International Forum

Delegate Introduction:

Ted Atwood,
Office of Clean Coal Technology/
U.S. Department of Energy
Robert Munn/Albert Doub,
United States Energy Association

Delegations from Eastern European countries, the Russian Federation and Asian countries were available for discussions regarding the strategic plans for coal and potential opportunities for coal and clean coal technologies in their respective countries.

Session 5

Coal Combustion/ Coal Processing

Co-Chairs:
Robert M. Kornosky,
Pittsburgh Energy Technology Center/
U.S. Department of Energy
Douglas M. Jewell,
Morgantown Energy Technology Center/
U.S. Department of Energy

ROSEBUD SYNCOAL® PARTNERSHIP ADVANCED COAL CONVERSION PROCESS DEMONSTRATION PROJECT

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ROSEBUD SYNCOAL PARTNERSHIP ADVANCED COAL CONVERSION PROCESS DEMONSTRATION PROJECT

INTRODUCTION

Rosebud SynCoal® Partnership's Advanced Coal Conversion Process (ACCP) is an advanced thermal coal drying process coupled with physical cleaning techniques to upgrade high-moisture, low-rank coals to produce a high-quality, low-sulfur fuel.

The coal is processed through two vibrating fluidized bed reactors that remove chemically bound water, carboxyl groups, and volatile sulfur compounds. After drying, the coal is put through a deep-bed stratifier cleaning process to effect separation of the pyrite rich ash.

The process enhances low-rank western coals with moisture contents ranging from 25-55%, sulfur contents between 0.5 and 1.5%, and heating values between 5,500 and 9,000 Btu/lb. The upgraded stable coal product has moisture contents as low as 1%, sulfur contents as low as 0.3%, and heating values up to 12,000 Btu/lb.

Construction of the 300,000 ton per year (tpy) demonstration plan adjacent to Western Energy Company's Rosebud mine unit train loadout facility near the town of Colstrip in southeastern Montana was completed in 1992. Rosebud SynCoal's demonstration plant is sized at about one-tenth the projected throughput of a multiple processing train commercial facility.

Demonstration operations began in April 1992 and are continuing. Initial operations discovered the normal variety of equipment problems which delayed operational and process testing. As operational testing has proceeded, the product quality issues that have emerged are dustiness and stability. The SynCoal® product has met the BTU, moisture and sulfur specifications. The project team is continuing process testing and is working toward resolution of the operational and process issues.

The ACCP Demonstration Facility is a U.S. Department of Energy (DOE) Clean Coal Technology Program Project with 50% funding from the DOE and 50% from the Rosebud SynCoal Partnership.

The Rosebud SynCoal Partnership is a venture involving Western SynCoal Company and Scoria Inc.. Western SynCoal is a subsidiary of Western Energy Company (WECo) which is a subsidiary of Entech Inc., Montana Power Company's non-utility group. Scoria Inc is a subsidiary of NRG Energy Inc., Northern States Power's non-utility group.

STATUS OF DEVELOPMENT

Much of the early ACCP development was performed using a small, 150 pound per hour pilot plant located at the Mineral Research Center, south of Butte, Montana. Up to 100 ton lots were produced to assess shipping and handling stability as well as chemical characteristics. A variety of coals and process conditions were tested to determine the process capabilities.

Development is continuing as construction and startup has been completed and demonstration operation is continuing at the 300,000 ton per year demonstration plant at Western Energy's Rosebud Mine near Colstrip, Montana. Many of the demonstration components are near commercial size. A larger commercial plant would use multiple modules.

PROCESS DESIGN DESCRIPTION

In general, the ACCP is a drying and conversion process using low pressure, superheated gases to process coal in vibrating fluidized beds. Two vibratory fluidized processing stages are used to heat and dry the coal followed by a water spray quench and a vibratory fluidized stage to cool the coal. The solid impurities are then removed from the dried coal using pneumatic separators. Other systems servicing and assisting the coal conversion system are:

Product Handling
Raw Coal Handling
Emission Control
Heat Plant
Heat Rejection
Utility and Ancillary

The nominal throughput of the demonstration plant is 450,000 tpy (1,640 tpd) of raw coal, providing 270,000 tpy (988 tpd) of coarse coal product and 66,000 tpy (240 tpd) of coal fines (minus 20 mesh). The fines are to be collected and sold, giving a combined product rate of 335,000 tpy (1,228) tpd of high-quality, clean coal product. The central processes are depicted in Figure 1, the Process Flow Schematic.

Coal Conversion

The coal conversion is performed in two parallel processing trains. Each consists of two 5-feet wide by 30-feet long vibratory fluidized bed dryer/reactors in series, followed by a water spray quench section and a 5-feet wide by 25-feet long vibratory cooler. Each processing train is fed 1,139 pounds per minute of sized coal.

In the first-stage dryer/reactors, the coal is heated using recirculated combustion gases, removing primarily surface water from the coal. The coal exits the first-stage dryer/reactors, at a temperature slightly above that required to evaporate water, and is gravity fed into the second-stage dryer/reactors. Here the coal is heated further using a superheated gas stream, removing water trapped in the pore structure of the coal, and promoting decarboxylation. The superheated gases used in the second stage are actually produced from the coal. The make-gas from the second stage system is used as an additional fuel source in the process furnace, incinerating all the hydrocarbon gases produced in the process. The particle shrinkage that liberates ash minerals and imparts a unique cleaning characteristic to the dried coal also occurs in the second stage. As the coal exits the second-stage dryer/reactors, it falls through vertical quench coolers where process water is sprayed onto the coal to reduce the temperature. The water vaporized during this operation is drawn back into the second-stage exhaust gas. After quenching, the coal enters the vibratory coolers where the coal is contacted by cool inert gas. The coal exits the cooler at less than 150 degrees Fahrenheit (F) and is conveyed to the coal cleaning system. The cooler exit gas is cooled by direct contact with water prior to returning to the vibratory fluidized coolers.

Coal Cleaning

The coal entering the cleaning system is screened into four size fractions: plus 1/2 inch, 1/2 by 1/4 inch, 1/4 inch by 6 mesh, and minus 6 mesh. These streams are fed in parallel to four deep-bed stratifiers (stoners), where a rough specific gravity separation is made using fluidizing air and a vibratory conveying action. The light (lower specific gravity) streams from the stoners are sent to the product conveyor; the heavy streams from all but the minus 6 mesh stream are sent to gravity separators. The heavy fraction of the minus 6 mesh stream goes directly to the waste conveyor. The gravity separators, again using air and vibration to effect a separation, each split the coal into light and heavy fractions. The light stream is considered product; the heavy or waste stream is sent to a 300 ton storage bin to await transport to an off site user or alternately back to a mined out pit disposal site. The dry, cool, and clean product from coal cleaning enters the product handling system.

Product Handling

Product handling conveys the clean product coal to two 6,000 ton capacity concrete silos and allows unit train loading with the mine's tipple loadout system.

Raw Coal Handling

Raw coal from the existing stockpile is screened to provide 1 x 1/4 inch feed for the ACCP process. Coal rejected by the screening operation is conveyed back to the active stockpile. Properly sized coal is conveyed to a 1,000 ton raw coal storage bin which feeds the process facility.

Emission Control

The fugitive dust from the coal cleaning system is controlled by placing hoods over the generation sources and conveying the dust laden air to fabric filter(s). The bag filters can remove 99.99 percent of the coal dust from the air before discharge. All fines report to a fines handling system than can briquette or cool the fines for product sales or make a slurry for disposal.

Sulfur dioxide emission control philosophy is based on injecting dry sorbent into the ductwork to minimize the release of sulfur dioxide to the atmosphere. The sorbent, sodium bicarbonate, is injected into the first stage dryer gas stream as it leaves the first stage dryers to maximize the potential for sulfur dioxide removal while minimizing reagent usage. The sorbent, having reacted with sulfur dioxide, is removed from the gas streams in the particulate removal systems. A 60 percent reduction in sulfur dioxide emissions should be realized.

Heat Plant

The heat required to process the coal is provided by a natural gas fired process furnace. This system is sized to provide a heat release rate of 58 MM BTU/hr. Process gas enters the furnace and is heated by radiation and convection from the burning fuel. Process make gas from coal conversion is used as fuel in the furnace. A commercial scale plant would most likely use a coal fired process furnace due to the much lower energy cost of coal.

Heat Rejection

Heat rejection from the ACCP is accomplished mainly by releasing water and flue gas to the atmosphere through the exhaust stack. The stack design allows for vapor release at an elevation great enough that, when coupled with the vertical velocity resulting from a forced draft fan, maximize the dissipation of the gases. Heat removed from the coal in the coolers is rejected using an atmospheric induced-draft cooling tower.

Utility and Ancillary Systems

The coal fines that are collected in the conversion, cleaning and material handling systems are gathered and conveyed to a surge bin. The coal fines are then briquetted and returned to the product stream.

The common facilities include a plant and instrument air system, a fire protection system, and a fuel gas supply and distribution system.

The power distribution system includes a 15 KV service, a 15 KV/5 KV transformer, a 5 KV motor control center, two 5 KV/480 V transformers, two 480 V load distribution centers, and six 480 V motor control centers.

Control of the process is fully automated including duel control stations, duel programmable logic controllers, distributed plant control, and data acquisition hardware.

PRODUCT CHEMISTRY

Rosebud SynCoal's Advanced Coal Conversion Process yields a synthetic solid fuel that represents an evolutionary step in the coalification process. Western lignite and sub-bituminous coals are converted by the thermal environment of the ACCP to a higher rank fuel.

The ACCP changes the chemical composition and structure of the coal feedstock. The changes include:

- Increased higher heating value;
- Increased aromaticity;
- Increase fixed carbon;
- Decreased moisture content;
- Decreased sulfur content per million Btus;
- Decreased ash content per million Btus;
- Decreased hydrogen to carbon ratios;
- Decreased oxygen to carbon ratios; and
- Decreased oxygen functional groups.

The above changes are the result of the thermo-chemical reactions induced by the ACCP and result in the upgraded synthetic coal product.

The average analyses of the coal feedstock and upgraded product from the demonstration plant are shown in Table 1. The first section of the table shows standard proximate and ultimate coal analyses of the coal feedstock and the synthetic coal product. The second section of the table shows petrographic and additional analysis showing the upgrading of coal through the process.

Moisture is essentially eliminated from the coal during the ACCP. This moisture removal is due to thermal dehydration of the coal particle and the chemical condensation reactions which the feedstock experiences during its residence in the high temperature environment of the second-stage reactor bed.

The moisture-free analysis of the feedstock and the upgraded product also show that, to a large extent, both the volatile matter and the fixed carbon content is retained in the SynCoal product. This phenomenon is significant and desirable, because normally raw coal, when subjected to the temperatures of the ACCP, would undergo devolatilization and substantial gasification.

The reduction in total sulfur is due primarily to the mechanical removal of pyrites during the cleaning step. However, the ability to remove these pyrites is a result of the chemical repolymerization and consequent shrinkage of the organic components of the coal, which causes fracture release of the ash or mineral components. A small amount of organic sulfur is volatilized from the coal in the form of hydrogen sulfide (H_2S) during the upgrading process.

PROJECT STATUS

Construction of Rosebud SynCoal's ACCP Demonstration Facility was completed during the first quarter of 1992 at a total cost of approximately $35 million. Initial equipment startup was conducted from December 1991 through March 1992. Initial operations discovered the normal variety of equipment problems. The project's startup and operations groups worked together to overcome the initial equipment problems and achieve an operating system. The fines handling equipment was undersized originally and required a significant modification to expand the capability of this system. This modification was completed in August 1993. The lack of fines handling capacity prevented the facility from achieving full production rate and limited operating hours due to frequent fines handling equipment failures. The new fines handling system is expected to allow full production and more reliable operations.

The SynCoal® product has displayed a tendency towards self heating that was not expected. The project's technical and operating team continues to follow an extensive process testing program in order to determine the cause of the product's lack of stability. A number of approaches have been partially successful; however, to date, the demonstration product has not met the level of resistance to spontaneous combustion that was apparent in the earlier pilot plant work. This has reduced the storage life and as a result delayed the full-scale test burn program; therefore, a more limited test burn program is being planned at Montana Power's Corette station. A significant amount of handling and storage testing has been conducted in preparation for the anticipated full-scale test burn program. The results from these tests have been positive and the project team is looking forward to moving on with the full-scale combustion test program.

SynCoal's engineering team has been developing a proprietary product stabilization process step which has shown good promise at bench scale. Currently, a 500 pound per hour reactor is being tested and, if successful, a modification to the demonstration plant is planned for next year.

PROJECTIONS FOR THE FUTURE

The Rosebud Syncoal Partnership intends to commercialize the process by both preparing coal in their own plants and by licensing to other firms. The target markets are primarily the U.S. utilities, the industrial sector and Pacific Rim export market. Current projections suggest the utility market for this quality coal is approximately 60 million tons per year. The Partnership's goal is to start construction on a commercial facility designed to produce 3 million tons per year in 1995.

CONCLUSION

The ACCP is a relatively simple, low pressure, medium temperature coal drying and conversion process. The synthetic upgraded coal product exhibits the characteristics of reduced equilibrium moisture level, reduced sulfur content and increased heating value. The SynCoal product retains a majority of its volatile matter and demonstrates favorable ignition characteristics.

Although some difficulties have been encountered, SynCoal's technical and operating team are resolving the initial problems. The ACCP Demonstration program is continuing with a complete team effort involving all three of the major participants. It is expected that the ACCP demonstration will continue to produce test results over the next couple of years.

