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ABSTRACT

The use of pulverized coal as a fuel for diesel engines can be a practical and efficient means of substituting coal for oil and gas in medium size applications such as railroad locomotives, ships and industrial stationary and co-generation power. These applications could result in reducing the oil and gas consumption of the U.S. by 2% to 10%, depending on the market penetration. The extensive German development of the use of pulverized coal in diesels during the period 1930 to 1944 demonstrated that coal-fueled diesels can be a practical heat engine. Although the German development used dry pulverized coal as a fuel, it now appears that beneficiated coal-water slurries will be a more practical and economical form of fuel. Operation on coal-water slurries is likely to pose some problems with ignition and particle agglomeration which require investigation. In this paper the background on coal-fueled diesel engines is reviewed and the potential applications and benefits are briefly presented. The technical problems in developing a coal-water slurry diesel are reviewed and possibilities for overcoming these problems are presented and discussed. A coal-fueled diesel research and development program is recommended.

IT IS GENERALLY ACKNOWLEDGED that Rudolf Diesel conceived of the compression ignition (CI) cycle as a method for combustion of both solid and liquid fuels in reciprocating internal combustion engines. His patent, issued in 1892, covered the principles of one of the most important technological devices of our industrialized society. From the time of his invention, diesel engine applications have slowly advanced to the point where they have become the dominant and almost sole heat engine for all heavy duty applications where high fuel efficiency, reliability, and long life have high priority.

The size range of diesel engines is truly impressive, ranging from 4 kW single cylinder engines, high speed automotive engines (30 - 80 kW), heavy duty truck engines (120 - 400 kW), locomotive and smaller marine engines (800 - 2500 kW), medium speed marine and stationary engines (4000 - 12,000 kW), to slow speed marine and stationary engines (15,000 - 30,000 kW). This is a range of almost four orders of magnitude in power with overall thermal efficiency ranging from about 33% to 48%. Only in consumer items such as automobiles, motorcycles and hand-held tools, in airplanes, and in large electric utility generating stations do spark ignition, gas turbine and steam turbine heat engines command the market.

Significant advances in diesel engine technology are presently underway. They are based on the use of improved materials, largely ceramics, and improved combustion and mechanical design. The performance improvements sought are higher efficiency, lower pollutant emissions, wider range of acceptable fuels, and increased service life. The use of high temperature, heat insulating ceramic materials in the combustion chamber (the adiabatic diesel engine concept) has been shown to result in higher efficiency, along with the promise of lower pollutant emissions and wider fuel tolerance (1). The use of hard, corrosion resistant ceramic coatings will result in longer life, especially when lower grade fuels are employed (2). There is some promise that self-lubricating, low friction materials can be developed that will reduce the friction power loss in an engine and permit operation at high temperatures without the use of an oil lubricant (3).

The on-going diesel engine development activities indicate a fairly aggressive, self-sufficient industry with ample unexplored technical possibilities for significant improvements in engine performance. These improvements are largely evolutionary and are able to proceed in small steps in response to market demands. The development of coal-fueled diesels, the subject of this paper, is made easier by these on-going evolutionary developments. However, the use of coal will require some major changes in design. This in turn will require a significantly improved understanding of a number of combustion and wear related phenomena. Major changes entail higher risk and a less evolutionary pattern of development. In such a situation government support can be very beneficial in developing the technological base and demonstrating the economic and technical feasibility. The Department of Energy has begun a modest program in this area (4). The purpose of this paper is to show, on the basis of what is presently known, that there is both a strong economic incentive for a coal-fueled diesel engine industry, and good technical prospects for the development of reliable, efficient and cost-effective coal-fueled diesel engines.

SUMMARY OF PREVIOUS WORK

After some unsatisfactory experiments, Rudolf Diesel abandoned the use of coal as a fuel and concentrated his work on petroleum liquid fuels. Serious work on coal-fueled diesel engines was renewed in 1911 by Rudolf Pawlikowski, a former co-worker of Diesel. Many technological problems were encountered, leading to a number of ingenious ideas and patents (5). In 1928 Pawlikowski announced that the major hurdles had been overcome and that his four-stroke, medium speed engine design was ready for commercial development and application. One of Pawlikowski's earliest one cylinder engines, with 60 kW and operating at 160 rpm, allegedly operated successfully for over 11,000 hours.

In the interval from 1928 to 1944, four German firms took up the development of the coal-fueled diesel, initially by taking options on Pawlikowski's patents and in two cases by beginning with one of his engines. These four firms (and also Pawlikowski's firm) reported the successful construction and operation of 19 engines spanning the horsepower range from 10 to 600 and engine speed from 160 rpm to 1600 rpm. The engineers at these firms contributed many technological advances and it appeared that satisfactory solutions had been found for both wear problems and fuel injection and combustion problems. However, none of these engines were commercially produced and there was considerable controversy over their technical performance and economic viability. At best, it appears that pulverized coal-fueled diesel engines were cantankerous machines.

J. Jehlicka, the leader of the engine development at I. Bruenner MFG, was recently interviewed by the author (6). Jehlicka stated that the high speed (1000 rpm) coal-fueled diesel engine they developed had undergone extensive testing and had demonstrated satisfactory performance. Mass production was about to begin in 1944 when the facilities were destroyed. He displayed evidence, which appeared convincing, to support his claims.

