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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 considers substituting ceramics for high temperature 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 presented a continuing challenge to the materials community. Indeed the evolution of the gas turbine engine to the sophisticated machine we know today has been paced by material developments that have allowed operating temperatures to increase. Yet, today gas turbine designers are relying more on complicated and costly cooling schemes in order to let working fluid temperatures rise while maintaining material temperatures at acceptable lower levels dictated by material properties. Cooling is costly both in terms of original hardware cost and performance penalties. Because of this unending drive to higher temperatures gas turbine engineers have always felt a certain attraction to the potential offered by ceramics - and have always been frustrated in their attempts to realize this potential.

The purpose of this paper then is to consider the use of ceramics in a variety of gas turbine applications and hopefully reach some realistic projections as to the possibility of substituting ceramics for high temperature alloys in advanced gas turbine engines.

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 stresses due to aerodynamic loads and thermal gradients. The turbine blades probably experience the most severe combination of environmental factors. In addition to the corrosive 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 blades. In the roots of blades, that is, the attachment portions where they join the disk, high shear and bending stresses can be encountered. Today's aircraft blades are made of cast nickel alloys and because of the unidirectional airfoil stress are often produced in an aligned microstructure having highly anisotropic properties. Turbine blades are attached to the periphery of the turbine disk. The disk 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 alloy 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 abradable and allow "wear-in" of the blade tips. Currently 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 are being 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 (Si_3N_4) 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 not to the state 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.

*Numbers in parentheses designate references at the end of paper.

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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; to 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 are for an early stage of processing, that is, alloy ingot and ceramic powders. This cost comparison, as well as most others in the literature does not include for ceramics the cost of consolidation, surface finishing, and inspection. Ceramics certainly have great potential for ultimately 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 rotors 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 that they contain no strategic materials. Our 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 their 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 range that is required for blade materials in aircraft engines. It shows that our current superalloys are useful for blade applications to slightly over 1800° F. Other advanced materials are shown increasing this temperature capability. The wide temperature range shown for superalloys reinforced with refractory metal wires is due to the fact that volume fraction of wires and wire orientation may be varied. The ceramic data are based on bend stress-rupture testing (rather than the usual tensile mode used in alloy testing). Yet, for comparison the bend data has been divided by a factor of 2 to allow for the lower strength of ceramics in tension than in bend. Even so, we see the ceramics offering potential blade temperature to the 2400° to 2500° F range, far in excess of any of the competing metallic systems.

Figure 4 illustrates the superiority of a ceramic over coated alloys in surface stability (2). Both test samples were exposed to a simulated gas turbine environment at 2200° F. The ceramic sample is somewhat discolored due to slight oxidation 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 Si_3N_4 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 Thyne when he said, "Metals are metals and ceramics are bloody 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 concentrations. The ceramics are totally "unforgiving" in this sense and have no capacity to accommodate even minor stress concentrations. Therefore, they require a very exact design approach entailing new and unique concepts and methods. Also, the brittleness of ceramics usually prevents them from providing any advanced warning of impending failure. That is, without the creep or plastic deformation most alloys exhibit prior to failure, ceramic parts will not rub, distort, or otherwise give any indication of impending failure that would allow replacement.

CERAMICS COMPARED TO CERMETS

Let us consider a bit of history before going further. The last serious attempt to introduce brittle materials into gas turbine usage was in the middle 1950's when a class of materials known as "cermets" was under development (3). As their name implies, cermets attempted to combine the most desirable properties of ceramics with those of metals. This was done by mixing ceramics with metals, usually by liquid phase sintering, resulting in a two-phase structure quite similar to carbide cutting tools. The concept was to provide a final material that combined the oxidation resistance and strength of ceramics with the ductility of metals. However, such a utopia was not achieved and more often than not cermets exhibited the major liabilities of both components rather than their assets.

Skeptics from the cermet era, and there are a great many left, justifiably ask the question: what has changed? why do we expect today's ceramics to offer any greater chance of success than we experienced with the cermets?

Figure 5 attempts to answer this question by outlining the reasons for the renewed interest in ceramics and some of the major features that are different today than in the 1950's. Today we have much stronger and compelling reasons for going to higher temperatures than were recognized in the 1950's. At higher operating temperatures allowed by ceramics, engine pollution can be reduced, particularly carbon monoxide and unburned hydrocarbons. As mentioned before, a direct result of higher operating temperature is higher efficiency which means more effective use of fuel or lower fuel consumption. In addition to the obvious benefit in fuel conservation, ceramics, because of better corrosion resistance than alloys, also offer the potential of using lower grade fuel giving lower fuel costs as well as a greater variety of fuels from which to choose.

The current ceramics represent a class of materials generally of higher quality in terms of properties and reliability than was available in the 1950's. A major difference between SiC and Si_3N_4 compared to more classical ceramics is their ability to withstand thermal shock. This quality is of course, essential for the start-stop operation of most gas turbines.

Today's ceramics can be fabricated by techniques that lend themselves to mass production. With techniques such as injection molding one can visualize ceramic production rates adequate for even high volume markets such as automotive.

Finally as indicated in Fig. 5, a most important factor is the availability of three-dimensional finite element analysis. With such techniques a complex component can be divided into a three-dimensional grid of individual elements. Each element can then be analyzed for such things as temperature, strain, stress, and the interaction of elements analyzed by the computer. In such a technique component design can be readily changed and evaluated by computer and allow design iterations before a final design is committed to fabrication. Such techniques are far superior to the more familiar "make 'em and break 'em" approach and have enjoyed a great deal of success in ceramic component programs (4,5).

