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ENCOAL CORPORATION

ENCOAL® MILD COAL GASIFICATIONPROJECT

PROJECT PERFORMANCE SUMMARY
CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

NOVEMBER 1999

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COAL PROCESSING FOR CLEAN FUELS

ENCOAL Corporation

ENCOAL® Mild Coal Gasification Project

Overview

LFC® process technology provides a way to fully use our nation's vast western coal reserve by converting low-rank coal into clean, high heating value fuels and valuable liquid products. Enhancing product value reduces transportation costs, allowing penetration of products throughout the United States.

The products of the LFC® process are capable of lowering emissions and enhancing the environment without costly pollution control equipment. Coproduction of a high heating value solid fuel and a liquid with fuel and chemical product potential makes the process economics attractive both domestically and abroad for countries with low-rank coal reserves.

Efforts are now underway to build a commercial scale plant in Wyoming's Powder River Basin. In addition, projects in China, Indonesia, and Russia are being pursued.

ENCOAL® has successfully demonstrated the conversion of low-rank western coal into two clean, high-energy fuel forms at Triton Coal Company's Buckskin Mine site. The Liquid-From-Coal (LFC®) process developed by SGI International uses mild gasification to produce a solid fuel, Process-Derived Fuel (PDF®), and a liquid product, Coal-Derived Liquid (CDL®), which can be used as a fuel or chemical feedstock.

The project is part of the U.S. Department of Energy's Clean Coal Technology (CCT) Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. Cost-shared partnerships with industry were sought through five nationally competed solicitations to accelerate commercialization of the most advanced coal-based power generation and pollution control technologies. The CCTDP, valued at nearly $6 billion, has leveraged federal funding twofold through the resultant partnerships encompassing utilities, technology developers, state governments, and research organizations. This project was one of 13 selected in December 1989 from 48 proposals submitted in response to the Program's third solicitation (CCT-III).

The LFC® process not only dries the moisture-laden low-rank coal, but chemically converts it to new substances through controlled heating in the absence of oxygen (pyrolysis). The pyrolysis drives off volatile compounds, which are converted to the CDL® liquid product and gas used to fuel the LFC® process. The solid PDF® product is stable (not prone to self-heating under normal handling conditions), unlike conventionally dried low-rank coal.

PDF® has even less sulfur than the low-sulfur feedstock and has excellent combustion characteristics, making PDF® a compliance option for meeting Clean Air Act SO_2 emission requirements. Also, PDF®'s high-carbon and low-volatile composition makes it valuable for steel industry use in blast furnace pulverized coal injection, granular coal injection, and direct iron-making.

The liquid CDL® product is a low-sulfur, high aromatic content, heavy oil. CDL® has fuel characteristics similar to a low-sulfur No. 6 fuel oil, except that the sulfur content is significantly less. The real market for CDL®, however, lies in upgrading to higher value fuels and chemicals.

By the end of the five-year demonstration, the LFC® facility had processed approximately 260,000 tons of raw coal into over 120,000 tons of PDF® and 5,101,000 gallons of CDL®. Over 83,500 tons of PDF® had been shipped to seven customers in six states, as well as 203 tank cars of CDL® sent to eight customers in seven states.

The Project

The project addresses the pollution prevention path to meeting increasingly stringent emission requirements and expands the market for the nation's vast, yet underutilized, low-rank coal reserves. Coals in the western United States are, by and large, naturally low in sulfur and relatively easy to mine, but are high in water content, which makes these coals expensive to transport and precludes their use in many boilers.

Simple coal drying approaches to upgrade the western coal reserves have met with stability problems—a tendency toward spontaneous combustion. The LFC® process changes the low-rank coal chemistry to make the solid product stable.

Project objectives were to:

- Provide sufficient products for full scale test burns;
- Develop data for the design of future commercial plants;
- Demonstrate plant and process performance;
- Provide capital and operating cost data; and
- Support future LFC® technology licensing efforts.

The 1,000 ton/day demonstration plant represents a reasonable scale-up from the 200 lb/hour pilot plant and is of sufficient scale to design a 5,000 ton/day commercial module. Process design made maximum use of commercial equipment and was simplified, including only the CDL® liquid product rather than the slate of upgraded products envisioned for a commercial unit.

The construction and startup phases for the LFC® demonstration plant were completed in July 1992. By June 1994, the plant had completed a two year test and evaluation program, incorporated modifications to correct shortcomings, and commenced production runs of PDF® and CDL®. After a successful five-year operating period, the facility was idled in 1997.

The LFC® demonstration plant is adjacent to the Triton Coal Company's Buckskin Mine, ten miles north of Gillette, Wyoming. Triton provides a ready supply of Powder River Basin (PRB) coal and other services for the project. Powder River Basin (PRB) coal was chosen for the feedstock because of its particularly low-sulfur and low-ash content.

