CERAMIC MATERIALS FOR VEHICULAR GAS TURBINE APPLICATIONS

W. Bunk
DFVLR - Institut für Werkstoff-Forschung
Cologne, Germany

Abstract

The objectives of the German R+D Program 1974-1980 concerning the application of ceramic components in a vehicular gas turbine are - among others -:

- service temperatures of 1350 °C to gain higher efficiency,
- a low fuel consumption and more flexibility in type of fuels.

The goals can be achieved by introducing new ceramic materials, advanced manufacturing techniques, and new design methods.

Gas turbine engineers, mechanical engineers, and ceramic materials scientists from industry and research institutions cooperate very closely to meet these goals.

1.0. Introduction

A snapshot of today's state of the art in developing ceramic gas turbine components (Fig. 1) by one of the German gas turbine producers may enlighten the scenery like a flash; the future of the ceramic gas turbine has started already [1]!

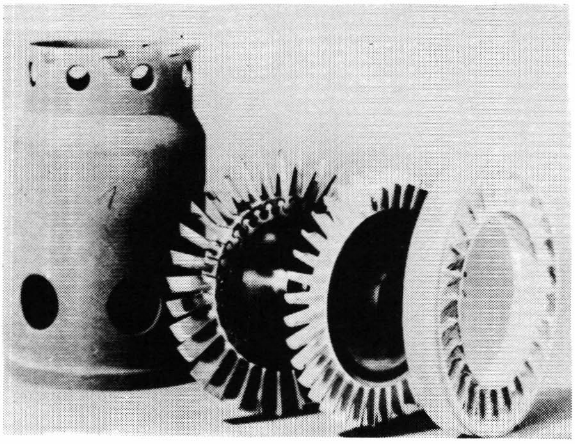


FIG. 1: CERAMIC GAS TURBINE COMPONENTS (VW, 1978)

Decades ago engineers unsuccessfully attempted to employ conventional ceramics for turbine applications. What made engineers optimistic some years ago to introduce ceramics into the gas turbine world again? New non-oxide ceramics with an outstanding potential at high stresses and temperatures! One more very important parameter was taken into serious consideration from the beginning: the importance of a new design philosophy based on the applications of brittle materials which are not forgiving.

1.1. Background

From Carnot we learned more than one century ago: the hotter the heat engine the more efficient is its use of energy.

Today jet engine designers have pushed turbine temperatures to 1250 °C and higher by introducing sophisticated cooling techniques. Metallic blades sustain about 1000 °C, especially when directionally solidified upon casting. Following Carnot's principles, material scientists looked for materials having a higher temperature potential. They discovered new ceramic materials of the SiN and SiC type which demonstrated a rather high level of strength up to 1350 °C. Designers were interested in the first news from the materials front but complained about the brittleness and lack of reliable mechanical data, the unusual scatter of properties and so on. Therefore, the materials-design-canyon dominated the first part of the discussion between excited material scientists and skeptical gas turbine designers. Both sides started to build bridges across the canyon by improving materials homogenity and learning to design with brittle material. Fracture mechanics, slow crack growth results, NDE, Weibull statistics, etc. helped a great deal in building of confidence in these new materials and design concepts. In addition, numerous efforts were started and followed with great passion to develop new design concepts based on finite element calculations and statistical methods which adequately coped with distribution of flaws. This is of great relevance since metals are forgiving of designer errors or fabrication defects, but ceramics are not. Therefore, if ceramics were ever to find their way into highly stressed parts in heat engines it would only be through adopting rather refined design concepts specially tailored to the brittleness of ceramic materials. Materials engineers on the other hand discovered that the new family of non-oxide ceramics shows an improved toughness as service temperatures climb higher and higher.

1.2. Fuel Saving Potential

Due to the energy crisis engineers are more concerned with fuel consumption of vehicular engines. Fig. 2 explains the current views for developing a gas turbine with remarkable low fuel consumption. Better mileage with ceramics could and should become a slogan for gas turbine producers and users. Ceramic gas turbines with operating temperatures of 1300 °C are characterized by a remarkable fuel-saving potential. Such a gas turbine delivers as much power as today's eight cylinder piston engine [2]. Fig. 3 describes the fuel saving potential of gas turbines in comparison to Diesel and Otto engines for different vehicular weights. These curves express the rather cautions prognosis of an european car manufacturer which is known for high mileage engines.

