SUBSTITUTION OF CERAMICS FOR HIGH TEMPERATURE ALLOYS

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ABSTRACT

Ceramics such as silicon nitride and silicon carbide are currently receiving a great deal of attention as potential materials for advanced gas turbine engines. The primary advantage offered by ceramics is their high temperature capability which can result in turbine engines of improved efficiency. Other advantages when compared to the nickel and cobalt alloys in current use are raw material availability, lower weight, erosion/corrosion resistance, and potentially lower cost. The use of ceramics in three different sizes of gas turbine engines is considered; these are the large utility turbines, advanced aircraft turbines, and small automotive turbines. Special considerations, unique to each of these applications, arise when one compares the two ceramics for high temperature metal alloys. The effects of material substitutions are reviewed in terms of engine performance, operating economy, and secondary effects.

THE QUEST FOR HIGHER temperature materials for use in gas turbine engines has been pursued since the very introduction of the engine in the late 1930's (1). The gas turbine, like any heat engine, achieves greater efficiencies of energy conversion as working fluid temperatures are allowed to increase. Thus the development of high temperature materials for gas turbines has been of major importance. With the advent of high temperature gas turbines, even the largest engine manufacturers are considering the use of ceramics in their engines. In recent years, the development of ceramic alloys has been influenced by a number of factors, but one of the most significant has been the introduction of the ceramic-toughened metal (CTM) concept (2). CTM materials have been developed for turbine engine applications where the high temperature environment may not be severe enough to allow the use of a monolithic ceramic.

THE GAS TURBINE ENGINE

By way of review, Fig. 1 offers a schematic view of a gas turbine engine. This particular engine configuration is similar to those currently powering our jumbo jets using high pressure and low pressure axial turbines with twin spools and a by-pass fan. Although configurations can vary widely this figure illustrates the essential components, particularly those in the hot gas path where material capabilities at high temperatures are of major concern. The temperatures shown represent, for the most part, those anticipated in advanced aircraft turbines.

Combustors are sheet metal components fabricated from nickel or cobalt alloys and film cooled. They are subjected to severe thermal stresses and oxidation. Vanes are static components which divert the hot combustion gases into the turbine blades. Vanes are also either nickel or cobalt alloys which see high temperatures but relatively low stresses, usually only elastic stress due to aerodynamic loads and thermal gradients. The turbine blades probably experience the most severe combination of environmental factors. In addition to the corrosion effects of hot gases they are exposed to both high temperature and high stress. Blade stresses are for the most part unidirectional along the long axis of the airfoil, resulting from the high centrifugal loads generated by the high speed rotation of the blade. Blade stresses can be calculated by assuming that the blade is a massive rotating piece experiencing very high centrifugal stresses especially near its hub. While the disk experiences high stresses, fortunately its temperature level is considerably less than components in the hot gas path. Disks are forged nickel alloys, with hot isostatically pressed nickel powders holding a great deal of promise for future applications. Adjacent to the turbine blade tips is the shroud or turbine seal. This component is intended to form a minimum clearance seal with the blade tips in order to minimize gas leakage over the blade tips. It is essential that shroud materials be abrasion and allow "wear-in" of the blade tips. Current porous nickel alloys are used.

When one speaks of ceramics in connection with gas turbine usage some qualifications are in order. In a certain sense ceramics are currently in use if one considers the intermetallic aluminide coatings used for oxidation and corrosion protection as being "ceramic." Also, glass ceramics in the aluminum silicate and magnesium aluminum silicate systems have been developed as heat exchange materials in connection with automotive gas turbine projects. However, in the context of this paper these materials will not be considered but rather we will consider only materials in the silicon nitride (Si₃N₄) and silicon carbide (SiC) families that have potential for use as monolithic components. It is these materials, that is, the nitride and carbide, that have received so much recent attention as potential turbine materials.

It must be understood that the use of the word "substitution" in reference to ceramics for high temperature alloys does not have the usual connotation. The technology of these ceramics is of the type that would allow a one-for-one substitution as one might substitute one alloy for another. Quite to the contrary, the very nature of the ceramics requires special design considerations so that their eventual substitution will have to be in engines incorporating fairly substantial design modifications.

