An Assessment of the Performance and Requirements for "Adiabatic" Engines

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A review of research on low heat rejection engines, on cooperative efforts in the United States and abroad to incorporate ceramics in intermittent combustion engines, and on the use of ceramics in these engines is presented. The reduction of heat loss from the combustion chamber of diesel engines improves fuel efficiency only 3 or 4 percent. Some other gains may be possible from a smaller cooling system, recovery of exhaust energy, and improvements in aerodynamics. It is judged that designs of low heat rejection engines will have the greatest initial impact on armored combat vehicles. Organization, coordination, planning, and cooperation on R&D for the use of ceramics in intermittent combustion engines appear to be greater abroad than in the United States.

SINCE THE ADVENT OF THE INTERNAL COMBUSTION ENGINE, many evolutionary changes in design have taken place to improve its performance and reliability and at the same time to reduce its costs. In the past 20 years, the demand for acceptable air quality has accelerated design changes to improve emissions of intermittent combustion engines, both spark ignition and diesel, and reciprocating or rotating engines. The oil embargo of 1973 and the escalation of energy prices during the 1970s and early 1980s also stimulated developments to reduce the weight of automobiles and improve the fuel efficiency of all types of engines (*1*).

The U.S. engine industry, important for its economic impact and employment aspects, as well as a source of engines for the military, has been under increasing pressure from foreign competition. To remain economically competitive, U.S. R&D in engines must result in improved engine performance at competitive costs. Consequently, a strong advanced engine program in the private sector is important for economic and national security reasons.

One direction of R&D that has been emphasized since the early 1970s, both in the United States and abroad, has been to reduce heat loss from engines, particularly from the combustion chamber. Insulating the combustion chamber results in higher compression temperatures, which tends to produce unacceptable "knock" in the traditional spark-ignited, gasoline engine. Hence, this in-cylinder insulation approach (that is, insulation of the components that define the combustion chamber, such as the valves, the cylinder liner, the top of the piston, and the bottom of the head) is most suitable for diesel engines, reciprocating or rotary.

Reducing heat losses from the hot gases increases the exhaust gas temperature and therefore increases the potential for conversion of exhaust energy into work performed by the piston; to achieve these gains, appropriate additional hardware must be used. This recovered energy can be transferred to the drive train of a vehicle, which will enhance overall fuel economy.

Insulation of the cylinder wall causes higher cylinder wall temperatures, which leads to reduced oil viscosity and increased oil deterioration. As an example, although a formidable challenge, air lubrication might be used. The low viscosity of air would reduce engine friction and enhance fuel economy. The combination of insulated design, with other advanced engine developments has come to be referred to as an "adiabatic" engine (*2, 3*). However, this is a misnomer because the term adiabatic means no heat transfer to or from a system and should include only those gains resulting from zero heat transfer. Zero heat transfer (adiabatic) from the gas is the limiting case and is attainable only with a wall material having either zero conductivity or mass. Thus, the strategy of reducing heat rejection from the engine by suitable design will be referred to as a low heat rejection engine (LHRE).

Benefits claimed for LHREs include substantial improvements in fuel economy for both heavy-duty and light-duty applications, reduced heat rejection resulting in reduced cooling system volume, increased capability to burn a wide range of fuels, increased reliability and durability with reduced service and maintenance, reduced emissions, and increased system power density (*3*). These potential improvements make LHRE technology of interest for commercial applications, both for trucks and for automobiles, as well as to the military for use in tactical and combat vehicles.

In the United States, LHRE R&D has been funded by U.S. and foreign industries, by the U.S. Army through the U.S. Tank Automotive Command (TACOM), and by the U.S. Department of Energy (DOE). The initial predictions of gains to be achieved, which were often based on the broad definition of "adiabatic" engine, have not been well supported by recent experimental LHRE results. Consequently, in 1985, the National Research Council, through its Energy Engineering Board, formed the Committee on Adiabatic Diesel Technology to assess the state of the art and projected developments of this technology (*4*).

Design Approaches

The reduction of heat transfer from the engine working fluid to either the engine's cooling or lubricating systems can be accomplished in different ways. Techniques to reduce heat rejection have been introduced into commercial engines over the past 10 years. The use of stainless steel liners with air gaps or ceramic exhaust port

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liners, partial cylinder cooling, and insulated exhaust manifolds and turbine housings have all contributed to reduced heat rejection to the cooling system. Reduced heat rejection also results if components are operated at elevated temperatures by increasing the temperature of the coolant or eliminating it completely. However, this approach may decrease the durability of parts unless suitable materials are used. If the same heat transfer fluid is used, increased coolant temperatures also permit the use of smaller heat exchangers.