Also advantageous is the multi-fuel potential of gas turbines in contrast to piston engines. This fact might have a surprising impact on the relevance of vehicular engines in the future when an alternative source of energy such as hydrogen becomes a reality.

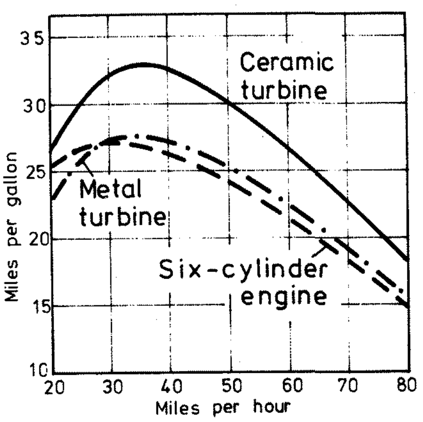


Fig. 2:
Fuel-saving potential (ERDA/Chrysler 1976)

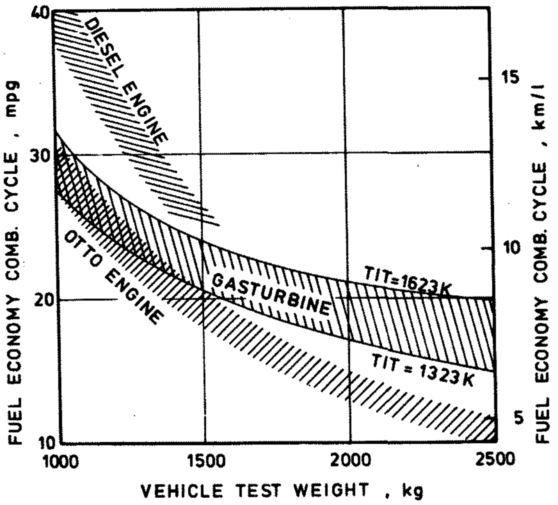


FIG. 3: FUEL ECONOMY POTENTIAL OF GAS TURBINES (VW, 1976)

1.3. Raw Materials Safeguarding and Environmental Protection

One other aspect of relevance to the future is the safeguarding of scarce raw materials and/or strategic metallic materials which could become unavailable because of shortages or political reasons. Silicon nitride and silicon carbide are based on abundant available raw materials in all industrial nations. These materials have remarkable low densities of 3.2 g/cm^3 or lower compared with 9 g/cm^3 for superalloys used in today's high performance gas turbines.

Environmental protection causes no difficulty at all. There are no fuel additives like lead needed and the emission standards are easily met. A gas turbine produces less vibration than a piston engine and generates less noise.

2.0. State of the Art in Materials and Design Development of Vehicular Ceramic Gas turbine Components

During the last decades an evolution of higher strength ceramics took place (Fig. 4). Some very interesting non-oxide ceramics, namely silicon nitride and silicon carbide, are presently marketed. The situation has thus changed by leaving metallic materials behind and looking forward to the higher temperature capabilities of these new ceramics. Fig. 5 draws the picture for all known high

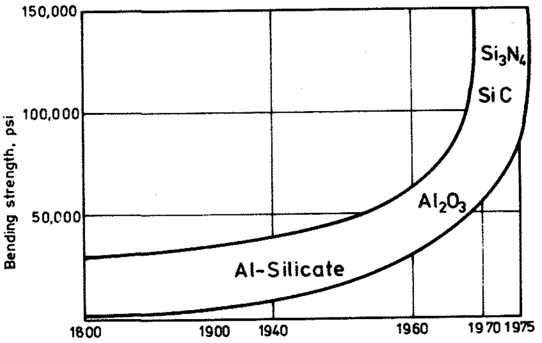


Fig. 4: Development of high strength ceramics

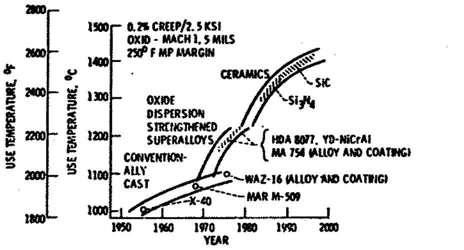


Fig. 5. - Increased use temperature projected for ODS superalloys and ceramics for high temperature low stress applications NASA 77

