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## The automobile engine: test bed for fine ceramics

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*The automobile industry is merely a good avenue for introducing ceramic technologies with far broader applications, reports Thoula Frangos, an engineer with the Fusion Energy Foundation.*

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The high temperature tolerances of ceramic materials have been useful to man for a variety of purposes since the beginning of civilization. One of the earliest energy-related uses was for refractories in ovens and furnaces. Today, high-technology ceramic technologies are emerging for many diverse applications, from prosthetics to insulating blankets for the Space Shuttle (Figure 1). The development of high-performance heat-engine ceramics has received a great deal of attention in the past 10 years. There are presently joint government-industry programs in the major industrial nations, coupling development of advanced heat engines and ceramic materials.

The automobile industry is a good test bed for high-technology structural ceramics for two reasons. First, many components of the heat engine go through intense thermal and mechanical stresses, which the ceramic materials must survive. Second, due to the efficient mass-production of millions of cars a year, this is a good industry to develop production techniques very rapidly, once the economic benefits are perceived. This industry, being one of the largest, will more immediately realize the financial benefits of such an investment in improved engine efficiency. This makes the automobile industry a good avenue by which to introduce these ceramics to other parts of the economy.

The payback in investment in advanced heat engines for automobiles, is potentially enormous. In 1984 dollars, with 1984 fuel prices, a 20% increase in fuel efficiencies alone would reduce the U.S. balance of payments deficit by \$15 billion. Argonne National Laboratory did an economic study in 1983, which estimated a gain of \$278.9 billion to the U.S. economy over the seven-year period until 1990, were the United States to achieve hegemony in the world ceramics market—with a gain to the economy of 250,000 new jobs.

The Japanese currently have the greatest national commitment to ushering in the "new ceramic age." If the United States is to compete and realize the potential benefits of ceramic technologies, a major long-term government-sponsored program must also be launched.

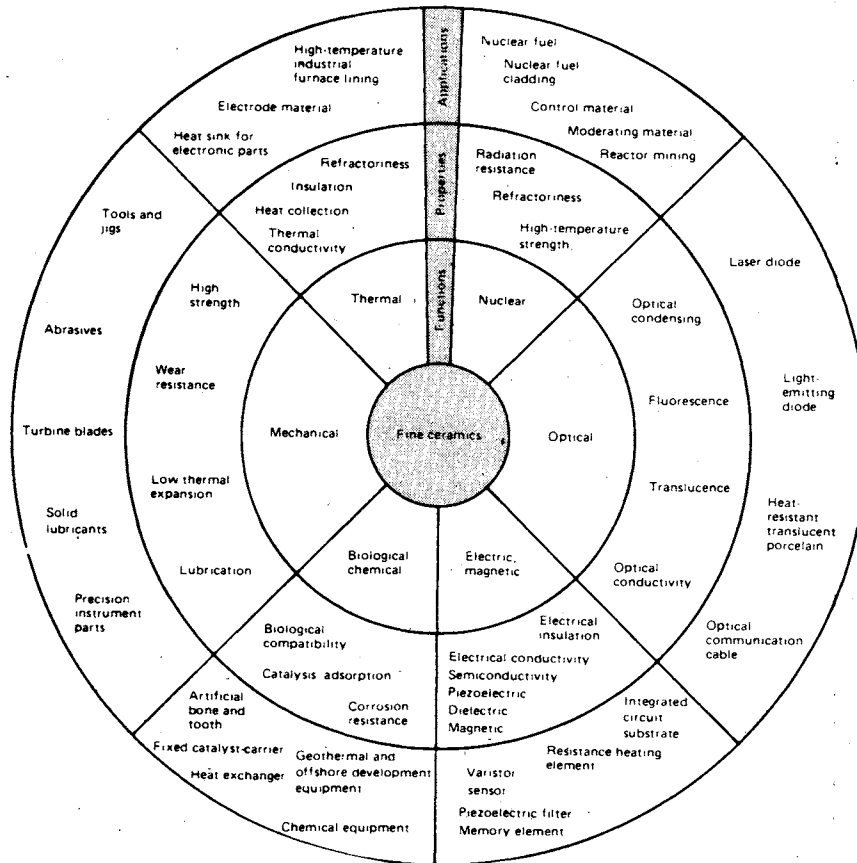
The materials for ceramics are very abundant, making up about 90% of the Earth's crust. What defines high-technology, or fine ceramics, is a highly controlled composition and structure of crystalline solids composed of metallic and non-metallic elements. The extreme strength, chemical inertness, and heat and abrasion resistance of the technical ceramics stems largely from their structures. The atoms are typically locked in rigid lattices. The application of heat and pressure in processing causes these already strong microcrystals to interlock and fuse, forming an extremely tough network. However, the rigidity of the crystal lattices in ceramics results in their brittle characteristic.