Following World War II, ample supplies of low cost oil removed the economic incentive for the development of coal-fueled diesels. As a result, there was no serious further development either in Germany or elsewhere in the world. It is of interest to note the magnitude of the German development effort. Each of the four major companies apparently had a team of up to 50 engineers and technicians involved for a period ranging from 7 to 13 years. My estimate is that about 2000 man-years of research and development were carried out. By comparison, the work carried out in the U.S., primarily since 1970, probably represents not more than 15 man-years.

In the post-World War II years, some exploratory work on coal-fueled diesels, mostly with coal-oil slurries, was carried out in the United States. These efforts almost solely consisted of the operation of existing, small displacement, high speed engines with minimal modifications to the injection, combustion and wearing surface components. These tests resulted in generally unsatisfactory performance and show that it is necessary to make major design changes in order to burn coal satisfactorily in a diesel engine.

Some recent tests have been carried out in Europe on a slow speed research engine at Sulzer Bros (7). Satisfactory combustion of coal-oil slurries was achieved, although there were serious injection and cylinder wear problems. A brief test with a coal-water slurry was also reported (8) with encouraging results.

An abbreviated summary of previous work on coal-fueled diesel engines is given in Table I. Caton (9) has also presented an overview and discussion of the previous work and the future propects for coal-fueled diesel engines.

A CONCEPTUAL COAL-FUELED DIESEL

A brief description of a conceptual coal-water slurry fueled diesel engine design is given, primarily as a means to illustrate the possible applications of such an engine, the technical problems and possible solutions, the areas where innovative development and a better understanding of the basic phenomena are needed, and the economic forces which would make such an engine a commercial success. The basic size and design is intended for railroad application, which assures a substantial market in the U.S. Figure 1 shows a schematic of the power head design, and Table 2 gives the basic specifications for the engine and fuel. It would operate on coal-water slurry, a fuel that should cost a fraction of that for oil and could be transported and stored as a liquid (with proper additives). The combustion chamber would use heat-insulating ceramics in order to operate at a high temperature to aid in combustion, maximize efficiency and minimize deposits. It

Table 1
Summary of Previous Work on Coal-Fueled Diesel Engines

Date	Investigator	Fuel	Speed (rpm)	Power (kW)	Cylinders	Injection	Comments
A. Early German Development							
1911 to 1940	Kosmos Co. (Pawlikowski)	coal dust	160	60	1	air assist and self-injection	Allegedly operated for 11,000 hours. 7 other engines also tested, with speeds from 400 rpm to 16000 rpm.
1925 to 1929	I-G Farben Industrie	coal dust	215	330	4	air assist	Probably terminated for economical reasons. 2 to 3 other engines built and tested.
1930 to 1939	Schichau Werke	coal dust	375	450	6	self-injection	Demonstration engine, but never installed. At least one other development engine built and tested.
1930 to 1945	I. Bruenner MFG	coal dust	250 1000	220 ∿80	3	self-injection self-injection	Six engines built and demonstrated. Successful small high speed engines.
1935 to 1945	HANOMAG	coal dust	220	75	1	air assist	Second engine built but never operated.
B. U.S. Sponsored Work							
1949	North Carolina	coal-oil <50μ	1200	15	4	20% coal	excessive wear
1957	Southwest Research	coal-oil <20μ	1000	15	1	30% coal	excessive wear
1959	Virginia Polytechnic	coal dust <450μ	1800	8	1	fumigated oil pilot	poor combustion excessive wear
1969	Howard University	coal dust <75μ	1000	6	1	fumigated oil pilot	unsuccessful operation excessive wear
1977	Virginia Polytechnic	SRC I-oil 2μ	1800	8	1	15% SRC I	sticking fuel injection excessive wear
1979	Southwest Research	coal-oil <10μ	1800	40	1	micronized 20% coal	injection pump failure excessive wear
1979	Sulzer Bros.	coal-oil <10μ	120	1500	1	31% coal micronized	accumulator injection some wear problem combustion satisfactory
to 1980		water-oil <10μ	120	1500	1	34% coal micronized	combustion satisfactory with pilot fuel injection

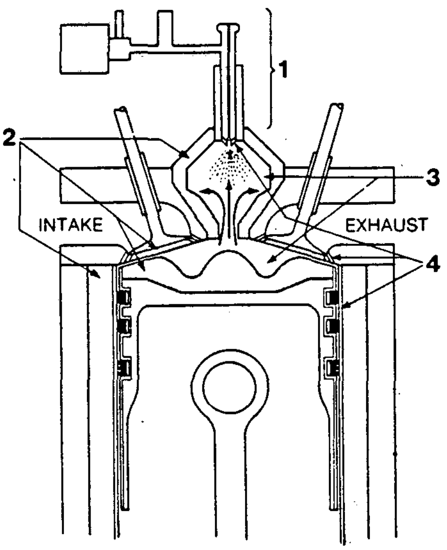

Figure 1. Coal-Water Slurry Diesel Engine Conceptual Uncooled Powerhead Designs. 1) Superheated, pressurized injection system. 2) High temperature ceramic insulation for combustion chamber. 3) High turbulence, low swirl pre-combustion and combustion chambers. 4) Hard ceramic coatings and inserts for control of wear and erosion.

would use a superheated injection system and high turbulence pre-chamber design to obtain satisfactory ignition and combustion. It would use hard ceramics and ceramic coatings to reduce wear and abrasion resulting from the coal ash. Finally, in some applications it may need an effective exhaust clean-up system to minimize the pollutant emissions.

