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THE USE OF CERAMICS IN ENGINES,(U)
MAR 78 D J GODFREY

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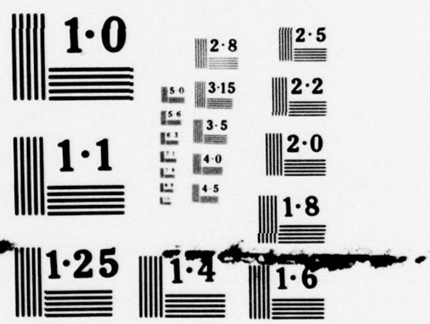

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THE USE OF CERAMICS IN ENGINES (U)

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THE USE OF CERAMICS IN ENGINES (U)

by

D J Godfrey

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After discussing the potential advantages of using ceramics in engines, application studies of their use in gas turbines (with particular emphasis on recent US work) and diesels are reviewed. Considerable progress and success with several components is now being reported, and a valuable background of practical experience is accumulated. A strategy for future progress is discussed; this should include adequate stress analysis and operating environmental definition, previous experience with engineering ceramic testing, a design and test reiteration capability, well-supported fabrication facilities, non-destructive evaluation and proof-testing of components, and strong engineering and materials science research efforts.

The substance of this Report will be published in Proc. Brit. Ceram. Soc. as an introductory review in the Proceedings of a Conference on 'Engineering Applications and Properties of Ceramics'.

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INTRODUCTION

1. For nearly two decades, it has been realized,[1,2] that certain ceramics can exhibit high strength and oxidation resistance at temperatures 400-600°C greater than the maximum operating temperatures of nickel and cobalt superalloys, and ways in which they might be used in engines have been proposed, discussed and investigated[3-9]. However, the inductility of ceramics has engendered a great reluctance to investigate their practical application, despite the benefits which their use offers. This diffidence arises principally because of the awareness of the problem of bird/runway debris ingestion in aircraft propulsion turbines, and also the problem of combustor carbon or engine-component fragment impaction at the high velocities which are usual in gas turbines. The low toughness of ceramics also raises fears about the degrading effects of damage insufficient to cause fragmentation, and about fabrication defects. These misgivings have led to a general supposition that ceramics would not prove capable of operation as gas turbine or internal combustion engine components, because these usages impose severe mechanical and thermal loads and shocks beyond the endurance of even strong ceramic materials.

2. This gloomy view is now beginning to be modified as ceramic components are increasingly being evaluated in gas turbine and diesel engine environments, and evidence emerges that they can survive, given certain provisions. These include (1) designs that are produced with a sufficiently-thorough knowledge of the operating conditions, (2) adequate computer or photoelastic analysis of the stresses which will be generated, (3) practical experience in the design of ceramic components for operation in engine environments, (4) the opportunity to make one or more design and test iterations when components fail, (5) a capacity to nurture sources of good quality ceramics, and (6) facilities to inspect components for defects by the best appropriate NDE techniques and by proof testing.

THE ADVANTAGES OF USING CERAMICS IN ENGINES

3. It is difficult to find much quantitative information about the potential benefits of using ceramics in engines, although these have been reviewed several times (e.g. [7,10,11,13]). The thermal efficiency η of a gas turbine is related to operating temperature by the expression

$$\eta = ((T_3 - T_4) - (T_2 - T_1)) / (T_3 - T_2)$$

where T_1, T_2, T_3 and T_4 are respectively the absolute temperatures of the gases at the compressor inlet and outlet, and the turbine inlet and outlet. For example, an unsophisticated turbine operating at a pressure ratio of 5 with an efficiency of 0.2563 at a turbine entry temperature T_3 of 1089 K would increase in efficiency to 0.2905 with a T_3 of 1689 K. The amount of improvement for a given temperature rise falls off progressively as temperatures are raised, in conformity with Carnot efficiency principles; for instance, raising T_3 from 1089 to 1189 K gives a 3.9% improvement to 0.2662, but raising it from 1689 to 1789 K gives only a 0.9% improvement to 0.2931. Increases in T_3 cause related increases in T_4, the exhaust temperature, and the benefits of using these in combined gas turbine/steam generation plants have been established[12]. The possibility also exists of improving the specific power of installations; recent estimates for a 533 kW (715 HP) gas turbine with a 101 μg/J (0.6 lb/HP/h) specific fuel consumption were a 40% increase in output power to over 746 kW (1000 HP) as well as a 10% lower fuel consumption (91 μg/J, 0.54 lb/HP/h), when ceramic stator vanes, rotor blades and flame can are used[13,14], permitting components to operate up to 1371°C (2500°F).

4. Other considerations are important. Weight-saving is most often a prime concern for aircraft turbines, although inertial effects may be a relevant factor affecting the acceleration of automotive turbine units, and ceramic densities of 2.5 - 3.2 Mg/m^3 compare favourably with those of superalloys ($\sim$8 Mg/m^3). The centrifugal stress developed in rotor blades is directly proportional to their density. World supplies of nickel and cobalt are limited, and the sometimes-poor fabricability of modern superalloy components greatly adds to their cost. Sharp rises in the prices of hydrocarbon fuels have focussed attention on their efficient utilisation, but more wide-spread use of efficient gas turbines for automotive and marine propulsion would exacerbate these turbine material supply and cost difficulties. Silicon nitride and carbide ceramics are made from abundant and cheap raw materials. Processes such as injection moulding when applied to reaction-bonded silicon nitride (RBSN)[8] fabrication offer attractive mass-production solutions to manufacture and cost problems. Whilst ceramic materials are not immune to high-temperature corrosion, sea-salt sulphidation tests at temperatures at which superalloys are attacked severely have been very encouraging, as have V_2O_5 corrosion tests, although certain molten sodium salts may present a problem e.g. boiler furnaces. Nevertheless, there is hope that ceramics will

allow the use of lower-grade fuels in gas turbines. They certainly have an important part to play in heat exchangers which will be used increasingly with gas turbines, as they give very worthwhile improvements in efficiency. In the i.c. engine field the potential advantages of ceramics are less obvious, since their high temperature capability may be difficult to exploit without quite marked changes in engine design, but materials with a 1000°C greater capability than aluminium alloys and under half the density of cast iron surely have a place in diesel technology[15,16,17]; especially as their use in low thermal conductivity forms could enable engine cooling systems to be reduced markedly in size and cost, and otherwise-wasted fuel energy transferred to the exhaust and utilized by single or multi-stage turbocharging. There is also interest in their use in Stirling[18] and Lysholm-compressor[19] engines.