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SynCoal® is a registered trademark of the Rosebud SynCoal Partnership.

TABLE 1

FEEDSTOCK AND SYNCOAL ANALYSES

	ROSEBUD MINE			
Proximate Analysis	Rosebud Feedstock	MF*	SynCoal* Product	MF*
% Moisture	24.1	--	1.0	--
% Volatile Matter	27.4	36.1	37.6	38.0
% Fixed Carbon	37.1	48.9	51.6	52.0
% Ash	11.4	15.0	9.7	9.9
BTU/lb.	8,421	--	11,832	--
% Increase in BTU/lb.			40.51	
Ultimate Analysis				
% Carbon	49.18		67.71	
% Hydrogen	6.57		5.20	
% Oxygen	30.99		15.78	
% Nitrogen	0.69		1.04	
% Sulfur	1.18		0.48	
% Organic Sulfur	0.50		0.40	
Petrographic Analysis				
% Huminite	77		81	
% Exinite	5		2	
% Inertinite	18		14	
Reflectance	0.42		0.51	
Surface area (cm^2/g)	288		55**	
H/C Ratio	1.60		0.92*	
O/C Ratio	0.24		0.09*	
Apparent Aromaticity		0.46		0.66*
% COOH	0.74		0.53*	
Classification				
ASTM	Sub-bituminous C		High-volatile bituminous	
C				

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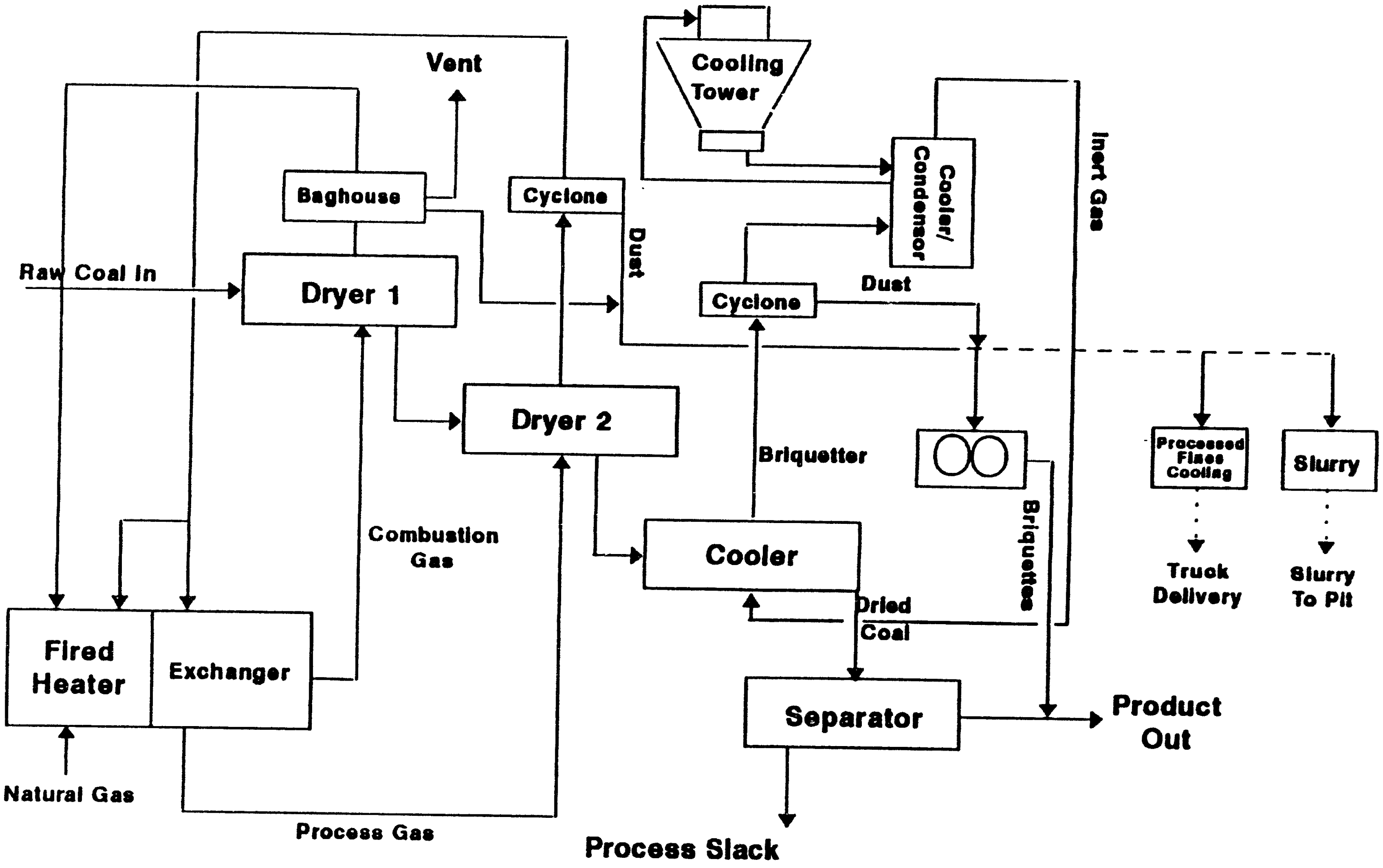
* MF indicates moisture free proximate analysis of feedstock and Coal Product.

** Indicates increased coal rank of Coal Product.

Process Flow Diagram



Flowdgm

START-UP AND OPERATION OF THE ENCOAL MILD COAL GASIFICATION PROJECT

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ABSTRACT

ENCOAL Corporation, a wholly owned subsidiary of SMC Mining Company, which is a subsidiary of Zeigler Coal Holding Company, has completed the start-up and initial operation of its 1000 ton per day Liquids From Coal (LFC) plant at Triton Coal Company's Buckskin Mine near Gillette, Wyoming. The plant has now produced several thousand tons of Process Derived Fuel (PDF), an upgraded coal product similar to a bituminous coal with very low sulfur. In addition, about 5000 bbls. of Coal Derived Liquid (CDL) have also been produced. CDL resembles a very low sulfur #6 fuel oil.

The plant has completed 15 runs and logged over 1400 hours of operation on Powder River Basin (PRB) coal. Some major pieces of equipment have run for more than 2300 hours. Most of the objectives of these runs have been related to plant testing, equipment shakedown and data gathering. Small quantities of CDL have been shipped to a customer, but no PDF has been delivered. It has all been used for laboratory and on site testing. The plant is currently shut down for a major modification - the addition of a continuous product finishing step that has only been done by batch methods so far.

This paper summarizes the project activities to date. A brief discussion of background information including the plant and process design is presented. Also included is a discussion of the modifications to the LFC plant already completed or underway. While no final conclusions can be drawn at this time as to the commercial application of the LFC technology, a summary of the operating results and product testing is presented.

BACKGROUND INFORMATION

Objectives

Beneficiated low sulfur Powder River Basin subbituminous coals should be one component in the strategy to reduce sulfur dioxide emissions from power plants throughout the world. In the ENCOAL Project, beneficiation is being accomplished by application of the Liquids From Coal (LFC) process. LFC Technology uses a mild gasification process, or mild pyrolysis as some know it, to produce a liquid fuel as well as a solid fuel. Thus dependence on imports of foreign oil could also be reduced by the installation of commercial scale LFC plants.

ENCOAL's overall objective for the Project is to further the development of full sized commercial plants using the LFC Technology. In support of this overall objective, the following goals were established:

- 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
- Support future LFC Technology licensing efforts.

This paper highlights several areas of immediate interest to potential customers and licensees. The first is the status of the ENCOAL plant and the operating experience so far. A second area is the product properties from recent long, continuous runs. Another area includes the results of combustion tests on samples taken from some of the initial ENCOAL Plant runs. In addition, the LFC Technology is reviewed with emphasis on [illegible] cess steps successfully demonstrated.

General Description

ENCOAL Corporation is a wholly owned subsidiary of SMC Mining Company (SMC) which in turn is a subsidiary of the Zeigler Coal Holding Company. ENCOAL has entered into a Cooperative Agreement with the United States Department of Energy (DOE) as a participant in Round III of the Clean Coal Technology Program. Under this agreement, the DOE is sharing 50% of the cost of the ENCOAL Mild Coal Gasification Project. A license for the use of LFC Technology has been granted to ENCOAL from the technology owner, TEK-KOL, a partnership between SGI International of La Jolla, California and SMC Mining Company.

The ENCOAL Project encompasses the design, construction and operation of a 1,000 ton per day mild coal gasification demonstration plant and all required support facilities. The Project is located near Gillette, Wyoming at Triton Coal Company's Buckskin Mine. Existing roads, railroad, storage silos and coal handling facilities at the mine significantly reduced the need for new facilities for the Project.

A substantial amount of pilot plant testing of the LFC process and laboratory testing of PDF and CDL was done.[1] The pilot plant tests showed that the process was viable, predictable and controllable and could produce PDF and CDL to desired specifications. Key dates and activities in bringing the project from the pilot plant stage to its current status are:

- Through early 1987: Development of the LFC process by SGI.
- Mid 1987: SMC joined with SGI on further development.
- Mid 1988: Feasibility studies, preliminary design, economics and some detailed design work by SMC.
- June 1988: Submittal of an application to the State of Wyoming for a permit to construct the plant - Approved July 1989
- August 1989: ENCOAL Project submitted to the DOE as part of Round III of the Clean Coal Technology Program.
- December 1989: Project selected by the DOE for funding.
- September 1990: Cooperative Agreement signed. Contract awarded to The M. W. Kellogg Company for engineering, procurement and construction.
- October 1990: Ground breaking at the Buckskin Mine site.
- July 1991: Basic design work completed and construction well underway.
- April 1992: Mechanical completion - commissioning begun.
- June 1992: First 24 hour run in which PDF and CDL were produced.
- November 1992: SMC Mining Company and its subsidiaries, including ENCOAL, acquired by Zeigler
- April 1993: ENCOAL achieves two week continuous run
- June 1993: Plant shut down for major modifications.

The plant produces 500 tons/day of a solid Process Derived Fuel (PDF), which has the high heat content of Eastern coals but with low sulfur content, and 500 barrels/day of a Coal Derived Liquid (CDL), which is similar to a low sulfur Number 6 fuel oil. While CDL is different from petroleum derived oils in its aromatic and oxygen content, it has a low viscosity at operating temperatures and is comparable in flash point and heat content. The plant is supplied at the rate of 1,000 tons/day of subbituminous PRB coal.

Not a pilot plant or a "throw-away", ENCOAL's processing plant is designed to commercial standards for a life of at least 10 years. It uses commercially available equipment as much as possible, state of the art computer control systems, BACT for all environmental controls to minimize releases and a simplified flowsheet to make only two products matched to existing markets. The intent is to demonstrate the core process and not make the project overly complicated or expensive.

The ENCOAL Project is demonstrating for the first time the integrated operation of several unique process steps:

- Coal drying on a rotary grate using convective heating
- Coal devolatilization on a rotary grate using convective heating
- Hot particulate removal with cyclones

- Integral solids cooling and deactivation/passivation
- Combustors operating on low Btu gas from internal streams
- Solids stabilization for storage and shipment
- Computer control and optimization of a mild coal gasification process
- Dust suppressant on PDF Solids.

The product fuels are expected to be used economically in commercial boilers and furnaces and to reduce sulfur emissions significantly at utility and industrial facilities currently burning high sulfur bituminous fuels or fuel oils.

Process Description

Figure 1 is a simplified flow diagram of ENCOAL's application of the LFC Technology. The process involves heating coal under carefully controlled conditions. Nominal 3" x 0" run-of-mine coal is conveyed from the existing Buckskin Mine to a storage silo. The coal from this silo is screened to remove oversize and undersize materials. The 2" x 1/8" sized coal is fed into a rotary grate dryer where it is heated by a hot gas stream. The residence time and temperature of the inlet gas have been selected to reduce the moisture content of the coal without initiating chemical changes. The solid bulk temperature is controlled so that no significant amounts of methane, carbon monoxide or carbon dioxide are released from the coal.

The solids from the dryer are then fed to the pyrolyzer where the temperature is further raised to about 1,000°F on another rotary grate by a hot recycle gas stream. The rate of heating of the solids and their residence time are carefully controlled, because these parameters affect the properties of both solid and liquid products. During processing in the pyrolyzer, all remaining free water is removed, and a chemical reaction occurs which results in the release of volatile gaseous material. Solids exiting the pyrolyzer are quickly quenched to stop the pyrolysis reaction, then are further cooled indirectly and transferred to a surge bin. Because the solids have no surface moisture and, therefore, are likely to be dusty, a dust suppressant is added as PDF leaves the product surge bin.

The gas produced in the pyrolyzer is sent through a cyclone for removal of the particulates and then cooled to stop any additional pyrolysis reactions and to condense the desired liquids. Only the CDL is condensed in this step; the condensation of water is avoided.

Most of the residual gas from the condensation unit is recycled directly to the pyrolyzer, while some is first burned in the pyrolyzer combustor before being blended with the recycled gas to provide heat for the mild gasification reaction. The remaining gas is burned in the dryer combustor, which converts sulfur compounds to sulfur oxides. Nitrogen oxide emissions are controlled via appropriate design of the combustor. The hot flue gas from the dryer combustor is blended with the recycled gas from the dryer to provide the heat and gas flow necessary for drying.