The above approaches may be viewed as modifications to a conventional liquid-cooled engine; other approaches include major new engine designs (Fig. 1 and Table 1). Engine 1 consists of a current production diesel engine with modifications to reduce heat rejection. Engine 2 (A, B, and C) incorporates a variety of high-temperature materials and advanced designs. There is minimum liquid cooling in selected parts of the engine. Three approaches to insulate the combustion chamber are possible.

Engine 2A. Use metallic superalloys together with air gaps. The advantage of metallic superalloys is that they are currently used in engines, can function in high temperatures, and have known reproducible characteristics suitable for engine design.

Engine 2B. Apply ceramic thermal barrier coatings on the valves or the piston crown.

Engine 2C. Use solid ceramic components for some parts of the production engine. For example, partially stabilized zirconia (PSZ) has been considered for interference fits into cast iron engine components.

Engine 3, fabricated from structural ceramic or composite components, represents the most advanced engine concept. Since water cooling is eliminated, these components must withstand all of the thermal and mechanical stresses of engine operation.

The Engine Environment, Materials, and Lubricants

Reducing the heat rejection from the combustion chamber results in higher in-cylinder temperatures than those existing in conventional engines; for a fully insulated engine, the time-averaged temperatures of the piston and cylinder walls can reach 1100°C, with the combustion gas temperature varying during each cycle from ambient to about 2400°C. The surface temperature of the combusion chamber follows these cyclic gas temperature variations but at a reduced average level and cyclic amplitude. Surface temperature variations can be as high as 30°C for metal surfaces and up to an order of magnitude higher with different wall materials. The conventional aluminum alloys and cast irons used in production engines lose much of their strength at these temperatures. Metallic alloys such as nickel and cobalt superalloys and molybdenum alloys retain their strength better at high temperatures and can be used under these temperature conditions, but they are expensive. An advantage of metallic alloys is that extensive experience and a design database exists for superalloys in engine applications.

Ceramics are also under consideration for LHRE applications (Fig. 2). In general, the thermal expansion coefficient of ceramics is lower than that of most metals, and their flexural strength is higher at high temperatures. Not all ceramics have low thermal conductivity for insulation purposes, but some do.

Engine 2B (Fig. 1 and Table 1) illustrates the use of plasma-sprayed zirconia, for example, on piston crowns and valves to provide insulation. The goal is to build a coating of sufficient thickness that will not crack and chip under the engine environment. Some success has been achieved with coatings of 1 mm or less, but a thickness on the order of 2 mm is sought. Other designs incorporate aluminum titanate ceramic inserts in a cast iron piston crown.

Table 1. Description of various types of LHREs (4). Abbreviations: CI, cast iron; max., maximum; min., minimum; syn., synthetic; temp., temperature; and UC, upper cylinder.

Features	Baseline	Engine 1	Engine 2			Engine 3	Engine 4 AIPS (14)	Engine 5 CCTDE (14)	Engine 6 ADRE (14)
			A	B	C				
Materials, cylinder/liner	CI	CI	CI-superalloy, air gap	Ceramic-coated CI	Ceramic insert in CI	Ceramic	Piston and head ceramic coatings; alloyed CI with wear coating	Superalloy, air gap	Ceramic air gap—insulated hot section
Head	CI	CI	CI-superalloy	Ceramic-coated CI	Ceramic insert in CI	Ceramic	Alloyed CI	Superalloy, air gap	
Pistons	Aluminum	Aluminum	Aluminum-superalloy, air gap	Ceramic-coated CI	Ceramic insert in CI	Ceramic	Aluminum rings with wear coating; superalloy		
Valves	Steel	Coated steel	Superalloy, air gap	Ceramic-coated steel	Ceramic-coated steel	Ceramic	Superalloy		
Cooling	Water	Water	Min. selective	Min. selective	Min. selective	None	Min. and selective lube; oil-cooled entire engine	Min. and selective lube; oil-cooled entire engine	No engine coolant
Lubrication	Oil	Syn. oil	Syn. oil and separate system for UC	Syn. oil and separate system for UC	Syn. oil and separate system for UC		Syn. oil	Syn. oil	Gas phase or solid lubrication
Max. temp.	230°C	315°C	482°C	482°C	482°C		427°C	650°C	
Sump temp.	104°C	120°C	149°C	149°C	149°C		149°C		
Exhaust energy recovery	No	No	Yes	Yes	Yes	Yes	No	Yes	?