PRACTICAL EXPERIENCE WITH CERAMICS IN ENGINES

Gas Turbines

5. Very little early experimental work with ceramics in gas turbines has been reported[10,20,21]. In the early 1970's US Government agencies began to support work at the Ford Motor Company to work on a small 164 kW automotive gas turbine concept, which would employ ceramic stator vanes, rotors and combustor parts[22,23a]; and at Westinghouse Electric Corporation, who were subcontracted to investigate the use of ceramic stator vanes (and ultimately rotor blades) for 100 MW industrial power generation turbines[24,25]. A target was set of 1371°C (2500°F) operation for periods of up to 200 h with a maximum speed of 64,000 rev/min and including realistic duty cycles. This target has been met by Ford with nearly all turbine components (but not yet with a complete engine); but initially the development of the all-ceramic turbine proved to present a degree of difficulty commensurate with its novelty[13].

6. Quite early in the Ford programme the use of reaction-bonded silicon carbide (RBSC) flame cans and RBSN combustor nose-cones was demonstrated successfully, after earlier failures. By June 1977 RBSC combustors had accumulated over 200 h in "durability testing", including 175 h at 1054°C and over 26 h at 1371°C; and RBSN pre-slotted nose cones 221 h at 1054°C and 25 h at 1371°C. Carbon formation in the test rig has been a problem; the

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design fuel flow rate was 0.97 kg/s (2.14 lb/s) flow, but carbon-free operation only up to 0.6 kg/s had been achieved by March 1977. The development of first and second stage RBSN stators has required more design iterations, and improvements in fabrication technology have also been very helpful. Design A, 2.2 Mg/m^3, injection-moulded stators failed in a few 982°C cycles, and were found to be poorly bonded to the blade ring. Thermal mismatch between blades and outer shroud was undesirably high and the shroud was made lighter; no failures then ensued in a 25 h test, but 7 blades failed when a rotor was used with the stator, probably due to vibration. With the Design B components in which the rotor tip shroud was separate from the stator, the outer shrouds failed and cracks appeared in blade aerofoil mid-spans, and also in the root fillets. In thermal shock tests all blades failed in less than 1000 cycles (RT to 1370°C), some very quickly. The mid-span was heating too rapidly; in the next iteration this was scooped out, and no failures occurred in 3000 cycles. Shroud and blade-tip interference gave some failures in rig testing. In the Design C iteration the blade cord was reduced by 21% and the assembly procedures improved. Blades then had lives of 2.5 to 30 h before developing cracks, and only 2 outer-shroud cracks were found in a ring tested for 150 h. Quality control was improved when it was found that 5% of all injection-moulded blades were being produced with fine hairline cracks. In iteration D there were two modifications of the outer shroud: components were moulded together in a single operation and 2.55 Mg/m^3 material was used. Thermal shock performance was as good as with Design C (unfailed after 3000 cycles). Each assembly was qualification-tested by 10 light-up cycles; 35 passed and one failed. However in the static rig 22 out of 27 failed by cracking and there were 11 secondary failures (1 vane and 10 shroud location), with a 25 h lifetime Weibull modulus of only 0.58. Processing was improved, with more intense qualification testing in which blades were loaded individually by 44 N (10 lbf), and the outer shroud stressed to 27 MPa. A complete set of RBSN stationary flow path components (a nose-cone, two stators and two shrouds) have now survived testing without rotors in a turbine engine for 175 h at 1054°C and 25 h at 1371°C - the programme time and temperature target. A Ford RBSC stator also has survived similar 200 h test[23b].

7. Rotor development has proved to be the most difficult problem as high strength in the hub is required, but the 125 mm O.D. 36-blade rings present a severe fabrication problem. A successful compromise was to hot press a silicon

nitride hub into an RBSN blade ring, which had been single-shot injection-moulded with polymer-bound silicon powder and subsequently nitrided. Many rotors with shortened blades were subjected to testing in cold and hot spin - pit test facilities, with tests of good quality rotors in an engine environment rig in the later stages of the programme. A ceramic rotor/metal stator "rub" was experienced, but this did not fracture the rotor. Many design iterations of the fabrication scheme have been necessary, combined with quality assessment of the product, and experience has been built up with several hundreds of rotor fabrication experiments. Determined and painstaking work has now begun to yield results. Rotors have been tested at various speeds and temperatures, culminating in a test at 50000 rev/min and an average temperature of 1232°C for 25 hours of continuous operation. The temperature was subsequently raised to 1371°C and held there for 1.5 h, rising occasionally as high as 1416°C. Temperatures near the rotor mounting were greater than expected, and the test was shut down slowly, but at 1038°C inlet temperature a sliding ceramic/metal fit on the shaft seized, and in the ensuing failure the rotor was shattered. However it appears that the 50 h rotor target can be achieved.

