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Heat Engines

Technology Status Report

Editors
N.F. Rekos, Jr.
E.L. Parsons, Jr.

September 1989

U. S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER
MORGANTOWN, WEST VIRGINIA

DISCLAIMER

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EXECUTIVE SUMMARY

For the past decade, the Department of Energy (DOE) has sponsored projects to develop diesel and gas turbine engines capable of operating on low-cost, coal-based fuels. The program began as an exploratory effort and has grown into a proof-of-concept program that includes major manufacturers of both diesels and turbines. Much of the current work addresses the use of coal-water fuel (CWF) in both types of engine, although there is some work with dry coal feed and other coal fuels. Potential applications for these engines range from transportation (locomotive and marine uses) to industrial, cogeneration, and utility systems.

Both the diesel and gas turbine portions of the program include proof-of-concept and support projects. Support projects address barrier issues to technology commercialization. Proof-of-concept projects target several different applications; such applications typically include a short period of engine operation at small commercial scale. Significant progress has been made in both types of projects, and technical feasibility of the systems is close to being demonstrated. Economic evaluations show that the technologies have realistic promise for commercialization.

Specific highlights of the coal-fueled diesel program are noted below.

- Engine tests and economic analyses have shown that CWF can replace 70% of the diesel oil used in the duty cycle of a typical main-line locomotive. (CWF would be the primary fuel at high notch settings, and diesel oil would be used at the lower settings. This dual fuel capability would assure high locomotive availability.) A 1985 General Electric Company (GE) system study (Hapeman and Savkar 1986) that was updated in 1989 (GE Transportation Systems 1989) suggests that many railroads could profitably cut the oil consumption of their total fleet in half or better by converting an optimum fraction of their locomotive fleet to CWF. Discounted rates of return of 20% and higher were identified for a number of railroads with diesel prices at $6.30/MBtu and CWF prices at $3.19/MBtu.

- A.D. Little and Cooper-Bessemer completed a system and economic study of coal-fueled diesel engines for modular power and industrial cogeneration markets. The projected total cost of a 6 megawatt (MW) system was $0.0685 per kilowatt hour (kWh), including CWF costs, capital charges, overhead and maintenance costs, and emission control costs. The cost premium for the coal-fueled diesel was estimated at $1.67 million over the base engine cost of $3.5 million, making the coal-fueled diesel competitive at fuel oil prices of $5.50 per million British thermal units (MBtu).

- Over 200 hours of testing have been completed using CWF in full-scale, single-cylinder diesel engines. Combustion efficiencies have exceeded 99%. Several hardened materials for diesel rings and liners have been tested. The wear rates with CWF are comparable to those experienced with diesel oil. The wear rates of standard fuel-injector nozzles were found

to be high with CWF, but GE laboratory tests of superhard materials (diamond compacts) and advanced injector geometries tested by Cooper-Bessemer suggest that this problem is also solvable.

- Diesel engines burning petroleum-based fuels produce relatively high levels of nitrogen oxide (NO_x) emissions, but recent CWF tests indicate that NO_x levels are in many cases reduced by half.

Specific highlights of the coal-fueled gas turbine program are noted below:

- Both CWF and dry coal fuel forms can be burned in short residence time "in-line" combustors and in "off-base" combustors with a combustion efficiency of over 99%. Ceramic insulation applied to the inside of the combustor and transition segments is effective in controlling heat loss and is an aid in combustion stability.

- Rich/lean combustion systems employed by the three major DOE contractors have demonstrated low NO_x emissions levels. Solar Turbines, Inc., Westinghouse (with Avco as a major subcontractor), and Allison Gas Turbines have all measured below 66 parts per million (ppm) NO_x in their subscale combustors; some recent results at Avco have been as low as 10 ppm.

- The contractors have also achieved promising results for controlling sulfur oxide (SO_x) emissions using calcium-based sorbents, although emission control is proving somewhat more difficult for SO_x than NO_x. Sulfur capture levels of 50 to 80% have been demonstrated. Performance is expected to improve as the combustion and cleanup systems are optimized, and in-process sulfur removal will be augmented by the removal of sulfur during the preparation of the fuels.

- The slagging combustors have achieved between 65 and 95% slag capture, which will limit particulate loading on pre-turbine cleanup devices. Fuel additives have been identified that raise the fusion temperature of the ash and nearly eliminate deposits on the turbine surfaces. Periodic nutshelling and water washing of turbines have also proven effective for removing coal ash deposits; pre-turbine cleanup systems such as impact separators, cyclones, and barrier filters will reduce both deposits and erosion.

For many of the gas turbine and diesel applications addressed by the program, emission standards do not exist. Our goal is to develop coal-fueled diesels and gas turbines that not only meet all applicable emission standards that do exist, but also are capable of meeting possible future standards. Advanced in-situ cleanup devices appear to be the systems of choice for coal-fueled gas turbines, while the coal-fueled diesel is expected to rely on more conventional exhaust cleanup technologies.

1.0 INTRODUCTION

This report gives an overview of the Heat Engines Program managed by the DOE's Morgantown Energy Technology Center (METC). Detailed information about the individual projects may be found in the proceedings of the Heat Engines Contractors Meetings, held each year in Morgantown (Byam and Markel 1987; Crouse 1984, 1985, 1986; Dellefield and Webb 1988). Further information may also be obtained from the many published contractor reports available from the DOE's Office of Scientific and Technical Information, and from papers published by the contractors.

Although there are significant overlaps and much of the work is complementary, the diesel and gas turbine programs are treated separately in this report. In both areas, the program approach is to support engine development by major manufacturers, who are expected to commercialize the coal-fueled engines upon completion of the program. This will avoid technology transfer difficulties when the projects are completed. The manufacturers share costs on their projects, which helps assure the sincerity of the participants and leverages Government research and development (R&D) expenditures. The technical support projects, treated only lightly here, are directly relevant to the major projects. In many cases, technical support work is carried out under subcontract to the proof-of-concept contractors.

2.0 DIESEL PROGRAM, INTRODUCTION AND TECHNOLOGY DESCRIPTION

Rudolf Diesel conceived the compression ignition cycle prior to 1900 as a method for combustion of both solid and liquid fuels (Carpenter and Crouse 1985). Although coal was discussed in his original patent, Diesel experimented with petroleum fuels for several years before he initiated tests with coal fuels. However, fuel handling, safety, and ash deposition problems discouraged Diesel from further work on coal as an engine fuel.

Coal fuel testing in compression ignition engines continued through the early 1900s with the work of Pawlikowski (1928) and others. There was extensive German use of pulverized coal in diesels during the period of 1920 to 1944, but this development ended with the end of World War II. The availability of inexpensive petroleum fuels in the 1950s and 1960s interrupted the development of the coal-fueled diesel. Interest in coal was renewed with the rising price of and uncertainty in oil supplies. In the early 1980s, research on slow (120 revolutions per minute [rpm]) coal-fueled diesels was sponsored by the DOE Office of Conservation. Recent work on medium-speed (greater than 250 rpm) coal-fueled diesels has been sponsored by the DOE's Office of Fossil Energy, Morgantown Energy Technology Center.

The results from early DOE-funded slow-speed diesel tests were encouraging (Nydick 1986). A Swiss-manufactured Sulzer diesel-engine test-rig was fueled by a 50/50 CWF with a mean coal particle size of up to 16 micrometers (μm) in diameter. The engine was operated at various power levels with a fuel efficiency equal to a No. 2 petroleum diesel, and greatly reduced wear. Wear and rheological problems did exist, however, and it was concluded that additional research was needed in these areas.

The current DOE diesels program (Carpenter and Crouse 1985; McMillian and Webb 1989) is supporting research to develop U.S.-manufactured, heavy-duty, medium-speed diesel engines for transportation, industrial, cogeneration, and utility applications. The program is being implemented through multiple projects with industry, private laboratories, national laboratories, and universities, as well as through internal DOE R&D.

3.0 DIESEL PROGRAM DESCRIPTION

3.1 Diesel Systems Research Program

In 1985, DOE/METC awarded R&D contracts to GE, Allison Gas Turbines (AGT)/General Motors Corporation (GM), and A.D. Little (ADL)/Cooper-Bessemer. Both the GE and GM programs included systems assessments of several different coal-fueled locomotive systems (Hapeman and Savkar 1986) and coal-fueled tests in both small-scale and full-scale (9.5-in. bore) single-cylinder engines. The ADL program included a systems assessment of the industrial, cogeneration, and small modular utility market (Arthur D. Little, Inc. 1986), laboratory-scale tests at the Massachusetts Institute of Technology (MIT), and a coal-fueled, full-scale (13-in. bore), single-cylinder engine test at Cooper-Bessemer. These early efforts showed that CWF could be efficiently burned in medium-speed diesels, that wear of cylinder and ring was high but remedied through hardened materials, and that CWF NO_x levels were significantly lower than with diesel fuel. The majority of these technical efforts were completed in 1988, and final reports were published in 1989 (Allison Gas Turbine Division 1989; Arthur D. Little, Inc. 1988; Leonard, Hsu, and Flynn 1989).

The GE team included the Corporate Research and Development Center (CR&D) in Schenectady, New York, and GE Transportation Systems Business Operations (TSBO) in Erie, Pennsylvania. The program focused on the preliminary design of the coal-fueled locomotive, shown in Figure 1, and development and testing of a CWF injection system. Several prototype injection systems were developed at GE CR&D and delivered to Erie for testing on their single-cylinder, locomotive-size engine. The prototypes included both positive displacement (jerk pump) and accumulator designs. In all cases, the fuel pumping system was isolated from the hydraulic working fluid by a diaphragm-type pump. The prototype systems proved successful; the accumulator design showed better performance at part-load conditions. Wear tests were conducted using a small Yanmar engine that had alumina oxide particles added to the lube oil. Tests in the Yanmar and other small laboratory wear-rigs permitted screening of candidate ring and liner materials. An earlier coal-fueled locomotive market

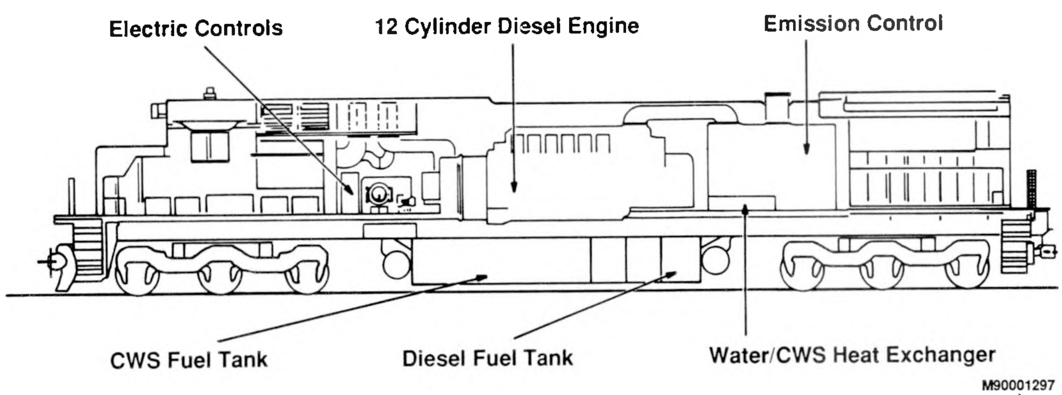

Figure 1. GE Coal-Fueled Diesel Locomotive

assessment for Burlington Northern Railroad was updated during this program; the results indicated the system had economic promise.

