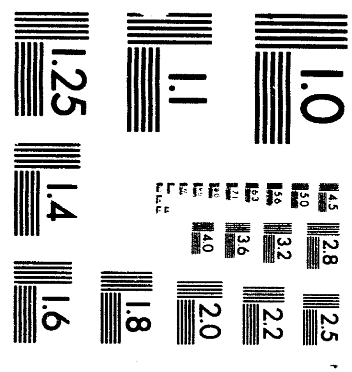

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Coal-Fueled Diesel Engines for Locomotive Applications

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Contractor:

GE Transportation Systems
Erie, PA 16531

Contract Number:

DE-AC21-88MC23174

Conference Title:

Joint Contractors Meeting: FE/EE Advanced Turbine Systems Conference, FE Fuel Cells and Coal-Fired Heat Engines Conference

Conference Location:

Morgantown, West Virginia

Conference Dates:

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Conference Sponsor:

U.S. Department of Energy, Morgantown Energy Technology Center

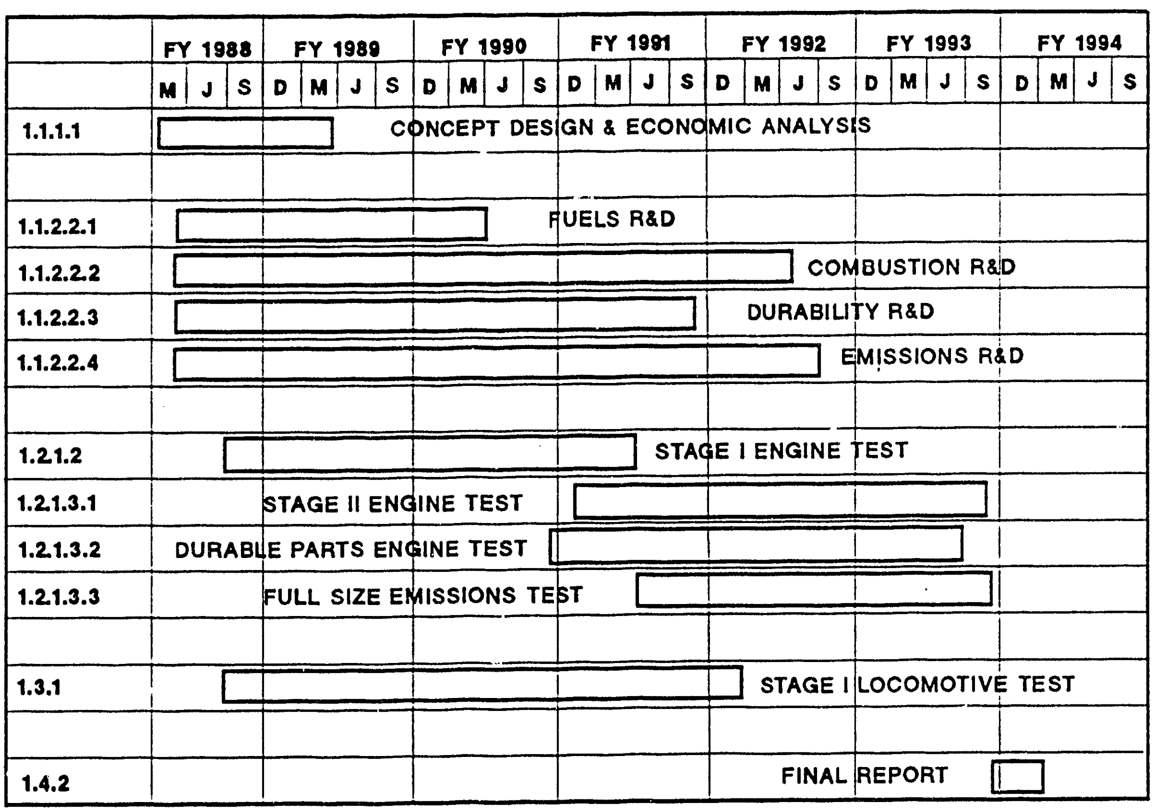
DISCLAIMER

2.2 Coal-Fueled Diesel Engines for Locomotive Applications

CONTRACT INFORMATION

Contract Number:	DE-AC21-88MC23174
Contractor	GE Transportation Systems Erie, PA, 16531. 814-875-2110
GE Program Manager:	Bertrand D. Hsu, GE Transportation Systems
Principal Investigators:	Bertrand D. Hsu, GE Transportation Systems David J. Najewicz, GE Corporate Research Charles S. Cook, GE Environmental Systems
METC Project Manager:	William C. Smith
Period of Performance:	March 3, 1988 to January 31, 1994

Schedule and Milestones



OBJECTIVES

The objective of this program is to develop the technology necessary for future commercialization of a coal-fueled diesel locomotive. The engine under development is a medium speed diesel (1050 rpm) that operates at 250 hp per cylinder in locomotive applications.

BACKGROUND INFORMATION

The General Electric Company has been active in coal burning technology programs for the past 40 years. About nine years ago, under the partial sponsorship of the Burlington Northern and Norfolk Southern Railroads, GE Transportation Systems (GE/TS) completed a two and one half year study into the economic viability of a coal fueled locomotive. The coal fueled diesel engine was deemed to be one of the most attractive options.

Building on the BN-NS study, a proposal was submitted to DOE to continue researching economic and technical feasibility of a coal fueled diesel engine for locomotives. The contract DE-AC21-85MC22181 was awarded to GE Corporate Research and Development (GE/CRD) for a three year program that began in March 1985. This program included an economic assessment and a technical feasibility study.

The economic assessment study examined seven areas and their economic impact on the use of coal fueled diesels. These areas included impact on railroad infrastructure, expected maintenance cost, environmental considerations, impact of higher capital costs, railroad training and crew costs, beneficiated coal costs for viable economics, and future cost of money. The results of the study indicated the merits for development of a coal-water slurry (CWS) fueled diesel engine.

