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# Testing of a Coal-Fired Diesel Power Plant

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Contractor:

Arthur D. Little, Inc.
20 Acorn Park
Cambridge, MA 02140

Contract Number:

DE-AC21-88MC25124

Conference Title:

Ninth Annual Coal-Fueled Heat Engines, Advanced Pressurized Fluidized Bed Combustion (PFBC) and Gas Stream Cleanup Systems Contractors Review Meeting

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Conference Sponsor:

U.S. Department of Energy Morgantown Energy Technology Center

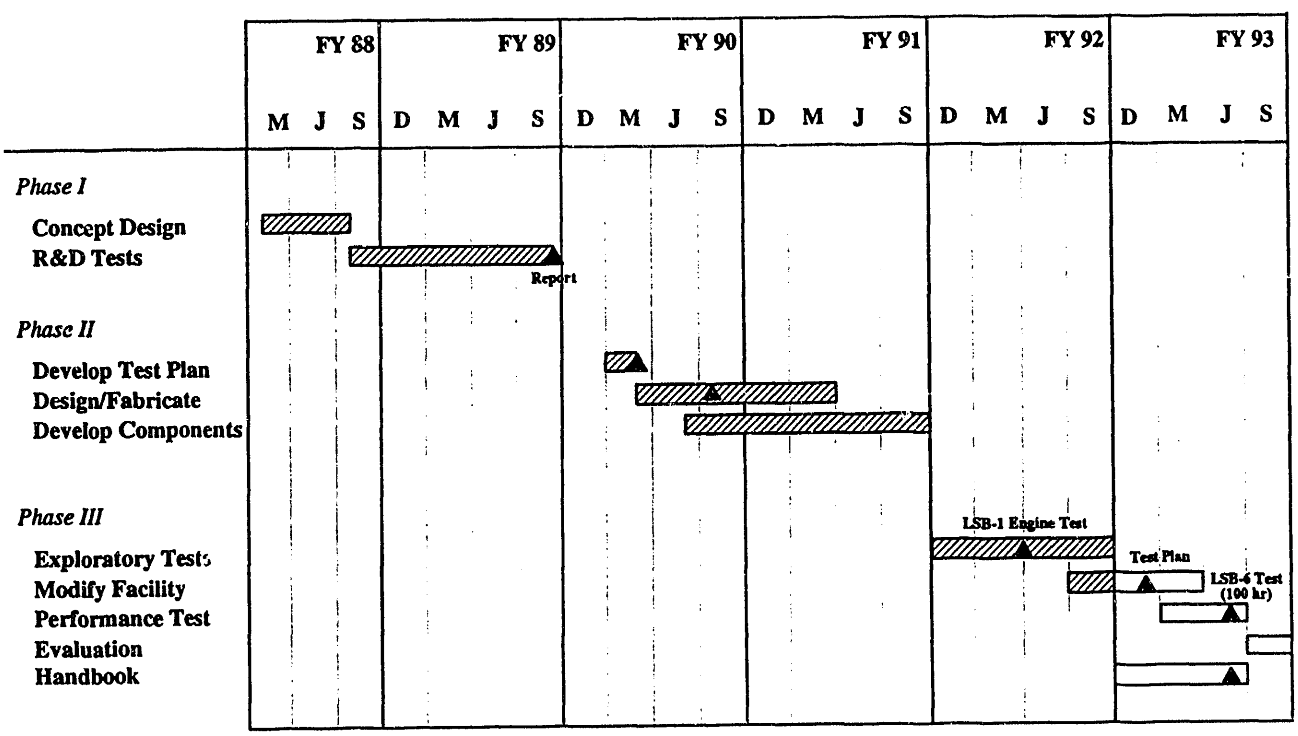
# Testing a Coal-Fired Diesel Power Plant

## CONTRACT INFORMATION

| | |
|---|---|
| **Contract Number** | DE-AC21-88MC-25124 |
| **Contractor** | Arthur D. Little, Inc.<br>20 Acorn Park<br>Cambridge, MA 02140<br>(617) 498-5000 |
| **Contract Project Manager** | Robert P. Wilson |
| **Principal Investigators** | Eric N. Balles (Arthur D. Little)<br>Kam Rao (Cooper-Bessemer)<br>Fred Schaub (Cooper-Bessemer)<br>Jack Kimberley (AMBAC)<br>Karen R. Benedek (Arthur D. Little)<br>Charles E. Benson (Arthur D. Little)<br>Dan Itse (PSI Technology) |
| **METC Project Manager** | W. Cary Smith |
| **Period of Performance** | March 1, 1988 to September 30, 1993 |

