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COAL FUELED DIESEL ENGINES — 1992 —

INTERNAL COMBUSTION ENGINE DIVISION

EDITED BY
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COAL FUELED DIESEL ENGINES — 1992 —

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FOREWORD

The coal-fueled, reciprocating, internal-combustion engine continues to be the subject of intense research and development. Since the late 1970s the U.S. Department of Energy has been largely responsible for the technical progress of the coal-fueled diesel engine. In addition to steady technical progress in fuels formulation, ignition, combustion, wear, and emissions, new developments include the operation of multi-cylinder coal-fueled engines.

This publication contains ten technical papers which were presented during the Coal Fueled Diesel Engines sessions of the ASME Internal Combustion Engine Symposium of the Energy-sources Technology Conference and Exhibition (ETCE), held January 26–30, 1992, at the Adam's Mark Hotel in Houston, Texas. This is the ninth year that technical sessions on coal-fueled engines have been part of the ETCE. These papers include descriptions of major research and development programs by four engine manufacturers. In addition, other papers report on the injection characteristics of coal-water slurries, novel injector techniques, wear characteristics and gasified-coal-fueled engines.

A number of people have contributed to the success of this publication. The support of the Associates of the Internal Combustion Engine Division is a major reason for this success. The outstanding work of the authors is appreciated and is, of course, the reason this publication exists. All technical papers were peer reviewed and conform to ASME publication guidelines. The efforts of the reviewers of these papers are especially appreciated.

Jerald A. Caton
Holmes A. Webb
Session Organizers

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COAL-FUELED DIESEL ENGINE DEVELOPMENT UPDATE AT GE TRANSPORTATION SYSTEMS

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ABSTRACT

The U. S. Department of Energy is sponsoring a General Electric Company development program for using coal water slurry (CWS) to power a diesel engine and to test it in a locomotive. The first locomotive system test was successfully completed in 1991 on GE/TS test track. The first phase coal fueled 12 cylinder diesel engine used in the locomotive test employed a modified positive displacement fuel injection system and developed 2500 hp in the engine laboratory. The final phase all electronic controlled fuel injection equipment (FIE) diesel engine has completed individual component development phases. Combustion research evaluated a broad range of CWS fuels with different source coals, particle sizes and ash contents. The electronic controlled FIE single cylinder test engine yielded 99.5% combustion efficiency. Envelop filter, copper oxide sorbent have been chosen to cleanup the engine emissions after extensive evaluation of various hot gas cleaning methods. The projected removal rate of particulate is 99.5% and that of SO_2 is 90%.

Over ten diamond insert injector nozzles performed well on the test engines. Bench test of one nozzle has been run for over 500 engine equivalent hours without significant wear. Tungsten carbide (WC) coated piston rings and cylinder liners were identified to be effective in overcoming power assembly wear. A matrix of WC spray parameters were investigated, and the best process was used to apply coatings onto full scale rings and liners. These and other test parts are currently running in two coal fuel operated cylinders on a converted eight cylinder endurance test engine.

All of these developed technologies will be applied onto the second phase engine and be used in the final phase locomotive test. An economic analysis was also completed on a concept locomotive design. Additional equipment cost and the level of diesel fuel price to repay the investment were analyzed. Thus the economic environment for the commercialization of the modern coal fueled locomotive is defined.

INTRODUCTION

Under the sponsorship of the U.S. Department of Energy (DOE), Morgantown Energy Technology Center (METC), the General Electric Company Transportation Systems is conducting a proof of concept program using coal water slurry (CWS) fuel to power a locomotive. Some results of this study have already been reported in a previous paper [Flynn et al., 1990]. In recent years, significant progresses were made in the completion of the first phase multi-cylinder engine laboratory test and the first stage coal fueled diesel locomotive track test. CWS fuel, for the first time, was used successfully in powering a diesel engine at 1050 rpm and developed 2500 HP (16 MPa BMEP) in a GE-7FDL 12 cylinder engine [McDowell et al., 1991]. This engine was transferred to a GE Dash 8 locomotive and completed preliminary system test on GE corporate test track.

The GE program is planned, in which four phases: "Technology R&D", "Engine Component Development", "Locomotive Integrated Systems Test", and "Conceptual Locomotive Design and Economic Analysis", are performed in parallel. At the core of the tasks, there are two phases of full size 12 cylinder engine tests as well as two stages of locomotive systems tests. The highlights of the project are shown in Figure 1. Briefly, the four phases are described as follows.

<u>Technology R & D</u>

The major technical areas: combustion, fuels, emissions, and durability, are to be investigated in bench scale tests and on the single cylinder research engine. The first task of the combustion R&D is to burn the coal water slurry fuel with minimal modifications to the existing mechanical diesel fuel injection equipment (FIE) in order to gain the operating experience of a full size multi-cylinder engine as quick as possible. This experience is going to be used to guide the second task of developing an improved electronic controlled fuel injection system to be able to optimize the combustion of coal fuel in a diesel engine. The fuels R&D task is intended to identify some of the intrinsic CWS fuel parameters that influence engine combustion, as well as to broaden the engine acceptance of the widest range of source fuel specifications. The emissions R&D

	1988	1989	1990	1991	1992	1993
TECHNOLOGY RES. & DEV.	TEST PLAN MECHANICAL FUEL INJECTION	ELECTRONIC FUEL INJECTION MATERIAL	EMISSIONS CONTROL FUELS	CLEAN COMBUSTION FULL FLOW EMISSIONS		
ENGINE DEVELOPMENT	START BUILD FIRST 12 CYLINDER ENGINE	MECHANICAL FUEL INJECTION HARDWARE	TEST FIRST 12 CYLINDER ENGINE	ELECTRONIC FUEL INJ. HARDWARE DURABLE ENGINE PARTS	ELECTRONIC FUEL INJ. ENGINE WITH EMISSIONS CONTROL	
LOCOMOTIVE SYSTEM TEST	CONCEPT LOCOMOTIVE DESIGN	FUEL SUPPLY SYSTEM	FIRST PHASE LOCOMOTIVE CONVERSION	TRACK TEST 1ST PHASE LOCOMOTIVE	BUILD 2ND PHASE LOCOMOTIVE	RAILROAD TEST OF 2ND PHASE LOCOMOTIVE
ECONOMIC ANALYSIS		CONCEPT LOCOMOTIVE ECONOMICS		(UPDATE)		UPDATE & REPORT

Fig. 1. Coal Fueled Diesel Locomotive Project Highlights

objectives are to first characterize the coal fired diesel engine emissions and then to develop the control system that will allow the engine to operate as clean as the original diesel fuel counter part. The durability objective is to develop the materials and processes that are needed to provide engine life comparable to today's oil fueled diesel within reasonable cost.