The technical feasibility study examined the combustion of CWS through lab and bench scale experiments. The major accomplishments from this study have been the development of CWS injection hardware, the successful testing of CWS fuel in a full size, single cylinder, medium speed diesel engine, evaluation of full scale engine wear rates with metal and ceramic components, and the characterization of gaseous and particulate emissions.

PROJECT DESCRIPTION

The project is planned to operate in four parallel phases. They are: Concept Design and Analysis, Technology Research and Development, Engine Component Development, and Locomotive System Test.

The first phase conducts a conceptual design and economic analysis of a coal fueled diesel locomotive.

The Technology Research and Development phase is to perform bench scale and single cylinder engine tests on fuel injection equipment (FIE), combustion system, CWS fuels, materials, and emission control systems.

The Engine Component Development phase is to design, build and operate two consecutive phased 12 cylinder engines to develop the combustion and operating characteristics. A full scale emission control system will be tested on the second phase 12 cylinder engine. Two cylinders of another eight cylinder engine will be operated on CWS fuel to evaluate the durability of engine components.

The Locomotive System Test phase was to be conducted in two stages. The first stage locomotive will only be conducted on the GE/TS test track for a short time. The engine used in the first stage test does not have durable engine parts or emissions cleaning setup. This test is a system checkout of design concept.

The original second stage locomotive test was to be conducted on commercial railroad with all the latest developed technologies. However, in 1991, due to the persistency of low oil prices in recent years, the market interest of the coal fueled systems did not realize. The U.S. buget deficit called for the winding down of all federal funded alternate fuels program that does not see any short term commercialization prospect. The GE program scope was reduced. It was decided to eliminated the second phase of locomotive test. Details of the original project are in [2] and [27].

RESULTS

Conceptual Locomotive Design and Economic Analysis

A concept locomotive was designed for economic study and eventual production. It is envisioned as a modified GE Dash 8 4000 hp, 6 axle, microprocessor controlled locomotive. As shown in Fig. 1, the primary modifications involve the engine, fuel tank, and emissions control system. The additional equipment to inject the slurry, resist wear, and control exhaust SO_2 and particulates significantly increases the cost of building the coal-fueled locomotive. An itemized cost roll-up indicates that a coal-fueled locomotive will require a price premium of about $280,000 over the price of an oil-fueled locomotive. A topical report, Integrated System Design Report was issued to DOE in July, 1989.

An economic analysis was performed on the investment in coal-fueled locomotives by calculating the fuel cost savings for three duty cycles and deducting the additional maintenance and operation costs. Production CWS costs were estimated by Otisca and Amax Research to be about $3.10/MBtu. The net savings were used to pay off the investment in locomotive and infrastructure at 15 and 20 percent depreciated rates of return (DCRR). The heavier duty cycles with more savings allow the investment to be justified at lower diesel fuel prices. An average duty cycle for eastern railroads could be justified at $0.91/gallon diesel fuel compared to the average

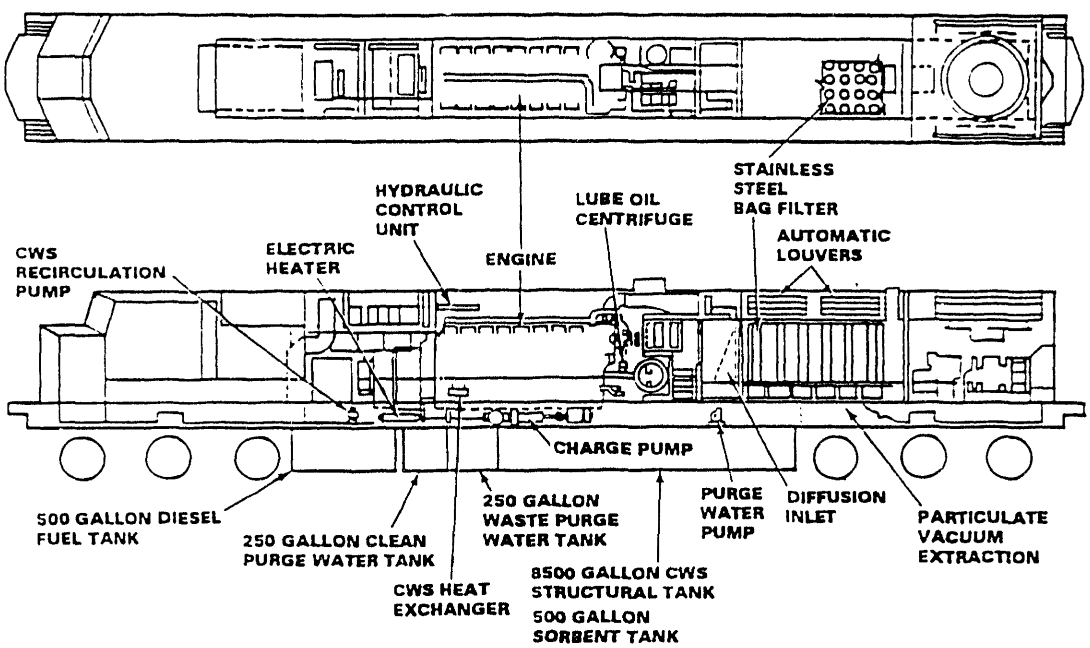


Fig. 1 Concept Coal-Fueled Diesel Locomotive

western duty cycle, which could pay off the investment at $0.81/gallon. The most attractive scenario was a unit coal train operating in Wyoming's Powder River Basin. This application had a heavy-duty cycle and a low-cost, readily available coal source, which combined to generate a very high level of fuel cost savings. The economic analysis showed that this "Best Case" application could be justified with diesel fuel as low as $0.47/gallon. A topical report, Coal Fueled Diesel Locomotive Conceptual System Economic Analysis, was issued to DOE in September, 1989. They are also described in [11] and [31].