Project Sponsor
ENCOAL Corporation (a wholly owned subsidiary of Bluegrass Coal Development Company)

Additional Team Members
Bluegrass Coal Development Company (formerly named SMC Mining Company, a wholly owned subsidiary of Zeigler Coal Holding Company) — cofunder
SGI International — technology developer
Triton Coal Company (a wholly owned subsidiary of Bluegrass Coal Development Company) — host and coal supplier
The M.W. Kellogg Company — engineer and constructor

Location
Near Gillette, Campbell County, WY (Triton Coal Company's Buckskin Mine site)

Technology
SGI International's Liquids-From-Coal (LFC®) process

Plant Capacity
1,000 tons/day of subbituminous coal

Coal
Powder River Basin subbituminous coal with 0.4–0.9% sulfur

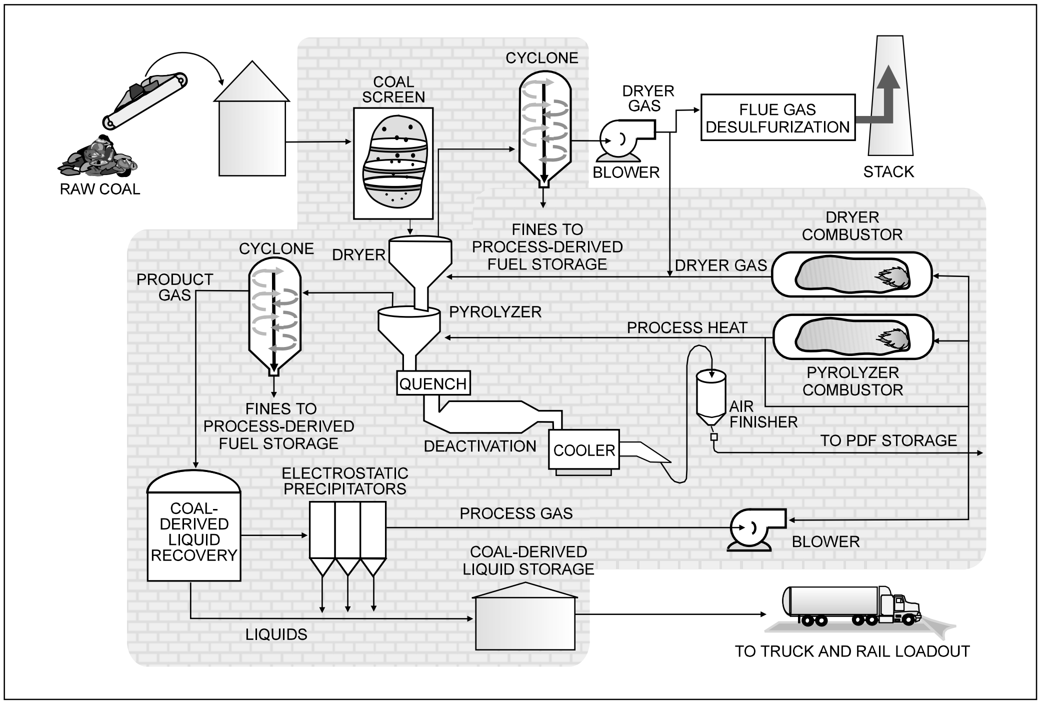
Demonstration Duration
July 1992 – July 1997

Project Funding

Total project cost	$90,664,000	100%
DOE	45,332,000	50
Participant	45,332,000	50

Process unit enclosure with PDF silo on right and coal storage silos and train loading station on left

THE TECHNOLOGY



The process involves heating coal under carefully controlled conditions. Coal sized to 2" x 1/8" enters a rotary grate dryer, where it is heated by a hot flue gas stream. A programmable logic controller (PLC) precisely controls residence time and inlet gas temperature. These controls ensure that moisture is removed without initiating chemical changes and that no significant amounts of methane, carbon monoxide, or carbon dioxide are released from the coal.

The solids from the dryer enter the pyrolyzer, where recycled hot gas raises the temperature to about 1,000°F on another rotary grate. The rate of heating and residence time of the solids are carefully controlled to produce the desired properties of both solid and liquid products. The pyrolyzer removes all remaining water and induces a chemical reaction that releases volatile gaseous material. Solids exiting the pyrolyzer are quickly quenched to stop the pyrolysis reactions.

In the original process concept, the quench table solids were further cooled in a rotary cooler and transferred directly to a surge bin. However, stabilization of the product required addition of a vibrating fluidized-bed (VFB) to control uptake of oxygen before leaving the plant. In the VFB unit, the partially cooled, pyrolyzed solids contact a gas stream containing a controlled amount of oxygen. A reaction, termed “oxidative deactivation,” occurs at active surface sites in the particles, reducing the tendency for spontaneous combustion. The heat generated by this reaction is recovered and excess gas helps fuel the dryer combustor.