Engine Component Development

The major technologies are to be scaled up to operate full scale, multicylinder engines. Two consecutive phased 12 cylinder engines are to be built and tested on test stands. The first phase engine uses mechanical FIE without any emission control equipment. As technology is developed, the second phase engine will use the all electronic controlled FIE with fully developed emission controls system. Combustion, emissions and operating data will be taken. In addition, two cylinders of another eight cylinder engine are converted to CWS operation to provide a test bed for durability development. The engine for durability test will be operated for 1000 cylinder hours to collect long term component wear data.

Locomotive Integrated Systems Test

Two stages of locomotive development are to be conducted. The first stage locomotive carries its CWS fuel on a tender. The first phase engine was transplanted onto the first stage locomotive and it has operated on GE Transportation Systems test track in 1991. The second stage test locomotive will use the second phase engine with all electronic control FIE, and will contain all the technologies developed during the project, including the emission control system. Track test will include operation in realistic railroad service.

Conceptual Locomotive Design and Economic Analysis

The coal fueled locomotive which contains the technology to be developed in this program has been conceptually designed and its cost estimated. The investment in such a locomotive will be analyzed for different operating scenarios. This economic analysis will be updated at the end of the program.

This paper provides an update of the achievements obtained on the various aspects of the program.

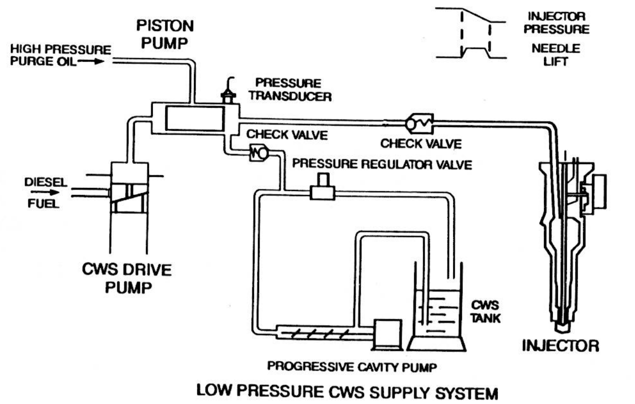


Fig. 2. Accumulator CWS Injection System Schematic

TECHNOLOGY R&D

Combustion R&D

The combustion development for the mechanical CWS FIE and the mechanical pilot/starting diesel fuel system was completed in 1989. Its CWS fuel injection hardware was first developed under a previous DOE contract (DE-AC21-85MC22181) granted to GE and described in a paper by Hsu [1988]. This system was not designed with durable parts and could only run for a short period of time. The combustion efficiency reached was only about 95%. The system and its main operation results on single cylinder engine were summarized in the earlier overview paper [Flynn et al., 1990]. This system was subsequently built onto the first phase 12 cylinder engine and completed full scale engine test to be discussed later.

An electronically controlled accumulator CWS injection system, matched with an electronic start/pilot injector has been developed on the GE single cylinder test engine. The basic CWS accumulator injection hardware was also developed under the previously mentioned earlier DOE contract and reported by Hsu et al. [1989]. A schematic of the system is shown in Figure 2. It can be briefly described as follows. A conventional jerk pump is used to pump diesel fuel oil onto the backside of a free floating piston in an CWS isolation pump. The CWS on the opposite side of the piston is thus pressurized and pushed into the accumulator injector. A check valve was included in the injector inlet to trap the high pressure CWS in the injector on the refill cycle of the piston. A check valve is also included in the CWS fill line of the piston pump to keep it from reverse flowing during the pressurized cycle. The injector needle movement is controlled by servo oil pressurizing the appropriate side of a piston attached to the upper end of the injector needle. Thus, electronic signals feeding into a high speed serve oil valve can provide the injection timing and duration in a prescribed manner.

An electronic start/pilot diesel fuel auxiliary injection system, developed by BKM, Inc. of San Diego, CA, is used together with the accumulator CWS hardware. The pilot diesel fuel system is of the common rail accumulator type. Therefore it does not require each cylinder to carry its own pump, thus, simplifying the engine structural design. A general cross section layout of one cylinder with both the CWS and pilot fuel systems is shown in Figure 3. This layout will be used on the second phase 12 cylinder engine for each of the cylinders.

A computer model of the CWS combustion in engine has been completed by Ricardo, North America and described in detail in another published technical paper [Wahiduzzaman et al., 1990]. It has contributed greatly in the understanding of the combustion performance of the engine. Further, it was also used to pursue the best ways to optimize the engine operation conditions [Wahiduzzaman et al., 1991]. In-cylinder combustion photography and high speed data systems were procured and the cylinder on the research engine was modified to accommodate the probes. This work will be completed later, and is expected to enhance significantly to the knowledge of CWS in-cylinder combustion characteristics and further contribute to better combustion optimization.

Since February, 1990, the GE program has been expanded to include a study titled "Characterization of Coal Water Slurry Fuel Sprays from Diesel Engine Injectors." It is performed by the Mechanical Engineering Department of the Texas A&M University. This work is closely coordinated with the development need at GE. Some results of the study have already beneficiated the actual engine combustion design. Preliminary findings were published in a brief technical paper [Caton and Kihm, 1991]. A thorough description of this work is also in printing [Seshadri et al., 1992].