ORGINAL PAGE IS OF POOR QUALITY
CERAMICS COMPARED TO SUPERALLOYS

Let us make some general comparisons between ceramics and the nickel-base super alloys. These are shown in Fig. 2. The most obvious advantage of the ceramics is their potential for high temperature use; temperatures far in excess of the melting point of nickel alloys. In a high temperature air environment these ceramics form a protective surface layer of silica and thus do not require the costly coatings that are routinely used to protect alloys from the environment. As shown in Fig. 2 material costs are lower than alloys, however this advantage must be tempered with the realization that such cost comparison is for an early stage of testing that is required by the materials and is in production. This cost comparison, as well as most others in the literature does not include for ceramics the cost of consolidation, surface finishing, and inspection. Ceramic parts usually being cost competitive with superalloys, however, as of now ceramic components are not cheap. The lower density of ceramics is an asset in all gas turbines as it can result in rotation of lower inertia; and the direct weight savings is of special interest to aircraft and automotive applications. From a material substitution standpoint ceramics offer the added advantage they contain no strategic elements. That nickel base superalloys contain on the average about 15 percent chromium, an element for which we are totally dependent on foreign supply. We are also heavily dependent on foreign nations for our supplies of nickel. Contrasted to this, these ceramics contain elements which are abundant; silicon, carbon, and nitrogen.

To more specifically illustrate some of the advantages of ceramics Figs. 3 and 4 offer dramatic comparisons. In Fig. 3 the high temperature strength potential is illustrated. Here the stress to density ratio for 1000 hours stress-rupture life is plotted against temperature. Also included is the stress to density ratio for 1000 hours stress-rupture life plotted against temperature, and the direct weight savings is of special interest to aircraft and automotive applications. From a material substitution standpoint ceramics offer the added advantage they contain no strategic elements. That nickel base superalloys contain on the average about 15 percent chromium, an element for which we are totally dependent on foreign supply. We are also heavily dependent on foreign nations for our supplies of nickel. Contrasted to this, these ceramics contain elements which are abundant; silicon, carbon, and nitrogen.

Figure 4 illustrates the superior creep resistance of a ceramic coating of silicon nitride. Both test samples were exposed to a simulated gas turbine environment at 2200°F. While the ceramic sample is somewhat different due to slight addition but otherwise shows no distress. On the other hand, the coated alloy has suffered severe leading edge recession due to oxidation and large thermal fatigue cracks have developed in the leading edge due to the thermal cycles.

With these many outstanding advantages offered by Si₃N₄ and SiC a natural question is: Why haven't we used these materials before now in the gas turbine? The answer of course is their inherent brittleness and the whole problem was summed up most succinctly by Prof. Ken Jack of the University of Newcastle Upon Tyne when he said: "Metals are metals and ceramics are blowy brittle!

Designers rely on the ductility of metals to provide "forgiveness" to their designs. That is, the ductility of metals can often provide small amounts of plastic flow and thereby relieve stress concentrat-
and have enjoyed a great deal of success.

Current interest in ceramics is certainly high-risk technology, when all the factors displayed in Fig. 5 are considered. There does seem to be justification for some cautious optimism and certainly little question that today’s research has a higher chance of success than was ever realized with the ceramics.

CURRENT INTEREST IN CERAMICS

Although there are numerous current programs supported by private and public funds devoted to various aspects of ceramics in gas turbines, there are two programs that manifest the current major thrusts in this technology. These programs are summarized in Fig. 6. Both were originally funded by the Advanced Research Projects Agency of the Department of Defense and are now being supported by the Department of Energy.

The first major program in this technology was conducted at Ford Motor Co. (6) and Westinghouse Electric Corp. (7). Its goal was to demonstrate that components made of brittle materials could indeed be designed by modern techniques and survive in the gas turbine environment. This program applied three-dimensional finite element design techniques to components of two gas turbine engines differing greatly in size, the small a combustor and the large central station utility power plant engine. The program was initiated in 1971 and over 25 million dollars of government money have been contributed to its implementation. In addition both Ford and Westinghouse have contributed large amounts of corporate funds. In both cases designs were to accommodate gas temperatures as high as 2500°F. In the Ford portion, a great many ceramic components, including an all ceramic rotor were studied. In the Westinghouse portion full attention was directed toward the large stator vane. The Ford program, made of brittle materials, was planned to demonstrate the several components in an engine test. All components except the rotor have survived program goals as individual components (8). The all ceramic rotor, the component subjected to the most severe stress-temperature combination has undergone many iterations in design and fabrication approaches. It has survived hot spin testing for 25 hours at 2250°F and 15 hours of 2500°F (8). This latter test was cut short by too high temperatures and distortion of metallic components.

The Westinghouse program has been completed with three vanes out of eight surviving the total program target (9). Failures could readily be traced to a combination of thermal stresses and scatter in material properties. However, a significant finding was that no failures resulted from mechanical loads inherent in the design, that is, mechanical designs to accommodate brittle materials were successfully demonstrated.