**Schedule and Milestones**

**Program Schedule**



## OBJECTIVES

Development of coal-burning heat engines for 2 - 50 MW modular stationary power applications requires significant technical advances in engine design, fuel preparation and handling, durable components, and emission controls. The overall goal of this DOE/METC funded program is to advance the state-of-the-art for *stationary coal-fired diesel engines* to the next plateau of technical readiness and thus provide the springboard to commercialization. The objective in this phase of the program is to develop practical, durable engine system components which are compatible with engine grade coal slurry fuel and are also capable of achieving low emission levels. These components have been integrated into a 1.8 MW coal-fired power plant which has been successfully run on coal fuel and is being prepared for a 100 hour (continuous) proof-of-concept (POC) demonstration test in 1993.

## BACKGROUND INFORMATION

The POC coal-fired power plant consists of a Cooper-Bessemer LSC-6 engine (15.5 inch bore, 22 inch stroke) rated at 400 rev/min and 208 psi bmep producing approximately 1.8 MW of power. The power plant is fueled with 'engine grade' coal slurry which has been physically cleaned to an ash level of approximately 1.5 to 2% (dry basis) and has a mean particle size of approximately 12 micron. CWS is injected directly into the combustion chamber through a fuel injector (one per cylinder) which was designed and developed to be compatible with the fuel. Each injector is fitted with a 19 orifice nozzle tip made with sapphire inserts in each orifice. The combustion chambers are fitted with twin diesel pilot injectors which provide a positive ignition source and substantially shorten the ignition delay period of the CWS fuel. Durable coatings (typically tungsten carbide) are used for the piston rings and cylinder liners to reduce wear rates. The emission control system consists of SCR for $NO_x$ control, sodium sorbent injection for $SO_x$ control, and a cyclone plus baghouse for particulate capture. The cyclone is installed upstream of the engine turbocharger which helps protect the turbine blades.

## PROJECT DESCRIPTION

Arthur D. Little, Inc., is leading a five-year, three-phase component development program with Cooper-Bessemer as the principal subcontractor responsible for development testing. Cooper-Bessemer is the premier manufacturer of 300-450 rpm engines in the United States, and is the only U.S. manufacturer of 300-450 rpm engines which has successfully operated a test engine on coal water slurry. Phase I, the R&D effort, which is complete, explored candidate alternative solutions to the most pressing design issues. Laboratory, bench-top and engine experiments were conducted as appropriate. The Phase I research efforts were selected with the benefit of results and discoveries from the 1986-1987 METC-sponsored Cooper-Bessemer/ADL coal diesel project. During Phase II, we developed working hardware prototypes for each component technology (clean coal fuels, injection, combustion, wear and emissions). Cooper, PSI, CQ, Inc., EI, SwRI, AMBAC, and Battelle carried out experimental activities in each component technology area.