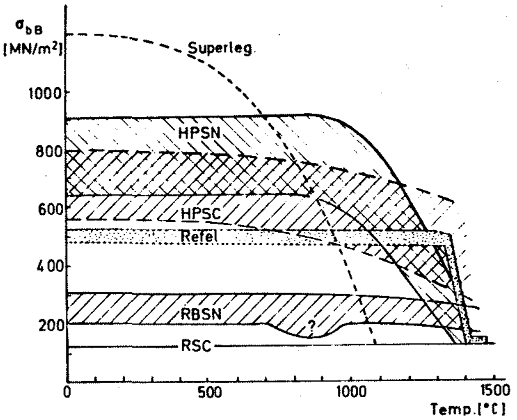


FIG. 6: HIGH TEMPERATURE STRENGTH OF Si_3N_4 AND SiC (THÜMMLER, 1978).

temperature materials of vital interest to the engineers [4]. Superalloys can do the job up to 1000 °C while ceramics are capable of withstanding 1300 °C and higher. Fig. 6 compares superalloys with the new class of ceramic materials. One realizes at once the enormous potential of these ceramic materials [5].

2.1. Advanced Materials and Processing Techniques

Covalent bound materials like silicon nitride and silicon carbide are regarded as difficult to densify by sintering. Because of this, material engineers developed a number of advanced processing techniques.

2.1.1. RBSN (Reaction Bonded Silicon Nitride)

The reaction bonded process takes silicon powder which is milled and mixed with a plastic binder. This mixture is injection moulded to form a green part having the desired final product shape. After burning off the plastic binder the silicon skeleton is nitrided in a special reactor controlled process for more than 100 hours. Densities of 2.6-2.7 g/cm^3 are state of the art. Slip castings are also regarded as an economical manufacturing technique for combustors, etc.

2.1.2. HPSN (Hot Pressed Silicon Nitride)

Hot pressing of silicon nitride powder with a sintering aid, like MgO or more recently Y_2O_3, leads to bending strength properties of 600-800 MN/m^2, much higher than RBSN. Hot pressing of RBSN is possible and has some potential for further development, especially for joining of RBSN and HPSN components.

2.1.2.1. Pseudo-Isostatic Hot Pressing of Silicon Nitride [6]

One line of thinking is a "pseudo isostatic" hot pressing of a special composition silicon nitride. If this method could be developed economically it could replace the other concepts of duo-density parts like rotors of RBSN blades and a pseudo isostatic hot pressed hub (Fig. 7).

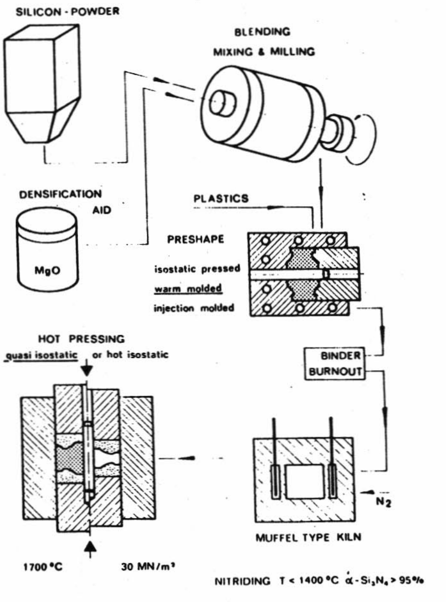


FIG. 7: MANUFACTURING SCHEME OF "PSEUDO-ISOSTATIC" HOT PRESSING OF TURBINE HUB (CERANOX, 1977)

2.1.3. HIP (Hot Isostatic Processing)

Hipping of silicon nitride is the most modern and most unknown advanced processing concept. It appears that a sintering aid is not necessary and strength properties better than 800 MN/m^2 are feasible. Fig. 8 shows the first successful experiments of incapsulation and hipping of silicon nitride [7].