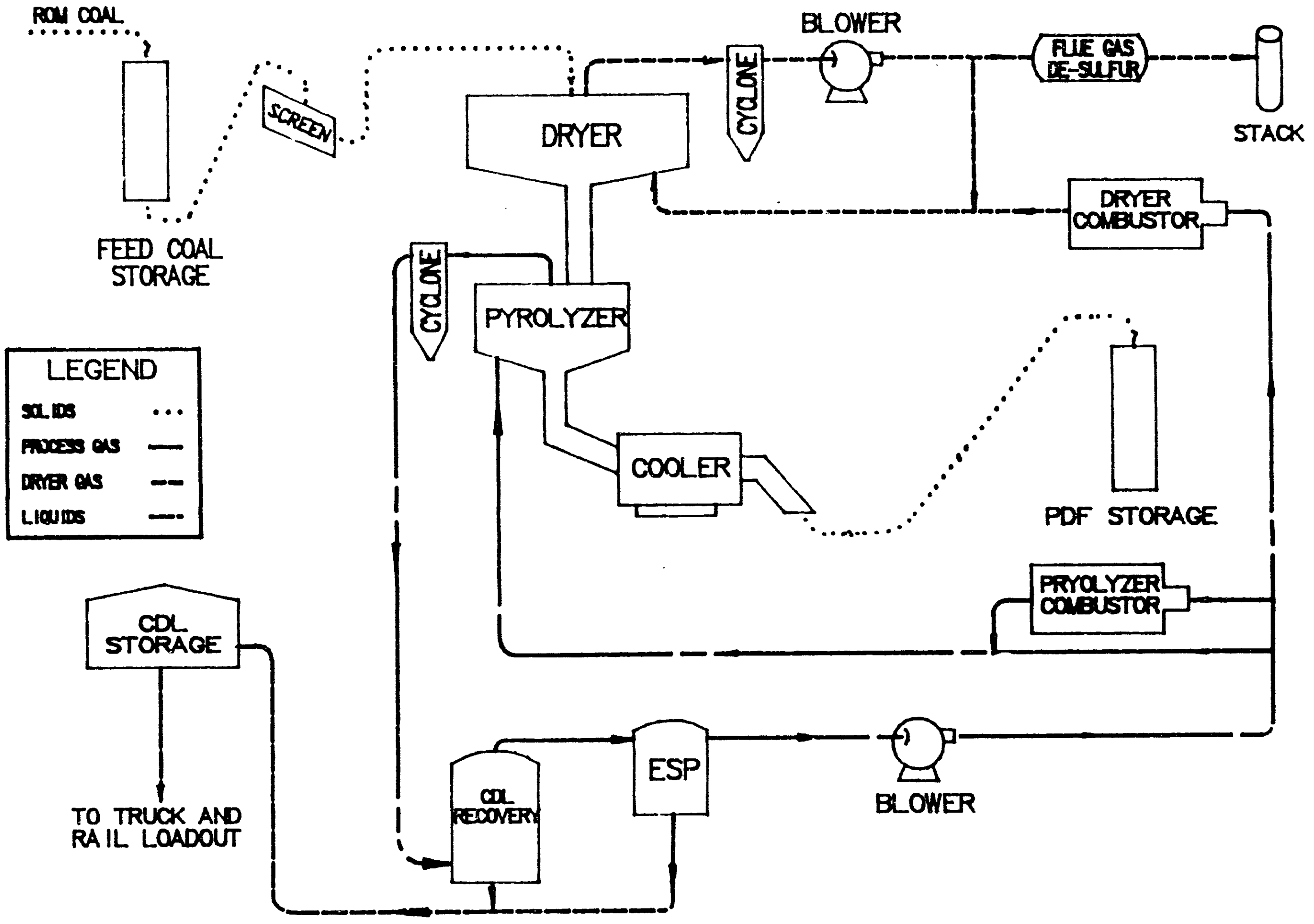


FIGURE 1. SIMPLIFIED FLOW DIAGRAM

The off-gas from the dryer is treated in a wet gas scrubber and a horizontal scrubber, both using a water-based sodium carbonate solution. The wet gas scrubber recovers the fine particulates that escape the dryer cyclone, and the horizontal scrubber removes most sulfur oxides from the flue gas. The treated gas is vented to a stack. The spent solution is discharged into a pond for evaporation. The plant has several utility systems supporting its operation. These include nitrogen, steam, natural gas, compressed air, bulk sodium carbonate and a glycol/water heating and cooling system.

Figure 2 is a plot plan for the ENCOAL Plant facilities including the Buckskin Mine rail loop which is used for shipping products.

START-UP AND MODIFICATIONS

During the final months of construction, ENCOAL developed a Start-up Plan and strategy for the first start-up and, separately, for subsequent start-ups. In general, the following steps are followed:

- Commissioning of plant or changes
- Complete pre-start checklist
- Complete valve alignment procedure
- Proceed with start-up sequence
- Perform run plan and testing
- Follow shut-down procedure

Seventy-eight steps over a period of 36 hours are required to achieve full operation on coal. Much of this time is spent ramping the temperatures up to a hot stand-by condition (ready for coal). The plant start-up is computerized and has been successfully tested on automatic through the start-up of all major equipment. Ultimately, the entire sequence of start-up and shut-down will be automated.

The start-up of the ENCOAL plant facilities has been typical of what one would expect from a first-of-its-kind technology application. Along with the 15 successful plant runs there have been many more false starts or planned partial starts. Valuable information is gained from every run. successful or not, and this information is carefully evaluated to define necessary equipment repairs, plant modifications and process adjustments.

A detailed review of equipment repairs and plant modifications through August 1992 has been presented[1]. Since that time the need for further process and equipment modifications has become evident as start-up and initial operations have progressed. These can be grouped into the following categories:

- Electrostatic precipitators (ESP)
- Material handling system

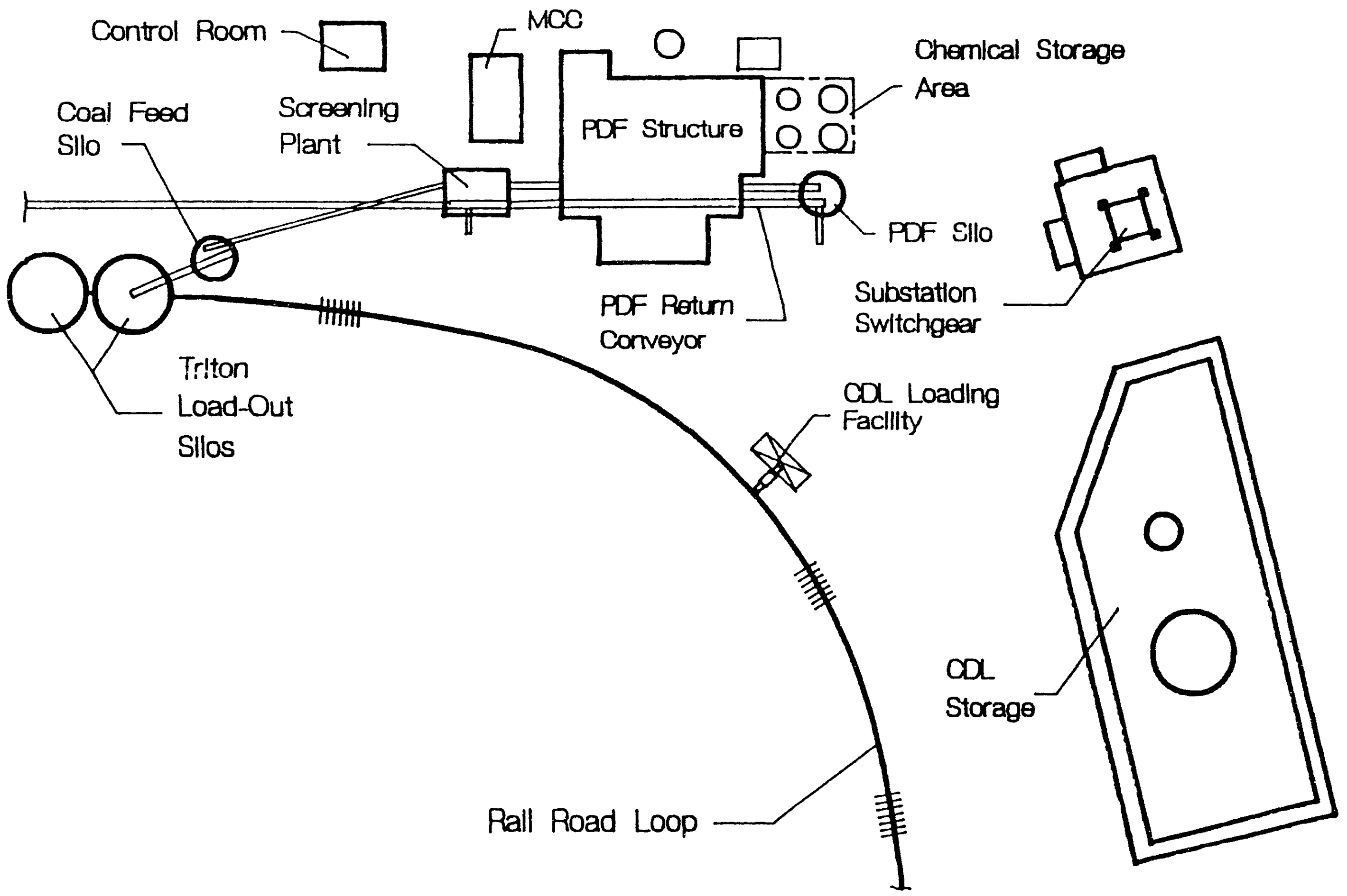


Figure 2: ENCOAL Project Plot Plan

- PDF quenching and cooling
- Dryer and pyrolyzer internal seals
- Combustor controls

Electrostatic Precipitators

Electric insulators in the three ESP's in the ENCOAL plant, in virtually all of the runs prior to April, 1993, have failed and caused plant shutdowns and upsets. Though at first thought to be an alignment problem, condensation of liquids on the insulators was eventually identified as the cause of failure. A new high alumina ceramic insulator was installed along with a new thermal blanket with temperature controls to keep the insulators hot and thus prevent condensation. In the April-June runs, for the first time, the plant ran for a total of 31 days without an insulator failure. Post shut-down inspection showed the new insulators to be clean and ready for continued service.

Material Handling System

No longer a significant problem, chute plugging and coal flow restrictions once caused plant shut-downs and interruptions. Modifications to the equipment as well as the start-up procedures have eliminated these problems. In the June run, the plant was successfully tested at the full 1000 ton per day feed rate. However, there remains a serious problem with spillage under the two vertical rubber-bucket conveyors (S-belts). Work is currently in progress on both S-belts to add a clean-up trench at the bottom and dribble control at the top.

PDF Quenching and Cooling

One of the areas in the process that had limited definition from the pilot plant studies and preliminary design work was the PDF quenching and cooling. Finishing and stabilization of the solid product is to take place in these steps, but this has proved to be elusive in actual practice. A plant test in January was set up specifically to determine if the existing plant equipment could be modified to achieve controlled cooling and stabilization. This test proved the opposite; the existing equipment was inadequate. Following the January run, a study was commissioned to develop alternatives solutions. It was decided that additional equipment would have to be added to the plant.

The study group also recommended a series of laboratory tests and vendor equipment tests using actual PDF made in the ENCOAL plant to confirm the equipment selection and sizing. A plant test plan was developed for the April run that would also confirm on a batch basis at reduced plant throughput that the proposed solution would be effective. Several hundred tons of stable PDF was produced in the April run and stored in an open stockpile on site. Additional PDF was added to the pile in the June run. At the present time, about 1200 tons of PDF are stored in an open, uncompacted stockpile, with no evidence of self-heating after more than two months.

Based on the successful tests in April, ENCOAL proceeded with the design of the added unit operations and placed orders for the new equipment. The plant was shut down in June for construction with a planned completion and start-up of the new equipment late this year.

In a related part of the PDF quenching and cooling system, there has been a significant amount of dust and hydrocarbons present in the steam from the quenching step. This has repeatedly resulted in the plugging of lines and a steam condenser in the downstream water recovery system. A new stripping tower using water sprays has been added to remove the dust. The unit was tested in the April/June runs and proved to be very effective.

Dryer and Pyrolyzer Internal Seals

ENCOAL's process uses convective heating in the dryer and pyrolyzer. This is accomplished by passing hot gasses through a slotted, rotating grate upon which rests a bed of coal. The seal between the rotating grate and the vessel wall, which prevents the hot gas below the grate from bypassing the coal bed, is a blade attached to the rotating member immersed in a stationary tub of sand. See Figure 3 for the details. This seal design has proved to be very troublesome.

In particular, besides the higher than expected wear and maintenance problems in both units, the sand seal in the pyrolyzer does not allow operation at full differential pressure across the grate. In order to operate, the flow rate in the pyrolyzer loop must be reduced to avoid blowing out the sand in the seal. The lower gas flow rates result 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 is transferred to the coal resulting is less severe pyrolysis. Attempts have been made to raise the on-gas temperature to compensate for the lower gas flow rate but this generates heavier CDL and lowers the liquid dew point in the off-gas. Condensation of liquid has occurred ahead of the quench column where it combines with the dust in the system creating unacceptable buildups in the ductwork.

ENCOAL is currently working with the vendor on alternate designs for the sand seal. In addition to modifications to the existing design, mechanical seals and alternate fluids are being evaluated. The plan is to implement any changes while the plant is down for the current construction.