The strength of a given ceramic is strongly dependent on the size of its crystal grains. A material with large particles or with a random distribution of particle sizes is generally weaker than a ceramic with fine-grained or uniform-size particles. This is because large or random-size grains fit together with relatively large spaces in between; smaller or more uniform grains can fit together more closely.

The ceramics of interest for heat engine applications are silicon nitride, silicon carbide, sialons, and more recently, partially stabilized zirconium. These new industrial ceramics can operate at about 2,500°F without cooling gear, while similar "hot parts" made of metal superalloys operate only at 1,900°F and require costly heavy cooling systems. These ceramics are also lightweight, have a low coefficient of thermal expansion, and low frictional properties, making the components of the machines very durable, and reducing en-

FIGURE 1

## Uses and properties of fine ceramics



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gine wear and extending longevity.

The U.S. Departments of Energy and Defense are currently funding a two-pronged program, supporting development of advanced heat engines on the one hand, and the development of ceramic materials capable of withstanding the high-temperature, stressful regime of the heat engine on the other (Table 1).

Oak Ridge National Laboratory is the major center of research planning. Its Ceramic Technology for Advanced Heat Engines Program Plan is a five-year, \$140-million research plan, under the initiation of the Department of Energy (DOE), with 60% of the funding to be carried out by private industry, and the rest of the bill to be picked up by the national labs (30%) and universities (10%).

The goal of the program is to develop an industrial-technology base capable of providing reliable and cost-effective high-temperature ceramic components for application in advanced heat engines. The three major development areas are materials and processing, design methodology, and data base and life prediction.

While ceramic parts have been and will continue to be introduced into engine design, to construct a ceramic engine

as such there will have to be significant gains in fracture toughness and high strength margins. The specific objectives of this program are to develop improved, and new, synthesis and fabrication technology and to improve the reliability and performance of monolithic and toughened carbide- and nitride-base ceramics for structural applications; to develop technology for the synthesis and fabrication of improved high-temperature-toughened oxide ceramics primarily for thermal barrier and wear applications; to develop the ceramic joining technology base required by industry to design and fabricate reliable ceramic attachments; to develop the mechanisms controlling those ceramic bulk properties that govern long-term reliability in advanced heat engine environments; and to determine the mechanisms controlling static and dynamic interface behavior of bulk ceramics and coatings to provide long-term reliability under heat engine conditions. Another offshoot of the program is advances being made in introducing sophisticated non-destructive evaluation techniques into the automobile industry.

A method of strengthening ceramics by fiber reinforcements has been developed at Los Alamos National Laboratory. Here, silicon-carbide crystals, referred to as whiskers,

TABLE 1

**Applications of fine ceramics**

Fields of application	Parts	Demands and characteristics
<b>Engines</b>		
Gas turbine	Blade	Oxidation resistivity, thermal shock resistivity, high temperature strength
	Rotors	Strength, creep rupture resistivity
	Stators, shroudings, combustion cylinders	Oxidation resistivity, high-temperature strength, thermal shock resistivity
	Bearings	Wear resistivity, tenacity
Diesel engine	Pistons	Oxidation resistivity, high strength, low thermal conductivity, thermal shock resistivity
	Cylinders	Wear resistivity, strength, low heat conductivity
	Preheating chambers, nozzles	Thermal shock resistivity, oxidation resistivity, corrosion resistivity
	Valves	Strength, mechanical shock resistivity, corrosion resistivity, wear resistivity
	Tappets, cams	Wear resistivity
	Turbochargers, rotors	High-temperature strength, thermal shock resistivity, oxidation resistivity
	Bearings	Wear resistivity

are being grown to reinforce ceramics that will replace metals in mechanical parts such as valves, turbine blades, and heat exchangers with the advantage of being more resistant to corrosion, heat, and wear than metals. George Hurley, manager of the whiskers project, predicts that ceramics with these whiskers incorporated could be potential replacements for strategic materials such as superalloys and other exotic metals.

The most important factor determining the strength of a given ceramic is the method of processing and production. New methods of processing and powder production are being developed to overcome the weaknesses of ceramics, such as brittleness.