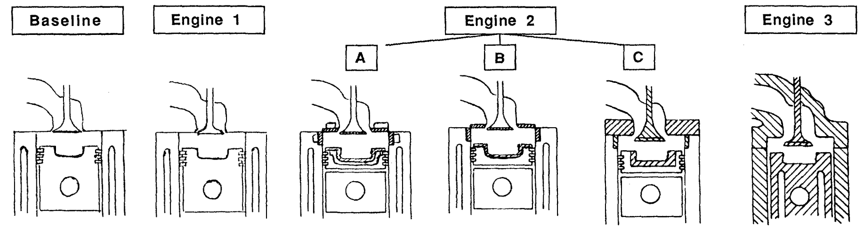

Fig. 1. Schematic of different design approaches to LHREs (all are assumed to be turbocharged and intercooled). The approaches include the following range of engines: baseline, current production; engine 1, current advanced technology; engine 2A, superalloys with air gaps; engine 2B, ceramic-coated cast iron; engine 2C, ceramic inserts; and engine 3, structural ceramics and composites. Details of these engines and of engines 4 to 6, advanced concept engines, are given in Table 1 (*4*).

Cylinder liners of zirconia, zirconia-capped pistons, zirconia cylinder headface plates (which insulate the top of the cylinder), and PSZ engine components in the valve train such as valves and valve guides are under investigation. Additionally, parts are being made from silicon carbide, silicon nitride, alumina, sialons (compounds containing silicon, aluminum, oxygen, and nitrogen), and modified lithium-aluminum-silicate compositions.

There are problems in the use of ceramics. Their brittleness is a serious problem for an engine application. Another difficulty is the need to manufacture uniformly consistent parts in mass production; presently, there is great variability in manufactured ceramic parts (*5*). There are no production cost data, and there is considerable disagreement and uncertainty about final production methods and costs. Finally, for metals, there is an extensive database as well as design experience, which do not exist for ceramics. Thus, new design approaches for ceramics will probably be needed.

Lubrication difficulties arise at the high temperatures of rubbing surfaces in an LHRE. Conventional lubricants will break down chemically, resulting in high deposit rates, which give unacceptable levels of friction and wear. Thus, significant development is required for an adequate lubricant, requiring new oils and oil additives that are compatible with ceramics.

A design approach that can ameliorate the need for high-temperature lubricants is to insulate only the upper part of the cylinder above ring travel, reducing the temperatures with which the piston rings and lubricating oil come in contact. Another approach is to lubricate the upper part of the cylinder with a separate high-temperature lubrication system. For advanced LHREs (engine 3 in Fig. 1 and Table 1), the cooling system might be eliminated entirely. Solid lubricants and gas lubrication have been considered for the piston and cylinder, but these methods are judged to be viable only in the long term, if at all.

Potential Benefits

Designs for LHREs are in an early stage of development with various theoretical and empirical results indicating expected levels of performance (*6*). In a conventional diesel engine, the conversion of fuel energy is approximately as follows: 40% is converted to mechanical power, 25% is rejected to the engine's cooling and lubricating fluids, and 35% appears as thermal energy in the exhaust. An LHRE design is expected to achieve on the order of a 40 or 50% reduction in the heat rejection. New designs incorporate the use of a single fluid to act as coolant as well as lubricant. However, lubricating oils generally have less favorable heat transfer characteristics than water. The 40 to 50% reduction in heat rejection and higher coolant temperatures can result in about a 50% total reduction in the volume requirements of the heat exchangers. For a military combat vehicle, this translates into a 10 to 11% volume decrease in total engine package size.

Oil-cooled engines, however, have problems. The useful life of lubricants could be reduced if exposed to elevated temperatures, and leakage from the oil system is of concern because of the flammability of oil and the high probability of an engine compartment fire. For an LHRE with a water-based cooling system, the size of the heat exchanger could be reduced but no parts could be directly eliminated. A design strategy to provide only local cooling in areas of high heat flux could be pursued.