Following the VFB, an indirect rotary cooler cools the solids to near atmospheric temperature and adds a controlled amount of water to rehydrate the PDF® to near its ASTM equilibrium moisture content. A patented dust suppressant is added as PDF® leaves the storage bin to counter dust generation in shipment due to the absence of free surface moisture.

The hot gas produced in the pyrolyzer passes through a cyclone for solids removal and then a quench column for cooling to stop any additional pyrolysis reactions and to condense the desired liquids. Temperatures are kept above the dew point of water to ensure that only CDL® is condensed in this step. An electrostatic precipitator (ESP) removes any remaining liquid droplets or mist from the gas stream. Most of the residual gas from the liquid recovery unit is recycled directly to the pyrolyzer. The remainder of the gas provides fuel for the pyrolyzer and dryer combustors, which provide process heat.

Demonstration Results

- Steady state operation exceeding 90% availability was achieved for extended periods for the entire plant (numerous runs exceeded 120 days duration).
- The LFC® process consistently produced 250 tons/day of PDF® and 250 barrels/day of CDL® from 500 tons/day of run-of-mine PRB coal.
- Integrated operation of the LFC® process components over five years has provided a comprehensive database for design of a commercial unit.
- Over 83,500 tons of PDF® were shipped via 17 unit trains and one truck shipment to seven customers in six states. Shipments included 100% PDF® and coal blends from 14–94% PDF®.
- PDF®, alone and in blends, demonstrated excellent combustion characteristics in utility applications, providing heating values comparable to bituminous coal, more reactivity than bituminous coal, and a stable flame.
- In utility applications, PDF® reduced SO_2 emissions, reduced NO_x emissions (through flame stabilization), and maintained rated boiler capacity with fewer coal pulverizer mills in service.
- The low-volatile PDF® also showed promise as a reductant in direct iron reducion testing and also as a blast furnace injectant in place of coke.
- Nearly 5 million gallons of CDL® were produced and shipped to eight customers in seven states.
- CDL® demonstrated fuel properties similar to a low sulfur No. 6 fuel oil, but with the added benefit of lower sulfur content. High aromatic hydrocarbon content, however, make CDL® more valuable as a chemical feedstock.
- A commercial plant designed to process 15,000 metric tons/day would cost an estimated $475,000,000 (2001 year dollars) to construct, with annual operating and maintenance costs of $52,000,000 per year.

Operational Performance

The LFC® facility operated for more than 15,000 hours over a five year period. Steady-state operation was maintained for much of the demonstration, with availabilities of 90 percent for extended periods. The length of operation and volume of production proved the soundness and robustness of the process. By the end of the demonstration, approximately 260,000 tons of raw coal had been processed into more than 120,000 tons of PDF® and 121,000 barrels of CDL®. Process design was validated by producing about ½ ton of PDF® solid product and ½ barrel of CDL® liquid product per ton of raw coal and achieving consistent product quality. Almost all of the process product entered the marketplace and provided effective performance.

The LFC® process successfully produced both high quality solid and liquid fuels. *Table 1* provides key characteristics of the PDF® relative to the Powder River Basin raw coal. *Table 2* provides key characteristics of CDL® relative to a low-sulfur fuel oil (LSFO).

Table 1. PDF® Characteristics

Property	Feed Coal	PDF (1995 Avg)
Heating Value (Btu/lb.)	8,400	11,200
SO_2 (#/MMBtu)	1.1	0.7
H_2O (% wt.)	29	9
Ash (%wt.)	5	8
Volatiles (%wt.)	31	24
Fixed Carbon (%wt.)	35	59
Sulfur (%wt.)	0.45	0.4
Ash Fusion Temp. (°F)	2,220	2,220

Table 2. CDL® Characteristics

Property	LSFO	CDL (1995 Avg)
API Gravity (°)	5	2.3
Sulfur (%)	0.8	0.6
Nitrogen (%)	0.3	0.7
Oxygen (%)	0.6	10.8
Viscosity @ 122°F (cs)	420	240
Pour Point (°F)	50	80
Flash Point (°F)	150	218
Btu/gal	150,000	140,000

Table 3 summarizes ENCOAL's production history. By the end of the demonstration, over 83,500 tons of PDF® were shipped via 17 unit trains and one truck shipment to seven customers in six states. Shipments included 100% PDF® and blends from 14–94 percent PDF®. Over 5 million gallons of CDL® were produced and shipped to eight customers in seven states.

As with most demonstrations, however, success required overcoming many challenges. Some of the more difficult challenges, and those with product implications, faced by ENCOAL are highlighted here.

Major Challenges

Sand Seals — Sand seals failed to perform at process design conditions. Located between the rotating grate and the vessel wall, the seals prevent the hot gas below the dryer and pyrolyzer grates from bypassing the coal bed atop the grates. The seal was comprised of a blade attached to the rotary member immersed in a stationary tub of sand. Problems arose from higher than expected wear, sand degradation, coal dust build-up, and maintenance problems. Operation was impacted by having to reduce the flow rate in the pyrolyzer loop to avoid blowing out the sand in the seal. The internal sand seals were replaced with an external water seal, which performed well.

