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The ENCOAL® Mild Coal Gasification Project A DOE Assessment

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Executive Summary

This report is a post-project assessment of the ENCOAL® Mild Coal Gasification Project, which was selected under Round III of the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) Demonstration Program. The CCT Demonstration Program is a government and industry cofunded technology development effort to demonstrate a new generation of innovative coal utilization processes in a series of commercial-scale facilities.

The ENCOAL® Corporation, a wholly-owned subsidiary of Bluegrass Coal Development Company (formerly SMC Mining Company), which is a subsidiary of Ziegler Coal Holding Company, submitted an application to the DOE in August 1989, soliciting joint funding of the project in the third round of the CCT Program. The project was selected by DOE in December 1989, and the Cooperative Agreement (CA) was approved in September 1990. Construction, commissioning, and start-up of the ENCOAL® mild coal gasification facility was completed in June 1992. In October 1994, ENCOAL® was granted a two-year extension of the CA with the DOE, that carried through to September 17, 1996. ENCOAL® was then granted a six-month, no-cost extension through March 17, 1997. Overall, DOE provided 50 percent of the total project cost of $90,664,000.

ENCOAL® operated the 1,000-ton-per-day mild gasification demonstration plant at Triton Coal Company's Buckskin Mine near Gillette, Wyoming, for over four years. The process, using Liquids From Coal (LFC™) technology originally developed by SMC Mining Company and SGI International, utilizes low-sulfur Powder River Basin (PRB) coal to produce two new fuels, Process-Derived Fuel (PDF™) and Coal-Derived Liquids (CDL™). The products, as alternative fuel sources, are capable of significantly lowering current sulfur emissions at industrial and utility boiler sites throughout the nation thus reducing pollutants causing acid rain. In support of this overall objective, the following goals were established for the ENCOAL® Project:

- Provide sufficient quantity of products for full-scale test burns.
- Develop data for the design of future commercial plants.
- Demonstrate plant and process performance.
- Provide capital and O&M cost data.
- Support future LFC™ technology licensing efforts.

Each of these goals has been met and exceeded. The plant has been in operation for nearly 5 years, during which the LFC™ process has been demonstrated and refined. Fuels were made, successfully burned, and a commercial-scale plant is now under contract for design and construction.

1 Introduction

The Clean Coal Technology (CCT) Demonstration Program, which is sponsored by the U.S. Department of Energy (DOE), is a government and industry co-funded technology development effort conducted since 1985 to demonstrate a new generation of innovative coal utilization processes. One of the major objectives of the CCT Program is to develop technologies for reducing emissions of sulfur dioxide (SO_2), which is one of the primary contributors to acid rain. SO_2 is formed through the combustion of sulfur contained in the coal. Burning typical medium- and high-sulfur coals produces SO_2 emissions that exceed the allowable limits under the 1990 Clean Air Act Amendments. The major options available to utilities to comply with the regulations consist of (1) precombustion removal of sulfur, (2) in-situ removal of SO_2, (3) post-combustion removal of SO_2, (4) switching to lower-sulfur coals, and (5) purchasing SO_2 emissions allowances.

Another objective is to provide the technical data necessary for interested parties in the private sector to proceed confidently with commercial replication of the demonstrated technologies. An essential part of meeting this goal is the effective dissemination of results from the demonstration projects. The post-project assessment report is an independent DOE appraisal of the success of a completed project in meeting its objectives and aiding in the commercialization of the demonstrated technology. The report also provides an assessment of the expected technical and environmental performance of the commercial version of the technology as well as an analysis of the commercial market for the process and its products.

The ENCOAL® Liquids from Coal (LFC™) process incorporates mild coal gasification, and upgrades low-rank coals to two new fuels, Process-Derived Fuel (PDF™) and Coal-Derived Liquid (CDL™). By the end of May 1997, 246,900 tons of coal had been processed into 114,900 tons of PDF™ and 4,875,000 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™ to eight customers in seven states. The LFC™ upgrading is beneficial because of the following:

- The removal of water increases the specific heating value of the low-rank coal, however a portion of the volatile matter is also removed to stabilize the PDF. This results in a solid fuel product that handles, ships, and burns very much like bituminous coal.
- There is a reduction of the sulfur content of the low-rank feed coal during its conversion to PDF™.
- The co-produced CDL™ is an acceptable substitute for heavy industrial fuel (e.g., Number 6 fuel oil) as it is.
- CDL™ can be fractionated into its major constituents, several of which are valuable chemicals.

Also, at the American Electric Power (AEP) Clifty Power Station, in tests of blends of Ohio high-sulfur coal with 70- to 90-percent PDF™, unit capacity was increased and at least a 20-percent reduction in nitrogen oxides (NO_X) was realized because of a more stable flame than usual with the normal fuel.

The project was partially funded by DOE under Round III of the CCT Program. DOE contributed about $45,332,000 (50 percent) of the $90,664,000 demonstration project cost, with the remainder provided by ENCOAL®. At its inception, ENCOAL® was a subsidiary of Shell Mining Company. In November 1992, Shell Mining Company changed ownership, becoming a subsidiary of Ziegler Coal Holding Company of Fairview Heights, Illinois. Renamed successively as SMC Mining Company and then Bluegrass Coal Development Company, it remained the parent entity for ENCOAL®, which operated the CCT demonstration plant near Gillette, Wyoming. The ENCOAL® facility, having a coal-feed capacity of 1,000 tons per day, was operated at the Buckskin mine, owned by Triton Coal Company, another Ziegler subsidiary.

ENCOAL®, as the owner, manager, and operator of the demonstration plant, was responsible for all aspects of the project, including design, permitting, construction, operation, data collection, and reporting. The M.W. Kellogg Company was the engineering contractor for the project.

Coal processed in the ENCOAL® plant was purchased from Triton's Buckskin mine, which also provided labor and administrative services, access to the site, associated facilities, and infrastructure vital to the project. Additional technical development support was provided by TEK-KOL, a partnership between SGI and a subsidiary of Ziegler that also had the primary responsibility for marketing and licensing the technology. All assets were assigned to ENCOAL®, while all technology rights are held by TEK-KOL and licensed to ENCOAL®.

2 The Demonstrated Technology

2.1 Description of the Technology

2.1.1 Pre-Project Technology Status

The ENCOAL® project uses, at its core, a mild gasification based on LFC™ Technology. This process was originally developed by SGI International of La Jolla, California, to produce two new low-sulfur fuels, PDF™ and CDL™, from sub-bituminous coal. There are two elements in the LFC™ technology that differentiate it from other coal-gasification technologies. First, the technology takes into consideration the coal heating and decomposition rate and temperature level, which affect the governing kinetics of gasification reactions. Second, for the purpose of controlling the gasification conditions to get the correct end product, SGI International developed working computer models of reaction kinetics and control methods.

The LFC™ technology was developed using a program of laboratory tests in retorts of increasing size. The scale-up involved bench-scale development units whose batch processing capacity was 4 pounds, and a 44-pound batch-process test unit. Throughout the bench-scale test program, computer models were developed to assist with the ultimate process design and commercialization of the LFC™ technology. Data from the tests were used to calibrate and verify the computer models.

The successful bench-scale tests and computer modeling led to the construction of a process-development unit (PDU) in 1986 to produce design information and products for analysis. The PDU was located at Salem Furnace Company's development laboratory in Pittsburgh, Pennsylvania. The PDU underwent extensive changes as development of the LFC™ Technology evolved. Originally a batch system, the PDU was upgraded in late 1987 to operate in a semi-continuous manner at an equivalent input rate of 200 pounds per hour of as-received coal. Shell Mining company conducted a number of campaigns at the PDU in 1987 and 1988 to generate products from Buckskin coal for product-yield analysis and property evaluations in support of the project. The PDU was approximately 1/500 of the demonstration-plant scale for the dryer and 1/350 for the pyrolyzer.

2.1.2 LFC™ Process Concept

The LFC™ technology is built around a mild pyrolysis or mild gasification process that involves heating the coal under carefully controlled conditions. In contrast to conventional drying, which leads only to physical changes, the process causes chemical changes in the feed coal. Low-rank coals contain considerable water, and conventional drying processes physically remove some of this moisture, causing the heating value to increase. The deeper the coal is dried, the higher the heating value and the more the pore structure of the coal permanently collapses, reducing reabsorption of moisture. However, deeply dried Powder River Basin (PRB) coals exhibit significant stability problems when dried by conventional thermal processes. The LFC™ process fixes these stability problems by thermally altering the solid to create PDF™ and CDL™.

Specification PDF™ is a stable, low-sulfur, high-Btu fuel similar in composition and handling properties to bituminous coal. CDL™ is a low-sulfur industrial fuel oil that can potentially be upgraded for chemical feedstock or transportation fuels.

The LFC™ process first dries the mined coal to very nearly zero-percent moisture. The dried coal is then mildly pyrolized under carefully controlled conditions, during which about 60 percent of the original volatile matter and a portion of the sulfur are removed. These two steps alter the basic coal characteristics both physically and chemically, helping to eliminate many of the problems associated with coal drying. The coal char is then treated in a multiple-step process adding moisture and oxygen, followed by cooling, to produce PDF™.

Volatile matter driven off during pyrolysis is partially condensed in a multiple-step process that produces the CDL™ oil. The noncondensed gases are returned to the combustors as a fuel source and vehicle for the drying and pyrolysis steps. The ENCOAL® process produces approximately 1/2 ton of PDF™ and 1/2 barrel of CDL™ from each ton of feed coal.