While there is no question that ceramics in gas turbines is certainly a 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 effort has a higher chance of success than was ever realized with the cermets.

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 one is now receiving support from 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 automotive engine 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 seeks a 200-hour demonstration of all 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 1½ hours of 2500° F (8). This latter test was cut short by over temperature and distortion of metallic components.

The Westinghouse program has been completed with three vanes out of eight surviving the total program target (7). 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 Si_3N_4 while the blade ring is injected molded using silicon powder in an organic vehicle. After molding the silicon is converted to Si_3N_4 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 AiResearch 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 final 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 of 3 years duration. Garrett Corporation is also contributing corporate funds to the program. As an example of hardware emerging from the AiResearch 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 a so-called compliant layer.

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 absorb 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 DOD, DOE, and NASA which deal with material characterization, preparation, and consolidation as well as fabrication, inspection, and design techniques.

As mentioned earlier, the size and configuration 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 come under consideration 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 costs 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 both configurations by the use of ceramic components. Current utility gas turbines use cooled superalloys with metal temperatures limited to the 1500° to 1600° F range primarily by hot corrosion considerations. This limits gas temperatures to 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 air or water cooling could still maintain alloy temperatures near 1600° F while allowing gas temperature to rise to about 2500° F. This higher gas temperature results in efficiency increases to about 34 and 49 percent for simple and combined cycles, respectively. By the use of ceramic components cooling can be eliminated resulting again in increased efficiencies most dramatic in the combined cycle case where efficiencies approaching 53 percent are projected.

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 saving is difficult in the current times of rapidly increasing prices for distillate fuels. 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 8 to 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. Ceramics should not have to contend with oxidation and hot corrosion problems that have plagued metallic components. Therefore, lower grade fuels such as heavy residual fuels or possibly even coal derived fuels might be used. Ceramics should be resistant to attack by impurities contained in these fuels, however, this point needs yet to be fully verified in a wide range of residual and synthetic fuels.

Without cooling the plumbing requirements of a large utility turbine are considerably simplified and should therefore contribute to lower cost components. In addition, the use of ceramics could result in reduced initial plant costs as indicated in Fig. 15. Use of ceramic vanes could reduce specific (dollars per kilowatt) plant costs by 10 percent while the use of ceramic vanes and blades could effect a 15-percent reduction (15). With the need for cooling reduced or eliminated, higher specific power outputs, that is, kilowatts per pound of air per second are achieved. Thus for a given air handling capacity, that is, frame size, more power can be produced using ceramic components giving lower specific costs. This benefit is gained in spite of possibly higher costs for disks, shafts, and bearings due to higher speed and temperature.

In spite of these obvious payoffs, the substitution of ceramics for alloys in utility gas turbines is probably not in the near future. Cooling of metallic components is an obvious competing technology. Also there is the larger problem of acceptance by the utility industry of the gas turbine being a replacement of acceptable reliability to the tried and true steam turbine (16). If there are yet questions of reliability in utility operation of metallic gas turbines, then how much larger will be the problem of demonstrating adequate reliability with ceramic turbines.

CERAMICS IN AIRCRAFT GAS TURBINES

In the large civil aircraft gas turbine a logical component to consider for ceramic substitution is the turbine shroud. A shroud is shown schematically in Fig. 16. The shroud is essentially a seal that defines the gas path and minimizes tip leakage of hot combustion gases thus forcing the expanding gases to pass through the turbine and do useful work. Ceramic shrouds would bring about two immediate results. They can run hotter than metallic shrouds and have considerably less thermal expansion, therefore required cooling air could be reduced and tip clearance reduced.

In a study by Pratt & Whitney Aircraft (17) the benefits of a ceramic shroud were calculated as shown in Fig. 17. Here a 2900° F material temperature capability was assumed and a tip clearance reduction of 0.015 inch. Also a 50-percent cost penalty was assigned to the ceramic shroud over current alloy shrouds. The results indicate 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 $43 000 per engine.

In a study by General Electric Company the effect of substituting ceramics for alloy turbine vanes was addressed (18). The assumptions and results of this study are summarized in Fig. 18. This study assumed a material capability of 2900° F and superior erosion resistance. Some improved resistance to ballistic impact was also assumed and component costs were placed at about half that anticipated for advanced dispersion strengthened alloys. Results of the study indicate a sizeable reduction in fuel consumption of 1.47 percent, reduced operating costs of 2.21 percent, and an increased return on investment of 0.72 percent. All of the benefits combined to produce a present worth value of about 66 million dollars. This present worth is today's estimate of the total value of the new technology when applied to an entire fleet of intercontinental jumbo jets over their total useful service life period. In this case of ceramic vanes applied in the first and second stages of the high pressure turbine the total present worth is calculated to be in excess of 66 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 to take place until far in the future. There is one major reason for this prognosis; it is risk to life. Component reliability 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 could conceivably 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 lifetime required is lower than the other two applications we have considered as illustrated in Fig. 11. Also noted in Fig. 11 the potential market volume is more enticing to ceramic manufacturers to make necessary investments in process scale-up.