8. Consideration of the extensive fabrication experimentation and cold and hot spin testing summarized in Figure 1 shows that progress has been steady in the face of severe but not-insurmountable difficulties, and suggests that the chances of success in the near future are high, especially if a 50,000 rev/min 3-stage design[13] is used instead of the original 62,240 rev/min 80 mm disc concept. The outlook for ceramic heat exchangers in gas turbines is also very auspicious, since McLean[13b] has reported that, despite earlier setbacks with sodium/sulphur corrosion effects in lithium aluminium silicate-type ceramic rotary regenerators, lives of almost 7000 h at 800°C and over 2500 h at 980°C have been demonstrated with aluminium silicate cores. Investigations at Chrysler supported by the US ERDA have also been concerned with the use of ceramic heat exchangers for gas turbines[23c]. The ceramic work at Westinghouse Electric Corporation[24] has been concerned with assemblies of eight 90 mm-long aerofoil stator vanes in a 30 MW turbine test rig. The HPSN vanes had domed ends which seated in ellipsoidally-dished socket end-caps of HPSN, which fitted into insulating shoes of (first) glass ceramic and (later) boron nitride; the stacked blade assembly being clamped with radially-oriented springs[25,26]. In the first series of tests with 8 HPSN vanes at a maximum

temperature of 1204°C 106 cycles were completed, including thermal down-ramps at a rate of 13.9° C/s, and also two severe flame-outs in which near-instantaneous cooling from 1204°C to 316°C occurred. Four aerofoils and two end-caps cracked in these tests, although no components fragmented. Cracking was due to line-contact stresses which arose because the cap socket was not machined accurately to the design configuration. In the second series of tests at 1371°C four vanes each of HPSN and hot pressed silicon carbide (HPSC) were used. After 3 transient cycles two of the four HPSC vanes had developed cracks but had not fragmented, and the HPSN blades were undamaged. In the fifth cycle the temperature rose to 1649°C and the metal flame can melted, and shed solid pieces and liquid metal. A large piece of metal combustor was wedged directly against the HPSN vanes, which were impacted with molten metal; they were apparently unaffected; however dye-penetrant and other NDE tests showed that one had a crack which had originated at a fabrication defect. All of the HPSC vanes were shattered. A rebuilt rig was fitted with twelve HPSN (NC132) vanes and end-caps and M-type boron nitride insulators. Some preoxidized HPSN vanes were included since >30% oxidative strength degradation of some types of HPSN can occur. The combustor was redesigned, and this led to a more-peaked temperature traverse in the test section, which stress analysis later showed increased vane stresses significantly. After 25 cycles it was found that the vanes had shifted, due to an assembly error, and several had cracked due to high line-contact stresses. A preoxidized HPSN vane had a thermal stress crack. Cracked vanes were replaced, and two preoxidised vanes were again included. After 35 transient cycles, two aerofoils had become cracked (although not exposed to the highest temperatures), one of which was a pre-oxidized vane. Both were replaced and a further 43 cycles were carried out which included temperature peaks as high as 1466° (2670°F). The vanes and end-pieces were apparently intact after the test; subsequent non-destructive evaluation showed that only one (an outer vane) had developed a crack, apparently because it touched the metal shroud of a metal side vane. The long supply and machining times with HPSN material meant that very few design iterations could be carried out in the four year period, otherwise the results summarized in Figure 2 might have been even more encouraging.

9. In addition to stator vane research, work at Westinghouse has recently been concerned with ceramic rotor blades[27,28]. Spin-testing has confirmed

that with HPSN blades fitted with a compliant interlayer of 125 μm thick, 8 μm fibre 'Felt-metal' into a metal disc socket suffered root failure at higher speeds (7515 and 8205 rev/min) than without such an interlayer. The blade-root "nominal" stresses at failure were in the range 161 - 175 MPa (23400 - 25400 psi). Further work has shown that current improved designs can have failure speeds 9% greater than the design speed when formed by longitudinal grinding with a 325 mesh diamond wheel. 'Feltmetal' 0.5 mm thick with 8 μm fibre appeared to give a ductile interlayer with the best load-spreading characteristics.

10. In work which commenced in 1976, at the AiResearch Division of the Garrett Corporation, a study is being made of the use of ceramics in a T.76-type gas turbine intended for marine propulsion[14]. The engine specification is summarized in Figure 3. The work is a prime example of enlightened development of engineering with ceramics. At first the work had a large design content, with computer-aided interative optimisation playing a large part in the heat transfer and temperature estimations, and engine and component design evolution. For instance iterative computation of blade design parameters enabled stress levels to be reduced by 30%. Blade root optimisation and ductile interlayer research has culminated in a high degree of success in spin testing, with 90 HPSN blades tested in a Waspaloy hub to a speed 30% greater than the design speed of 41730 rev/min, and only 4 blades failed this stringent 69% overstress qualification test. In tests of RBSN stators (second-stage vane rings containing 21 vanes), one blade fractured in testing at 982°C (1800°F) and full power, and six failed in a 'light-up to full power' test. The major cause of failure was blades moving and jamming under gas loading: this was cured and 3 sets of 21 blades were then tested. The failure of only 7 blades out of the 105 tested, with the cause of their failure eliminated, must be considered very promising at this stage of the programme. By late October 1977 first-stage stators had been run at full aerodynamic loading, and second-stage at full loading and temperature. The results (which are summarized in Figure 3) indicate that experience developed in earlier programmes can fertilize design capabilities and accelerate engineering success.

11. Ceramics are generally regarded as unsuitable for aircraft turbines because of their low impact strength. It is often assumed that their behaviour in small particle impact will therefore be poor, and consequently

work at the Solar Division of International Harvester (summarized in Figure 4) is of considerable interest[29]. Erosion of 713 L superalloy blading in a 10 kW radial-inflow gas turbine had been a serious problem, with lives as short as 68 h being reported, when operating in dusty or desert conditions. Such problems are aggravated because small combustor systems cannot be designed to operate quite as efficiently as large systems, and carbon particle erosion also occurs, as does the possibility of overheating due to suboptimal temperature distributions across the turbine entry duct. However, various simulated service evaluations, including injection of Arizona road dust, demonstrated that erosion could be reduced by a factor of 50 by substituting HPSN for 713 L metal vanes, and that HPSN vanes and RBSN shrouds could survive 500 engine-simulator thermal cycles. In a 60 kW turbine test with -140 mesh silica (44 mg/kg air), a N-155 metal vane receded 12 mm whilst recession on HPSN vane was not measurable. In a 10 kW turbine test, ten HPSN vanes survived, but five cracked due to high contact stresses caused by thermal distortion of a metal shroud. After re-design an engine test in June 1977 showed the complete survival of ceramic nozzles and shrouds. The now-evident value of using ceramics where dust impact is a problem might be crucial in relation to the problems of using coal gasifier products as gas turbine fuels, since erosion by fine ash particles will present serious difficulties in metallic turbines.