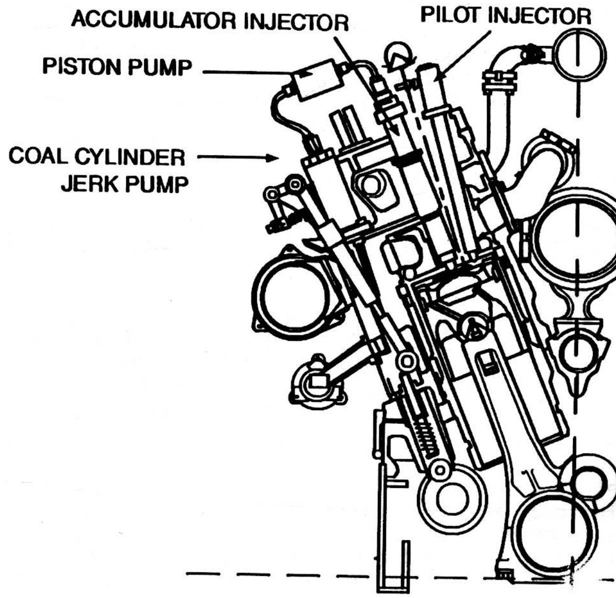
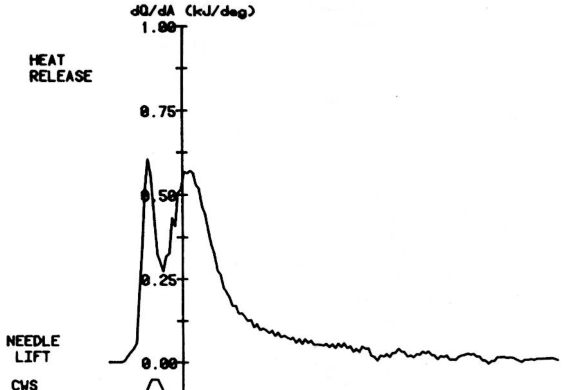
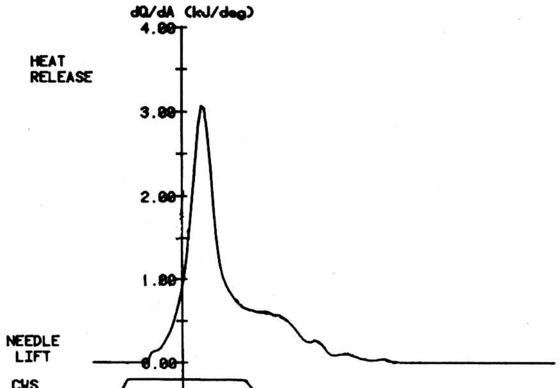


Fig. 3..Engine Cross Section Layout of One Cylinder

An extensive CWS combustion optimization study has been completed on the single cylinder engine. The goal is to provide the highest combustion efficiency (burnout rate) while not exceeding the firing pressure limit of engine components and having reasonable fuel consumption rates. It is also a goal to use the least practical amount of pilot diesel fuel. Among the parameters studied, included CWS injection pressure, CWS and pilot injection timings, CWS injector hole size, number, shape and spray included angles, as well as engine inlet air conditions. Many interesting phenomena were noticed. For instance, for all practical purpose, CWS fuel ignites after its spray impinges on the combustion chamber walls. Impingement does not necessarily hamper combustion as long as it is not overly attached to the walls or hit the cooler cylinder liner surface. Another interesting point that has been observed lies in the fact that, for optimum combustion, at the lower



Low Load



High Load

Fig. 4. Typical Combustion Heat Release Diagrams

loads, the pilot diesel fuel is injected early in the cycle to serve as an igniter. However, at full load, pilot fuel should only be introduced late in the cycle to become a combustion enhancer after allowing a long delay time for the water in CWS fuel to evaporate before ignition ("Delayed Ignition"). Typical combustion heat release diagram of low and high load operation are shown in Figure 4. Achievements obtained so far include the followings.

- o The combustion efficiency at full engine load has reached 99.5% (as compared to 95% before), which greatly reduced the loading of the hot gas particulate removal system.
- o The lowest load that can burn CWS fuel has been lowered from "Notch 5" load (960 rpm, 1.0 MPa MEP) to "Notch 2" load (620 rpm, 0.3 MPa MEP) and less pilot fuel under each load condition. As a result, the duty cycle CWS consumption increased from about 66% of the first phase mechanical FIE engine to 80%, which exceeds the program goal of 75% [Flynn et al., 1990].
- o The coal fuel diesel engine cycle efficiency is comparable to the oil fuel counter part.

Details of findings are published in another paper [Hsu et al., 1992]. All the above R&D results are presently being incorporated into second stage coal fueled multi-cylinder engine.

Fuels R&D

In the past, only one kind of domestic source bituminous coal (Kentucky Blue Gem) prepared by one fuel manufacturer into CWS (OTISCA Ind., of Syracuse, NY) was used on the GE engine. This fuel specifications are shown in Table 1.

Table 1. Kentucky Blue Gem Coal Nominal Lot Analysis

Proximate Analysis		Ultimate Analysis	
% Ash	0.80	% Carbon	82.59
% Volatile	39.40	% Hydrogen	5.34
% Fixed Carbon	59.80	% Nitrogen	2.08
		% Chlorine	0.18
Particle Size		% Sulfur	1.01
Mass Mean Diameter (microns)	5.47	% Oxygen (diff.)	7.58
Heating Value		High Heating Value (kJ/kg)	34630

One of the tasks of the project is to investigate the tolerance of injection hardware to CWS fuel variations. The CWS fuel comparison tests were completed during 1990. Fuels were procured from Otisca, AMAX of Golden, CO and UNDERC of Grand Forks, ND. Source coals included bituminous coal from Kentucky and Pennsylvania and subbituminous coal from Wyoming. Cleaning methods ranged from heavy media cyclone to oil agglomeration and chemical cleaning. Ash levels ranged from 0.7% to 2.8%. Mean particle sizes ranged from 3 microns to 15 microns. The GE diesel engine, using the accumulator fuel injection system, was able to burn all the CWS fuels at relatively high burnout levels (Table 2). However, the engine required different combustion parameters and some possible hardware modifications for optimum performance with each fuel (e.g. injector hole configurations etc.). A more thorough description of the CWS fuel test results has been presented by Hsu and Confer in an ASME paper [1991].

Emissions R&D

Early in the program, an emissions sampling system was constructed to extract a small portion of the exhaust of the single cylinder engine. The system can test a sub-scale cyclone, fabric filter or granular bed, singly or in combination. Calcium sorbents were also tested on engine to capture SO_2 from the exhaust. Lime was either mixed into the CWS fuel or injected into the exhaust manifold. Details of the findings have been reported by Slaughter et al. [1990].