A comprehensive review of the potential of ceramics for automotive applications was performed by the Jet Propulsion Laboratory (JPL) (ref. 19) under sponsorship of the Ford Motor Company. In this study other alternative engines in addition to the gas turbine were studied; these included Diesel, steam, Stirling, and electric engines. All were compared to current and advanced conventional (Otto cycle) engines. The conclusion of that study was that the gas turbine engine is a realistic alternative to the present engine.

Although the present discussion concerns the automotive gas turbine, it should be emphasized that a gas turbine engine in the automotive power and size range has other areas of application in which the introduction of ceramics is attractive. Two of these are portable powerplants and unmanned limited life aircraft for both military and civil applications. Also, in a size range slightly larger than automotive, the gas turbine with ceramic components can offer an attractive alternative power source for trucks and buses (20).

Before considering some of the findings of the JPL study a few definitions from that study are necessary. The study considered three gas turbine engines in the time scale, that is, current, mature, and advanced. The current engine refers to experimental engines currently under study at automotive manufacturers, for example, Ford, Chrysler, and General Motors. The mature engine is considered to be a near term improved version of current engines based totally on uncooled and uncoated metallic components and all required technology developments being available in the 1980 decade. The advanced engine assumes liberal use of ceramics and requires significant research and development in ceramics accompanied by significant advances in ceramic properties and processing. The required advanced ceramic technologies are assumed to be available in the late 1980's or later.

Figure 20 shows schematically the two schemes most often considered for an automotive gas turbine, the single shaft engine, and the free turbine. In the single shaft concept the compressor, turbine, and power output are all on a single shaft. This is the simplest configuration and is somewhat more efficient than the free turbine. However, it requires a continuously variable transmission which is an added complexity. On the other hand, the free turbine places the compressor and gasifier turbine on one shaft while a power turbine drives a separate output shaft. This engine can be coupled to a conventional transmission which is the primary reason why most experimental automotive gas turbine studies to date have used the free turbine. Both types would require heat regeneration in which waste heat in the exhaust gases would be extracted and used to preheat the incoming combustion air.

In Fig. 21 some comparisons are made among the current, mature, and advanced engines (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 because of the necessity (at the time of the JPL study) of stainless steel regenerators. Engine weight is high at 600 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 aluminum silicate regenerator materials now under development. A much lighter engine of 366 pounds and 33 percent efficiency results. Ultimately, the utilization of ceramics will allow turbine inlet temperature to rise to 2500° F with regenerative temperature of 2000° F. Another decrease in engine weight to 290 pounds is realized along with an efficiency of 46 percent. By comparison, efficiency of advanced internal combustion piston engines is projected to be about 29 percent. All of the improvements noted in 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 8.9 to 19 mpg for a 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 of today's consumer is what his 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 is projected to be very comparable in costs to an advanced internal combustor 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, although 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.

Figure 24 compares the amount of chromium required in various automotive engines (19). Prior to the wide spread use of the catalytic converter a conventional automobile engine required about 1½ pounds of chromium. With an added 6.4 pounds of chromium 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 4¼ 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 4¼ 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 engine 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 of an automotive ceramic gas turbine would require major retooling and corporate decision to commit to such a retooling would involve many complex economics factors as well as technical factors of the type summarized here.

The remotely piloted vehicle (RPV) appears to be an ideal test bed in which to gather both production experience and field experience for a ceramic gas turbine engine in the automotive size range. Also, although engines smaller than automotive 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 provided to an automotive 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 considered. In all three it is apparent that ceramic components can contribute to fuel savings, conservation of strategic materials, and quite possibly lower component costs.

Specifically, in large utility gas turbines, ceramics offer a 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 far into the future. 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. Among the more obvious special needs for aircraft applications are ce ic components of ultra high reproduceability 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 to detect life limiting flaws. And, of course, design techniques and refinements must be carried to their n^{th} degree to provide component designs 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. The efficiency 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-automotive 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 commitments will have to be made to 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, much 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 end in temporary failure, however, if such approaches are conceived in sound technical assessment the failures can provide a valuable learning experience from which to launch a renewed and ultimately successful attack. The more damaging failures are those which are predestined because of unwise nontechnical 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 "oversold." This indeed may be a valid observation, however, in view of the great payoffs one might alternatively argue that ceramics have been "under-supported" and "under-researched."

REFERENCES

1. H. J. Wagner and W. F. Simmons, "Materials for Gas Turbines," in "Sawyers Gas Turbine Engineering Handbook," Vol. 1, 2nd ed., Stamford, Conn., Gas Turbine Publications, Inc., 1972.