The ADL project team included Cooper-Bessemer, MIT, and AMBAC International (American Bosch). MIT conducted single-event combustion and injection/atomization tests in their rapid compression machine (RCM). The combustion tests identified the essential conditions in the engine at top dead center for good CWF ignition and combustion. The RCM, which was fitted with an optical viewing port, was used to observe the CWF spray penetration and combustion characteristics.

Results from the MIT work were used to guide the full-scale engine tests later conducted at the Cooper-Bessemer facilities in Mount Vernon, Ohio. The full-scale engine tests were conducted with a jerk pump and an accumulator-type injection system. AMBAC worked closely with Cooper-Bessemer to develop a non-jamming injector system. The simpler jerk-pump injection system was finally selected because of its superior performance at full-load conditions. The Cooper-Bessemer engine is primarily a constant (full-load) system, with minimal part-load requirements. ADL conducted a system assessment of the industrial and cogeneration market that identified promising markets for coal-fueled diesel cogeneration and power units in the 5- to 20-MW size range.

GM/AGT also developed a coal-fueled diesel engine for locomotive applications. The project team included AGT (who provided contract management support), the GM Electromotive Division, Southwest Research Institute (SWRI), and Adiabatics, Inc. In support of the GM development efforts, SWRI conducted diesel tests in their half-scale, three-cylinder engine (Urban et al. 1988). One of the three cylinders was operated on a coal fuel. The screening tests included a variety of coal fuels (e.g., CWF, coal methanol, and coal oil) and provided GM with critical information on coal fuel performance, engine configurations, and operational characteristics. GM conducted CWF tests in a full-scale (9.5-in. bore), single-cylinder engine. Candidate wear materials and coatings identified by Adiabatics were also evaluated by GM, and a set of ring/liners was developed and fabricated. GM also completed an assessment of coal-fueled, 2-cycle diesel locomotive systems (Koch et al. 1986); the assessment concurred with the positive commercialization potential identified earlier by GE.

3.2 Proof of Concept

Building on the technology base established in earlier projects, the DOE coal-fueled diesel program was expanded in 1988 to address the technical and economic barriers to commercializing coal-fueled diesel engines. Two major proof-of-concept projects and one proof-of-principle project (shown in Table 1 and Figure 2) were awarded. The two contracts for proof-of-concept testing to GE and ADL/Cooper-Bessemer are 5-year efforts to demonstrate the use of coal-fueled diesels for locomotive and industrial cogeneration applications. Both major engine manufacturers are cost-shared at up to 20%. GE will test a CWF-fueled locomotive in commercial service for a short period. Cooper-Bessemer will conduct 400-hour coal-fueled tests on a 400 rpm, six-cylinder, industrial diesel engine. The third major contract, a 3-year effort awarded to Caterpillar, Inc., will explore a higher risk approach to coal-fueled diesel

Table 1. Diesel Proof-of-Concept Projects

Company	Application	Fuel
ADL/Cooper-Bessemer	Modular Utility/ Cogeneration	Coal-Water Fuel/ Dry Powder
General Electric	Locomotive Stationary Power	Coal-Water Fuel
Caterpillar	Locomotive Stationary Power	Coal Processor Gas

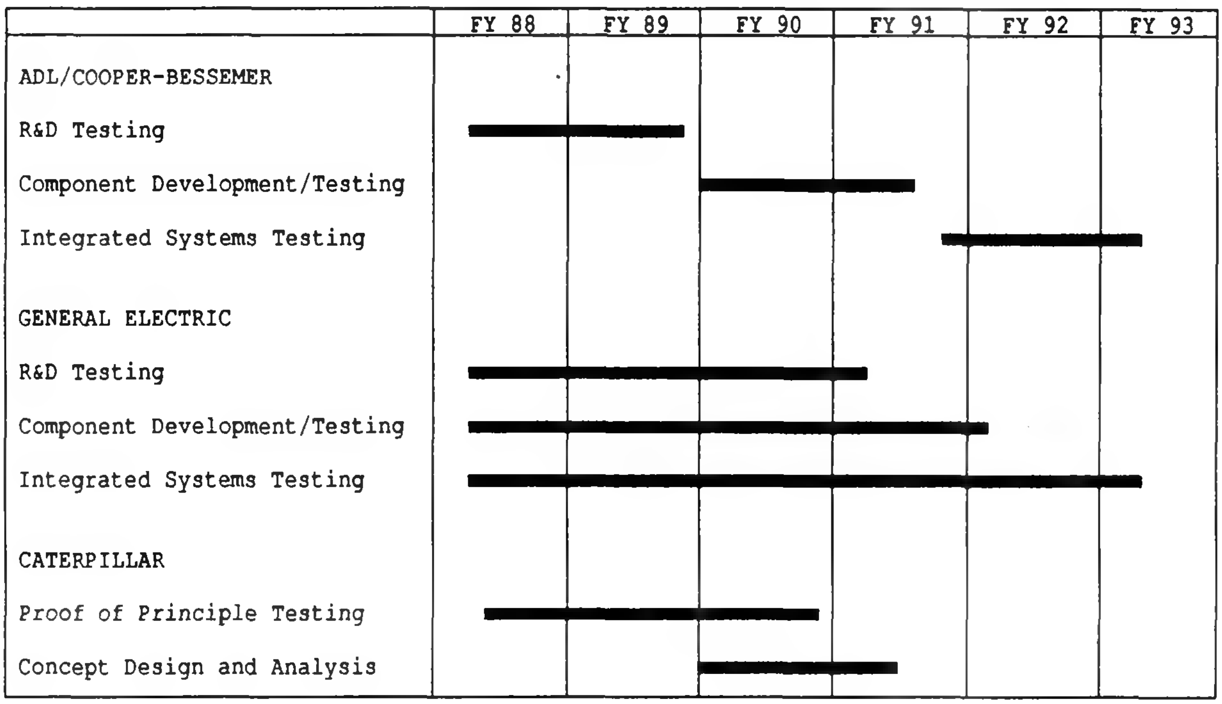

Figure 2. Coal-Fueled Diesel-Engine Program Schedule

operation. Caterpillar will develop a high-pressure coal-fuel processor to gasify coal in exchangeable cartridges to produce a low-Btu gas for combustion in a locomotive diesel engine.

3.2.1 GE Proof-of-Concept Testing

GE is a major manufacturer of locomotives with diesel engines rated from 2,000 to 4,000 horsepower (hp), operating at around 1,050 rpm. The development team for the proof-of-concept locomotive contract includes three GE divisions: GE CR&D, TSBO, and GE Environmental Services, Inc. (GEESI). The entire project represents over $21 million during the next 5 years. DOE is providing $17.9 million; the remaining costs are shared by GE, Norfolk Southern Railroad, New York State Energy Research, and the Pennsylvania Energy Development Authority.

The technical effort includes research and component development tasks that feed results to a 3-stage integrated locomotive task. The Stage I locomotive will have a full-scale, 12-cylinder diesel engine with all cylinders operating on CWF. The fuel storage tank, pumping system, and control system will be mounted on a trailing flatcar. The fuel system will be a flexible design to allow for in-test modification to the CWF tank, Moyno pumps, and delivery lines. Information collected from these tests will be used to integrate the CWF fuel system into the locomotive car for Stage II, scheduled for 1991. An emissions cleanup system will be installed and tested in the Stage III locomotive in 1992 to 1993. All locomotives will be tested statically in the GE TSBO facility as well as dynamically on their outdoor test track in Erie, Pennsylvania. In addition, Stage II and Stage III coal-fueled locomotives will be tested on nearby railroad property.

3.2.2 ADL/Cooper-Bessemer Proof-of-Concept Testing

Cooper-Bessemer, the primary subcontractor to ADL, is a major manufacturer of stationary power engines in the 3- to 20-MW range. The ADL team for the proof-of-concept contract includes Cooper-Bessemer, AMBAC International, Battelle Columbus Laboratories, Physical Sciences, Inc., SWRI, and AMAX Research and Development Center (AMAX). This 5-year contract is a $14.6 million effort with DOE providing over $12.4 million and the remaining costs being shared among Cooper-Bessemer, ADL, and AMAX. Work during the first year of the contract has concentrated on critical issues such as nozzle erosion, deposition, ash removal, component wear, engine performance, and emissions control.

3.2.3 Caterpillar, Inc., Proof-of-Principle Testing

The goal of Caterpillar, Inc.'s proof-of-principle contract is to demonstrate the feasibility of a high-pressure coal fuel processor that directly feeds a locomotive diesel engine. The contract is valued at nearly $4 million with the Caterpillar cost share at approximately 5.6%. Coal Technology Corporation, as a subcontractor to Caterpillar, will design the coal fuel processor/reactor, which will be tested separately from the diesel engine. A conceptual design illustrating the major elements of the fuel processor is shown in Figure 3. Designs for the direct gas-injected diesel engine will be developed by Caterpillar, and combustion tests of the diesel engine running on simulated low-Btu product gas will be performed in late 1989. Integration of the gasifier with the modified diesel engine is not within the scope of this contract, but could be pursued at a later date.