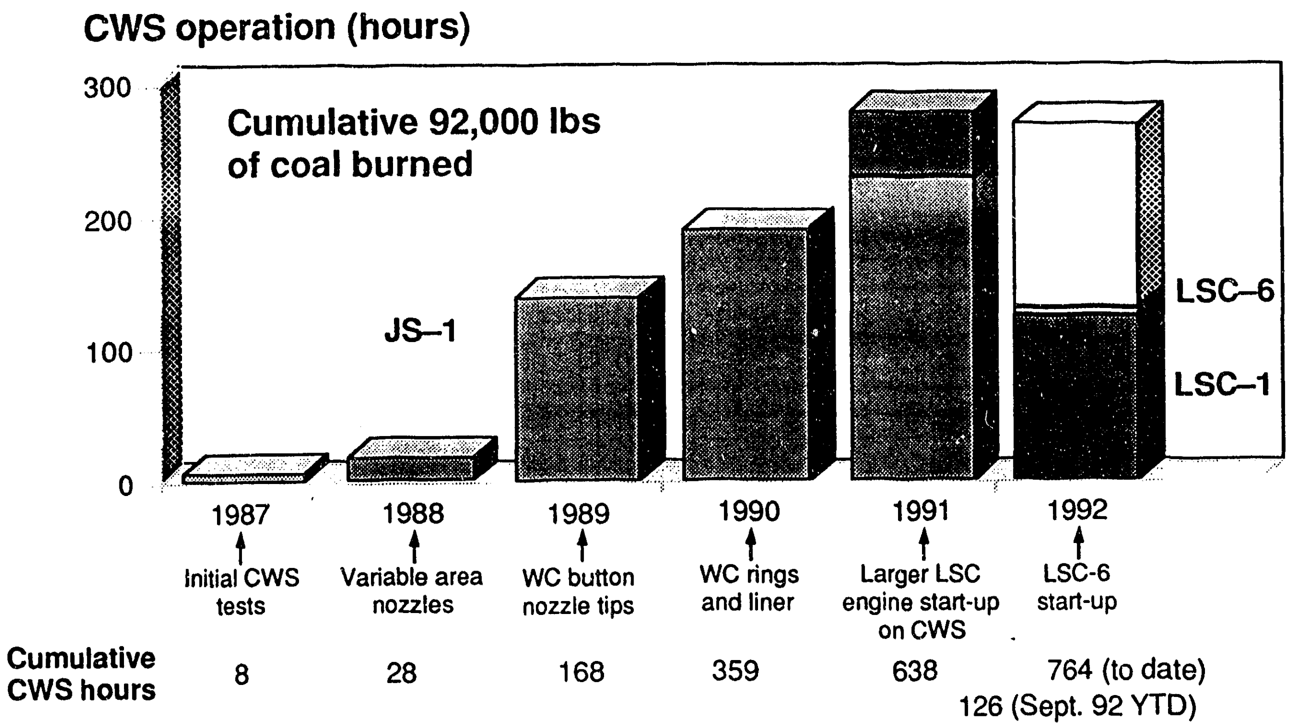
## RESULTS

Over the past several years, significant progress has been made in developing coal engine components in preparation for the 100 hour POC test. A total of more than 685 hours of CWS operation have been logged on Cooper-Bessemer engines. Over 560 hours of CWS testing have been accumulated on a single cylinder research engine (JS-1) to develop fuel specifications, durable components and combustion system configurations. An additional 125 hours of CWS testing have been accumulated on the full-scale LSC-1 engine (one cylinder on coal). The LSC-6 (all six cylinders on coal) has also been successfully run on CWS. These engine tests have provided valuable insights into coal diesel combustion phenomena and engine component design. Table 1 summarizes the key development efforts for the three test engines. Figure 1 illustrates the history of Cooper-Bessemer test experience from 1987 to date.

**Table 1. Coal-Fired Power Plant Development**

| | | |
|---|---|---|
| **JS1** | **13 inch bore**<br>**16 inch stroke**<br>**single cylinder** | **Exploratory CWS Tests**<br>• Fuel handling<br>• Injector system development<br>• Durable components<br>• Coal diesel combustion phenomenon |
| **LSC-1** | **15.5 inch bore**<br>**22 inch stroke**<br>**1 cylinder CWS**<br>**5 cylinders DF2**<br>**436 bhp/cylinder** | **Full-Scale Development Tests**<br>• Injection system<br>• Emission controls<br>• Combustion optimization |
| **LSC-6** | **15.5 inch bore**<br>**22 inch stroke**<br>**6 cylinders CWS**<br>**2,616 bhp** | **Proof-of-Concept Demo**<br>• 6-cylinder fuel system<br>• Additional combustion optimization<br>• 100-hour POC test |

**Figure 1. History of Engine Test Experience**



## LSC Configuration

In the past year, Cooper-Bessemer has adapted their six cylinder LS series engine to operate one cylinder on coal with the other five on diesel fuel. The research results and component designs from the single cylinder JS-1 tests were scaled-up and translated to the full-scale LS engine. Approximately 125 hours of CWS testing on the LSC-1 were completed. The research results were used to develop and refine the full-scale fuel injection and combustion system before switching over to all six cylinders on coal.

Cooper then undertook the substantial task of converting the LS to six cylinder coal operation. A number of major engine components were redesigned to accommodate the coal engine requirements. Substantially larger jerk pumps were installed because larger fuel flow rates are required with CWS compared to DF2. A new cam shaft was installed to obtain the desired fuel injection rate and to carry the increased load from the larger jerk pumps. The cylinder block was also redesigned to accommodate the jerk pumps and larger cam shaft size.