Figures 7 and 8 are representative of some of the hardware and designs generated in this program. Figure 7 is the all ceramic rotor in the Ford effort. Two separate components are joined to make this monolithic rotor of about 4½ inches diameter. The hub is hot pressed Si₃N₄ while the blade ring is injected molded using silicon powder in an organic vehicle. After injection, the part is converted to Si₃N₄ by a reaction sintering process in a nitrogen atmosphere.

Figure 8 shows some essential features of the Westinghouse vane design. The ends of the vane airfoil are curved in three dimensions to mate with corresponding depressions in support blocks.

The second and more recent major program shown in Fig. 6 is being conducted at AllResearch Manufacturing Co., a division of Garrett Corp. (9). Its purpose is to design, fabricate, and conduct demonstration tests of ceramic hot flow path components in an existing Garrett engine. By the use of uncooled ceramic components the base power level of the engine is expected to be increased from 750 hp to the 1000 hp level with an accompanying 10 percent reduction in specific fuel consumption. Average turbine inlet temperature is 2200°F and a wide variety of components will be redesigned as ceramics and introduced into the engine. The fuel in this demonstration was originally planned for a small naval patrol craft, however, it appears now that the final demonstration will not be in a vehicle but rather on a test stand. The program was originally planned as a 12 to 13 million dollar program for 3 years duration. Garrett Corporation is also contributing corporate funds to the program. As an example of hardware emerging from the AllResearch program, Fig. 9 shows individual turbine blades machined from hot pressed silicon nitride. These are small blades; total airfoil height being about 3/4 inches, and are designed to be run in an alloy disk by use of exact design analysis and so-called compliant layers.

The compliant layer concept is more clearly illustrated in Fig. 10 which is taken from a NASA program at Pratt-Whitney Aircraft (10). In this case the compliant layer, a 0.015 inch thick platinum foil can be seen around the blade root. Its purpose is to relieve any local stress concentrations by deforming plastically and thus minimize strains being transmitted to the ceramic blade root. In the configuration shown in Fig. 10 the blade is ready for hot spin testing; the other items apparent in the figure are an axial retaining bolt and a thermocouple.

In addition to these two major programs summarized on Fig. 6 there are many other programs sponsored primarily by DOE, DOT, and NASA which deal with material characterization, preparation, and consolidation as well as fabrication, inspection, and design techniques. As mentioned earlier, the large scale introduction of a gas turbine engine can vary widely depending on its intended use. Figure 11 is intended to illustrate the breadth of this wide spectrum of engine sizes by listing three engine types and some of their differing features. In addition to great size differences ranging from 5-inch diameter rotor to over 80 inches, we see great differences also in power level, expected service life, and potential market volume. These factors along with many other must be considered when the use of ceramics is considered. Therefore, after considering such factors, the final balance between risk, costs, and pay-offs can be quite different among the various applications.

For example, in the utility engine a high component reliability is demanded by the long life. Such large engines represent a comparatively small market (11). However, since they are major capital investments, one might afford to pay a cost premium to obtain high reliability components. At the other end of the spectrum, the automotive engine is not as demanding in life expectancy; however, the high potential market volume makes low cost mass produced ceramics components absolutely necessary. The civil aircraft engine lies somewhere between these two extremes in size, life, and market volume (12). It must put highest priority on reliability because of the risk to life involved and yet ceramic components must be competitive with competing metallic materials. Thus, the potential of ceramics and the likelihood of their eventual substitution for metal depends upon many factors and often these factors are unique to individual applications. Therefore, we cannot speak in generalities of the use of ceramics in gas turbines but rather have to consider each application separately.

For the remainder of this paper each of the applications shown in Fig. 11 will be reviewed in more detail in order to reach a prognosis for the use of ceramics in each.
CERAMICS IN UTILITY GAS TURBINES

The gas turbine may be used in the electric utility industry in several ways. Two of the most obvious are shown in Fig. 12. The simple cycle is straightforward with a gas turbine engine directly driving an electrical generator. Due to the high exhaust gas temperatures of the gas turbine it can be used more efficiently in the combined cycle in which waste heat in the gas turbine exhaust is used to generate steam for a conventional steam turbine.

Figure 13 (13,14) illustrates benefits to be gained in most of these cases by the use of ceramic components. Current utility gas turbines use cooled superalloys with metal temperatures limited to the 1500°F to 1600°F range primarily by hot corrosion considerations in the neighborhood of 2000°F and produces thermal efficiencies of about 30 and 43 percent for the simple and combined cycles, respectively. Future gas turbines with advanced cooling could in late fuels. However, if a price range is taken as $2 million dollars per year per plant, the present value of the total comes to about $60 million dollars.