At GE Corporate Research & Development, a small size Yanmar engine was set up with the exhaust gas passing through candle type stainless steel filters as shown in Figure 5. The filters are equipped with reverse pulse air cleaning. The engine fuel was doped with carbon disulfide (CS_2) to increase the engine exhaust SO_2 concentration. Promising results were obtained using copper oxide (CuO) sorbent coupled with ammonia injection to simultaneously greatly reduce SO_2 and NOx emissions.

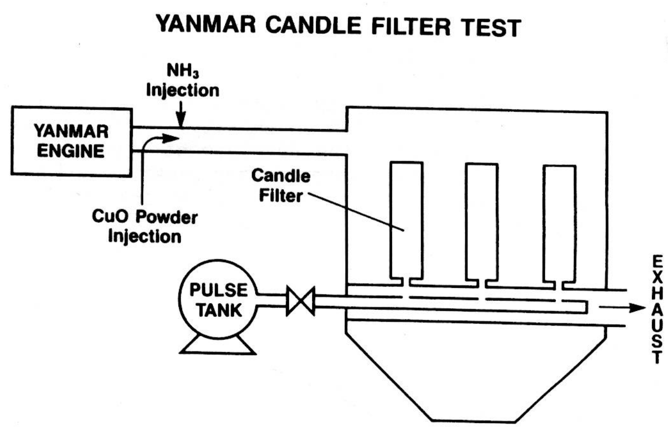


Fig. 5. Small Scale Engine Emission Test Configuration

Table 2. Test Fuels and Combustion Results

Fuel No.	Fuel Vendor	Coal State Origin	Seam Name	Coal Type	Cleaning Process	Mean Micron Size	Ash %	Comb. Eff. %
1	OTISCA	Kentucky	Blue Gem	Bitum	Physical	4.6	0.7	99.2
2	OTISCA	Kentucky	Blue Gem	Bitum	Physical	4.8	0.8	98.8
3	OTISCA	Kentucky	Blue Gem	Bitum	Physical	3.1	0.7	98.7
4	OTISCA	Kentucky	Blue Gem	Bitum	Physical	3.2	0.7	99.2
5	OTISCA	Penn.	Pitt	Bitum	Physical	2.5	1.7	98.7
6	UNDERC	Wyoming	Kemmer	Subbit	Chemical	13.9	2.8	99.5
7	UNDERC	Wyoming	Sprg Crk	Subbit	Phys+Chem	14.7	2.1	99.0
8	UNDERC	Wyoming	Sprg Crk	Subbit	Chemical	14.9	2.8	99.2
9	AMAX	Kentucky	Splint	Bitum	Physical	8.2	2.5	97.7

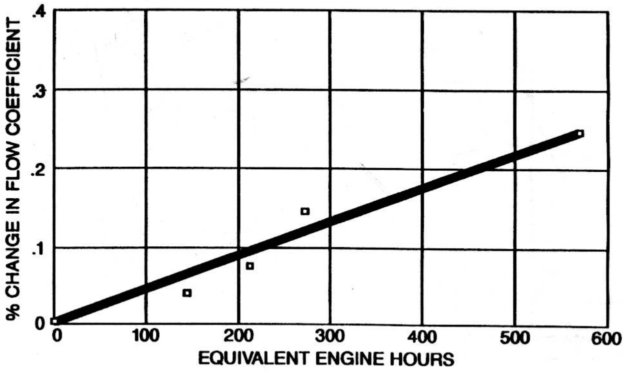


Fig. 6. Erosion Rate of Diamond Compact Orifice on Test Stand

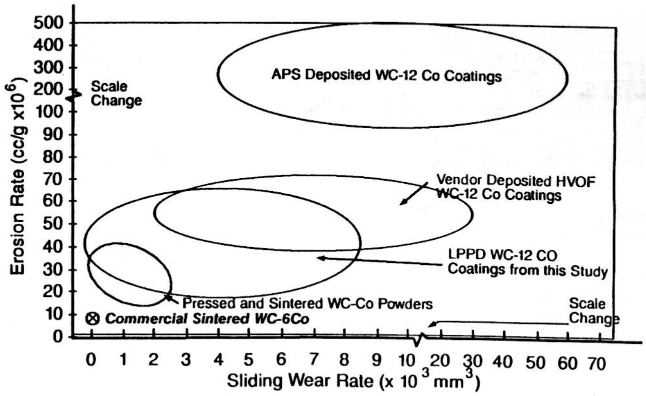


Fig. 7. Tungsten Carbide Plasma Spray Application

Based on findings of the above investigation, cyclone was rejected for its inability to remove particulate with the required efficiency. Lime based SO_2 sorbent was found to be insufficient. The granular bed option is potentially promising. However, in order to develop it into a locomotive engine system, the cost and time will be much more than the presently selected system. The final selected methods are:

- o Regenerative CuO sorbent and ammonia injection downstream of turbo charger;
- o High temperature barrier filter downstream of sorbent injection;
- o Off line regeneration of sorbent.

The expected individual emission removal efficiencies of the system are:

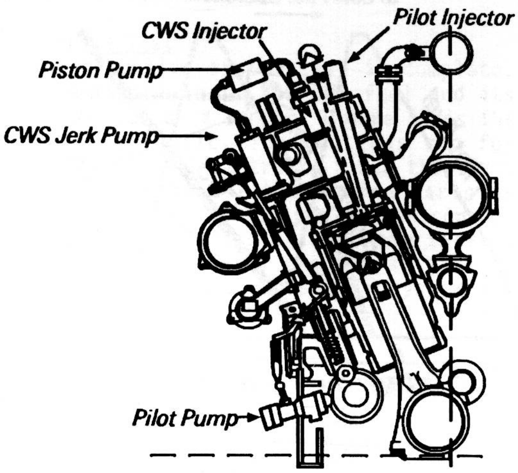
- o Particulate 99.5%
- o SO_2 90%
- o NOx 90%

A cold flow facility of the envelop type barrier filter has been built and tested. It is now designed into a full flow single cylinder engine test system. Its fabrication is underway and will be later tested on actual engine. Details of this part of the program has been presented in another reference paper [Gal et al., 1991].