The cooling system is relatively complex. In the Cummins Engine Company demonstration of an "Uncooled NT-250" engine, 361 components were eliminated from the installation when the conventional cooling system was removed (*7*). Thus, a simplification of the cooling system would be expected to result in reduced service and maintenance requirements.

The fuel economy benefits of LHREs vary depending on the design and application. Theoretical predictions of improvements in fuel economy vary from 1 to 17% depending on the reduction in heat rejection, whether the engine is turbocharged, and whether operation occurs at part load (part throttle) or full load (full throttle) (*2*, *3*, *8*, *9*) (Fig. 3). Comparable experimental results are limited with some results indicating fuel economy benefits and others showing decreased fuel economy from in-cylinder insulation alone. There are some indications that the fuel economy benefits are greater at part load than at full load. Weighing the admittedly incomplete analytical and experimental evidence, we conclude that in-cylinder insulation alone could improve full-load fuel economy 3 to 4%. Although detailed systematic studies are not available, part-load savings of up to 13% have been projected for small, high-swirl engines (*9*). These engines have high heat transfer rates, and their insulation has a proportionally greater effect than insulation in larger engines. However, analysis of the fuel economy benefits of an optimized LHRE over a specific operating test cycle have not been reported.

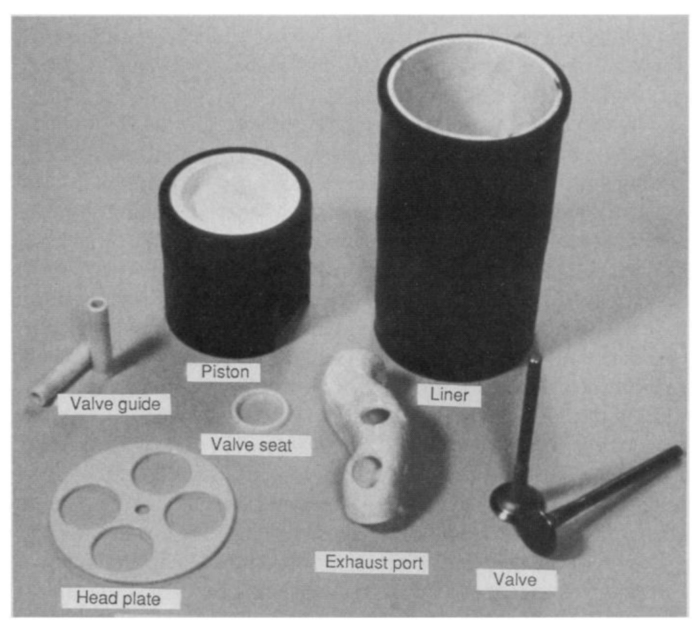

Fig. 2. Some ceramic parts for reciprocating engines. [Reprinted with permission of Cummins Engine Company]

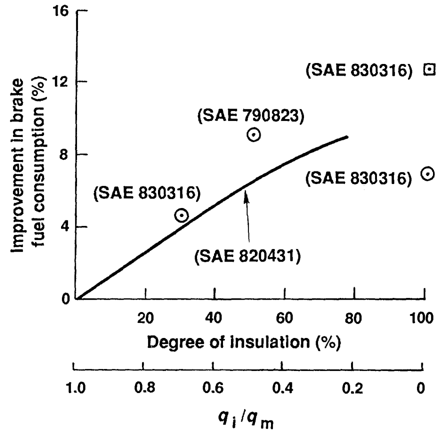

Fig. 3. Comparisons of various predicted gains (improvement in brake fuel consumption) of heat-insulated turbocharged engines showing rated power conditions (q_i/q_m is the ratio of heat rejection for the insulated engine to that for the metal engine) (*4*). Circles indicate isothermal condition for the walls of the combustion chamber; the square indicates an adiabatic condition. The curve indicates estimates for a range of different degrees of insulation. Society of Automotive Engineers (SAE) numbers with circles, square, and curve refer to reports in (*15*). [Reprinted from (*8*) with permission © 1984, Society of Automotive Engineers, Inc.]

Additional fuel economy benefits are possible in some cases because of reduced cooling power requirements. The magnitude of this gain depends on the engine application and would be greatest for armored vehicles, such as tanks, in which cooling power can represent 10 to 15% of the total fuel consumption. For most conventional truck designs (both commercial and military) the fan is declutched to reduce or eliminate the fan load when additional air flow is not required. With this design, the benefit of lower cooling power requirements from an LHRE design is greatly reduced.