12. In the work so far described rotor blades have either been bonded to an HPSN hub, or held in slots in a metal hub; at Pratt and Whitney[30] a metal disc (AF2-1DA alloy) has been forged around the roots of HPSN blades. A 50 h test of a 30-bladed rotor which included 10 cycles to 45,000 rev/min and 1232°C has been completed successfully, and is continuing as detailed in Figure 5.

13. In addition to the five quite-successful projects which have just been detailed, other promising studies on the use of ceramics in gas turbines are proceeding in the USA, but have not been reported extensively. In Germany, Volkswagen, Mercedes-Benz and MTU are actively and successfully investigating ceramic turbines for automotive use, and extensive development of ceramics suitable for turbines is also proceeding[13]. In Britain, the level of activity is at present quite low. Significant progress with ceramic heat exchangers, rotors and combustors for gas turbines has been described[16,21,31,32,33], but

there is currently little funding of such work, and still a great scepticism about its potential because of the inductility of ceramics and their low toughness.

Internal Combustion Engines

14. The demonstration that an RBSN piston and piston rings could survive operation in a small petrol engine[34,35], and subsequent success at the Royal Naval Engineering College with an RBSN piston in a 700 kPa (100 psi) brake-mean-effective-pressure (bmep) single-cylinder Gardner diesel engine[35] was followed by a more comprehensive investigation[16,37] of RBSN for the piston of a single-cylinder 1590 kPa (230 psi) bmep Petter diesel at AED Limited. Although failure of 4 out of 8 pistons ultimately occurred, it appears quite possible that with minor design changes RBSN components could be used successfully in highly-rated diesel engines, despite the latter's very high rate of pressure rise on ignition and extreme thermal fluxes[16]. At the Cummins Engine Company, the use of ceramics in diesel engines is being investigated, with the aim of reducing specific fuel consumption (SFC) from 61 to 31 μg/J (0.36 to 0.22 lb/HP/h)[38], as summarized in Figure 6. With a 347 kW (465 BHP) engine having an SFC of 61 μg/J (0.36) 0.36 lb/HP/h, turbocompounding is estimated to raise the maximum power to 406 kW and lower SFC to 56 μg/J. The use of insulating ceramic components to produce an adiabatic turbocompound engine could give 477 kW and 47 μg/J, and with the use of gas bearings to reduce frictional losses 533 kW and 42 μg/J. Finally, the addition of a Rankine bottoming cycle might yield 608 kW (815 BHP) with an SFC of 37 (0.22). These optimistic forecasts call for the development of a cheap fabricable material with the low thermal conductivity and thermal expansion of lithium aluminium silicate ceramics and the strength and good tribological properties of HPSN. In a computer study, Griffiths[39] examined the effects of increasing cylinder head and piston crown temperatures from 283 to 617°C in a turbocharged intercooled 1380 kPa (200 psi) bmep diesel. He found that the indicated thermal efficiency rose by about 2.7% (0.4480 to 0.4602). The proportions of fuel energy going to the piston and head at 283°C were 5.1 and 3.9%, falling to 2.1 and 1.6% at 617°C; such changes would allow very important reductions in engine cooling system requirements. It was estimated that the efficiency of the turbo-charger in using the extra exhaust heat was just over 12%. Greater head and piston temperatures would however tend to heat the induced air more, slightly reducing

the volumetric capacity if the air/fuel ratio was nearly stoichiometric. The cooling fan may in some vehicles absorb up to 15% of the engine power and be very noisy, and reducing its size might be quite beneficial. The use of a low expansion material could diminish piston-slap noise, a characteristic feature of the operation of aluminium pistons in iron cylinders (thermal expansions being 19 vs 11 x $10^{-6}/^{o}C$ respectively). The use of ceramics might allow radical changes in the combustion process and reduce hydrocarbon and smoke emissions. Improvements in fuel economy for diesel-powered small cars are foreseen if warm-up times are reduced and impressive service experience is being accumulated with ceramic prechambers in automotive diesels[16,40].

A STRATEGY FOR SUCCESS

15. Although at least five US ceramic gas turbine programmes exhibiting a great measure of success now exist, it proved difficult at first to demonstrate even short-term survival of components in realistic tests, but the potential advantages of ceramics were generally recognized. Paradoxially, in diesel engines successful short-term demonstration of pistons and prechambers liners in engines has been achieved without design reiterations, but this is unknown to the majority of i.c. engine designers, and the potential advantages are largely unrecognized.

16. Nevertheless, the interest in using ceramics is growing, and a strategy for deploying effectively the slender resources which are likely to be available must be developed. The problems that are caused by inductility require the painstaking analysis of operating stresses in ceramic components to a far greater degree than with metals, and thorough optimisation, evaluation and quality assurance of the materials which are used. When used adjacent to metallic parts ceramics require effective arrangements for accommodating the very dissimilar thermal expansions, and particular care where they are joined or held to avoid high contact-stress loadings. The need to demonstrate a credible feasibility for their utilisation, before sufficient funding is allocated to research on the problems of engineering with ceramics, has been a grave impediment. It underlines the value of simple experiments which can be performed with modest resources, and for component designs to be as easily-made as possible, to facilitate expeditious fabrication and permit rapid design and test iterations. For engineering design exploratory studies the very fabricable RBSN material is sometimes