Technology Research and Development

Fuels R&D. One of the tasks of the project is to investigate the combustion tolerance of injection hardware due to CWS fuel variations. The CWS fuel comparison tests were completed during 1990. Fuels were procured from Otisca of Syracuse, NY, 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 (over 98%) at engine full load. However, the engine required different combustion parameters and some possible hardware modifications for optimum performance with each fuel (ex. injector hole configurations etc.). A thorough description of the CWS fuel test results are in the topical report, Priliminary Investigation of the Effects of Coal-water Slurry Fuels on the Combustion in GE Coal Fueled Diesel Engine, released in June, 1990. They are also in [7] and [35].

Combustion R&D - Mechanical FIE Combustion Optimization. The first task of the combustion R&D is to develop a mechanical CWS FIE with a mechanical pilot/starting diesel fuel system based on the technology developed during the previous DOE contract. This system is to be built onto the first phase 12 cylinder engine and complete full scale engine test. This system does not have durable parts and could only run for a short period of time. It is intended to help identify some of the coal engine and locomotive system problems for better focus on R&D needs.

This task was completed in 1989. The mechanical FIE combustion system enabled CWS fuel to be successfully used from N8 (locomotive throttle position) full load down to N5 part load with over 90% burnout. Diesel fuel was used as pilot from N5 to N8 loads and all diesel fuel was used for the lower loads. The pilot fuel injector was also used to start the engine. Calculated for a tylical locomotive duty cycle, it used 66% CWS and 34% diesel fuel. A topical report, System II Positive Displacement Fuel Injection Equipment First Phase R&D Report, was issued in December, 1988. The results are also in [2] and [29].

Combustion R&D - Electronic Fuel Injection Hardware Development. All electronic controlled FIE systems, both for coal and diesel fuels, were developed under this part of the program. The main CWS system employs the previously (earlier DOE contract) developed accumulator injector with the capability of providing over 80 MPa injection pressure. Piston isolation pump replaced the diaphragm type to increase the pumping efficiency and the system reliability. The durability of the check valve used in the system was greatly improved by carefully designing the pressure decade characteristics created by the charge pump element.

The pilot injection system is an electronically controlled common rail type fuel injection system with a pressure intensifier built into each injector. It was developed by BKM, Inc. of Sandiego, CA for this project. The pilot system enables the engine to be started and idle with diesel fuel only. It can also provide the small amount of pilot fuel for partial and full load operation.

For both systems, the injection timing and duration are controlled by electrical pulses. The appropriate individual control signals are determined for best engine combustion during the single cylinder research engine test. They can later be programmed and executed by a master controller when used on the second phase coal fueled diesel engine. These are described in [11].

Combustion R&D - Pressure Chamber CWS Fuel Spray Investigation. Experiments were conducted at Texas A&M University (TAMU) to characterize coal-water slurry fuel sprays from diesel engine injectors. Since the combustion event is a strong function of the fuel spray, full characterization of the spray is a necessity for successful engine design and for modeling of the combustion process. Two experimental facilities were used at TAMU to study the injection of coal slurry fuels. The first experimental facility incorporates GE mechanical fuel injection system (injection pump, fuel line, and nozzle) and a specially designed diaphragm to separate the abrasive coal slurry fuel from the moving parts of the pump. The second experimental facility is based on the electronically controlled accumulator injector from GE. A pressurized visualization chamber was used to provide a spray environment which simulated the engine gas density and permitted the use of spray diagnostic techniques.

The study included high speed movies and direct photography of CWS sprays. Specific characteristics such as spray growth, penetration, shape, and cone angles were determined as functions of operating conditions and nozzle design. In addition to this overall characterization of the spray, this study also characterized the details of the atomization quality. A laser diffraction imaging technique was used to examine the atomization quality by measuring the droplet size and droplet size distribution in the spray. Both spatial and temporal droplet size variations were investigated in detail as a function of fuel injection pressure, nozzle orifice dimensions and background air condition. The drop-size measurement study in conjunction with the spray visualization provides a good knowledge base of isothermal CWS diesel sprays and insures a sound foundation for the study of CWS diesel engine combustion. A topical Report, Characterization of Coal-Water Slurry Fuel Sprays From Diesel Engine Injectors, was issued in June, 1993. Results are also reported in [10], [13], [17], [18], [23], [24], [25], [26], and [37].

Combustion R&D - Engine Combustion Computer Simulation. A combustion model has been developed for a direct injected diesel engine fueled with CWS and assisted by diesel pilot injection by Ricardo, North America. The model combines the unique heat and mass transport and chemical kinetic processes of CWS combustion with the normal in-cylinder processes of a diesel engine. It includes a two stage evaporation submodel for the drying of the CWS droplet, a global kinetic submodel for devolatilization, and a char combustion submodel describing surface gasification by oxygen, carbon-dioxide and water vapor. The combustion volume is discretized into multiple zones, each of whose individual thermochemistry is determined by in-situ equilibrium calculations. This provides an accurate determination of the boundary conditions for the CWS droplet combustion submodels and the gas phase heat release. A CWS fuel jet development, entrainment and mixing submodel is used to calculate the mass of unburned air in each of the burned zones. A separate submodel of diesel pilot fuel combustion is incorporated into the overall mode, as it has been found that pilot fuel is required to achieve satisfactory combustion under many operating conditions.

The combustion model is integrated with an advanced engine design analysis code, IRIS, which is also developed by Ricardo. Simulations have been performed from generating maps of fuel consumption rate and peak pressure at each notch (locomotive throttle load and speed) setting, thus allowing selection of the best combination of CWS and pilot injection timing under the constraint of maximum firing pressure. In addition, the model has been used as a tool to explore the tradeoffs between different operating options. Detail description of this task and results are in the topical report, Development and Application of a Comprehensive Model for Pilot-Ignited Coal/Water Mixture Combustion in a Direct Injection Diesel Engine, Sept., 1991, and references [3] and [8].