An additional potentially large advantage regarding fuel usage by ceramic utility gas turbines is the possibility of using lower grade fuels of lower costs. Current utility gas turbines use cooled superalloys with metal temperatures limited to the 1500°F to 1600°F range primarily by hot corrosion considerations in the neighborhood of 2000°F and produces thermal efficiencies of about 30 and 43 percent for the simple and combined cycles, respectively. The use of ceramic components cooling can be eliminated resulting further in increased efficiencies most dramatically in the combined cycle case where efficiency increases from 30 to 49 percent for simple and 43 to 58 percent for combined cycles, respectively. By the use of ceramic components cooling can be eliminated resulting further in increased efficiencies most dramatically in the combined cycle case where efficiency increases from 30 to 49 percent for simple and 43 to 58 percent for combined cycles, respectively.

Further, there are several ways ceramic components cooling can be eliminated resulting further in increased efficiencies most dramatically in the combined cycle case where efficiency increases from 30 to 49 percent for simple and 43 to 58 percent for combined cycles, respectively.

A more direct comparison of the payoffs offered by these improved efficiencies is shown in Fig. 14. Here, for the combined cycle, thermal efficiencies of 49 percent achievable with advanced cooling being increased to 53 percent by the use of uncooled ceramics can result in an 8 percent reduction in annual fuel consumption for a plant in the 1000 MW size range (13). Translating this to monetary savings is difficult in the current inflationary times. However, if a price range is taken as $2 to $3 per million Btu fuel heat content then the 8 percent reduction in fuel consumption can yield savings of $12 million dollars per year per plant.

An additional potentially large advantage regarding fuel usage by ceramic utility gas turbines is the possibility of using lower grade fuels of lower costs. Current utility gas turbines use cooled superalloys with metal temperatures limited to the 1500°F to 1600°F range primarily by hot corrosion considerations in the neighborhood of 2000°F and produces thermal efficiencies of about 30 and 43 percent for the simple and combined cycles, respectively. By the use of ceramic components cooling can be eliminated resulting further in increased efficiencies most dramatically in the combined cycle case where efficiency increases from 30 to 49 percent for simple and 43 to 58 percent for combined cycles, respectively. By the use of ceramic components cooling can be eliminated resulting further in increased efficiencies most dramatically in the combined cycle case where efficiency increases from 30 to 49 percent for simple and 43 to 58 percent for combined cycles, respectively.

Overall, this study indicates a slightly more costly engine, however, fuel consumption is reduced by about 1.2 percent. Direct operating costs are somewhat reduced and return on investment is improved. Overall, the total life cycle costs of an engine containing ceramic shrouds would be reduced by about $43 million dollars.

An essential comparison to be made in any proposed new technology is its present worth versus its estimated development costs. That is, is the margin between present worth and development costs sufficient to justify the undertaking? Figure 19 compares ceramic technology applied to several components in terms of present worth and estimated development costs (18). Ceramic vanes certainly represent the largest payoff in terms of present worth. However, vanes and shrouds are comparable when compared in terms of present worth and estimated development costs. In both cases present worth is seen to be about a factor of 10 times greater than estimated development costs. Ultimately the development of shrouds would probably be preferred to vanes due to lower ceramic failure risks associated with the shroud. Based on this General Electric study ceramic combustor liners for large aircraft engines would not appear to be a very likely technology because of the relatively low present value compared to relatively high development costs.

In spite of the large payoffs evident by the introduction of ceramic components into large aircraft
engines, this introduction is the start of a major change until far in the future. There is one major reason for this proposal; it is risk to life. Component reliabilty will first have to be demonstrated in other lower risk applications. There is, however, one component that when made of ceramics might offer acceptably low life risks; this is the shroud. A shroud failure cannot be tolerated without catastrophic results and therefore ceramic substitution might be seen in the foreseeable future in shrouds.

CERAMICS IN AUTOMOTIVE GAS TURBINES

The automotive-sized turbine engine is one in which the introduction of ceramics seems very promising for a number of reasons. This size engine presents component sizes which are quite amenable to ceramic mass production processes. Also the small component size makes cooling more difficult as an alternate approach to achieve higher gas temperatures. Component lifetimes in ceramic engines are quite shorter than the free turbine. Both types would require heat regeneration in which waste heat in other exhaust streams would be extracted and used to preheat the incoming combustion air.