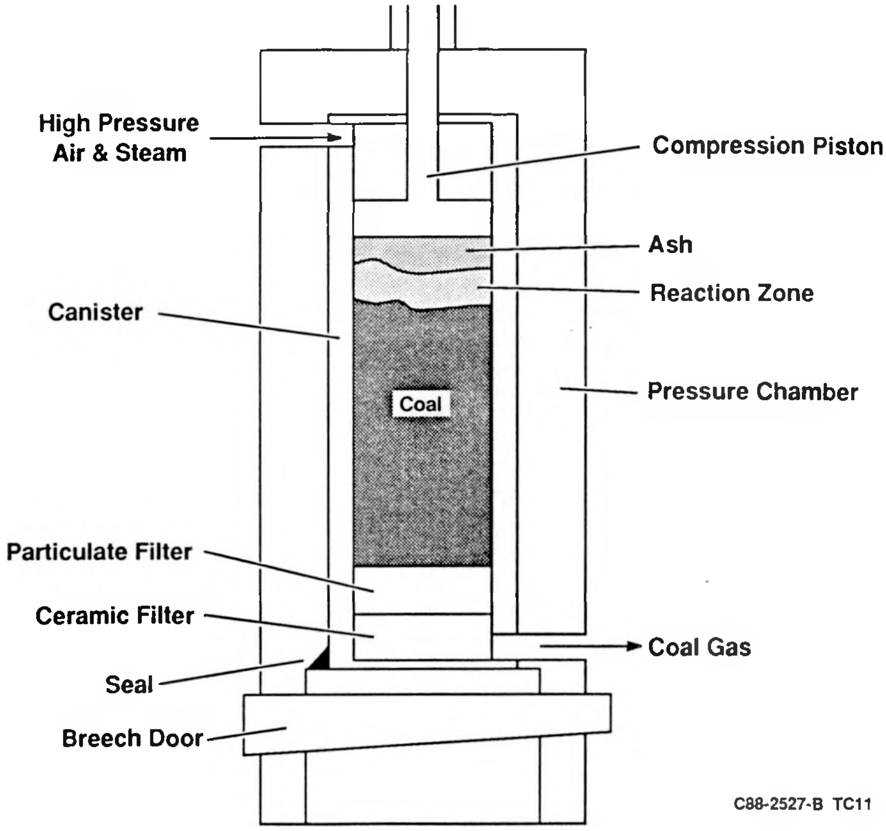

Figure 3. Caterpillar Gasifier Design

3.3 Technology Support Projects

Support projects complement the work done by addressing critical technology issues. Adiabatics, Inc., has conducted tests with dry powder fumigated into the air intake manifold of a single-cylinder diesel engine (Kakwani et al. 1989). The tests were conducted using bituminous coal, 10 to 21 µm in size, in a single-cylinder, 5.125-in. bore engine at speeds of 800 to 1,800 rpm. Adiabatics is continuing their diesel work, specifically addressing fuel injection, combustion, and wear issues. Advanced fuels such as mild gasification liquids are being tested at METC in an advanced diesel research engine (a Ricardo Proteous, 5-in. bore, single-cylinder engine). Fuel combustion characteristics are predicted from combustion bomb results before engine tests are conducted. The engine experiments explore the combustion and emission characteristics of these advanced fuels and their effects on engine performance. A cooperative project with the National Institute for Occupational Safety and Health is being conducted to characterize the chemical composition and the biological activity of diesel emissions with coal-based fuels.

Modeling studies at METC support the engine testing and are used to assess engine performance, emissions, and economic incentives of diesel systems fired with coal-derived fuels. Most studies use a model developed at the Texas A&M University for METC (Caton 1986). Because diesels are part of total systems, the diesel engine modeling work is frequently integrated with modeling of other system units (e.g., gasification, sulfur removal, heat recovery).

Support contracts were awarded in 1988 to SWRI, Tecogen, and Mechanical Technologies, Inc. (MTI). These projects are looking at techniques to overcome problems with ring and liner wear. Tecogen is evaluating a liquid ring flushing system, while MTI is determining the feasibility of using dry powders as lubricants. SWRI is performing research to identify fundamental causes of coal-ash-related wear, and is investigating techniques to reduce coal-induced wear in diesel engine components. Specifically, SWRI hopes to determine whether wear is caused by adhesion, abrasion, or both. This determination will aid manufacturers in developing solutions to wear problems through hardened materials, lubricants, or ash chemistry modifications.

4.0 DIESEL SYSTEMS AND ECONOMIC ASSESSMENT

Significant progress has been made in understanding the economics of diesel engine systems. Recent studies have shown that both coal-fueled diesel locomotives and stationary coal-fueled diesel systems in the 2- to 20-MW size range will be economically attractive if fuel costs can be brought down to less than $2/MBtu above the cost of the source coal (Arthur D. Little, Inc. 1986, 1988; Morgantown Energy Technology Center July 1986). This assumes an increase in oil prices to $25 per barrel (bbl). These prices would provide enough economic incentive to build both coal-fueled engines and fuel manufacturing plants.

While oil is the fuel of choice in transportation applications, natural gas is also a competitive fuel source for stationary power applications. Recent predictions show that a large amount of natural gas is recoverable at modest prices (Argonne National Laboratory 1988), and that a slow rate of increase in natural gas prices should be expected for at least the next decade. ADL has estimated that the break-even point for a cogeneration system will be reached when gas prices increase above $5.00/MBtu delivered (Arthur D. Little, Inc. 1986).

Changing an engine system from oil or natural gas to CWF changes not only the cost of fuel but the costs for engine capital, maintenance, and emissions control. Recent estimates by ADL and Cooper-Bessemer include a cost premium of $0.33/kWh for maintenance and overhaul of a 6-MW coal-fueled engine. Engine wear because of the use of coal fuel causes the increased maintenance and overhaul costs.

An increase in the capital cost of the installed engine system is expected because of the increased cost of durable engine components designed to withstand the increased wear from a coal fuel. An engine cost-premium of $1.67 million over the base cost of $3.5 million for a Cooper-Bessemer 6-MW engine is predicted. Emission control costs are expected to be $0.0103/kWh, including both capital and operating costs. ADL projects a total cost of $0.0685/kWh, including the cost of CWF ($3.00/MBtu), capital charges, overhead and maintenance costs, and emission control costs.

GE determined that acceptable profits of a 20% discounted rate-of-return (DCRR) on investment were achievable with average western CWF fuel costs at $3.19/MBtu and diesel fuel at $6.30/MBtu ($0.85/gal) (GE Transportation Systems 1989). Coal-fueled locomotives operating on eastern railroads, with lighter duty cycles than western railroads, were competitive at higher diesel fuel prices of $0.95/gal. In this report, GE also identified a "best case" for a coal-fueled locomotive operating on the Union Pacific line hauling coal from the Powder River Basin, Wyoming, to North Platte, Nebraska. A 58.3% DCRR was calculated for this best case, even at today's low diesel fuel prices of $0.65/gal ($4.98/MBtu). This high DCRR was because of CWF costs ($1.64 MBtu) and Union Pacific's very high duty cycle. The CWF price was based on a low-sulfur raw coal cost of $6.00/ton and coal processing at the mine mouth (thereby eliminating CWF transportation charges). The unit train for this 700-mile trip also operated at notch No. 8 (full power) 29% of the time, which was nearly double the average for Western railroads. GE estimates are based on a $279,000 capital cost premium for the coal-fueled diesel locomotive, which includes a baghouse for particulate control.

5.0 DIESEL PROGRAM RESULTS AND STATUS

Results of these projects are confirming the merit of fueling diesel engines with coal. The contractors are defining coal-fueled engine requirements for successful operation, including fuel specifications, combustion limits, performance parameters, requirements for environmental compliance, physical size limitations, and infrastructure constraints. Having the diesel manufacturers conduct major portions of the research will lessen the difficulties of technology transfer from developer to manufacturer.

5.1 Coal Fuel Processing, Handling, and Injection

Understanding the impact of fuel composition and fuel processing economics, while developing fuel specification guidelines, is of key technical importance for coal-fueled diesel engines. Currently, CWF, coal powders, and coal gasifier fuel streams are of primary interest in the DOE diesel program. Advanced coal-derived fuel forms are being developed that promise to be easy to handle and cost competitive.

The program has focused on coal in a water carrier (CWF), although Adiabatics has successfully operated a diesel engine on dry coal fumigated into the engine. The evolution of a viable coal fuel specification will depend on fuel cost considerations as well as on the performance and economics of the engine system and the effect of coal fuels on the engine and the environment. A typical CWF specification is shown in Table 2. This specification requires a coal that is cleaned to less than 2% total ash and grinding of the coal to a size of less than 20 μm. The small particle size is needed to reduce clogging of the passages in the diesel injector and to reduce the time needed for complete particle burnout. Rheological characteristics of the CWF are critical to its pumpability, atomization, and long-term stability.

Table 2. Coal Properties of Typical Coal-Water Fuels for Diesel Engines

Particle Size:	
Top	20 μm
Average	5-10 μm
Heating Value (HHV)	14,000 Btu/lb Net
Volatility (Coal Basis)	30-35% by Weight
Ash (Dry Basis)	0.8-1.5% by Weight
Sulfur	1% by Weight
Coal Loading in Slurry	50-60% by Weight

To handle the CWF, positive-displacement- and accumulator-type injection systems have been developed that can adequately meter, inject, and atomize a variety of CWFs. A schematic of the positive displacement system is shown in Figure 4. All systems require flushing of the injection lines upon shutdown. Stability of the CWF is controlled through the use of additives. Care must be taken, however, to design a pumping and injection system that can prevent subjecting the CWF to elevated temperatures or high shear forces, both of which contribute to breakdown of the additives. To reduce the shear forces, progressive cavity pumps are generally used for bulk transport of the CWF, and injectors are modified to operate between 9,000 and 12,000 pounds per square inch (psi), which is half the pressure of normal diesel fuel injectors. Operational injection systems now exist that allow the diesel engine to operate on CWF. These systems will be optimized in the near future to improve their performance, reduce their complexity, and to tailor them to a specific application (i.e., incorporating the CWF system into a locomotive envelope).