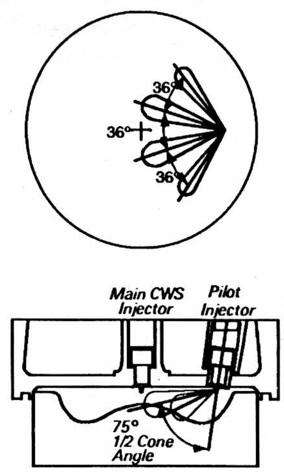
Durability R&D

The consistency of combustion and emissions testing has been greatly improved by the durability of the diamond compact nozzle, the development of which has been described in a previous paper [Flynn et al., 1990]. Over ten diamond compact nozzles of different designs have since been tested on actual engines. Although the longest running time accumulated by one nozzle was no more than 100 hours, no sign of wear was detected and they all ran very reliably. Single diamond orifices have been tested for 500 hours on a research test stand with less than .5% increase in flow, as shown in Figure 6. Previously, TiB_2 coating was also considered as a potential candidate for injector wear protection. TiB_2 coatings are very resistant to CWS erosion and two orifices have performed very well, but failure of the coating leads to catastrophic wear of the soft metal substrate. Work on developing alternate nozzle materials has thus been discontinued.

After extensive bench scale test, it was identified that Tungsten Carbide (WC) coated piston rings and liner provide the best possibility to overcome the power assembly wear problem [Flynn et al., 1990]. Development effort to define the relationships between plasma spray conditions and the properties of WC+Co and metal matrix composite coatings was completed. It was found that "Low Pressure Plasma Deposition" (LPPD) processing can be used to produce piston rings with high quality WC+12%Co coatings, particularly if the spray gun made by Electro-Plasma, Inc. was used. The findings can best be summarized as depicted in Figure 7. A technical paper describing this effort has been presented to a DOE heat engines coating meeting [Rairden et al.,



Engine Layout



Combustion Chamber Layout

Fig. 8. Stage I Coal Fueled Diesel Engine General Layout

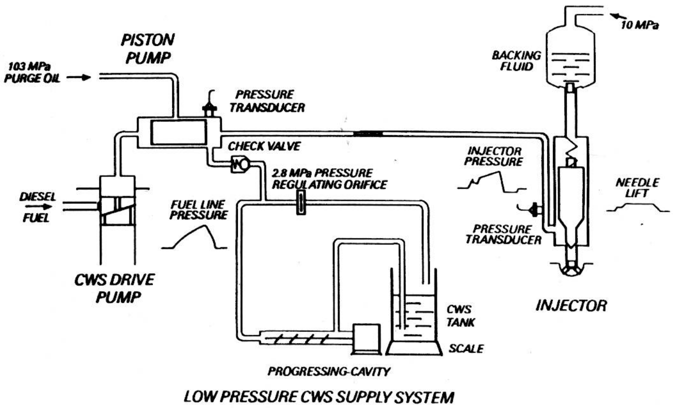


Fig. 9. Stage I Coal Fueled Engine CWS Injection System Schematic

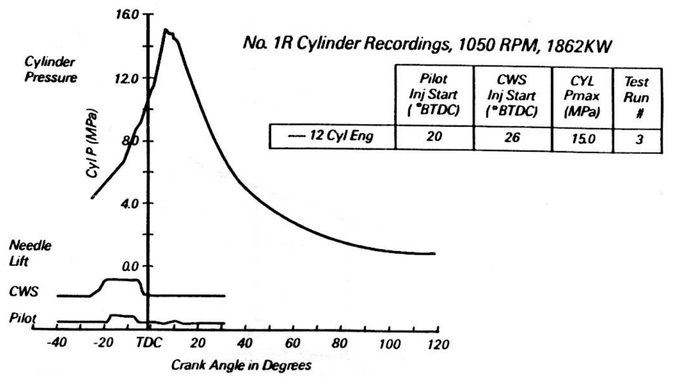


Fig. 11. Stage I Coal Engine Full Load Cylinder Pressure

1990]. TiN coated piston ring was found to be very effective in preventing side wall wear. It was proven in a 165 hours run of the small Yanmar test engine using contaminated fuel.

Besides WC plasma coatings, piston crowns have been coated with nitride and boride coatings to reduce wear in the ring groove and monolithic exhaust valves and piston rings have been ordered. The R&D effort of durability is essentially complete. The technologies developed are presently being used to make full size engine parts to be tested in the endurance engine.

ENGINE DEVELOPMENT

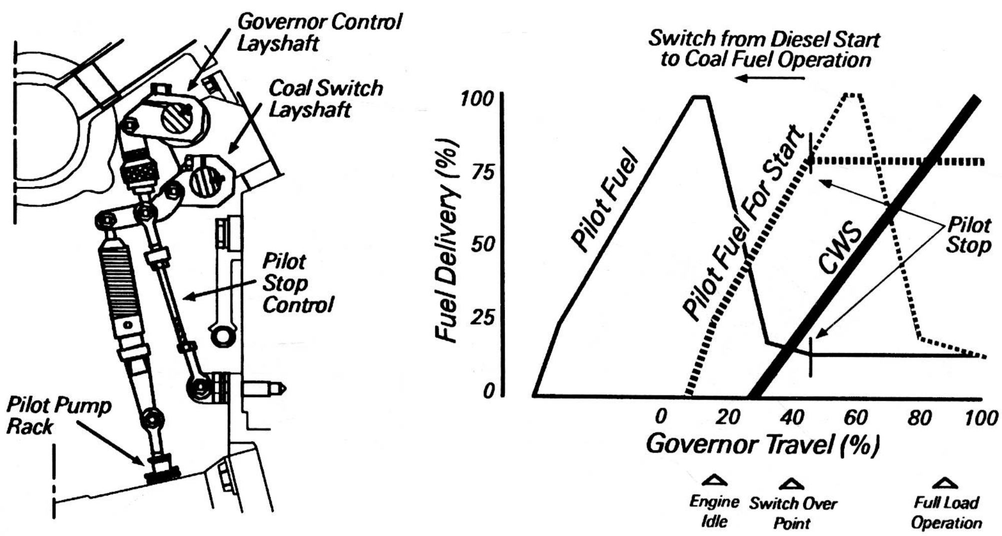
Phase I 12 cylinder Engine

This engine uses both mechanical pilot fuel injection and mechanical CWS injection hardware. Each cylinder has two injectors and two fuel injection pumps. The pilot pump is mounted on the side of the engine and the CWS jerk pump mounts on top of the engine. In each cylinder, a CWS injector is in the center and a pilot injector is on the side. These layouts are shown in Figure 8.