COAL-WATER SLURRY FUEL - This is the most promising form of coal fuel as it should be inexpensive, safe to handle, and able to use a large part of the existing infrastructure for transportation and storage. Figure 2 shows schematically the stages of the projected coal-water slurry use cycle. First it is mined, then pulverized and cleaned in a coal preparation plant, then shipped to end-use site by pipeline, rail and barge, and finally used for rail and marine transportation and for co-generation of heat and electricity for industrial use.

The specifications of a satisfactory coal-water slurry are yet to be determined, but reasonable estimate would be a particle size in the range of 10-20 microns, 60% coal by weight, and cleaned (beneficiated) to substantially reduce the fraction of foreign, abrasive and polluting materials present in the original coal. Additives would be necessary to reduce the viscosity and permit higher coal content, and to stabilize the coal solids and prevent rapid settling. Table 2 gives the author's estimates based on available information on coal particle burning rates and the costs of pulverizing and cleaning coal (10), balanced against the severity of the combustion and wear problems.

Table 2 - Engine and Fuel Specifications for Conceptual Coal-Water Slurry Diesel Engine

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Engine Specifications

Four stroke, turbocharged
Bore : 25 cm
Stroke: 28 cm
Speed : 1000 rpm
Power : 200 kW/cylinder

Fuel Specifications

Stabilized coal-water slurry
Coal particle mean size: 10 to 20 microns
50%-60% coal by weight
Beneficiated to ~3% foreign matter
High volatile, high reactivity coal

There is presently intensive development of coal-water slurries, primarily for use as a boiler fuel for conversion of oil fired boilers to coal, which will establish much of the technology and economic factors (10). These developments are leading towards a coal refining industry which will deliver coal slurries meeting various specifications of beneficiation, particle size and fluid properties. The exhaust pollutant problems normally associated with the

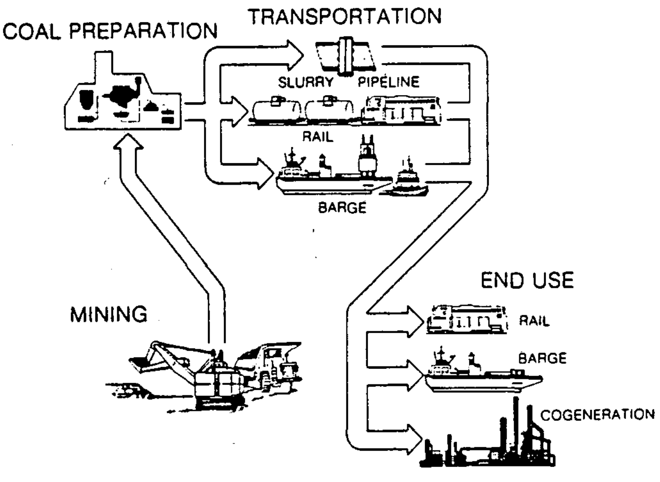

Figure 2. Projected Coal-Water Slurry Use Cycle for Diesel Engines

burning of coal may be largely overcome in a cost-effective manner through the refinement of the coal. This holds great promise for diesel engine applications, which may thereby eliminate the need for expensive and difficult-to-maintain exhaust traps and scrubbers, as well as provide an inexpensive fuel that is acceptable for diesel engine use.

SUPERHEATED FUEL INJECTION SYSTEM - Fine atomization of the coal-water slurry spray is likely to be very important to successful operation of the engine. Besides aiding in ignition and in mixing the fuel and air, it will minimize the agglomeration of the coal particles into larger sizes which will be slow in burning and will form large particles of slag and ash. Superheated fuel injection, which has had considerable investigation for liquid fuels (11), is a very promising technique for coal-slurry fuel atomization and should have several beneficial effects.

The time required for ignition and combustion of a coal-water slurry spray is likely to be critical for engine speeds in the range of 1000 rpm. The water must be evaporated from the droplets, then the coal particles heated sufficiently to drive off and ignite the volatiles, finally, the remaining char must be burned. All of this must be accomplished in less than 10 msec (based on 60° of crankshaft rotation). Further, as the droplets of slurry are heated and the water evaporates, the coal particles may agglomerate, forming large particles that will require a longer time to burn. The ash in these large particles is likely to fuse into larger slag particles. While small ash particles in the range of 10 microns may not be expected to cause severe wear and erosion of the piston rings and cylinder walls, large particles in the range of 100 microns and up would be expected to cause significant gouging and removal of material, even with hard ceramic coatings on the wearing surfaces.

Preheating the coal-water slurry at high pressure to a temperature which is above the boiling point of water in the combustion chamber will cause "flashing", or very rapid boiling, of the water when it is injected into the combustion chamber. The boiling will occur at surface-liquid boundaries and, depending on the various competing rates, may also occur within the water volume. This flash boiling will take place very rapidly during the injection process, beginning as soon as the slurry has left the injection nozzle and the pressure has lowered to that in the combustion chamber. Under proper conditions it should take place with an explosive effect, driving the water off the coal particles and also separating the coal particles and driving them apart sufficiently to prevent agglomeration. Further, the heat in the coal particles will aid in evaporation of the water remaining within the pores of the coal and the subsequent heating to ignition temperatures by the hot air in the combustion chamber.