preferable to HPSN, despite the higher strength of the latter, as a comparison of the number of design iterations made in the Ford and Westinghouse work shows. A gradual and exploratory approach with the objective of achieving better capabilities from components as designs and material quality improve, is probably more practicable than an attempt to design all at once a component or engine to demonstrate the performance advantages and survive the full operating regime. For rapid progress strong HPSN components are sometimes specified, but the utilisation of high-grade analytical facilities for both component stresses and the operating environments and thermal fluxes still is highly desirable. Although there has recently been a considerable amount of research on engineering ceramic materials, their properties are still not ideal, and much research still needs to be done to optimize them for the rigorous environments found in engines. Sanday[41] discussed engineering property levels necessary for ceramics to be usable in industrial gas turbines. He gave a target of a creep strain of 0.45% after 10,000 h and extrapolated a strain of 3.7% at 1260°C and 69 MPa load from data for Westinghouse improved material. Data given by Lange[13] for very recent Westinghouse HPSN extrapolate to a 10,000 h strain of 1.04%, so progress is still being made in this respect. The vitreous phase failure effects which are responsible for creep in HPSN also lead to reductions in high temperature strength and 'static' fatigue strength ('slow crack growth'). Improvements have been made by carefully controlling the ratio of the added oxides to the silica present in the Si_3N_4 powder, to reduce the amount of glass present, and by adding oxides which will improve the refractoriness of the glass (e.g. yttria and also zirconia and lanthanon oxides). Another approach which has received less attention is to develop purer glass-free fully-dense forms of silicon nitride; only pyrolytic CVD silicon nitride appears to meet this description, although fairly-pure materials may emerge from the work in progress on hot isostatic pressurized sintering of silicon nitride. Present CVD-Si_3N_4 strengths are modest (up to 300 MPa-44000 psi) and considerable research will be necessary as with HPSN to improve properties. Engineers familiar with metallic materials inevitably ask for ceramics with metallic toughness to be developed, but we are usually unable to improve this property significantly. Fibre-reinforcement appears to be the only feasible method for engine ceramics, but interest in toughening by silicon carbide fibre incorporation[42] has not been forthcoming, and promising work with tantalum fibres[43] has the drawback that component weights would be increased seriously.

17. The considerable advantage of using RBSN with its impressive fabricability has been apparent in the Ford Motor Company work described earlier. Recently RBSN blades, similar in shape to HPSN blades which had a mean spin-failure speed of 73,200 rev/min[32] when slotted into a 11.8 cm diameter steel disc, had an average spin-failure speed of 60,620 $\pm$ 3110 rev/min in tests at NGTE. The ratio of these failure speeds is 1:0.85 whereas, on a basis of expected strength (HPSN 800 MPa, RBSN 250 MPa) and density (3.2 vs 2.5) the RBSN should have failed at 0.63 times the speed of the HPSN blades. This result supports the contention that if RBSN materials were improved by modification of the size and character of their strength-controlling voids, 50% improvements in strength might be possible, and its widespread application in engines with adequate safety margins would be feasible.

18. Because of their inductility, ceramics have a greater sensitivity to defects than metals. There is therefore a greater necessity for non-destructive evaluation of components, and the defects that should be sought range down to smaller sizes than in metals; in high strength HPSN approaching an extreme limit of 20 μm[44]. In fabrication work at Ford considerable experience has been obtained detecting and characterising large defects occurring in fabrication processes (e.g. injection moulding), and this is enabling fabrication technology and the yield of high quality components to be improved progressively. Stereo-microscope inspection and X-radiography are both valuable techniques, and defects as small as 25 μm with high X-ray contrast can be detected, although small carbon, silicon carbide, silicon and boron nitride inclusions are difficult to resolve well. Computer enhancement of X-ray images can be useful. Sophisticated ultrasonic techniques are showing promise for dense ceramics, and can detect low atomic number inclusion defects better than X-radiography[44]. Proof testing is an invaluable alternative or ancillary to effective NDE, and merits very serious examination of its feasibility with ceramic components. Static loading has been used successfully by the Ford Group[13], to give quality assurance for the blades of multi-bladed stators. The valuable quantitative approaches developed by Evans, Weiderhorn[45,46] and Davidge[47] for the effects of high-temperature slow crack growth on strength include methods of quantifying the value of proof testing.

CONCLUSIONS

19. Following a period of experimental activity in the United States, convincing proof is emerging that the problems of using ceramics in gas turbines are not insoluble, and in addition to the obvious thermodynamic benefits resulting from high-temperature operation there may be other advantages such as lower cost and unlimited supply of materials, weight-savings and corrosion and oxidation resistance. The survival of ceramic pistons in diesel engines has proved easier to demonstrate in terms of both research resources and time, but the advantages which may result from the use of low conductivity ceramics are more subtle and have not yet been demonstrated clearly. They appear likely to include reductions in the size, cost and power requirements of cooling systems, and there may be modest improvements in efficiency, combustion and emissions resulting from hotter exhaust gases. The greater refractoriness of ceramics as compared with aluminium alloys might be helpful in highly-rated engines. Effective progress with ceramic components in engines requires great skill in estimating thermal and mechanical conditions in engines, and in analysing the stresses which they produce. A cautious piecemeal approach to the design and evaluation of components, rather than whole engines, is probably the most cost-effective strategy, to provide experience to guide the ingenuity of the engine designer. The use of readily-fabricable ceramics is advisable whilst design is in this exploratory and formative stage, despite their modest mechanical properties. It is necessary that the designer is supported and encouraged during initial component failures; too many projects have been stopped before design and test iterations have been tried. When promising results are obtained, the more-extensive use of hot-pressed silicon nitride, sintered sialon (Lucas) or sintered silicon carbide may be necessary to give low failure probability, despite their high cost of production. The high temperature properties of HPSN still give cause for concern, although very worthwhile improvements continue to be made, and the value of pure dense materials would be great if they could be fabricated easily and with high strength. The very fabricable reaction-bonded silicon nitride and silicon carbide ceramics have undoubted manufacturing advantages which favour mass-production methods, and research is urgently needed to improve their properties. Growing concern about the limited potential for the discovery of new liquid hydrocarbon fuel resources,

and the rising cost of energy, reinforce the case for examination of ways in which high temperature ceramics can be used effectively. There is now increasing evidence which indicates that currently-available materials can be employed successfully in engines, given engineering experience and iterative experimentation to optimize design concepts. We may confidently expect adequately-supported studies of materials science and technology to yield improved materials, which will allow major advances to be made in high-temperature heat engine technology.

RECOMMENDATIONS

20. Progress in applying ceramics in engines is accelerating, especially in the USA, Germany and Japan, and the increasing success being attained merits greater allocation of resources for engineering research and evaluation studies and materials science and technology.

