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Commercialization of Coal Diesel Engines for Non-Utility
and Export Power Markets

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Contractor:

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

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CONTRACT INFORMATION

Contract Number: DE-AC21-88MC-25124

Contractor: Arthur D. Little, Inc.
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Contract Project Manager: Robert P. Wilson

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James Parkinson (CQ, Inc.)

METC Project Manager: W. Cary Smith

Period Of Performance: March 1, 1988 to September 30, 1993

Schedule and Milestones

FY93 Program Schedule

- Installed cost \$1300/kW (1992 dollars)
- Efficiency 48.2% (LHV) (demonstrated: 41% - LHV)
- NO_x emissions 0.11 lb/MMBtu (demonstrated: 0.18 lb/MMBtu)
- SO_x emissions 0.37 lb/MMBtu (equivalent to emissions from 0.3% sulfur diesel fuel oil)
- Particulate emissions 0.01 lb/MMBtu

Basis of Competition - Other Clean Coal Powerplant Technologies

The advantage of this 10-100 MW clean coal diesel technology is that it is targeted for NUG and small utility capacities, whereas all other clean coal technologies have been designed for the central station utility market (generally 200-500 MW).

• IGCC	200-500 MW
• PFBC	100-300 MW
• Fuel Cell with Integrated Gasification	200-500 MW

Fuel cell technology is under rapid development and, although initially more costly, fuel cell power plants using natural gas reformers will eventually compete in the 100kW-10MW range. Figure 2 illustrates the unique market position of the clean coal diesel with respect to its competitors.

In the early market introduction (2000-2010), the clean coal diesel will compete against both natural gas technologies and small coal plants (10-100MW) of the PC, AFB, and stoker variety. The more favorable the price difference between coal and gas (or oil), the more competitive the coal diesel will be.

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. (This engine speed range is significant because the feasibility of burning coal directly in an engine becomes increasingly difficult above the 500 rpm range.)

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. Phase II, Component Development, is also complete (see schedule). The program is now in the final stages of Phase III, Performance Testing.

RESULTS

In 1993, the Cooper-Bessemer prototype engine has been demonstrated with technology advances in all critical areas, including over 100 hours of proof-of-concept testing.

Significant subsystem advances have been made to develop the 6-cylinder, 1.8 MW Cooper-Bessemer coal engine components in preparation for the 100-hour proof-of-concept testing of the integrated system. The key achievements in 1992-1993 were as follows:

- The full-scale (six cylinders--1800 kW) Cooper-Bessemer Model LS engine - coal configuration - was assembled and demonstrated on clean coal slurry. This engine burns 15 times the amount of coal as the previous JS-1 engine (2.5 x per cylinder). This same engine can be built in 6.3 MW configuration without any scale-up of cylinder size--just by increasing the number of cylinders from 6 to 20.
- An improved lower-cost slurry preparation approach was developed by CQ Inc. Integration of the "engine grade" coal cleaning module with conventional mine mouth cleaning lowers cost. Now, with this revised approach, the clean coal can be shipped dry (by rail or barge)

Figure 1. 14 MW Coal-Fueled Diesel Powerplant with Steam Turbine Bottoming Cycle

Figure 2. Coal-Fueled Diesel is an Attractive Option for a 10-100 MW Powerplant

economically over longer distances, and simple modular on-site slurry plants are economical (5-20 ton/hr typical size).

- A full scale, 6500 gallon slurry storage and handling system was fabricated and demonstrated at the test facility.
- The full scale 1.8 MW emissions control system was demonstrated; NO_x emission data indicated that the coal diesel is competitive with gas turbine NO_x emissions (0.13 lb/MMBtu).
- Another 200 hours of engine testing was achieved on coal water slurry, bringing the total to 760 hours (see Figure 3). The engine tests have provided valuable insights related to component design.

Energy Efficiency (Heat Rate) of the Coal Diesel Powerplant

The current prototype coal-diesel being used in the technology development is the Cooper-Bessemer LS Series engine. This engine series is nominally rated at 315 kW per cylinder and can be built either as an in-line engine or as a vee- form engine (up to 6300 kW). The brake mean effective pressure (bmep) for this engine is 208 psi, which is relatively conservative. This engine has a simple cycle efficiency of approximately 40 percent and a combined cycle efficiency of approximately 45 percent. However, in its mature configuration, the commercial coal diesel plant will be based around high-bmep, larger diesel engines which will have a simple cycle efficiency of 45 percent and a combined cycle efficiency of approximately 49 percent.