2.1.3 LFC™ Process Description

In the ENCOAL® demonstration plant, run-of-mine (ROM) coal is conveyed from existing Buckskin mine storage silos to ENCOAL®'s 3,000-ton feed silo. Up to 1,000 tons per day of coal from this silo is continuously fed onto a conveyor belt by a vibrating feeder, crushed and screened to 2 ×1/8 in., and conveyed about 195 feet to the top of the building.

The coal is then fed into a rotary-grate dryer where it is heated by hot gas. The solids residence time and temperature at the inlet of the heating gas are selected to reduce the moisture content of the coal without initiating pyrolysis or chemical changes. The solids bulk temperature is controlled so that no significant amounts of methane, carbon monoxide (CO) or carbon dioxide (CO_2) are released from the coal.

The solids leaving the dryer are fed directly to the pyrolyzer rotary grate, where a hot recycle gas stream raises the temperature to about 1,000°F. The rate of heating and residence times are carefully controlled as these parameters affect the properties of both the PDF™ and CDL™ products. During processing in the pyrolyzer, all remaining free water is removed, and a chemical reaction occurs in which volatile gaseous materials are released. After leaving the pyrolyzer , the solids are quickly cooled in a quench table to stop the pyrolysis reactions.

Figure 1 shows the process diagram. In the original process concept, the quench-table solids were further cooled in a rotary cooler and transferred directly to a surge bin. About halfway into the project life, extensive testing showed a need for a separate, closed vessel for deactivating the solid product prior to final cooling and storage. The process was thus altered to include a vibrating fluidized bed (VFB) as part of a PDF™ deactivation loop. In the current process, quench-table solids are fed into the deactivation loop where they are partially fluidized and exposed to a gas stream in which temperature and oxygen content are carefully controlled. A reaction, termed *oxidative deactivation*, occurs at active sites in the particles, the effect of which is to reduce the tendency of the product to spontaneously ignite. The heat generated by this reaction is absorbed by the fluidizing gas stream.

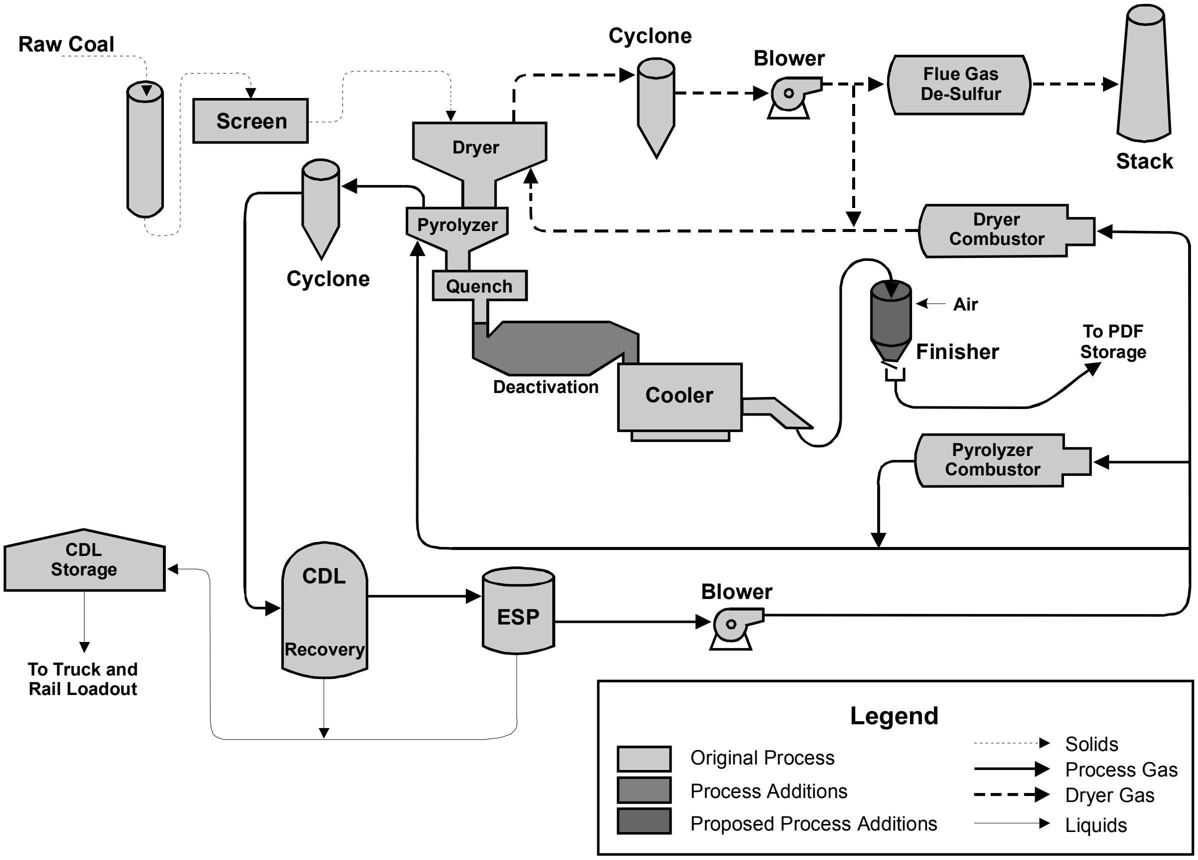

Figure 1. The ENCOAL® Mild Gasification System

The deactivation gas system consists of a blower to move the gas stream, a cyclone to remove entrained solid fines, a heat exchanger to control gas temperature, and a booster blower to bleed off gas to the dryer combustor. The residence time, oxygen content, and temperature of the gas stream are selected to deactivate the coal within the VFB unit.

After treatment in the VFB system, the solids are cooled in an indirect rotary cooler. A controlled amount of water is added in this cooler to rehydrate the PDF™ to near its equilibrium moisture content, an important step in the stabilization of PDF™. A final or "finishing" step, the second stage of deactivation, has also been tested as an addition to the original process. In this step, PDF™ is oxidized at low temperatures and then transferred to a surge bin. Since the solids have no surface moisture, they require the addition of a dust suppressant. MK, a dust suppressant patented by SMC Mining Company, ENCOAL®'s former parent company (now Bluegrass Coal Development Company), is added to the solid product as it leaves the surge bin immediately prior to shipping. PDF™, the resulting new fuel form, is transferred to storage silos from which it is shipped by rail through existing Buckskin Mine loadout facilities.

The pyrolysis gas stream is sent through a cyclone to remove entrained particles and then cooled in a quench tower to condense the final oil product and to stop any secondary reactions. Only the CDL™ is condensed; the condensation of water is avoided. Electrostatic precipitators (ESPs) recover any remaining liquid droplets and mists from the gas leaving the condensation unit.

About half of the residual gas from the condensation unit is recycled directly to the pyrolyzer, while some is burned in the pyrolyzer combustor before being blended with the recycled gas to provide heat for the pyrolyzer. The remaining gas is burned in the dryer combustor, converting sulfur compounds to sulfur oxides (SO_X). NO_X emissions are controlled by appropriate design of the combustor. The hot flue gas from the dryer combustor is blended with the recycle gas from the dryer to provide the heat and gas flow necessary for drying.

The exhaust gas from the dryer loop is treated in a wet scrubber followed by a horizontal scrubber, both using a water-based sodium carbonate (Na_2CO_3) solution. The wet gas scrubber recovers fine particulates that escape the dryer cyclone, and the horizontal scrubber removes most of SO_X from the flue gas. The spent scrubber solution is discharged into a clay-lined pond for evaporation.

2.2 Benefits of the Technology

The high moisture content of the PRB coal accounts for its relatively low heating value. PRB coals normally have moisture contents in the order of 25 to 30 percent, with heating values ranging from 8,000 to 8,700 Btu/lb. The LFC™ process first dries the mined coal to very nearly zero-percent moisture, then subjects it to a controlled pyrolysis where approximately 60 percent of its original volatile matter and a portion of its sulfur are removed. These two steps physically and chemically alter the basic coal characteristics, which helps to eliminate many of the problems usually associated with coal drying. The resulting coal char is then finished in a multi-step process, where moisture and oxygen are added and the char is cooled to finally produce the PDF™. The volatile matter driven off during pyrolysis is partially condensed in a multi-step process that produces the hydrocarbon liquid CDL™.

The ENCOAL® project sponsors believe that their project benefits from the following intrinsic economic advantages:

- PDF™ and CDL™ are both clean-burning fuels.
- PDF™ has multiple market applications. Among these are utility fuel blending and steelmaking.
- The decline of the coking industry in the U.S. has reduced the supply of coal liquids, which suggests potential markets for CDL™, and has at the same time increased the potential market for PDF™ in steelmaking.

A number of factors make PDF™ an increasingly valuable boiler fuel. PDF™ has distinct transportation advantages. It is a readily available, competitively-priced fuel with low sulfur content, low NO_X emissions and low ash-fusion temperatures. Electric-utility deregulation and more stringent NO_X emission regulations make PDF™ an even more attractive fuel choice, both now and for the future. Also, as high costs and environmental noncompliance problems continue their pressure on the declining U.S. coke industry, the steel industry is replacing coke in blast furnaces with pulverized coal injection. PDF™ may become a viable injected fuel/reactant for these blast furnaces. In the emerging Direct Reduction of Iron (DRI) technologies, PDF™ appears to be an excellent alternative source of carbon and fuel.

CDL™ is a highly aromatic coal liquid that has found some acceptance in the residual fuels market in the U.S. However, low natural gas prices and the abundance, at present, of heavy fuel oils, have kept this market depressed during ENCOAL®'s operating period. This has led the project sponsors to pursue the higher value CDL™ fractions such as crude cresylic acid, petroleum refinery feedstock similar to a petroleum gas oil, oxygenated middle distillate usable as an industrial fuel, and pitch suitable for blend stock into anode binder products, among other applications.