The use of in-cylinder insulation results in a significant increase in exhaust gas temperature; the energy in the exhaust gases of a turbocharged LHRE is about 45% of the fuel energy compared to 35% for a conventional diesel engine. One approach to convert exhaust gas energy into useful work is turbocompounding, in which a second turbine in the exhaust system (there is a turbine with the turbocharger) provides additional power. For an engine operating on a heavy-duty cycle, such as a truck operating at high speeds over long periods of time, turbocompounding could provide additional fuel economy benefits comparable in magnitude to those resulting from in-cylinder insulation (*10*). For light-duty cycle applications (for example, vehicles such as a tank or automobile with mostly light-load operation), little, if any, additional gains could be realized; in fact, losses could accrue.

Energy in the exhaust stream can be converted to useful work for the vehicle with a "bottoming cycle," that is, a device using a working fluid heated by the exhaust gases. An experimental "add-on" bottoming cycle system that uses a synthetic working fluid has been demonstrated to improve fuel economy by 12% on a Mack truck (*11*). However, the widespread use of bottoming cycles as add-on systems is improbable for vehicles because of their volume, service and maintenance requirements, and cost. For stationary engines having a heavy-duty cycle, add-on bottoming cycles may be practical to produce additional work output.

The reduced LHRE package size in a vehicle may allow more aerodynamic shaping of the front end to reduce aerodynamic drag: this could result in significant improvements in vehicle fuel economy. For armored vehicles such as tanks, the smaller engine package size and increased system power density permit greater flexibility in the design of the vehicle and result in smaller and lighter vehicles, all of which give a tactical advantage. These factors could also result in some fuel economy savings, but the magnitude has not been quantified.

Fuel characteristics affecting diesel engine performance have deteriorated in recent years (*12*). A claimed advantage of the LHRE is a higher tolerance than the conventional diesel for lower cetane number fuels. (Cetane number is a measure of the time delay between the time when the fuel is injected and when it starts to burn.) For highly turbocharged engines operating at heavy load, ignition delays are short and cetane number is relatively unimportant. If the combustion chamber walls, cylinder liner, cylinder head, and piston crown are insulated with materials having a thermal conductivity lower than that of PSZ, significant increases of air temperature on the compression stroke can be achieved. This should result in reduced ignition delay of the fuel at light loads and may make it possible to use lower cetane fuels when operating at low ambient temperatures.

Data are inadequate to make a definitive judgment on emissions of oxides of nitrogen and particulates from LHREs since both increases and decreases of these pollutants have been reported. Further R&D is needed to optimize combustion chamber designs and better understand what emission levels will be produced.

The effect of LHRE designs on reliability, service, and maintenance is difficult to determine. Ceramic part reliability, as well as the extent to which cooling system service and maintenance can be reduced, are uncertain. Additional information and experience is required to determine the operation and service costs of LHREs, which are the greatest life-cycle costs. At this point, the data are insufficient to judge the market cost of production LHREs relative to that of conventional engines.

Insulation can also be used on parts of the engine other than those surrounding the combustion chamber. Exhaust port insulation such as aluminum titanate, which is being used by the Porsche Company, increases the temperature and energy of the exhaust gases. These increases can result in improvements in turbocharger transient response, in improved operation of catalytic converters for gasoline engines, and in a marked reduction of cooling system heat rejection.

Ceramics for Noninsulation Purposes

In their pursuit of ceramic parts development for LHREs, many companies are also considering the potential benefits of using ceramics in engines for other than insulation purposes (Figs. 2 and 4 and Table 2). These other uses of ceramics will probably precede their use for insulation; in fact, some ceramic automotive parts are already in production.

Ceramics have been used in spark plugs for a long time. Ceramic glow plugs for diesel engines, which provide much improved ease of starting, are now manufactured at a rate of tens of thousands per month. For example, the preheat time for Isuzu's ceramic glow plug is virtually zero compared to 30 seconds for a conventional metallic glow plug. Ceramics are also used as the substrate for the catalyst in catalytic converters. Emission requirements for diesel engines may demand the use of ceramics to withstand the high temperatures in particulate traps.

