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Clean Coal Diesel Demonstration Project

A DOE Assessment

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EXECUTIVE SUMMARY

The U.S. Department of Energy's (DOE's) Clean Coal Technology (CCT) Program seeks to offer the energy marketplace more efficient and environmentally benign coal utilization technology options by demonstrating these technologies in industrial settings. This document is a DOE post-project assessment of the Clean Coal Diesel Demonstration Project, one of the projects selected in Round V of the CCT Program. Coal-water fuel (CWF) is an alternative to conventional petroleum-derived diesel fuel for firing a diesel engine that powers a generator. Development of a diesel engine burning CWF would not only decrease our dependence on imported crude oil but would also use our most abundant domestic fuel—coal. This project consisted of the installation, at the University of Alaska in Fairbanks (UAF), of an 18-cylinder diesel engine designed for coal-fueled operation and the testing of a two-cylinder, coal-fueled diesel engine in Wisconsin. The original Cooperative Agreement was awarded in 1994, and the project was withdrawn in 2006 by mutual agreement between TIAX LLC and DOE. Project cost was $41.6 million; DOE provided 50 percent of the total project funding.

As presented in the initial Cooperative Agreement, the overall objective of this project was to demonstrate an advanced coal diesel engine combined cycle (CDCC) technology for 6,000 hours of operation, based on Cooper-Bessemer's LSB/LSVB diesel engine series, at Easton Utilities in Maryland. The CDCC system was to utilize CWF and demonstrate high efficiency while generating cost-competitive, environmentally compliant electric power. It was anticipated that CDCC technology could become commercialized beginning in 2000. When Easton withdrew because the projected increase in capacity demand did not materialize, the project was relocated to UAF.

For a variety of reasons, the goal of this project was not achieved. Although a CWF-ready 18-cylinder diesel engine was built and installed at UAF, no source of CWF for this engine was located. As a result, the engine was not operated on CWF, although it could be in the future. As an alternative, it was decided to perform CWF testing on a two-cylinder engine at Fairbanks Morse's engine test facilities in Wisconsin. Since, on a per cylinder basis, the 18-cylinder engine at UAF and the two-cylinder engine at Beloit were essentially identical (same horsepower, emissions, fueling rate, wear, exhaust flow, etc.), it was felt that this change to the project would still provide valid data. The Fairbanks Morse engine was run successfully for a little over one hour on CWF, long enough to demonstrate several important points:

- The special CWF injectors functioned well.
- The CWF fuel ignited and burned well with no cylinder deposits.
- Engine efficiency was as expected.
- Emissions were quite low, even without the selective catalytic reduction unit.
- Fairbanks Morse gained the know-how to build and operate a diesel engine burning CWF.

These are all short-term conclusions; more run time is needed to confirm them. Additional run time was planned but was not carried out, primarily because matching cost share did not materialize during an extended hiatus in testing. Also, modifications to the test facility were required before further testing could take place because carryover of incompletely burned coal particles caused a fire in the baghouse and damaged some of the bags. Although a design to solve this problem was developed, it was not implemented. No further CWF tests were conducted before the project was withdrawn.

Like gasoline engines, diesel engines are internal combustion engines that generate power by the combustion of fuel in a cylinder. The major difference between these engines is that gasoline engines use spark ignition, whereas diesel engines use compression ignition. When a gas is compressed, its temperature rises. In a diesel engine, air is compressed, and when fuel is injected into this hot air, combustion occurs. Because coal is a solid that can cause erosion of engine parts, some modifications are necessary to enable operation with CWF. The fundamental challenge of a diesel engine burning CWF is to protect the moving parts of the engine that are exposed to either the CWF, which is abrasive, or the solid particulate products of combustion, which contain both ash and traces of unburned coal. Specific engine components that need protection include the fuel injection pump system and nozzle tip, piston rings and liners, exhaust gas valves and seats, turbocharger rotors and blades, and crankshaft bearings that require protection from contaminants picked up in the oil, such as ash.

CWF is a slurry made by mixing pulverized coal with water in approximately a fifty-fifty mixture, plus a small quantity of additives. It is black, with an appearance similar to that of crude oil, and has complex flow and combustion characteristics. Important properties of an acceptable CWF include a low settling rate of solid particles, tolerance to flow at the high shear rates encountered in diesel injection systems, adequate atomization and evaporation of slurry sprays, and a particle size small enough for ignition and combustion at conditions achievable in diesel engines. Additives are normally used to improve CWF properties. With bituminous coals, cleaning to reduce the ash content is typically all that is required to prepare the coal for CWF production. However, with Alaskan subbituminous coal, more complex preprocessing is required to reduce the coal's moisture content and to seal the coal particle surfaces.

Effective controls for nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate emissions are essential for the successful commercialization of stationary diesel engines burning CWF. The clean coal diesel installed at UAF included an exhaust-gas treatment system, consisting of a selective catalytic reduction (SCR) unit for NO_x control, a sorbent injection system for SO_x control, and a cyclone and baghouse for particulate control.

This project was implemented in three phases. As originally specified, Phase 1 consisted of the development of designs, specifications, and engineering drawings for all systems necessary to construct and operate a 14-MWe, CWF-fired CDCC at Easton Utilities' Plant No. 2. The CDCC was to consist of two 20-cylinder Cooper-Bessemer LSVB diesel engines, nominally rated at 315 kW/cylinder (6.3 MWe per engine) plus a 1.4 MWe steam bottoming cycle. Part of Phase 1 included modification and operation of Cooper-Bessemer's six-cylinder Model LSC-6 lab engine on CWF for 1,000 hours minimum and the design of a CWF preparation facility. When Easton Utilities withdrew from the project because their anticipated need for additional capacity did not materialize, the project was relocated to UAF and involved a single 18-cylinder engine without a steam-bottoming cycle. After only a portion of the planned 1,000 hours of engine testing at their facility was performed, Cooper-Bessemer withdrew from the project because of a decision in 1997 that they would no longer produce diesel engines.

Phase 2 consisted of engine fabrication, delivery, and installation; emissions control-system design, fabrication, and installation; and design of the supporting CWF preparation plant. A coal diesel engine, supplied by Fairbanks Morse, was installed at UAF.

Phase 3 involved operation of the CWF diesel. Subsequent to awarding the Cooperative Agreement, several changes to the Statement of Work (SOW) were made to accommodate the changing circumstances. When the project was moved to UAF, it was intended to build and operate a CWF plant based on Alaskan coal. However, as the design of this unit progressed, the estimated cost exceeded the budget allocation, so it was not feasible to proceed with construction. Therefore, the SOW was modified to permit purchase of CWF from an outside supplier, but this did not solve the problem, since Alaskan subbituminous coal requires a specialized pre-processing facility and no outside supplier was found who would build and operate such a facility.

The lack of a source of CWF made it impossible to perform the desired engine testing at UAF. Therefore, in 2003 the SOW was again modified to move engine testing to Fairbanks Morse’s engine test facility at Beloit, WI, and make use of a two-cylinder test engine. Two fuels were to be tested, a CWF based on Alaskan coal supplied by the University of North Dakota’s Energy & Environmental Research Center (EERC) and a CWF based on Kentucky coal. Ultimately, the EERC’s CWF was successfully run for one hour and nine minutes on the first attempt. This was a significant achievement, paving the way toward longer term operation. Earlier pioneering tests at Copper Bessemer had required over a year of intermittent ten-to-fifteen minute runs before a continuous one-hour run was achieved.

During this test period, coal slurry fuel was successfully injected, ignited, and burned in a Fairbanks Morse Model PC2 Engine. The pilot and main CWF injectors worked without problems, the expected net power was produced, and the combustion diagnostics showed good combustion (although there was some variation from cycle to cycle). No problems were experienced during the switchover from diesel fuel to CWF and back to diesel fuel. Injector traces showed that the fuel injection into the cylinder was repeatable and consistent, although some engine tuning is needed to improve performance.

The cyclone used successfully in the earlier Cooper Bessemer engine tests was not installed for the Fairbanks Morse engine tests. This lack allowed glowing coal embers to be carried into the exhaust ducting. As a result, a fire was inadvertently ignited in the baghouse, and some bags were damaged. TIAX and Fairbanks-Morse developed a cost-effective remedy to this problem, but it was not implemented, and no further CWF tests were run as part of this project.

At a 25 percent engine load, the engine-out NO_x level was only 150 parts per million (ppm) or 0.45 pounds per million BTU, compared to 430 ppm for diesel fuel operation (60 percent reduction). This was an engine-out figure, and the stack NO_x level will be 80 to 85 percent lower because an SCR unit is part of the design. The estimated stack emission at a 25 percent load would be about 30 ppm or 0.09 pounds per million BTU, which is well below the required standard for coal-fired power plants.

The potential market for coal diesel engines and associated CWF process plants, as estimated in the final report is 60 CWF plants worldwide with a CWF production rate of 60 million tons per year (1 percent of world coal consumption). Estimated potential power capacity of CWF diesels is 30,000 MW (150 billion kWh per year, assuming each engine runs 5,000 hours per year at full load, or 0.8 percent to 1.2 percent of worldwide generation capacity).