The most promising method at this time, is injection molding. This process not only minimizes brittleness of ceramics; it results in a near net shape which avoids or drastically reduces the need to machine the final product, and permits, for the first time, the mass production of industrial ceramic objects that have complex shapes, like turbine rotors. Machining which requires diamond-tipped tools, will exacerbate a ceramic's brittleness. Any time a ceramic surface is machined, its surface integrity is destroyed and the material is sensitized to the initiation of fracture.

Another process to reduce the susceptibility of structural ceramics to fracture is hot isostatic pressing (HIP), pioneered by Battelle in the mid-1950s for joining nuclear fuel elements. It relies on high temperatures and high pressures applied in three dimensions simultaneously.

In its June 1984 report, *Ceramic Technology for Advanced Heat Engines*, the Martin Marietta Corporation described the U.S. strategy for joint development of structural

ceramics and advanced heat engines.

The authors wrote: "The most promising advanced heat engines for highway vehicle propulsion have been identified from research and assessment analysis by industry and government over the past decade. These engine types include the internal continuous combustion gas turbine, the internal intermittent combustion adiabatic diesel, and the external continuous combustion Stirling engine. In all of these advanced engines, in fact in almost any advanced energy conversion system—overall cycle efficiencies are increased greatly by increased operating temperatures. The realization of these increased efficiencies necessitates the development of materials such as ceramics, that can withstand the higher operating temperatures."

The United States has demonstration programs for all three: the Stirling engine, being built by General Motors (with Mechanical Technologies Incorporated, and the Swedes); the advanced gas turbine engines, AGT 100 and AGT 101, supported by the DOE and administered by NASA, which were begun in 1979 and should be completed by 1986; and a joint project of Cummins Engine and the U.S. Army Tank Command, for a ceramic diesel engine.

### **The Adiabatic Diesel**

The Adiabatic Diesel Engine is an advanced design which seeks to maximize the conversion of heat to mechanical energy or operate at near adiabatic conditions. (The term adiabatic means a system which does not lose heat as it operates). It is probably the best candidate for the marketable ceramic automotive engine. The goal is to ultimately increase fuel efficiencies by 50% because of ceramics' tolerance of

higher temperatures in the combustion chamber (see **Figure 2**).

The engine accomplishes work by taking air into a turbocharger where it is compressed and then forwarded to an insulated, high-temperature combustion chamber, located in the piston unit. Combustion occurs and useful energy is extracted from the piston unit. The high-temperature exhaust gas is then expanded through two turbine wheels to extract as much as possible of the remaining energy. One wheel is used to drive the compressor, and the second is connected by gears—in a turbocompounding system—to the engine crankshaft to further increase the useful power output of the engine.

With the part-ceramic diesel, the goal has been to retain the roughly one-third of an engine's heat output for useful work, which must normally be bled off by the engine's cooling system. This heat content is recovered from the exhaust gas through the use of a turbocompound concept providing additional shaft power. Heat loss is trimmed by insulating key engine components with ceramics, which allows the water-cooling system to be entirely eliminated. Among the diesel components that have been ceramic-insulated on a trial basis are pistons, liners, cylinder heads, valve seats, and valve guides. With these ceramic components, the Adiabatic Engine can operate at 2,210°F. The most successful materials used to date have been partially stabilized zirconia and silicon nitride and silicon carbide.

By greatly reducing lost energy and essentially eliminating the need for a conventional cooling system, the Adiabatic Engine improves fuel economy and provides a 40% reduction in weight and volume over all metal diesel engines. Engine testing has shown that the Adiabatic Engine is the most fuel-efficient of the diesels, and has the highest thermal efficiency of any engine under design.

The engine is presently being adapted to use as a V-8 engine, used in tracked combat vehicles. The aim of the program is to remove the radiator, water pump, fan belts, and coolants. The long-term redesign goal is to also eliminate the engine block and cylinder head cooling. Since the radiator is thin-walled, it is extremely vulnerable on a tank, and its removal will mean a sharp increase in combat efficiency, as well as a 10% to 15% increase in fuel economy. Maintenance down-time will also be reduced, since half of heavy engine failures are cooling system related.