Some ceramics have lower densities than conventional metals. Components fabricated from silicon carbide and silicon nitride have densities about one half of those made from cast iron. Lower weight ceramic turbochargers, individually proof-tested, have already been put into commercial production for automobiles in Japan. Although costs are high, the faster response time and the image of a ceramic part have been strong selling points. Lower weight, and consequently lower inertia, would be attractive for all moving parts in an engine because of reduced forces and improved response times. At NGK–Spark Plug in Nagoya, Japan, a lighter weight ceramic valve in a test engine allowed reduced tension in the valve springs and lighter parts in the valve train. The reduced forces in the valve train mechanism resulted in lower frictional forces and improved fuel economy.

Most ceramic materials are harder than cast iron, steel, and aluminum. When used with the proper mating material, this hardness can result in lower wear for such components as valves, cam followers and lifters, rocker arm pads, and bearings. One example of the application of ceramic materials arising from their higher modulus of elasticity was the use of a silicon nitride piston pin at Daimler-Benz. The greater stiffness of the ceramic piston pin allowed a simpler design for the piston, with the potential for cost savings.

In addition to insulation, coatings can protect and permit continued use of low-cost metallic parts under adverse conditions. For example, ceramic coatings on metal parts can reduce chemical corrosion from low-quality fuels containing vanadium. One- and 2-mm zirconia coatings have been tested for this purpose in marine diesel engines. Furthermore, coatings can reduce the temperature of the underlying metallic part in high-temperature environments, thus allowing the continued use of cheaper materials.

In summary, there are several advantages to incorporating ceramic parts into engines, the total of which may substantially improve engine performance and durability. Many of these performance advantages are under investigation, and experience and knowledge are being gained concerning the design, fabrication, and testing of ceramic parts. However, at this point, ceramic parts are too unreliable and costly to consider as a substitute for metals except where their different properties give them a special advantage.

Cooperative R&D in the United States and Abroad

Research and development on intermittent combustion engines is important to maintain competitiveness in the production of cars and trucks. The fuel situation as well as air quality constraints place severe demands on engine technology to keep pace with a changing world. Although fuel prices are presently low, it is expected that petroleum prices will rise in the 1990s (*13*). Over the somewhat longer term, petroleum will diminish in availability (especially in the United States), and other energy sources will need to be used in the transportation sector. All of these factors demand continuing evolution and development in engines. The U.S. Army procures engines from domestic manufacturers who must be able to design, test, and fabricate these engines. Combat engines are designed to meet Army requirements and are not commercial derivatives. For reasons of national security, a domestic commercial engine sector that is capable of designing and producing both conventional and special military engines is essential.

There is an impressive effort abroad to coordinate public and private R&D on materials for advanced reciprocating engines and to conduct other advanced engine development. Although there is some excellent government-supported research in the United States, we judged both the planned coordination and rate of activity observed abroad to be greater. Several observations led to this impression. Engine companies in the United States obtain the majority of their ceramic parts from Japan; Kyocera alone has 60 engineers working on the application of ceramics to diesel engines; three LHRE vehicles are operating in Japan (one at Isuzu, two at Kyocera) compared to one in the United States. There is already limited commercial production of a ceramic turbocharger in Japan; commercial production of exhaust port liners is beginning in Europe; and much production experience with ceramics is being gained abroad with such diverse products as ceramic scissors, knives, and fishing rod line guides.

Our impression of increased organization, coordination, planning, and cooperation between companies with strong and interactive government assistance, particularly in Japan and the European Economic Community countries of West Germany, France, and the United Kingdom, is more difficult to quantify. In Japan, the Ministry of International Trade and Industry (MITI) has for a long time supplied development funds as have the Department of

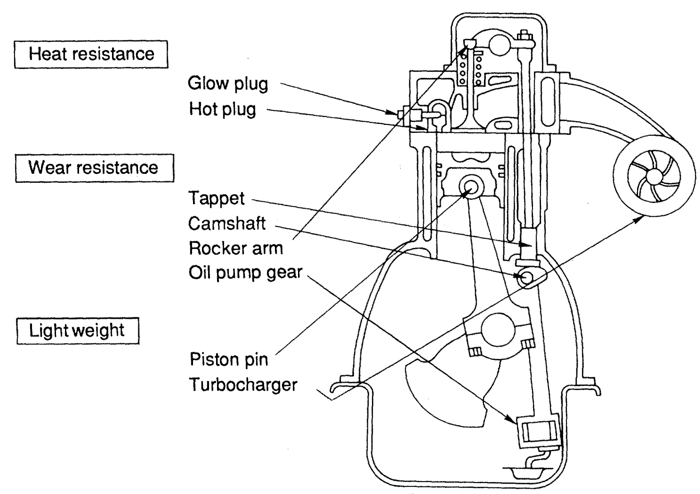

Fig. 4. Schematic examples of the use of ceramic components in reciprocating engines for their heat-resistant, wear-resistant, and lightweight attributes. Ceramics for insulation, as in an LHRE, are not included as examples.