Table 3 - Superheated Coal-Water Slurry Injection Conditions

Critical point for water:	$T_{crit} = 374^{o}C$ $P_{crit} = 218$ atm
Injector accumulator conditions	$T_{acc} = 360^{o}C$ $P_{acc} = 240$ atm
Cylinder conditions	$P_{cyl} = 38$ atm $T_{sat} = 248^{o}C$
Percentage water which will flash to vapor	36%
Percentage water evaporated from heat in coal	7%

The elements of a superheated injection system are shown in Fig. 1. A high pressure (240 atm) coal-water slurry supply chamber maintains the injector accumulator at this pressure, while an injector oven raises the temperature to about 350°C prior to the injector nozzle. For fuel injection, the injector valve is opened and the superheated slurry is sprayed into the combustion region. As indicated in Table 3, the water will be in a superheated condition in the combustion chamber and approximately 36% will "flash". In addition, there will be enough heat in the coal particles to boil an additional 7% of the water. These effects will significantly accelerate the heating of the coal to ignition.

The effect of superheated boiling on liquid fuel sprays has been investigated both experimentally and analytically (for example, see ref. 11). These results support the general behavior predicted above and form the basis for detailed investigation of superheated coal-water slurry sprays.

TURBULENCE AND COMBUSTION RATE - The power-head design of Fig. 1 incorporates a high turbulence pre-combustion chamber combined with high turbulent mixing in the main cylinder. The design shown is a fairly standard configuration used in some older diesel engines (12) for obtaining short ignition delay and rapid combustion rate. A high swirl type design was specifically avoided in order to minimize the deposition of coal particles and ash on the walls.

A pre-combustion chamber design is known to have a lower efficiency than modern direct injection engine designs, due to the higher turbulent heat transfer to the combustion chamber walls and to pressure losses in the turbulence generating passages. The heat losses can be minimized by operating the combustion chamber walls at a high temperature. They would be constructed using a heat insulating ceramic material, such as the partially stabilized zirconia used in the Cummins adiabatic diesel engine design (1). These hot surfaces will also have other beneficial effects; they will result in a higher charge air temperature which will aid in the fuel ignition, they will aid in the oxidation of coal and char particles which strike the surface, and they may aid in reducing the ash deposits by driving particles away from the surface through the thermophoretic force (13).

There are two lines of evidence that the combustion rate of the coal will be sufficient to permit operation of a diesel engine at speeds in excess of 1000 rpm. The first is from the early German work and the second is from a recent computational study. In the early work the highest development seems to have been reached by I. Bruenner MFG, which reported successful operation of engines at speeds up to 1200 rpm. Although almost no data has been made public, Jehlicka, the leader of this project, stated that these engines ran satisfactorily with good efficiency (5,6). These engines were operated on pulverized coal which had been compacted into solid rods, subsequently re-pulverized by a simple device attached to the engine. Jehlicka did not state the coal size, but from the context of the conversation it appeared that the particles were not larger than 50 microns, and that the coal (a German lignite) had been beneficiated by a flotation technique. This engine used a high turbulence pre-combustion chamber, equipped with a glow plug. It appears convincing that sufficiently rapid ignition and combustion of coal dust was achieved to permit satisfactory operation of an engine at 1000 rpm. The size of the coal dust probably did not exceed 50 microns, and for reasons of the available technology at that time, was likely not less than 20 microns. Besides the work of I. Bruenner MFG on higher speed engines, Hanomag also designed a 750 rpm engine, which was not completed, and Pawlikowski reported a 1600 rpm engine for which there are no details available. My interpretation of this information is that it is technically feasible to obtain satisfactory ignition and combustion in a coal-fueled diesel engine at speeds up to 1000 rpm, using coal particles in the size range of 20 to 50 microns.

In addition to the inferred test results of the German development effort, Caton and Rosegay (14) have recently reported in a computational study that 20 micron particles will be totally burned at engine speeds less than 1500 rpm. They carried out a coal-char particle numerical combustion simulation in a diesel engine for a variety of conditions, based on the use of experimental laboratory burning rate data. Their calculations assumed a base case of 20 micron particles and 1500 rpm engine speed, and considered only the char burnout time. The problems associated with devolatilization and ignition, and with coal-water slurries, were not addressed. Their results, however, are quite informative and testify to the value of engineering modelling in assessing the combustion conditions for a coal-fueled engine. Based on their results, coal particles in the range of 20 to 30 microns would be expected to burn completely in a 1000 rpm engine, without the assistance of high levels of turbulence or other methods to accelerate the combustion rate.

WEAR PROTECTION - The conceptual engine design shown in Fig. 1 relies primarily on hard ceramic coatings for wear protection from the coal slag and ash. Compatible materials for the cylinder wall, ring and piston wearing surfaces would be used. The ring design, piston clearances and other engineering details can strongly affect the wear rate through the degree of trapping of the coal ash. Different types of ceramic coatings, or ceramic inserts, are probably more suited for the wearing surfaces of the intake and exhaust valves and the injector nozzle and valves. The temperature of the exhaust valve and all surfaces must be kept below the ash fusion temperature in order to prevent rapid buildup of slag deposits.