Combustion R&D - Single Cylinder Engine Combustion Optimization. Extensive CWS combustion optimization study was completed on the single cylinder engine. The goal is to provide the highest combustion efficiency (burnout rate) while not exceeding the firing pressure limit 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 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"). As a result of optimization, the combustion efficiency at full engine load reached 99.5%. Details of all the findings are documented in a topical report, Coal Slurry Combustion Optimization on Single Cylinder Engine, September, 1992, and references [12] and [15].

Combustion R&D - In-Cylinder Combustion Photography Study. The high speed in-cylinder combustion photography study is conducted to better understand and improve the engine performance. In the photographs, distinct flames of pilot and CWS combustion were noticed. It was proven that the coal fuel burns after piston impingement and secondary atomization. Agglomerated particles will develop when combustion conditions are not favorable. Cylinder pressure data were simultaneously recorded for each film frame. Heat release data can thus be produced for each photo study. Most of the findings of earlier combustion studies on engine performances were confirmed. Detail findings are summarized in a technical paper [21].

Emissions R&D. The goal for emissions control was to reduce the pollutant levels of the coal engine to the levels of a conventional diesel engine. Achieving the minimum goal requires a reduction of approximately 50% in SO_2 emissions and a 90 to 95% reduction in particulate emissions, the actual percentages varying with the fuel. NOx emissions from the coal diesel are approximately 50% of the conventional diesel level.

The space limitations on board the locomotive present the greatest obstacle to the design of an emissions control system. The cleanup system must be compact as well as multifunctional. The development of a particulate collection device was undertaken by GE Environmental Services, Inc. (GEESI). Among the options evaluated were high-temperature metal filters, cyclones, and a granular bed. The development of a cleanup method for SO_2 and possibly NOx was undertaken at GE/CRD. A process was sought which could incorporate one of the particulate removal devices under consideration.

At GE Corporate Research & Development, bench scale tests were conducted to investigate the effectiveness of using both the copper oxide (CuO) supported pellets and the CuO/Al_2O_3 powder to remove sulfur in the emissions. Later, a small size Yanmar engine was set up with the exhaust gas passing through candle type stainless steel filters. The filters were 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. This effort is described in [39].

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 in the topical report, Characterization and Control of Exhaust Gas from Diesel Engine Firing Coal-Water Mixture, March, 1990, as well as [4] and [32].

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:

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

The expected individual emission removal efficiencies of the system are:

- Particulate 99%
- SO_2 90%
- NOx 85%

A cold flow facility of the envelop type barrier filter has been built and successfully flow tested. It was designed into a partial hot flow single cylinder engine test system of 500 acfm capacity. Test on actual engine of this system confirmed the effectiveness of the selected cleanup methods chosen. Details of this part of the program has been presented in the technical papers [22] and [41].

Durability R&D. The abrasive and erosive nature of coal water slurry and its combustion products impaired previous development of the coal fuel engine. Earlier tests demonstrated that the primary wear componenets in a coal-fueled diesel engine were injector nozzle tips, piston rings, and cylinder liners. The development of suitable materials and processes for these parts were undertaken at GE/CRD.

The development of an erosion resistant nozzle for the coal-fueled locomotive was given the highest priority.

Extensive dry erosion and orifice flow erosion tests were conducted. Results demonstrated that nozzles built of synthetic diamond would withstand the erosive nature of the high-velocity slurry. Nozzles with diamond orifices were designed, fabricated, and sucessfully tested in an actual engine.

The development of piston rings and cylinder liners that could withstand the abrasive nature of the coal-ash deposited on the combustion liner was also a high-priority activity. Pin-on-disc and ring segment bench scale tests were used to select optimized materials and processing conditions for plasma-deposited coatings. Tungsten carbide/cobalt was the material of choice for both the ring and liner. Small-scale engine components were built and tested. The materials performed very well. Large engine components were built and tested in the durability engine at GE/TS engine lab. Finally, tests were conducted to identify the optimum plasma spray processing conditions for deposits of tungsten carbide/cobalt mixtures.

Details of the studies have been summarized in the topical report, Improved Materials for Durable Rings, Liners, and Injector Nozzles, R&D Final Report: Durability, December, 1991, as well as [9], [19], [30] and [33].

Engine Systems Verification

Mechanical FIE 12 Cylinder Engine System. The mechanical FIE 12-cylinder coal-fueled engine was modified from a General Electric model 7FDL diesel engine by having dual positive-displacement fuel injection systems. A cross section of one of the 12 cylinder layout is shown in Fig. 2. The fuel injection system for CWS is used exclusively at higher loads. The CWS main injector is centrally mounted in the combustion chamber, with a nozzle having ten holes of 0.55mm diameter. The pilot injector is mounted off-center in the cylinder head and sprays into the combustion chamber from the side through four unequal holes (two 0.50mm, two 0.30mm). The diesel fuel injection system provides both a small amount of pilot to enhance coal combustion and large amounts of diesel fuel for starting and low loads. The pilot diesel fuel pump is mounted on the side of the engine. A unique mechanical fuel-rack linkage controls the amount of both CWS and diesel fuel injected into the cylinders on the 12-cylinder coal fueled diesel engine. The linkage synchronizes both CWS main and diesel fuel pilot injection pumps on all twelve cylinders during start up, acceleration on diesel fuel, transition to coal combustion, and high power running on CWS. This engine was operated for 10 hours at up to 1880 kW at 1050 rpm. Details of the design and testing of this engine are in [14], [34] and [38].