The CWS injection system schematic is depicted in Figure 9. Essentially, it is a conventional diesel jerk pump injection system with a pressure isolation pump between the pressurizing diesel fuel and the injected CWS fuel. The injector has backing fluid to keep the injector needle free from sticking.

For this mechanical FIE engine, both the pilot and CWS pumps are controlled by a single mechanical governor. A carefully conceived linkage system was designed to make the engine start on diesel fuel and switch to mostly CWS fuel through a secondary layshaft, which is manually operated at an appropriate time. The linkage and fuel delivery schedule schematics are shown in Figure 10.

After extended efforts made, the switch over of the engine from diesel start to coal fuel operation was successful. The engine developed 2500 hp at 1050 rpm using mostly coal fuel. A typical cylinder firing pressure trace in one of the cylinders taken while the coal fueled engine was running at 2500 hp is shown in Figure 11. In the lower half of the figure the CWS fuel and pilot diesel fuel needle lifts are shown to indicate the fuel delivering timing schedule. It ran for approximately 10 hours in the engine laboratory and was moved onto the first stage locomotive for track test. Details of the testing of this engine are published in another technical paper [McDowell et al., 1991].



Fuel Control Linkage

Fuel Control Operation

Fig. 10. Stage I Coal Engine Fuel Control Schematic

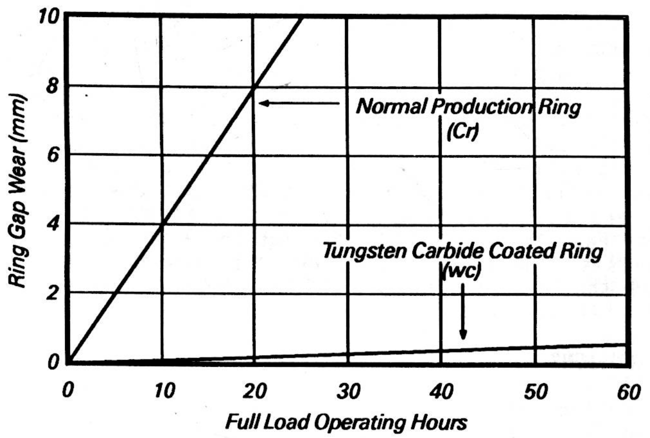


Fig. 12. Top Piston Ring Wear Comparison

Phase II 12 Cylinder Engine

The second phase 12 cylinder test engine will have all electronic controlled pilot and CWS FIE as described before. It will use all the durable engine parts developed in this program. The exhaust gas emissions cleanup system will also be built for this engine. At present, the building of the new engine is almost completed. It is schedule to start testing in 1992.

Durability Engine Test

The endurance test engine is operational since spring, 1991. Durable full size engine parts built with the technologies developed in the R&D phase have been under test. They include WC coated liners, WC coated rings, accumulator injectors with diamond compact inserted nozzles. The engine has accumulated over 100 hours of test time.

Recent full size WC coated piston rings and liner ran on the single cylinder combustion test engine for over 60 hours have shown very promising results. Figure 12 shows the top piston ring wear as expressed in ring gap comparison for a conventional production ring and a WC coated ring. Other coating process ring will continue to be evaluated.

LOCOMOTIVE INTEGRATED SYSTEMS TEST

First Stage Locomotive Test

The first phase locomotive system test is complete. For this stage locomotive test, the CWS fuel and its supply system are carried on a tender. Figure 13 is the test configuration schematic. The test was run for about 10 hours on the GE/TS test track. Since the first phase engine does not have durable engine parts or emission cleaning setup, it is mainly a design concept system checkout. The experiences gain on the overall operation of a coal fueled diesel engine, as well as its controls and supporting fuels supply system are being implemented onto the second stage engine and locomotive design.

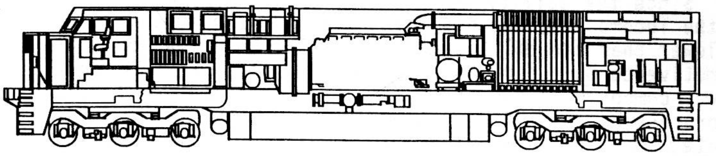


Fig. 14. Concept Design of Coal Fueled Diesel Locomotive

Second Stage Locomotive Test

The design of the second and final phase locomotive is almost complete. After the first phase locomotive test, the test locomotive will be modified. The overall length is to be extended to accommodate a larger CWS tank carried under the main frame. Above the extended part of the main frame, the full size emissions cleanup system will be installed. The second phase all electronic controlled CWS fueled engine will be used. This engine also will have all the endurance parts developed under the program. The final locomotive test will include operation on commercial railroad tracks.

CONCEPTUAL LOCOMOTIVE DESIGN AND ECONOMIC ANALYSIS

Conceptual Locomotive Design

Earlier in the program a conceptual locomotive was designed [Flynn et al., 1990]. It is shown in Figure 14. The concept locomotive was based on a 4000 horsepower GE Dash 8 locomotive with addition systems necessary to support CWS operation. It was designed to complete a 50 hour mission without re-fueling or discharging its waste products. Its platform was lengthened by 10 feet to accommodate a larger fuel tank necessary to carry an adequate amount of the lower energy density fuel. This design carried all the CWS fuel on the locomotive. The extra length was also necessary to house the emission control system.

Economic Analysis

The concept locomotive was estimated to cost $280,000 more to the customer than the diesel oil fueled locomotive on which it was based. The majority of the cost increase was associated with emission control components. The second largest category was the engine components. The cost increases for the concept locomotive are itemized in Table 3.

Table 3. Incremental Cost Increase of Coal Fueled Diesel Locomotive.