The commercial coal diesel plant is illustrated schematically in Figure 4, which illustrates a 45 MW plant. The commercial coal diesel plant is expected to range from 14 MW (two 6 MW engines plus steam turbine) to 160 MW (six 25 MW engines plus steam turbine), with a typical size being 45 MW (three 14 MW engines plus steam turbine), as illustrated. Key performance parameters for the commercial coal diesel plant are given below:

Coal heat input:	318.5 MMBtu/hr
Diesel engine electrical output:	42.0 MW
Diesel engine heat rate (LHV):	7582 Btu/kWh
Steam turbine electrical output:	3.0 MW
Total plant electrical output:	45.0 MW
Plant heat rate (LHV):	7078 Btu/kWh
Overall generating efficiency (LHV):	48.2%

This plant is based on modern diesel engines which operate at 45 percent simple-cycle efficiency. Such engines are currently in commercial production for liquid and gaseous fuel operation and can be converted (with Cooper-Bessemer designs) for coal-water slurry operation. Table 1 lists examples of high efficiency diesel manufacturers and engine models. All of these engines are rated in the range of 280-320 bmep.

**Table 1. Proven High Efficiency For Selected Diesel Engine Models
(Over 10 MW Output)**

Manufacturer	Model	kW/Cy l	Rating (MW)	Simple Cycle Efficiency (% LHV)
MAN B&W	K 80 MC-C	3410	40.9	49.2
Pielstick (Coltec - Fairbanks Morse Div.)	PC 4.2	1210	21.8	43.4
Mitsubishi	UEC 85 LSII	5250	42.0	53.0
New Sulzer	RTA 84C	3820	30.6	50.8

One example of a high efficiency diesel engine is the MAN-B&W 9K80MC-S two- stroke engine. This engine operates at 100 rpm, generates 24.5 MW, and has a simple cycle efficiency of 50.2 percent (LHV) on fuel oil. A 50 MW combined cycle power plant at Coloane in Macau, based on two such engines, has an overall generation efficiency of 52.5 percent (LHV). Future diesel engines are expected to achieve simple cycle efficiencies of up to 53 percent and combined cycle efficiencies of up to 55 percent. The fact that actual existing diesel plants operate at 52.5% (LHV) supports the projection that the

Figure 3. History of Engine Test Experience

Figure 4. Flow Diagram for Commercial, 45 MW Coal-Fueled Diesel Combined Cycle Plant

coal diesel will readily reach these performance levels when offered to the NUG and small utility market.

Cost of Electricity Estimates For Coal Diesel Plants

The mature clean coal diesel technology is estimated to achieve a levelized cost of electricity as low as 6¢/kWh for installations in the 2000 - 2010 time period, as shown in Table 2 (estimates are in 1992 dollars). This estimate is based on capital and operating cost estimates for a 45 MW commercial Coal Diesel Combined Cycle plant operating at an 80% percent capacity factor, with capital cost of \$1300/kW. The economics of the coal-fueled diesel plant has been continually re-evaluated as new information on coal fuels, emission control technologies, engine component performance and other factors has been developed.

The cost estimates for the commercial Coal Diesel Combined Cycle (CDCC) plant are summarized and compared to those for conventional IC engines in Figure 5. Our conclusions, as explained in detail below, are that:

- The projected levelized cost of coal diesel power is 6¢/kWh for installations in the 2000 - 2010 period.
- Coal diesel technology will be competitive with gas and oil technologies when gas and oil prices reach approximately \$4.50/MMBtu (the National Energy Strategy expects this to occur in 2000 - 2005). At that time, the price of coal is estimated to be \$1.64-1.73/MMBtu (in 1992 dollars).
- Economic viability hinges on the cost of CWS production (the engine-grade CWS price must be kept below approximately \$3/MM Btu).

Table 2. Comparison of Projected Cost of Power For 45 Mw Coal Diesel Plant and Oil/Gas Diesel Plant

Cost Element	Coal Plant ¢/kWh	Oil/Gas Plant ¢/kWh	Notes
Capital (installed)			
Engines + gen sets	1.46	1.22	
Emissions control	0.29	0.13	Oil/gas plant has SCR
Bottoming cycle	0.25	0.25	
Balance of plant	0.25	0.25	
Subtotal	2.25	1.85	
Variable Operating			
Fuel	2.40	3.67	Fuel - CWS \$2.95/MMBtu,
Non-fuel variable	0.58	0.10	Oil/Gas: \$4.50/MMBtu
Non-Fuel			
			Coal: sorbent + waste + NH ₃ + catalyst
			Oil/Gas: NH ₃ + catalyst
Subtotal	2.98	3.77	
Fixed O&M	0.88	0.63	
Total Cost of Power	6.11	6.25	

Assumptions:

45 MW combined cycle plant
Plant heat rate: 7078 Btu/kWh
Plant capacity factor: 80%
Future oil/gas: \$4.50/MMBtu
All costs are in 1992 dollars

Figure 5. Cost of Power for Coal-Fueled Diesel Combined Cycle Plant Is Competitive With Oil- Or Gas-Fueled Plant

Engine Component Cost Premiums Associated with Coal

The use of beneficiated coal-water slurry necessitates certain modifications to the standard large diesel engine, both in terms of special components and special maintenance practices. Modified coal-tolerant engine components include larger fuel pumps for CWS; larger hardened injectors; modified fuel cams; larger camshafts; a modified engine block; AMBAC-designed CWS injection system; ceramic coated piston rings and liners; and a ceramic coated turbocharger.

Present maintenance practices for Cooper-Bessemer oil or gas diesel engines are compared to those for the coal diesel in Table 3.

The cost associated with the increased level of maintenance and overhaul is projected to be \$22.8 million over a 20 year period versus \$9.8 million for the standard diesels. This corresponds to 0.36 ¢/kWh for the coal engine versus 0.16 ¢/kWh for the standard diesel. Thus the engine purchase and maintenance cost premiums associated with the use of coal for the 45 MW commercial coal diesel plant is approximately 0.44 ¢/kWh.

Table 3. Impact of Coal Fuel on Maintenance and Overhaul Practices.

Item	Standard Diesel	Coal Diesel Projections	20-Year Overhaul Cost ¹
Injectors	2,000 hr	1,000 hr	\$5.93M
Minor maintenance checks	8,000 hr	4,000 hr	\$2.28M
Top-end overhaul	25,000 hr	12,000 hr	\$4.56M
Major overhaul	100,000 hr	25,000 hr	\$10.03M
Total			\$22.8M

¹Coal Diesel Combined Cycle plant, engine overhaul costs only (45MW)

Cost to Produce Engine-Grade Coal Fuels

An essential ingredient in the future of coal-fueled diesels is the eventual emergence of a

price advantage of the engine-grade coal fuel over gas or oil. Our CWS costing is based on detailed inputs from CQ Inc., AMAX, and Otisca.

Our approach to a low cost clean coal is based on premium coal (0.5-2.0% ash) as a by-product. Coal sources that have some premium coal content are selected and the premium coal is extracted as a by-product of the existing coal cleaning operations using conventional coal cleaning technology such as heavy media cyclones. The overall process is as follows:

- Coal is physically cleaned at the mine in a 250 tph addition to an existing cleaning plant. Premium coal is extracted for transport to the slurring plant and middlings are extracted for sale as utility steam coal.
- Premium coal is transported to a 100 tph slurring plant located in the supply region.
- The engine-grade CWS is transported by tanker truck (or rail if economical) a mean distance of 25 miles to the coal diesel power plant.

The CWS cost for fuel delivered to the coal diesel plant based on these assumptions is projected at \$2.97/MMBtu (see Table 4). The economics are based on \$14.59/ton for operating the coal cleaning plant and \$42.8 million for capital cost of a 100 tph slurry plant and associated cost cleaning equipment.

Table 4. Projected CWS Price For Regional Production

Cost Component	Cost (\$/MMBtu)	% of Total CWS Cost
Feed coal ¹	0.888	29.9
Coal Cleaning		
O&M	0.188	6.3
Capital recovery ²	0.112	3.8
Subtotal	0.301	10.1
Coal transportation	0.264	8.9
Coal slurring		
O&M	0.513	17.3
Capital recovery ²	0.542	18.3
Subtotal	1.055	35.6
CWS transportation	0.461	15.5
Total	2.979	100.0

¹Pre-cleaned feed coal is \$24/ton. It is re-cleaned producing middlings that are sold for \$22.98/ton and premium coal with a feed cost equivalent to \$25.25/ton.

²Capital recovery includes 12.5% cost of money.

Market Analysis of Modular Powerplants, 2005-2030

The basic motivation behind this development effort is to provide coal-burning heat engine technology primarily for 10-100 MW modular stationary power applications in the next decade and beyond, when oil and gas prices may return to the \$5-7/MMBtu range. There are three major target markets for the clean coal diesel technology:

- Non-utility (NUG) new capacity (an estimated 98,000 MW between 2005 and 2030).
- Small utility repowering (an estimated 28,000 MW between 2005 and 2030).
- Exports to the developing countries of coal technology below 100 MW plant size (an estimated 57,000 MW in U.S. exports between 2000 and 2030).