In Fig. 11 some comparisons are made among the current, mature, and advanced engine performances (19). These comparisons are for engines nominally in the 150 hp power level. Current engine technology allows turbine inlet temperatures near 1850°F with regenerator temperature limited to 1300°F (at the time of the JPL study) of stainless steel regenerators. Engine weight is high at 500 pounds and efficiency is 26 percent. The mature metallic engine will allow turbine inlet temperatures to rise to 1900°F and regenerator temperature to 1800°F. This large increase in regenerator temperature will be permitted by the use of improved aluminum silicate and/or magnesium silicate regenerator materials now under development. A much lighter engine of 360 pounds and 33 percent efficiency results. Ultimately, the utilization of ceramics will allow turbine inlet temperature to rise to 2500°F with regenerator temperature of 2000°F. Engine weight is reduced to about 50 pounds and efficiency is 46 percent. By comparison, efficiency of advanced internal combustion piston engines is projected to be about 29 percent. All of this improvement in both weight and efficiency is going from the mature to the advanced engine are the direct result of the use of ceramic components.

While these comparisons are impressive the consumer today is most interested in what all of this means in terms of gas mileage. Some comparisons are given in Fig. 22. The mature metallic engine would provide a doubling of gas mileage over the current experimental gas turbine engines from about 8 mpg to 19 mpg for the full size car on the EPA city driving cycle (19). Of course, the mileage figures for a mature gas turbine installed in a compact car are even more impressive as shown in Fig. 22. The gains in mileage offered by the ceramic gas turbine are dramatic with mileages as high as 46 mpg being projected for a compact car powered by a ceramic gas turbine.

Another major concern is what the costs will be in order to reap the benefits of such an improved engine. The ultimate costs of future gas turbine engines is difficult to predict, however some comparisons are offered in Fig. 23. The mature metallic gas turbine engine is projected as relatively low cost in terms to an advanced internal combustion piston engine (Otto engine), that is, in the $1300 to $1400 range (19). If cooling and/or coatings are required in the mature engine its costs will of course be greater. The final cost of an advanced ceramic automotive gas turbine engine is impossible to predict at the present time. However, some major factors that will affect this cost are evident. Lower material costs and possibly lower processing costs certainly would tend to lower engine cost. However, there are also factors in the production of a ceramic engine not encountered in a metallic engine which would tend to drive up the cost. For example, a high raw material costs may be lower, higher scrap rates might be expected with ceramic components. High costs for inspection and, in all probability, component proof testing would contribute to higher production costs. Higher warranty costs might also be anticipated for a ceramic engine. How all of these factors would combine to determine the final cost of a production ceramic gas turbine engine is not presently known.

An advantage offered by ceramics when substituted for superalloys is a conservation of strategic elements, particularly chromium and nickel. This is an especially important consideration in such a high volume industry as the automotive. The United States
currently imports essentially 100 percent of our chromium from such countries as South Africa, Rhodesia, Turkey, and Russia (19). We import over 70 percent of our nickel from Canada and Norway (19). Since chromium and nickel are major constituents in high temperature alloys their conservation by the substitution of ceramics would be beneficial.

A comparison of the amount of chromium required in various automotive engines (19). Prior to the widespread use of the catalytic converter a conventional automobile engine required about 4 pounds of chromium per engine. In an automotive engine used in the remainder of the vehicle the automotive industry accounted for 8 percent of our total national consumption of chromium. This assumes an annual production rate of 10 million vehicles. With the current use of the catalytic converter the chromium required per engine is about 44 pounds and the automotive industry consumption rate jumps to about 11 percent of the total domestic consumption. The mature metallic gas turbine would also require about 44 pounds of chromium per engine. Although this engine would not require a catalytic converter, it would not impact chromium consumption, since it does require high chromium superalloys and stainless steels. The advanced ceramic turbine could reduce chromium usage to less than 1 pound per engine and cut the automotive portion of domestic consumption level to less than 8 percent. A similar comparison shows that the advanced ceramic turbine could reduce automotive nickel consumption to less than one-half of current levels (19).

The automotive size gas turbine appears to be ideally suited to reap the maximum benefits from the introduction of a ceramic gas turbine. This is primarily because of the small compact size, the large market size, and the dramatic payoffs in terms of fuel economy. Of course, production experience and field experience for a ceramic gas turbine engine in the automotive size range. Also, although engine size smaller than automobile were not considered here, there are some applications where small gas turbine appears to be very promising, and the use of ceramics in these small engines should provide benefits similar to those anticipated for the advanced ceramic gas turbine. Two such applications involving high volume markets are motorcycles and lawn care equipment such as riding mowers. In the recreational area, compact power units for outboard motors and snowmobiles would also appear as applications of high potential.