Stage II Electronic Controlled FIE 12 Cylinder Engine. The Phase II coal fueled diesel engine was also constructed by modifying a production GE 7FDL12 engine. The cylinder liner and

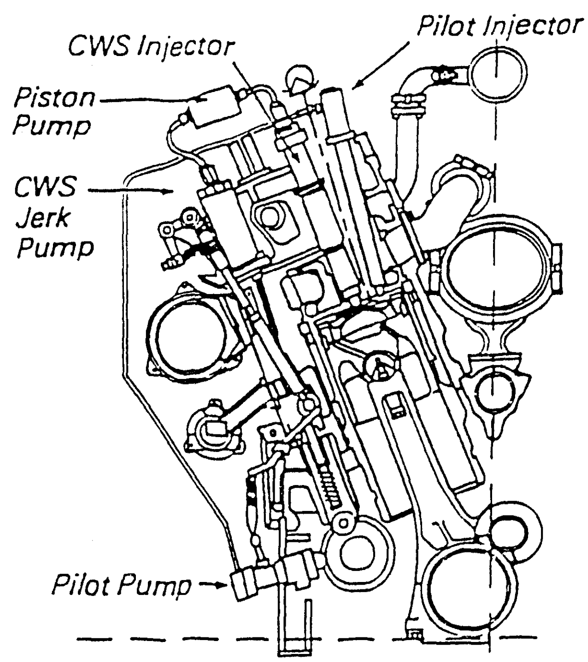


Fig. 2 Mechanical FIE Engine

the piston rings of this engine were Tungsten Carbide coated for wear resistance. It also has the full size emission control system to cleanup the exhaust gas. The cross section of one of the 12 cylinders is shown in Fig. 3. This engine has a dual accumulator type fuel injection system with electronic control. One system, the main system, is used to inject CWS into the combustion chamber when the engine is under load. The second system, the pilot injection system, is used to idle the engine, to provide a source for ignition in the low horsepower notches, and to enhance combustion under full load. Both systems are electronically controlled and independent of one another. A master controller was developed by Woodward Governor Co. of Ft. Collins, CO. Each injector subsystem, pilot or coal, is watched over by the master controller which governs engine speed and engine safety parameters such as oil pressure and water temperature. The master controller also determines injection timing and injection duration for each load and speed

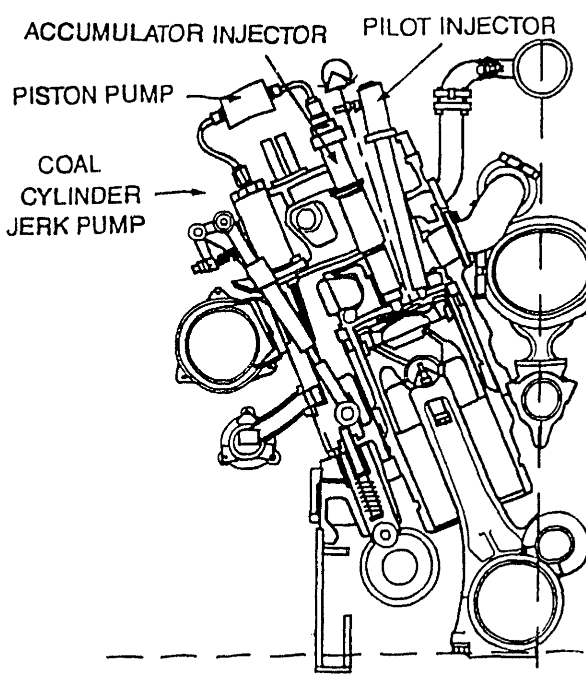


Fig. 3 Electronic FIE Engine

combination (Notch) and provides an interface for Notch selection from the operator. This engine is presently under test at GE/TS engine laboratory.

12 Cylinder Engine Emission test. A simplified flow diagram of the emissions control system is illustrated in Fig. 4. This system was designed by GEESI and installed at GETS engine laboratory. It is presently being tested.

Gas enters the system by passing through a two-way bypass/isolation damper. The ductwork system upstream of the envelope filter casing is compact and encloses a sorbent storage hopper. Sorbent particulate is metered into the gas stream by a rotary feed valve. The sorbent may be a regenerative type, copper oxide coated on alumina particles, or a throwaway type, Nahcolite/sodium bicarbonate. Process stoichiometry using copper oxide sorbent removes exhaust gas SO_2 by the formation of copper sulfate. Ammonia gas injected into the exhaust gas, in the presence of copper sulfate, produces a reduction of NOx. However, when throwaway Nahcolite/sodium bicarbonate sorbent is used, there is no reduction of NOx accomplished.

Exhaust gas, including the sorbent/precoat and CWS ash particulates, enters the filter through a plenum at the top of the casing. The barrier filter elements, made of a compaction of Inconel metal fibers, consist of 28 two sided envelopes approximately 6 ft. high by 6 ft. wide and produce approximately 2000 sq. ft. of filtration area and a filtration velocity (air/cloth ratio) of 10 ft./min. Entry of the gas into the top inlet plenum results in gas flow in a general downward direction to approach the filter media. The combination of downward gas flow and the baffles creates a favorable situation for direction of collected particulates downward into the filter hopper.

Particulate is collected on the out-side of the envelope filters. Cleaned gas exits from the envelopes to one side into a cleaned gas plenum and exits the filter system in an upward direction. The design of the entire envelope filter system is consistent with the size and space constraints required for installation on a CWS fuel diesel engine locomotive. Cleaning of the envelope filters is accomplished by a high pressure air directed into the interior of the envelopes. It creates a short duration reverse flow through the filter media to remove collected particulates. Cleaning control may be automatic, controlled by filter pressure drop, or manual activation at any time for any desired duration. It is expected that maximum filter pressure drop will be controlled to a range of 10-15 in. H_2O pressure drop.