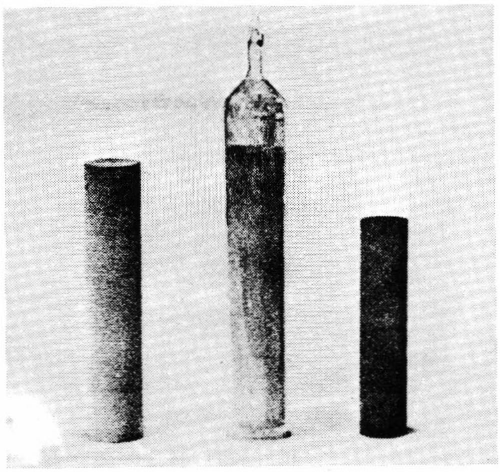


Fig. 8 - Machined green body, encapsulated green body resp. dense HIP silicon nitride (left to right) (ASEA, 1977)

2.1.4. Manufacturing Processes for Silicon Carbide

Hot pressing and infiltration of silicon in silicon carbide are conventional techniques. Some years ago sintering of silicon carbide micro powder doped with C and B became popular because it seams to be economical.

2.1.5. Microstructure of New Ceramic Materials

Looking through the microscope one can easily differentiate between the porous structure of low density RBSN (Fig. 9a) and highly density RBSN (Fig. 9b) [8]. Concerning SiC one recognizes the globular sintered structure of α-SiC and the typical needle like β-SiC which is wanted for high strength and reliability (Fig. 10) [9]. For some special applications CVD coatings of Si_3N_4 on top of porous RBSN might draw some interest. Fig. 11 shows a microstructure of such a coated substrate [10].

2.1.6. Creep Properties at High Temperature

In contrast to metals like superalloys, ceramic materials have the benefit of very low creep rate which makes them excellent candidates for components in high temperature applications. Fig. 12 demonstrates the extreme low creep rate in ceramic materials of high density quality.

The thermoshock resistance of ceramic materials to quick changes in temperatures and high temperatures gradients is an area of major concern in many research labs. Most experts hope for a compromise of materials quality tailored to design needs with respect to thermoshock.

a) $= 2{,}3\ [g/cm^3];\ {}_B = 150\ [MN/m^2]$

b) $2{,}6\ [g/cm^3];\ {}_B\ 300\ [MN/m^2]$

IG. 9: STRUCTURE OF RBSN WITH DIFFERENT DENSITIES AND STRENGTHS (DEGUSSA, 1978)

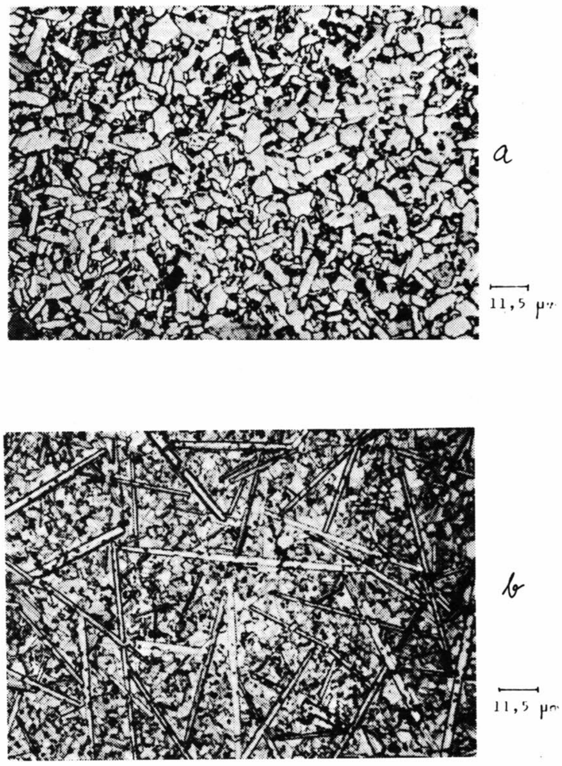


FIG. 10: STRUCTURE OF α-SIC (a) AND β-SIC (b), 95 - 96 % THEORETICAL DENSITY (SIGRI, 1978)

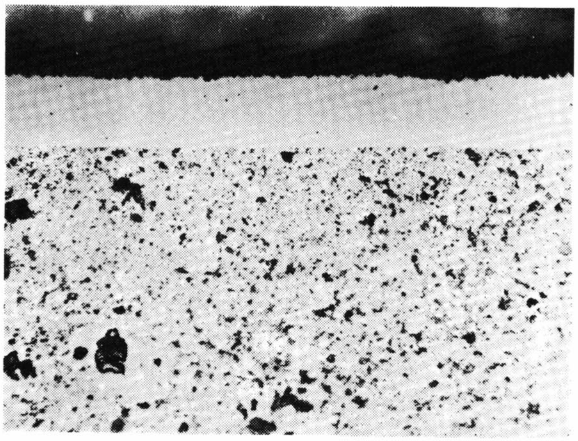


FIG. 11: CVD-SILICON NITRIDE COATED RBSN (MERCEDES-BENZ, 1978)