As mentioned previously, the size of the slag particles left after combustion of the coal will be minimized by preventing agglomeration of the coal particles through fine atomization of the injected coal slurry. This will be accomplished by a combination of superheated slurry, high injection pressure and high air turbulence. To the extent that the particles are smaller than the lubricant film thickness, they will not contribute to the wear.

The lubricant will be quite important, with special additives required to minimize sludge deposits and other unwanted effects. Cleansing of the cylinder walls has been used in previous work. The oil must be kept clean by proper filtration, and it is especially important to prevent abrasive materials from getting into the engine bearings through the oil system. A crosshead engine design, as used in slow-speed engines, would isolate the cylinder area from the bearings in the crankcase and would also eliminate side pressure of the piston on the cylinder walls. The additional engine size and weight associated with a crosshead design may be preferred to control the oil contamination, piston wear and friction.

Another factor in reducing cylinder wear is to minimize the deposit of particles on the cylinder walls by controlling the fluid mechanics during the combustion and exhaust cycles. For that reason swirl-type turbulence was avoided in the conceptual design shown. Detailed analysis of the fluid mechanics should lead to considerable improvement in this area.

Operation with high temperature cylinder walls may have an additional beneficial effect. The thermophoretic force (13) is a molecular force acting on small particles in a gas with a temperature gradient, and is directed towards decreasing temperatures. It is most widely known for its influence in depositing soot on cold surfaces, such as in wick-type kerosene lanterns. When the gas temperature is lower than the cylinder wall temperature, as occurs later in the expansion stroke, this effect should reduce the number of particles striking the surface.

Much of the German work was directed at reducing the wear of the injectors, valves and cylinders. Great progress was made, and cylinder wear rates approaching that for oil diesel engines at that time were reported. The principal factors were the use of special hardened materials, and fluid mechanical designs which minimized the deposition of coal particles on critical surfaces. In particular, Jehlicka showed the author (6) a graph from a report (originally intended for publication) giving the wear rates of piston rings for various materials and designs. The best of these curves indicated satisfactory operation for more than 1000 hours.

In summary, the present knowledge of ceramic materials and of wear phenomena should be adequate to develop coatings for the cylinder-piston interface, the valves and the injector components which will give acceptable life. The engine will require good fluid mechanical design to minimize particle deposits on the walls and in other critical locations. These developments will probably proceed rather slowly and in an evolutionary manner, indicating that early prototype coal fueled diesel engines are likely to require considerably more maintenance than oil-fueled diesels.

APPLICATIONS AND ECONOMICS

Development work on coal-fueled diesel engines needs to be justified by the projected existence of a sizeable U.S. market for these engines. In order to compete in this market, the coal-fueled engines must show promise of satisfying a number of economically related factors. They must result in a significant reduction in fuel costs, compared to present and future alternative power sources. In addition, they must result in a reduction in total operating costs, including capital investment, fuel, and maintenance. They must meet the needs of the industry concerned insofar as reliability, personnel requirements, part load operation, fuel availability and capital investment are concerned. It is also important that they substitute the use of coal for oil more efficiently than other alternatives. A proper study of these issues would be valuable in defining the overall benefits associated with projected coal-fueled diesel engine applications. In this section some of the more important points are briefly discussed in order to show that, on cursory examination, it appears that these engines are clearly capable of filling a significant role in U.S. power requirements.

The U.S. energy consumption as a function of fuel source is shown in Fig. 3 (1977 data, ref. 15). On this scale, a 1% reduction in oil and gas in favor of coal is significant economically and justifies the expenditure of substantial research and development effort. For instance, 1% of the total U.S. energy requirement is about 130 MBY (million barrels of oil equivalent per year) which, at an oil price of \$25 per barrel, costs \$3.2 billion dollars per year. If a coal-fueled diesel was technically and economically feasible and had an applications niche which could account for 1% or more of the U.S. energy consumption, then an aggressive federally financed research and development program would be highly justified. By comparison, nuclear power has received a great amount of governmental research and development aid (presently at least 200 million dollars per year), yet as of 1977 provided only 4% of our power requirements.

Three major market areas where coal-fueled diesels could be used are readily identified. These are 1) railroad and domestic marine transport, 2) industrial co-generation, and 3) international marine transport. The projected oil and gas displaced for each of these markets is given in Table 4 (1977 data, ref. 15). Conversion of the railroads alone to coal use would amount to 1% of the U.S. energy requirement and 2% of the oil requirement. Co-generation of electricity with industrial use of the process heat represents a large possible market. High seas marine trade is an international market; the oil figure in Table 4 is for fuel purchased in the U.S. only. Worldwide conversion to coal would be in the distant future and is more relevant to the worldwide rather than the U.S. oil consumption.