Engine Test of Durable Parts. Components specifically designed for running in a medium speed coal fueled diesel engine were durability tested. The test bed was a slightly modified General Electric model 7FDL V-8 diesel engine, with the left bank provided with two durability cylinders to run on coal water slurry fuel using #2 diesel fuel as pilot and the right bank standard. The other two cylinders on the left bank provided the pilot to the coal fueled cylinders and produced no power. A standard four-pipe exhaust manifold allowed both the two coal fueled cylinders and the two dummy cylinders to be isolated in the exhaust up-stream of the turbocharger turbine. The engine is started on the right bank; the coal fueled durability cylinders are then brought on line at full speed, half load. Components tested include: tunsten carbide coated cylinder liners and piston rings, and fuel injection nozzles for CWS fuel operation. 200 cylinder hours have been run on the above various parts. Results are presently being evaluated.

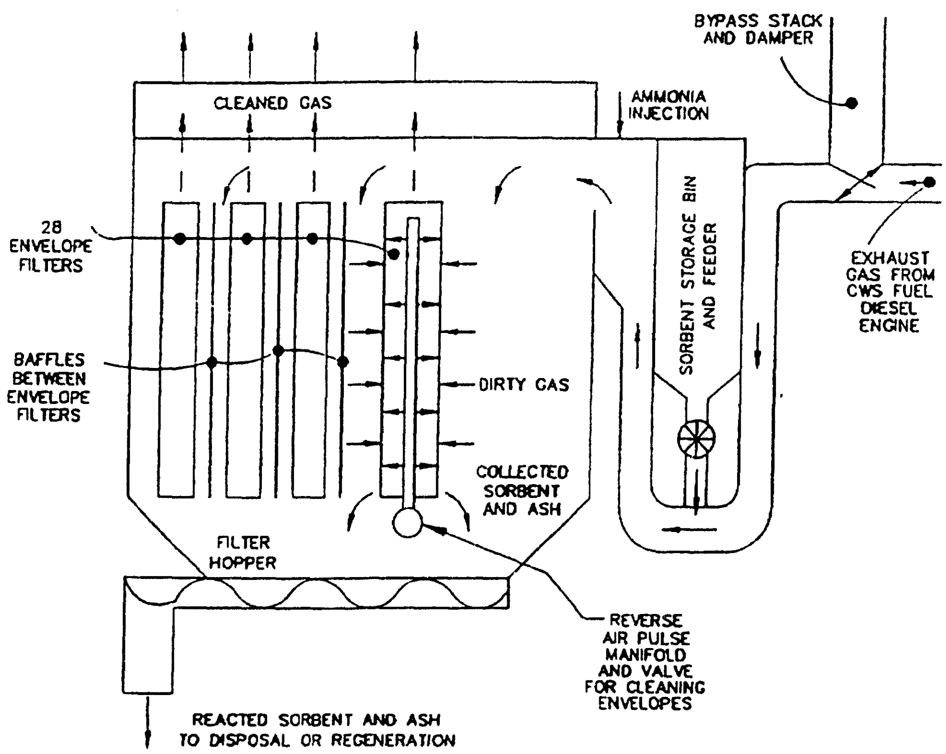


Fig. 4 Emissions Cleanup System Schematic

Locomotive System Test.

The main thrust of the first stage coal-fueled diesel locomotive testing was to verify that the various engine support and control systems functioned as required, gaining operational experience and identifying problems. A test locomotive, GE 609, was modified for this test. It is a model C39-8, a microprocessor controlled, six-axle locomotive, having motor-driven blowers, radiator fans, and air compressor. The first stage 12-cylinder coal-fueled diesel engine was installed in this locomotive after completion of testing in the GE diesel engine laboratory.

The first stage coal-fueled diesel locomotive testing included a fuel tender car coupled to its rear, see Fig. 5. The fuel tender uses a railroad flatcar to carry the tanks, pumps, valves, and associated controls for the first stage locomotive CWS fuel system. CWS is supplied to the locomotive from the tender, along with purge water. Having a separate fuel tender car facilitated testing to study problems related to CWS mixing, long-term storage, freezing, and variations in coal loading within a large tank.

Locomotive testing included both stationary testing and running on the GE/TS Erie test track. During the stationary test, the locomotive runs in self-load mode. After some system debugging, self-load test of the locomotive was successful. It made the transitions from starting with diesel fuel both into and out of coal combustion and purging the CWS fuel injectors prior to shutdown. The test track at GE/TS is about 4 miles long. For the track run, two diesel-electric locomotives, operating in dynamic braking mode, were used as load units for the coal-fueled diesel locomotive (GE 609) to simulate a trailing train. After the completion of the stationary test, successful track test runs were made in November of 1991.

Many locomotive systems operation requirements on engine were learned. They included the sudden load change needed on the engine during "wheel slip" and the requirement on the engine during "tunnel operation" mode. The first locomotive system did not have provisions to accommodate these. However, for future railroad test, they have to be designed into the control system of the engine. A video tape was made of the actual test run and presented to the DOE Contractors' Review Conference and the ASME coal-fueled diesel meeting in 1992. A technical paper [40] was written describing the details of the test.

Conclusions

Important achievements in technology have been made in bringing a coal fueled diesel engine for locomotive application into reality. Approximately 500 hours of engine operation has been accumulated