Cummins Engine Company has road-tested a five-ton truck over 8,000 miles. This zirconia-insulated diesel was not turbocompounded, but it had no radiator, fan, or water pump, and had 361 fewer parts than the standard diesel. Engine volume was reduced by 20 cubic feet, and 338 pounds. On-the-road fuel consumption decreased by 50%, from 6 to 9 miles per gallon. There was a 42% reduction in heat loss (heat not converted into work), with a present goal of 70% reduction. Another direction of development is the elimination of the lubricant system due to the low coefficient of

friction of ceramics.

The higher combustion efficiency of the Adiabatic Diesel lowers the nitrogen oxide in emissions: Due to the more complete oxidation rate, particulates formed in early stages of combustion are reduced by as much as 50%.

## The Stirling engine

The advantages of the Stirling are that it can use absolutely any fuel for combustion, has low emissions, low noise, and low vibrations (see **Figure 3**).

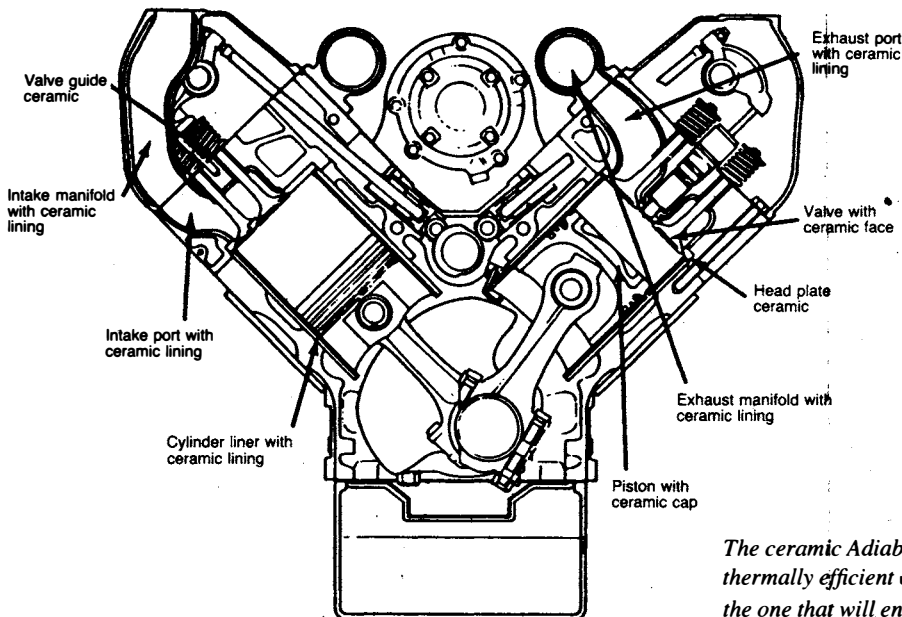
The Stirling engine is an external rather than internal-combustion heat engine—in that sense, like the steam engine; however, unlike the steam engine, it does not vent its working fluid to the atmosphere. The fluid, usually hydrogen, is contained in a cylinder, through which it circulates as it alternately contracts and expands. Usually, the Stirling passes the fluid through a "regenerator" which cools the fluid by capturing its heat, and then on the return pass, heats the fluid, by releasing that heat to it. The gaseous hydrogen working fluid is passed through a series of small thin-walled tubes, which are required for efficient heat transfer from the combustion gases to the working fluid. The hot hydrogen expands in the cylinder to drive a piston which activates the drive system. At the opposite end of the tubes, in addition to the regenerator, which absorbs heat from the hydrogen working fluid, there may be a cooler that permits contraction of the hydrogen. This process of heating and cooling the working fluid and extracting work forms the Stirling cycle.

Today, Stirlings have a wide application as stationary engines, and in situations where there is a premium on reducing noise, as in submarines. They also are of particular value in space applications because they can run in a vacuum. They are used today for irrigation systems, particularly in remote areas where there is not an adequate electrical grid, as in India, and for heat pumps and refrigeration; and are planned for certain military and space applications. During the Second World War, they were used in tanks which had to fight under desert conditions, because of the fact that the working fuel in a Stirling is sealed off from the environment, in contrast to the internal-combustion engine. They have also been used in remote outposts to power radio receivers and transmitters.

They are being studied in the Ceramic Heat Engine program, for application to automotive transport, because they can operate at high temperatures; and they can burn any fuel: wood, kerosene, alcohol, gasoline, or use new fuels like lithium fluoride. Lithium fluoride changes state in the neighborhood of 1,550°F. This transformation property can be utilized in place of combusting the fuel to release the heat.