Table 2. Examples of foreign firms and their investigation or production of ceramic parts (X) for reciprocating engines (*4*).

Organization	Bearings	Connecting rod	Exhaust port liner	Glow plugs	Piston pin	Piston protective coating	Prechamber	Rocker arm pads	Turbocharger rotor	Valves	Valve guides
Daimler-Benz			X		X	X			X		
Deutz			X								
Hoechst-Ceramtec			X						X		X
I.K. Technology						X					
Isuzu				X	X		X	X	X	X	X
Kyocera				X			X	X	X	X	
Mitsubishi				X				X			
NGK–Spark Plug		X						X	X	X	X
NTK							X	X	X	X	X
Peugeot							X	X			
Porsche			X								
Toshiba	X								X	X	
Toyota							X				

Defense and DOE in the United States. Also, MITI has required that most of the development money be supplied by the company being funded by it, which is a joint venture approach similar to that found in Europe. In addition, MITI and the recently formed Japan Fine Ceramics Center in Nagoya are coordinating work among automobile engine and parts manufacturers on ceramic components for engines. We formed the impression that in Japan there is thoughtful cooperative planning for long-term objectives, with the goal of retaining and increasing competitiveness in the field of reciprocating engines.

There is also a recent coordination of efforts in Europe that appears significant and growing. In the United Kingdom, two significant cooperative efforts are the Ceramic Applications in Reciprocating Engines and the Advanced Ceramics for Turbines projects. The European Research Coordination Agency (EUREKA) was established in Europe in 1985 and has several highly targeted programs under way in different countries for R&D on ceramic applications in advanced engine systems, including turbines. These more extensively coordinated foreign efforts will probably lead to more rapid developments abroad since a comparable rate of activity is not taking place in the United States.

Conclusions

The LHRE technology is at an early stage of development, which will proceed in an evolutionary manner. Although significant claims have been made for "adiabatic" engines, the use of in-cylinder insulation alone can result in only a 3 to 4% improvement in fuel economy at full load and possibly as much as 13% for small, high-swirl engines having high heat transfer rates. Additional savings may accrue from reduced cooling needs, although designs that reduce fan power when not needed reduce the LHRE advantage in this area. For engines operating on a heavy-duty cycle, turbocompounding can recover more of the exhaust energy, enhancing fuel efficiency by the same approximate amount as in-cylinder insulation. The size and reliability of bottoming cycles probably precludes their use in vehicles, although they may be suitable for stationary engines. Smaller or no radiators could allow better aerodynamic design of the front ends of commercial vehicles, with potential fuel economy benefits.

The LHRE designs will probably have the greatest initial impact on armored combat vehicles, since they have the most demanding requirements for cooling, power density, fuel economy, and fuel flexibility. For combat vehicles, installed load-cycle gains in fuel economy of 5 to 10% over conventional engines, as well as greater vehicle design flexibility and reduced cooling system maintenance, seem achievable for LHREs.

Because of the competition from abroad in reciprocating engines and the technology-forcing nature of such R&D, the U.S. Army and DOE should continue working with industry on LHREs and other advanced engine developments. The adverse economic and national security impacts of not having an internationally competitive U.S. advanced engine industrial base are obvious. A better understanding of how the U.S. government and private industry can best use their funds and enhance cooperative activity in advanced engine R&D is needed.

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14. The Advanced Integrated Propulsion System (AIPS) diesel engine, for the next generation of tanks, and the Compound Cycle Turbine Diesel Engine (CCTDE), for a military helicopter, are using highly alloyed cast iron or superalloys with air gaps. Lubricating oil is the cooling fluid. The CCTDE will use turbocompounding. The Adiabatic Diesel Reference Engine (ADRE) is a DOE-sponsored effort proposed for a 1995 technology demonstration for truck applications including ceramic air gap–insulated hot section (exhaust energy recovery may be used).
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