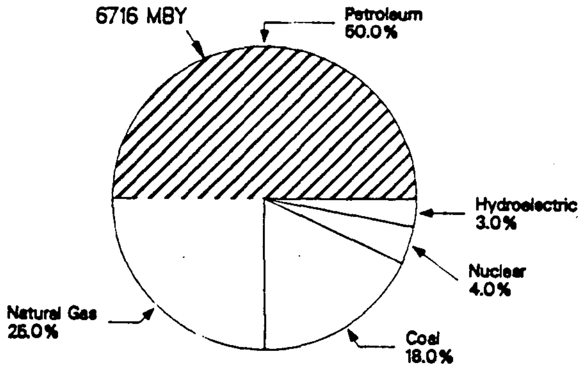

Figure 3. U. S. Energy Consumption, 1977 Data MBY (million barrels of oil equivalent per year) = 6.1×10^{15} J/year

Table 4 - Substitution of Coal for Oil and Gas

Sector	Oil and Gas Replaced* 10^{18} J/year
Railroad and Domestic Marine Transport	0.98
International Marine Transport, Purchased Domestically	0.49
Industrial Co-generation (36% of Estimated Maximum)	4.3
Total U.S. Oil	41
Total U.S. Gas	20
Total U.S. Other	21

*10^{16} J/year = 1.6 MBY (million barrels of oil equivalent per year)

Table 5 - Relative 1982 Cost of Fuels

Fuel	Cost Dollars/10^9 Joule
No. 2 fuel oil	\$10.00
No. 6 fuel oil	7.60
Stabilized, beneficiated coal-water slurry	4.00
Coal, Bituminous, average	1.70

Table 6 - Comparison of the Efficiency of Energy Conversion for Diesel, Gas Turbine and Steam Turbine Heat Engine

Engine Type	Size Range (10^3 kW)	Efficiency (%) Oil	Coal Slurry
Diesel	1-30	38-45	30-40
Gas Turbine	1-100	25-35	20-30
Steam Turbine	1-1000	12-45	10-35

The cost for various fuels strongly favors the use of coal as is shown in Table 5. These prices are taken from ref. 16 except for the coal-water slurry. Based on various papers given at the 5th coal slurry symposium (10), along with the accompanying discussions, the fuel specifications given in Table 2 are relatively easy to obtain and should not require expensive processing. The value given is the author's best judgement; a better value would require more detailed fuel specifications, selection of beneficiation and attrition processes, and detailed analysis of the cost for scaled-up operations.

There are three practical alternative heat engines to be considered for these three market areas; diesel, gas turbine and steam. All three operate using oil and can, in principle, be converted to coal. Table 6 roughly indicates the size ranges and overall thermal efficiencies for these heat engines. A conservative de-rating is used to estimate the performance on coal-water slurry, resulting in the lower thermal and mechanical stresses necessary to obtain satisfactory service life. In the smaller size range of 10^3 to 10^4 kW the diesel cycle efficiency is sufficiently superior that it is the clear leader. This is currently true in present applications using oil, and thus it is reasonable that a coal-fueled diesel, if technically satisfactory, will be preferred to either gas or steam turbines. Since this smaller size range encompasses railroad and marine transportation as well as most of the potential co-generation applications, the coal-fueled diesel has well defined market areas in which it is economically the superior choice and which constitute a significant amount of the nation's oil and gas requirements. Based on projected relative costs for coal-water slurries, these applications would both significantly reduce the cost of fuel used as well as displace imported oil.

RAILROAD AND MARINE APPLICATIONS - The conceptual design of the coal-water slurry fueled diesel engine outlined in Table 2 and Fig. 1 is primarily intended to be used for railroad locomotive use. A smaller but important use for these engines would be in domestic marine transportation as power for tug and tow boats and smaller ships. As indicated in Fig. 3 and Table 4, these two applications constitute about 2.5% of the U.S. petroleum requirements.

The railroads are a good candidate for the initial use of coal-water slurry diesel engines. They have a fairly centralized fuel distribution system which could accommodate both demonstration of and evolution to coal slurry fuel. They presently use diesel engines and are familiar with their operation and maintenance. Historically, the railroads used coal; further, some railroads have large coal resources. There is already industrial and railroad interest as shown by the recent agreement between General Electric Locomotive Division and the Burlington Northern Railroads to investigate methods of using coal for locomotives (17). A recent study (16) of fuel conservation measures for railroads shows the strong economic advantage of substituting coal for oil in railroad applications, although not specifically considering coal-fueled diesels. Another important aspect of railroad use is the relative lack of exhaust pollutant restrictions; coal-fueled diesels are likely to produce more particulates and other pollutants than oil-fueled diesels. The prospects for control of the exhaust pollutants are quite good, but will require considerable additional development. By initially not having to deal with the exhaust pollutants, early demonstration and commercial application of coal-fueled diesels will be facilitated. The establishment of a sound commercial market will encourage the development of the technical refinements necessary to control the exhaust pollutants.

Ships used in high seas trade generally have larger (medium and slow speed) diesel engines than the size considered here. These ships presently operate using low grade bunker fuels, resulting in considerable savings compared to No. 2 diesel fuel. Assuming that the smaller coal-fueled diesel is successful, these larger engines could certainly be developed into a coal-fueled version. However, this area does not appear to be a likely candidate for the first applications for coal-fueled engines. First, almost all of these engines (and ships) are of foreign design and manufacture; second, use of coal-water slurry fuel in high seas commerce would require a worldwide fuel distribution network. However, in the long term, high seas marine transportation is an excellent candidate for conversion to coal-fueled diesel engines. The early development of these engines in the U.S. could open up a major international market for U.S. industry.