2. W. A. Sanders and H. B. Probst, "Behavior of Ceramics at 1200 C in a Simulated Gas Turbine Environment," Society of Automotive Engineers, Paper 740240, Feb. 1974.
3. A. J. Meyer, Jr., and G. C. Deutsch, "Application of Cermets to Aircraft Powerplants," in "Cermets," J. R. Tinklepaugh and W. B. Crandall, eds., New York, N.Y., Reinhold Publishing Corp., 1960.
4. A. Paluszny and P. Nichols, "Analytic Techniques for Predicting the Reliability of Ceramic Rotors," in "Ceramics for High-Performance Applications," Newport, R.I., March 1977.
5. D. J. Tree and H. L. Kington, "Ceramic Component Design Objectives, Goals, and Methods," in "Proceedings of the 1977 DARPA/NAVSEA Ceramic Gas Turbine Demonstration Engine Program Review," J. W. Fairbanks and R. W. Rice, eds., Battelle Columbus Laboratories MCIC Report 78-36, 1978; pp. 41-75.
6. A. F. McLean, "Ceramics in Small Vehicular Gas Turbines," in "Ceramics for High-Performance Applications," J. J. Burke, A. E. Gorman, and R. Katz, eds., Metals and Ceramics Information Center, 1974.
7. R. J. Bratton and D. G. Miller, "Brittle Materials Design, High Temperature Gas Turbine," Army Materials and Mechanics Research Center, AMMRC CTR 76-32, Vol. 1, Dec. 1976.
8. V. deBiasi, "Ford Runs Uncooled Ceramic Turbine Engine at 2500° F," Gas Turbine World (July 1977) pp. 12-18.
9. F. B. Wallace, "Garrett-Air Research Program Overview," Proceedings of the DARPA/NAVSEA Ceramic Gas Turbine Demonstration Engine Program Review," J. W. Fairbanks and R. W. Rice, eds., Battelle Columbus Laboratories, MCIC Report 78-36, 1978.
10. G. Calvert, "Si_3N_4 Blade-Metal Disk Evaluation," in "Ceramics for High Performance Applications," Newport, R.I., March 1977.
11. R. C. Farmer, ed., "Sawyers Gas Turbine Catalog 1976," Vol. 14, Gas Turbine Publications, Inc., Inc., 1976.
12. Aerospace Facts and Figures 1976/77, New York, N.Y., McGraw-Hill, 1976.
13. S. Wander, "Ceramics for Utility Application ERDA/Fossil Energy Program Background," Workshop on Ceramics for Advanced Heat Engines, CONF-770110, Jan. 1977.
14. Anon., "2500° F Target for 30-MW Ceramics Test Turbine," Gas Turbine World, Aug. 1972.
15. F. L. Robson and A. J. Giramonti, "The Effect of High-Temperature Materials on Combined-Cycle Performance," in "Ceramics for High-Performance Applications," J. J. Burke, A. E. Gorum, and R. N. Katz, editors, Metals and Ceramics Information Center, 1974.
16. A. Cohn, "Ceramic Gas Turbine Work," Workshop on Ceramics for Advanced Heat Engines, CONF-770110, Jan. 1977.
17. J. W. Bisset, "Cost/Benefit Analysis of Advanced Materials Technologies for Future Aircraft Turbine Engine," NASA CR-135107, Nov. 1976.
18. R. V. Hillery and R. P. Johnston, "Cost Benefit Study of Advanced Materials Technology for Aircraft Turbine Engines," NASA CR-135235, Sep. 1977.
19. "Should We Have a New Engine," An Automobile Power Systems Evaluation, Vol. II, California Institute of Technology, Jet Propulsion Laboratory, 1975, JPL-SP-4317.
20. R. A. Harmon, "Turning Point in Automotive Gas Turbine Development," Gas Turbine International, May-June 1975.

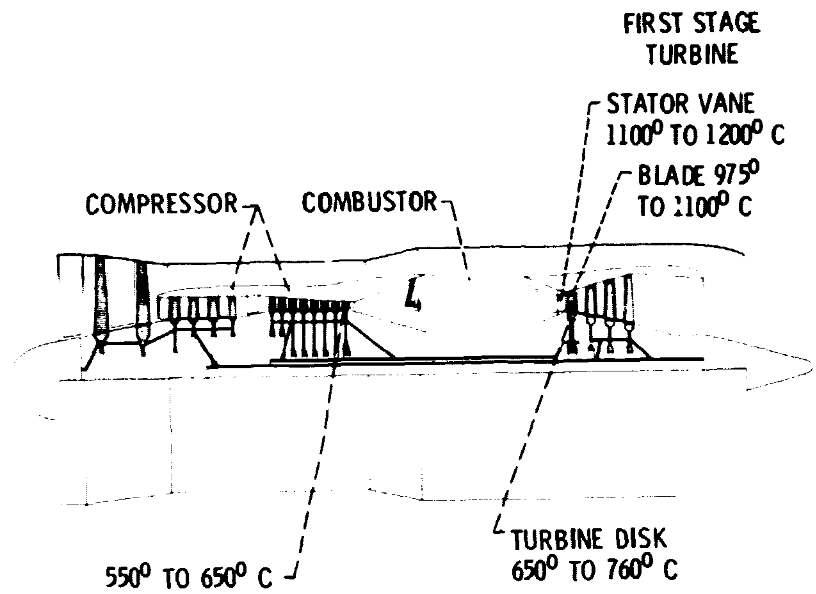


Fig. 1. Schematic of aircraft gas turbine engine.

	Ni-BASE ALLOY	SiC/Si_3N_4
HIGHER TEMP	~1250° C MELTS	1700° C/1450° C
SUPERIOR CORROSION RESISTANCE	NEED COATINGS	NO COATINGS
LOWER MATL COST	5-30 $/lb (INGOT)	0.4-2 $/lb (POWDER)
LOWER DENSITY	~8 g/cc	3.2 g/cc
NO STRATEGIC MATLS	Ni + ~15% Cr	$Si\text{-}C\text{-}N_2$