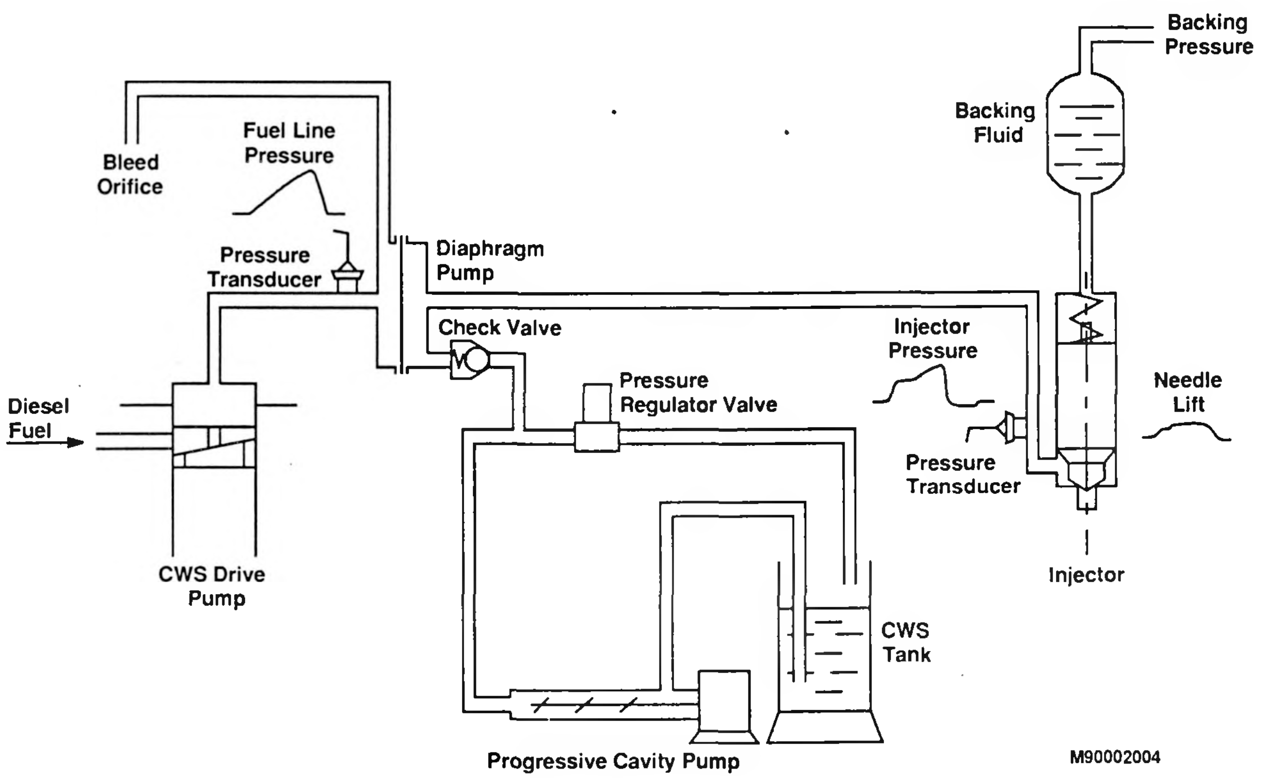

Figure 4. CWF Injection System

Advanced coal fuels, including mild gasification liquids distilled from coal, have been successfully burned in small laboratory rigs and in the METC diesel engine. Many of these fuels demonstrate good combustion characteristics and show potential as substitutes for diesel fuels.

5.2 Combustion

The diesel engine must achieve complete combustion of the coal fuel within a limited residence time for high system efficiency and for reduced degradation of the engine and environment. The ability to intermittently ignite and burn coal fuels in a diesel engine is critical. The combustion of coal fuels in a diesel engine is a function of fuel properties, spray pattern, and in-cylinder conditions, including combustion residence time. The relative influences of chamber geometry, fuel characteristics, and changes in engine operation on coal particle burnout need to be fully understood in order to optimize engine performance.

By mid-1989, the heat engines program had achieved over 200 hours (h) of testing using CWF in full-scale, single-cylinder diesel engines. Combustion efficiencies have exceeded 99%. The overall efficiency of the diesel engine operating on coal is often higher than its operation on diesel fuel. Experiments have shown that while a delay in ignition occurs because of the evaporation of water in the fuel, coal burnout (heat release) with CWF is higher and contributes more energy at the top of the piston stroke than diesel fuel. This contribution of energy at the top of the piston stroke can overcome the thermal efficiency losses caused by water in the combustion process. This phenomenon is evident in the GE heat release curves in Figure 5 (Hsu, Leonard, and Johnson 1988).

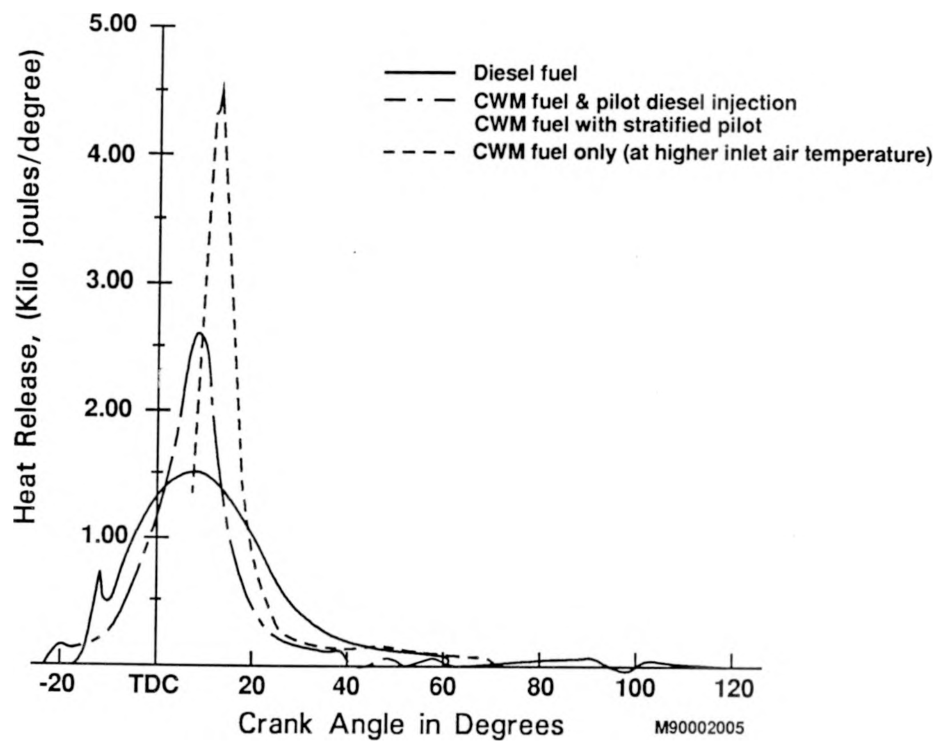

Figure 5. Heat Release Curves

In general, both the GE and Cooper-Bessemer engines operate with a maximum of 5% pilot diesel fuel at full-load conditions. The pilot fuel requirement increases at part-load conditions. Pilot fuel is primarily used to ensure correct ignition timing of the CWF. Cooper-Bessemer has also demonstrated that a diesel engine can operate at full-load conditions without a pilot fuel by increasing the manifold air temperature.

ADL/Cooper-Bessemer is continuing to make progress in their full-scale, 400 rpm, 13-in. bore, single-cylinder engine tests (Arthur D. Little, Inc. 1988). This engine has successfully operated on an AMAX-produced CWF (55% solids loading) with a specific fuel consumption and combustion efficiency comparable to a No. 2 petroleum fuel. These results have been verified through heat release and pressure analyses, exhaust particulate measurements, and carbon monoxide (CO)/carbon dioxide (CO_2) ratios. Ignition delays were acceptable and reproducible, and the engine has operated on 100% CWF on several occasions.

Adiabatics developed and was granted a patent for their thermal ignition and control system for a dry-coal-feed diesel engine. This system used a heated combustion prechamber in conjunction with exhaust gas recirculation as an ignition timing-control device. The coal is metered and then fumigated into the intake manifold at sub-atmospheric pressure. The project developed a low-pressure and low-cost, single-cylinder, four-cycle, dry-coal-fueled engine. Adiabatics successfully operated the engine on 100% coal fuel, without an external ignition aid (i.e., natural gas pilot or heated intake air). A wide range of medium to high operating speeds (800 to 1,800 rpm) was demonstrated on various coals, including eastern bituminous and western lignites.

5.3 <u>Component Durability</u>

The chemical and physical processes that affect coal ash constituents, like those that affect coal combustion, are not totally understood. Trace amounts of some coal elements can change the characteristics (abrasiveness, hardness, stickiness, and shape) of ash particles, affecting how ash interacts with the diesel engine (Carpenter, Crouse, and Halow 1985). Minimizing the effects of coal contaminants on the performance of the diesel engine is critical. Problems stem from the ash and any unburned coal and char particles that cause accelerated wear of the injector systems, cylinder walls, rings, valves, pumps, and downstream components.

5.3.1 Injectors

GE and Cooper-Bessemer have taken several different approaches to solving the injector wear problem: coal cleaning, innovative injector design, and application of durable materials. As a result, both contractors have developed prototype injectors that have projected operating lives of over 500 h, although none has been tested this long.

GE has completed over 50 h of engine testing with a new CWF injector that has nozzle orifices fabricated from synthetic diamonds. As shown in Figure 6, 10 diamond inserts were mounted to a tungsten carbide plug, laser drilled to obtain .017 in. orifices, and the entire assembly was brazed to the CWF injector body. These diamond inserts are being considered for use in a coal-fueled diesel locomotive to reduce the abrasive wear caused by the high-pressure

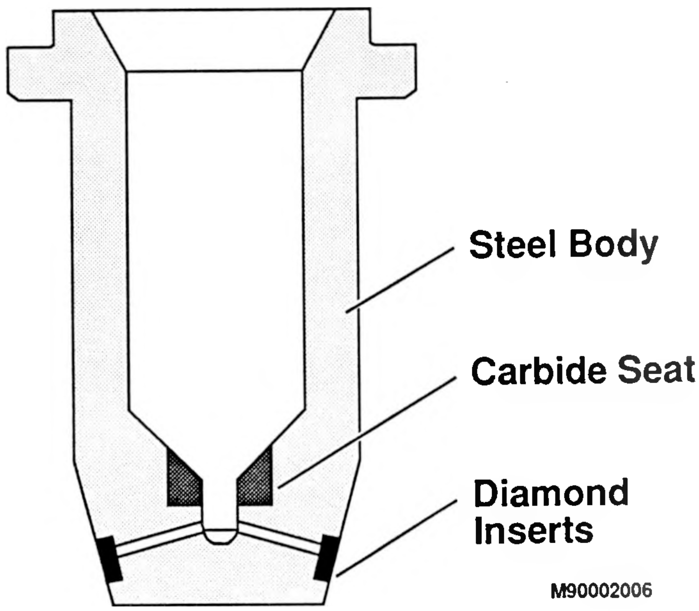

Figure 6. GE Diamond Inserts Injector

injection of CWF fuels. Erosion tests have indicated that CWF wear rates on diamond compacts are comparable with diesel fuel operation. GE has estimated that a commercial CWF injector with synthetic diamond inserts will cost approximately $500, compared to diesel fuel injectors at $50.