Economics are based on information provided by TIAX LLC in the final report, except that a capital charge factor of 0.124 for constant dollar estimates was used; TIAX LLC used a factor of 0.089, which seems low. A 10 MW coal diesel engine is projected to cost $15 million installed ($1,500 per kW), including $240 per kW for emissions control equipment. The estimated maintenance and overhaul costs for a coal diesel (6 MW engine) amount to $190,000 per year versus $70,000 per year for a comparable conventional diesel or natural gas engine of equivalent size. Emissions control operating costs are estimated at 1.4 to 1.8 cents per kWh, depending on engine size. The estimated cost of CWF is about $3.70 per million Btu at the plant gate, based on a coal cost of about $45 per ton, including CWF delivery cost averaging about $0.50 per million Btu. Based on these values, and assuming a capital charge factor of 0.124, the estimated cost of power from a diesel/generator set operating on CWF is 11.7 cents per kWh (current dollars).

The coal diesel engine can be compared with competing technologies by back-calculating the prices of diesel fuel and natural gas that give the same price per kWh of electricity as for the coal diesel engine. This calculation shows that the coal diesel engine is competitive with a conventional diesel engine at any diesel-fuel price above $1.27/gallon, but the price of natural gas must be higher than $9.90 per million Btu before the coal diesel engine is competitive.

Commercialization of the clean coal-diesel technology confronts the proverbial “chicken and egg” problem. Achieving successful commercialization will require both a coal diesel engine supplier and a CWF supplier. No company is likely to manufacture coal diesel engines if no CWF supply is available, and no company is likely to invest in CWF production facilities if no market exists for the product. This project was intended to overcome this dilemma by demonstrating a commercial-size engine and constructing a CWF plant to supply the necessary fuel. As indicated above, the CWF plant was not built; and, although an 18-cylinder coal diesel engine was installed at UAF, it was prevented from running on CWF by lack of a CWF supply. As a result, commercialization will remain problematic until a diesel engine burning CWF has operated long enough to ensure reliability and establish operating costs.

This project showed that a diesel engine burning CWF has the potential to meet the efficiency and emissions targets. However, longer run times are needed to estimate useful lifetimes of certain engine components, particularly the useful life of piston rings and exhaust valves. Thus, the next step toward commercialization is a field demonstration program with 6,000 hours of engine run time on coal fuel. This will require a minimum of three years due to the need to conduct the work in several lengthy test periods, rather than by continuous operation. Therefore, even if a test run were started today, commercial introduction (plant orders) would not be possible until sometime beyond 2010, assuming a successful field demonstration and a favorable fuel price structure.

Although the goal of operating a diesel engine on CWF is a worthy objective, especially in light of current oil prices that are unlikely to moderate significantly, this project did not appreciably advance the technology toward commercialization and therefore cannot be considered a success. However, the project did have some accomplishments. A Fairbanks Morse engine with full-size cylinders was successfully operated on CWF, which had not been done before. Thus, the project did preserve and advance CWF diesel know-how and put Fairbanks Morse in a position to offer coal diesel engines when the market is receptive. In addition, UAF now has a fully commissioned 18-cylinder coal diesel engine which can be used for a demonstration whenever the CWF fuel is made available.

I. INTRODUCTION

The U.S. Department of Energy's (DOE's) Clean Coal Technology (CCT) Program seeks to offer the energy marketplace more efficient and environmentally benign coal utilization technology options by demonstrating these technologies in industrial settings. This document is a DOE post-project assessment of the Clean Coal Diesel Demonstration Project, one of the projects selected in Round V of the CCT Program.

Coal-water-fuel (CWF) is an alternative to conventional petroleum-derived diesel fuel for firing a diesel engine that powers a generator. Development of a diesel engine burning CWF would decrease our dependence on imported crude oil while using our most abundant domestic fuel—coal. In response to the CCT Round V solicitation, Arthur D. Little, Inc. (ADL) submitted a proposal to DOE to demonstrate a diesel engine operating on CWF for electric power generation. In July 1994, DOE awarded a Cooperative Agreement to conduct this project. The project was restructured in August 1996, and in 2002 it was novated to TIAX LLC, who had acquired the research contracts of ADL, and sited at the University of Alaska in Fairbanks (UAF). In 2003, the project was rescoped, and testing was performed in Wisconsin on a two-cylinder engine. The Cooperative Agreement was modified in September 2003 to recognize this change.

Construction of the unit at UAF started in June 1998, and the unit was successfully tested on diesel fuel in 2000. Brief testing of the two-cylinder engine on CWF was achieved in April 2004. The project was withdrawn in April 2006. Project cost was $41.6 million; DOE provided 50 percent of the total project funding.

II. PROJECT/PROCESS DESCRIPTION

A. Project Description

Clean coal-diesel technology was developed over the period from 1982 to 1993 under a series of DOE-funded projects, culminating in a successful proof-of-concept prototype test based on a modified Cooper Bessemer six-cylinder, 1,800 kWe, diesel engine that was operated for over 1,000 hours on CWF. (The Final Report presents an extensive history of coal diesel engine research and development activities.) Since a demonstration of the technology was the next logical step in positioning coal-diesel technology for commercialization, Arthur D. Little, Inc., submitted a proposal under the Clean Coal Technology Demonstration Program. The Clean Coal Diesel Demonstration Project was one of the projects selected under Round V of this program, and a Cooperative Agreement was awarded in July 1994. The original project proposal involved the installation of two 20-cylinder, 6.3 MWe, CWF-fired, Cooper-Bessemer diesel engines at Easton Utilities Commission's Plant No. 2, located in Easton, MD. However, in 1995, Easton Utilities withdrew from the project when their load growth declined and they found they could purchase power at relatively low rates, thus avoiding the need to add generating capacity.

In 1996, the project was relocated to the UAF's campus in Fairbanks. In 1997, Fairbanks Morse replaced Cooper-Bessemer, who had decided to stop manufacturing diesel engines, as the engine manufacturer. Installation of an 18-cylilnder Fairbanks Morse coal diesel engine in a campus energy park was initiated in 1998 to serve as a 6.2 MWe coal-capable addition to the university's power plant that consisted of two oil-fired boilers and two stoker-type coal-fired boilers owned and operated by the University. R.W. Beck, Inc., was the architect and engineering firm for the installation. The UAF power plant utilizes local coal brought by truck from the Usibelli Mine in Healy, AK. In September 2000, the engine and associated equipment were run on conventional diesel fuel and successfully passed the acceptance test.

As part of this project, it was planned to construct and operate a five-tons-per-hour CWF processing plant in Alaska. However, after the project was well underway, the necessary commercial partners needed to provide matching funds and to act as additional fuel customers were not identified, and it was not feasible to build the CWF processing plant with the available funds. In 2002, TIAX LLC acquired the research contracts of Arthur D. Little, Inc., and became the participant in the Clean Coal Diesel Demonstration Project.

Because of the failure to raise the capital needed to build a CWF plant, the Cooperative Agreement was modified to permit a one-time purchase of CWF from a supplier rather than building a plant to provide it. Because no Alaskan supplier of CWF was identified, in 2003 the project was rescoped, and the decision was reached to conduct initial testing on a two-cylinder engine at Fairbanks Morse's engine test facility in Beloit, WI, using CWF produced by the University of North Dakota's Energy & Environmental Research Center (EERC) from Usibelli coal. In 2001, hardened parts were installed in the two-cylinder engine preparatory to running on CWF, and CWF injector tests were successfully completed.

The two-cylinder engine was successfully operated on CWF for a short period on April 14, 2004. Although short, the run was long enough to demonstrate several important points:

- The special CWF injectors functioned well.
- The CWF fuel ignited and burned well with no cylinder deposits.
- Engine efficiency was as expected.
- Emissions were quite low, even without the selective catalytic reduction (SCR) unit.
- Fairbanks Morse gained the know-how to build and operate a diesel engine burning CWF.

Additional run time, critical to confirming these results, was planned but not carried out, primarily because matching cost share did not materialize during an extended hiatus in the testing. Modifications to the test facility were required because carry-over of incompletely burned coal particles had caused a fire in the baghouse. Then, in 2005, Fairbanks Morse announced a restructuring, which resulted in reduced availability of their engine laboratory. Due to lack of an engine test site and a lack of further matching funds, a letter was sent to DOE in December 2005 requesting termination by mutual agreement. This was accepted by DOE, and the project was terminated in April 2006.

The project team included at various times ADL, original participant; TIAX LLC, who acquired the assets of ADL's technology group; Easton Utilities, original host site provider; the University of Alaska, Fairbanks, alternative host site provider and co-funder; the Cooper Bessemer Reciprocating Division of Cooper Energy Services (Cooper), diesel technology provider; Fairbanks-Morse Engine (FME), host site provider and diesel engine technology vendor; CQ, Inc., CWF formulation and production; EERC, CWF provider; and the Usibelli Coal Mine, Inc., coal supplier. The Ohio Coal Development Office provided valuable support during Phase I of the project.