3 Results of the Demonstration

3.1 Summary of Testing

Following engineering and design, procurement, construction, commissioning, and start-up, plant operations began with the ENCOAL® plant's first 24-hour run in June 1992. The "Phase III" portion of the project as defined in the Cooperative Agreement (CA) between ENCOAL® and the DOE officially began on July 17, 1992, 60 days after the submission to DOE by ENCOAL® of the Continuation Application for the project.

The almost 5 years comprising Phase III were a period of intense activity. As a first-of-its-kind technology, design and process difficulties were expected. Much of Phase III was devoted to identifying and solving those difficulties, especially the problem of PDF™ deactivation. As ENCOAL® teams resolved problems and collected and analyzed operating data, the duration of the plant runs increased, with some months demonstrating better than 90-percent availability. PDF™ and CDL™ were produced and shipped using conventional equipment and successfully burned at test sites. The operability of the plant and its equipment was proven, and a vast body of data was generated.

Although the ENCOAL® plant's tall structures, hot gases, and large rotating equipment would seem to create a real potential for injury, one of ENCOAL®'s most important accomplishments is its safety record. Since 1990, only nine reportable accidents and four lost-time accidents have been reported for all personnel, including contractors and associated workers. This lost-time accident rate is less than a third of the most recent available rate for petroleum and coal processing industries, while the number of reportables is less than one fifth. As of May 31, 1997, ENCOAL® workers had amassed 1,600 days—over 4 years—without a lost-time accident.

Compliance with federal and state environmental regulations has also been an important goal for the ENCOAL® project. Regular Mine Safety and Health Administration inspections since 1990 yielded only 10 minor noncompliance citations. With the exception of one Notice of Violation for the land farm, issued by the Wyoming Division of Environmental Quality (WDEQ) Land Quality Division (LQD), Wyoming state inspections were consistently positive. Ongoing contractor and operations safety meetings, and comprehensive, continuing operator training contributed to these safety and compliance achievements.

3.1.1 Operation and Maintenance

Table 1 makes the division between pre-VFB operations and those after its introduction quite apparent. Because it improved PDF™ stability, this new equipment made it possible for the first time to ship PDF™ for test burns. At the same time the VFB was being installed, other major changes paved the way for increased PDF™ and CDL™ production: the sand seals in the pyrolyzer were replaced with water seals, and all three ESPs were fitted with improved design insulators. A third modification, the installation of a process-water fines handling system , also contributed to the considerable improvement in plant performance and subsequent production.

Table 1. Pre- and Post- Vibrating Fluidized Bed Operations

Pre-VFB			Post-VFB				SUM
	1992	1993	1994	1995	1996	1997*	
Raw Coal Feed, tons	5,200	12,400	67,500	65,800	68,000	28,000	246,900
PDF™ Produced, tons	2,200	4,900	31,700	28,600	33,300	14,200	114,900
PDF™ Sold, tons	0	0	23,700	19,100	32,700	7,400	82,900
CDL™ Produced, barrels	2,600	6,600	28,000	31,700	32,500	14,700	116,100
Hours on Line	314	980	4,300	3,400	3,600	1,944	14,538
Avg. Run Length, days	2	8	26	38	44	81	

* *Through May 31, 1997*

Before VFB Installation (1992-1994)

ENCOAL®'s first 24-hour run took place in June 1992. After that landmark event, mechanical problems, system debugging, and equipment modifications were the primary focus until September 1992, when the ENCOAL® Plant achieved a continuous 1-week run. A month later, the first shipment of 60,000 gallons of CDL™ was sent to TexPar, Inc., which experienced unloading problems. These experiences prepared ENCOAL® to work with other customers, such as Dakota Gas, to handle CDL™ with heat tracing and tank heating coils. Customers reported no further CDL™ handling problems.

The first shipment of CDL™ to TexPar contained more solids and water than predicted, but was considered usable as a lower-grade fuel 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. As insulation was installed, CDL™ contained less water than previous batches, but still had a slightly higher solids content than desired.

The months following the first production milestone included equipment problems that frequently shut down production. While some delays in the new facility had been expected, numerous runs were stopped while equipment was modified and repaired. To minimize the impact of these delays, tests were performed during each run, and data were aggregated to provide information for ongoing and future changes. Problem areas such as ESP failures, combustor controls, and coal-slurry handling were gradually resolved, although some difficulties with the sand seals, programmable logic controllers, material handling, and process blowers remained. April 1993 had an extremely successful 16-day run, which was continuous except for a 24-hour stoppage when the dryer sand seal failed. All planned tests were completed within the first 7 days. More plans were drawn up, and over 5,000 tons of raw coal were ultimately processed. A June run processed over 4,000 tons of coal and produced 2,500 barrels of CDL™ before ending in a planned shutdown.

Although improved in heating value, early batches of PDF™ revealed a tendency to self-ignite. In an attempt to stabilize PDF™ using in-plant equipment, ENCOAL® engineers first tried manipulating the process: speeds on the rotary cooler were varied; and solids flow, temperature, and PDF™ oxidative deactivation were controlled in three separate stages within the rotary cooler. Mechanical equipment failures shortened the runs, but considerable data were collected for further study. Modifications were made to control solids flow during product cooling, but deactivation remained elusive. Early in 1993, it was concluded that a separate, sealed vessel was needed for product deactivation, and a search for a suitable design began immediately. In June 1993, the first of two planned VFBs was installed in series with the original plant equipment. Installation was completed in December 1993, and the entire system was commissioned in mid-January of the following year.

After VFB Installation (1994-1997)

The VFB was designed to handle only half the ENCOAL® plant's designed capacity. When results were proven, a second VFB was to be installed. During the test runs, the plant achieved operation at 50 percent of the design rate, as predicted. Operations became notably smoother and more productive. 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 pyrolyzer sand seal with a water seal and the installation of the process-water-fines handling system.

All these improvements combined to produce a major landmark when ENCOAL® shipped its first trainload of PDF™ on September 17, 1994, to Western Farmers Electric Cooperative in Hugo, Oklahoma. During three runs in the winter of 1994, approximately 4,300 tons of coal were processed, producing nearly 2,200 tons of PDF™ and 81,000 gallons of CDL™.

The best run to-date occurred in May 1994—54 days of continuous operation, followed by a 68-day run in the fourth quarter of the year. However, VFB deactivation was not complete. Stabilization still involved "finishing" using pile layering as well as blending with ROM coal, increased silo retention time, and higher rehydration.

3.1.2 Test Burns

Commercialization of PDF™ took a major step forward in the fall of 1994 when ENCOAL® shipped six trains to two customers. Shipments made to the first customer, the Western Farmers Electric Cooperative in Hugo, Oklahoma, started at a 15-percent blend level and went up to 30-percent PDF™, the upper level being determined by the fuel heat content limit imposed by the design of the boilers. Shipments to the second customer, Muscatine Power and Water, in Muscatine, Iowa, started at 40-percent PDF™ and went up to 91 percent. The rail cars in this shipment, the first full unit train of PDF™ contained nearly 100-percent PDF™ with a cap of ROM coal to prevent fines losses. The shipped PDF™ exhibited no problems with handling, dust, or self-heating.

ENCOAL® met all its goals for these first shipments: to demonstrate its ability to coordinate with the Buckskin Mine in loading and shipping consistent blends; to ship PDF™ with dust generation comparable to, or less than, ROM Buckskin coal; and to ship PDF™ blends that were stable with respect to self-heating. Furthermore, ENCOAL® intended to demonstrate that PDF™ could be transported and delivered to customers using regular commercial equipment. With respect to utilization, the goal was for customers to burn trial amounts (1/2-unit-train minimum) of PDF™ blends with minimal adjustment of equipment.

ENCOAL®'s test-burn shipments became international when Japan's Electric Power Development Company (EPDC) evaluated 6 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.

Early 1995 saw increased plant volume when 13,700 tons of raw coal were processed in a 1-month period. Plant availability reached 89 percent, with downtime attributable to the replacement of the original quench-table heat exchanger with a new, high capacity unit. ENCOAL® shipped two additional trains to Muscatine and three trains to its third customer, Omaha Public Power District in Omaha, Nebraska. This customer had been burning PRB coal in a boiler designed for bituminous coal for some time, and the increased heat content of the PDF™ blends helped increase plant output.

ENCOAL® began shipping unit trains of 100-percent PDF™ for the first time in 1996. By the end of October, two 100-percent PDF™ unit trains were delivered to two separate utilities for test burns. The first was burned in Indiana-Kentucky Electric Cooperative's Clifty Creek Station, which is jointly owned by AEP. The PDF™ was blended with Ohio high-sulfur coal at the utility and burned in the Babcock and Wilcox open-path, slag-tap boiler with full instrumentation. Blends tested ranged between 70- and 90-percent PDF™ and burn results indicated that, even with one pulverizer out of service, the unit capacity was increased significantly relative to the base blend. More importantly, the utility experienced at least a 20-percent NO_X reduction as a result of a more stable flame. Completion of this test burn achieved a primary project milestone of testing PDF™ at a major U.S. utility. The remaining 100-percent- PDF™ unit train was sent to Northern Indiana Power Services company and to Union Electric's Sioux Plant near St. Louis, Missouri.

By the end of May 31, 1997, 246,900 tons of coal had been processed into 114,900 tons of PDF™ and 4,875,000 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™ to eight customers in seven states.