Engine Systems	$60,171
Emissions Control Systems	$160,446
Locomotive Structure	$58,195
Total	$278,812

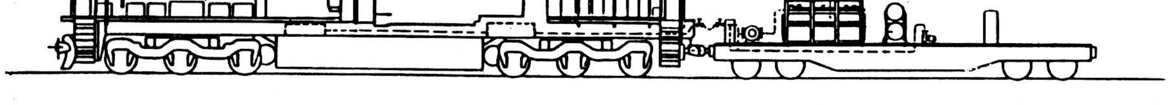


Fig. 13. Stage I Test Locomotive Configuration

Since the ability to burn coal increases the cost of the locomotive, the cost of the coal based fuel must be lower than the oil based fuel for the coal fueled locomotive to be economically attractive. The CWS fuel cost was composed of raw coal cost, transportation cost, and processing cost. Three operating scenarios were evaluated in the economic analysis: Eastern, Western and Best Case. The Eastern and Western cases served all the mainline track in their respective regions.

Table 4. CWS Fuel Costs ($/MBtu)

		Eastern Bitum.	Western Subbit.
Otisca Physical Process			
	Coal	$1.18	$ .57
	Production	$ .79	$1.29
	Transport	$ .95	$1.44
	Total	$2.92	$3.30
Amax Physical Process			
	Coal	$1.18	$ .57
	Production	$ .92	$1.07
	Transport	$ .95	$1.44
	Total	$3.05	$3.08
Best Case:			
	Coal		$ .35
	Production		$1.29
	Transport		$ .00
	Total		$1.64

They required significant transportation costs to move the coal to the process plant and ship the processed slurry to the fueling depots. The Best Case scenario modeled a specific dedicated coal train serving the Powder River Basin. Since the coal was mined, processed and used in the same location, no transportation costs were included. The CWS costs from the three regions are itemized in Table 4.

The return on an investment in coal fueled locomotive was evaluated as a function of the cost of diesel fuel, as shown in Figure 15. A diesel fuel price of $.91, $.81 and $.59 per gallon would be necessary to repay the investment at a DCRR level of 15%, for the Eastern, Western, and Best Case duty cycles respectively. The Eastern case requires the highest diesel price because of its lower average duty cycle. The Western case has a higher duty cycle which causes more savings to be generated with the higher fuel use. The Best Case has the highest duty cycle due to its dedicated coal train operation. It also has the lowest CWS cost due to low western coal prices and the lack of transportation cost. For a more detailed description of the economic analysis, the reader is referred to the full report which should be published by DOE in the near future.

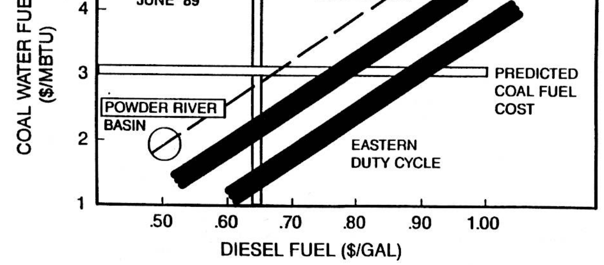


Fig. 15. Coal Fueled Diesel Locomotive Economic Analysis

CONCLUSIONS

Excellent progress has been made on all aspects of the coal fired diesel locomotive program. The completion of the first phase coal fuel locomotive track test marked a major milestone in the development of using coal fuel again since the disappearance of the steam locomotive. The R&D phase of the current program is essentially complete. Preliminary results of component development using the R&D technology findings are yielding promising returns. All signs indicate a successful second stage locomotive test on commercial railroad to be highly possible. If the market environment predicted in the economic analysis of the program becomes a reality, the technologies will be there to support a modern coal fueled diesel locomotive transition.

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FEATURES AND PERFORMANCE DATA OF COOPER-BESSEMER COAL-FUELED SIX-CYLINDER LSB ENGINE

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ABSTRACT

The six-cylinder Cooper-Bessemer LSB engine has been converted to operate with one-cylinder on coal water slurry (CWS) fuel and with five cylinders operating on diesel fuel. This development followed the successful operation of the single-cylinder JS engine on CWS for over 600 hours to date. The CWS injection system was scaled up about a factor of two in fuel volume from the JS system. A new cam box drive was fabricated for the LSB single-cylinder operation. The engine was operated and full power output was achieved from the CWS cylinder. Preliminary test results indicate good operating efficiency. Exhaust emission control system is in place for the proposed operation of all the six cylinders on CWS and major engine components are on hand. These results mark a significant milestone in the progress toward commercial readiness of the coal-fueled diesel engine system.

NOMENCLATURE AND CONVERSION FACTORS

ATC	-	After Top Center
BTC	-	Before Top Center
CWS	-	Coal Water Slurry
DF2	-	Number 2 Diesel Fuel
I.D. Fan	-	Induced Draft Fan
MAT	-	Manifold Air Temperature
NO_x	-	Oxides of Nitrogen
SCR	-	Selective Catalytic Reduction
bhp	-	brake horsepower
bmep	-	brake mean effective pressure
bsfc	-	brake specific fuel consumption
ihp	-	indicated horsepower
rpm	-	revolutions per minute
1 Btu	=	1.055 kJ
1 hp	=	745.5 W
1 inch	=	25.4 mm
1 psi	=	6.895 kPa

INTRODUCTION AND BACKGROUND

This research effort is being conducted under as part of the Heat Engines Program of the Morgantown Energy Technology Center of the U.S. Department of Energy. The objective of this project is to demonstrate efficient and low-emission operation of the Cooper-Bessemer LSB-6 engine on CWS, as a proof-of-concept of the feasibility of using CWS as fuel for large stationary diesel engines. A 100-hour continuous proof-of-concept test is scheduled to be performed in 1993.

Over the past four years, the Cooper-Bessemer/Arthur D. Little team has gained experience in operating the single-cylinder laboratory JS-1 engine on CWS. The JS engine operation has helped to identify and resolve the problems in CWS handling, injection and combustion as well as to develop highly durable combustion chamber components. Testing has also helped to identify the levels of pollutants in the untreated exhaust gas, thereby establishing realistic design targets for the emission control system.

Based on this experience, the six-cylinder LSB engine located at the Cooper-Bessemer R&D Laboratory in Mt. Vernon, Ohio, has been redesigned to operate on CWS and equipped with a full flow emission control system. The operation of the engine on CWS will be performed in two stages. First, the engine was operated with only the #1 cylinder fueled with CWS. The preliminary results of these tests are described in this paper. Once the various injection and combustion parameters are optimized, all six cylinders will be operated on CWS.