B. Process Description

1. Coal-Fired Diesel Engine

Like gasoline engines, diesel engines are internal combustion engines that generate power by the combustion of fuel in a cylinder. The major difference between these engines is that gasoline engines use spark ignition, whereas diesel engines use compression ignition. When a gas is compressed, its temperature rises. In a diesel engine, air is compressed, and when fuel is injected into this hot air, combustion occurs. Diesel engines run at higher compression ratios (up to 25:1) than spark ignition engines (up to 12:1). Because of their design, diesel engines have a much wider range of possible fuels. This was recognized from the beginning by Rudolf Diesel, the inventor of the diesel engine, who designed his engine to run on pulverized coal and peanut oil.

Diesel engines are classified as two-stroke or four-stroke, depending on their mode of operation, and as high-speed (~1,200 rpm), medium-speed (300 to 1,200 rpm), and low-speed (60 to 120 rpm), depending on revolutions per minute. High-speed diesels are used largely in the transportation sector to power cars, trucks, buses, tractors, etc. Medium-speed diesels are used for ship propulsion and mechanical-drive applications, such as compressors, generators, and pumps. Low-speed diesels are used mainly to power large ships. The 18-cylinder engine installed at UAF and the two-cylinder engine tested at Beloit were four-stroke, medium-speed diesels.

Because coal is a solid that can cause erosion of engine parts, some modifications are necessary to enable a diesel engine to operate with CWF. The first critical area is the fuel injection system. The diesel-fuel injection pump and injector form a high-precision device operating with a close-tolerance plunger to produce high-pressure pulses of known volumes of fuel at very precise timing. Since CWF would cause erosion and seizure in any close-tolerance moving parts, a novel approach was necessary. This consisted of a shuttle piston operating on diesel fuel to produce the dynamic volumetric displacement events required to inject CWF (see Figure 1). On each engine cycle, the predetermined correct volume of coal slurry is placed into the nozzle tip by a check-valve mechanism. Certain parts in the check valve and injector nozzle were made of tungsten carbide to resist erosion.

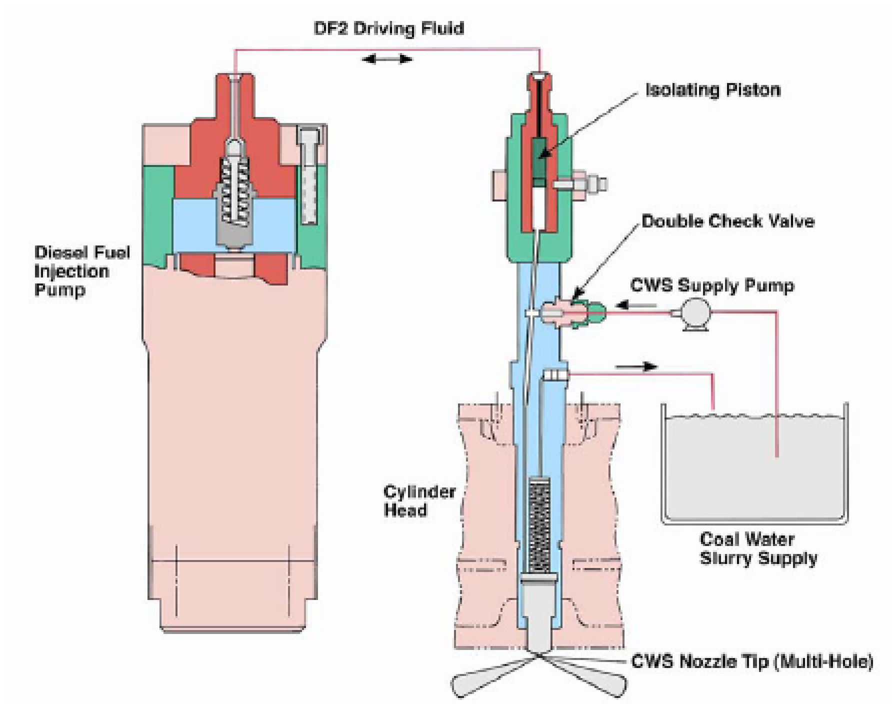

Figure 1: Layout of CWF Injection System with Shuttle Piston

The fundamental challenge for a diesel engine burning CWF is to protect the moving parts of the engine that are exposed to either the CWF, which is abrasive, or the solid particulate products of combustion, which contain both ash and traces of unburned coal. Specific engine components that need protection include the fuel-injection pump system and nozzle tip, piston rings and liners, exhaust gas valves and seats, turbocharger rotors and blades, and the crankshaft bearings that require protection from contaminants picked up by the oil, such as ash. Figure 2 shows areas on the CWF diesel that need protection.

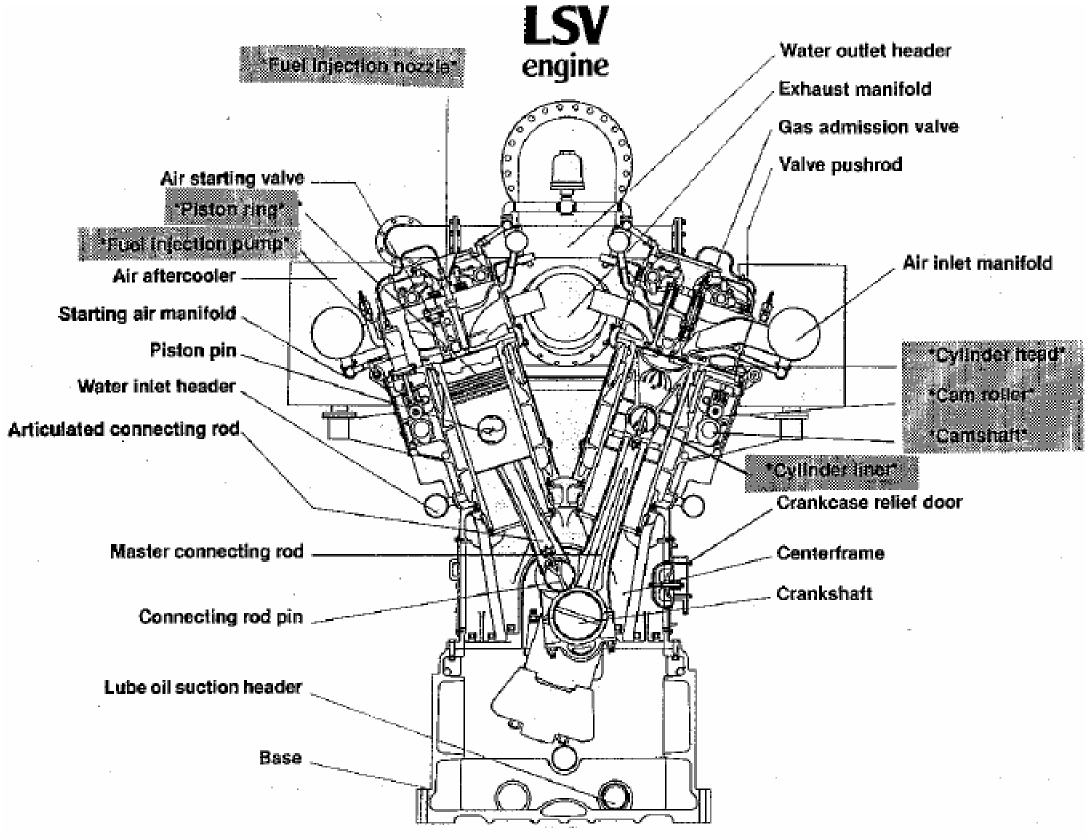

Figure 2: Drawing of CWF Diesel Engine Showing Areas Needing Protection

2. Coal-Water Fuel

CWF is a slurry made by mixing pulverized coal with water in approximately a fifty-fifty mixture. It is black, with an appearance similar to crude oil, and has complex flow and combustion characteristics. Important properties of an acceptable CWF include low settling rate of solid particles, tolerance to flow at the high shear rates encountered in diesel injection systems, adequate atomization and evaporation of slurry sprays, and a small enough particle size for ignition and combustion at conditions achievable in diesel engines. Additives may be used to improve CWF properties.

CWF properties are dependent on coal rank and source, particle size distribution, mass loading of coal, and the types and concentrations of additives that are used to improve stability, compatibility, and flow at high shear rate. Tests have indicated that mean particle-size distributions in the range of 3 to 20 microns are acceptable, with maximum sizes up to 85 microns. Table 1 lists the range of CWF properties evaluated in studies which led to this project.

Table 1: Range of CWF Properties Tested

Effect	Coal Property	Range Tested	Results
Combustion Performance	Volatile Content	27–41%	Satisfactory
	Rank	Bituminous & Subbituminous	Both satisfactory
	Heating Value	10,000–15,000 Btu/lb (dry)	Satisfactory
	Particle Size	3–20 microns mean 10–85 microns max	Satisfactory
Emissions	Sulfur Content	0.7–1.0 wt%	<2% is O.K.
	Nitrogen Content	1.2–1.8 wt%	TBD
Handling	Solids Content	48–55 wt%	Satisfactory
	Viscosity	200–400 cP	Satisfactory
Wear	Ash Content	0.5–3.8 wt%	<1.8% is O.K.
	Hard Mineral Content	---	TBD

Typically, coal must be cleaned to reduce its mineral content before it can be processed into a satisfactory CWF. One way to accomplish this is through heavy media separation, which can produce cleaned coal suitable for an engine-grade product. The clean coal is metered along with water to a ball mill where it is reduced to approximately 250-micron particles. The final steps are micronizing to below 20 microns mean size, followed by slurry formation.