Water System — All water systems were found to be undersized and a modification was made to combine the entire quench spray system, oily water system (washdown and seal water), and a portion of the seal water system into a larger capacity, redesigned process water system. Included was a process water fines removal system, consisting of a collection system, clarifier, vacuum drum filter, heat exchanger, and two new slurry pumps. Also, to achieve efficient rehydration of the PDF®, a water lance with spray nozzle was installed in the rotary cooler.

PDF® Stability — By June 1993, efforts ceased in trying to correct persistent PDF® stability problems within the bounds of the original plant design. The rotary cooler failed to provide the deactivation necessary to quell spontaneous ignition of PDF®. It was concluded that a separate, sealed vessel was needed for product deactivation. A search for a suitable design led to adoption of a vibrating fluidized-bed (VFB). A 500 ton/day VFB was installed between the quench table and rotary cooler. (Installation of a second 500 ton/day VFB was planned but never implemented.)

By Spring of 1994, operations became notably smoother and more productive, achieving continuous runs of 54 and 68 days by mid-year. This was attributable not only to the VFB's improved stabilization of the PDF® and the subsequent increased ease of handling, but also to the replacement of the dryer and pyrolyzer sand seals with water seals and the installation of the process water fines handling system.

Although the VFB enhanced deactivation, the PDF® still required "finishing" to achieve stabilization. Extensive study revealed that more oxygen was needed for deactivation. Two courses of action were pursued: (1) development of interim measures to finish deactivation external to the plant, enabling immediate PDF® shipment for test burns; and (2) development of an in-plant process for finishing, eliminating product quality and labor penalties for external finishing.

"Pile layering" was the primary external PDF® finishing measure adopted. Blending with run-or-mine (ROM) coal, increased silo retention time, and higher rehydration also contributed to stabilization. In pile layering, PDF® is spread in 12-inch-thick layers, allowing time for oxygen uptake and heat dissipation before adding successive layers. However, PDF® quality becomes somewhat impaired by impacting size, moisture and ash content.

Table 3. ENCOAL Production

	Pre-VFB		**Post-VFB**				
	1992	**1993**	**1994**	**1995**	**1996**	**1997[1]**	**Sum**
Raw Coal Feed (tons)	5,200	12,400	67,500	65,800	68,000	39,340	**258,300**
PDF Produced (tons)	2,200	4,900	31,700	28,600	33,300	19,300	**120,500**
PDF Sold (tons)	0	0	23,700	19,100	32,700	7,400	**82,900**
CDL Produced (bbl)	2,600	6,600	28,000	31,700	32,500	20,300	**121,700**
Hours on Line	314	980	4,300	3,400	3,600	2,603	**15,197**
Ave. Length of Runs (Days)	2	8	26	38	44	75	

[1]*Through June 1997*

Construction shot with coal screen in foreground, quench table immediately behind, and CDL quench column in the middle

Pursuit of a finishing process step resulted in establishment of a stabilization task force composed of private sector and government engineers and scientists. The outcome was construction and testing of a Pilot Air Stabilization System (PASS) to complete the oxidative deactivation of PDF®. PASS controls temperature and humidity during forced oxidation. Over 2½ months starting in November 1995, the PASS system successfully processed ½ to 1 ton of solids per hour, 24 hours per day, and produced a stable PDF® that could be stored in uncompacted piles without pile layering. The data obtained were used to develop specifications and design requirements for a full-scale, in-plant PDF® finishing unit based upon a commercial (Aeroglide) tower dryer design.

CDL® Product — The first shipment of ENCOAL's liquid product experienced unloading problems. The use of heat tracing and tank heating coils solved the unloading problems for subsequent customers. The CDL® also contained more solids and water than had been hoped for, but was considered usable as a lower grade oil. To reduce water content, ductwork and major equipment such as ESPs and the pyrolyzer cyclone were insulated, allowing temperatures throughout the process to remain above the dew point of water. After installing insulation, CDL® contained less water than previous batches, but still had a higher solids content than desired.

Following initial start-up, CDL® quality improved. The pour point ranged from 75º to 95 ºF, and the flash point averaged 230 ºF, both within the design range. Water content was down to 1–2 percent, and solids content was 2–4 percent. These improvements resulted from more consistent operation and lower pyrolysis temperatures and higher pyrolysis flow rates enabled by the new pyrolyzer water seal.

Environmental Performance

PDF® Product — PDF® offers the advantages of low-sulfur Powder River Basin coal without a heating value penalty. In fact, the LFC® process removes organically-bound sulfur, making the PDF® product lower in sulfur than the parent coal on a per-Btu basis. For comparison purposes, theoretical combustion of ROM Buckskin coal would emit approximately 1.0 lb/10^6 Btu of SO_2 (year 2000 Clean Air Act SO_2 emission limits) while PDF® would emit approximately 0.7 lb/10^6 Btu. Since the ROM coal is low in ash, PDF® ash levels remain reasonable after processing, even though the ash level is essentially doubled (ash from one ton of ROM coal goes into ½ ton of PDF®).