General Motors is developing the automotive Stirling, in cooperation with Mechanicals Technologies, Inc., for placement in its Chevrolet Celebrity. They claim success for their second-generation (mod II) Stirling-powered car, scheduled for demonstration in 1987. It will operate with pressurized

FIGURE 2



*The ceramic Adiabatic Diesel is the most thermally efficient engine and probably the one that will enter the marketplace first.*

hydrogen, and at a temperature of 1,508°F. The most critical component in the engine is the heater head, which consists of the cylinders, heater tubes, and regenerator housing. The materials now being used for the "hot parts," such as the cylinder and regenerator, and the heater tubes are alloys of cobalt, a strategic metal. Obviously this is a good candidate for the substitution of ceramics, but the Stirling engine program, per se, has as its narrow goal the use of only those technologies which can be implemented in hardware by 1987.

The critical components for cost and performance are the preheater, combustor, and fuel nozzle. The preheater alone contains 1,000 very thin corrugated stainless steel plates. When these are replaced by oxide ceramics, it is estimated that costs will be reduced from \$245.48 to \$43.10. One saving is immediately realized by the fact that neither the Stirling nor the diesel engine need catalytic converters or emission controls.

### The Advanced Gas Turbine engine

In the United States, Garrett Engines and Ford Motor Company, in cooperation with NASA, are working on developing a ceramic Advanced Turbine Engine, and General Motors Diesel Allison Division is working on its own model (see Figure 4).

The AGT is the most powerful engine of the three models. Aircraft engine rotors, and gas and furnace turbines, as well as turbochargers, already utilize ceramics. Clearly, advances in ceramic turbines will have immediate applications far beyond automotive and airplane engines, for example, in power generation.

The gas-turbine engine is an internal-combustion heat engine which utilizes turbomachines, rather than conventional pistons, for compression and expansion of fuel substances. Fuel is burned in a combustor located between the compressor and the expander. Compressed air from a turbocompressor enters one end of the combustor; fuel is sprayed into the other end. The fuel-air mixture ignites, creating hot gases which can be directed against the surfaces of a turboexpander, in order to turn it. The mechanical energy of the turboexpander can then be transferred to a rotating shaft by which useful work is performed.

The advantage of the gas turbine is the greater power to weight ratio which it has in comparison with other engines. It consumes a wide range of fuels, and with its simple rotational motion, runs without the problems of vibration and inertia inherent in reciprocating engines of the piston type. The efficiency of the gas turbine engine increases with increasing temperatures; however, because of its high fuel consumption, high cost of manufacture, and high noise level it has so far been restricted to use on aircraft, except in experimental designs.

The mechanical and thermal stresses of the gas turbine engine are much higher than for other engines, especially in the hot section. Besides the high stresses (25 kilopounds per square inch—ksi; and temperatures of 2,500°F), turbine components are exposed to high velocity oxidative or corrosive combustion gases. Over a period of engine operation, these factors can lead to time-dependent failure. The turbine must also meet challenges such as: high combustor inlet temperature; high centrifugal stress; thin wall structure for

the regenerator; good sealing to prevent leakage; temperature measurement for engine control. To achieve higher temperatures, the hot parts of the engine are being replaced by ceramics in the demonstration models AGT 100 and AGT 101 conducted under the DOE. These parts are the combustor, regenerator, flow transition lines, turbine stator, diffuser, turbine rotor, bolts, and compressor. The models are operated at inlet temperatures of 2,500°F and maximum stress of 44 ksi, and achieve 100,000 revolutions per minute.

It is for these reasons of very high thermal and mechanical stresses that the DOE considers the AGT as the test bed for structural ceramics. It is the most highly funded of the three demonstration programs.

GM's AGT 100 engine, is a lightweight, 100-horsepower two-shaft motor with a regenerative system that reuses exhaust gases with the aid of a rotary ceramic heat exchanger. The ceramics used were: sintered alpha silicon carbide for the fabrication of the turbine rotors, turbine vanes, combustors, scrolls, exhaust diffusers, and seals; reaction-bonded silicon carbide for the turbine rotors, scroll vanes, and flow-path walls; sintered silicon nitride for the turbine rotors, and aluminum silicate for the regenerator disks.