Cooper-Bessemer has tested the conventional multihole and the variable area nozzle design injectors illustrated in Figure 7. The Cooper-Bessemer single-cylinder test engine has operated with both tungsten carbide- and titanium carbide-coated, poppet-type nozzle injectors for 5.5 h (each) with no discernible visual wear on either the nozzle valve or seat. The nozzle still had considerable life remaining. The success of this design is caused partly by using (1) titanium carbide as the hardened valve and seat material with a smooth surface finish, (2) rounded orifice geometries to reduce cavitation, and (3) lower CWF injection pressures (7,000 to 9,000 psi). A CWF injector with a monolithic, tungsten carbide (WC), multihole nozzle tip was also tested and operated in the engine for 38 h, which is the longest run yet by a single nozzle. Post-test inspection of the nozzle indicated that considerable life (200 h total) could be expected from this hardened nozzle. Further improvements in nozzle design and materials are expected to result in commercially acceptable nozzles with lifetimes on the order of 1,000 h.

5.3.2 **Rings and Liners**

Cooper-Bessemer has conducted over 100 h of wear testing on a cylinder-ring combination of cast iron and tungsten carbide in an Ajax test engine. The Ajax engine, which has nearly identical geometries to the Cooper-Bessemer

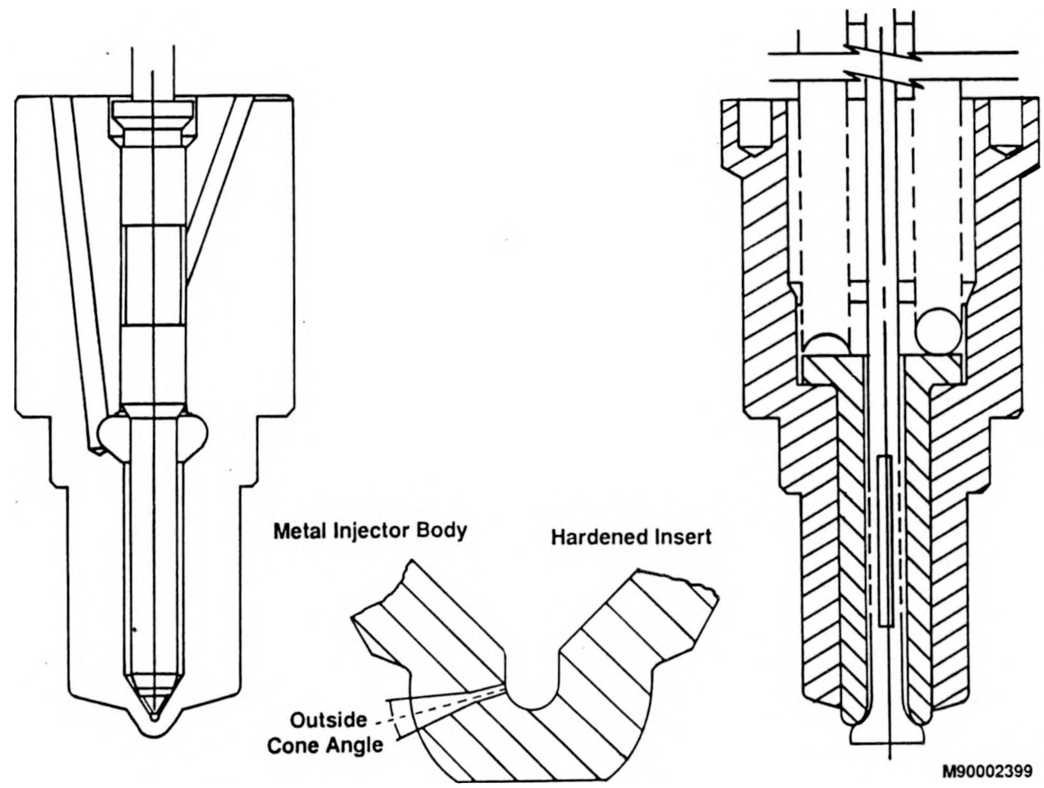

Figure 7. Pintle Type (ADL/Cooper, GE) and Variable Area (ADL/Cooper) Nozzles

model JS diesel engine, was operated on natural gas with an abrasive coal-oil fuel injected circumferentially around the piston-cylinder interface. The amount of abrasive material injected into the cylinder was determined so that the wear rates induced in the Ajax engine corresponded to wear rates typical of the coal-fueled Cooper-Bessemer JS test engine. The ring set experienced low wear rates of less than two thousandths of an inch of end gap wear during the 100-h test. Cooper-Bessemer plans to install the tungsten carbide rings in the JS engine for coal-water fuel testing. Similar wear rates with tungsten carbide materials have been measured by GE. This material shows promise in solving the ring and liner wear problems associated with coal-fueled diesel engines.

5.4 Emissions and Cleanup Systems

Coal-based fuels contain ash particles, fuel-bound nitrogen, and sulfur compounds. These elements are of environmental concern. System studies and experimental research programs are necessary to develop a scientific, engineering, and economic understanding of the environmental aspects of coal-fueled diesel engines. For many applications, emission standards do not exist. However, at minimum, the engines to be developed must not increase the emission levels of those power systems that they will displace. Diesel engines burning petroleum-based fuels typically produce relatively high levels of NO_x emissions, but recent CWF tests indicate that NO_x levels are in some cases reduced by half (Arthur D. Little, Inc. 1988). This is brought about by a reduction in thermal NO_x from the flame caused by the cooling effects of the water in the fuel. CO and hydrocarbons were also reduced in slow-speed diesel engine tests. Although initial emissions measurements are encouraging, further testing is needed to characterize and control emission levels, especially for locomotive and cogeneration applications.

GE has conducted a series of single-cylinder diesel engine tests at full power (270 hp at 1,050 rpm). The measured NO_x levels (0.9 lb/MBtu) confirmed the previous finding of Sulzer that NO_x levels were less than half the normal values typically measured for petroleum-fueled diesel engines (Hsu, Leonard, and Johnson 1988).

GE has also tested a copper-oxide sorbent that demonstrated sulfur dioxide (SO_2) capture of over 80%. The tests were conducted in a fixed-bed laboratory reactor at temperatures of 1,000 °F, typical of the diesel exhaust upstream of a turbocharger. The 80% SO_2 capture was maintained over a 40-h test period, during which 20% of the sulfur sorption capacity of the copper-oxide was utilized. Additional tests to evaluate the long-term effectiveness of the copper-oxide bed and its regeneration characteristics are planned.

Physical Sciences, Inc., a subcontractor to the coal-fueled, stationary, diesel engine development program, completed sorbent injection experiments at baghouse temperatures for SO_x control. During these tests, the sorbent material was either injected into the duct upstream of the filter, or the filter material was precoated with sorbent. In an actual engine system, nearly all of the SO_x reduction takes place at the filter because of the long residence time (10 to 15 times greater than in the sorbent injection duct). SO_x reductions of 70% were obtained at filter temperatures of 20 to 30 °F above the saturation temperature, using a dolomitic sorbent. The saturation temperature at the filter is approximately 150 to 160 °F. The low-temperature sorbent-injection technique is the lowest cost cleanup technique envisioned for coal-fueled diesel engines.

Physical Sciences has also conducted preliminary fixed-bed experiments to investigate engine particulate matter as a NO_x reduction catalyst. The engine particulate matter was captured from earlier single-cylinder, coal-fueled diesel engine test runs. Up to 50% NO_x capture occurred at residence times from 1 to 2 seconds (s). The level of NO_x capture obtained exceeded that by commercially available activated carbon, which was tested under the same conditions. Approximately 70% of the particulate matter was consumed during the test. While these results should be viewed as mainly qualitative in nature, the similarity between the particulate matter in a coal-fueled diesel engine and activated carbon is very encouraging. Significant reductions in emission-control costs for coal-fueled diesel engines could be realized by using the "free" carbon particulate in the engine.

In summary, cost-effective emission cleanup systems have been identified that should potentially meet all applicable emission standards. Selection of the final system will depend on the results of ongoing testing, size and weight limitations (locomotives), cleanup system effectiveness, as well as capital and operating costs.

6.0 GAS TURBINE PROGRAM, INTRODUCTION AND TECHNOLOGY DESCRIPTION

6.1 Applications

Gas turbine engines, also called Brayton cycle engines, are widely used in diverse applications, ranging from small auxiliary power units of less than 100 kW to utility-scale units at over 150 MW. There is a full range of gas turbine applications, including mechanical drive, flight propulsion, marine propulsion, and industrial cogeneration.

Gas turbines are dominant in applications where a high power-to-weight ratio and a high volumetric power density are important, such as flight propulsion. In larger power applications (5,000 hp and larger), gas turbines also enjoy a decided cost/hp advantage over other types of heat engine. In stationary thermal power systems, where compressor intercooling, steam injection, and various combined cycles and other heat recovery options may be used, gas turbines systems can now be built with overall system thermal efficiencies of well over 50%. Gas turbines require far less routine maintenance than other types of internal combustion heat engines; some industrial units have demonstrated the capability of running continuously at full power for up to 30,000 h.

The main disadvantages of gas turbines are their relatively low efficiency at part-load, high cost/hp in smaller sizes, and their low tolerance for certain fuel contaminants, especially sodium, vanadium, and particulate matter. For these reasons, reciprocating engines dominate land transportation and small marine, mechanical drive, and power generating applications; "dirty" fuels such as coal are the nearly exclusive domain of indirectly fired systems, such as Rankine cycles.

6.2 History of Coal Utilization

Almost from the inception of practical commercial applications for the gas turbine, attempts have been made to burn coal in gas turbines, despite the formidable challenges. These efforts were motivated by the desire to take advantage of the low cost and ready availability of coal while benefiting from the inherent advantages gas turbines offer in power generation systems. Pressurized fluidized-bed combustion (PFBC) and integrated gasification combined cycle (IGCC) systems have undergone extensive development; these systems integrate gas turbines into a coal-fueled power system. These systems have had a high degree of technical success and are rapidly approaching commercialization. The goal of building a successful direct coal-fired gas turbine (DCFGT) has also been pursued over the past 40 years and has included coal-fueled turbine tests in the U.S. (Smith et al. 1967) and Australia (Australian Department of Minerals and Energy 1973). The first attempts to directly fire coal were straightforward. Researchers simply fed pulverized coal into the gas turbine's fuel nozzles and hoped for the best. Predictably, these early efforts were unsuccessful because of the destructive effects of coal combustion products on the combustor and turbine components. Turbine blades were eroded and corroded away by the highly abrasive alkaline ash, and the turbine gas path was rapidly fouled and plugged by the buildup of ash deposits. There was no solution to these problems at the time, because the appropriate fuel preparation, combustion, and cleanup technologies to allow coal to be efficiently and reliably burned in a gas turbine were lacking.