With bituminous coals, cleaning to reduce the ash content is typically all that is required to prepare the coal for CWF production. However, with Alaskan subbituminous coal, more complex preprocessing is required. This coal was submitted to EERC’s hot water drying process (see Figure 3). In this process, low-rank coal (LRC) is heated in water at a high pressure. Under these conditions, the duration of the coalification process is reduced from millions of years to minutes, so that the LRC is changed from hydrophilic to hydrophobic, thus reducing its inherent moisture content.

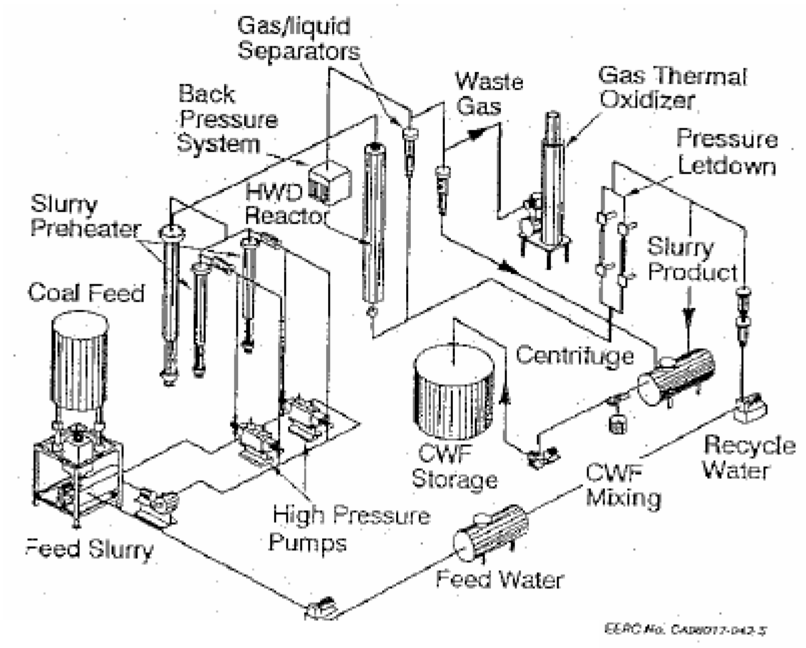

Figure 3: Schematic Drawing of EERC's Hot Water Drying Process

Additives, such as xantham gum and surfactant, were necessary to control the low and high shear viscosity of the slurry, and dispersants were added to prevent agglomeration. Small amounts of each additive (approximately 0.5 to 1.0 percent each) were adequate. The CWF tested at Fairbanks Morse was prepared at EERC from Usibelli coal. A typical analysis of run of mine (ROM) coal from the Usibelli mine is given in Table 2.

Table 2: Typical Analysis of Usibelli Run-of-Mine Coal

Proximate Analysis, weight percent	
Moisture	26.35
Ash	8.20
Volatiles	34.56
Fixed Carbon	30.89
Ultimate Analysis, weight percent	
Moisture	26.35
Ash	8.20
Carbon	45.55
Hydrogen	3.45
Nitrogen	0.59
Sulfur	0.17
Oxygen	15.66
Chlorine	0.03
Estimated Heating Value (HHV), Btu/lb	
As received	7,815
Moisture Free	10,610

3. Emissions Control System

Effective controls for nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate emissions will be essential for the successful commercialization of stationary diesel engines burning CWF. A typical emissions control system arrangement is shown in Figure 4.

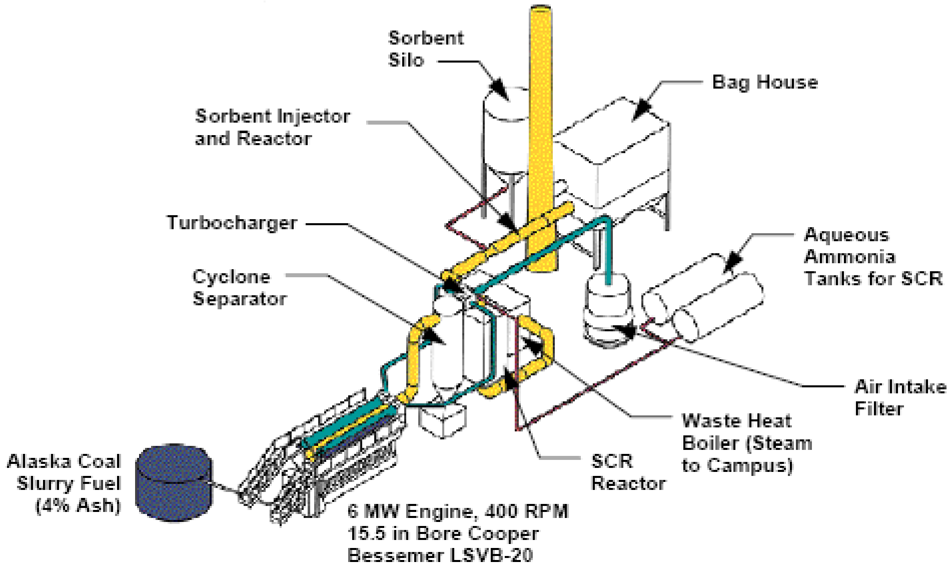

Figure 4: Typical Emissions Controls Arrangement for a CWF Diesel

Emissions-control system performance targets were established based on the projected needs of 10 to 100 MWe cogeneration and independent power plants in the period from 2010 to 2030. Table 3 summarizes the emissions targets (based on Alaskan coal) and control methods to reach these levels. The clean coal diesel installed at UAF included an exhaust-gas treatment system consisting of a cyclone, an SCR unit, a sorbent injection system for SO_x control, a baghouse, and a new exhaust stack to ensure appropriate control and dispersion of air emissions. During the prior DOE Morgantown Energy Technology Center (now a part of the National Energy Technology Laboratory) funded development program, a full-scale emission control system, sized for a 1,800 kW coal diesel engine, was demonstrated to be capable of meeting all of these performance goals. This system was moved and recommissioned at Fairbanks Morse and operated as part of the demonstration project in 2003-2004.

Table 3: Emission Control Target Levels (Alaskan Coal)

Pollutant	Emissions Target	Control Method
NO_x	0.15 lb/million Btu	Water injection (CWF), SCR
SO_x	0.12 lb/million Btu	Coal cleaning, Dry sorbent injection
Particulates	0.08 lb/million Btu	Cyclone, Baghouse

When operated on CWF as designed, the UAF diesel was expected to result in significant reductions in overall annual emissions from the UAF power plant. In a period of maximum coal-diesel utilization, it is estimated that the four criteria pollutants (SO_2, NO_x, particulates, and CO) would be 35 to 50 percent lower than without the coal-diesel in operation.

As part of the demonstration project, an engineering company completed detailed specifications and purchased components under competitive bidding for the emission-control system that was installed at UAF. Included in the design document were conceptual arrangements, heat and material balances, and performance requirements for the silencer, cyclone, SCR reactor, sorbent injection system, and baghouse.

C. Project Objectives and Statement of Work

As presented in the initial Cooperative Agreement, the overall objective of this project was

> to demonstrate an advanced Coal Diesel Engine Combined Cycle (CDCC) Technology, which for the purpose of this demonstration will be based on Cooper-Bessemer's LSB/LSVB diesel engine series. The CDCC system which utilizes coal-water fuel (CWF) will demonstrate high efficiency, cost competitive, environmentally compliant electric power. Overall, the CDCC technology is expected to operate at very low NO_x and SO_x emission levels (50 to 70 percent below current New Source Performance Standards). In addition, the CDCC demonstration plant's expected 45 percent efficiency (with future plants designed to reach 48 percent efficiency) will result in 25 percent lower CO_2 emissions (a greenhouse gas) compared to current coal steam plants. The parties anticipate that, if the Demonstration Project is successful, the CDCC Technology could become commercialized beginning in the year 2000 and will be capable of

> significantly advancing the efficiency and environmental performance of coal using technologies at new or existing facilities.

When the project was moved to UAF in 1997, the Cooperative Agreement was modified, and the objective was restated as follows:

> The overall objective of this Project is to demonstrate an advanced, Clean Coal Diesel Engine (CCD) Technology, which for the purpose of this demonstration will be based on the Fairbanks Morse heavy duty diesel engine. The CCD system, which utilizes low rank coal-water fuel (LRCWF), will demonstrate high efficiency, cost competitive, environmentally compliant electric power. Overall, the CCD technology is expected to operate at very low NO_x and SO_x emission levels (50 to 70 percent below current New Source Performance Standards). In addition, the CCD demonstration plant's expected 41 percent efficiency (with future plants designed to reach 48 percent efficiency) will result in 25 percent lower CO_2 emissions (a greenhouse gas) compared to current coal steam plants. The parties anticipate that, if the Demonstration Project is successful, the CCD Technology could become commercialized beginning in the year 2004 and will be capable of significantly advancing the efficiency and environmental performance of coal using technologies at new or existing facilities.

This project was implemented in three phases:

- Phase 1: Design and Permitting
- Phase 2: Construction
- Phase 3: Operation

During Phases 1 and 2, ADL was the participant, and during Phase 3, TIAX LLC was the participant.