Combustor Controls

Both of the combustors in the ENCOAL plant are required to burn very low Btu fuel gas, on the order of 50 Btu/ft^3. A minimum amount of natural gas trim is added to provide heat under temperature control to the dryer and pyrolyzer. Oxygen in the flue gas must be kept very low, and CO and NO_x formation in the dryer combustor must be minimized. Control of these units is not a trivial matter. Through a series of hardware changes, mainly a system of properly sized and sequenced valves for combustion air, and rigorous software routines in the PLC based control computers, the combustors now operate very smoothly. They no longer require a full time operator's attention and no longer cause frequent plant shut-downs.

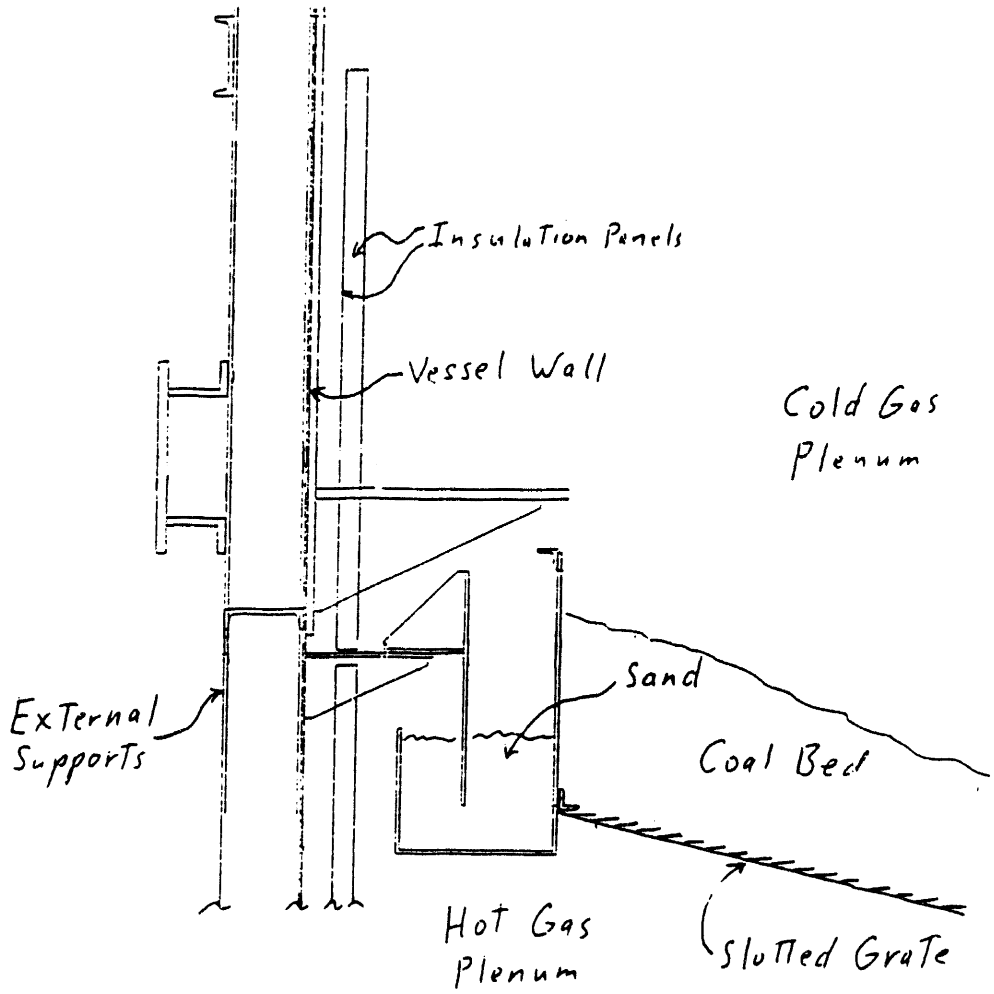


Figure 3. Detail of Dryer and Pyrolyzer Sand Seal.

PLANT OPERATING EXPERIENCE

Equipment Reliability

ENCOAL's LFC plant and facilities have now operated in an integrated mode producing PDF and CDL for more than 1400 hours. The total comes to more than 1800 hours adding the time products were not being made, but coal was entering the plant. Many of the major pieces of equipment, including the large blowers, combustors, dryer, pyrolyzer and cooler have operated for more than 2300 hours overall. Minor problems have been worked out for the most part and this equipment now operates reliably.

Process Controls - Workforce

Automation is a key goal of the project. Although most of the start-up and shut-down sequences are still hands-on, the plant operates in an integrated mode with the computer in full control of all equipment when the plant is on line. With only five operator set points, there is little need for operator intervention. Currently four operating technicians per shift run the plant plus one technical support person, one instrument/computer specialist and one supervisor. It is now evident that the plant can ultimately be operated with three operations technicians and one instrument specialist once the few remaining problems are worked out and plant testing is completed.

Carrying the automation to the next step, the start-up and shut-down sequences are already programmed and partially tested. This system should become operational over the next few runs. Ultimately a supervisory computer program should be able to close the loop on the plant and control the product qualities and recoveries based on on-line analysis of the feed coal and product streams. This program is operational now and is currently gathering data to fine tune its predictive algorithms. Computer control provides the means to optimize the revenue streams from a commercial plant as well as to safely control the plant operation.

Operating and Maintenance Costs

Operating and maintenance costs for the ENCOAL project are being tracked closely. This information is needed for estimating the costs of a commercial plant. So far, the costs for labor, chemicals, utilities, raw materials and administration are very close to the original projections. Although there have been significant plant changes and modifications as discussed above, these costs are still running below original projections. The cumulative cost for the operations phase of the Project ($21,000,000 budget) is currently about 10% below the estimate, mostly due to lower run times on the plant. This is expected to come back to the budget projection once the plant reaches steady state operation.

Safety and Environmental Experience

Environmentally, the plant is exceeding all expectations for emissions control. The flue gas scrubber system is working very well and the particulates and sulfur emissions are half or less of the permitted values. The combustors are also performing very well so that the CO, NO_x and hydrocarbons are below the permitted levels. Having no process water discharge, the plant was designed to be environmentally benign. Wash down water from the coal side of the plant does report to a settling pond, as is typical of most coal operations.

Safety is the highest priority at ENCOAL. From the beginning, the plant was designed with safety in mind. Three HazOps reviews were conducted on the plant during the design and construction phase and all HazOps issues were addressed. A HazOps review was also done on the new product finishing unit operation. The plant interlock and alarm system are programmed for safety first. Because of this emphasis, the plant has proven time and again that it starts, stops and operates safely, and there have been many opportunities to test this due to the many "crashes".

An ambient air monitoring system was installed in the plant to warn against fugitive toxic or noxious gases. It has work well with the exception of nuisance alarms for SO_2. Ambient air surveys have been conducted by outside experts with no findings of harmful gases in concentrations even close to OSHA Threshhold Limit Values. Odors were a problem for some people, so a vapor collection system with an activated carbon filter has been installed. Noise and heat in the plant have been much less of a problem than originally feared. Two additional ventilation fans have been added. Ear plugs are required for extended exposure inside the plant building.

Capacity and Availability

Third party testing of the plant stack and point sources has not yet taken place. This is because the plant has not been able to sustain design capacity for long periods. Coal has been processed at design rates and gas flow rates have reached design levels without coal in the unit, but the combination has not been sustainable because of the limitations discussed in the start-up section. Until the changes currently underway are completed, tested and proven, it is expected that the plant will operate at no more than 500 tons per day of feed, or 50% of design capacity.

During the last two extended runs, the plant availability exceeded 90% once the plant start-up sequence was initiated. Both of these runs were longer than two weeks, and in both cases the plant was intentionally shut down rather than crashing. Better weather was a factor in this success, but so were the many improvements to the plant.

Production

ENCOAL's LFC plant has now completed 15 runs where products were produced. PDF production from the April/June runs was about 4500 tons. An accurate figure is hard to determine because calibration of the plant weight measurement system is not yet completed and it is unreliable. CDL production is much more reliable because it is collected in a tank that can be measured. About 5500 barrels were produced in the April/June runs. Three tank cars of CDL have been shipped to a customer, but no PDF has been shipped. It has all been used for on-site and laboratory testing. Including cold coal runs, the plant has processed 17,400 tons of PRB coal from the Buckskin Mine.

Product recoveries from the feed coal have varied somewhat from the original projections. In the case of PDF, it has been lower. This is because more fines are generated in the process than expected and they are not recovered at the present time. CDL recovery is apparently higher than expected. However, the changes in yields are well within the error bands of the pilot plant data.

PRODUCT ANALYSIS

The ENCOAL LFC plant is still in the testing and initial operation mode and has not begun steady state operation. However, it has been demonstrated that product quality can be affected by plant operating conditions. Analyses of PDF are shown in Figure 4. Heating value, moisture, ash and sulphur fall in the range projected from pilot plant studies. Analyses of the CDL product are shown in Figure 6. The range of values is fairly broad in these initial CDL samples, but are close to or encompass the projected values. The analytical results for both products are discussed in more detail below.

PDF properties will be discussed first on an as-produced basis and then on a moisture and ash free basis. The former is of direct interest to customers with respect to utilization costs. The latter reveals how depth of pyrolysis impacts the organic matrix.

PDF As-Produced

PDF properties reflect quality variations of the feed ROM coal and the conditions of processing. During the lengthy steady state runs in April/June, process conditions were intentionally varied to determine the effect on PDF heating value, moisture content and residual volatility. Figure 4 shows data on 27 PDF samples collected during the April/June runs. The first 18 samples were collected in April, the rest in June.

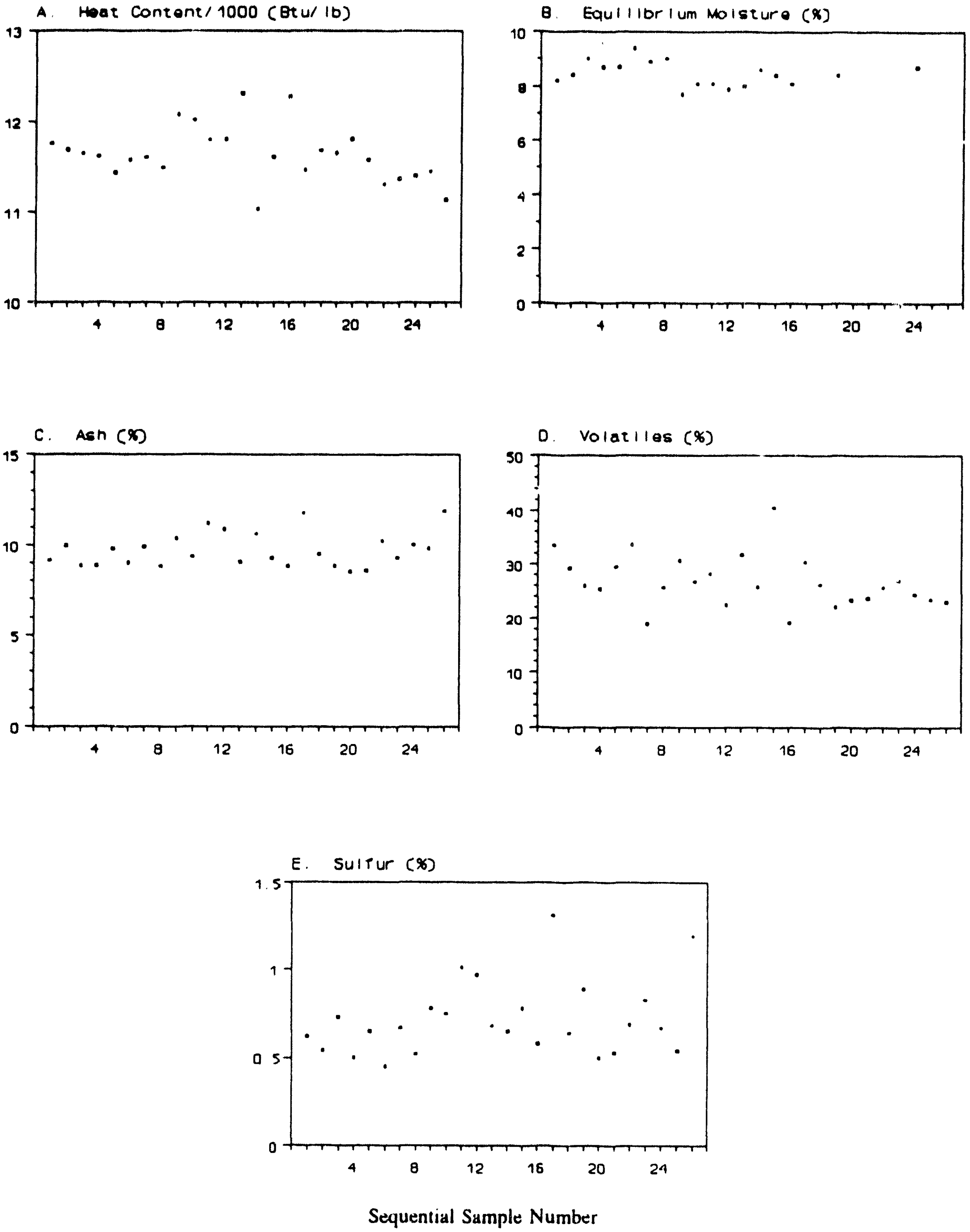


Figure 4. ENCOAL Mild Coal Gasification Project PDF Analytical Data April - June, 1993

Higher Heating Value (HHV). Heat content can be controlled somewhat in the plant by varying pyrolyzer loop operating conditions. As can be seen in Part A of Figure 4, the heat content of the produced material ranged above 12,000 Btu/lb, which is the projected value for operating the Plant in a commercial mode. The significance of moisture and ash free results will be discussed in the next section.