PDF®'s bituminous coal heating value and low-sulfur characteristics established the potential of PDF® as a Clean Air Act SO_2 emission compliance option. Test burns at utilities were performed to validate the acceptability of transportation, handling, combustion, and ash deposition characteristics.

Over the course of the demonstration, ENCOAL shipped PDF®/ROM coal blends in the range of 14–94 percent PDF® as well as 100 percent PDF®. Demonstrated was the ability to: (1) coordinate with the Buckskin Mine in loading and shipping consistent blends; (2) ship PDF® with dust generation comparable to or less than ROM Buckskin coal; (3) ship PDF® and PDF® blends that were stable with respect to self heating; and (4) transport and deliver PDF® using regular commercial equipment.

In handling PDF®, operators observed that PDF® seemed to flow more readily than ROM coal, clearing unloader bunkers more quickly. Also, bull dozer operators noted a tendency of PDF® to roll away from the blade but offer more resistance than normal. These characteristics were attributed to the high percentage of small particles in a narrow band width. The enhanced flow caused no problems in conveying.

Two factors contributed to acceptable dust generation—the addition of a patented dust suppressant (MK) and the particle size distribution of PDF®. Since PDF® has no surface moisture to naturally supress dust emissions, MK is sprayed on the PDF® to coat the surface as it leaves the storage bin.

FIGURE 1. PARTICLE SIZE COMPARISON

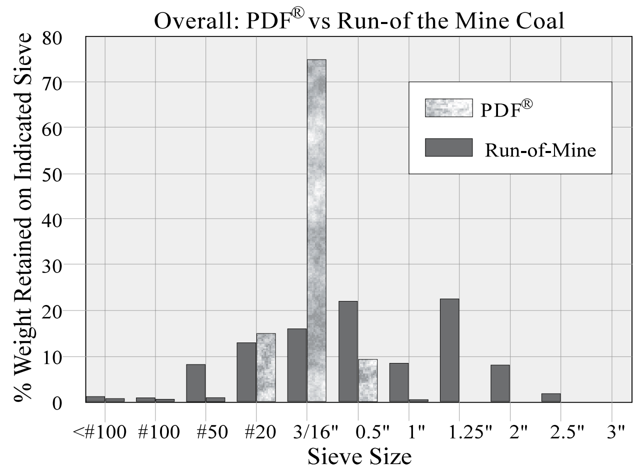


Figure 1 shows that the PDF® particle size distribution is narrower than that of ROM coal. While having a larger fines content, PDF® has fewer particles in the fugitive dust range than ROM coal.

Between September and December 1994, ENCOAL shipped six trains of PDF® to two customers for qualitative assessment of handling and combustion characteristics. Western Farmers Electric Cooperative tested blends of PDF® and PRB coal (PRB is baseline coal), ranging from 14.4 to 31.9 percent PDF®, in a 400 MWe wall-fired unit at its Hugo, Oklahoma Plant. The upper blend level was determined by the heat content limit of the boilers. *Table 4* summarizes performance observations.

TABLE 4. PERFORMANCE AT 400 MWE HUGO PLANT

- While testing a 25 percent PDF® blend, the plant's performance monitoring system calculated a possible 10–20 °F decrease in furnace exit gas temperature, indicating some increase in furnace heat absorption.
- Pressure drop across the pulverizers increased between 0–10 percent when the PDF® blends were introduced.
- The amount of pulverizer material passing 200 mesh at a given coal feed rate decreased with PDF® blends.
- Feed rate through the pulverizers decreased at a given boiler load with the PDF® blends. The compensating effect maintained particle size distribution within operating criteria.

Muscatine Power and Water, in Muscatine, Iowa, tested PDF® and PRB coal blends (PRB is baseline coal), ranging from 39.0–90.7 percent PDF®, in an 80 MWe cyclone unit. The shipment included the first full unit train of near-100 percent PDF® with a cap of ROM coal to prevent fines losses. The PDF® shipped exhibited no handling, dustiness, or self-heating problems. *Table 5* summarizes performance observations.

TABLE 5. PERFORMANCE AT 80 MWE MUSCATINE PLANT

- Use of PDF® blends in the cyclone boiler reduced electrostatic precipitator efficiency and opacity problems—attributed to the low sulfur content of PDF®, which increases particulate matter resistivity.
- Brief testing with near 100 percent PDF® achieved SO_2 emissions of less than 0.8 lb/10^6 Btu while SO_2 emissions with the Buckskin parent coal were around 1.6 lb/10^6 Btu.
- Testing indicated some positive effect on NO_x emissions at the 90.7 percent blend.