3.1.3 Project Coordination and Environmental Permitting

Service agreements were finalized with Triton for administrative support and plant operation, with Shell Mining Company for technical and administrative support, and with SGI for technical services. The Project Management Plan and a draft of the Environmental Monitoring Plan were submitted to the DOE in accordance with the CA.

The WDEQ Air Quality Division permit application was submitted in June 1988, and approval was received in June 1989. This removed a serious potential obstacle to the project as submitted to DOE. This permit to construct was required to break ground. Coinciding with the ground breaking, the federal government review process was completed with the issuance of an Environmental Assessment (EA), a requirement of the National Environmental Policy Act (NEPA). As part of this process, DOE issued the Finding of No Significant Impact Report. Fulfillment of the NEPA requirements completed CA requirements and cleared the way for initiation of Phase II construction and start-up activities.

State permitting took place with the WDEQ. Most early permitting activities centered around the question of a precipitate-disposal pond. Because the WDEQ questioned the location of a permanent precipitate-disposal pond, ENCOAL® submitted an alternative permit application to allow modification of an existing Buckskin Mine sediment pond. With the addition of an 18-inch thick clay liner, this would serve as a temporary storage pond for ENCOAL®'s precipitates. Approval of the application was critical, as lack of approval would have postponed construction until 1992. The WDEQ approved the application, giving the go-ahead for construction of all facilities except the permanent disposal pond. The temporary pond served into 1997, when the permanent precipitate-storage reservoir was completed.

3.1.4 Data Collection and Reporting

Monthly and quarterly technical progress reports and quarterly environmental monitoring reports were submitted on a regular basis, while other reports were delivered as scheduled. Data collection included compilation of information from all production runs. ENCOAL® developed test plans prior to each start-up, and organized the data collected into "run books." This proprietary information is kept at the ENCOAL® plant site and is available for review on an as-needed basis for those covered by confidentiality agreements.

3.1.5 Alternate Coal Testing

Two of the ENCOAL® Project's major goals involved demonstrating the LFC™ technology and collecting data applicable to a commercial plant. In support of those goals, ENCOAL® demonstrated the processing of Buckskin Mine coal and sought to test a variety of other coals. Alternate coal testing first took place in November 1995, when 3,280 tons of North Rochelle Mine subbituminous coal were processed at the same plant parameters as those for Buckskin Mine coal. The plant performed well, but non-typical high ash content in the feed coal limited increases in heating value, the fines rate was doubled, and CDL™ yield was lower than predicted.

A second alternate coal test took place in December 1996, when the ENCOAL® Plant processed approximately 3,000 tons of Wyodak coal, and the Black Hills Corporation reciprocated with a test burn of a mixture of PDF™ fines and ROM coal. Results from the tests were analyzed and used to determine the viability of a commercial plant sited at the Wyodak mine. Results of both ENCOAL® and Black Hills tests indicated no problems with operation or handling.

Alaskan subbituminous coal, North Dakota lignite and Texas lignites were also considered for alternate coal testing. For North Dakota lignite, laboratory testing was carried out in two stages over a 4-year span. In 1992, a blend of two seams of Knife River lignites was tested at the Tek-Kol Development Center. In 1996, Freedom Mine and Knife River lignite samples were strength tested to determine which coals were more suitable for processing. The 1992 tests verified the applicability of the LFC™ Process, while the 1996 strength tests indicated that the lignite would not break down excessively during processing.

Because the laboratory tests of these lignites appeared promising, ENCOAL® solicited joint funding from the North Dakota Lignite Research Council for a North Dakota lignite alternate coal test at the ENCOAL® Plant. This application was turned down in November 1996, and the test was abandoned. Based upon the successful laboratory screening test, however, ENCOAL® believes that North Dakota lignite is an acceptable candidate for LFC™ processing.

3.1.6 Administration

ENCOAL®'s move into Phase III operations was followed by the transition from Shell Mining Company ownership and administration to that of Ziegler Coal. Ziegler became the source for legal and administrative services, as well as providing funding and Project guarantees through Bluegrass and Triton. Other services once furnished by Shell became the province of ENCOAL®'s sister subsidiaries. Franklin Coal Sales supplied marketing, Americoal provided accounting and purchasing support, and Triton leased the site, provided utilities and services, sold coal to ENCOAL®, and handled accounts payable/receivable, purchasing, payroll, and general accounting. These organizational changes were reflected in the updated Project Management Plan.

One of ENCOAL®'s primary administrative tasks was tracking progress toward completing milestones. Late in 1994, it became apparent that the project's primary objectives would not be attainable in the time remaining because of delays caused by construction of the PDF™ deactivation facilities and other plant modifications. An extension request for 2 years' additional operation with joint funding was submitted to the DOE by ENCOAL® in July 1994, together with an Evaluation Report and Extension Plan. The key objectives of the extension period were those necessary to achieve commercialization of the LFC™ technology: the collection of cost and design data for commercial plants, testing of alternate coals, and test burns to support commercial contracts. DOE granted a no-cost, 30-day, extension to October 17, 1994, to evaluate the request. It approved the extension in October 1994, expanding ENCOAL®'s participation to September 17, 1996. After that time, the DOE granted no-cost extensions to complete alternate coal testing and final reporting by July 17, 1997.

3.1.7 Environmental Compliance

Compliance with environmental regulations has been an integral component of demonstrating the LFC™ technology, and considerable time and effort was dedicated to that goal.

Air Quality Issues

Late in 1992, ENCOAL® met with the WDEQ to discuss the status of plant operation, notification requirements, and the status of stack-gas monitoring. As a result of this discussion, a letter was sent to WDEQ confirming the stack-gas monitoring schedule and explaining ENCOAL®'s temporary noncondensible-gas venting arrangements for the pyrolyzer quench table. The letter, which also discussed the quench-table steam condenser tests scheduled for January, was approved in December 1992.

In mid-1993, ENCOAL® submitted a permit application for a vapor collection system exhaust on the process-water system. The vapor collection system uses a small blower and an activated carbon filter to collect and filter nuisance odors from the existing process-water containment areas prior to exhausting the filtered air outside the building. Although a permit was not required by current regulations, it was agreed that a permit would be prudent, and data were collected from plant runs to support a permit application.

In October 1995, a third-party testing firm mobilized to perform stack-gas emissions testing necessary to obtain ENCOAL®'s permit to operate from the WDEQ. The stack and emissions testing using WDEQ-approved protocol was successfully completed in November 1995, and indicated that the plant is operating within permitted limits for NO_X, SO_X, CO, volatile organic compounds (VOCs), and particulates. The SO_2 Continuous Emission Rate Monitoring System for the ENCOAL® plant stack gas was certified as a result of the testing.

Revisions to the air quality permit, delayed since the beginning of Phase III by interruptions in plant operation, were reviewed by the WDEQ in March 1996, and ENCOAL® responded to the Department's questions. In mid-1996, ENCOAL® received a notice of completeness for its application for a Section 21 Air Quality (AQ) permit from the WDEQ. The permit included a 5 1/2-acre laydown area that was not anticipated in the original application. The application proceeded smoothly through the technical review and was formally approved in November 1996.

Land Quality Issues

A permanent precipitate storage reservoir was part of ENCOAL®'s original plan, but because the WDEQ questioned the location of the permanent precipitate-disposal pond, an alternative permit application was submitted, modifying an existing mine sediment pond. Because the temporary pond was adequate far longer than originally believed, ENCOAL® was allowed to defer permitting and construction of the permanent disposal pond until 1995.

The WDEQ reviewed the application for revisions to the permanent pond, and ENCOAL® responded to WDEQ questions in March 1996. At that time, a bid package for construction of the permanent reservoir was sent to potential contractors. The permit for construction cleared public comment and was sent to WDEQ's head office; final approval for the reservoir was received in June. Reservoir construction began the first week in July and continued through 1996. This reservoir is scheduled to be commissioned for use in July 1997.

Early in 1993, ENCOAL® initiated discussions for construction and permitting of an on-site land farm. The land farm, conceived in response to the collection of greater amounts of process-water fines than originally anticipated, would biologically eliminate hydrocarbons from process fines prior to on-site disposal. It was intended as a temporary facility, since the ultimate plan is to transfer fines back into the PDF™ product.

The first step in the development of the land farm was the collection and testing of fines samples and the gathering of information from plant runs. In the fall of 1993, ENCOAL® reviewed a preliminary design for the land farm before submission to the WDEQ, and construction began when preliminary approval from the WDEQ was received. Workers completed earthwork and underground piping installations in November 1993, and final piping and commissioning were scheduled for mid-January of the following year. Final approval was received in August 1994.

In the fall of 1995, the LQD of the WDEQ approved a permit for revisions that included a new concrete holding area for wet fines, a higher retaining dike to improve capacity, and provisions for continuous operation with disposal of treated fines. Specifications to complete the modifications were developed, and a bid package was issued. Modifications began in July 1996 and were completed 2 months later, and the facility was commissioned in October of the same year.

3.2 Problems Overcome—Plant Equipment

Numerous changes were made to the ENCOAL® plant facilities during the nearly 5-year operating history. These ranged from simple changes to correct minor design and/or construction oversights, to significant alteration of the process itself.

3.2.1 Solids Handling Systems

Problems in the solids-handling areas included spillage control, dribble chutes, and inadequate space for collection and cleanup. Also, screw conveyors for fines transfer were neglected in the original design. A means of removing raw coal from the feed-coal silo without running it through the plant became important during unplanned, lengthy shutdowns. This oversight had safety ramifications. In the case of the flexible-wall vertical plant feed and PDF™ conveyors (s-belts), the excessive spillage and fluid-drive systems proved very troublesome. Sampling for the extensive calibration testing needed for these analyzers also was a problem because it had to be done by hand. Drag conveyors in the plant, all of single-chain design with hardened flights, were very high maintenance items.