CONCLUSIONS

In summary, the use of ceramics in gas turbines for three different applications has been examined. In all three it is apparent that ceramic components are currently advantageous, can be advanced, and possess lower component costs. Specifically, in large utility gas turbines, ceramics offer great potential for conservation of current fuels as well as the possibility of using lower grade, more corrosive alternate fuels. However, advanced metallic cooling concepts offer lower risks and nearer term payoffs. In spite of the large payoffs evident for the use of ceramics in civil aircraft gas turbines the high risk to life and competing advanced metallic concepts will delay the introduction of ceramics to this market for at least 15 years. The high pressure turbine tip shroud is a possible exception that could see earlier usage of ceramics. The ultimate use of ceramics in large aircraft powerplants will depend heavily upon the confidence gained by applying ceramics in other, namely, ground based, applications. However, looking to the day when that confidence will come, there are special consideration for ceramics in aircraft that should be addressed now so as to hasten that day and be prepared for its arrival. Proper special needs for aircraft applications are ceramic components of ultra high reproducibility and reliability. Such high levels of reliability require improved materials and processes capable of producing components with truly minimal risk of failure. Coupled with the necessary improved properties and processes are the required order of magnitude improvements in the capability of nondestructive evaluation (NDE) techniques. Instruments to detect and diagnose that will accommodate brittleness. Through these combinations of confidence, from ground based experience and absolute minimization of risk of failure by improved materials, processes, NDE techniques and component designs ceramics will some day provide the reliability required for airborne applications.

The automotive size gas turbine appears to be the most likely for application of ceramics. Component size requirements are most amenable to high capacity ceramic processing techniques. Perhaps the most significant change and consequently improved gas mileage which a ceramic gas turbine can provide a passenger vehicle is dramatic and certainly a carrot worthy of vigorous pursuit. Also in the near-automatic sized engine other obvious applications are remotely piloted aircraft, trucks, buses, and portable power units.

In order to bring the promises of ceramics to fruition in any of the above areas, that is, utility, aircraft, or automotive, will require a great deal more research and development efforts in all aspects of basic materials behavior, processing, NDE, design, and related disciplines. Also, in the not too distant future some major economic decision must be made and production of a ceramic gas turbine so that the necessary confidence-building production and field experience can be accumulated.

Indeed, ceramics in gas turbine applications have outstanding potential; however, as of today, they are neither a quick, simple, nor cheap solution to material and energy problems. Some day they can be; however, such work remains to be done. In pursuing this work we must have patience and realize that we are presently low on the learning curve. We must be tolerant of false starts yet be sure we are attempting the proper starts. Some approaches may and in temporary failure, however, if such approaches are conceived in sound technical assessment the failures can provide a valuable learning experience from which to learn a renewed and ultimately successful attack. The more damaging failures are those which are predicated on unwise non technical decisions of a political or economic nature. From these we usually learn little of technical value. Some have ventured the opinion that at this point in time ceramics have been "over sold." This indeed may be a valid observation, however, in view of the payoffs one might alternatively argue that ceramics have been "under-supported" and "under-researched."

REFERENCES


Fig. 1. Schematic of aircraft gas turbine engine.

Fig. 2. Major advantages of ceramics for gas turbine engines.

<table>
<thead>
<tr>
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<th>Ni-BASE ALLOY</th>
<th>SiC/Si$_3$N$_4$</th>
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<tbody>
<tr>
<td>Higher Temp</td>
<td>~1250°C C MELTS</td>
<td>1700°C C/1450°C</td>
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<tr>
<td>Superior Corrosion</td>
<td>NEED COATINGS</td>
<td>NO COATINGS</td>
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<tr>
<td>Resistance</td>
<td>5-30 $$/lb (INGOT)</td>
<td>0.4-2 $$/lb (POWDER)</td>
</tr>
<tr>
<td>Lower Matl Cost</td>
<td>~8 g/cc</td>
<td>3.2 g/cc</td>
</tr>
<tr>
<td>Lower Density</td>
<td>Ni + ~15% Cr</td>
<td>Si-C-N$_2$</td>
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<tr>
<td>No Strategic Matls</td>
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Fig. 2. Major advantages of ceramics for gas turbine engines.
Fig. 3. Stress-to-density ratio for 1000 hour life vs temperature for advanced high temperature materials.