ENCOAL's test burn shipments became international when Japan's Electric Power Development Company (EPDC) evaluated six metric tons of PDF® in 1994. The EPDC, which must approve all fuels being considered for electric power generation in Japan, found PDF® acceptable for use in Japanese utility boilers.

In 1995, ENCOAL shipped two additional trains to Muscatine and three trains to its third customer, Omaha Public Power District (OPPD), in Omaha, Nebraska. OPPD had been burning Powder River Basin coal in a boiler designed for bituminous coal for some time, so the increased heat content of the PDF® blends helped increase plant output.

In October 1996, instrumented combustion testing was conducted at the Indiana-Kentucky Electric Cooperative's (IKEC) Clifty Creek Station, Unit #3. Boiler performance with a baseline blend of 60 percent PRB/20 percent high-sulfur Ohio/20 percent low-volatile Virginia coals was compared to 70/80/90 percent PDF® and high-sulfur Ohio coal blends. PDF® was blended with high-sulfur Ohio coal in order to maintain the same amount of SO_3 in the flue gas (for efficient precipitator performance). The initial 70 percent PDF®/30 percent high-sulfur Ohio coal blend contained roughly the same amount of sulfur on a lb/Btu basis as the baseline coal blend. Unit #3 is a 232 MWe Babcock and Wilcox (B&W) Open Path boiler with 14 B&W crosstube burners arranged on three elevations on the front wall of the furnace, which is designed for slag-tap operation.

Table 6 summarizes the IKEC test results. Direct comparisons between baseline and PDF® operation were not possible because baseline data was limited to 190 MWe, while PDF® data was taken at 230 MWe. However, a number of important findings were made.

Table 6. IKEC Test Results Summary

- Full generating capacity using PDF® was possible with one mill out of service — not possible on the baseline fuel and a source of concern. Operation on PDF® afforded time to perform mill maintenance and calibration without losing capacity or revenues, increased capacity factor and availability, and decreased operating and maintenance costs.
- NO_x emissions were reduced by 20 percent due to high PDF® reactivity, resulting in almost immediate ignition upon leaving the burner coal nozzle. Baseline coal was igniting 1–2 feet away from the coal nozzle where oxygen concentrations were greater (maximum volatile nitrogen release occurs just upstream of ignition).
- PDF® sustained effective combustion (maintaining low loss on ignition) with very low excess oxygen (1.7 percent flue gas O_2; stoichiometric air/fuel ratio of 1.1), which is conducive to low NO_x emissions.
- PDF® handling was not affected by drenching rains that caused significant feeding problems for the baseline coals. Unit #3 achieved an extra 20 MWe over the course of each operating hour by avoiding feeder trips.
- PDF® use increased ash deposits in the convective pass that were wetter than those resulting from baseline coal use. The cause was attributed to the increased amount of calcium-rich PRB coal ash in the PDF®/Ohio coal blend as compared to the baseline blend. Increased sootblowing was required to control build-up.
- It is likely that furnace exit gas temperature (FEGT) with the PDF® blend was higher by an estimated 20–30 °F due to higher flame temperature and lower fuel moisture (not validated by measurement).

Also in October 1996, a 100 percent PDF® unit train was sent to Northern Indiana Public Services Company and to Union Electric's Sioux Plant near St. Louis, Missouri. However, no instrumented testing was conducted.

CDL® Product — The CDL® liquid product is a low-sulfur, highly aromatic, heavy liquid oil. CDL® fuel characteristics are similar to a low-sulfur No. 6 fuel oil, except that the sulfur content is significantly lower. Its market potential as a straight industrial residual fuel, however, appears limited. The market for CDL® as a fuel never materialized and CDL® has limited application as a blend for high sulfur residual fuels due to incompatibility of the aromatic CDL® with many straight-chain hydrocarbon distillates.

Dakota Gasification Company was by far the largest user of the CDL®, purchasing 101 tank cars and blending the CDL® into one of the liquid streams at its Great Plains Coal Gasification Facility. Dakota Gasification completed a thorough characterization of CDL® in June 1995. A determination was made that a centrifuge was needed to reduce solids retention (tests validated a 90 percent removal capability); and an optimum slate of upgraded products was identified. The upgraded products were: (1) crude cresylic acid (50 percent cresylics/50 percent neutral oils); (2) coal tar for pitch products; (3) refinery feedstock (Low-oxygen middle distillate); and (4) oxygenated middle distillate (industrial fuel).

Plant — NO_x emissions from the ENCOAL® plant were controlled by appropriate design of the combustors, based on evaluation of NO_x control technologies for low-Btu gases. SO_2 was controlled by a sodium carbonate solution sulfur recovery scrubber, which achieved 97 percent SO_2 removal as well as particulate control. The scrubber incorporates a venturi scrubber followed by a wet gas horizontal scrubber with three water curtains, both using a water-based sodium carbonate solution. The scrubber combination removes fine particulates and most of the SO_2 from the flue gas. The spent solution discharges into a clay-lined pond for evaporation.