Moisture. Equilibrium moisture is shown in Part B of Figure 4. As-received moisture content and equilibrium moisture are affected by process conditions in the dryer pyrolyzer and PDF cooler. As received moisture has varied in the test so far from 2% to close to equilibrium values. During commercial operation of the Plant, the moisture content of PDF is projected to be in the range of 5 to 7%. Equilibrium moisture content was in the 8 to 9% range, these data being consistent with earlier laboratory data and prior ENCOAL Plant runs.

Ash. Because ash content from the Buckskin Mine runs around 5%, because roughly 2 tons of feed coal produce 1 ton of PDF and because all the ash stays with the solid product, an ash content of 10% is expected for PDF. Ash data for these runs is consistent as shown in Figure 4, Part C.

Volatiles. For most of the April/June runs, the target value for volatiles content was approximately 23%. Note that, from Figure 4, Part D, it *appears* that the target was attained only in the June part of the run. In fact, this is an artifact of the ASTM Volatiles analysis procedure, described as follows.

The ASTM procedure for determining volatiles content presents problems when PDF is analyzed. PDF is a sparking fuel. If normal ASTM procedures are followed, solid particles are ejected from the sample boat during the analysis. This phenomenon yields a greater weight loss than would have occurred from volatiles release only. The reported volatiles content is then higher than the actual value.

The samples taken in April were analyzed in routine fashion by a commercial laboratory. The samples taken in June were analyzed by the same laboratory, but with special attention being given to the volatiles analysis. Hence, the smaller scatter in volatiles results after the 18th sample.

However, using a different procedure based on thermogravimetric analysis developed by SGI International at their SGI Development Center Lab in Ohio, the volatiles content obtained is more reproducible and is generally lower than the ASTM results. Their results for volatiles from four of the same samples from the April run sent to the commercial labs vary from 13% to 18%.

Sulfur. Variability of sulfur in the product PDF is dependent on variability of sulfur in the feed, as long as the plant is run in a steady-state mode. Because sulfur in the feed coal was intentionally varied for the purpose of calibration of the plant's Gamma-Metrics Analyzers, there is significant variability of sulfur in the April/June run as shown in Figure 4, Part E.

PDF Moisture and Ash Free

Considering the properties of the produced PDF on a moisture and ash free basis reveals the effects of operating conditions on the coal organic matrix.

General. Table 1 compares some of these results between the feed coal and the product PDF. The number of feed coal samples is much smaller, 7 total, than the number of PDF samples. Because of the variation in depth of pyrolysis, variability of PDF properties is greater than the feed coal, as reflected in the standard deviation.

COMPARISON OF PDF WITH ROM FEED COAL
MOISTURE AND ASH FREE BASIS

	Feed Coal		Product PDF	
	Average	Std. Dev.	Average	Std. Dev.
Heating Value (Btu/lb)	12,740	85	13,840	220
Carbon (%)	73.4	0.6	84.0	1.6
Hydrogen (%)	5.5	0.1	3.6	0.2
Nitrogen (%)	1.1	<0.1	1.3	<0.1

Table 1. Comparison of PDF with ROM Feed Coal

On the average, the moisture and ash free heat content of the product PDF is 1,100 Btu/lb greater than the feed coal. This value is consistent with laboratory data. Also as expected, carbon content (ultimate analysis, not fixed carbon from proximate analysis) increased while hydrogen content decreased. While the nitrogen content increased, the value for PDF increased less than 10% over the feed coal, on a #Nitrogen/MMBTU basis.

Volatiles were not included in the table because of the analysis problems mentioned above for PDF. The decrease is still substantial, even with the error, at 47% volatiles for the feed coal versus 32% for the product PDF on a moisture and ash free basis. Sulfur is not included because of the high variation in feed coal sulfur content and relatively small number of feed coal samples taken.

Correlation of Data. While one would expect volatiles to vary inversely with the heat content on a moisture and ash free basis, the scatter in ASTM based analysis may preclude identifying a correlation on a routine basis. However, carbon content does correlate with the heat content on a moisture and ash free basis and either of these values may be a better indicator of the condition of the product PDF, when relying on routine analyses. The data are shown in Figure 5. Also included are the linear regression lines for all the data and also for just the PDF samples. A similar plot for volatiles versus heat content or carbon content on a moisture and ash free basis shows significant scatter, as indicated above.

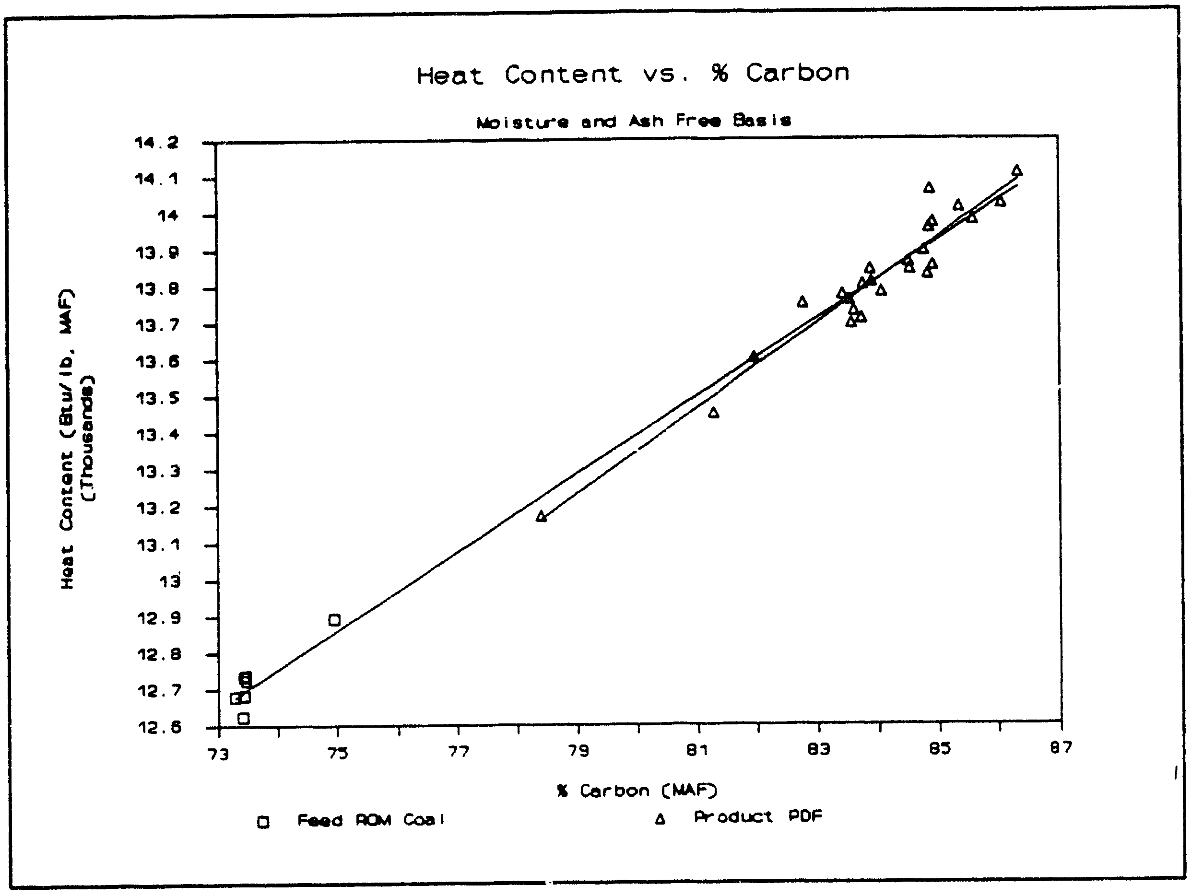


Figure 5. Heat Content vs. % Carbon.

CDL

General

While properties of PDF are essentially fixed in the pyrolyzer, those of the CDL are also influenced by operation of equipment in the pyrolysis gas loop, including the pyrolyzer cyclone, the quench tower and the electrostatic precipitators. In addition, because of the relatively large inventory of CDL in the quench tower, CDL properties take a long time to reach a new steady state when process or equipment operating conditions are changed. It may take as long as 24 hours for the CDL properties to reflect such operating changes.

Of the 15 CDL samples taken and analyzed, the first 12 were taken during April and the last 3 during June. Data taken on these samples are shown graphically in Figure 6.

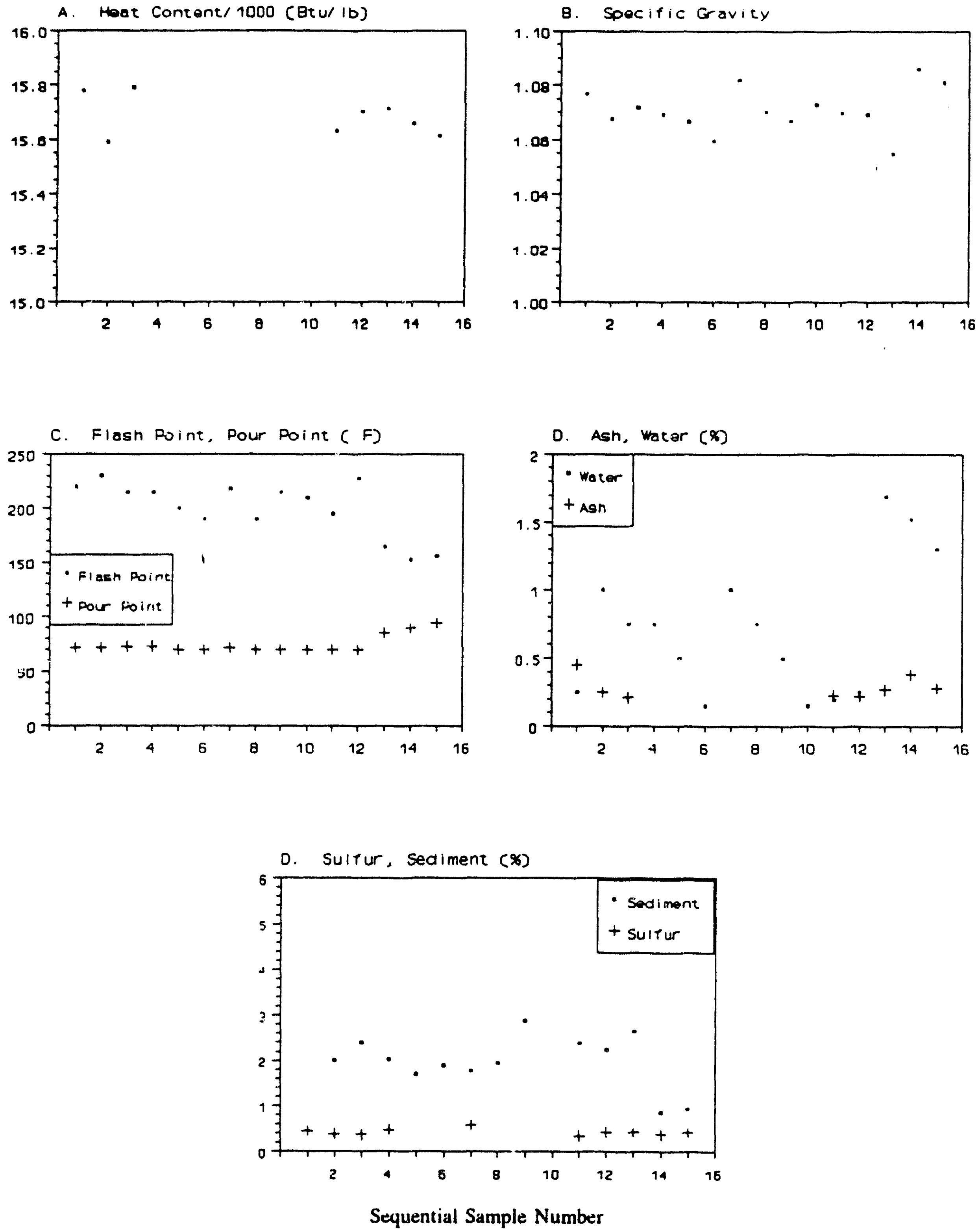


Figure 6. ENCOAL Mild Coal Gasification Project CDL Analytical Data April - June, 1993

Properties

The average heat content of the samples analyzed was 139,000 Btu/gal, slightly under the value of 144,000 Btu/gal projected for commercial operation of the Plant. The data are shown in Part A of Figure 6. Because the Plant was operated under pyrolysis conditions a little less severe than planned for commercial operation, this value is consistent with expectations.

Data for specific gravity are shown in Figure 6, Part B. The specific gravity averaged 1.07 (API Gravity = 0.61°). This is somewhat more dense than the projected 1.03.

Operation of the pyrolysis loop was changed between April and June as indicated by the flash point and pour point data, shown in Part C of Figure 6. The June samples show higher pour points and lower flash points relative to the April samples. This may be because the April data on pour points were in error.

Ash content and water content are shown in Part D of Figure 6. Ash content was less than 0.5% for all samples analyzed. Water content was more variable, being less than 1% for all the samples collected in April, but somewhat higher in samples collected in June.

Sulfur was quite consistent, varying from 0.35% to 0.45%, except for one sample at 0.58%. The average #Sulfur/MMBtu was 0.26, which compares favorably to a value of about 0.46 for low sulfur No. 6 oil. The sulfur data are shown in Part E of Figure 6, along with sediment data. Sediment results will reflect how much ash and fine coal particles are entrained in the pyrolysis gas and pass through the pyrolyzer cyclone. Most samples were between 1.7 and 2.9% sediment. Two samples were much higher at 5.1% and 11.4% and two samples were lower, being less than 1%. These last two low sediment values may represent, again, the different mode of operation in June versus April.