CO-GENERATION - As indicated in Table 4, co-generation represents the largest potential application for coal-fueled diesel engines. Effectively, this would result in the generation of electric power by coal, but at small industrially located sites rather than at large utility stations. Since the diesel engine efficiency is comparable to that of a modern coal-fired steam utility plant, the overall efficiency of coal use for electric power would be unchanged. However, the heat normally rejected to the environment, representing about 60% of the energy in the coal, could satisfy a large part of the industrial process heat demand. For co-generation applications diesel engines are the preferred choice by two measures; the thermal efficiency for producing mechanical power is the highest, and they also have the highest exhaust temperature. Higher exhaust temperatures results in higher temperature and pressure steam, and reduces the size of heat exchangers. The recent installation of a 24 megawatt slow-speed diesel engine for co-generation at the Hoffman-LaRoche plant in New Jersey (18) attests to the advantage of the diesel engine for this application.

PRESENT RESEARCH AND DEVELOPMENT ACTIVITY

Most of the present work in the U.S. is supported by the Department of Energy. The potential for coal-fueled diesel engines to displace oil and gas in favor of coal has only recently been recognized and a major commitment to an R & D program has yet to be made. There is presently about a 6 man-year level of support for some exploratory investigations primarily directed at determining the conditions required to burn coal-water slurries in a diesel. This work is supported by the Heat Engines Section under the Assistant Secretary for Energy Technology. Developmental testing of coal-water slurries in a large, slow speed diesel is being supported by the Assistant Secretary for Conservation and Solar through Industrial Energy Conservation. This work is being carried out by the Thermo Electron Corporation in collaboration with Sulzer Bros. in Switzerland (7,8). This work is intended to demonstrate the feasibility of using coal-water slurries in these large engines.

At Bartlesville Energy Technology Center a modest program has been underway for about two years, intended to demonstrate the combustion of various slurries, including coal-oil, coal-methanol and coal-water, in a small test engine and in a heated bomb (19). Reasonable success has been achieved with coal-oil and coal-methanol mixtures; combustion of coal-water slurries appears to be more difficult. They have made most of their own slurries and intend to screen a number of slurry fuel candidates in an effort to arrive at a preliminary fuel specification. With the coal-water slurry, pilot fuel injection has been used to ignite the slurry.

The Southwest Research Institute is conducting an investigation of injection systems that may be suitable for use with coal slurry fuels (20). The Energy and Environmental Corporation in Irvine, California is carrying out combustion tests of several slurry fuel candidates (21) in a somewhat larger research engine than available at Bartlesville.

The Lawrence Berkeley Laboratory is carrying out a study of the ignition and combustion of coal-water slurries in a small single cycle diesel engine simulation device. This is equipped with transparent cylinder walls and uses high speed photographic diagnostics so that the development of the spray and the subsequent ignition and combustion can be observed photographically. The Sandia Combustion Research Facility is studying the ignition and combustion of coal-water slurries in a bomb using high speed photography (22). Finally, some interesting modelling studies have been carried out at Texas A & M University (14). This work, which was mentioned in section 3.3, indicates that 20 micron coal char particles should undergo complete combustion in a diesel engine operating at 1500 rpm.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this paper was to review the technological and economic data regarding coal-fueled diesel engines, and to present arguments justifying development activity intended to support a coal-fueled diesel engine industry. Review of the early German development effort indicates that pulverized coal burning engines were reasonably close to practical application at that time, and that a wide range of engines sizes with speeds up to 1200 rpm were successfully demonstrated. An example of a conceptual engine design which incorporates features aimed at 900 rpm operation on coal-water slurry fuel was discussed and used to illustrate the principle technological problems which will require research and development effort. The potential applications of such engines for railroad and marine transportation appear to be economically feasible and should result in a significant reduction of costs as well as a significant savings of oil. If co-generation applications were fully developed, there would be a substantial shift in the energy economy of the country towards coal accompanied by significant reduction in total energy requirements due to the increased fuel utilization made possible by the co-generation concept.

I believe that there is ample justification for the initiation of a broad-based coal-fueled diesel engine development program. The effort should emphasize fresh ideas to solve the challenging practical problems a commercially successful engine must overcome. It should also provide the ground work of fairly basic studies related to the combustion, fuel handling and materials wear problems necessary for a general understanding of the important phenomena. This information is necessary to serve both as a basis for the engineering judgement of the practical viability of the concept, and for the developmental work necessary to produce a demonstration prototype. There should be ongoing review of the program by an advisory panel with an appropriate mix of industrial, research laboratory and government scientists and engineers.

The important technical areas where initial effort is needed are in combustion, wear, fuel properties, and fuel handling. These areas are interdependent; for example, the rate of combustion will depend on the fuel particle size and composition, and on the degree of atomization and mixing in the combustion space. Also, the wear rate will be dependent on the ash content of the fuel, the degree of atomization of the spray, the fluid mechanics of combustion, and the materials and designs used for the wearing surfaces. In assessing the degree of importance of each of these areas, the combustion of the fuel and the wear of the working parts of the engine are the most critical. We need to know how a coal-water slurry sprays, ignites, and burns under diesel conditions, and techniques for obtaining satisfactory combustion need to be conceived and developed. The basic wear related phenomena must be investigated and the types of materials and designs which will minimize wear and erosion need to be identified and tested. Only when satisfactory combustion and wear protection designs have been tested can proper evaluation of different fuel characteristics be carried out.