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REFERENCES

1. PARR, N L, MARTIN, G F and MAY, E R W. "Special Ceramics" (London Ed. P Popper, Academic Press, 1960), p.102.

2. GLENNY, E and TAYLOR, T A. Power Metallurgy, (1/2), 189, 1958.

3. GODFREY, D J. Metals and Materials, 2 (10), 305, 1968.

4. GODFREY, D J and MITCHELL, K W. The Engineer, 224, 737, 1968.

5. GODFREY, D J and PARR, N L. "Combustion in Advance Gas Turbine Propulsion Systems", Ed. (London, Ed. I E Smith, Pergamon Press, 1968) p.379.

6. GODFREY, D J and TAYLOR, P G. Engineering Materials and Design, 12, (9), 1339, 1969.

7. MCLEAN, A F, ASME Publication No. 70-GT-105, 1970.

8. GODFREY, D J. (Ed.), "Ceramics for Turbines and Other High Temperature Engineering Applications", Proceedings 22, Brit. Ceramic Soc. June 1973, 487 pp.

9. BURKE, J J, GORUM, A E and KATZ, R N. (Eds.), "Ceramics For High Performance Applications", (Chestnut-Hill, Mass. Brook Hill Publ. Co. 1974, 772 pp.)

10. PENNY, R N. SAE Transactions, 72, 131, 1964.

11. DE CORSO, S M and HARRISON, D E. ASME Paper 72-GT-94, 1972.

12. ROBSON, F L and GIRAMONTI, A J. Ref. 9 pp.147-156.

13. Proceedings of the 5th Army Materials Technology Conference "Ceramics For High Performance Applications II", March 1977, in course of publication.

14. WALLACE, F B, NELSON, N R and STONE, A J. "ARPA/Navy Ceramic Engine Design Summary" in Ref. 13.

15. GODFREY, D J. Proc. NATO Adv. Study Conf. "Nitrogen Ceramics". Ed. F L RILEY, Publ. Noordhoff, Leyden, 647, 1977.

16. GODFREY, D J. 'The Performance of Ceramics in the Diesel Engine' Ref. 13.

17. KAMO, R. 'Cycle and Performance Studies for Advanced Diesel Engines', Ref. 13.

18. TOMAZIC, W A and CAIRELLI, J E. 'Ceramic Applications in the Advanced Stirling Engine' NTIS Report N77-23487, 1977.

19. MOHR, P B. 'Preliminary Design of a Subscale Ceramic Helical-Rotor Expander', Ref. 13.

20. GODFREY, D J. Ref. 8. p.22.

21. PENNY, R N. 'The Development of the Glass Ceramic Regenerator for the Rover 2S/150R Engine' SAE Paper 660361, June 1966.

22. KATZ, R N and MCLEAN, A F. Ref. 8, pp.409-427.

23(a). MCLEAN, A F. Ref. 9, pp.9-36.

23(b). FISHER, E A and MCLEAN, A F. Private Communication November 1977.

23(c). WAGNER, C E. 'Baseline Gas Turbine Development Program' Report COO-2T49-T2 and idem -T12 (US NTIS).

24. HARRISON, D E. Ref. 8, pp.391-408.

25. BRATTON, R J and HOLDEN, A N. Ref. 9, pp.37-59.

26. BOOHER, C R and ROUGHGARDEN, J D. Ref. 9, pp.79-122.

27. BRATTON, R J. 3rd Conference on Gas Turbine Materials in a Marine Environment. Bath 20-23 September 1976. Session IV Paper 4.

28. ANDERSON, C A, BRATTON, R J, COHN, A, BOOHER, C R and SANDAY, C A. 'Progress of EPRI Ceramic Rotor Blade Program' Ref. 13.

29. NAPIER, J C and METCALFE, A G. 'Application of Ceramic Nozzles to 10 kW Engine', Report RDR-1797-16 (AD-A035329), August 1976. (See also SAE Paper 770342, March 1977).

30. CALVERT, G. 'Pratt and Whitney Si_3N_4 Blade-Metal Disc Evaluation', Ref. 13. See also 'A Program Plan for the Design and Spin Testing of Ceramic Blade-Metal Disc Attachments'. Paper 76-GT-37, 21st Gas Turbine Conf. New Orleans, 1976.

31. O'NEILL, S. Ref. 8, pp.355-376.

32. GODFREY, D J. 3rd Conf. on Gas Turbine Materials in a Marine Environment, Bath 20-23 September 1976. Session IV, Paper 1.

33. SEDGWICK, G. ibid, Session IV Paper 5.

34. GODFREY, D J and MAY, E R W. 'Ceramics in Severe Environments', Ed. W W KRIEGEL and H PALMOUR III, Plenum Press, New York, 149, 1971.

35. GODFREY, D J. Ref. 8, p.20-21.

36. GODFREY, D J. Trans. SAE, 83, (2), 1036, 1974.

37. PARKER, D A and SMART, R F. 'An Evaluation of Silicon Nitride Diesel Pistons'. To be published in Proc. Brit. Ceram. Soc. 1978.

38. KAMO, R. 'Cycle and Performance Studies for Advanced Diesel Engines', Ref. 13.

39. GRIFFITHS, W J. 'Thermodynamic Simulation of the Diesel Engine Cycle to Show the Effect of Increasing Combustion Chambers Wall Temperatures on Thermal Efficiency and Heat Rejection', Wellworthy Topics, (63), pp.7-10, Winter 1976/77.

40. PANTON, J. (Ricardo and Co Engs. (1927)) and MCLAUGHLIN, D. (AME Ltd) To be published in Proc. Brit. Ceram. Soc. 1978.

41. SANDAY, S C. 'Design, Analysis, Failure Prediction and Testing of Ceramic Structural Components for Industrial Gas Turbines with an Evaluation of Commercially-Available Si_3N_4 and SiC; Proc. 12th CIMAC Conference, Tokyo, 1977.

42. BROWN, R L, GODFREY, D J, LINDLEY, M W and MAY, E R W. 'Special Ceramics 5' (Ed. P Popper, BCRA Stoke-on-Trent, 1972) p.345.