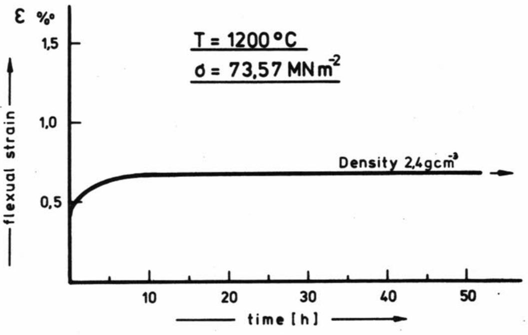


Fig.12:
4-point bending creep curve of RBSN [DFVLR,1978]

2.2. New Design Philosophies

As an example the new approach in design of rotors could be described as the hybrid metal hub-ceramic blades concept.

2.2.1. Hybrid Ceramic Rotor

Fig. 13 demonstrates an 120 mm diameter hybrid rotor. The hub is a forged superalloy and the blades are injection molded RBSN. This corresponds to the designers needs for a ductile hub of medium high temperature strength and blades of outstanding high temperature potential. Designers concentrated on optimizing the mechanical joint between both parts made of different materials (RBSN and HPSN).

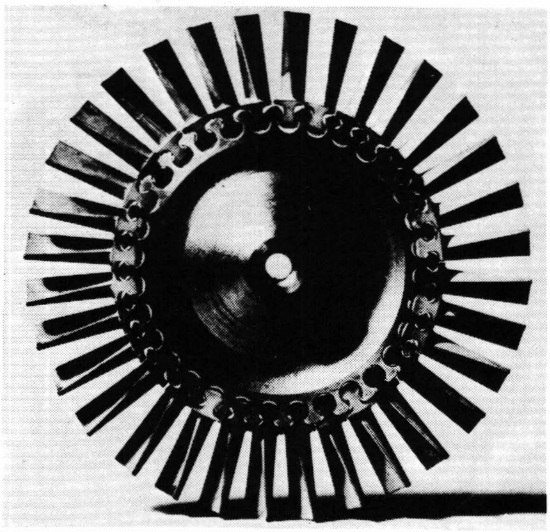
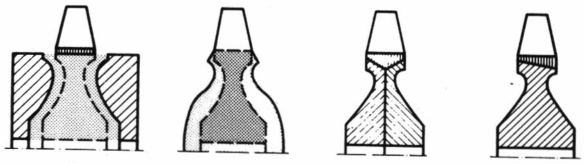


Fig. 13: 120 mm diam. Turbine Wheel, Metallic Hub, Ceramic Blades (VW, MTU, 1978)

2.2.2. Duo-Density Silicon Nitride Components

Some gas turbine producers started from the beginning using the duo-density rotor concept for joining a HPSN hub with a RBSN ring of blades (Ford, VW) (Fig. 14) [11].



Concept A
Blades RBSN
Hot Pressed HPSN Hub

Concept B
Blades RBSN
"Pseudo-Isostatic"-
Hot Pressed RBSN Hub

Concept C
Blades RBSN
Joined HPSN Hub

Concept D
Blades RBSN
Joined HPSN Hub

Fig. 14: Some Concepts of Duo-Density HPSN-RBSN Turbine Wheel (VW, 1977)

Although the project is not yet finished it looks like concept B (hot pressing of RBSN-hub) has more promise than others. Time will tell which concept will please gas turbine engineers. But it looks quite promising that the difficult problem of designing a turbine wheel for 1300 °C and about 60,000 rpm can be solved in the near future. Fig. 15 shows stresses in the different parts of the rotor for different revolutions.