The original LFC™ technology concept included GAMMA-METRICS, a closed-loop process control scheme that relied on rapid, reliable on-line feed-coal analysis as well as PDF-solid product analysis. In the fall of 1996, both GAMMA-METRICS analyzers were removed. Samples of coal and PDF™ were subsequently taken manually once per shift and analyzed on site to maintain process checks. To solve the problem of removing raw coal from the storage silo without going through the plant, a bypass chute was added in the screening building. A dribble chute was also added on the plant feed belt to catch spillage. The drag conveyors remained high-maintenance items, because neither money nor time was available to change them to the dual-chain design that would be much more reliable.

3.2.2 Dryer and Pyrolyzer Modifications

The ENCOAL® Project used the Salem Furnace Company's rabbled- rotary- hearth furnaces for the dryer and pyrolyzer units. This seal design proved to be very troublesome. Besides the higher than expected wear, sand degradation, coal-dust buildup, and maintenance problems in both units, the sand seal in the pyrolyzer did not allow operation at full design differential pressure across the grate. In order to operate, the flow rate in the pyrolyzer loop had to be reduced to avoid blowing the sand out of the seal. The lower gas flow resulted in loss of efficiency in the cyclone, dust carryover in the piping, solids in the CDL™ product and plugging of lines. In addition, less heat was transferred to the coal, resulting in less severe pyrolysis. Attempts were made to raise the gas temperature to compensate for the lower flow but this generated heavier CDL™ product and raised the dew point in the off-gas. Condensation of liquid then occurred ahead of the quench column where it combined with the dust in the system creating unacceptable ductwork plugging.

At significant expense, the manufacturer, worked with ENCOAL® to develop an alternate design using external water seals rather than the internal sand seal. This revision was one of the major contributors to longer runs in the ENCOAL® plant . Cleanup of the Salem grates became more of an issue once longer plant runs were possible. The manufacturer again was asked to assist with the problem and they came up with a steam broom, a series of nozzles located above the normal coal level and directed toward the soaking-pit outlet. During shutdown, the steam is turned on and the nozzles blow the residual coal off the grate. In addition, a steam blaster was added to both units that swings down near the grate to clean the slots in the grate without entering the dryer or pyrolyzer. These have been used successfully to extend a run when the plugging of the grates is moderate.

3.2.3 Dryer and Pyrolyzer Cyclones

Operation of the dryer cyclone was very successful with no modifications being made to the cyclone itself. However, the fines handling system at the discharge of the unit was significantly changed. The original design included indirect heat exchange via a screw cooler prior to being slurried to the sump system. Because of maintenance and plugging problems with the screw cooler, this unit was removed. The final layout simply mixes the fines with water immediately under the rotary-valve airlock prior to draining to the plant sump system.

Operation of the pyrolyzer cyclone was not as successful as that for the dryer. The pyrolyzer cyclone was originally designed to be 97-percent efficient; however, problems with limited loop flow rates, cyclone pressure drop, and the small size and quantity of the fines made this cyclone only 75-percent efficient. The pyrolyzer water-seal modification discussed above did allow for higher flowrates and pressure drop, but the cyclone still did not perform as designed. This resulted in high sediment concentrations in the CDL™. The gas inlet and the vortex finder were then modified to aid in flow direction and pressure drop increase. These modifications were somewhat successful, yielding a CDL™ with an average sediment of 3 weight percent. Although not 97-percent efficient, the pyrolyzer cyclone operation did become acceptable. Other modifications to the pyrolyzer cyclone included extensive changes to the fines handling system. The fines-slurry mix tank and pump system originally designed for handling the pyrolyzer cyclone fines continually plugged and experienced high wear. This system was therefore removed. Like the dryer cyclone, the present fines handling system is a simple water-fines mixing box immediately under the rotary airlock prior to gravity draining to the sump system. This arrangement is easy to maintain and does not need any motorized equipment to operate.

3.2.4 Pyrolyzer Quench Table and Quench-Steam Condensing System

Few problems were encountered in the operation of the pyrolyzer quench table. The quench table spray-nozzle system supplied with the original equipment frequently plugged and could not be maintained while the plant was on-line. The nozzle assemblies were modified to be removable on-line for unplugging, and a supply header was fabricated to simplify the supply piping and organize the nozzles. This new arrangement was very successful in reducing the maintenance of the system and increasing operator understanding of the quench-table operation.

Several problems were encountered with the operation of the quench-steam condensing system. Excessive coal fines build-up was experienced in both the piping to the condenser and in the condenser tubes themselves. Plugging of the condenser caused over pressuring of the quench table, which, in turn, required the opening of a pressure relief valve. Many plant shutdowns were attributed to this phenomenon. A fines knock-out drum and piping wash nozzles were installed between the quench table and the condenser to strip the coal fines from the steam. The knockout drum addition was successful in allowing the plant to run for longer periods; however, extended plant operation would eventually foul the single condenser and cause a plant shutdown. A second (redundant) condenser was then installed to allow for on-line switching between condensers without requiring a plant shutdown for cleaning. With these modifications, the operation of the quench-steam condensing became routine.

3.2.5 PDF™ Deactivation System

Problems with PDF™ product self-heating in 1992 and 1993 led to several minor plant modifications and extensive testing in hopes of using original plant equipment to produce stable PDF™. However, results of a January 1993 test run indicated that PDF™ deactivation would require a separate, sealed vessel. Subsequent plant and laboratory tests were run in February and March of the same year in order to establish effective criteria for deactivation. Based upon the results of these tests, an option for PDF™ deactivation was chosen. For the modification, a 6 × 30 foot VFB unit and support equipment, the first of two planned systems, was installed in series with the original plant equipment to deactivate PDF™. The system was designed to handle one-half the plant throughput, with a second, identical unit to be installed after the concept had proven itself. Installation of the PDF™ deactivation facilities began in June 1993, adjacent to the ENCOAL® plant. Construction and start-up of the facilities were completed in January 1994.

By the spring of 1994, the plant was experiencing considerably smoother and longer production runs. The new deactivation system allowed for shipment of PDF™ to utility customers for the first time; however, even as PDF™ stability was notably improved with the addition of the VFB, deactivation of PDF™ still required additional oxygen prior to shipment. Over 20 different operating conditions were varied and evaluated to increase the amount of oxygen absorbed in the VFB system, but were not entirely successful. The decision was made to "finish" the oxidation deactivation of the solids by laying the PDF™ on the ground outside the plant. This process, which came to be known as "pile layering," involves spreading the PDF™ in 12-inch deep layers, thus allowing PDF™ particles to react with oxygen and become stable. As each layer is stabilized, another layer may be added on top. This method of stabilization, combined with ROM coal blending, increased silo retention times, and slightly higher rehydration rates, has been used to deactivate PDF™ for subsequent shipments.

3.2.6 PDF™ Cooler and Rehydration

The cooler is a rotating cylindrical vessel which indirectly cools the PDF™ using internal cooling-water tubes and a tumbling action to accomplish the heat exchange. The unit was found to be a very efficient heat exchanger, and few mechanical or operating problems were encountered. Several temporary modifications were made to the PDF™ cooler in late 1992 in an effort to improve PDF™ stability using in-plant equipment. These modifications included the addition of a fan, ductwork, and entrained fines removal equipment to circulate a controlled oxygen atmosphere through the cooler. These modifications proved unsuccessful, and it was determined that a separate, sealed vessel would be required to deactivate PDF™. Other modifications made to the unit, however, were more successful. The original design of the ENCOAL® plant placed the rehydration step in the process at the top of the PDF™ silo, spraying water on the PDF™ as it dropped vertically into storage. This technique proved to be inconsistent, as it was difficult to obtain uniform distribution of water on the PDF™ and there was not adequate mixing as PDF™ entered the silo. The cooler was modified to include a small water lance and spray nozzle to inject rehydration water into the interior of the unit. Quality greatly improved with the relocation of the rehydration spray to the interior of the cooler, the distribution of rehydration water, and the consistency of PDF™ moisture.

3.2.7 Quench Tower

The quench tower in the ENCOAL® plant is located where the overhead gas from the pyrolyzer is cooled to form CDL™. One problem did occur in the column inlet piping and gas distributor. An oily mixture of coal fines and heavy pitch would build up at the column-inlet distributor. This accumulation caused several plant shutdowns and many hours of cleanup in the piping. A revised distributor eliminated the problem, and the plant operated for nearly 2 years without measurable buildup. Prior to that, the piping required cleaning on about 3-month intervals.

3.2.8 Electrostatic Precipitators

As a result of the less than optimum efficiency of the quench tower, much of the liquid condensation took place in the precipitators. Numerous plant shutdowns were a result of failed insulators in all three ESP units. ENCOAL® worked in conjunction with the ESP manufacturer to establish the cause of the failures. Several modifications were implemented, solving the operational difficulties with the ESPs.

- New, non-glazed ceramic insulators were fabricated and installed.

- Heating blankets and external insulation were added to maintain the hot surface of the insulators , thus preventing condensation on the insulator surface.

- Thermocouples, equipped with alarms, were installed to monitor the temperature of the insulator cans.

- The flows through the three ESPs were balanced to ensure uniform loading.

- A nitrogen purge was added to all insulator mounts to keep CDL™ from condensing on the insulators' surface.