These data indicate that a liquid product can be produced with specifications close to what had been projected in laboratory tests. Furthermore, there appears to be some flexibility in affecting the liquids product by how the pyrolysis loop is operated. There is much more to be learned about the effects of plant operating parameters on liquid quality in future runs.

Product Shipments

Both PDF and CDL have been produced in the ENCOAL Plant as indicated above. To date, 1500 barrels of CDL have been delivered to TexPar Energy, Inc., which has contracted for the purchase of most of the CDL from the ENCOAL Plant. A PDF sample has been shipped for combustion testing at Shell Development Company. Results of these combustion tests are described below.

As discussed above, the plant is currently shut down for major modifications to add the finishing and stabilization equipment. The objective is to complete the construction work and test the system by the end of the year. When this objective is attained, production runs to supply customers for full scale testing will commence.

A contract is in place for initial test burns of PDF in some of Wisconsin Power and Light's (WP&L) cyclone boilers, both blended and unblended. Because the ash elemental composition for PDF is essentially the same as that of run-of-mine PRB coal and because these WP&L units can operate successfully on unblended PRB coal, ash viscosity is not expected to be a factor. Following the work with WP&L, tests are planned on pulverized coal-fired units.

Considering that partially devolatilized subbituminous coal in quantities sufficient for testing in commercial units has never been available before and that laboratory scale testing indicates significantly different flame properties compared with other fuels, there is much to look forward to in field tests.

PRODUCT EVALUATION

Factors in PDF Utilization

The unique nature of PDF, a devolatilized subbituminous coal, leads to the need to assess its utilization characteristics. There are several characteristics that are critical to potential users. Other factors need to be evaluated with respect to how readily PDF can be substituted for the design coal in any given unit. The quality characteristics that were deemed significant and were evaluated as being acceptable to proceed with the ENCOAL Project have been described previously[2]. The source of material for the these first evaluations was either PDF generated in the SGI pilot plant or dried PRB coal.

The ENCOAL plant has now produced PDF and CDL from each of 15 different runs over the last year. In October, 1992 some drums of PDF were shipped to Shell Development Company in Houston for laboratory combustion tests. Descriptions given below are based on these tests and will generally be described as being in comparison to run-of-mine PRB coal.

Coal quality characteristics that would render a new solid fuel useless to potential users are excessive dust, accelerated spontaneous combustion or an unstable flame.

Dustiness. Nuisance dust (particle sizes less than 100 microns) can be especially serious for coals with zero surface moisture. For PDF, a fuel with no surface moisture, control of nuisance dust generation was anticipated with the following measures. First, handling of samples from the pilot plant indicated the tendency to form nuisance dust was less than that of run-of-mine PRB coal. Second, the feed coal is screened to remove the minus 1/8th inch fraction in the ENCOAL plant. Third, provision was designed into the ENCOAL plant for applying a dust control additive, designated as MK. MK was successfully demonstrated on dried coal in large scale tests (pile size, 100-200 tons) at the Buckskin Mine[2].

In the preliminary results with PDF generated at the ENCOAL plant the amount of nuisance dust appears comparable to or less than run-of-mine PRB coal. However, the dosage of MK has not been optimized.

Spontaneous Combustion. PDF produced in pilot plant studies was stable with respect to spontaneous combustion. In fact, testing of these samples indicated that PDF would have a lower tendency for self-heating under ambient air conditions than run-of-mine PRB coal[2]. At the present time, the PDF produced at the ENCOAL plant has not attained the same resistance to spontaneous combustion as the SGI pilot plant samples. Ongoing work at the ENCOAL plant is directed toward diminishing self heating of PDF in order to match the stability toward spontaneous combustion demonstrated by PDF samples generated in the pilot plant studies.

Flame Stability. The question of flame stability arises from the volatiles content of PDF. Results of combustion tests on PDF samples generated from the pilot plant have been reported[2]. These samples included a 22% volatiles product and a 17% product. A sample of PDF from the ENCOAL plant has recently been tested in the same 100 lb/hour laboratory combustor. This sample had 22% volatiles.

The results are quite favorable, especially with respect to flame stability. In the tests on PDF pilot-plant samples, carbon monoxide levels were only slightly higher than the parent run-of-mine PRB coal and carbon burnout was equivalent to the run-of-mine PRB coal. No problems were noted with respect to pressure pulsation in the furnace. If the flame were unstable, increased pressure pulsation, which is associated with blowout of the flame and re-ignition of the fuel, would be expected. Furthermore, the flame was less luminous due to the lower volatiles content.

Three PRB coals, including Buckskin, were used in the series of tests reported here. These will be designated PRB1, PRB2 and Buckskin. Two lower sulfur Eastern bituminous coals were also run as part of blend tests. The two Eastern coals vary significantly, both in volatiles and sulfur content. These will be designated as E1 and E2. PDF from the ENCOAL plant was run unblended and as a blend with PRB2.

Furnace pressure is plotted as a function of time for a typical one hour period for several of the tests in Figures 7 and 8. Figure 7 compares unblended PRB1 with unblended PDF. Quite surprisingly, the variation in pressure is significantly *reduced* for PDF compared to the run-of-mine coal. These data correlate with the difference in appearance of the flames. The PDF flame is short and compact with a relatively fixed flame pattern. In contrast, the run-of-mine PRB coal flame is about twice as long, using the same burner setting, with a changing ill-defined flame pattern as is normal with a coal flame. If one did not know a solid fuel were being burned, the PDF flame would be described as a natural gas flame.

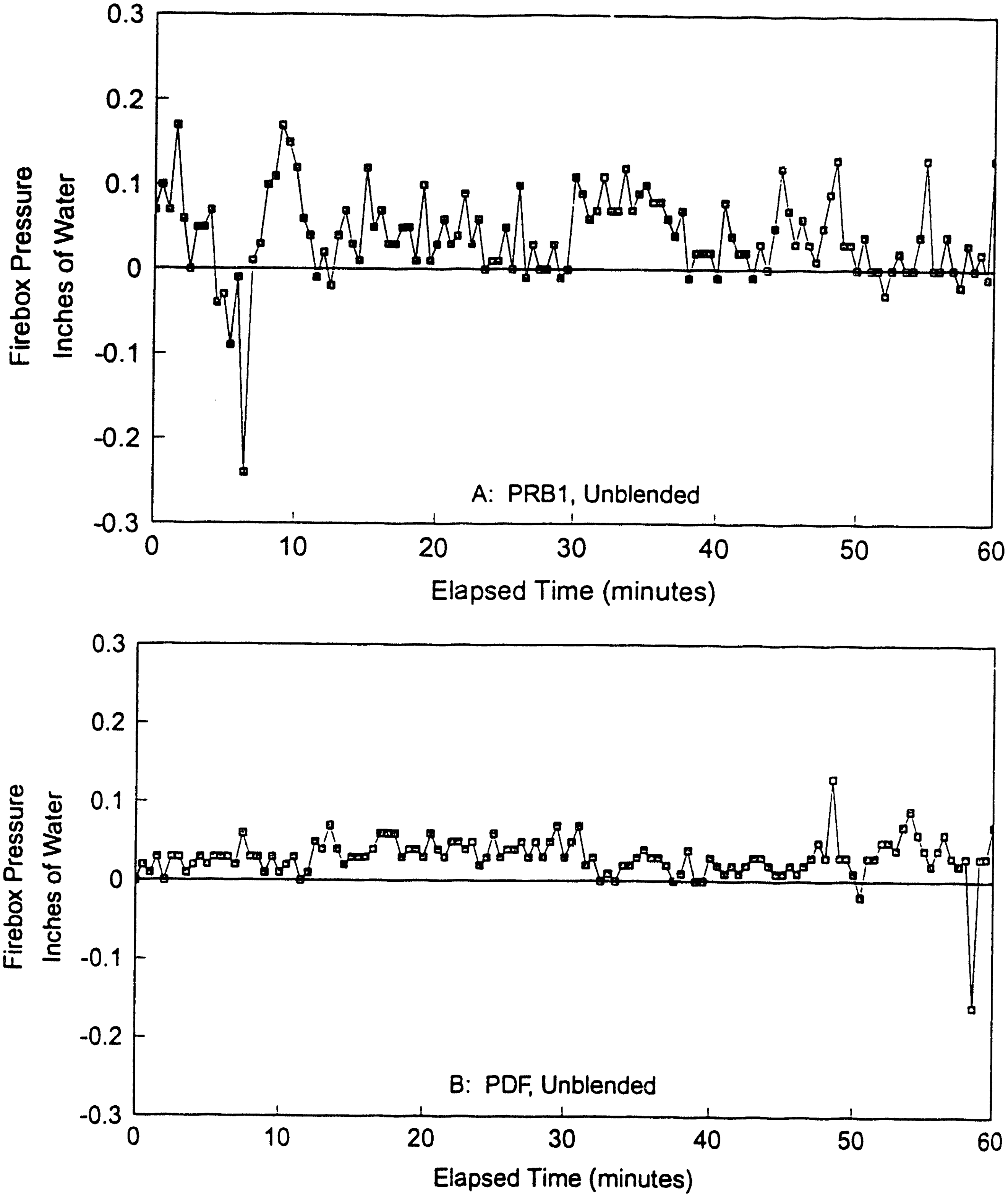


Figure 7. Furnace Pressure vs. Time for Typical One Hour Period for Unblended PRB1 and Unblended PDF

The blend test results for PRB2 are shown in Figure 8. These include a blend with 20% E1, another with 20% E2 and a third with 25% PDF. The blends show a somewhat reduced furnace pressure fluctuation relative to 100% PRB, but still distinctly greater than 100% PDF. The unexpected result is that the pressure fluctuations of the 25% PDF blend are quite low, comparable to the 100% PDF results. One can speculate, based on the blend tests, that PDF may enhance combustion when blended with other coals.

The flame for the two PDF samples obtained from the pilot plant had been less luminous than that of run-of-mine PRB coal. For the PDF sample from the ENCOAL plant, the flame luminosity was closer to that of a run-of-mine coal flame. It is believed that a lower volatiles PDF from the ENCOAL plant will also be less luminous than run-of-mine PRB coal.

Carbon monoxide data from this series of tests are shown in Table 2.

	Buckskin	PRB1	PRB2
PRB, Unblended	18*	N/A	
PDF (from ENCOAL) Unblended	16		
Blended with 25% PDF			13
Blended with 20% E1	8	6	9
Blended with 20% E2	25	28	21

*From previous tests
N/A, Not available for this test

Table 2. AVERAGE CARBON MONOXIDE LEVELS (ppm), TAKEN OVER ENTIRE TEST

CO values ranged from a low of 6 to a high of 28 ppm. As can be seen from the table, the value of 16 ppm for unblended PDF from the ENCOAL plant is in the range of values measured for PRB/Eastern coal blends. It can be inferred from these results that good combustion conditions exist in the flame. The data support the furnace pressure information indicating good flame stability. The data reported previously[2] on PDF samples from the pilot plant show CO values ranging from 25 to 32 ppm. The slight difference between the results in the two test series could be due to a different burner setting or a higher furnace exit gas temperature (50°F to 150°F) for the recent tests on PDF from the ENCOAL plant versus the earlier tests on PDF samples from the pilot plant.

Other Factors. In addition to the above characteristics, that are critical to potential users, are others that determine PDF's utilized value. With respect to handling, these include moisture resorption, bulk density, grindability and flow attributes. Ash deposition, heat transfer and NO_X generation are of particular interest with respect to combustion.