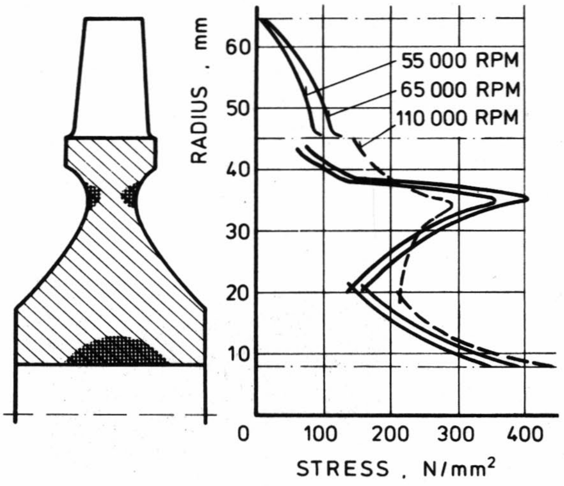
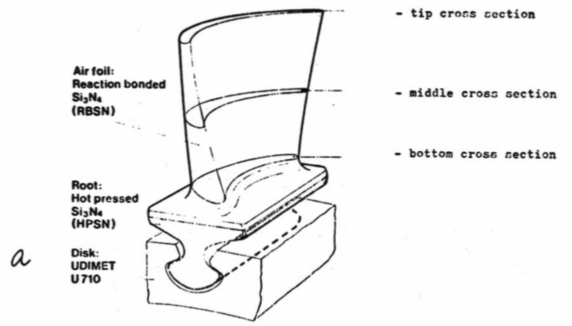


Fig. 15: Ceramic Rotor Stresses At Different RPM (VW, 1976)



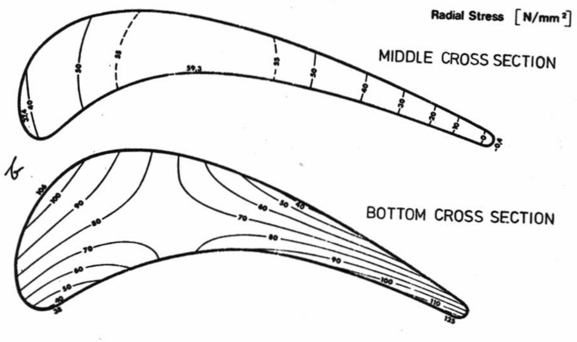


Fig. 16a: Ceramic Turbine Blade of Duo-Density SN, for Hybride Rotor Concept (MTU, 1977)

Fig. 16b: Steady-State Stress Distribution in the Cross Section of the Ceramic Turbine Blade of Fig. 16a (MTU, 1977)

Another example of applying the duo-density concept of silicon nitride is the ceramic turbine blade for a hybrid rotor. Fig. 16 gives details of this design including the calculated stress distributions in the cross section of the blades [12].

2.2.3. Heat Exchangers

The recuperator type of heat exchanger is an example of a successful cooperation between materials and turbine engineers. Fig. 17 shows the extruded silicon nitride module with the essential 0.3 mm wall thickness needed for sufficient heat transfer. Such heat exchangers are prone to extreme thermoshock conditions. Fig. 18 gives insight into the rather sophisticated thermoshock test rig employed to examine such components [13, 14].

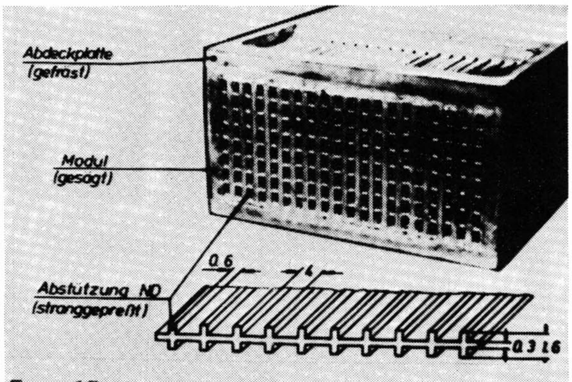


FIG. 17: HEAT EXCHANGER MODULE RBSN (ROSENTHAL, 1978)