1. Phase 1

As originally specified, Phase 1 consisted of the development of designs, specifications, and engineering drawings for all systems necessary to construct and operate a 14-MWe, CWF-fired CDCC at Easton Utilities's Plant No. 2. The CDCC was to consist of two 20-cylinder Cooper-Bessemer LSVB diesel engines, nominally rated at 315 kW per cylinder (6.3 MWe per engine) plus a 1.4-MWe, steam-bottoming cycle. Part of Phase 1 included modification and operation on CWF of Cooper-Bessemer's six-cylinder Model LSC-6 laboratory engine, which was to run 1,000 hours minimum, and the design of a coal-cleaning and CWF-preparation facility. As indicated above, Easton withdrew from the project, and the project was relocated to UAF and involved a single 18-cylinder engine without a steam-bottoming cycle. After only a portion of the 1,000 hours of engine testing at their facility was performed, Cooper-Bessemer withdrew from the project because of a decision in 1997 to no longer produce diesel engines.

2. Phase 2

Phase 2 consisted of engine fabrication, delivery, and installation; emissions control system design, fabrication, and installation; and design of the supporting CWF preparation plant. For the re-sited demonstration in Alaska, the coal diesel engine, supplied by a new engine manufacturer (FME), was installed at UAF (see Figure 5).

Figure 5: Picture of the Fairbanks Morse Coal Diesel Engine Installed at UAF

3. Phase 3

The original intent was to perform a minimum of 6,000 hours of diesel-engine testing while operating on CWF. Although an 18-cylinder engine and support facilities were installed at UAF, this engine was never operated on CWF due to lack of a specialized process plant to produce the required CWF. Instead, testing was shifted to a two-cylinder engine at Fairbanks Morse's test facilities, where a little over an hour of testing was performed using LRCWF prepared by EERC from Alaskan (Usibelli Mine) coal.

Subsequent to awarding of the Cooperative Agreement in 1994, several changes to the Statement of Work (SOW) were made to accommodate changing circumstances as the participant attempted to proceed with the demonstration with new team members. In 2002, the SOW was modified to remove construction and operation of the LRCWF plant. When the project was moved to UAF, the intention was to build and operate a CWF plant based on Alaskan coal. However, as the design of this unit progressed, the estimated cost exceeded the budget allocation, so it was not feasible to proceed with construction. Therefore, the SOW was modified to permit purchase of CWF from an outside supplier. Unfortunately, this did not solve the problem, since the Alaskan subbituminous coal requires a specialized pre-processing facility, and no outside supplier was located who would build and operate such a facility.

The lack of a source of CWF made it impossible to perform the desired engine testing at UAF. Therefore, in 2003, the SOW was again modified to move engine testing to Fairbanks Morse's engine test facility at Beloit, WI, and make use of a two-cylinder test engine (see Figure 6). On a per cylinder basis, the 18-cylinder engine at UAF and the two-cylinder engine at Beloit are identical: same horsepower, emissions, fueling rate, wear, exhaust flow, etc. Two fuels were to be tested, an EERC-supplied LRCWF based on Alaskan coal and a CWF based on Kentucky coal from Gatliff Coal Company and produced by CQ, Inc.

Figure 6: Picture of the Fairbanks Morse's Two-Cylinder Test Engine

D. CWF Properties

The CWF used in the test on the two-cylinder engine was prepared by EERC earlier for previous phases of the project, but not used at that time. It was shipped in drums to Fairbanks Morse's facilities in Beloit, WI. Some of the properties of this material are presented in Table 4.

Table 4: Properties of CWF Tested in Fairbanks Morse's Two-Cylinder Engine

Property	Value
Coal Concentration in Slurry	47.7 wt%
Heating Value of Coal	10,610 Btu/lb of coal
Xantham Gum Stabilizer Concentration	32 g/gal
Slurry Density	1.1 g/cm^3
Coal Source	Usibelli Mine

III. REVIEW OF TECHNICAL AND ENVIRONMENTAL PERFORMANCE

The goal of this project was to demonstrate reliable and economic performance of a medium-speed 6.2-MWe diesel engine running on CWF. This system was expected to have pollutant emission levels lower than New Source Performance Standards. During the period from June 1998 to September 2000, an 18-cylinder Fairbanks Morse engine, generator, and pollution-control system were installed at UAF and tested on diesel fuel. Continued testing occurred during the period from September 2000 through August 2003 to correct some startup problems. Ultimately, due to failure to identify a supplier of Alaskan CWF, this engine was never run on CWF. Rather, the decision was made to switch testing to a two-cylinder engine at Fairbanks Morse's engine test facility. As summarized below, a short (one hour and nine minutes) but significant test run on CWF was carried out. This test demonstrated many of the performance and emissions attributes of the coal diesel despite the short duration. Obviously, long-term wear and fouling characteristics were not demonstrated.

A. Technical Performance

The specifications of the Fairbanks Morse two-cylinder test engine are given in Table 5.

Table 5: Specifications of Two-Cylinder Test Engine

Specification	Value
Bore	400 mm
Stroke	460 mm
Compression Ratio	11.4:1
Brake Mean Effective Pressure (BMEP)	2,220 kPa (322 psi)
Power	1,050 kW
Maximum Cylinder Firing Pressure	14.4 MPa (2,100 psi)
Operating Speed	514 RPM

The main change made to the test engine was a redesigned fuel system. Pilot injectors were installed in the engine to deliver conventional diesel fuel to start the engine and to assist with CWF combustion, and specially designed main injectors were installed.

During initial testing, consisting of short tests to determine combustion quality, hardened parts were not installed in the engine. Due to fuel-flow limitations, the two-cylinder engine was derated to 1,000 bhp. Switching between No. 2 diesel and CWF was controlled by a three-way valve that performed without problems. During this test period, it was discovered that the CWF storage method is important. One batch of CWF was believed to have frozen and then thawed, after which it did not perform properly.

Control of the engine was accomplished using a Rockwell Automation programmable logic controller. To ensure proper engine operation and operator safety, essential parameters, such as exhaust temperature, cooling water and lubricant temperature, intake manifold temperature and pressure, engine speed, turbocharger speed, and baghouse pressure drop, were monitored. In addition to these parameters, high-speed data acquisition was used to monitor and record the injection and cylinder pressure for the two cylinders and four injectors (two main, two pilot) on the engine.

Engine tests on April 14, 2004, were conducted using CWF prepared by EERC from Usibelli coal. This CWF was successfully fired in the engine for approximately one hour at 17 percent to 25 percent load; then the engine was switched back to No. 2 diesel. Following this, the engine was again switched to CWF for another 9 minutes run time. Table 6 presents a summary of the operating conditions for this inaugural run on CWF.

Table 6: Summary of Engine Operating Conditions During Testing

Operating Parameter	1st Test	2nd Test	1st Test	2nd Test
Fuel	Diesel	Diesel	CWF	CWF
Engine Load, %	50	25	25	17
Engine Power, bhp	503	254	254	168
Engine Speed, rpm	506	506	506	506
Pilot Fuel, %	3.6	4.7	11.6	12.4
BMEP, psi	55.8	28.2	28.2	18.7
Fuel Rate, lb/hr	227	173	629	588
Specific Fuel Consumption, Btu/bhp-hr	8,105	12,281	10,663	15,031
Fuel Conversion Efficiency, %	31	21	24	17
Air Rate, lb/hr	7,532	6,232	---	5,240
Air/Fuel Ratio, lb/lb	33.3	36	---	18.7
Fuel/Air Ratio, lb/lb	0.03	0.028	---	0.053
NO, ppm	1,100	430	150	142
CO_2, %	6.4	5.1	6.3	5.9
CO, ppm	463	385	>1,000	>1,000
O_2, %	11.8	13.9	13.3	13
Total Hydrocarbons (C_3H_8), ppm	406	---	---	910

Combustion, while operating on CWF, was excellent on most engine cycles, but some cycle-to-cycle variability was observed. Pilot ignition timing had not been optimized, so combustion should improve following tuning. Combustion of coal slurry was over 95 percent complete, based on the amount of net power produced. There was no evidence of unburned coal buildup in the cylinders or on the liner walls. Differences in the cylinder pressure traces between diesel fuel operation and CWF operation can be seen by comparing Figures 7 and 8.