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

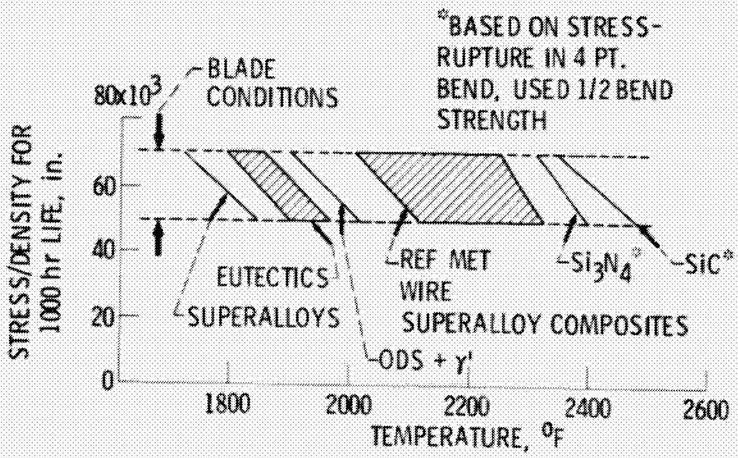
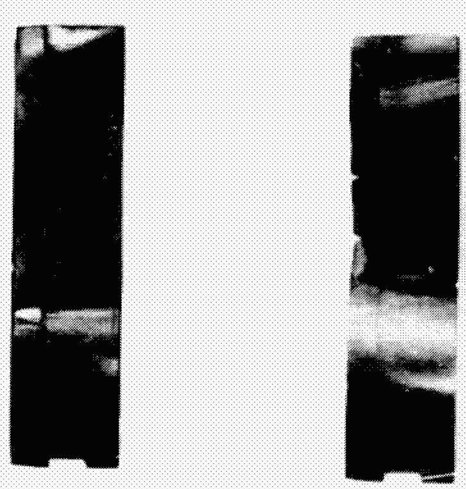


Fig. 3. Stress-to-density ratio for 1000 hour life vs temperature for advanced high temperature materials.



NORTON (HS-130) HOT PRESSED Si_3N_4
NO DAMAGE FOUND
Δ Wt - 0.50 MG/CM^2

COMERCIALLY COATED TD NiCr
ΔWt - 41.5 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.

CONTRACTOR	SPONSORING AGENCY	TOTAL COST TO GOVT, $\$ \times 10^6$	PROGRAM DURATION	ENGINE SIZE	GAS TEMP, °F	MAJOR CERAMIC COMPONENTS	APPLICATION	DEMONSTRATION TARGET LIFE, hr
FORD (PRIME) & WESTINGHOUSE	ARPA & DOE	25+	CURRENTLY 6 yr (7/71 START)	200 hp AUTO & 30 MW UTILITY	2500	VANES ROTOR SHROUDS COMBUSTOR NOSE CONE	AUTO	200
						30 MW- VANES ONLY	UTILITY	10
AIRESEARCH	ARPA	12.5	PLANNED 3 yr (3/76 START)	750 hp	2200	VANES BLADES SHROUDS COMBUSTOR TRANSITION SECTION	NAVY SHIP	50

Fig. 6. Major ceramic gas turbine programs (6, 7, 9).

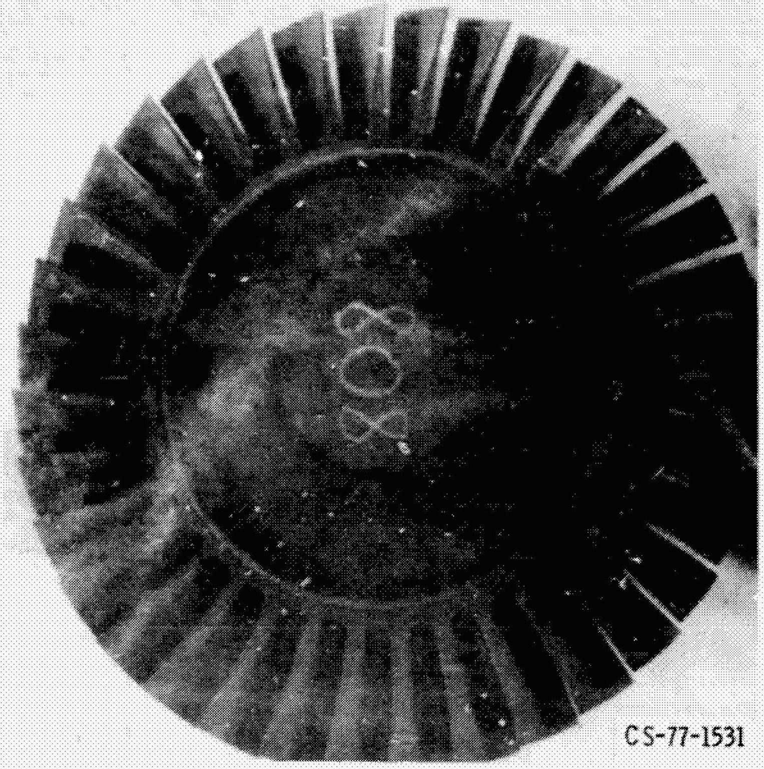


Fig. 7. - Ford duo-density rotor; hot pressed Si_3N_4 hub; reaction sintered Si_3N_4 blade ring (6).