7.0 GAS TURBINE PROGRAM DESCRIPTION

Since 1982, METC has sponsored projects to develop gas turbines that will operate on coal-based fuels. The common aim of these projects is to develop environmentally acceptable, economically attractive, coal-based alternatives to using conventional natural gas and petroleum-derived fuels in these engines. The DCFGT program began as an exploratory effort and has grown into a proof-of-concept program that includes major gas turbine manufacturers, support contractors, and METC in-house programs. Much of the current work addresses the use of CWF, although there is some work with dry coal feed and other coal fuels. The most attractive potential applications now targeted for DCFGTs are industrial cogeneration and utility power generation systems.

7.1 Early DOE Coal-Fueled Gas Turbine Program

Significant breakthroughs in coal processing (cleaning and fueling) and improvements in gas turbines led DOE in the early 1980s to revitalize research and testing of this technology. In order to assess the economic viability, METC funded three economic and systems studies of utility applications of coal-fueled gas turbines. Westinghouse Electric Corporation (Berman 1984), GE (Cincotta 1984), and United Technologies Research Center (UTRC) (Giamonti et al. 1984) evaluated systems fueled directly by CWF and systems incorporating coal gasifiers. Results were mixed, but overall the reports pointed to opportunities for coal-fueled systems. An issue identified as critical to system economics was CWF cost. In some cases, on-site fuel preparation was needed for the large utility systems considered. In these cases, the cost of the on-site fuel preparation was also critical to system economics.

Early technical results supported the promising economics. A DOE/GE test program, initiated in the early 1980s, demonstrated that minimally cleaned low-Btu gas from a coal gasifier could be successfully burned in a GE MS6001 gas turbine combustor and passed through a turbine cascade with no significant deposition or erosion. In 1982, METC re-directed a number of DOE/National Aeronautics and Space Administration (NASA) contracts to investigate the combustion of highly cleaned and micronized CWF in combustors designed to produce low NO_x. This program showed that CWF could be successfully burned in gas turbine combustors with significant reductions in NO_x compared to conventional fuels (Morgantown Energy Technology Center 1985). An expansion of the program followed in 1984, with contracts awarded to Westinghouse Electric Co., GE (Ross 1987), UTRC (Rosfjord 1986), GM/AGT (Wenglarz et al. 1986), and Solar Turbines (LeCren et al. 1987) to develop combustors specifically designed to burn coal cleanly and efficiently. Success in these component development projects led to the establishment of the current proof-of-concept program (Ross 1987; Rosfjord 1986; Wenglarz et al. 1986; LeCren et al. 1987).

7.2 Proof-of-Concept Contracts

Four contracts for proof-of-concept projects were awarded in 1986 to GM/AGT, Solar Turbines, Westinghouse, and GE. The goal of these projects is to develop coal-fueled combustor and turbine systems, with limited duration testing at small commercial-scale to be completed by 1992. GE withdrew from the program by mutual agreement with DOE in 1988 and is now preparing a final report. GE based their decision to withdraw on the low commercial potential of their coal-fueled system, which utilizes an aircraft derivative turbine with downstream cleanup.

Each of the four contractors has developed a unique, power-system design philosophy, based on a particular grade of CWF and designed with compatible combustion and cleanup systems. Each contractor has also developed a commercial-size reference system, based on the chosen design concept, which must be economically evaluated and shown to fit into a potential commercial market.

Table 3 gives summary information about the three remaining proof-of-concept projects, and Figure 8 is a schematic of the system concepts being developed. Two of the systems are intended for use initially in industrial cogeneration, while the Westinghouse concept is directed toward utility applications. Each of the three systems will be fueled by CWF, although Westinghouse may select dry pulverized coal. All include significant sulfur capture and particulate cleanup before the hot gas stream reaches the gas turbine. Staged combustion and the use of slurries rather than dry coal will help hold NO_x levels down. Although two of the three systems are in a size range to which current Federal emission regulations do not apply, it is being assumed for their development that 90% sulfur capture (including credit for coal beneficiation) will be required, along with NO_x emissions below 0.5 lb/MBtu and particulate emissions of less than .05 lb/MBtu.

Table 3. Turbine Proof-of-Concept Projects

Company	Application	Combustor	Turbine	Size (MW)
Solar Turbines	Cogeneration	Off-Base Slagging	Centaur	4
GM/AGT	Cogeneration	Can	AGT-501	5
Westinghouse	Utility	Off-Base Slagging	W501	207[1]

[1] Two gas turbines with a steam turbine bottoming cycle.

Testing conducted to date has shown (1) that advanced coal fuels can be burned efficiently with the combustors designed for relatively low residence times that are practical for a land-based gas turbine, and (2) that the coal combustion products can be cleaned to sufficient levels to permit their passage through state-of-the-art turbine hot sections without undue degradation. The program is now moving from primary research and bench-scale component development into the integrated development and testing phase, which will

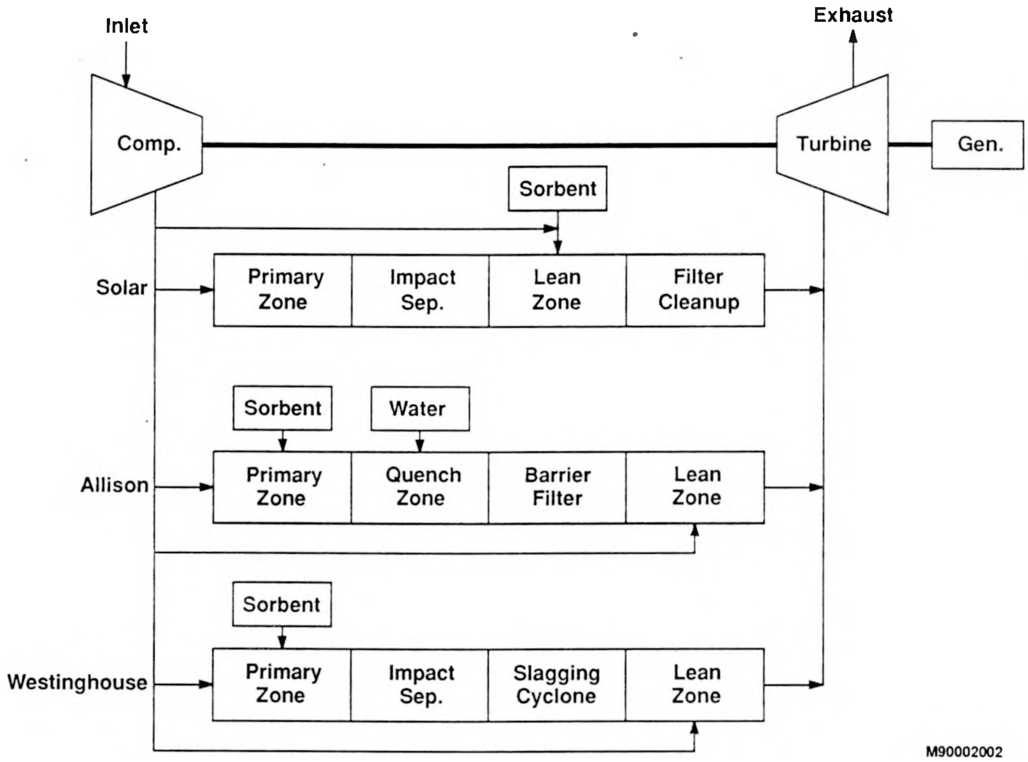

Figure 8. Block Diagram of the Three DCFGT Contractor Systems

lead to proof-of-concept testing of fully integrated coal-fueled gas turbine power systems at a reasonable scale to permit commercial decision-making. Market introduction is expected by the late 1990s.

7.3 Technology Support Projects

The DCFGT program includes support projects as well as proof-of-concept projects. The support projects address specific barrier issues to technology commercialization, in a manner that is complementary to and logically integrated with METC in-house research efforts. Technical support projects are being conducted by industrial and university laboratories, national laboratories, and by the in-house research staff at METC.

METC in-house activities in coal-fueled heat engines are focused on lead technology development and integration, but also support and validate key technology areas closely linked to contracted projects. The combustion behavior of coal fuels; cleanup technologies for dealing with gas stream contaminants; and related chemical, transport, and thermodynamic phenomena are studied in computer modeling studies, laboratory-scale test rigs, and bench-scale engine simulation rigs.

In-house computer studies range from systems analyses of entire coal-fueled thermal power systems to highly detailed combustion models that predict the behavior of microscopic individual coal particles. The systems studies are used to compare the efficiency and economics of various coal-fueled heat engine power systems and to optimize their integration with suitable gas stream cleanup concepts. Detailed, mechanistic computer models of combustion, transport, and contaminant behavior give initial guidance to new hardware and process designs for coal-fueled heat engines, and provide a basis for interpreting experimental data from coal-fueled heat engine test programs. The experimental data are also used to validate and update the models.

Ash deposition is being studied at METC in a device that heats and burns coal in a controlled environment, and then impacts the resulting ash onto a cooled target. Effects of combustion conditions, target cooling, various coal properties, sulfur and alkali levels, and gettering additives have been studied. The results have provided insights into the mechanisms of and the parametric effects on deposition.

An electrodynamic balance is used at METC to study the combustion behavior of individual coal particles and CWF droplets; the purpose is to understand controlling mechanisms and to determine limiting time scales associated with droplet evaporation and atomization, coal particle agglomeration and swelling, and coal devolatilization, which are all important properties for determining overall combustion performance. These data will factor into the design of advanced heat engine combustors currently being developed at METC. An integrated effort to evaluate and develop new strategies for rapid sulfur cleanup by direct injection of sorbents into heat engine combustors is also in progress. This program incorporates mechanistic modeling of the relevant transport and chemical processes with laboratory- and bench-scale combustion/cleanup tests, including detailed analyses of combustion products (solids and gases). The goal is to assess the feasibility of in-combustor sulfur cleanup and to develop process control strategies for heat engine applications.

In transparent flow-visualization models, combustor gas-flow streamlines and trajectories of entrained particulates are studied by various optical and photographic techniques, including the injection of neutral-density helium bubbles and high-speed motion pictures. A bench-scale pressurized combustor is used to simulate conditions in a coal-fueled gas turbine combustor on a larger scale. A planned, advanced combustion facility will contain a broad spectrum of coal-fueled combustors, ranging from small well-stirred reactors to a proof-of-concept-size unit capable of firing a small industrial gas turbine.