3.2.9 CDL™ Handling and Storage

The only modification made to the original CDL™ handling and storage systems was the removal of the loadout flow meter after loading the first rail car. The meter fouled with CDL™ and became inoperable. It was decided that this high-maintenance instrument should be replaced, and a system of tank-car measurement and weighing of the cars was utilized for all further shipments. The loadout pump was also relocated from the loadout area to the CDL™ storage tank. Insufficient suction head of the pump necessitated its relocation closer to the storage tank.

3.2.10 Process Fans

Both the dryer and the pyrolyzer fans were found to operate acceptably, as designed, for the process flow and temperature conditions, but were grossly inadequate in terms of sealing the process gases. Several iterations were made on sealing the units, and finally an ENCOAL® "home-made" packing-gland-type seal with high temperature grease was found to be the best and longest-lasting seal. Today, a carbon-gland seal with a nitrogen purge is used on the suction side of the fan, and a packing-gland grease seal is used in the pressure side.

3.2.11 Combustors

Control of the combustors was found to be difficult during start-up. The transition from secondary air to primary air in the combustor ramping sequence was not smooth. Once the combustors were ramped past the transition point, the air control would improve, but the fuel-to-air ratios would fluctuate. An 8-inch trim control valve was added to both the pyrolyzer and dryer primary air intakes, and this improved stability of the combustor air flows. Programming changes were also made to both combustors that allowed natural gas flow to follow the combustion air flow rates. This change was necessary to dampen oscillations and prevent oxygen excursions resulting from improper air-to-fuel ratios.

3.2.12 Purge-Gas Treatment

The sodium-carbonate-solution sulfur-recovery scrubber system in use at the ENCOAL® plant is another system that has worked very well and has not required major modifications.

3.2.13 Dust Scrubbers

Operation of the two original raw-coal-dust scrubbers proved that the patented design of these units worked very well to collect dust from conveyor transfer points. However, during startup and shutdown conditions, there are times when the facilities are not operating at design conditions, and dried, underpyrolized coal (off-specification PDF™) is produced. This condition led to excessive amounts of dust at the PDF™ transfer points, early on in plant operation. Two additional dust scrubbers were therefore installed to gather dust from the PDF™ s-belt, PDF™ cooler, and the PDF™ transfer points.

3.2.14 PDF™ Finishing

Extensive testing and plant modification was done in the effort to stabilize the PDF™ product using in-plant equipment. The addition of the VFB system in 1993 was to have accomplished this task, but additional measures were required. In order to produce PDF™ for utility test burns "pile-layering" on the ground was utilized. This method is labor intensive and impacts PDF™ quality.

A PDF™ stability task force was formed in late 1994, and several avenues were pursued in efforts to resolve the stability problems. These included spray-on additives, additional plant equipment, and changes to plant operation. The task force called upon engineers and scientists from the Pittsburgh Energy Technology Center (PETC) and the Morgantown Energy Technology Center (METC) for help in identifying areas where assistance was required. (PETC and METC combined forces as the newest national laboratory, the National Energy Technology Laboratory (NETL)). As a result of this meeting, a Cooperative Research and Development Agreement (CRADA) between ENCOAL® and PETC, and a project involving ENCOAL®, Western Syncoal, and PETC was begun. The objectives were to develop measurement methods, define reaction kinetics and mechanics, and evaluate new stabilization techniques. As a result, a Bureau of Mines test, nicknamed "Jar-O-R," was modified to measure product reactivity.

By July 1995, the task force performed successful bench-scale tests for oxidizing PDF™ at low temperatures and the team recommended the construction and testing of a Pilot Air Stabilization System (PASS) to complete the oxidative deactivation of PDF™ without drying the product. This concluded the efforts of the CRADA.

Design and installation of the PASS was completed in November 1995 and the unit operated from late November 1995 to January 1996. The PASS testing was successful—the unit processed 1/2 to1 ton of solids per hour, 24 hours per day, for 2 1/2 months. More significantly, stable PDF™ was produced for the first time and stable, uncompacted piles were made without the ground stabilization layering techniques. The resulting data were used to develop specifications and design requirements for a full-scale, in-plant, PDF™ finishing unit based on an Aeroglide tower drier design. As part of the commercialization effort, these same data were then scaled-up for application to a full commercial-scale plant. Financial restrictions delayed the fabrication and installation of an ENCOAL® plant full-scale finishing unit, but ENCOAL® continued to seek private funding for this effort.

3.3 Problems Overcome—Utilities

The original ENCOAL® plant utility systems required few modifications to bolster reliability and operability during the years of plant operation. In the spring of 1995, a permanent process-water fines removal system was installed. Other modifications were minor in nature.

3.3.1 Nitrogen

The original vaporizer serving the plant's liquid nitrogen (LIN) storage facility suffered capacity restrictions because of its natural-gas fired vaporizer. This was exchanged with the facility vendor for a circulating glycol vaporizer to provide the inert gas necessary to the support of plant start-up and purging activities. For operating safety reasons, a redundant circulating glycol system also was installed.

Other changes to the nitrogen system included the addition of a centralized distribution header and a nitrogen membrane package to generate nitrogen on-site. The membrane system has sufficient capacity to support normal plant operations, and the original LIN remains on line in parallel with the membrane system. The membrane system has reduced overall plant operating costs. It is maintained by the plant's nitrogen supplier.

3.3.2 Instrument and Utility Air

Changes were made to the air dryers to improve equipment reliability. A new heated air dryer was installed in October 1993 which utilized electric heaters to eliminate the occasional freezing of condensed water in the air-distribution system.

3.3.3 Steam System

Utility steam is provided by a 10,000 lb/hr, 135 psig (lbs per square inch) boiler, to supply steam for cleanup, emergency VFB-system purge, analyzer heat tracing, and heating for the glycol system during plant outages. This boiler is sized correctly for plant outages, but is much too large for periods of plant operation when process heat is available. A second, 1,000 lb/hr unit was installed in parallel with the main unit in 1995 for use during operating periods. This change resulted in savings in water treatment chemicals, fuel, etc.

3.3.4 Cooling Water

Modifications made to the cooling-water circulation system included the addition of chlorination and scale inhibitor systems to inhibit algae growth and scale formation, and to increase pump capacities. The high-pressure water system also was equipped with a larger pump and a spare pump to enhance system reliability.

3.3.5 Sump System

The original concept for the ENCOAL® plant included several sumps to collect various waste streams. This system caused difficulty and extensive revisions were made. A new, large drive-in sump was constructed adjacent to the PDF™ silo to serve as the ENCOAL® plant main sump collection point. Piping was reconfigured to remove bends wherever possible, and pipes were routed above ground inside the plant to facilitate maintenance of the lines.

3.3.6 Car Topper

Not included in the original ENCOAL® plant design, the car topper system was developed to aid in the transport of PDF™ in conventional coal cars. Because of the average size of the PDF™ product is 1/4 inch, a rail-car topping system was installed to apply a coat of the dust suppressant, MK, on the PDF™ in the rail cars to stop small particles from blowing out during transport. MK is a dust suppressant patented by SMC Mining Company, ENCOAL®'s former parent company (now Bluegrass Coal Development Company). This system was first utilized in 1995, and was found to be very effective in preventing PDF™ loss.

3.3.7 Vapor Recovery

Excessive odor from the plant process-water circulation and sump system in early plant operation led to the design and installation of a vapor-recovery system. Extensive ambient-air testing was done to ensure there were no harmful levels of toxic materials in the ENCOAL® plant, but odors did have a nauseating effect on some people working in the plant for extended periods. The system uses a small blower and an activated-carbon filter to collect and filter odorous air from the process-water containment areas in the plant. Once filtered, the gases are exhausted to the atmosphere outside the plant. This system has been very successful in reducing plant odors.

3.3.8 Process Water

The original purpose of the process-water system was to gather and contain all washdown and seal water that could include dissolved hydrocarbons, and use this water to slurry fines from the pyrolyzer cyclone to be injected as rehydration water on PDF™. In addition to being undersized, the contained solids would plug spray nozzles in reinjection and washing services, requiring frequent shutdowns for cleaning. The permanent process-water-fines removal equipment was installed in early 1995. The fines removal equipment was housed in a separate, contained building near the PDF™ silo. Filter cake discharged from the vacuum filter was hauled to the ENCOAL® land farm for hydrocarbon treatment as discussed below.

3.4 Environmental Modifications

ENCOAL®'s policy was to always operate in an environmentally responsible manner. The goal was to have zero citations or Notice of Violations; the original plant was designed to have no effluents other than normal coal washdown water, and no solids waste streams. Emissions were designed to be less than 100 tons per year of SO_X, NO_X, methane, particulates, or CO. As expected, the demonstration plant has provided a great learning experience in the control of environmental releases. The following list includes some of the more significant environmental modifications made to the ENCOAL® facilities.

- Solids collected in the process-water stream cannot be recovered in the product stream as originally conceived. They are very expensive to recover in the quantities produced, so a biological disposal method, or land farm, was developed.
- The requirement of atmospheric exposure for finishing PDF™ has led to a need for longer-term laydown and storage areas than was envisioned for PDF™ pile testing in the original plant concept.
- Production at less than design capacity resulted in modifications to the operating permits requested from the State of Wyoming.
- Low production delayed the need for installation of the permanent precipitate storage reservoir. This resulted in permit revisions and addition of an evaporation system to the temporary reservoir.
- Installation of a vapor recovery system was required to reduce odors. (See section 3.3.7.)