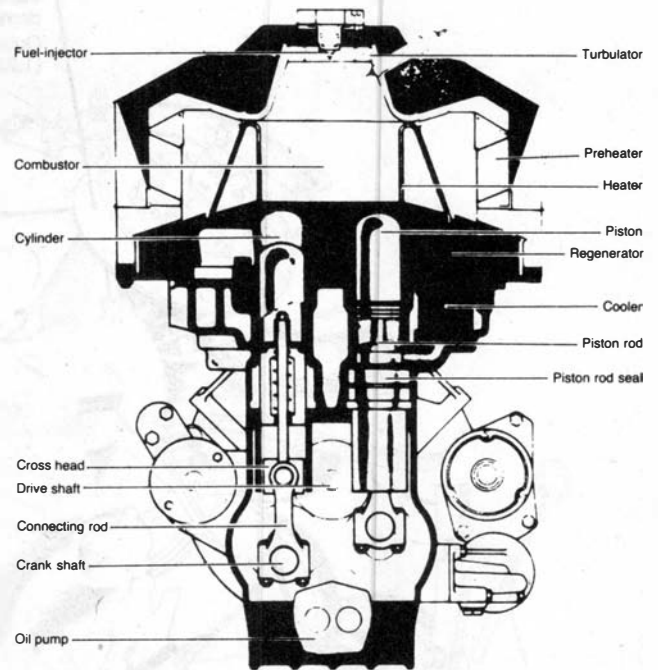
These ceramics held up to the 2,350°F turbine inlet temperature, while earlier, superalloy-metal gas turbine engines could only operate at 1,800°F. When the engine is incorporated into a 3,000-pound passenger car, these higher temperatures permit a 30% increase in fuel efficiency (42.5 miles per gallon) over standard spark-ignition engines and superalloy gas turbines. The specific fuel consumption was .326 lb/hp-hr (pounds per horsepower hour).

The AGT 101 program, carried out by the Garrett Corp. and the Ford Motor Co., has goals of successful engine operation at 100 horse power and a very low specific fuel consumption of 0.3 lb/hp-hr. The conceptual design completed in 1980 has the following characteristics: complete hot flow path designed for ceramics; single-shaft, single-stage design to minimize complexity and number of ceramic components; one-piece ceramic radial rotor attached at the coil end to a metal shaft; rotating components (ceramic rotor, metal compressor, and output gear) supported by an air-lubricated ball bearing; exhaust heat reclaimed by a rotary ceramic heat exchanger (regenerator) to preheat the compressed inlet air; symmetrically designed ceramic components designed to provide more uniform stress distribution and to ease component fabrication; inlet airflow surrounding and counterflow to combustion gas flow to cool engine casing and minimize heat loss. Like the AGT 100, the turbine inlet temperature was 2,500°F and with similar ceramic materials it has achieved, at this point in time, a similar fuel efficiency of .32 lb/hp-hr.

Unfortunately, road tests for the AGT 100 and AGT 101 have been eliminated from the current program due to DOE budget cuts.

Current and prior programs have demonstrated that it is possible to design with brittle materials and that ceramic

FIGURE 3



*The ceramic Stirling engine has potentially many applications besides the automobile.*

components can operate in the severe environment of a gas turbine, but these programs have not been able to demonstrate a degree of component reliability adequate for industry to commit to production. To achieve reliability and durability will require continued extensive effort in design, material property improvement, component fabrication, and quality control.