NORTON (HS-130)
HO1 Pressed Si$_3$N$_4$
NO DAMAGE FOUND
\[ \Delta Wt = 0.05 \, \text{mg/cm}^2 \]

COMMERCIALLY
COATED TO NiCr
\[ \Delta Wt = 41.5 \, \text{mg/cm}^2 \]
CS-68523

Fig. 4. Ceramic and coated alloy blades after 100 one hour cycles in Mach 1 burner at 2200°F (2).
NEED FOR HIGHER EFFICIENCY
REDUCE POLLUTION
CONSERVE FUEL

BETTER MATERIALS NOW AVAILABLE THAN IN "CERMET ERA"
HIGHER STRENGTH
BETTER RELIABILITY
IMPROVED THERMAL SHOCK RESISTANCE

BETTER PROCESSING
CAN MAKE INTRICATE SHAPE BY "MASS PRODUCTION" TECHNIQUES

BETTER DESIGN METHODS
3D FINITE ELEMENT ANALYSIS

Fig. 5. Reasons for the renewed interest in ceramics for gas turbines.

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>SPONSORING AGENCY</th>
<th>TOTAL COST TO GOVT. ($x10^8)</th>
<th>PROGRAM DURATION</th>
<th>ENGINE SIZE</th>
<th>GAS TEMP. (°F)</th>
<th>MAJOR CERAMIC COMPONENTS</th>
<th>APPLICATION</th>
<th>DEMONSTRATION TARGET LIFE, hr</th>
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<tr>
<td>FORD (PRIME) &amp;WESTINGHOUSE</td>
<td>ARPA &amp; DOE</td>
<td>25+</td>
<td>CURRENTLY 6 yr (7/71 START)</td>
<td>200 hp AUTO &amp; 30 MW UTILITY</td>
<td>2500</td>
<td>VANES, ROTOR, SHROUDS, COMBUSTOR, NOSE CONE, 30 MW- VANES ONLY</td>
<td>AUTO</td>
<td>200</td>
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<td>AIRESEARCH</td>
<td>ARPA</td>
<td>12.5</td>
<td>PLANNED 3 yr (3/76 START)</td>
<td>750 hp</td>
<td>2200</td>
<td>VANES, BLADES, SHROUDS, COMBUSTOR, TRANSITION SECTION</td>
<td>NAVY SHIP</td>
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Fig. 6. Major ceramic gas turbine programs (6, 7, 9).
Fig. 7. Ford duo-density rotor; hot pressed Si₃N₄ hub; reaction sintered Si₃N₄ blade ring (6).

Fig. 8. Westinghouse vane assembly; hot pressed Si₃N₄ (7).
Fig. 9. AiResearch rotor blades, hot pressed Si$_3$N$_4$ (9).

Fig. 10. Pratt-Whitney blade, hot pressed Si$_3$N$_4$ (10).

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>APPROXIMATE SIZE (ROTOR DIAM)</th>
<th>POWER LEVEL</th>
<th>LIFE, hr</th>
<th>ANNUAL MARKET VOLUME (ENGINES)</th>
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<tr>
<td>ELECTRIC POWER</td>
<td>UP TO =80 in.</td>
<td>20-100 MW</td>
<td>30 000</td>
<td>~200</td>
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<td>GENERATING UTILITY</td>
<td></td>
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<tr>
<td>CIVIL AIRCRAFT</td>
<td>UP TO =30 in.</td>
<td>15 000-50 000 lb THRUST</td>
<td>3000-10 000</td>
<td>~3500</td>
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<td>AUTOMOTIVE</td>
<td>=5 in.</td>
<td>100-200 HP</td>
<td>3 500</td>
<td>$10^7$ POTENTIAL</td>
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Fig. 11. Spectrum of gas turbine engines (11, 12).
Fig. 12. Schematic of utility gas turbine cycles.

Fig. 13. Payoffs of ceramics in utility gas turbines (13, 14).

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<tr>
<th>STATE OF ENGINE EVOLUTION</th>
<th>HOT PATH MATL TEMP, °F</th>
<th>MAX GAS TEMP, °F</th>
<th>THERMAL EFF, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CURRENT - CONTINUOUS DUTY</td>
<td>1500-1600</td>
<td>1900-2100</td>
<td>-28</td>
</tr>
<tr>
<td>FUTURE - ADVANCED AIR &amp;/OR WATER COOLING</td>
<td>1500-1600</td>
<td>2500+</td>
<td>-34</td>
</tr>
<tr>
<td>FUTURE - UNCOOLED CERAMICS</td>
<td>2500+</td>
<td>2500+</td>
<td>-36</td>
</tr>
</tbody>
</table>

Fig. 14. Fuel savings by use of ceramics in 1000 MW combined cycle powerplant (13).
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>RELATIVE SPECIFIC COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR COOLED METALLIC (1500°F METAL TEMP)</td>
<td>1</td>
</tr>
<tr>
<td>CERAMIC VANES ONLY</td>
<td>0.9</td>
</tr>
<tr>
<td>CERAMIC VANES &amp; BLADES</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Fig. 15. Relative initial powerplant costs ($/kW), 2400°F turbine inlet temperature, combined cycle (15).