The development program should address combustion and wear issues with high priority. The fuel properties and fuel handling areas would be secondary and used to support the two primary development areas. A fifth area, very important to an engineering development program such as this, is an on-going assessment of both the technical and economic practicality of the concept. This would be used to guide the development effort and provide the framework for programmatic decisions.

There are challenging technical problems associated with the development of coal-fueled diesel engines which require both in-depth study and innovative ideas. As a pay-off, there exists the possibility of the establishment of an industry with a product that will more efficiently utilize our coal reserves and thereby reduce our oil consumption and energy costs. Successful development will establish a U.S. lead in a highly competitive, worldwide industry. NASA has developed the techniques and materials to make the space shuttle a reality. DOE can also develop the materials and combustion technology to make the coal-slurry fueled diesel engine a practical device.

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REFERENCES

1. W. Bryzik and R. Kamo, "TACOM/Cummins Adiabiatic Engine Program," SAE paper 830314, Feb. 1983.

2. I. Kvernes, "Problems Encountered in Developing and Using Thermal Barrier Coatings on Diesel Engine Components," *Proceedings of the Second Conference on Advanced Materials for Alternative-Fuel-Capable Heat Engines*, J. W. Fairbanks and J. Stringer, co-editors, Electric Power Research Institute Report EPRI RD-2369-SR, p. 6.1 - 6.21, May 1982.

3. S. Timoney and G. Flynn, "A Low Friction, Unlubricated SiC Diesel Engine," SAE paper 830313, Feb. 1983.

4. L. Carpenter, Heat Engines Section, U.S. Department of Energy, Morgantown Energy Technology Center; personal communication.

5. E. E. Soehngen, "Development of Coal-Burning Diesel Engines in Germany," Energy Research and Development Administration Report, FE/WAPO/3387-1, Aug. 1976.

6. J. Jehlicka, personal communication, 1983. Further information is given in an unpublished trip report by F. Robben (1983).

7. J. B. Dunlay, J. P. Davis, H. A. Steiger and M. K. Eberle, "Performance Tests of a Slow-Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels", U.S. Department of Energy Report TE-7905-267-80, June 1980,

8. H. A. Steiger, "Coal Slurry Tests with a Slow-Speed Two-Stroke Cycle Diesel Engine, Conclusions and Predictions", *Proceedings of the Second Conference on Advanced Materials for Alternative-Fuel-Capable Heat Engines*, J. W. Fairbanks and J. Stringer, co-editors, Electric Power Research Institute Report EPRI RD-2369-SR, pp. 4-175 to 4-189, May 1982.

9. J. A. Caton and K. H. Rosegay, "A Review and Comparison of Reciprocating Engine Operation Using Solid Fuels", to be presented at the 1983 SAE International Off-Highway Meeting and Exposition, Sept. 12-15, Milwaukee, WI. SAE paper 831362.

10. *Proceedings of the Fifth International Symposium on Coal Slurry Combustion and Technology* Tampa, FL, Pittsburgh Energy Technology Center, April 25-27, 1983.

11. R. D. Oza and J. F. Sinnamon, "An Experimental and Analytical Study of Flash-Boiling Fuel Injection", SAE paper 830590, March 1983.

12. E. E. Obert, *Internal Combustion Engines and Air Pollution*, Intext Educational Publishers, New York (1973).

13. L. Talbot, R. K. Cheng, R. W. Schefer and D. R. Willis, "Thermophoresis of Particles in a Heated Boundary Layer", J. Fluid Mech. 101, pp. 737-758, 1980.

14. J. A. Caton and K. H. Rosegay, "An Analysis of Solid Particle Combustion in an IC Engine Environment", presented at the 1983 Spring Meeting, Central States Section, The Combustion Institute, March 1983.

15. D. B. Shonka, editor, *Transportation Energy Conservation Data Book: Edition 3*, Oak Ridge National Laboratory Report ORNL-5493, Feb. 1979.

16. S. G. Liddle, B. B. Bonzo, G. P. Purohit, J. A. Stallkamp, "Future Fuels and Engines for Railroad Locomotives", Jet Propulsion Laboratory publication 81-101, Nov. 1981.

17. R. D. Weeks, General Electric Transportation Systems Business Operations, personal communication.

18. J. P. Davis and S. E. Nydick, "U.S. Chemical Plant Chooses Slow Speed Diesel Cogeneration System", Modern Power Systems, pp. 57-61, Dec. 1981.

19. M. D. Gurney, Bartlesville Energy Technology Center presentation at the Coal-Fueled Diesel Contractors Meeting, Morgantown Energy Technology Center, 26 July 1983.

20. R. Phatak, Southwest Research Institute presentation at the Coal-Fueled Diesel Contractors Meeting, Morgantown Energy Technology Center, 26 July 1983.

21. W. R. Seeker, Energy and Environmental Corp. presentation at the Coal-Fueled Diesel Contractors Meeting, Morgantown Energy Technology Center, 26 July 1983.

22. T. M. Dyer, Sandia Combustion Research Facility presentation at the Coal-Fueled Diesel Contractors Meeting, Morgantown Energy Technology Center, 26 July 1983.

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