Venturi scrubbers also effectively controlled dust at critical conveyor transfer locations. With the aid of a blower, venturi scrubbers pull a suction and as the dust laden air passes through the scrubber, dual atomization nozzles disperse water and chevron separators remove coal dust and water.

A land farm was constructed for the demonstration to handle the larger than expected amount of process water fines. The land farm used biological means to remove hydrocarbons from the fines before disposal.

Economic Performance

ENCOAL's base case for the economics of a commercial LFC® plant was a 15,000 metric-ton/day, three-unit plant, with an independent 80-MW cogeneration unit, located at the North Rochelle Mine in Wyoming's Powder River Basin. The base case included cogeneration as a corollary to the design basis document because of the large quantities of fines produced in a commercial LFC® configuration. Power generation and/or agglomeration of fines for later use were determined to be the most economical possibilities. However, commercial plant economic analysis excluded the cogeneration facility, treating it as a unit owned and operated independently.

Capital cost estimates relied upon the ENCOAL demonstration plant design and the latest available information. Overall project economics were deemed to be not overly sensitive to variations in capital estimates, which were considered well within sensitivities of ±20 percent. *Table 7* presents a summary of the capital costs for the base case three-unit LFC® plant, along with the assumptions.

Economic benefits from an LFC® commercial plant derive from the margin in value between a raw, unprocessed coal and the upgraded products, making an LFC® plant dependent on the cost of feed coal. In fact, this is the largest single operating cost item. The balance of the operating costs for the three-unit LFC® commercial plant are developed from ENCOAL demonstration plant data and operating experience, including labor rates and productivity expectations. Assumed to be a stand-alone facility, the commercial plant does not rely on adjacent mine facilities for operating or administrative assistance. The total estimated operating cost is $9.00/ton of feed coal, including the cost of feed coal, chemical supplies, maintenance, and labor. A summary of the cost categories is presented in *Table 8* along with the assumptions.

Hot gas duct at top of pyrolyzer

Table 7. Capital Cost Summary

Item	Capital Cost ($000,000)
Main LFC Facilities	319
Support Facilities	37
Flue Gas Scrubbing	16
CDL Upgrading	19
Environmental	9
Engineering & Other	75
Total ($000,000)	**475**

- Construction management costs are assumed to be 4 percent of total capital.
- Engineering is assumed to be 9 percent of total capital.
- Contingencies are estimated to be $10 million.
- Design and construction will take 36 months. A non-overlap six-month lead is assumed for the design work.
- All three LFC® units are constructed at the same time.
- The LFC® plants are essentially stand-alone facilities, but do rely on the mine for raw coal storage, PDF® loadout, and water supply facilities.

A financial model was constructed using a spreadsheet to evaluate the project's financial viability. The key measurements used for internal evaluation were Internal Rate of Return (IRR) and Net Present Value (NPV). *Table 9* provides a summary of the economics for a three-unit commercial plant (base case – no synthetic fuel tax credit) along with the significant assumptions. The IRR and NPV are most sensitive to revenue, and to a lesser degree, capital investment. Operating costs variations had only a slight effect on IRR or NPV. An increase in revenue of 10 percent coupled with a decrease in capital cost of 10 percent would provide an unleveraged IRR in excess of 18 percent.

TABLE 8. OPERATING COSTS AT FULL PRODUCTION

Item	Capital Cost ($000,000/Year) (Year 2001 Dollars)
Feed Coal	26.0
Labor and Staff	7.2
Supplies and Services	9.2
Chemicals	5.4
Utilites and Fuel	4.8
Total Per Year ($000,000)	**52.6**

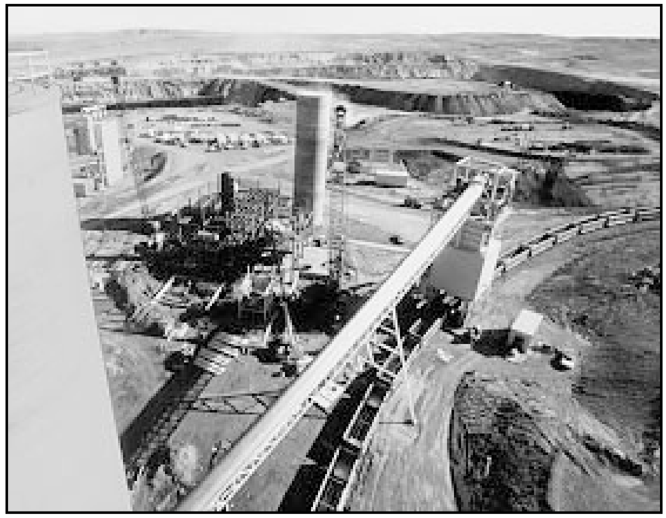
- Permanent employment of 80 operating technicians and 22 staff is anticipated.
- Periodic contract assistance is allowed for major turnarounds.
- Maintenance is assumed to be 2.5 percent of the major installed equipment cost.