3.4.1 Air-Quality Issues

Late in 1992, ENCOAL® staff met with the WDEQ to discuss the status of plant operation, notification requirements and status of stack-gas monitoring. As a result of this meeting, a letter was sent to the WDEQ confirming the stack-gas monitoring schedule and explaining ENCOAL®'s temporary noncondensible-gas venting system installed for the PDF™ quench table. The letter, which also discussed the quench-table steam condenser tests scheduled for January 1993, was approved by WDEQ in December 1992.

In mid-1993, ENCOAL® submitted a permit application for the vapor-collection system exhaust on the process-water system. Although a permit was not required by current regulations, it was agreed that a permit would be prudent, and data were collected from plant runs to support a permit application.

Stack-gas Emissions

In October 1995, a third-party testing firm was mobilized to perform emission testing necessary to obtain ENCOAL®'s permit to operate from the WDEQ. The stack and emissions testing using DEQ-approved protocol was successfully completed in November 1995, and indicated that the plant was operating within permitted limits for NO_X, SO_X, CO, VOCs, and particulates. The SO_2 Continuous Emission Rate Monitoring System for the plant stack gas was certified as a result of this testing.

Air-Quality Permit

Revisions to the AQ permit, delayed since the beginning of Phase III by interruptions in plant operation, were reviewed by the WDEQ in March 1996, and ENCOAL® responded to the Department's questions. In mid-1996, ENCOAL® received a Notice of Completeness for its application for Section 21 AQ permit from the WDEQ. The permit included a 5-acre laydown area that was not anticipated in the original application. The application proceeded smoothly through the technical review and was formally approved in November 1996.

3.4.2 Land-Quality Issues

Permanent Precipitate Storage Reservoir

A permanent storage reservoir was a part of ENCOAL®'s original plan but, because WDEQ questioned its location, an alternative permit application was submitted modifying an existing mine sediment pond. Because the temporary pond proved to be adequate for a far longer period than had originally been believed, ENCOAL® was allowed to defer permitting and construction of the permanent pond until 1995. After core sample analysis indicated that the soils at the proposed site were acceptable for the purpose, the design for the permanent pond was completed in cooperation with the WDEQ, and the permit application was finalized in June 1995. When WDEQ determined that public notice on the permit was required, construction was deferred until 1996, and options to extend the life of the temporary pond were again evaluated. After evaluating alternatives, a system to improve the evaporation rate was installed. This system included a portable, diesel-powered pump, a floating platform, and a nozzle bank to spray the effluent into the air. It was approved by WDEQ and started up in September 1996.

The WDEQ reviewed the application for revisions to the permanent pond, and ENCOAL® responded to WDEQ questions in March 1996. At that time, a bid package for construction of the permanent reservoir was sent to potential contractor-bidders. The permit for construction cleared public comment and was sent to WDEQ's head office. Final approval for the reservoir was received in June 1996. Construction began the first week of July and continued through the end of 1996. The reservoir was commissioned for use in July 1997.

Land Farm

Early in 1993, ENCOAL® initiated discussions for construction and permitting of an onsite land farm. Conceived in response to the collection of greater amounts of process-water fines than originally anticipated, the land farm would biologically eliminate hydrocarbons from process fines prior to onsite disposal. It was intended as a temporary facility, as the ultimate plan at that time was to recover the fines back into the PDF™ solid product.

The first step in development of the land farm was the collection and testing of fines samples and the gathering of information from plant runs. In the fall of 1993, ENCOAL® reviewed a preliminary design for the land farm before submission to the WDEQ, and construction began when informal approval was received. Earthwork and underground piping were completed in November 1993, and commissioning was scheduled for mid-January 1994. Final approval was received in August 1994.

In the fall of 1996, the LQD of the WDEQ approved a permit for revisions to the land farm that included a new concrete holding area for wet fines, a higher retaining dike to increase capacity, and provisions for continuous operation with pit disposal of treated fines. The facility was commissioned in October 1996.

3.5 Key Operating Parameters

The essence of the ENCOAL™ process is the conversion of low Btu coals, such as those found in the PRB, into PDF™, a stable, low-sulfur, high-Btu fuel, similar in composition and characteristics to bituminous coal; and CDL™, a heavy, low-sulfur liquid fuel, similar in properties to heavy industrial fuel oil.

The ENCOAL™ process accomplishes these objectives in two major processing steps, followed by several less major, but important, steps. First, a drying step in which the incoming coal is heated sufficiently to drive off moisture and volatile components. Following drying, the material is subjected to pyrolysis, in which it is heated to a much higher temperature (for this coal, about 1,000°F) by means of a hot recycled gas stream. In pyrolysis, thermal cracking takes place within the structure of the coal itself which results in the release of volatile gaseous materials.

The hot solid effluent from the pyrolyzer is quenched to stop the reaction, and then subjected to a deactivation step. Deactivation was found to be necessary because, early in the ENCOAL™ project, the PDF™ was found to be somewhat pyrophoric. Deactivation is accomplished in a separate, isolated reactor where the PDF™ is partially fluidized and treated at a controlled temperature by a gas stream containing specified levels of oxygen to effect a reduction in the tendency of the material to auto-heat or ignite.

3.5.1 Acceptable Coals

Not all low-rank coals are suitable for upgrading with the LFC™ technology. In order to identify suitable candidates, the coal's physical and chemical properties are compared to technical screening criteria. Agreement with these criteria suggest that success will be achieved in the next phase of testing. These criteria are the following:

- High-moisture-content raw materials add more value when upgraded.
- Low ash content is required because the ash remains in the solid PDF™ product.
- The lower the fuel ratio (weight ratio of fixed carbon to volatile matter (ultimate analysis)), the greater the amount of volatile matter available for recovery as CDL™.

- The hydrogen- to-carbon 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 (i.e., CO_2 and CO).

- Free swelling is an important consideration concerning coal handling and processing in the drying and pyrolyzing stages of the LFC™ process.

The second step in the evaluation process employs small-sample testing of the candidate coal in a thermogravimetric analyzer, where the sample is subjected to mild gasification conditions. Fourier Transform Infrared (FTIR) spectroscopy is used to analyze the gases generated during the testing. Combining FTIR results with proximate and ultimate data for the as-received coal and the residual solid product (char) facilitates generation of a mass balance suitable for preliminary LFC™ plant design. Successful completion of this step demonstrates the technical feasibility of using the LFC™ process for upgrading the candidate coal.

A Phase II Study was the third step in the evaluation process and was intended to demonstrate the viability of a commercial-scale LFC™ project. This step employs large-scale sample testing in a Sample Preparation Unit (SPU) equipped with a CDL™ recovery system and FTIR analytical capability for gas analysis. The SPU provided the necessary quantities of liquid CDL™ and solid PDF™ for a detailed product analysis; in turn, this analysis provides data for an accurate mass balance and for product marketing assessments. In addition to a budgetary plant design and marketing study, the Phase II Study also includes operating cost analysis, plant site and infrastructure assessment, and financial analysis.

4 Post-Project Achievements

4.1 Commercial Applications

The liquid products from mild coal gasification can be readily used in existing markets in place of No. 6 fuel oil. Also, there are relatively valuable constituents in the CDL™ which could be recovered by fractionation or some other separation techniques. The solid product can be used in most industrial or utility boilers and also shows promise for iron-ore-reduction applications. The feedstock for mild gasification is being limited to high-moisture, low-heating-value coals. The potential benefits of this mild gasification technology in its commercial configuration are attributable to the increased heating value (about 12,000 Btu/lb) and lower sulfur content (per unit of fuel value) of the new solid-fuel product compared to the low-rank coal feedstock, and the production of low-sulfur liquid products requiring no further treatment for the fuel-oil market. The product fuels are expected to be used economically in commercial boilers and furnaces and to significantly reduce SO_2 emissions at industrial and utility facilities currently burning high-sulfur bituminous coals or fuel oils.

4.2 Current Commercial Status of Mild Gasification Technology

As part of its mission to develop data for a commercial plant, ENCOAL® began work in March 1995 on a commercial plant cost and economics study. Teams developed a project definition and time-line schedule, and prepared to review plant design, capital costs, operating costs, CDL™ and PDF™ marketing, and overall costs and economics of a commercial venture. By April, the heat and material balance for the commercial plant design was completed, and work on material handling, cogeneration concepts, equipment selection, and site infrastructure began. CDL™ upgrading was also studied to determine its feasibility in a commercial plant design, and upgrading studies continued through contracts with Dakota Gas and Kellogg. Mitsubishi Heavy Industries (MHI) became actively involved in August 1995, when ENCOAL® delivered an updated heat and material balance, and MHI assisted by performing preliminary engineering, cost engineering, and cost estimating for the LFC™ commercial plant modules. Preliminary subsystem design, equipment data specifications, motor list, and flow sheets for a dryer/pyrolyzer system were completed in October 1995. One month later, an initial commercial plant design was assembled for a scoping estimate, and an economics model incorporating the capital and operating costs was completed in December.

This body of information was compiled in three detailed Phase II studies completed by the TEK-KOL/MHI team: the Powder River Basin study that focuses on the North Rochelle mine site near Gillette, and two international studies on Indonesian coal mines operated by P.T. Tambang Batubara Bukit Asam (PTBA) and P.T. Berau.

The PRB Phase II Study, the culmination of work by ENCOAL®, MHI, and TEK-KOL, provided the foundation for the decision to commence permitting a commercial-size plant at the New Rochelle mine site. To that end, schedules for permit applications for air quality, industrial siting, land quality, and Forest Service use have been developed and are being followed, and a hearing with the Industrial Siting Division resulted in issuance of an industrial siting permit in February 1997. Storm water, surface-water discharge, and groundwater permits must also be obtained from the State of Wyoming, and federal permits, especially a large water-storage-reservoir permit, must be obtained.