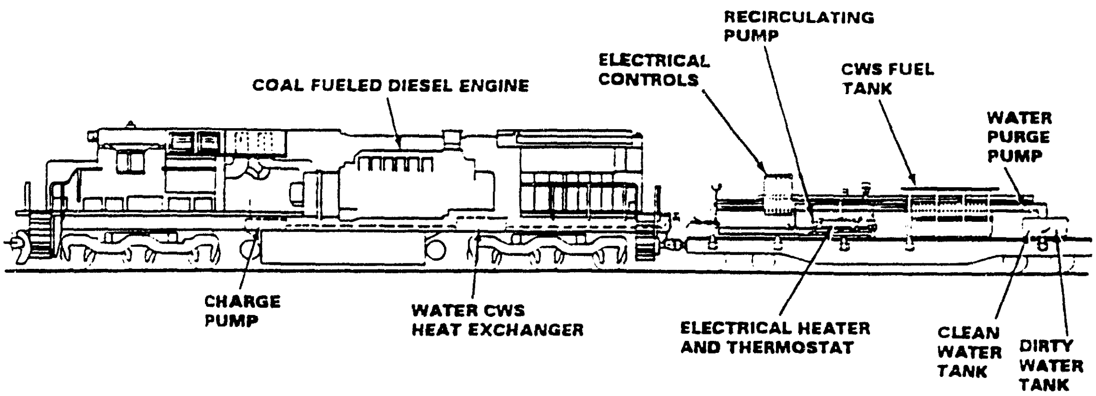


Fig. 5 Stage I Locmotive Test Configuration

with coal fuel. Due to the persistent low oil prices and the federal budget deficit, the present program scope was reduced. However, the critical technologies developed are retained and summarized in the completion of the second phase electronic controlled FIE engine with its emissions cleanup system. When market environment becomes favorable in the future, the technologies can be further improved and packaged into a commercial system very quickly.

REFERENCES

Publications in Technical Society Literatures

[1] Flynn, P.L., "Coal Fueled Locomotives: Energy Independence and Economic Sense," National Coal Association publication Landmarc, 1989.

[2] Flynn, P.L., Hsu, B.D. and Leonard, G.L., "Coal Fueled Diesel Engine Progress at GE Transportation Systems," ASME Transactions, Journal of Engineering for Gas Turbines and Power, Vol. 112, No. 3, July 1990, pp. 369-375.

[3] Wahiduzzaman, S., Blumberg, P.N., Keribar, R. and Rackmil, C.I., "A Comprehensive Model for Pilot Ignited, Coal Water Mixture Combustion in a Direct Injection Diesel Engine," ASME Transactions, Journal of Engineering for Gas Turbines and Power, Vol. 112, No. 3, July, 1990, pp. 384-390.

[4] Slaughter, D., Cohen, M., Samuel, E., Mengel, M., and Gal, E., "Control of Emissions in the Coal Fueled Diesel Locomotive," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 12, 1990, pp. 11-16.

[5] Hapeman, M.J., "Review and Update of the Coal Fired Diesel Engine," University of North Dakota Energy and Environmental Research Center, Preprints of the Opportunuties in the Synfuels Industry Proceedings, August 27-29, 1990.

[6] Rairden, J.R., Mehan, R.L. and Giammarise, A.W., "The Effects of Processing Conditions on the Wear Resistance of Plasma Sprayed WC-Co Coatings," Proceedings of the DOE Conference on Coatings for Heat Engines, Meeting held in Castine, Maine, August, 1990

[7] Hsu, B.D. and Confer, G.L., "Progress on the Investigation of Coal-Water Slurry Fuel Combustion in a Medium Speed Diesel Engine: Part 4 - Fuels Effect," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 14, 1991.

[8] Wahiduzzaman, S., Blumberg, P.N. and Hsu, B.D., "Simulation of Significant Design and Operating Characteristics of a Coal Fueled Locomotive Diesel Engine," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 14, 1991.

[9] Mehan, R.L., Flynn, P.L. and Giammarise, A.W., "Evaluation of Piston Ring Materials in Oil Containing Abrasive Using a Ring-On-Block Test Machine," Wear (Elsevier Sequoia S.A., Lausanne), No. 147, 1991, pp. 41-57.

[10] Caton, J.A., Kihm, K.D., Seshadri, A.K. and Zicterman, G., "Micronized Coal Water Slurry Sprays from a Diesel Engine Positive Displacement Fuel Injection System," Proceedings of the Central States Section /Combustion Institute Spring Technical Meeting, April, 1991, pp. 361-366.

[11] Hsu, B.D., "Coal Fueled Diesel Engine Development Update at GE Transportation Systems," ASME Transactions, Journal of Engineering for Gas Turbines and Power, Vol. 114, No. 3, July, 1992, pp. 502-508.

[12] Hsu, B.D., Confer, G.L. and Shen, Z.J., "Progress on the Investigation of Coal-Water Slurry Fuel Combustion in a Medium Speed Diesel Engine: Part 5 - Combustion Studies," ASME Transactions, Journal of Engineering for Gas Turbines

and Power, Vol. 114, No. 3, July, 1992, pp. 515-521.

[13] Seshadri, A.K., Caton, J.A., and Kihm, K.D., "Coal Water Slurry Spray Characteristics of a Positive Displacement Fuel Injection System," ASME Publication, ASME Transactions, Journal of Engineering for Gas Turbines and Power, Vol. 114, No. 3, July, 1992, pp. 528-533.

[14] McDowell, R.E., Basic, S.L. and Confer, G.L., "Design and Operation of a Medium Speed 12-Cylinder Coal-Fueled Diesel Engine," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 16, 1992, pp. 33-38.

[15] Hsu, B.D., Shen, Z.J. and Caton, J.A., "Combustion Characteristics of Coal-Water Slurry Fuel in a Medium Speed Diesel Engine," Proceedings of the Ninth Annual International Pittsburgh Coal Conference, Pitts., PA, October, 1992, pp. 335-340.

[16] Hsu, B.D., Johnson, R.N. and Jones, A.G., "Fuel Injection Equipment for a Coal-Water Slurry Fuelled Medium Speed Diesel Engine," I. Mech. E. Publication (UK), Diesel Fuel Injection Systems, 1992, pp. 45-52.

[17] Kihm, K.D. and Caton, J.A., "Synchronization of a Laser Fraunhofer Diffraction Sizing Technique with Intermittent Spray Systems," Journal of Applied Optics, Vol. 31, No. 23, 1992, pp.1914-1916

[18] Caton, J.A., Seshadri, A.K., and Kihm, K.D., "Spray Tip Penetration and Cone Angles for Coal Water Slurry Using a Modified Medium-Speed Diesel Engine Injection System," Proceedings of the Central States Section /Combustion Institute Spring Technical Meeting, April, 1992, pp. 234-239.