43. BRENNAN, J J. 'Special Ceramics 6' (Ed. P Popper, BCRA, Stoke-on-Trent, 1975) p.123.

44. EVANS, A G, KINO, G S, KHURI-YAKUB, P T and TITTMANN, B R. Materials Evaluation, 85, April 1977.

45. EVANS, A G. J. Materials Sci. 7, 1137, 1972.

46. EVANS, A G and WIEDERHORN. J. Materials Sci. 9, 270, 1974.

47. DAVIDGE, R V. et al. J. Materials Sci. 8, 1699, 1973.

FIGURE 1

SUMMARY OF FORD MOTOR COMPANY, DEARBORN, USA, WORK ON A CERAMIC AUTOMOTIVE TURBINE

PROGRAM GOAL:	OPERATION AT	1055°C (1930°F)	1371°C (2500°F)
	FOR	175 hours	25 hours

CURRENT ACHIEVEMENTS

RBSC FLAME CAN	175	26
*RBSN COMBUSTOR NOSE CONE	220	25
*RBSN STATORS	177	25
*RBSC STATORS	177	25
*RBSN SHROUDS	177	25

*Tested without rotors in turbine engine test rig.

DUODENSITY ROTOR
(Injection-moulded RBSN 125 mm O.D. blade ring integral with 80 mm O.D. HPSN hub)

45,000 rev/min for 10 hours	1204-1260°C	(2200-2300°F)	NO FAILURE
50,000 rev/min for 25 hours	1232°C	(2250°F)	NO FAILURE
50,000 rev/min for 1.5 hours	1371°C	(2500°F)	METAL FAILURE

After 1.5 h gas near front face of hub had reached 1038°C (higher than anticipated), and above softening point of metal parts used to mount ceramic rotor. During shut down metal distortion caused a failure in which the ceramic rotor was shattered.

FIGURE 2

WESTINGHOUSE TESTS ON HPSN STATOR VANES

(a) 1204°C (2200°F) CYCLIC TESTS

Upramp	5.5°C/s (10°F/s) to 1204°C and hold
Downramp	13.9°C/s (25°F/s) to 1093°C
Hold	45 s
Downramp	to 649°C (1200°F)
	TOTAL OF 106 CYCLES
ALSO	2 SEVERE FLAME-OUT SHOCKS

Downramp near-instantaneous from 1204°C to 316°C inlet air temperature.

RESULTS 4 vanes and 2 end-caps developed cracks traced to out-of-tolerance machining of socket causing severe Hertzian edge-loading. Correctly-machined vanes undamaged.

All lithium aluminium silicate end-cap insulators cracked.

(b) 1371°C (2500°F) CYCLIC TESTS

Ramp rates as for 1204°C test, but peak hold temp 1371°C. Shell pressure 724 kPa (~7 atmos). BN insulators used.

RESULTS Temperature accidently rose to 1649°C (3000°F) in fifth cycle, fuel valve closed, and vanes quenched instantaneously to 316°C; flame can inside combustor melted, imploded and impacted vanes. Large piece of can retained by HPSN vanes, which were also spattered with molten metal debris. Only HPSN vane 1 had a crack, originating at a flaw undetected by initial NDE.

All HPSC vanes shattered; Nos. 7 and 8 gone completely.

FIGURE 2 (Contd..)

(c) 1371°C CYCLIC TESTS WITH NEW DESIGN COMBUSTOR

RIG REBUILT, 100 cycles completed with HPSN

COMBUSTOR REDESIGNED - Gave more severe temperature traverse.

RESULTS After 25 cycles observed that vanes had shifted due to assembly error, and had edge-loaded. Six vanes cracked due to this; vane 3 had thermal stress crack. After 22 cycles vane 5 and after 35 cycles vane 6 cracked. Final 43 cycles up to 1466°C with these replaced. NDE revealed crack in vane 8 where it had touched an inner shroud of cooled metal side vane. All HPSN vanes OK; also BN insulators. Thermal stress analysis indicated a 3X increase in thermal stress from new metal combustor design.

FIGURE 3

AIRESEARCH DIVISION OF GARRETT CORPORATION

TSE 331C-1 CERAMIC GAS TURBINE

(a) Design Specification

OUTPUT POWER (40% up on T.76 all-metal turbine)	793 kW (1064 HP)
SPECIFIC FUEL CONSUMPTION (10% down on T.76 all-metal turbine)	88.6 μg/J (0.524 lb/HP/h)
ROTOR MAXIMUM SPEED	41730 rev/min
ROTOR BLADE O.D.	20 cm
HUB O.D.	16 cm
NUMBER OF ROTOR BLADES	28
MAX. LOCAL BLADE STRESS	302 MPa (43800 psi)
TURBINE ENTRY TEMP.	1204^{o}C (2200^{o}F)
TURBINE/STATIC PRESSURE RATIO	8.2

(b) Status of Design Evolution and Testing (Late 1977)

HPSN ROTOR BLADES SLOTTED IN WASPALOY ALLOY DISC

MULTIPLE CIRCULAR ARC NECK SHAPE
60^{o} CONTACT ANGLE
EXTENDED NECK
COMPLIANT LAYER (0.25 mm/HS25 alloy)
IN CONTACT ZONE
MINIMUM DISC NECK MASS
AND THICKNESS
LOW BROACH ANGLE BLADE PLATFORM

SPIN PROOF TESTING OF BLADES TO 54,000 rev/min
(30% OVER SPEED = 69% OVER STRESS)
90 BLADES TESTED
ONLY 4 FAILED

RBSN STATORS

FIRST STAGE RING OF 21 RUN TO FULL AERODYNAMIC LOAD AND
SECOND STAGE TO FULL LOAD AND TEMPERATURE

RBSN COMBUSTOR

METAL CAN TESTS AND COMBUSTOR DESIGN OPTIMISATION NEARLY COMPLETE.

FIGURE 4

SOLAR DIVISION OF INTERNATIONAL HARVESTER
USE OF CERAMICS IN RADIAL IN FLOW GAS TURBINE

IN ACCELERATED DUST EROSION TESTS UP TO 900 feet/s HPSN 50 X BETTER THAN 713 LC SUPERALLOY.