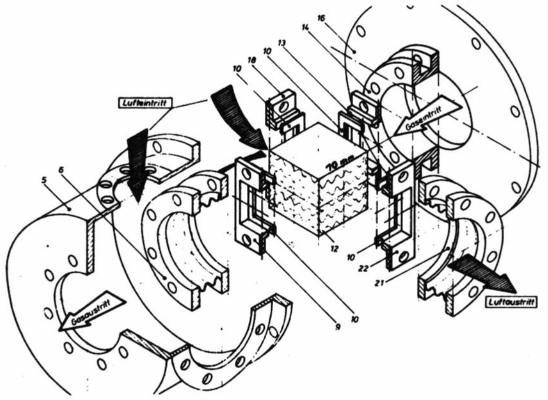


FIG. 18: THERMOSHOCK-TEST RIG FOR HEAT EXCHANGER MODULE (MERCEDES-BENZ, 1977)

2.2.4. Combusters

Fig. 19 shows an experimental combuster for a truck gas turbine being assembled. This example demonstrates the step by step approach of MTU Munich, in the direction of changing from metals to SiC-ceramics [15]. Fig. 20 shows another example of a slip cast RBSN combustor.

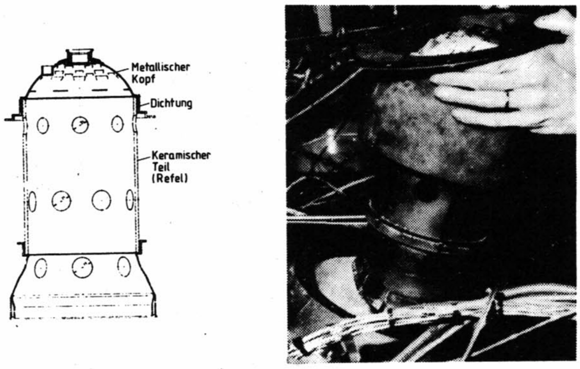


FIG. 19: ASSEMBLY OF AN EXPERIMENTAL COMBUSTOR INTO MTU-TRUCK TURBINE (1977)

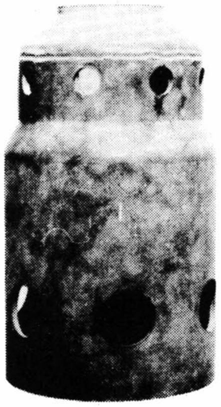


FIG. 20: SLIP CAST COMBUSTOR RBSN (CERANOX, 1977)

3.0. The German "Concerted Action" R+D Program

In 1974 at the start of the program which is funded by the German Government's Ministry of Research and Technology (BMFT), all applicants were placed in a common "boat". They were told by the program manager (the author) to try an interdisciplinary approach. At that time it looked most promising not to fund selected companies or to pick one main contractor. In contrast to the US approach all applicants from turbine business and ceramic materials producers were asked to join in a "concerted action". With one exception all agreed and started work with great enthusiasm.

The German ceramic program is truly a matching one: each company shares funding with the government, each side contributing 50 % of total expenditures. The interdisciplinary approach was formalized in a working group of materials scientists and turbine designers to which each company delegated their competent experts. The working group met every quarter at one of the company's sites. During the first two years each discipline tried hard to learn the language of the other side. Designers learned how to cope with brittle materials and material scientists learned to take designers needs into account during developing manufacturing processes and optimizing mechanical properties. After more than one tough discussion and numerous iteration steps, both sides of the "materials-design-canyon" came to the conclusion that the program is worthwhile. Further, they agreed to try hard and with continuous activity to reach the goals set by all participants.

One other key program management point was the activity of a group of consulting experts from research institutions and universities. This group tried to invision future developments in materials research and turbine design and to judge from a neutral point of view, with no personal involvment, the high risk, high pay-off R+D efforts.

A number of institutions from research organizations and universities contributed to the program by trying to solve special basic research problems. For example: Max Planck Institute for Material Science, Stuttgart, worked on Sialon: University of Karlsruhe, on creep behaviour and oxidation resistance; and FhG Institute z.WP, Saarbrükken, began to concentrate on NDE.

It must be emphasized that after four years of high level activities at labs and pilot shops the program is still continuing. The agreed milestone list calls for the realization of the previously defined goals by 1980. But it well could be that the government and the industry shall decide to continue the program if it looks promising to do so.

Silicon carbide, following silicon nitride was introduced into the program in 1975. The incorporation of SiC brought new companies into this high risk business. This idea proved to be fruitful because of new techniques in manufacturing and new materials qualities. The situation at the moment, in the program's fourth year, is characterized by a certain optimism in all quarters, although a definite breakthrough has not been reached so far. Of course, a number of steps in our list of goals have been successfully passed. Nevertheless all participants are motivated to look ahead and to work hard to reach the final goal of running pilot creamic turbine components at high efficiency.