[19] Gray, D.M., Rairden, J.R. and Giammarise, A.W., "A Parametric Study of the Effects of Processing Conditions on the Wear Resistance of Plasma Sprayed WC-Co Coatings," Presented to the International Conference on Metallurgical Coatings and Thin Films, Sandiego, CA, April 4-10, 1992.

[20] Hapeman, M.J. "The Coal Fired Locomotive Development," Presented to the 15th Annual Seminar on Transportation Polies and Coal Distribution (National Coal Association), Sarasota, FL, January 29-31, 1992.

[21] Hsu, B.D. and Branyon, D.P., "Progress on the Investigation of Coal-Water Slurry Fuel Combustion in a Medium Speed Diesel Engine: Part 6 - In-Cylinder Combustion Photography Studies," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 19, 1993, pp. 15-24.

[22] Cook, C., Gal, E., Mengel, M., and Van Kleunen, W., "Coal-Fuel Diesel Emissions Control Technology Development," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 19, 1993, pp. 9-14.

[23] Caton, J.A., Payne, S.E., Terracine, D.P., and Kihm, K.D., "Coal Water Slurry Atomization Characteristics of an Electronically Controlled Accumulator Fuel Injection System," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 19, 1993, pp. 25-32.

[24] Kihm, K.D., Terracine, D.P., Payne, S.E., and Caton, J.A., "Synchronized Droplet Size Measurements For Coal-Water Slurry Diesel Sprays of an Electronically-Controlled Accumulator Fuel Injection System," ASME Publication, Coal Fueled Diesel Engines, ICE Vol. 19, 1993, pp. 33-42.

[25] Kihm, K.D., Terracine, D.P., Payne, S.E., and Caton, J.A., "Properly Synchronized Measurements of Droplet Size For High Pressure Intermittent Coal-Water Slurry Diesel Sprays," Proceedings of the 1993 Joint Central and Eastern States Section /Combustion Institute Spring Technical Meeting, Paper No. 50, pp. 271-275, March, 1993.

[26] Caton, J.A., Payne, S.E., Terracine, D.P., and Kihm, K.D., "Coal Water Slurry from an Electronically Controlled Accumulator Fuel Injection System: Break-up Distances and Times," Proceedings of the 1993 Joint Central and Eastern States Section /Combustion Institute Spring Technical Meeting, Paper No. 76, pp. 404-409, March, 1993.

Publications in DOE Annual Heat Engine Conference Proceedings

[27] Flynn, P.L., B.D. Hsu, G.L. Leonard, and C.S. Cook. 1988. Coal-Fueled Diesels "Proof of Concept" Program. Fifth Annual Conference Proceedings, 11-19. DOE/METC-88/6094.

[28] Flynn, P.L., B.D. Hsu, G.L. Leonard, and C.S. Cook. 1989. Coal-Fueled Diesels for Locomotives. Sixth Annual Conference Proceedings, 79-90. DOE/METC-89/6101.

[29] Hsu, B.D. 1989. Coal-Fueled Diesel Technology Development GE Single Cylinder Diesel Engine Results. Sixth Annual Conference Proceedings, 169-175. DOE/METC-89/6101.

[30] Mehan, R.L., G.L. Leonard, and R.N. Johnson. 1989. Hardened Materials in Coal-Fueled Diesels. Sixth Annual Conference Proceedings, 211-225. DOE/METC-89/6101.

[31] Flynn, P.L., B.D. Hsu, G.L. Leonard, and C.S. Cook. 1990. Coal-Fueled Diesel Locomotives Overview. Seventh Annual Conference Proceedings, 11-22. DOE/METC-90/6110.

[32] Gal, E., E.A. Samuel, and M. Cohen. 1990. Coal-Fueled Diesel Technology Development Emissions: A Status Report. Seventh Annual Conference Proceedings, 206-215. DOE/METC-90/6110.

[33] Mehan, R.L., J.R. Rairden, and A.W. Giammarise. 1990. Wear Resistant Materials and Processes for the 7FDL Diesel Engine. Seventh Annual Conference Proceedings, 328. DOE/METC-90/6110.

[34] McDowell, R.E., G.L. Confer and S.L. Basic. 1990. 12-Cylinder Coal-Fired Engine Design. Seventh Annual Conference Proceedings, 440. DOE/METC-90/6110.

[35] Hsu, B.D., and G.L. Confer. 1990. Coal-Fueled Diesel Engine Performance - Fuels Effect. Seventh Annual Conference Proceedings, 262-271. DOE/METC-90/6110.

[36] Hsu, B.D., A.K. Kalafala, and C.S. Cook. 1991. Coal-Fueled Diesel Locomotives Overview. Eighth Annual Conference Proceedings, 72-80. DOE/METC-91/6122.

[37] Caton, J.A., and K.D. 1991. Coal-Water Slurry Atomization Characteristics. Eighth Annual Conference Proceedings, 273-282. DOE/METC-91/6122.

[38] McDowell, R.E., G.L. Confer and S.L. Basic. 1991. Design and Operation of a Coal-Fueled 12-Cylinder Medium Speed Diesel Engine. Eighth Annual Conference Proceedings, 283-292. DOE/METC-91/6122.

[39] Gal, E., W. Van Kleunen, R.W. Hamilton, and M. Cohen. 1991. Coal-Fueled Diesel Emissions Control Technology Development: A Status Report. Eighth Annual Conference Proceedings, 459-466. DOE/METC-91/6122.

[40] McDowell, R.E., G.L. Confer and S.L. Basic. 1992. Coal Fueled Diesel Locomotive Test. Ninth Annual Conference Proceedings, 39-50. DOE/METC-93/6129.

[41] Gal, E., M. Mengel, and W. Van Kleunen. 1992. Coal-Fueled Diesel Emissions Control Technology Development: A Status Report. Ninth Annual Conference Proceedings, 190-197. DOE/METC-93/6129.

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