Based on the LSC-1 findings, the initial LSC-6 configuration consisted of:

- injection cam: CB LSC-16-1C 'fast rate' cam
- injection jerk pump: L'Orange 36mm plunger and barrel
- nozzle tip: 19 x 0.633mm diameter holes with sapphire inserts
- nozzle spray angle: 140 degree
- injection timing: 23 degrees BTC port closure
- ignition aid: twin diesel pilot injectors at 120mm$^3$/stroke/injector (approximately 4 to 5% of the total fuel energy).

## Coal Water Slurry Fuel

Engine grade CWS fuel for these tests was supplied by CQ Inc. The coal was physically cleaned to approximately 1.8% ash with a 12 micron mean particle size. The slurry had a solids content of 48 percent which resulted in a heating value of 7300 Btu/lb. CWS properties are summarized in Table 2.

**Table 2. Coal Water Slurry Fuel**

| | |
|---|---|
| Ash | 1.8% (wt% dry basis) |
| Sulfur | 0.6% (wt% dry basis) |
| Volatile | 30% (wt% dry basis) |
| Fixed carbon | 61% (wt% dry basis) |
| Mean particle size | 12 microns |
| Solids loading | 48% (nominal) |
| CWS heating value | 7,300 Btu/lb |

## LSC Engine Performance

The LSC-6 underwent an extended break-in procedure and was then successfully tested on coal water slurry fuel. The break-in procedure was designed specifically for the hard in-cylinder components (piston rings and cylinder liners). Detailed borescope inspection of the tungsten carbide coated liners during and after the break-in run revealed nothing unusual. Transition from diesel operation (the engine is started and warmed-up on diesel) to CWS operation was demonstrated to be extremely smooth and quick. All six cylinders can be switched at once with the engine at full speed (400 rev/min) and 75% load (150 psi bmep). Transition from full diesel to full CWS takes place in less than 15 seconds once coal reaches the injectors. Other than a slight audible change in engine sound, the only outward indications the engine is running on CWS are the substantial reductions in $NO_x$ and CO emission levels (3 fold and 6 fold reduction respectively).

Table 3 summarizes the initial LSC-6 test results. The data was taken at full speed (400 rev/min) and 3/4 load (150 psi BMEP) yielding approximately 1900 brake horsepower. Peak firing pressure and exhaust temperature were well within design limits. The measured engine efficiency (7500 Btu/bhp•hr) was considered acceptable for the initial tests. It is important to note that initial combustion optimization was conducted on the LSC-1 and that additional optimization will be undertaken on the LSC-6. Table 3 also lists DF2 performance data taken under the same operating conditions using the CWS injection system. Diesel performance under conditions optimized for DF2 (nozzle hole size, injection timing, etc.) would be different.

**Table 3. Recent LSC-6 Engine Performance Results**

| | CWS (initial results) | DF2 (baseline)* |
|---|---|---|
| Speed (rev/min) | 400 | 400 |
| BMEP (psi) | 150 | 150 |
| Power (bhp) | 1,890 | 1,890 |
| Peak Firing Pressure (psi) | 900 | 1,320 |
| Cylinder Exhaust Temp (°F) | 870 | 930 |
| Specific Fuel Consumption (Btu/bhp•hr) | 7,500 (LHV) | 7,300 (LHV) |
| $NO_x$ (ppm) | 460 | 1,180 |
| CO (ppm) | 300 | 2,100 |
| $CO_2$ (%) | 7.5 | 5.8 |
| $O_2$ (%) | 11.5 | 12.3 |

*** Using CWS injection system (i.e. not optimized for diesel fuel)**

## Emission Control System Performance

The emission control system (ECS) was successfully tested at full flow with the engine operating on diesel fuel. Work thus far has focused on performance testing of the SCR and sorbent injection systems, operational testing of the mechanical components (ID fan, dampers, and rotary air locks), performance testing of the heat exchanger, and evaluation of the system controls and safety interlocks.