4.0. Program Objectives

Fig. 21 shows turbine producers and gas turbine models with their anticipated range of horsepower. A truck turbine of 350 PS is planned as well as two passenger car turbines of 75 and 175 PS respectively.

Company	Objectives	Turbine Wheel Concept
MTU	Truck GT 350 PS	Hybride Rotor
DB	Pass. Car GT 175 PS	Full Ceramic Rotor
VW	Pass. Car GT 75 PS 150 PS	Compressor Turbine = Ceramic Rotor Main Turbine = Hybride Rotor

Fig. 21: Objectives of German Turbine Producers

The truck turbine will have a hybrid rotor wheel with a superalloy hub and ceramic blades. The passenger car turbine's wheel will include the hybrid concept but also employ the full ceramic turbine wheel, probably of duo-density silicon nitride.

Fig. 22 lists all participarting ceramic companies and their main objectives. From 1974 until 1977 total funds amounted to about 30 million DM. Through 1980 more than 60 million DM will be spent by the government and industry.

Company	Components, Processes
CERANOX	RBSN, HPSN-Components, "Pseudo-Isostatic" Hot Pressing SiC Pressureless Sintering
DEGUSSA	RBSN-Components
ROSENTHAL	RBSN-Heat Exchangers, Combustors, Extrusion.
FELDMOHLE	RBSN-Injection Moulding
STARCK	Powder Production
SIGRI	SiC-Slip Casting
ESK	SiC-Hot Pressing
RESEARCH INSTITUTES	Basic Research, Mech. Prop., Program Management

Fig. 22: Objectives of German Ceramic Companies

Goals of the 4.-6. Year (1978-1980)

The goals of the program are:

1. Stationary Components (Combuster, Nose Cone, Stator, Rotor Shroud). Production of original components from various materials and 200 h-tests in a simulated duty-cycle with a max. combuster outlet temperature of 1370 °C and an inlet pressure of 73 psi.

2. Heat Exchanger. Production of Si_3N_4-recuperator with a wall thickness of 0.4 mm (second effort 0.2 mm), a pressure ratio of 5, an allowable leak rate of 5 % and a max. temperature of 1100 °C (later 1200 °C) inlet temperature, 10 h-test, eventually transfer experience to SiC.

3. Rotor

- Metal-Ceramic-Rotor (Cars and Trucks)
  200 h duty-cycle-test (inlet temperature 1250 °C)
- All Ceramic Rotor (Car)
  50 h duty-cycle-test (inlet temperature 1370 °C).

5.0. Conclusions and Outlook

Among the present unsolved problems are: scatter of mechanical properties of ceramic materials, quality control, advanced NDE techniques and technology transfer to full scale components.

Based on results of foreign programs and encouraged by a visible attitude of international cooperation, the German program is a step further in contributing to the ambitious goal of running a ceramic gas turbine in competition to the diesel engine in the late eighties. Although still a high risk item, one can imagine successful evaluation of advanced materials and design concepts, assuming funds will be available from government and industry.

If the teams of turbine engineers, designers and material scientists can be held together in a fertile process of encouragment, then we hope to be able to meet to the challenge from the materials and design front.

References

1. P. Walzer, 1977 Tokyo Joint Gas Turbine Congress
2. T. Alexander, Fortune 1976, 153
3. see 1.
4. J.C. Freche, G.M. Ault, AGARD-CP-229, 1976
5. F. Thümmler, BMFT Status Seminar, 1978
6. E. Gugel, H. Kessel, AMMRC Conf., Newport 1977
7. H. Larker et al, SAE-Congress 1977, 770335
8. E. Lange et al, BMFT Status Seminar 1978
9. E. Gugel, G. Leimer, BMFT Status Seminar 1978
10. W. Räuchle, D. Rösch, BMFT Status Seminar 1978
11. P. Walzer et al, MTZ, 1976, 11 + 12
12. K. Trappmann, AMMRC Conf., Newport 1977
13. H.-J. Pohlmann et al, BMFT Status Seminar 1978
14. E. Tank, BMFT Status Seminar 1978
15. G. Kappler, K. Giesen, BMFT Status Seminar 1978