**ASSUMPTIONS**
- 2900°F F MATERIAL CAPABILITY
- 0.015 in. TIP CLEARANCE REDUCTION
- 1.5 TIMES CURRENT COST OF METALLIC SHROUD

**RESULTS**
- ENGINE PRICE + 0.3%
- SPECIFIC FUEL CONSUMPTION - 1.2%
- DIRECT OPERATING COSTS - 0.17%
- RETURN ON INVESTMENT + 0.073%
- LIFE CYCLE COSTS/ENGINE - $43,000

Fig. 17. Effect of ceramic shroud on operation of large aircraft gas turbine engine (17).
ASSUMPTIONS
2900°F MATERIAL CAPABILITY
GAS EROSION LESS THAN 0.015 in. AFTER 500 hr IN 2400°F MACH 1 STREAM
0.5 TIMES COST OF ADVANCED DISPERSION STRENGTHENED ALLOY
3 in.-ID BALLISTIC IMPACT RESISTANCE WITHOUT CATASTROPHIC FAILURE

RESULTS
SPECIFIC FUEL CONSUMPTION -1.47%
DIRECT OPERATING COSTS -2.21%
RETURN ON INVESTMENT +0.72%
PRESERV WORTH (TOTAL FLEET, 15 yr LIFE) $66.6 x 10^6

Fig. 18. Effect of ceramic vanes (1st and 2nd stages) on operation of large aircraft gas turbine engine (18).

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>PRESENT WORTH, $ x 10^6</th>
<th>ESTIMATED DEVELOPMENT COSTS, $ x 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>VANES</td>
<td>66.6</td>
<td>6.0</td>
</tr>
<tr>
<td>SHROUDS</td>
<td>34.2</td>
<td>3.3</td>
</tr>
<tr>
<td>COMBUSTOR LINER</td>
<td>5.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*TOTAL VALUE OF THE TECHNOLOGY WHEN APPLIED TO ENTIRE INTERCONTINENTAL FLEET OVER 15 yr PLANE SERVICE PERIOD.

Fig. 19. Comparative value of ceramic technologies applied to large aircraft gas turbine engines (18).

Fig. 20. Schematic of automotive gas turbine configurations.
### Table 1: Comparison of Automotive Gas Turbine Engines

<table>
<thead>
<tr>
<th></th>
<th>MAX TURBINE INLET, °F</th>
<th>MAX REGENERATOR INLET, °F</th>
<th>BRAKE EFF, %</th>
<th>ENGINE WEIGHT, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>CURRENT¹</td>
<td>1850</td>
<td>1300</td>
<td>26</td>
<td>600</td>
</tr>
<tr>
<td>MATURE METALLIC²</td>
<td>1900</td>
<td>1800</td>
<td>33</td>
<td>366</td>
</tr>
<tr>
<td>ADVANCED CERAMIC²</td>
<td>2500</td>
<td>2000</td>
<td>46</td>
<td>290</td>
</tr>
</tbody>
</table>

¹FREE TURBINE.  
²SINGLE SHAFT.

Fig. 21. Comparison of automotive gas turbine engines; All 4:1 compression ratio and fully regenerated (19).

### Table 2: Projected Gas Mileage (mpg) for Automotive Turbines

<table>
<thead>
<tr>
<th></th>
<th>COMPACT (2660 lb)</th>
<th>FULL SIZE (3400 lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CITY³</td>
<td>HIGHWAY³</td>
</tr>
<tr>
<td>CURRENT¹</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>MATURE METALLIC²</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>ADVANCED CERAMIC³</td>
<td>32</td>
<td>46</td>
</tr>
</tbody>
</table>

¹FREE TURBINE.  
²SINGLE SHAFT.  
³FEDERAL DRIVING CYCLE.

Fig. 22. Projected gas mileage (mpg) for automotive turbines (19).
Fig. 23. Comparison of estimated costs of automotive engines (19).

Fig. 24. Chromium consumption in automotive engines (19).