8.0 GAS TURBINE SYSTEMS AND ECONOMIC ASSESSMENT

As one of the first steps in the proof-of-concept projects, the contractors conducted reference system studies, which included conceptual designs and economic evaluations of the systems they proposed to commercialize. This information is periodically updated by the contractors. For a mid-program assessment conducted in October 1988, the DCFGT contractors performed economic assessments on their reference systems. After the contractor assessments were normalized by METC to a common basis, it was found that the systems were roughly comparable in capital and operating cost per unit output.

Estimated coal-to-electricity heat rates were comparable for the cogeneration systems, but the Westinghouse combined-cycle utility system naturally had a much lower heat rate. The lower heat rate, plus a substantially lower delivered fuel cost (because of an on-site fuel preparation plant), gave the Westinghouse system a decided advantage in net fuel cost per unit of electrical output. However, capital costs for the Westinghouse system were increased by the inclusion of the steam bottoming cycle and an on-site fuel preparation plant. Therefore, despite major economies of scale (207 MW versus 3 to 5 MW), the Westinghouse total capital requirement (TCR) per unit electrical output was not greatly lower than the others.

Overall, the results of the reference systems studies and updates showed that direct coal-fired gas turbine systems could be economically attractive for cogeneration and utility applications. Probably the biggest factor affecting commercial attractiveness of the systems is the fuel price differential that can be realized between coal fuels and the fuels for alternative technologies. Certainly if natural gas prices were to remain at their current low prices for an extended period of time, commercialization of the coal-fueled turbine systems being studied would be delayed.

9.0 GAS TURBINE PROGRAM RESULTS AND STATUS

9.1 Fuels Technology

Coal fuel for direct turbine firing can be dry powder, CWF, or a coal-derived liquid. The DOE DCFGT has been run primarily on CWF. Major concerns in this area include fuel cost, rheology, volatility levels, degree of coal cleaning, particle distribution, stability, and quality assurance. In order to minimize overall system costs, trade-offs must be established between fuel quality, engine fuel tolerance, and ancillary components, including cleanup systems.

A key element of all DCFGT proof-of-concept projects is the development of specifications for CWF fuels that integrate effectively with the contractor's chosen combustion system, gas stream cleanup system, and fuel-handling systems, as well as provide acceptable power system economics. The preparation processes used for CWF fuel involve grinding the coal to a suitable particle size for fueling and some degree of contaminant removal. Coal type, particle size, and degree of contaminant removal are the principal options in the preparation process that must be considered by the system designer in arriving at a suitable CWF fuel specification for a coal-fueled gas turbine power system. These process options are also key factors in determining fuel combustion properties, handling characteristics, gas stream cleanup requirements, and cost.

Both CWF and dry pulverized coal have been used in combustor testing. Initial Westinghouse subscale testing at Avco Research Laboratory has successfully used dry powder and CWF. Solar Turbines and GM/AGT have used CWF and have not experienced any fuel handling, storage, or pumping problems with the fuel. Close monitoring of the CWF is, however, required to maintain consistency and solids loading at the typical 50%. Most of the CWF processed and burned has been high volatile bituminous coal, but slurries have been successfully formulated with subbituminous and lignite coals. Small quantities of coal liquids from a mild gasification process have also been produced and are undergoing laboratory testing and analysis at METC.

Generally, the program contractors have been moving toward using minimally cleaned and coarsely ground CWF in order to hold fuel costs down. Although initial combustion tests were conservatively run with highly processed slurries, subsequent tests with minimally cleaned CWF have been successful. Basic fuel and combustor parameters for the three major contractors are summarized in Table 4.

9.2 Combustion and In-Process Gas Cleanup

System diagrams for the three combustor-island systems are shown in Figure 9. All of the combustion systems feature externally mounted, multiple chamber, can-type combustors that are close-coupled to in-process gas cleanup devices located upstream of the turbine sections. External mounting is necessary because of the large size of the combustor and because of the need to integrate the combustor with its in-process particulate and sulfur cleanup

Table 4. Coal-Fueled Gas Turbine Combustor and Fuel Summary

Contractor	Westinghouse	Solar	AGT
Combustor Design			
Type	Slagging	Slagging	Dry Ash
Turbine Inlet Temperature (°F)	1850	1850	1970
Pressure Ratio	12.4	10.2	11.6
In-Process Ash Capture (?)	Yes	Yes	Yes
In-Process Sulfur Capture (?)	Yes	Yes	Yes
Fuel Specification			
Coal Loading (% Solids)	60	55.5	50
Fixed Carbon (Wt%)[1]	> 69		
Volatile Matter (Wt%)[1]	< 31	35	38
Ash (Wt%)[1]	3-15	3-10	1
Nitrogen (Wt%)[1]	<1.7	< 2	
Sulfur (Wt%)[1]	< 1	1-3.5	2
Total Alkali (ppm)[1]	< 1000	< 1000	
Particle Size (Top/Mean, μm)	300/40	45/10	25/6
Heating Value (Btu/lb)[2]	9,488	8,325	6,500
Apparent Viscosity (cp at 100 1/s)	< 500	< 200	< 100

[1] Dry coal basis; [2] HHV in 1 lb of slurry.

systems upstream of the turbine. These combustors also feature multiple chambers to allow staged rich-lean combustion to control NO_x formation. Combustion first occurs under fuel-rich conditions in the primary chamber, and then under fuel-lean conditions in the secondary chamber. The formation of NO_x is limited because maximum flame temperatures are kept low by staged combustion.

Both slagging and dry ash combustors are being investigated in the program. All of the residual ash from combusting the coal fuel is initially melted in the hot flame of the primary combustion zone. The ash may or may not solidify before leaving the primary zone, depending upon the gas temperature and amount of excess air present. If the ash does solidify before leaving the primary zone, the combustor is said to operate in dry ash mode. If it is still molten as it leaves the primary zone, the combustor is said to operate in slagging mode.

The Solar and Westinghouse systems run their primary combustion chambers in slagging mode and use inertial impactors to separate molten ash from the gas stream as it exits the primary combustion chamber. The Solar system has sulfur sorbent injection in the secondary combustion zone followed by a ceramic barrier filter. The Westinghouse system has sulfur sorbent injection in the primary zone, upstream of the inertial impactor, and is expected to require a conventional fabric filter downstream of the turbine for secondary

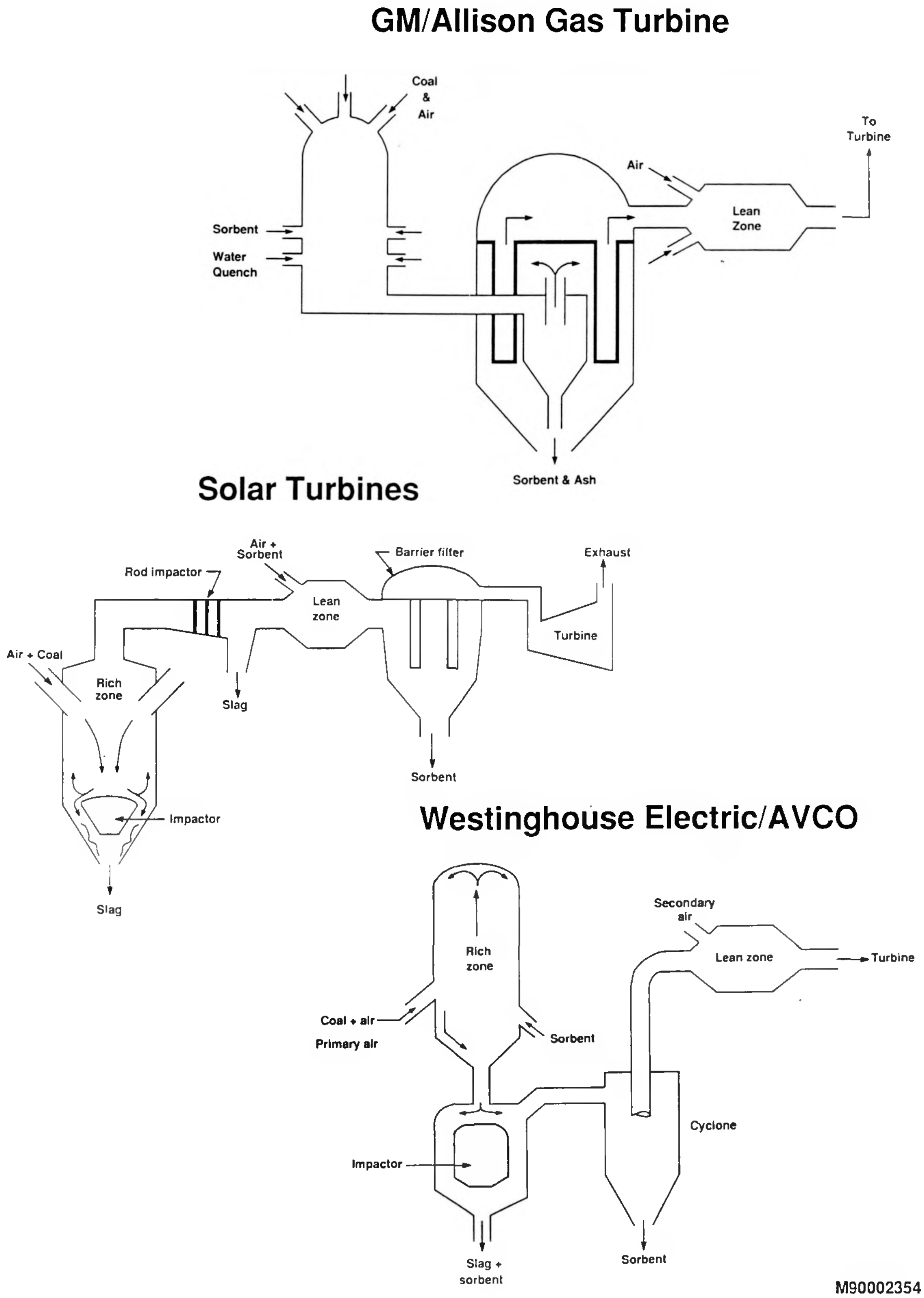

Figure 9. Combustion Turbine Proof-of-Concept Configurations

particulate cleanup. The AGT system operates the primary combustion zone in dry ash mode, with sulfur sorbent injection and a cyclone-barrier filter combination upstream of the secondary combustion zone.