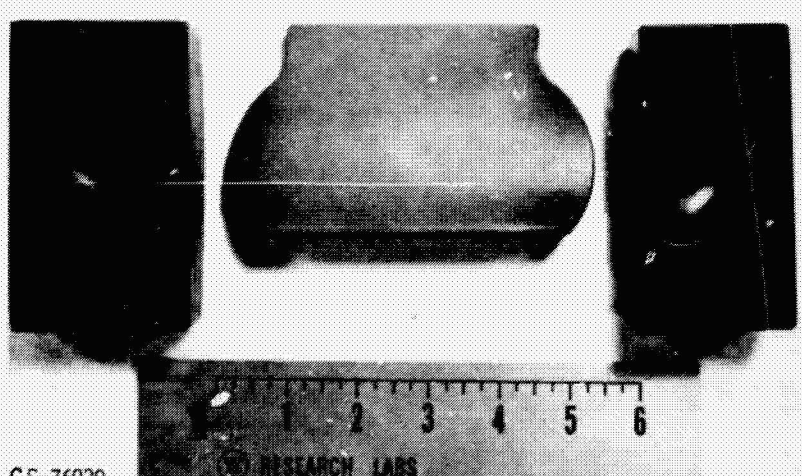


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Fig. 8. Westinghouse vane assembly; hot pressed Si_3N_4 (7).

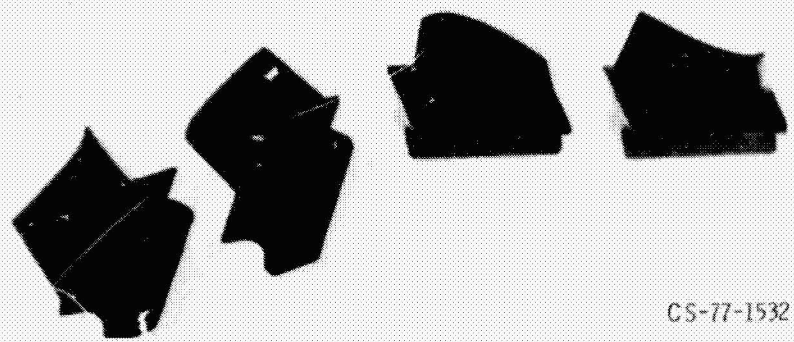


Fig. 9. AiResearch rotor blades; hot pressed Si_3N_4 (9).

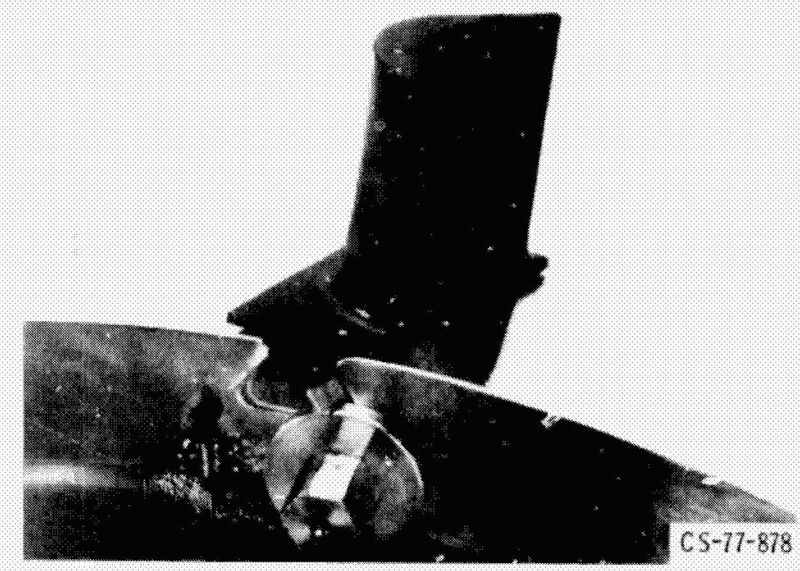


Fig. 10. Pratt-Whitney blade; hot pressed Si_3N_4 (10).

APPLICATION	APPROXIMATE SIZE (ROTOR DIAM)	POWER LEVEL	LIFE, hr	ANNUAL MARKET VOLUME (ENGINES)
ELECTRIC POWER GENERATING UTILITY	UP TO ≈80 in.	20-100 MW	30 000	~200
CIVIL AIRCRAFT	UP TO ≈30 in.	15 000-50 000 lb THRUST	3000-10 000	~3500
AUTOMOTIVE	≈5 in.	100-200 HP	3 500	10^7 POTENTIAL

Fig. 11. Spectrum of gas turbine engines (11, 12).

