joined material show the same strength level as bulk material.

Céramiques & Composites is pursuing another processing route. With a technique called Precursor Reaction Injection Moulding (PRIM) the turbine wheel can be injection moulded as one piece. This is realised by the introduction of a polymer binder, or precursor, which on pyrolysis is converted to a ceramic residue. With this technique less binder has to be burned out making this step easier for large cross section components. Gas pressure sintering is then used to give a high toughness, dense $Si_3N_4$ material.

Another important part of the turbine wheel project is the wheel to shaft joining. Joining will be performed by ceramic to metal brazing with a joint configuration, braze alloy selection and braze parameters specially developed within the AGATA project.

Spin discs as well as final design wheels will be cold spin burst tested. Hot spin testing will be performed in a gas turbine rig under realistic conditions regarding pressure, temperature and aerodynamic loading. The hot spin tests will be run as start/stop low cycle fatigue tests.

At this stage of the project material development has reached a stage were material properties presented are well above the stress levels given by the first and second design iterations. A failure probability analysis performed indicates a low enough failure probability. Hardware in the form of spin discs (and test bars) has been produced within the project.

## CERAMIC HEAT EXCHANGER

This sub-project has the following partners:

- Céramiques & Composites
- Onera
- Peugeot SA (Pilot)
- Renault

A recuperative fix geometry heat exchanger has been selected for the AGATA project. The efficiency goal has been set to $\eta = 0.90$. Two design concepts are studied, one plate concept and one tubular design. Céramiques & Composites has a long experience in green forming by extrusion and other forming methods for producing sintered SiC ceramics. The green forming techniques are developed further within the AGATA project to obtain extremely thin-walled parts. Another important area studied is ceramic-to-ceramic and ceramic-to-metal bonding for heat exchanger assembly.

Already ceramic prototypes have been produced and production scale-up capability has been demonstrated. Later in the project full scale testing of the heat exchanger will be performed.

## CONCLUSIONS

During the first year of the re-oriented AGATA program results regarding design, calculation, simulation, material development, material properties and prototype manufacturing have been obtained. So far all three sub-projects are on schedule and the full scale feasibility test demonstrating the goals of the technical specification looks achievable.

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