At the other extreme, Solar Turbines plans to use a minimally cleaned CWF and to do all of their gas cleaning before the turbine expander. Fuel will be burned in a substoichiometric combustor, and slag will be separated from the exhaust gas in an impact separator section. Air and sorbent will be added in a lean zone combustor, and a barrier filter will provide final particulate cleanup before the gas enters the turbine at 1,850 °F. This sequence of cleaning steps, along with coal beneficiation, should result in no further cleanup being required after the turbine. Because barrier filters have not been demonstrated under these operating conditions, the Solar test program includes subscale evaluation of candle and ceramic bag filters. The most attractive of these alternatives will be used in the proof-of-concept test.

The Westinghouse system also uses a rich zone combustor, followed by inertial slag separation and a lean zone combustor. In this case, however, the sorbent for sulfur capture is fed into the rich zone rather than the lean zone, so the used sorbent can be partially removed along with the coal ash in the inertial separation (impactor) and slagging cyclone between the rich and lean zones. There will be no barrier filter between the lean zone combustor and the turbine in this system; final particulate cleanup will be a baghouse downstream of the turbine.

The GM/AGT system will also have separated rich and lean zones, with sulfur capture and particulate cleanup between the two. In this case, the sorbent will be added in a quench zone following the rich zone combustor. This will lower the gas stream temperature so that a barrier filter after the quench zone will not be at slagging conditions. Required sulfur capture will be achieved through a combination of coal cleaning and the sulfur capture in the quench zone. Particulate cleanup requirements will be met by the barrier filter, and a baghouse downstream of the gas turbine will not be required.

The program has demonstrated that CWF and dry coal fuel forms can be burned in both short residence time in-line combustors and in off-base combustors with over 99% efficiency. These combustors can reliably change from distillate fuels (used during light-off) to 100% CWF. As shown in Table 5, slagging combustors have achieved between 65 and 95% slag capture, which will limit the particulate loading on pre-turbine cleanup devices.

9.3 Deposition, Erosion, and Corrosion

Early deposition tests showed that untreated CWF combustion products rapidly foul a turbine. However, tests at GE identified fuel additives that raise the fusion temperature of the ash and nearly eliminate deposits on the turbine surfaces. Periodic nutshelling and water washing of the turbine have also proven effective for removing coal ash deposits, and pre-turbine cleanup systems such as impact separators, cyclones, and barrier filters reduce both deposits and erosion. The three remaining major contractors all plan to use

Table 5. Subscale Combustor Performance Results

	Solar	AGT	Westinghouse
Fuel Specification Ranges			
Coal Form	(Dry/Slurry)	Slurry	(Dry/Slurry)
Size (Top/Mean, μm)	74/13	15/5	200/44
Ash (% Dry)	2.2	0.8	6.5
Sulfur (% Dry)	.72	0.6	1.0
Combustor			
TIT[1] or Combustor Exit (°F)	1,850	2,060	1,850
Pressure (atm)	6.5	10.9	6
Total Mass Flow (lbs/s)	2.6	4.1	7
Carbon Burnout (Efficiency)	98.3	99.6	> 99
Slag/Ash Rejection (%)	62	--	95
Primary Zone Res. Time (ms)	80	100	68
Emissions			
NO_x (ppm)	66	50	40
SO_x (Capture) (%)	80	50	80
Sulfur Sorbent Type	Dolomite	Dolomite	Limestone
Sorbent/Sulfur (Mole Ratio)	5/1	3.7/1	2/1

[1] Turbine inlet temperature.

pre-turbine cleanup systems, with exhaust output specifications based on particle characteristics and the tolerance of the turbines to particulate erosion. Testing of these particulate collection devices is scheduled to begin in late 1989.

Most erosion is caused by larger particles striking the rotating turbine airfoils. Particle separation devices upstream of the turbine, hardened airfoil materials, low-impact airfoil designs, or a combination offer potential ways to avoid erosion.

Coal contains a number of elements, including alkalies, sulfur, and chlorine, that can produce potentially corrosive compounds. Of these, gas phase alkalies, which condense as sulfate deposits on gas path surfaces, have the greatest corrosion potential. In order to protect the turbine from hot corrosion, combustion systems must be designed to inhibit the formation of gas phase alkali and other corrosive compounds. Other solutions may involve coal cleaning, the use of CWF additives to getter unwanted species, aerodynamic designs that prevent the arrival of these compounds at the metal surfaces, and anticorrosion coatings.

Corrosion of turbine system components has been investigated by both GE and GM/AGT. The GE results indicate that alkali condenses on particulates in the combustor exhaust, with the strong bond of the alkali to the aluminosilicate particles rendering them relatively inert. GM/AGT analyzed deposits from high-temperature pins installed downstream of their subscale combustor exhaust and found that deposits on hot metal surfaces could cause corrosion of the unprotected base metal. In response to these findings, corrosion resistant coatings for the turbine are being planned. Also, Solar Turbines will conduct a 5,000-h, laboratory-scale CWF test with a number of protective coatings to address this concern. It is anticipated that planned pre-turbine particulate cleaning, coupled with available turbine coatings, will be adequate for turbine protection; this will be demonstrated when the proof-of-concept tests are run.

9.4 Emissions

Achieving environmentally acceptable emissions is a key goal of the turbine program. Although emissions standards do not yet exist for the small cogeneration systems being developed by AGT and Solar, it is assumed that emission levels comparable to current New Source Performance Standards (NSPS) for industrial coal-fired steam plants will eventually apply. It is also assumed that credit will be taken for emission reductions because of coal beneficiation. SO_x, NO_x, and particulates are the primary emissions that must be controlled. Since most cleanup systems are volume-limited, emission control systems that operate in the high-pressure (minimum volume) region upstream of the turbine are preferred. NO_x control through rich/lean combustion systems should achieve emission levels at or below the anticipated emission standard. High-temperature sulfur gettering techniques using low-cost, calcium-based sorbents may also reduce sulfur emissions. Impact separators and barrier ceramic filters are being investigated to control particle and sorbent carryover to the turbine and exhaust. Achieving high levels of cleanup with minimal thermal and pressure loss is essential for a viable system.

The rich/lean combustion systems employed by all three major contractors have demonstrated low NO_x emissions levels. Solar, Westinghouse/Avco, and GM/AGT have all measured below 66 ppm NO_x in their subscale combustors, with some recent results at Avco being as low as 10 ppm. Achieving NO_x levels that are consistent with likely future regulations for these combustion systems appears very feasible. The NO_x emissions from the GE single-stage subscale system were significantly higher than for the rich/lean systems used by the other contractors, but development of an improved combustion air profile would likely have improved these results if that project had continued.

The contractors have also achieved promising results for controlling SO_x emissions using calcium-based sorbents, although emission control is proving somewhat more difficult for SO_x than NO_x. Sulfur capture levels between 50 and 80% have been demonstrated at calcium-to-sulfur molar ratios of between 2:1 and 3.7:1. Performance is expected to improve as the combustion and cleanup systems are optimized, and in-process sulfur removal will be augmented by the removal of sulfur during the fuel preparation. The 80% capture listed for Westinghouse may be misleading. This level of capture has been demonstrated at the exit of the rich zone combustor in their subscale facility at Avco, but not at the exit of the lean zone. There is some evidence that sulfur is being re-emitted from the slag after it is captured. The planned addition of slag removal to the subscale system should result in the demonstration of good sulfur retention through the lean zone combustor.

Meeting particulate removal standards should not present any insurmountable problems. In the Solar and GM/AGT projects, use of ceramic filters now being developed elsewhere should yield adequate cleanup before the turbine, so that a baghouse downstream will not be required. Westinghouse will use inertial slag separation and perhaps a cyclone before their turbine, and a baghouse downstream of the turbine will assure meeting NSPS standards.

The most serious technical concern for any project was the lack of preturbine cleanup for the GE system, and it was this factor more than system cost considerations that caused METC to be concerned about the viability of the GE system. GE, on the other hand, was concerned about the effect of natural gas prices on prospects for commercialization and about the lack of attractive downstream sulfur-removal systems. These factors led to GE's recommendation and DOE's concurrence that they defer development of their system and withdraw from the proof-of-concept program.

10.0 SUMMARY

DOE is supporting the development of coal-fueled gas turbine and diesel engines to serve a varied market. These two technologies are at the proof-of-concept stage, and a number of limited duration tests will be conducted at small commercial-scale within the next 3 years. These coal-fueled heat engine tests will use both CWF and dry coal as fuel. Significant technical progress has been made in the current program, and it now appears that the remaining technical barriers to commercialization can be overcome with approaches that have already been identified. However, a number of support projects address critical technical issues in order to provide backup technologies if unexpected problems should arise. Economic evaluations have shown that the technologies are competitive with petroleum-fueled systems, although displacement of natural gas firing will generally require a rise in the price of that fuel.

Overall, the prospect of efficient heat engines for operation with coal-based fuels has become increasingly realistic. Test results have shown that CWF and dry coal can be burned in both diesels and gas turbine combustors with good combustion and environmental performance, and significant progress has been made in addressing critical issues. Based on these encouraging technical results, the program is progressing with increasing confidence from engineering feasibility through component development to systems integration.

11.0 ACRONYMS AND ABBREVIATIONS

ADL	A.D. Little, Inc.
AGT	Allison Gas Turbines of GM
AMAX	AMAX Research and Development Center
AMBAC	American Bosch
bbl	Barrels
Btu	British thermal units
CO	Carbon monoxide
CO_2	Carbon dioxide
CR&D	Corporate Research and Development Center of GE
CWF	Coal-water fuel
DCRR	Discounted rate of return
DCFGT	Direct coal-fired gas turbine
DOE	U.S. Department of Energy
GE	General Electric Company
GEESI	GE Environmental Services, Inc.
GM	General Motors Corporation
hhv	Higher heating value
hp	Horsepower
h	Hours
IGCC	Integrated gasification combined cycle
in.	Inches
kWh	Kilowatt hours
lb	Pounds
MBtu	Millions of British thermal units
METC	Morgantown Energy Technology Center
MIT	Massachusetts Institute of Technology
MTI	Mechanical Technologies, Inc.
MW	Megawatts
NASA	National Aeronautics and Space Administration
NO_x	Nitrogen oxide
NSPS	New Source Performance Standards
PFBC	Pressurized fluidized-bed combustion
ppm	Parts per million
psi	Pounds per square inch
R&D	Research and development
RCM	Rapid compression machine
rpm	Revolutions per minute
s	Seconds
SO_2	Sulfur dioxide
SO_x	Sulfur oxide
SWRI	Southwest Research Institute
TCR	Total capital requirement
TSBO	Transportation Systems Business Operations of GE
μm	Micrometers
UTRC	United Technologies Research Center
WC	Tungsten carbide

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