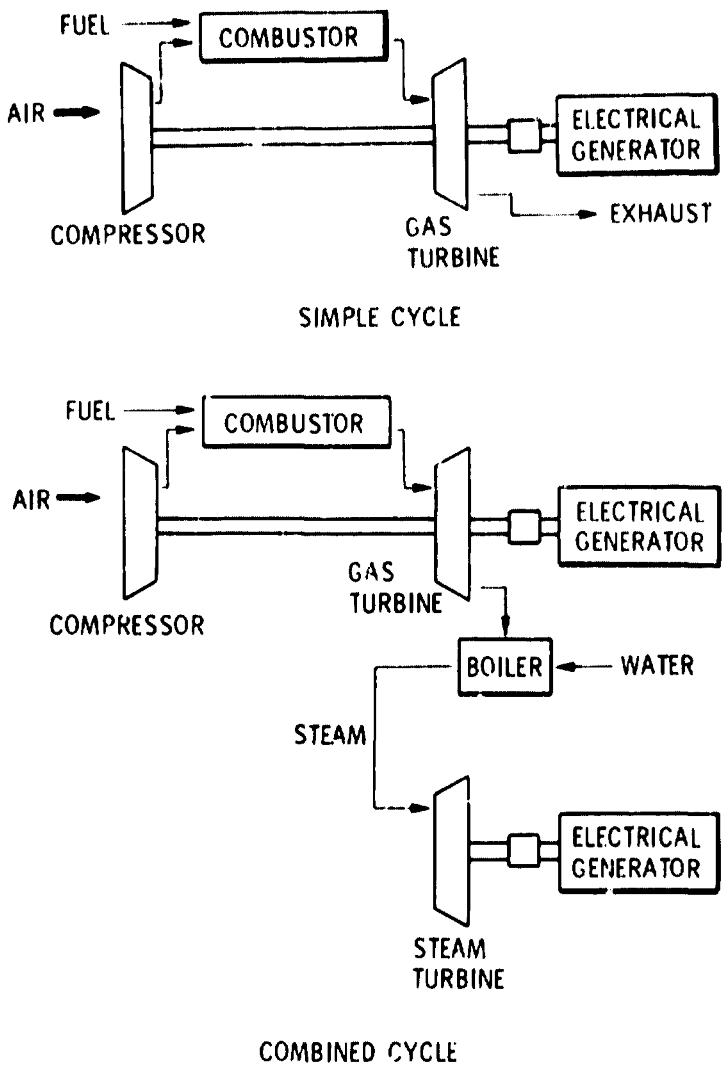


Fig. 12. Schematic of utility gas turbine cycles.

STATE OF ENGINE EVOLUTION	HOT PATH MATL TEMP, °F	MAX GAS TEMP, °F	THERMAL EFF, %	
			SIMPLE CYCLE	COMBINED CYCLE
CURRENT - CONTINUOUS DUTY	1500-1600 COOLED SUPERALLOYS	1900-2100	~28	~43
FUTURE - ADVANCED AIR &/OR WATER COOLING	1500-1600 COOLED SUPERALLOYS	2500+	~34	~49
FUTURE - UNCOOLED CERAMICS	2500+	2500+	~36	~53

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

SYSTEM	THERMAL EFF, %	
COOLED METALLIC	~49	RESULTS IN 8% REDUCTION IN FUEL USAGE
UNCOOLED CERAMIC	~53	

AT COST IN RANGE OF 2-3 $\$/10^6$ Btu
ANNUAL SAVINGS $\approx \$8\text{-}12\times10^6$

Fig. 14. Fuel savings by use of ceramics in 1000 MW combined cycle powerplant (13).

SYSTEM	RELATIVE SPECIFIC COSTS
AIR COOLED METALLIC (1500° F METAL TEMP)	1
CERAMIC VANES ONLY	.9
CERAMIC VANES & BLADES	.85

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

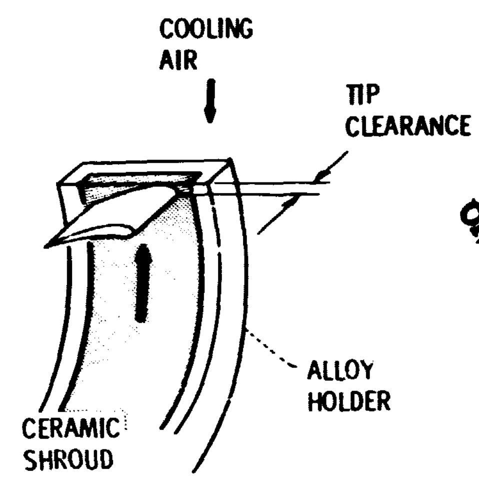


Fig. 16. Schematic of ceramic turbine tip shroud.

ASSUMPTIONS
- 2900° 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 - 0.179%
- 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 ft-lb BALLISTIC IMPACT RESISTANCE WITHOUT CATASTROPHIC FAILURE

RESULTS

SPECIFIC FUEL CONSUMPTION	-1.47%
DIRECT OPERATING COSTS	-2.21%
RETURN ON INVESTMENT	+0.72%
PRESENT WORTH (TOTAL FLEET, 15 yr LIFE)	$66.6x10^6$

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

COMPONENT	PRESENT WORTH,* $x10^6$	ESTIMATED DEVELOPMENT COSTS, $x10^6$
VANES	66.6	6.0
SHROUDS	34.2	3.3
COMBUSTOR LINER	5.7	3.0