The Indonesian studies were the culmination of over 5 years work promoting the advantages of the LFC™ process in meeting many of Indonesia's needs. The PTBA study revealed promising economics, and while the P.T. Berau coal was determined to be an excellent LFC™ process candidate, local issues, including the price of feed coal, will have to be resolved before a commercial LFC™ plant can be considered for the area. MHI and Mitsui SRC of Japan are working with TEK-KOL on continuing commercialization efforts in Indonesia and other Pacific Rim countries.

To date, three Phase II studies have been completed, and enormous opportunities await in other areas. China, the world's largest producer and consumer of coal, offers particular potential for commercialization of the LFC™ technology. Regions of China are experiencing rapid economic growth, with the concurrent appetite for electric power. The country possesses huge reserves of subbituminous coal and lignites that are promising candidates for LFC™ processing. These factors, combined with the potential for environmental problems resulting from burning large quantities of coal, especially high-sulfur coal, make China an ideal candidate for the commercial application of the LFC™ technology. China's Ministry of Coal Industry has expressed keen interest in the LFC™ technology, and TEK-KOL's representatives continue to cultivate market potential in that country.

Developments in Russia included the completion of a Phase I study in late 1995, which indicated that the coals tested were suitable for LFC™ upgrading. Work on a Phase II study is expected to begin this year, pending Russian agreement to proceed. If successful, this Russian endeavor could be the first of many projects in this country with huge potential reserves.

Other international opportunities await in the Pacific Rim, Southeast Asia, India, Pakistan, Eastern Europe, and Australia. Mixed results from coal testing and less favorable economics, however, make these areas less promising than Indonesia, China, and Russia, but background work will continue in all areas.

Domestically, Alaska, North Dakota, and Texas hold significant potential. The Beluga fields and Healy deposits in Alaska are considered promising locations for commercial LFC™ plants. Both have extensive reserves that are largely subbituminous and have low ash and sulfur, but both also involve high transportation costs. Laboratory tests of North Dakota coals from the Williston Basin have indicated that LFC™ processing would yield good quality PDF™ and CDL™, and economics appear attractive. Texas lignites have been tested at the TEK-KOL Development Center as well, and some indicate acceptable PDF™ quality and CDL™ recoveries. Existing Texas lignite mines are located close to plants designed to burn ROM material, making the export of upgraded lignites into other markets the most likely possibility.

4.3 Expected Performance of a Future Commercial Plant

The operation of the demonstration plant for over 4 years has yielded a mass of process data that is reflected in the design of a commercial plant. In a facility approximately fifteen times the capacity of the demonstration plant, (made up of three modules, each with five times the capacity of the demonstration plant), each commercial module will represent a five-to-one scale-up. Much research and testing has gone into selecting equipment for the commercial venture, in particular, tailoring the PDF™ deactivation and stabilization process equipment to fit a commercial-sized plant. A number of improvements in the production of CDL™ will also be incorporated into the larger plant design, based on production experience and research, as well as improved knowledge of marketing of that product.

ENCOAL® Corporation's newly formed company, NuCoal, L.L.C., has signed a contract with Mitsubishi International Corporation to construct a $460-million plant in Wyoming that will produce 15,000 metric tons per day. Feasibility studies also have been completed for two Indonesian projects and one Russian project.

5 Outlook for Mild Gasification Sales

5.1 Competitors

The competition for the ENCOAL™ application of the LFC™ process is embodied in any process that improves low-grade, low-sulfur, mostly western coals by driving off the moisture and other undesirable constituents, leaving a solid fuel that delivers materially more Btus per unit weight and thereby can be economically shipped over long distances for use as a compliance fuel or as a source of heat and carbon to processes such as blast furnaces and DRI processes.

Some of the current, or recent, technologies that have similarities to LFC™, or generate product with similar qualities are: a hot-water drying process developed at the University of North Dakota, the WECO advanced coal cleaning process; DOE's Lignipel process, the Anaconda, or ARCO process, and the Rosebud Syncoal CCT Project.

A steam-drying/mild pyrolysis process that now is in operation at commercial scale—also near Gillette, Wyoming—is the Koppelman, or K-fuel process, which drives off moisture under high temperature and pressure, then reabsorbs the non-water liquids into the dry solids, thus eliminating dusting and pyrophoricity problems. The K-fuel process, requiring high temperatures and pressures, is more capital intensive than LFC™.

5.2 Markets

Based upon market research studies, TEK-KOL believes that 80 percent of the PDF™ production from a three-module LFC™ commercial plant could be sold in the utility market. The opportunity represented by PDF™ metallurgical markets represents at least 20 percent of the plant capacity. For the purposes of the study, average PDF™ net back revenues in the range of $18 to $20 per ton were used.

CDL™ continues to be of interest in the fuel oil markets, but a far more attractive option is to separate it into the four higher-value products, i.e., crude cresylic acid, pitch, refinery feedstock, and oxygenated middle distillate, on 10 percent, 30 percent, 35 percent, and 25 percent ratios, respectively. Well-defined markets exist for each of the above products, and discussions with potential customers have indicated that the CDL™ fractions may be suitable for certain of their needs. The weight averaged net back value of CDL™ utilized in this study is in the $18 to $20 per barrel range.

5.2.1 Domestic Market

Utility Markets

The U.S. electric utility market is clearly the largest market for PDF™, but a relatively small but growing market for non-coking metallurgical coals appears to provide the best opportunity for higher net back values for PDF™.

In general, the wide acceptance of PDF™ into the broad utility, metallurgical, or industrial marketplace depends on PDF™ meeting three important product handling and utilization criteria:

1. The self-ignition tendency of PDF™ must be less than that for PRB.

2. PDF™ must be less dusty than PRB.

3. PDF™ must produce flame stability.

Laboratory combustion tests and large-scale commercial burns have demonstrated that PDF™ does meet these criteria. It has been proven that PDF™ will burn very well, that it is no more dusty (and sometimes less dusty) than run-of-mine PRB, and large-scale shipments of PDF™ stabilized by the ground-spreading technique have shown no tendencies toward self-heating.

Specifically, 53 power plants operated by 34 utilities were identified as the "best potential" market for PDF™ on the basis of requirements for low ash fusion, high Btu, low sulfur content, and favorable transportation economics. Another 37 power plants are considered "challenging" sales targets because the normal coal qualities required in these cases are somewhat different than those of PDF™.

A number of other factors could significantly impact the size and value of the potential utility market for PDF™, including observations made of the positive burning characteristics and reduction of NO_X emissions through the use of PDF™.

Metallurgical Markets

PDF™ has market opportunities in the steel industry where a declining U.S. coke industry is swinging the pendulum toward increasing imports of metallurgical coke from abroad, particularly from the People's Republic of China.

Potentially significant market opportunities exist in the following areas: straight substitution of PDF™ for a portion of the coke normally used; the utilization of PDF™ in place of other coals for pulverized coal injection and granular coal injection in a conventional blast furnace; and the use of PDF™ in direct reduction processes such as COREX, Hismelt, AISI direct steel making, Fastmet, the DIOS process, and the Romelt process. Coke will not be totally eliminated from the conventional blast furnace because of its role in providing porosity in the bed and physically supporting the stockline, but can certainly be reduced in quantity, using only enough to fulfill the supporting and porosity roles.

Tests have been performed to assess the acceptability of PDF™ in the metallurgical markets. The results showed that the reflectivity of the PDF™ is more like that of bituminous coals than the subbituminous PRB coals. Also, grinding-mill performance with PDF™ was found to be 60-percent better, and flowability tests indicated that PDF™ is suitable for dense-phase pneumatic conveying.

Transportation Issues

The most significant transportation issue that would affect the marketing of PDF™ is creating access to more than one railroad. For the commercial plant study, this problem is solved by the proximity of the plant to both the Burlington Northern Santa Fe, and the Union Pacific Railroads. This assures access to the most competitive transportation rates out of the Powder River Basin.

5.2.2 International Market

No formal information has been found specifically addressing the international market for the ENCOAL® Process, but it is an excellent candidate wherever the need to utilize low-rank coal coexists with a need for a high-Btu solid fuel, and where there are applications that can utilize the liquid by-product either as a fuel directly, or as a source of the specific chemicals that it contains.

6 Acronyms and Abbreviations

AEP	American Electric Power
AQ	air quality
Btu	British thermal unit
CA	Cooperative Agreement
CCT	Clean Coal Technology
CDL™	coal-derived liquids
CO	carbon monoxide
CO_2	carbon dioxide
CRADA	Cooperative Research and Development Agreement
DOE	U.S. Department of Energy
DRI	direct reduction of iron
EPDC	Electric Power Development Company (Japan)
ESP	electrostatic precipitator
FTIR	Fourier Transform Infrared Spectroscopy
LFC™	Liquids from Coal
LIN	liquid nitrogen
LQD	Land Quality Division (of WDEQ)
METC	Morgantown Energy Technology Center (now NETL)
MHI	Mitsubishi Heavy Industries
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NO_X	Nitrogen oxides
PASS	Pilot Air Stabilization System
PDF™	process-derived fuel
PDU	process-development unit
PETC	Pittsburgh Energy Technology Center (now NETL)
PRB	Powder River Basin
PTBA	P.T. Tambang Batubara Bukit Asam
ROM	run-of-mine
SO_X	sulfur oxides
SO_2	sulfur dioxide
SPU	Sample Preparation Unit
VOCs	volatile organic compounds
VFB	vibrating fluidized bed
WDEQ	Wyoming Division of Environmental Quality

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