The NUG market, which is the largest, is discussed further below. These new capacity applications typically involve multiple engines at a single plant where requirements are favorable for coal firing: high annual utilization, existing

infrastructure, space for coal handling and emission controls, and relatively constant load operation. The coal diesel, once demonstrated, potentially can capture a significant share of new capacity in these three markets from 2005-2030. The NUG market appears to be the primary target.

Trends in New Capacity Installations

The 1990's is expected to be the decade of natural-gas for new power capacity, and much of this capacity will be in the 10-50 MW "modular" size range, powered by prime movers rather than the traditional Rankine cycle. For plants built with smaller prime movers (below 15 MW unit size), reciprocating engines will continue to take the lion's share of this modular power market (recips outsell turbines by nearly 3 to 1 for this size class, both in the U.S. and worldwide). There are good reasons that reciprocating engines outsell turbines in smaller sizes: higher efficiency, better part load performance, excellent availability, and ability to burn much heavier fuels. However, gas turbines will be the preferred prime mover for, say, 40-100 MW modular power plants, because of lower capital cost, excellent baseload performance (as typified by the GE LM 6000 (40 MW)), and low emissions.

Developments in the power generation industry over the last year have strengthened the market prospects for the Coal-Fueled Diesel Power Plant, beginning in the 2000-2010 timeframe when natural gas prices are expected to rise. The following developments are relevant:

- Many utilities and non-utilities have demonstrated reluctance to commit to natural gas for major power needs, despite its current low price. Recent projections show that coal will be the preferred fuel for 57,000 MW out of the total 148,000 MW of new capacity and repowering expected to be installed by utilities and NUGs between 1995 and 2010 (Source: EIA, 1993).

- Faced with the Clean Air Act, a large fraction of utilities have elected clean coal, coal slurry, and coal switching, rather than SO₂ scrubbers. This will help build the infrastructure for engine-grade coal slurry.
- The non-utility power generation sector has continued to thrive. Currently, there are 184 coal-fired NUG units installed, totalling 7000 MW of capacity. Coal consumption by NUGs is projected to increase more than 300% from 6.1 million tons in 1991 to 21.2 million tons in 2000. The size of plants and other factors make this an excellent future market for coal diesel plants.
- Certain large public utility companies are champions of the "dispersed power" approach whereby 2-50 MW modular low emissions powerplants are installed at existing transmission/distribution substations. This avoids the need for new T&D, among other advantages. The coal diesel promises to capture part of this market sector on the basis of high-efficiency and low emissions.

NUG Market

The Non-Utility Generation (NUG) phenomenon has grown rapidly over the last five years, and the clean coal technology "industry" until now has not responded with suitable 10-100 MW products for NUG applications. The average coal NUG plant is 38 MW in capacity - only small PC boilers and small CFBs are being installed in these coal applications and these are not advanced clean coal technologies in the same class as the coal diesel. The NUG industry is expected to add 30,000 to 40,000 MW in each ten-year period in the U.S., or between 40%-50% of all new capacity installed. Recent EIA and NES projections confirm that 71,000 MW of new non-utility capacity is projected in the period 1991-2010, of which we conclude the dominant share will be for gas turbine and reciprocating engines. Figure 6 shows that coal-fueled heat engines will compete for 3160 MW/year after the year 2005 in the non-utility power sector. This level of engine production activity would

revitalize the U.S. large engine industry. The number of large stationary engines produced per year would increase from about 20-40 (current) to 200-400.

FIGURE 6. Coal NUG Plants Will Be Favored After 2005

Trends in U.S. power requirements over the next 40 years appear to be highly favorable for the adoption of these coal-fired diesel applications. The coal diesel stationary power plant is being demonstrated at a time when there is an ongoing upheaval in the stationary power industry. This upheaval is in large part driven by the steady growth in U.S. power requirement, which continues to grow at 2.2 to 2.6% per year nationwide, and up to 6% per year in certain regions. For perspective, each extra 0.2% of growth nationwide represents 10,000 MW of new capacity on-line. Another driving force has been the major changes to the infrastructure such as PURPA and the rise of independent power plants (IPPs) and other NUGs. Traditional procedures whereby utilities added stationary power capacity in the form of large central station generators, in increments of 250 to 1300 MW, are gradually giving way to new procedures whereby modular plants are installed in the 10 to 200 MW size range, and many of these are non-utility owned generators (NUGs). At the present time, the fuels of choice for these modular plants are natural gas and oil, due to two factors:

- Gas and oil are currently priced at attractive levels (\$2 to \$4 million Btu).
- There is no competitive coal-fueled modular power technology available with low emissions yet, particularly in the 10 to 50 MW range.

The coal diesel is positioned as a new technology option for this emerging NUG market starting in the 2005-2010 timeframe when gas and oil prices increase.

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