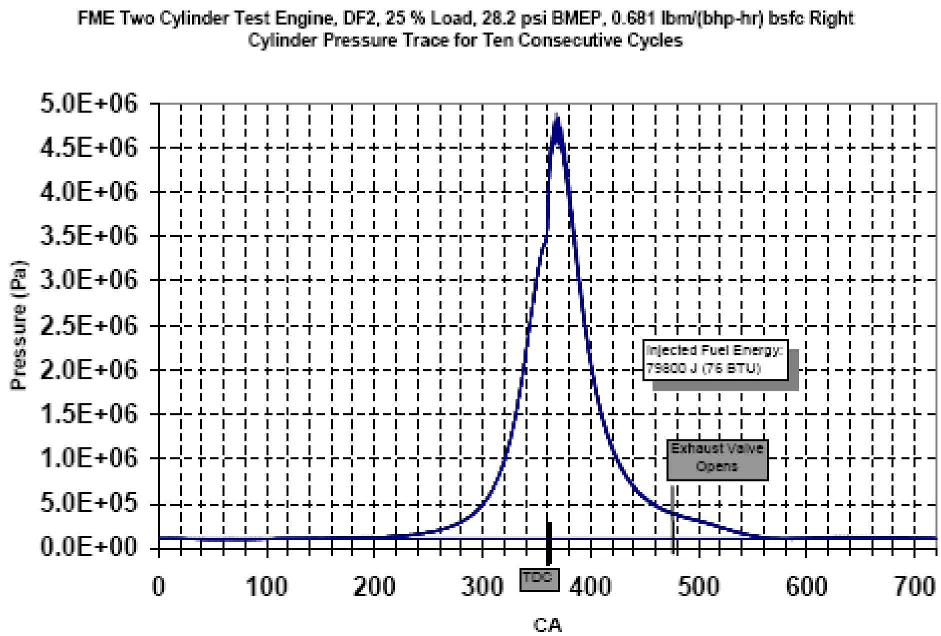

Figure 7: Cylinder Pressure Trace for Operation on Diesel Fuel

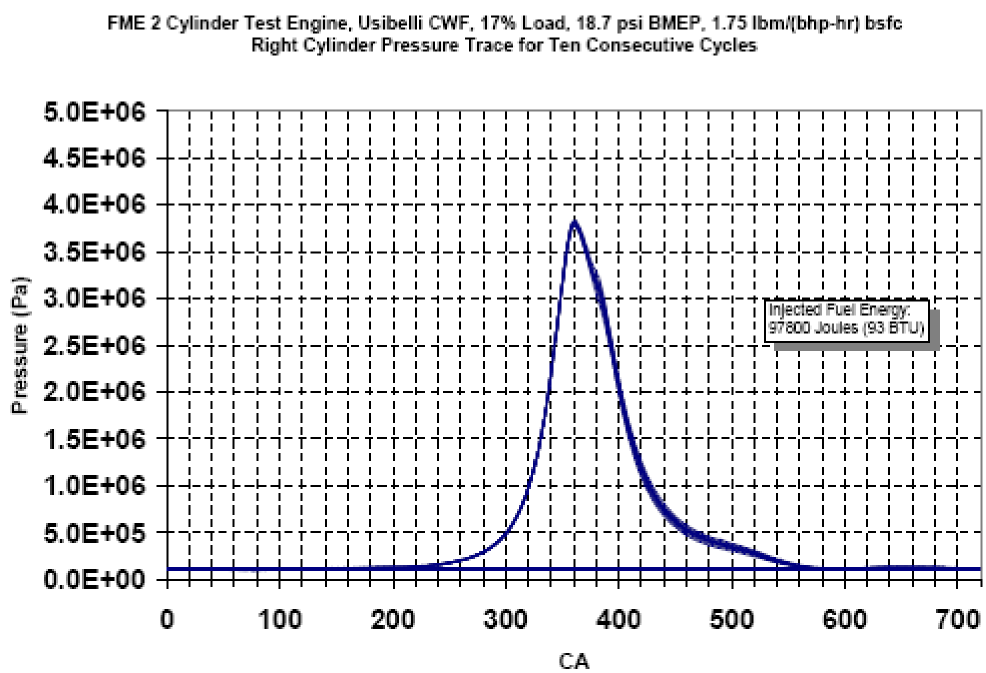

Figure 8: Cylinder Pressure Trace for Operation on CWF

Diesel fuel combustion, on average, produced a higher peak pressure than CWF combustion. From the shapes of the pressure curves, CWF combustion appears to be mixing controlled without the characteristic spike near top dead center, indicating premixed burning. It appears that diesel fuel pilot injection did not end before main CWF injection began. As the CWF was burning, it was competing with the late pilot injection for the same oxygen (in those regions where the sprays overlap). Diesel fuel combustion shows an initial energy release from premixed combustion (as indicated by the spike in pressure), which is followed by mixing-controlled combustion. The slow mixing-controlled combustion of the CWF is evidenced by the 6 to 7 degree longer burn time of the mixture, with the ignition delay of the CWF being twice as long as that of diesel fuel. The diesel fuel pressure traces presumably had a higher peak pressure due to the timing of injection being better matched to burn rate than for CWF with diesel fuel pilot injection. This should be correctable with tuning.

The gross heat-release plots showed more variability in total heat released, cycle by cycle, of the two-cylinder engine running on CWF compared to operation on diesel fuel. The late burn of CWF on certain cycles also reduced engine efficiency, because a percentage of chemical energy was not being converted to work on those cycles. Further engine tuning should correct for this variability.

At equal engine power (254 bhp), the specific fuel consumption for CWF was equal to or lower than for diesel fuel operation, even though this run was a preliminary result at 25 percent load without engine tuning. A summary of the combustion stability is shown in Table 7. Operation on coal had a coefficient of variation (COV) of 7 to 14 percent compared to 2 percent on diesel fuel.

Table 7: Summary of Combustion Stability

Variable				
Fuel	Diesel		CWF	
Load, %	25		17	
Cylinder	Left	Right	Left	Right
Average IMEP*, psi	85	88	74	83
IMEP COV, %	2	2	14	7
IMEP LNV, %	96	97	77	90

*Indicated mean effective pressure

Results from this test can be summarized as follows:

- Coal slurry fuel was successfully injected, ignited, and burned in a Fairbanks Morse Model PC2 Engine. The pilot and main CWF injectors worked without problems, the expected net power was produced, and the combustion diagnostics showed good combustion (although there was some variation from cycle-to-cycle). No problems were experienced during the switchover from diesel fuel to CWF and back to diesel fuel at the end of the engine test. Both the pilot injectors and the main CWF injectors were able to give repeatable injections for the test, as evidenced by the fact that the pressure traces fell on top of one another.
- The injector traces showed that fuel injection into the cylinder was repeatable and consistent, although some engine tuning is needed to improve performance.
- CWF combustion repeatability was adequate for net power production but not as good as the stability with diesel fuel, probably due to combustion phasing not being optimized.
- For the more successful CWF combustion events, where the majority of injected fuel energy was released, the energy release with CWF was comparable to diesel fuel energy release (90 percent to 95 percent). There was no evidence of buildup of unburned coal in the cylinders. CWF combustion exhibited what appears to be mixing-controlled combustion, as expected for a low volatile solid fuel, whereas the diesel fuel combustion showed initial premixed combustion followed by mixing-controlled combustion (characteristic of diesel combustion). The diesel fuel vapor premixed combustion presumably occurs at or near stoichiometric fuel/air ratio, where the charge temperatures are at the peak, producing much more NO_x during the spike in heat release. CWF produces lower NO_x not only for this reason but also because the water in the fuel lowers peak temperature in the flame zones.
- The cyclone used successfully in the earlier Cooper Bessemer engine tests was not installed for these Fairbanks Morse engine tests, allowing glowing coal embers to be carried into the exhaust ducting. As a result, a fire was inadvertently ignited in the baghouse, and some bags were damaged. TIAX and FME

developed a cost-effective remedy to this problem that included fan improvement and unburned particle suppression (see Figure 9); however, this was not implemented, and no further CWF tests were run.

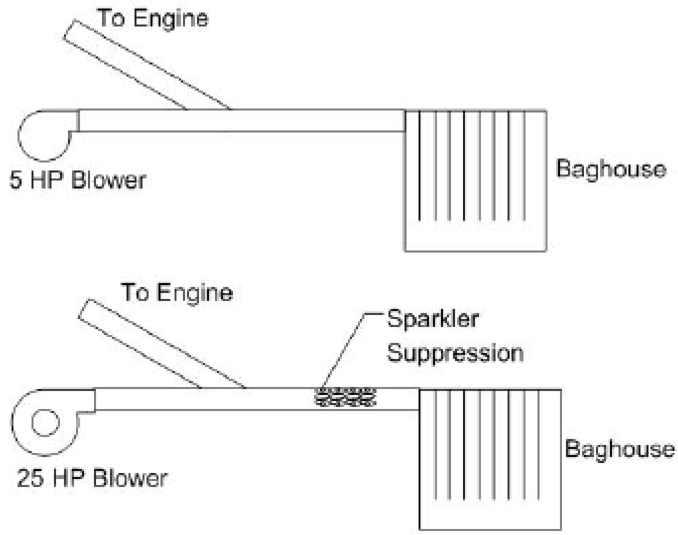

Figure 9. Schematic of Arrangement of Equipment Used in Test and Proposed Improvement to Eliminate Problem

B. Environmental Performance

At a 25 percent engine load, the engine-out NO_x level was only 150 parts per million (ppm), compared to 430 ppm for diesel fuel operation (60 percent reduction). The 150 ppm is equivalent to 0.14 g per kWh or 0.45 lb per million Btu. This was an engine-out figure, and the stack emission NO_x level will be 80 to 85 percent lower, because an SCR unit is part of the design. The estimated stack emission at 25 percent load would be about 30 ppm, which is equivalent to 0.03 g per kWh or 0.09 lb per million BTU. This is well below the required standard for coal-fired power plants.