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

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

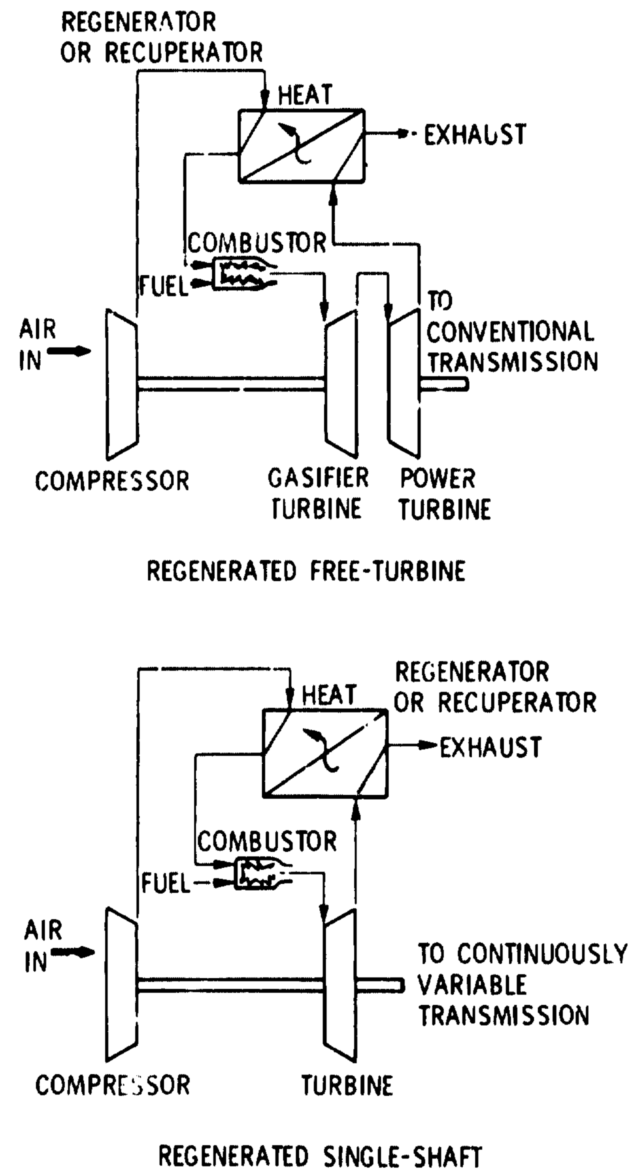


Fig. 20. Schematic of automotive gas turbine configurations.

	MAX TURBINE INLET, °F	MAX REGENERATOR INLET, °F	BRAKE EFF, %	ENGINE WEIGHT, lb
CURRENT[1]	1850	1300	26	600
MATURE METALLIC[2]	1900	1800	33	366
ADVANCED CERAMIC[2]	2500	2000	46	290

[1]FREE TURBINE.
[2]SINGLE SHAFT.

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

	COMPACT (2660 lb)		FULL SIZE (3400 lb)	
	CITY[3]	HIGHWAY[3]	CITY	HIGHWAY
CURRENT[1]	--	--	8.9	--
MATURE METALLIC[2]	23	33	19	28
ADVANCED CERAMIC[3]	32	46	----	--

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

Fig. 22. Projected gas mileage (mpg) for automotive turbines (19).

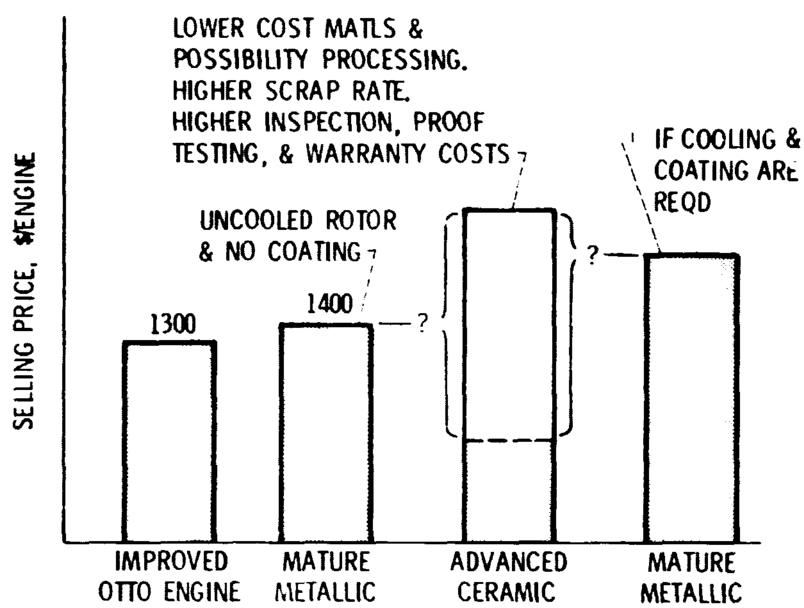
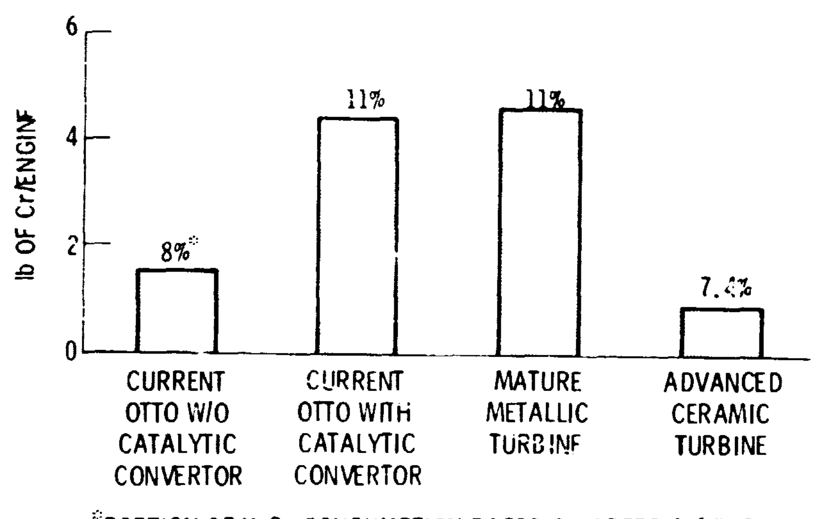


Fig. 23. Comparison of estimated costs of automotive engines (19).



*PORTION OF U.S. CONSUMPTION BASED ON ADDED 6.4 lb Cr IN VEHICLE & 10^7 ANNUAL PRODUCTION.

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