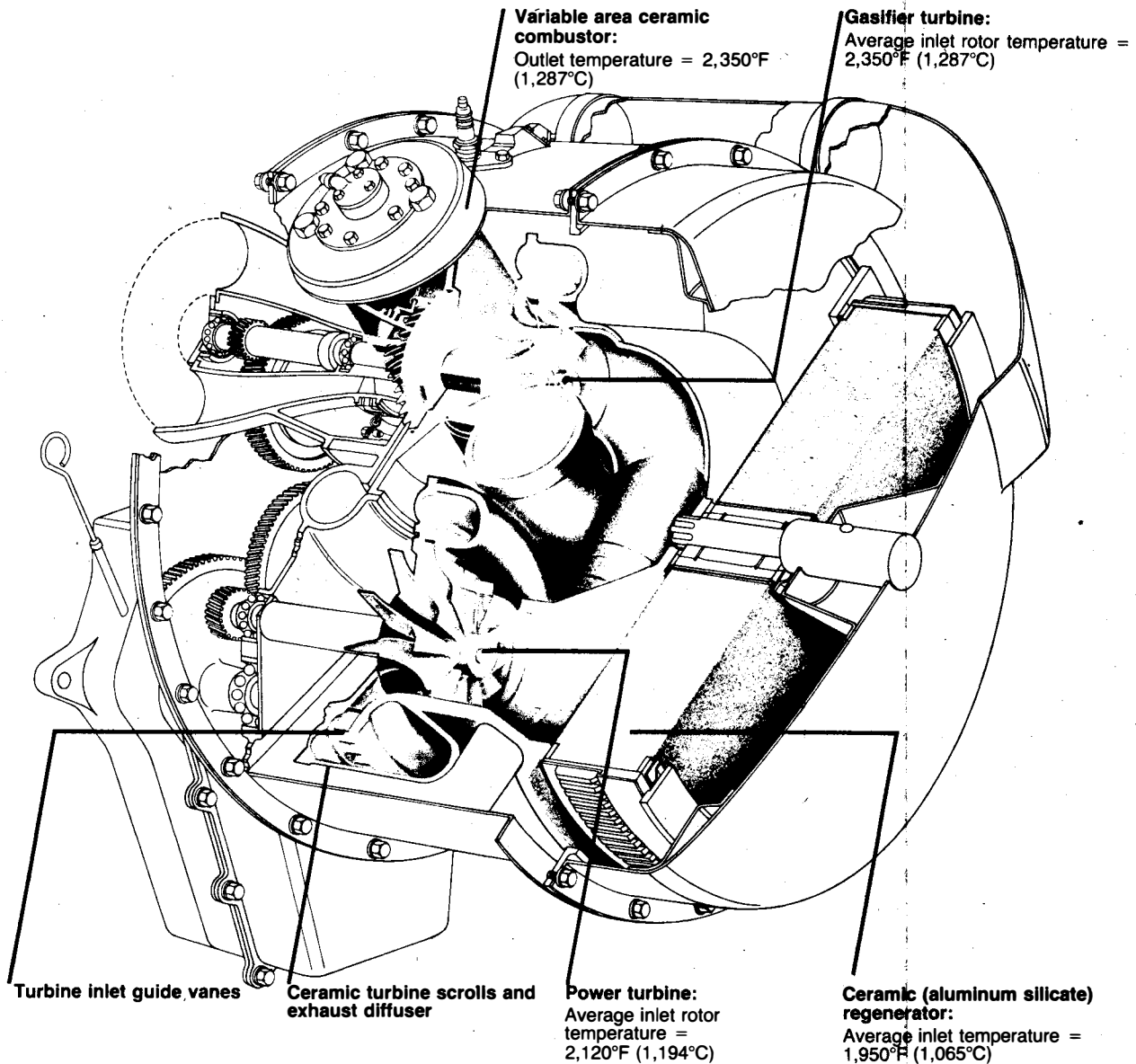
Looking at the overall significance of high technology ceramics, well perceived by the Japanese, the United States needs a more concerted effort in research and development of these new materials. Such an effort particularly in the initial phases, must inevitably be government-sponsored.

### The Japanese lead

Japan has the greatest national commitment to development of structural ceramics of any industrial nation. The majority of recent growth in the ceramic market and currently half of global production is located in Japan. In fact, Japan outnumbers the United States in the number of patents on ceramics by 10 to 1.

The Japanese already lead the world in the production of ceramic electronic components such as sensing devices now widely used in automobiles. Such parts as glow plugs, which give engines a quick-start capability, buzzers, fuel-level switches, and the mechanical seal for the water pump are also presently made of ceramics. What is now under devel-

FIGURE 4



*The ceramic Advanced Gas Turbine is the Department of Energy's major program. It has applications in aircraft and power generation as well as in automobiles. Of all the models, the AGT undergoes the most intense thermal and mechanical stresses.*

opment is the application of ceramics as structural substitutes for metals, in situations where they will undergo major thermal and mechanical stresses.

The Japanese Ministry of International Trade and Industry (MITI), with the aid of universities and industries, has developed a grand strategy for moving Japan into the "new ceramic" age.

There are two major programs, coordinated by MITI's Agency of Science and Technology, devoted to the development of an all-ceramic heat engine. The first, now concluded, was known as the Moonlight Project; the other, on-

going, is the Industrial Base Technology Development Project. Another Japanese ministry, the Ministry of Education, is also contributing by providing research funds for universities. In addition, Japan's Agency of Industrial Science and Technology initiated a five-year program to promote scientific and technological research in materials, with special emphasis upon ceramics.