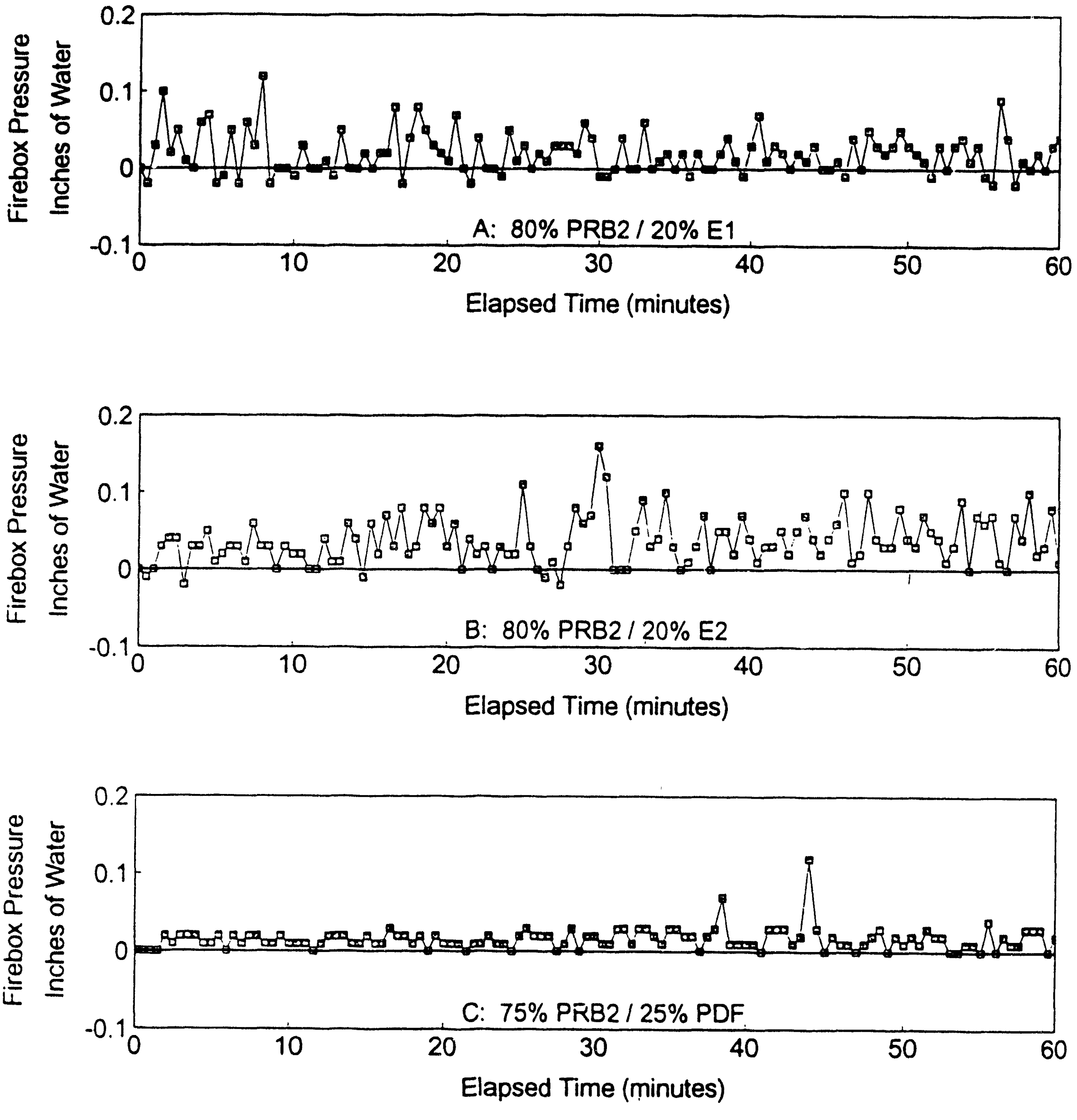


Figure 8. Furnace Pressure vs. Time for Typical One Hour Period for PRB2 Blends with E1, E2 and PDF

Because PDF is not yet being generated under steady state operation in the ENCOAL plant, the properties listed above have not been determined for commercially produced PDF. Moisture resorption was studied for PDF produced in the pilot plant and was determined not to be a significant factor[2]. With respect to flow attributes, the ENCOAL plant samples recently tested in the combustion facility exhibited good flow characteristics, even though top size was generally less than ½ inch.

COMBUSTION

Radiant Heat Transfer

Because PDF is derived from PRB coal, it is natural to compare the two fuels, particularly in steam generators not designed for PRB coals. There are cases in which an increase in furnace exit gas temperature is experienced when burning run-of-mine PRB coals relative to a unit's design coal. This is generally described as throwing the heat back into the convective pass. Because of the light color of ash from PRB coals, this condition is sometimes characterized as "bright furnace". Predicting how PDF will perform in full scale units, compared with run-of-mine PRB coal, is a non-trivial exercise. A very brief description of some factors follows.

Testing of PDF from the ENCOAL plant in the laboratory combustor shows a 400°F higher temperature for PDF relative to run-of-mine PRB coal at one flame location (2700°F vs. 2300°F). The higher temperature for PDF is encouraging in that it represents up to 70% higher radiant heat generation for PDF relative to run-of-mine PRB coal. Two possible reasons for the measured flame temperature difference are: first, heating value and second, moisture content of the pulverized coal particles exiting the burner. Regarding the first reason, the moisture and ash free heating value for PDF is on the order of 1300 Btu/lb higher than that for run-of-mine PRB coal. With respect to the second major difference, some field data indicate that only about half the water content in run-of-mine PRB coal has evaporated by the time the pulverized particles exit the burner. This residual water content would help suppress the flame temperature.

Heat transfer is dependent on a number of factors including radiation from the flame, absorption of radiation in the cooler part of the flue gas and deposit reflective and insulating characteristics. A series of model calculations indicates the net effect of heat transfer for PDF relative to run-of-mine PRB coal can vary significantly depending on these various factors. Sufficient information on these parameters is not available to allow accurate prediction of heat transfer in full scale boilers.

For example, in Figure 9 is shown the predicted effect of flyash particle size on run-of-mine PRB coal and PDF. Only particle size and ultimate analysis were varied in the input data. The effect of doubling the particle diameter in this range is dramatically larger for PDF relative to run-of-mine PRB coal. These results were generated using a zero-dimensional model[3]. The effect is likely due to the change in water concentration in the flue gas. Water is an effective

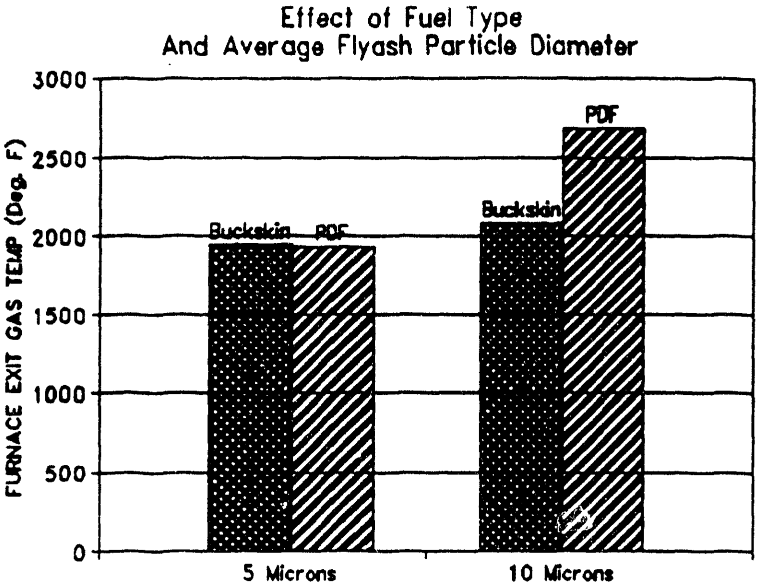


Figure 9A. Effect of Fuel Type and Average Flyash Particle Diameter

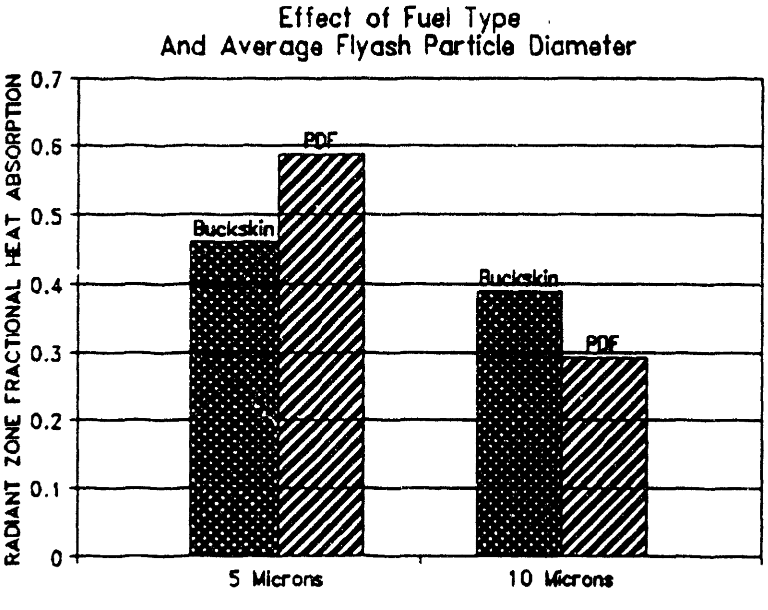


Figure 9B. Effect of Fuel Type and Average Flyash Particle Diameter radiating component. However, the percentage of water (molar basis) in the flue gas is on the order of 13% for run-of-mine PRB coal compared to 7% for PDF, a significant difference. With the reduced water content, radiation from flyash particles becomes a more significant factor for PDF relative to run-of-mine PRB coal. There is also about 40% more ash for Buckskin PDF on a lb. ash/MMBtu basis compared to run-of-mine Buckskin coal.

Other factors, such as soot (not varied in these calculations) and char concentrations in the flue gas and heat transfer properties of ash deposits also have a strong effect.

Field testing, particularly in pulverized-fired units, will be particularly important from the standpoint of understanding radiation effects on heat transfer.

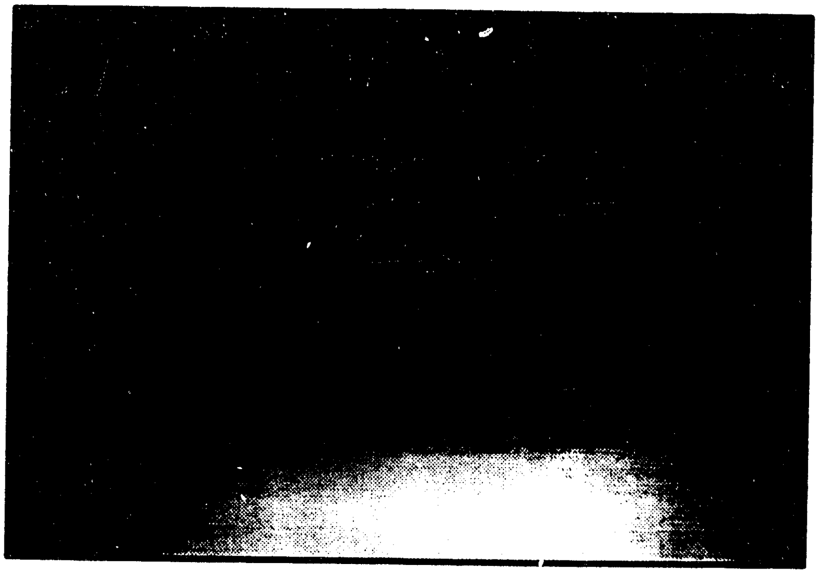
Ash Deposition

Ash elemental composition does not change appreciably during processing from the run-of-mine PRB coal feed coal to PDF in the ENCOAL plant. Ash loading in a steam generator will increase 35 to 40% on a lb/MMBtu basis considering that the weight percentage of ash will roughly double during processing. Thus, an initial prediction would be that ash deposition will increase for PDF relative to run-of-mine PRB coal. However, it can be inferred from tests in the laboratory combustor that other factors may come into play for PDF.

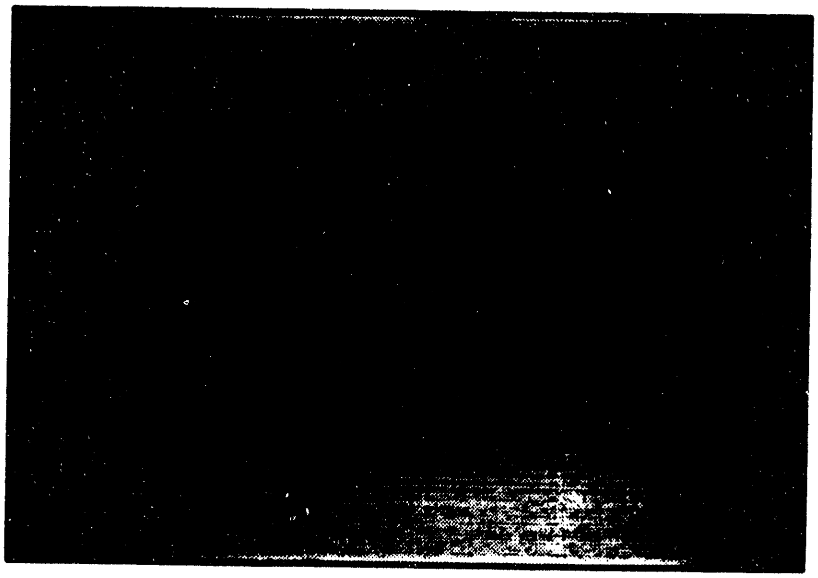
Deposits for PDF have a different appearance from run-of-mine PRB coal. On the waterwall panels, the deposits are more evenly distributed with less of the cauliflower-like deposits. Figure 10 shows the waterwalls at the end of the test before wallblowing, both for PDF and 100% PRB1. The spotty growing deposits shown for the 100% PRB1 sample also are observed for PDF. However, for PDF, they fall off under their own weight during the test. Only a small amount can be seen in the lower left hand corner.

In addition the ash from PDF seems to be more friable and to blow as readily as the run-of-mine PRB coal, which itself is easily removed by wallblowing. When blowing the waterwall panel, PDF deposits were readily knocked off at the lowest blowing pressure. Heat transfer to the waterwalls returned to initial values after wallblowing, confirming the observation of the ease of removing deposits by wallblowing. Decay of heat transfer versus time for PDF tracks that of run-of-mine PRB coal indicating that deposit buildup was not accelerated relative to PDF.

With respect to the superheater, the deposits for PDF seem to be larger than with Buckskin coal, but extremely light, as viewed on-line. Some of the PDF deposits fell off the superheater tubes while inserting the sootblower, before turning on the blower. The remaining deposits were easily removed. As with the waterwall data, heat transfer for PDF returned to initial values after sootblowing and decay of heat transfer tracks that of run-of-mine PRB coal.



A: PRB1, Unblended



B: PDF, Unblended

Figure 10. **Waterwall Appearance at End of Test Prior to Wall Blowing**

NO_X Generation

Generation of NO_X is dependent upon both fuel/air mixing and combustion gas temperature history and, therefore, is specific to furnace and burner configuration and operation. However, at least a comparison can be made between PDF and run-of-mine PRB coal in this combustion test facility (fast mix burner design). With the significantly higher flame temperatures, a greater amount of NO_X might be expected for PDF. One possible influence countering that of temperature is the more stable PDF flame which can lead to reduced NO_X production.