THIS FINDING CORROBORATED BY 10 h ENGINE TEST WITH 44 mg - 140 mesh silica dust/kg air WHEN SUPERALLOY VANES RECEDED 12 mm BUT EROSION OF HPSN VANE WAS NOT MEASURABLE.

IN A 70 h SEA-SALT CORROSION TEST AT 927°C ATTACK ON 713 LC WAS 270 μm AND ON HPSN 11 μm.

IN A 25 h ENGINE TEST WITH 50 START/STOP CYCLES IN A 10 kW TURBOALTERNATOR GAS TURBINE (P RATIO 3.5) 10 out of 15 HPSN VANES UNDAMAGED AND 5 SUSTAINED CHIPS AT TRAILING EDGE DUE TO THERMAL DISTORTION OF A SHROUD.

A SECOND ENGINE TEST IN JUNE 1977 WITH HPSN VANES AND A SLIGHTLY MODIFIED DESIGN WAS COMPLETELY SUCCESSFUL.

FIGURE 5

PRATT AND WHITNEY AIRCRAFT
CERAMIC-BLADED METAL-DISC GAS TURBINE ROTOR INVESTIGATION

PHOTOELASTIC MODELLING USED TO CONFIRM FINITE ELEMENT STRESS ANALYSIS OF BLADE ROOT DESIGN - MAX. STRESS 274 MPa (39700 psi).

NICKEL SUPERALLOY AF2-1DA DISC FORGED AROUND HPSN BLADES ("GATORIZING") WITH COMPLIANT METAL INTERLAYER INTRODUCED.

50 h TEST OF 30-BLADED ROTOR WITH 10 CYCLES TO 45000 rev/min AND 1232°C (2250°F) SUCCESSFULLY COMPLETED, AND ALSO A FURTHER 16 h WITH 10 THERMAL CYCLES AND 97 ISOTHERMAL LOW-CYCLE FATIGUE DWELL CYCLES.

(For further details of early work see NTIS Report AD-A022 158 "Design, Fabrication and Evaluation of Gatorized (TM) Ceramic-Wrought Alloy Attachment Concepts" by W D CARRUTHERS and B H WALKER, P & WA; and also Ref. 30).

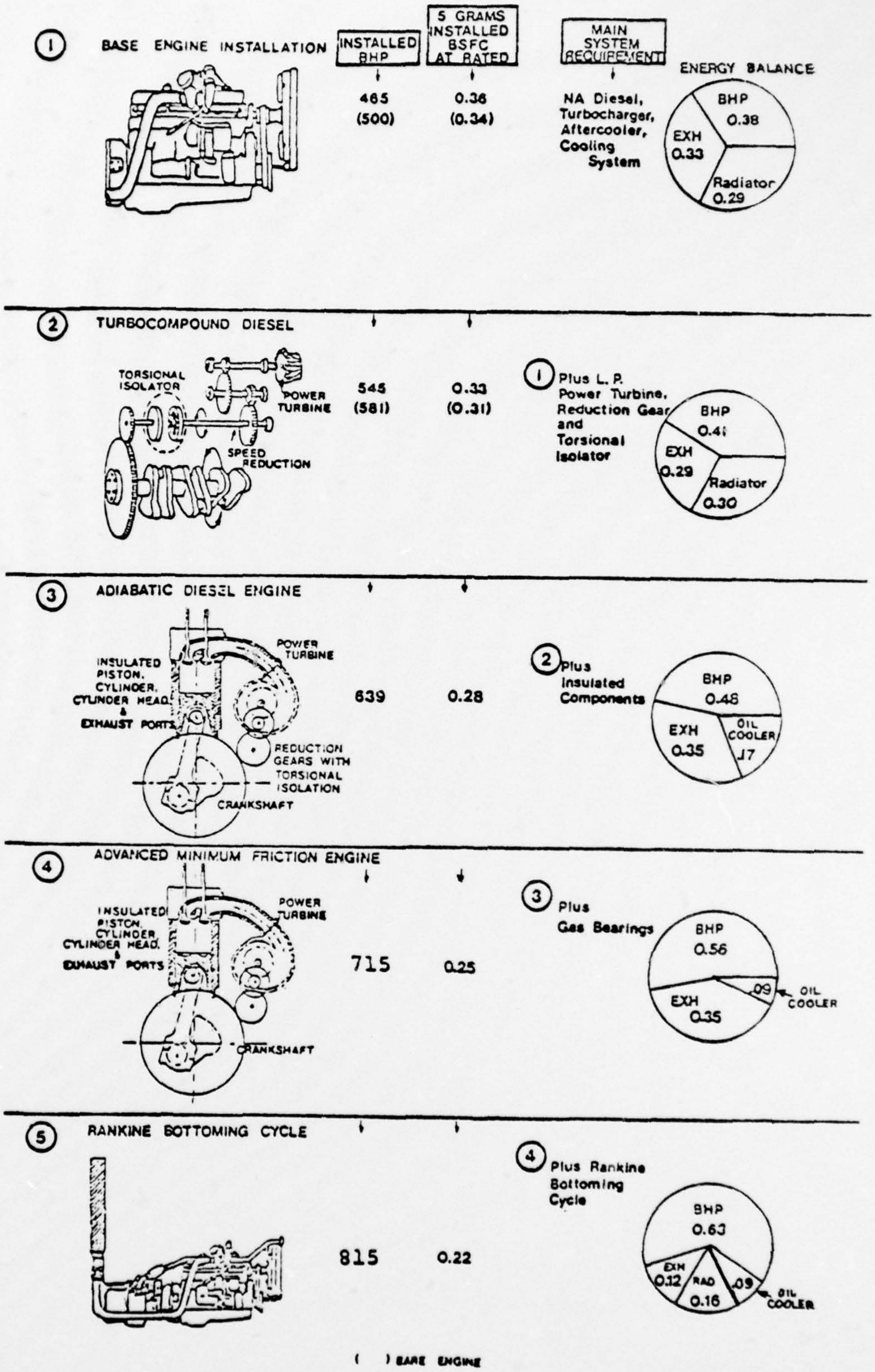

Fig. 6 KAMO's concepts for progressive improvement of diesel engines. (copied with permission from Ref 38 Preprint)

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