IV. MARKET ANALYSIS

A. Potential Market

The potential market for coal diesel engines, as estimated in the final report, is as follows:

- 60 CWF plants worldwide.
- A total CWF production rate of 60 million tons per year, distributed among several plants (1 percent of world coal consumption)
- Power production capacity of CWF diesels of 30,000 MW
- Electric power production of 150 billion kWh per year, assuming each engine runs 5,000 hours per year at full load (0.8 percent to 1.2 percent of worldwide generation capacity)

To successfully establish a market niche, CWF diesel engines will have to compete with other power production technologies in the 10 to 100 MW range, such as the following:

- Natural gas reciprocating engine/generator sets: The major challenges for this option are potential high natural gas prices and uncertain gas supply.
- Gas turbines (natural gas): These are particularly competitive at a size range above 30 MW; the challenges for this option include a lower efficiency than reciprocating engines at partial load and potentially high natural gas prices.
- Smaller clean-coal boiler systems based on fluidized bed combustion: The challenges for this option are that capital costs are higher than for coal diesel engines and the disadvantage of needing onsite coal storage.
- Reciprocating engine or gas-turbine generator sets operating on coal-derived synthetic fuel: The challenge for this option is that synthetic fuel from coal is likely to cost more delivered to the site than CWF.

Retrofitting of existing stationary engines to CWF is feasible only on a limited basis. Most stationary reciprocating engines in the United States are gas-fueled, and these engines are not set up with liquid-fuel storage tanks and injection equipment. Also, many natural gas engines have a lower compression ratio than diesels and therefore are not designed for the cylinder pressures of coal-diesel operation. Only heavy-oil-fueled engines are suitable for CWF retrofit. The cost of the retrofit, including engine parts, emission controls, and CWF tankage, is estimated to be 50 to 60 percent of that of a complete new coal diesel engine system.

B. Economics

The economics presented here are based on information in the final report, except that a capital charge factor of 0.124 (based on 20 years at 11 percent) was used, whereas the participant used 0.089 (based on 20 years at 6 percent), which seems low and gives lower costs. It should be noted that, due to estimates in the reported information and unresolved technical issues, these economics should be considered for guidance purposes only and used with caution.

1. Cost of Coal Diesel Engine

The use of CWF necessitates modifications to standard large diesel engine operations in terms of special hardened components, special maintenance practices, and more frequent parts replacements. Although the precise nature of these modifications cannot be determined until further demonstration and durability testing is complete, it is possible to project approximate cost increases based on engine manufacturers' current best judgments.

a. Capital Costs

Table 8, based on a 20-cylinder, 6 MW engine, lists engine components expected to be affected by CWF, generally the moving parts that are exposed to either the fuel or the products of combustion. The total increased cost compared to a conventional diesel is $1,115,000 at the manufacturer's plant, or $1,672,500 installed. This represents an almost 50-percent cost increase to enable operation on CWF. Installation costs carry a premium for the coal diesel because of extra slurry pumps, tanks, and piping; the offset turbocharger and related exhaust manifolding; the extra instrumentation; the diesel pilot fuel system; etc. Permits and compliance testing will also be more costly. These costs are accounted for by applying a 50 percent installation factor to the entire base engine cost. A 6 MW coal diesel engine is projected to cost $5.2 million installed.

Table 8: Estimated Cost Premium for Coal Diesel (20-Cylinders, 6 MW)

Engine Component	Cost, $*	
	Conventional Diesel	Coal Diesel
Lube System	30,000	65,000
Pistons and Rings	50,000	70,000
Cylinder Liners	100,000	200,000
Cylinder Heads	200,000	300,000
Valves and Seats	30,000	40,000
Fuel Pumps, Injectors, Supply System	100,000	300,000
Instruments	50,000	200,000
Turbocharger	200,000	600,000
Cam Shaft and Bearings	50,000	100,000
Miscellaneous Parts	200,000	250,000
Total Critical Parts	1,010,000	2,125,000
Noncritical Parts	1,350,000	1,350,000
Total Base Engine Cost	2,360,000	3,475,000
Installation Cost (50% of Engine Cost)	1,180,000	1,737,500
Installed Engine Cost	3,540,000	5,212,500

*Costs are representative values only and do not depict values for any particular diesel engine.

b. Operating Cost

Maintenance costs for a CWF diesel engine will be significantly higher than for a conventional diesel or natural gas engine. Not only are replacement intervals shorter with coal, but the parts are more costly. Table 9 shows the estimated replacement intervals and costs for a CWF diesel (of the same size as in Table 8) versus a conventional engine over a 20-year life. The estimated maintenance and overhaul costs for the coal diesel amount to cumulative $3.9 million over a 20-year period versus $1.4 million for the conventional diesel or natural gas engine, with significant uncertainty in estimated values at this stage of technology development. The participant estimates total operating and maintenance costs for a 10 MW CWF diesel as $360,000 per year.

Table 9: Engine Maintenance and Overhaul Costs (20-Cylinder, 6 MW engine)

Description	Conventional Diesel	Coal Diesel
Maintenance Interval		
Injectors, hour/cycle	2,000	500
Minor Parts, hour/cycle	8,000	4,000
Top End, hour/cycle	25,000	12,000
Bottom End, hour/cycle	100,000	25,000
Cost per Servicing		
Injectors, $	---	3,200
Minor Parts, $	10,000	10,000
Top End, $	90,000	60,000
Bottom End, $	290,000	290,000
Servicing through 1st Rebuild		
Injectors, No. of cycles	---	50
Minor Parts, No. of cycles	13	6
Top End, No. of cycles	4	2
Bottom End, No. of cycles	1	1
Cost through 1st Rebuild		
Injectors, $	---	160,000
Minor Parts, $	130,000	60,000
Top End, $	360,000	120,000
Bottom End, $	290,000	290,000
Total Cost through 1st Rebuild, $	789,000	630,000
20-Year Service Cycles		
Injectors, No. of cycles	---	315
Minor Parts, No. of cycles	20	39
Top End, No. of cycles	7	13
Bottom End, No. of cycles	2	6
20-Year Cost		
Injectors, $	---	1,008,000
Minor Parts, $	200,000	390,000
Top End, $	630,000	780,000
Bottom End, $	580,000	1,740,000
Total Maintenance Cost (20-yr life)	1,410,000	3,918,000
Maintenance Cost, ¢/kWh	0.19	0.52

c. Cost of Emission Control System

Detailed design and cost estimates based on vendor quotes for the UAF coal-diesel installation are the basis for selection of an emission-control package. Table 10 summarizes the emission-control modules and gives the corresponding total capital and operating costs. The capital cost amounts to $210 to $270 per kW, depending on power plant capacity. Emissions control represents an increase of about 20 to 25 percent over the basic installed capital cost of the coal diesel/generator set.

Table 10: Cost of Emissions-Control System

	Plant Capacity, MW		
Item	7.2	12	24
No. of Engines in Plant	4	2	4
Cylinders per Engine	6	20	20
Capital Cost*, $ million	1.957	2.866	5.114
Operating Cost, ¢/kWh	1.8	1.5	1.4

*Emission controls consist of SCR for NO_x control, sorbent injection for SO_x control, and cyclone and baghouse for particulate control.

2. Cost to Produce Engine-Grade CWF

If coal-fueled diesels are to have a future, an essential ingredient will be a price advantage for engine-grade CWF. The following cost estimate is based on information from manufacturers of coal slurries, using the following assumptions:

- Physical cleaning (resulting in a 1.0 to 3.0 percent ash product) is sufficient for CWF that is compatible with a coal diesel engine, thus avoiding an expensive chemical cleaning step.
- A dedicated engine-grade CWF facility is available with a capacity of 1.8 million tons of CWF per year to support several power plants comprising 75 engines, averaging 5 MW each, operating at an 80 percent load factor.
- Plant capital cost is $78 million, based on an nth plant facility.

- Delivered coal price is \$1.66 per million Btu, which includes \$0.57 per million Btu for rail transportation (\$0.0275 per ton-mile for 590 miles) and \$30 per ton for coal at the mine mouth.
- Electric power cost is \$0.04 per kWh with usage of 175 kWh per ton of CWF.

An operating and maintenance cost breakdown for slurry production is shown in Table 11. A significant fraction of the cost of the slurry is for additives, and much of the remaining cost (electricity, grinding media, and maintenance) is associated with fine coal grinding.

Table 11: Fixed and Variable Operating Costs for CWF Plant

Cost Component	Cost	
	$/million Btu of CWF	$ million/year
Fixed Cost*		
Labor	0.145	3.857
Maintenance	0.035	0.931
Total Fixed Costs	0.180	4.788
Variable Costs		
Coal	1.750	41.895
Electricity	0.135	3.232
Dispersant	0.211	5.051
Stabilizer	0.055	1.317
Grinding Media and Liners	0.045	1.077
Total Variable Costs	2.196	52.572

*Based on a 90 percent on-stream factor

Table 12 shows the projected engine-grade CWF price. This analysis indicates that engine-grade slurry will cost about \$3.70 per million Btu before tanker-truck delivery charges of about \$0.49 per million Btu (100 miles at \$0.065 per ton-mile).