LSB ENGINE PARAMETERS

The LSB engines come in 6- and 8-cylinder in-line configurations and are also available in the 12-, 16- and 20-cylinder "vee" configuration (LSVB Model). The LSV series was first introduced in 1948 with a total installed capacity at the present time of over two million horsepower. This provides ample opportunity for retrofitting the engines already in the field, once the coal-fueled diesel technology becomes commercial.

The LSB engine, shown in Figures 1 and 2, consists of a one-piece base, one-piece centerframe and one-piece cylinder block. The engine has wet-type cylinder liners which makes it convenient to coat the bore with hard materials for improved durability while operating on CWS. The cylinder head has two intake valves and two exhaust valves and a central diesel fuel injector. The camshaft is a single shaft that runs in a trough cast onto the side of the cylinder block. Cams are hydraulically mounted on the camshaft. The fuel is supplied by conventional jerk pumps driven by the camshaft. There is one fuel pump per cylinder. The pistons are two-piece pistons with forged steel crown and an aluminum skirt. A constant pressure turbocharger supplies the combustion air to the engine through an intercooler.

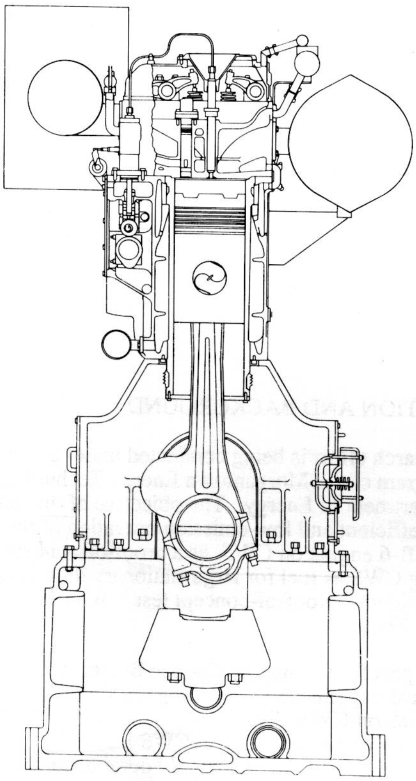

Figure 1. Cooper-Bessemer LSB Engine Cross Section

All the in-line and vee engines share a common bore and stroke of 15.5" x 22.0". The laboratory engine has six cylinders and the power generated is absorbed by a dynamometer. The operating speed range is 360-400 rpm. The rated maximum power output is 2605 bhp at a bmep of about 208 psi.

LSB DESIGN MODIFICATIONS

Objective

An effort was made to keep the major components of the coal-fueled engine the same as those of the straight diesel engine. This would keep the cost of the components to be manufactured to a minimum, both for the prototype and production engines. Also, this would result in a high degree of reliability and predictable performance of the components. Design modifications to meet specific needs of the coal-fueled engine are described below.

Cylinder Block

The starting point for the design modifications was the coal slurry fuel itself. The baseline fuel has an average particle size of 12 microns, 1.5% ash on dry coal basis, and approximately 50% coal solids loading by volume. With its heating value of approximately half that of the diesel fuel, the fuel injection pump needed to deliver approximately twice the volume of CWS compared to the diesel fuel, in about the same duration, in order to develop the same horsepower output as a diesel engine. The fuel injection pump on the standard diesel engine has a 26mm plunger and barrel. The fuel injection pump selected for coal fuel operation has a 36mm plunger and barrel. The fuel injection system was designed for a peak injection pressure of up to 18,000 psi, although the normal operating value is around 10,000 psi in practice. This design value of peak injection pressure is substantially higher than that of the standard LSB diesel engine.

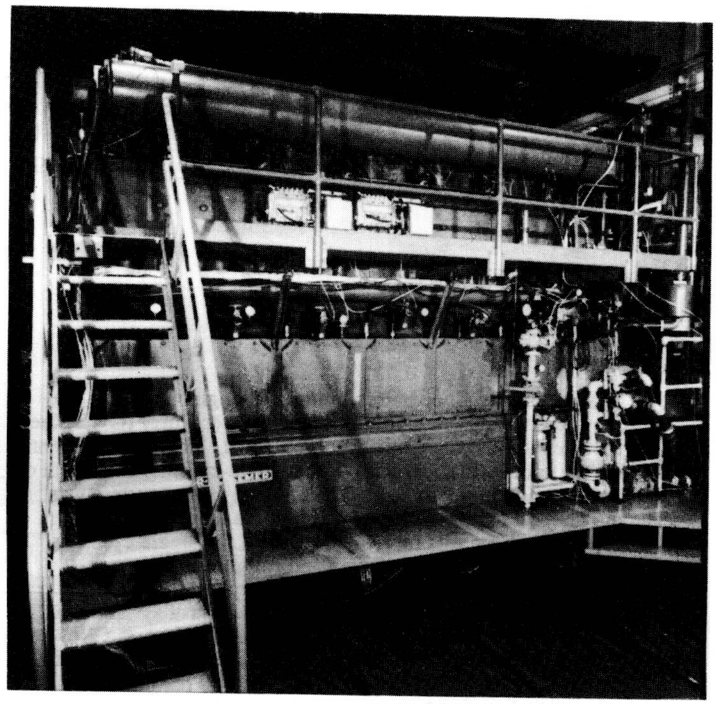

Figure 2. Coal-Fueled LSB-6 Laboratory Engine

This combination of higher injection pressure acting on a larger plunger area has resulted in a substantially higher loading on the camshaft which necessitated the increase of camshaft diameter from 4.125" to 6.5". Since the cylinder block houses the cylinder liners as well as the camshaft, the cylinder block was redesigned and substantially stiffened to accommodate the larger camshaft, larger cams and higher loads from the fuel pumps.

The cylinder block was the only major casting to be redesigned. No changes were needed to the base, centerframe, crankshaft, main and connecting rod bearings, connecting rods or air manifold.

Cylinder Head

The central hole in the cylinder head had to be slightly enlarged to accommodate the coal fuel injector. The location or size of the air inlet and exhaust valves has not been changed. The jet cell openings in the cylinder head were used to accommodate the diesel pilot injector hardware. The result is that the cylinder head for the coal-fueled engine can be machined from the same casting as the cylinder head for the diesel fuel engine. Because the two-cylinder heads are virtually identical, it is not anticipated that the CWS cylinder head would suffer any undue mechanical or thermal stresses if the peak firing pressures are kept within design limits.