TABLE 9. COMMERCIAL PLANT ECONOMICS SUMMARY

Item	Base Case
IRR – Unleveraged	~15%
NPV	~$169x10^6
Total Capital Investment (Excludes Capitalized Interest)	$475x10^6
Operating Cost $/Ton Feedstock	$9.00
Payback Period (Measured from Start-up)	9 years
Cumulative After Tax Cash Flow	>$2x10^9

- Project has a 30-year life from commissioning.
- Power plant is constructed, owned, and operated by a third party.
- Discount rate is 12% on after tax cash flows for NPV calculations.
- Utility market volume for PDF® is 80% and steel industry is 20%.
- Escalation equals inflation (3%) for revenue.
- Initial capital costs for construction are $475 million.
- Construction timeframe is 20–24 months from notice to proceed.
- Tax rate used for federal income tax is 35%.

A possible up-side to the base case is use of the non-conventional fuel tax credit, commonly referred to as 29c. This tax credit is calculated by converting PDF® and CDL® to a Barrel of Oil equivalent (BOE) base and then applying a rate per BOE. The addition of 29c to the base case evaluation adds over 15 percent to the unleveraged IRR, and more than doubles the project NPV.



Loading out coal train from coal bunker

Rotary cooler

COMMERCIAL APPLICATIONS

The envisioned commercial plant configuration differs from the demonstration design. Major differences are summarized in *Table 11*.

Also, PDF® would be marketed not only as a boiler fuel but as a supplement or substitute for coke in the steel industry. PDF® characteristics make it attractive to the metallurgical market as a coke supplement in pulverized coal injection and granular coal injection methods and as a reductant in direct reduced iron processes. The reduction in coke production provides a potential market for CDL® as a replacement for coal tars produced during the coking process.

A number of domestic and foreign applications of the LFC® process have been evaluated. Compatibility of coal with the process is essential and is examined first. The following screening criteria are used to determine compatibility of candidate coals with the LFC® process:

- Low-rank coal amenable to LFC® processing
- Sufficient reserves for a 30-year LFC® plant life
- Low mining costs
- Adequate infrastructure to transport LFC® products
- Available markets in which LFC® products can compete

High moisture content leads to more value through upgrading. Low ash content is required because the ash remains in the solid product. The lower the fuel ratio, the greater the amount of volatile matter available for recovery as CDL®. The H/C ratio needs to be high in order to ensure volatile matter will evolve with a high percentage of recoverable hydrocarbon vapor and not oxygen-based gases (e.g., carbon dioxide and carbon monoxide). Free swelling is an important consideration concerning coal handling and processing in the drying and pyrolyzing stages of the LFC® process. Furthermore, organic sulfur should comprise a significant portion of the sulfur content in order to realize a0 major sulfur reduction in processing.

Domestic coals beyond the Powder River Basin evaluated and determined to be compatible with the LFC® process include: Alaska subbituminous coals from the Beluga and Healy deposits, North Dakota lignites from the Williston Basin, and Texas lignites.

TABLE 11. COMMERCIAL PLANT CONFIGURATION

- Screening of raw coal will be eliminated to avoid parallel trains of screens and return of massive volumes of fines to mine. A vibrating grizzly will separate raw coal by size, placing coarse coal on bottom and fines on top of rotary grate. During drying, fines will fluidize, be recovered by a bank of cyclones, and either be fed into a cogeneration unit for combustion, or agglomerated and stored for later use as fuel.
- Although drying and pyrolysis remain discrete, a single rotary grate will be used for both process steps to mitigate capital costs.
- A quiescent bed deactivation unit will replace the VFB deactivator to avoid use of multiple trains of VFBs.
- A finishing unit will be incorporated, controlling temperature and humidity until oxygen uptake reaches equilibrium.
- Multiple high-efficiency cyclones will remove particulates in the pyrolysis circuit and a centrifuge will remove 90 percent of entrained solids from the CDL® to improve liquid product quality.
- An increased number of electrostatic precipitators will be used in the liquid circuit to enhance oil recovery and prevent mists from damaging downstream equipment.
- CDL® will be upgraded to cresylic acid, pitch, refinery feedstock, and oxygenated middle distillate. Oxygenated middle distillate, the lowest value byproduct, will be used in lieu of natural gas as a make-up fuel for the process (30 percent of the process heat input).

The domestic project identified for initial LFC® commercialization and the basis for the economic analysis markets was the 15,000 metric-ton/day, three-unit plant at a Powder River Basin Mine. An Industrial Siting Permit and an Air Quality Construction Permit had been issued and permitting was continuing at the close of the demonstration.

The ENCOAL plant attracted a large number of international visitors, especially from the Pacific Rim countries, interested in either using the technology with their own coal supplies or purchasing the derived products. Partners in the ENCOAL® project completed five detailed commercial feasibility studies — two Indonesian, one Russian, and two U.S.

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