The initial ECS performance tests have shown that the target reductions for NOx and $SO_2$ have been readily achieved. The SCR system alone is capable of 80 to 90% reduction in NOx. The sorbent injection process also reduces NOx emission. The level of reduction has been measured at 20 to 40% which corresponds to about 4 to 8% of the engine exhaust NOx emissions. Measured SO2 reduction at a $Na_2/SO_2$ mole ratio of 0.8 and a baghouse inlet temperature of 360 F was in the 75 to 80% range. These test results, summarized in Table 4, show that the integrated system is capable of low emission levels which also meet NSPS standards for electric utilities.

**Table 4. Latest Emission Control System Performance Results**

| | Engine Emissions | Target Reduction | Test Results | Integrated System Emissions Based on Test Results | NSPS for Electric Utilities |
|---|---|---|---|---|---|
| $NO_x$ | 1.3 lb/MM Btu | 80% (SCR) | 90% (SCR plus sorbent) | 0.13 lb/MM Btu | 0.6 lb/MM Btu |
| $SO_x$ | 1.5 lb/MM Btu | 70% | 80% (does not include credit for coal cleaning) | 0.30 lb/MM Btu | 1.2 lb/MM Btu (and 90% reduction in potential $SO_2$) |
| Particulates 1.75% ash 1% unburned C | 2.5 lb/MM Btu | 97.5% | (99%) Bag filter not tested yet | (0.025 lb/MM Btu) | 0.03 lb/MM Btu |

## FUTURE WORK

The LSC-6 is being prepared for the 100 hour (continuous) proof-of-concept demonstration test which is scheduled for mid-1993. Additional combustion optimization and emission control tests will be conducted to fine-tune the integrated system. Several 25 and 50 hour tests are scheduled prior to the 100 hour test to ensure refueling procedures are debugged. The program will culminate in a 100 hour continuous demonstration of the coal-fired diesel power plant.

## REFERENCES


Benedek, K.R., Menzies, K.T., Johnson, S.A., Wilson, R.P., Rao, A.K., Schaub, F.S., "Emission Characteristics and Control Technology for Stationary Coal-Fueled Diesel Engines," ASME Engine Emission Technology Conference, San Antonio, October 1988.

Mayville, R.A., "Abrasive Concentration Effects on Wear Under Reciprocating Conditions, International Conference on Wear of Materials, Denver, Colorado, April 1989.

Rao, A.K., Melcher, C.H., Schaub, F.S., Wilson, R.P., Balles, E.N., And Kimberley, J.A., "Operating Results of the Cooper-Bessemer JS-1 Engine on Coal Water Slurry," ASME Paper, Session ICE-12, Energy Sources and Technology Conference Exhibition, New Orleans, LA, January 1988.

Wilson, R.P., "Coal-Fueled Diesel Systems for Stationary Power Applications," Task 1 topical Report, Contract MC-22182-2242, U.S. Department of Energy, September 1986.

Rao, A.K., Wilson, R.P., Balles, E.N., Mayville, R.A., McMillian, M.H., Kimberley, J.A., "Cooper-Bessemer Coal-Fueled Engine System - Progress Report," ASME ICE - Vol. 7, p. 9, January 1989.

Johnson, S.A., Senior C.L., Katz, C.K., Wilson, R.P., "Development of $NO_x$ Control Technologies for Coal-fueled Stationary Diesel Power Plants," Stationary Sources $NO_x$ Symposium, San Francisco, March 1989.

Balles, E.N., Benedek, K.R., Wilson, R.P., and Rao, A.K., "Analysis of Cylinder Pressure and Combustion Products from an Experimental Coal-Fueled Diesel Engine," presented at the Internal Combustion Engine Division Technical Conference, Kansas City, MO, ICE Vol. 2, p. 75, ASME, October 1987.

Benedek, K.R., Menzies, K.T., Johnson, S.A., Wilson, R.P., Rao, A.K., Schaub, F.S., "Emission Characteristics and Control Technology for Stationary Coal-Fueled Diesel Engines", ASME, Journal of Engineering for Gas Turbines and Power, Vol. 111, pg. 507, July 1989.

Balles, E.N., Wilson, R.P., Rao, A.K., And Melcher, C.H., "Coal-Fueled Diesel Engine for Power Generation," ASME, Presented at the Joint Power Generation conference and Exhibition, Dallas, Texas, October 1989.

Mayville, R.A., Wilson, R.P., Rao, A.K., "Cooper-Bessemer Coal-Fueled Engine System: Recent Developments in Durable Components," ASME/ETCE Meeting, New Orleans, Jan. 1990.

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