Table 12: Estimated Cost of CWF at the Plant Gate

Cost Factor	Base, $\$10^3$	Current $		Constant $	
		Factor	$\$/10^6$ Btu	Factor	$\$/10^6$ Btu
Capital Charge	78,000	0.160	0.521	0.124	0.404
Fixed O&M Cost	4,788	1.314	0.263	1.000	0.200
Variable Operating Cost	52,572	1.314	2.886	1.000	2.196
Levelized Cost of CWF			3.67		2.80

3. Economics

The levelized cost of electricity for a coal-diesel plant depends on many factors, such as capital cost, required return on investment, annual hours of operation, CWF price, emission control costs, maintenance costs, system efficiency, etc. Table 13 summarizes the estimated cost of electricity for a reasonable set of assumptions. Economic viability clearly hinges on the cost of CWF, and emission control costs represent an important cost parameter that could impact the success of coal-diesel technology.

Table 13: Cost of Electricity Generated by a Diesel Burning CWF

Cost Factor*	Base, $\$10^3$	Current $		Constant $	
		Factor	¢/kWh	Factor	¢/kWh
Capital Charge	15,000	0.160	4.57	0.124	3.54
Fixed O&M Cost	360	1.314	0.90	1.000	0.68
Variable Cost**	840	1.314	2.10	1.000	1.60
Fuel Cost	1,665	1.314	4.16	1.000	3.29
Levelized Cost of Electricity			11.73		9.11

*Based on a 10 MW CWF diesel engine operating at an efficiency of 38 percent and 60 percent capacity factor.
**Mainly emission control costs

Table 14 compares the coal diesel engine with competing technologies by back-calculating the prices of diesel fuel and natural gas that give the same price of electricity as for the coal diesel engine. This calculation shows that the coal diesel engine is competitive with a conventional diesel engine at any diesel fuel price above $1.27 per gal; however, the price of natural gas must be higher than $9.90 per million Btu before the coal diesel engine is competitive. The capital charges are about 1.5 cents per kWh higher for the coal diesel than for a standard diesel and more than 2 cents per kWh higher than for a gas engine. The increased cost associated with the higher level of maintenance required for the coal diesel compared to a conventional diesel translates to about 4 mils per kWh.

Table 14: Comparison of Coal Diesel to Other Engines

Item	Type of Engine		
	Coal Diesel	Conventional Diesel	Conventional Natural Gas
Capital Cost, $/kW	1,500	1,000	800
Capital Cost, $	15,000,000	10,000,000	8,000,000
Maintenance Cost, $/yr	360,000	200,000	160,000
Cost of Electricity, current dollar basis*			
Capital Charge, ¢/kWh	4.57	3.04	2.44
Maintenance, ¢/kWh	0.90	0.50	0.40
Emissions Control, ¢/kWh	2.10		
Fuel, ¢/kWh	4.16	8.19**	8.89***
Total, ¢/kWh	11.73	11.73	11.73

*Based on a 10 MW plants operating at an efficiency of 38 percent and 60 percent capacity factor. The costs of diesel fuel and natural gas are set to give the same cost of electricity as for the coal diesel.
**Equivalent to $1.27 per gal for diesel fuel; this is a hypothetical breakeven fuel price; DOE-EIA forecasts are much higher for real diesel prices.
***Equivalent to $9.90 per million Btu for natural gas.

C. Commercialization

Commercialization of the clean coal-diesel technology confronts the proverbial "chicken and egg" problem. Achieving successful commercialization will require both a coal diesel engine supplier and a CWF supplier. No company is likely to gear up for the manufacture of coal diesel engines if no CWF supply is available, and no company is likely to invest in CWF production facilities if no market exists for the product. This project was intended to overcome this dilemma by demonstrating a commercial-size engine and constructing a CWF plant to supply the necessary fuel. For reasons discussed above, the CWF plant was not built; and, although an 18-cylinder coal diesel engine was installed at UAF, it was prevented from running on CWF due to lack of a CWF supply.

As a result, commercialization will remain problematic until another demonstration project is conducted.

Another problem facing commercialization is volatile energy prices. At an oil price of about $60 per barrel and a natural gas price of over $9 per million Btu delivered to an industrial site, CWF should look attractive, as indicated above. However, significant investment in the technology is unlikely unless consumers are convinced that oil and gas will remain at those prices or higher.

Once conditions are right for commercialization, it will probably proceed in two phases. The first phase would involve building a CWF plant near a mine producing suitable coal, preferably a low sulfur, low ash coal that would require little or no cleaning other than that performed at the mine. Simultaneously several CWF diesels would need to be installed, enough to keep the CWF plant in business. The CWF would most likely have to be delivered by tank truck, as there will be no suitable pipelines. This means the CWF diesels will have to be relatively close, within about 100 miles of the CWF plant.

The size of the CWF plant would probably need to be in the range of 100,000 to 200,000 tons per year, enough to support 15 to 30 MWe of coal-fueled diesel engine capacity. Plant economics project a processing cost of $1.40 per million Btu, including labor, capital charges, electricity, additives, and maintenance. Depending on the price of coal, CWF is projected to cost about $3.70 per million Btu at the CWF plant or $4.20 per million Btu, delivered to the coal-diesel site.

Once the first installation has proven its viability, similar installations could be replicated at other locations. At some point, the general availability of CWF would lead to the development of other uses, such as burning CWF as a substitute for fuel oil.

However, none of this can occur until the CWF diesel is fully demonstrated. This project successfully operated a two-cylinder engine with the same cylinder size as the 18-cylinder engine at UAF. The engine ran for a little over one hour at reduced rate; then the engine test was terminated as planned. The need to upgrade the facility for spark suppression was recognized, and plans were drawn up to do so. However, the engine manufacturer had to make some facility renovations, so following this test no further engine testing on CWF was performed (in part due to lack of matching cost share). In spite of the fact that some valuable information was generated, this was an insufficient test upon which to commence commercialization.

V. CONCLUSIONS

Starting in 1996 with the departure of Easton Utilities, this project suffered from turnover of the host site and other team members. Of the original major players, the CWF supplier, CQ Inc., remained at the end, and the TIAX personnel were the same people who conducted Phases 1 and 2 of the project for ADL. The change of engine manufacturer and host site (and associated relocations) may account, at least in part, for the extended duration of the project and may have contributed to diminished long-term testing results. Even with the maximum effort of team members, it is difficult to recover the momentum lost when major changes in project scope occur.

The total run time during the duration of this project was one hour and nine minutes, short but long enough to demonstrate several important points:

- The special CWF injectors functioned well.
- The CWF fuel ignited and burned well with no cylinder deposits.
- Engine efficiency was as expected.
- Emissions were quite low even without the SCR.
- Fairbanks Morse gained the know-how to build and operate a diesel engine burning CWF.

Although this effort showed that the diesel engine could operate successfully on CWF, the run was not long enough to optimize operating conditions or to demonstrate the life of critical parts. Overall, due to the failure to achieve the originally planned 6,000 hours of CWF operation, this project cannot be considered a success. However, the diesel engine at UAF is in place and could be run if funding and a source of CWF were found.

The project showed that this technology has the potential to meet efficiency and emissions targets. However, longer run times are needed to estimate useful lifetimes of certain engine components, particularly the useful life of piston rings and exhaust valves. Thus, the next step toward commercialization is a field demonstration program with

6,000 hours of engine run time on coal fuel. This will require a minimum of three years due to the need for the work to be conducted in several test periods rather than by continuous operation. Therefore, even if a test run were started today, commercial introduction (plant orders) would not be possible until sometime beyond 2010, assuming a successful field demonstration and a favorable fuel-price structure.

The capital cost of the coal-diesel plant should not be a barrier to commercialization, provided the cost of diesel fuel and industrial-site natural gas stay at current prices. The cost of all equipment modules for the plant has been established, and the installed plant cost estimates appear to be competitive: $1,600 per kW for early demonstration plants, which should decrease to $1,300 per kW for nth plants.

Test results have established CWF specifications and have shown that a wide range of coals can be utilized to prepare engine-grade slurry. The cost of the slurry will be under $2.00 per million Btu plus raw coal-feedstock cost, once adequate slurry-demand exists in a given region. The clean coal-diesel technology should target the 10 to100 MW non-utility generation and small utility markets, including independent power producers and cogeneration. A family of modular plant designs could be offered, with an 8 MW plant likely to be at the low end of what is economically attractive and a 50 to 150 MW capacity at the upper end.

The coal diesel engine could offer the following performance characteristics in its mature configuration:

- An installed cost of $1,300 per kW
- An efficiency of 48.2 percent (lower heating value)
- NO_x emissions of 0.20 lb per million Btu
- SO_x emissions of 0.08 lb per million Btu
- Particulate emissions of 0.003 lb per million Btu.

In conclusion, although the goal of operating a diesel engine on CWF is a worthy objective, especially in light of current oil and gas prices that are unlikely to moderate appreciably, this project did not significantly advance coal-diesel technology toward commercialization and therefore cannot be considered a success. However, the project did have some accomplishments. An FME engine with full-size cylinders was successfully operated on CWF, which had not been done before. Thus, the project did preserve and advance CWF diesel know-how and put FME in a position to offer coal diesel engines when the market is receptive. In addition, UAF now has a fully commissioned 18-cylinder coal-diesel engine that can be used for a demonstration whenever the CWF fuel is made available.

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