The Moonlight Project was a large-scale, energy-conservation technology development project which began in 1978 and concluded in 1984. One of its five sub-projects was the development of a ceramic advanced gas turbine, with a spe-

cial look at sialon and fiber-reinforced ceramics, and manufacturing technologies for these.

The Industrial Base Technology Development Project, which includes research in ceramic materials, began in 1981 and will continue for 10 years. The materials covered in the research and development of "fine ceramics" (as they are designated in Japan to differentiate them from ordinary potteries) are silicon nitride, sialons, silicon carbides, boron nitride, several oxide ceramics, and zirconia. The requisites for the above materials are the capability to fabricate complex sintered parts of corrosion resistance, wear resistance, high strength, high dimensional accuracy, and material reliability. Japanese demonstrations:

Hitachi has already built a complete passenger car powered by a silicon carbide-insulated diesel and has run it through 50 hours of road tests. This material consists of SiC powder with special aluminum sintering additives and maintains its high strength under 1,600°C, 100 kg/mm<sup>2</sup>, which is twice as high as the conventional SiC.

- Kyocera has manufactured and marketed silicon nitride glow plugs for light-weight diesel engines in Japan. They have greatly reduced the "waiting time" for diesel engine start-up because of the materials capability for rapid temperature increase.

- Isuzu (Tokyo) is developing a turbocharged Adiabatic Engine with a reported 30% improvement in fuel economy. Production is set for 1990.

- NGK Spark Plug has succeeded in the trial manufacture of an all-ceramic "Dream Engine." All parts except the bearings and piston rings are made of ceramics. The crankshaft, which is most difficult to form, has been reduced to a monoblock ceramic construction. The crank case alone is made of alumina ceramics, and all other parts are made of silicon nitride. The engine has performed very well in its test running for 50 hours.

- The most recent and significant development is Nissan's production of a silicon-nitride turbocharger which has been incorporated into its 300 ZX sports car, considerably improving turbo performance. The advantage of the ceramic turbocharger rotors is the low density of the material used—sintered silicon nitride. The low energy decreases the turbocharger response time by lowering the inertia, through increasing the intake of air. In future cars, engines should simply be made stronger and more thermally efficient without the need for turbochargers.

Judging by the current level of U.S. investment, the Japanese will gain in their lead in advanced engineering ceramics. The U.S. Department of Commerce cited the following as probable reasons: domination of the electronic components business and the supply of advanced ceramic powders, a larger and more organized effort, initial performance-cost characteristics of demonstration products, a long-term commitment to market development, and an outstanding record in developing and implementing superior commercial manufacturing processes and process technologies. There are

about 2,000 engineers and 4,000 technicians actively engaged in advanced ceramics technology in Japan. Based on these figures, their annual expenditure is between \$300 and \$400 million. Using similar reasoning, the Department of Commerce estimates annual U.S. advanced ceramics research and development at about \$100 million.

The U.S. government must make long-term commitments to funding, which will, along with better protection of patents and proprietary rights, ensure the continued participation of industry. The Department of Commerce has called for a five-to-ten-year budgetary commitment by government, which would allow American industry, like the Japanese, to engage in long-range planning.

## Ceramics can revive the failing auto industry

Despite reductions in auto production, which are due to a shrinking economy, the programs for high-technology structural ceramics in heat engines are continuing in the United States. A breakthrough in ceramic heat engines will bring an economic revival to the industry.

According to *Ward's Automotive Reports* of April this year, General Motors Corp., saddled with a million-car oversupply in recent weeks, has cut its third-quarter vehicle production plans by more than 8%. Nummi Corp., the joint venture between GM and Toyota Motor Corp. in Fremont, California, trimmed its third-quarter projections by almost 60% from a year ago. American Motors Corp. plans to slash output by almost 36.5%, and Volkswagen of America is planning a 21% reduction.

This economic situation is not holding back the research projects that have already begun in the United States for structural ceramics and their application to heat engines.

The Advanced Gas Turbine (AGT) project will be completed this year. This is the government's main demonstration ceramic heat engine. It will be followed up next year with the Advanced Turbine Technology applications project, which will further test the durability of ceramics. The AGT, because of its high thermal and mechanical stresses, is considered by the Department of Energy to be a test bed of structural ceramic technologies. It is hoped, of course, that the success of the AGT in automobiles will make it applicable also to aircraft which presently use turbines made of strategic metals. The second demonstration model is the Adiabatic Diesel Engine, which will continue to be funded next year. The third is the Stirling engine, the MOD II, which will be completed in FY87.