The data for PDF from the ENCOAL plant are shown in Table 3.

	Buckskin	PRB1	PRB2
PRB, Unblended		758	
PDF (from ENCOAL) Unblended	750		
Blended with 25% PDF			808
Blended with 20% E1	564	696	676
Blended with 20% E2	686	612	678

Table 3. Average NO_x Levels (ppm), Taken from Same 1 Hour Period as Furnace Pressure Data in Figure 7 and 8.

NO_X values are essentially the same for unblended PDF from the ENCOAL plant and unblended run-of-mine PRB coal in these tests. Thus, at least for these conditions, the significantly higher flame temperature does not produce a correspondingly higher level of NO_X. It does appear that the addition of 20% Eastern coal depresses NO_X somewhat. Optimizing burner conditions for minimal NO_X can have a significant impact on these relative values.

FUTURE WORK

The next step in the project is to get the plant re-commissioned and back on line upon completion of the latest modifications. Then the new finishing and stabilization equipment can be tested. Assuming the new equipment works well, steady state operation of the entire integrated plant should then commence. It will take at least two months of steady operation to generate enough PDF for the first test burn, anticipated to be with Wisconsin Power and Light.

Automatic start-up and shut-down should be achievable in the coming year. Early in the year, ENCOAL expects to evaluate the capacity of the new finishing and stabilization equipment and determine if a plant emissions test can take place. It is also anticipated to test at least one alternate coal during 1994.

In the long run, the goal is to achieve 90% availability of the plant, complete the plant testing program and move on to steady state production of PDF and CDL at plant capacity. The plant should continue to generate data for the design of commercial plants. It should also provide the product and information to evaluate the opportunity for upgrading of the CDL for chemical recovery or transportation fuels. Upgrading of the PDF or some of it is not out of the question either, since anode grade carbon and activated carbon markets are expected to grow.

CONCLUSIONS

The ENCOAL Project continues to progress toward its goals. The debugging phase is nearing completion and steady state operation is anticipated in the near future. Combustion testing on the solid product indicates it will burn in a stable, smooth, and environmentally acceptable manner. Plant availability is improving and it can be operated safely.

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GLOSSARY

ASTM	American Society of Testing Methods
API	Air Position Indicator
BACT	Best Available Control Technology
Bbls.	Barrels
Btu	British Thermal Unit
CDL	Coal Derived Liquid
CO	Carbon Monoxide
DOE	U. S. Department of Energy
ENCOAL	ENCOAL Corporation
EPA	Environmental Protection Agency
ESP	Electrostatic Precipitators
H_2O	Water
HazOps	Hazards of Operations
HHV	Higher Heating Value
lb.	Pound
LFC	Liquid From Coal
MK	Dust Control Additive
MMBTU	Million British Thermal Units
N/A	Not Available
NO_x	Nitrogen Oxides
OSHA	Occupational Safety & Health Administration
PDF	Process Derived Fuel
PLC	Programmable Logic Controller
PPM	Parts Per Million
PRB	Powder River Basin
ROM	Run-of-Mine
S-Belt	Vertical conveyor with flexible sidewalls and rubber buckets
SGI	SGI International
SMC	SMC Mining Company
SO_2	Sulfur Dioxide
Std. Dev.	Standard Deviation
TEK-KOL	Partnership between SGI International and SMC Mining Company
vs.	Versus
WP&L	Wisconsin Power and Light
wt.	Weight
#	Pound

THE COAL QUALITY EXPERT:
A FOCUS ON SLAGGING AND FOULING

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INTRODUCTION

No one would disagree that coal quality can affect the performance, reliability and economics of a coal fired power plant. From the very moment coal enters the premises of the power plant, coal quality begins to affect power plant operation. Variations in coal properties can affect everything from coal transport and storage to pulverization, combustion and emissions. Depending on the particular problem or focus at a power plant, attention might be preferentially given to a specific coal property, the coal's sulfur content, as an example. The use of low sulfur Western coals in units designed for Eastern bituminous coals is one common example of one approach for meeting SO_2 emissions. And while SO_2 would, indeed, be decreased there could be other problems ranging from inadequate pulverizer capacity to increased fouling in the convective passes of the boiler to decreased collection efficiency in the electrostatic precipitator. An accurate assessment of the impacts of coal quality must necessarily include all the impacts that a change in coal quality might have, over and above the one that might be the primary focus.

Under Round 1 of the U.S. Clean Coal Technology Program, the Department of Energy (DOE) and the Electric Power Research Institute (EPRI) made a decision to sponsor the development and demonstration of a powerful computer program called the Coal Quality Expert (CQE^{TM}).

What is the Coal Quality Expert? The CQE is a comprehensive, PC-based program that can be used to evaluate various potential coal cleaning, blending and switching options to reduce power plant emissions while minimizing generation costs. It is comprised of over 20 submodels (Figure 1) which are designed to predict all the impacts of coal quality on power plant operations, maintenance, economics and emissions. The design philosophy of the CQE and descriptions of the various submodels have been described in detail in previous papers [1, 2].

Arguably, the most difficult of all coal properties to accurately predict has been the behavior of the mineral matter during the combustion process, i.e., the formation of ash deposits, usually termed slagging and/or fouling, depending on their location in the boiler. The CQE contains an advanced methodology for predicting the formation of and the impacts from ash deposits which are generated under conditions resulting from the combustion of a particular coal.

Because of its' broad based , comprehensive nature, the CQE must be able to handle detailed calculations as well as a voluminous amount of data during its execution. An object based technology was chosen as being best suited to meet the needs of this program. Significantly, an accurate prediction of slagging and fouling must necessarily integrate the operating conditions of the boiler into the solution. Simply stated, the characteristics of ash deposits will be significantly affected by boiler operating conditions, and conversely, the impact of ash deposits will influence boiler operating conditions. Gas temperatures, for example, have a significant impact on the characteristics of ash deposits; gas temperatures will in turn be affected by "boundary conditions", such as the thermal resistance offered by ash deposits. It becomes apparent that an accurate prediction of ash deposit impacts will require computational interaction between boiler operating conditions (gas temperature) and the thermal resistance offered by the deposits. Since the CQE also contains a boiler performance model which computes, among other things, gas temperatures, it has the capability for achieving heat balance closure with regard to gas temperatures and deposit thermal resistance.

ASH DEPOSITION IN PULVERIZED COAL FIRED BOILERS

Overview of the Ash Deposition Process

The process of ash deposition in pulverized coal fired boilers is extremely complex and involves numerous aspects of coal combustion, mineral matter transformation and chemical reactions within deposits. The following can all play a role in the formation of ash and the ash deposition process:

- Coal organic properties
- Coal mineral matter properties
- Combustion kinetics
- Vaporization/condensation of ash species
- Mineral transformation and decomposition
- Fluid dynamics
- Ash transport phenomena
- Deposit chemistry: specie migration and reactions
- Heat transfer to and from the deposit

Moreover, the above phenomena are usually inter-related and generally strongly influenced by firing system and furnace design. The importance of furnace operating conditions on the combined results of each of the above can also spell the difference between a problem situation and one where no problem exists.

Because of the complexity of the ash deposition process it is difficult to reduce it to a few, dominant terms that might be reliably described and predicted by relatively simple bench scale tests. Indeed, the inability of routine bench scale analyses to reliably predict fireside performance has continued to motivate researchers to find more reliable solutions.

Impacts of Ash Deposits

The presence of ash deposits can cause the following problems in a coal fired boiler:

- Reduced heat transfer
- Impeded gas flow/increased pressure drop
- Physical damage to pressure parts (slag drops)
- Removal of bottom ash

The short term consequences of the above problems can result in the following:

- Excessive furnace outlet temperature
- Excessive attemperator spray
- Excessive tube temperatures
- Bridging of bottom ash hopper

Problems like the above can result in reduced generating capacity, unscheduled outages, reduced availability, lower plant efficiencies, higher maintenance costs and expensive modifications.

Ash deposits are often categorized relative to their location in the boiler and sometimes to the nature of the deposit. Slagging is the term used to describe ash deposition on heat transfer sections in the radiant sections of the furnace, deposits here frequently have a molten or semi-molten appearance. Fouling typically refers to ash deposition in the convective passes of the boiler; deposits in this region are generally sintered, but can be molten in more extreme cases.

The most important manifestation of an ash deposit is its' effect on heat transfer. Heat transfer can be impeded by a combination of radiant effects and conductive effects.

Changes in radiant heat transfer (absorptivities/emissivities) can occur relatively quickly since it is a surface phenomena; changes in thermal conductance will necessarily occur over a longer timeframe since deposit thickness will change with time. The Physical state of the deposit can also have a significant effect on the radiative properties; molten deposits, for example will result in higher emissivities/absorptivities than sintered or powdery deposits. Although thin, molten deposits are less troublesome from the standpoint of heat transfer than thick, sintered deposits, the former are much more difficult to remove and can eventually result in frozen deposits near the bottom hopper which can cause bridging in extreme cases.

Impeded gas flow can occur as the result of significant deposition on heat transfer surfaces in the convective passes. In addition to an increased pressure drop, ash deposition will change heat transfer, frequently referred to as a surface effectiveness factor. In the extreme, deposits can grow to the point where they cause bridging between the tubes in which case the free area is decreased and local gas velocities can become quite high.

Physical damage to pressure parts can occur when large deposits accumulate in the upper furnace and become dislodged or are blown off the soot blowers and proceed to fall onto the slopes of the bottom hopper where they can cause pressure part damage. Deposits of this type are usually characterized by their relatively high bonding strengths and their highly sintered structure which permits large deposits to form before becoming dislodged.

Historical Methods for Predicting Ash Deposit Effects

Bench scale techniques, notably ASTM tests, have been the most commonly used measurements for predicting ash behavior in a boiler. There have also been ASTM-derived indices such as base/acid and iron/calcium ratios. Specialty tests have been devised in the hopes of providing better predictive tools.

Pilot scale testing can provide results with much higher confidence levels than the traditional bench scale results, but at a price which is considerably higher than bench scale analysis.

Finally there is the option of full scale field tests. The results from such testing, of course, represents the "prime" standard, but usually at a price that far exceeds pilot scale testing. Unlike the bench scale tests, pilot scale and full scale testing have the advantage of being able to quantify the results as a function of boiler operating conditions. As previously noted the behavior of a particular coal is dependent on its' own properties as well as the conditions under which it is being fired.

Computational models have the ability to factor in both fuel properties as well as boiler operating conditions to provide an interactive analysis of ash deposit effects at reasonable cost. The difficulty for many computational models which try to predict slagging/fouling effects is the ability to provide a fundamentally sound, interactive model which has been formulated with and validated by bench, pilot, and field experimental results.

Overview to Predicting Slagging/Fouling in CQE

The goal under the CQE Program was to develop a fundamental, interactive, PC-compatible model for the prediction of slagging and fouling in a pulverized coal fired boiler. Specific objectives for the slagging/fouling model were to quantitatively determine:

- An operational limit beyond which continuous operation is not possible.
- Thermal resistance to heat transfer caused by deposits
- Frequency of sootblowing required to maintain acceptable boiler operation.
- Effect of boiler load decreases on slag shedding and cleanability.

EPRI's Coal Quality Impact Model (CQIM) has served as the foundation for CQE. One of the areas within the CQIM that was identified as a candidate for enhancement was the slagging and fouling submodel. In the CQIM, coal ash deposition impacts were based on a number of conventional indices, most of them being derivatives of ASTM analyses, which implicitly assume that coal ash is a homogeneous substance. Such an assumption is insensitive to the knowledge that individual fly ash particles have different compositions and therefore capacities for different behavior; for example, some particles might exhibit a high degree of stickiness because of their relatively low melting temperatures while others may have high melting temperatures and not exhibit any stickiness. In formulating an improved slagging/fouling predictive methodology under CQE, the following questions were asked:

- What minerals are present in the coal?
- How is the inorganic material associated with the organic fraction of the coal?
- What is the mineral size distribution?
- How do mineral interactions affect ash particle formation?
- Which ash particles initiate deposition?
- How does ash deposit strength change with time?

These issues cannot be addressed solely by the use of conventional analytical procedures which are based on bulk properties of the coal and ash; bulk properties cannot accurately represent the behavior of individual coal and ash particles in the boiler. Computer Controlled Scanning Electron Microscopy (CCSEM) represents an advanced analytical technique that allows an individual-particle-based approach to be used in the CQE advanced methodology.

PSI PowerServe (formerly PSI Technologies) and the University of North Dakota, Energy and Environmental Research Center (UNDEERC) were subcontracted by ABB Combustion Engineering to develop algorithms for predicting the effects of slagging and fouling, respectively. Both organizations had been involved in previous studies where they were developing models to predict fly ash formation and to characterize deposition processes. Figure 2 represents the key processes leading to ash deposition.

The foundation for accurate prediction of ash deposition effects is an accurate prediction of the fly ash size and composition. Each fly ash particle will behave in accordance with its' individual properties, size and composition being the two key factors. The size of the particle will largely dictate how it behaves in a particular flow field, i. e. whether or not it will impact a heat transfer surface. The composition will largely determine if the particle will stick once it has impacted the surface. Scanning electron microscopy (SEM) has provided the analytical means by which coal mineral matter can be evaluated; it has allowed a far more accurate prediction of fly ash particle size and composition than more conventional, ASTM-based analysis alone. It should be noted, however, that CQE will be operative if only ASTM results are available; surrogate SEM data can be internally chosen based on the ASTM data through a submodel Scanning Electron Microscopy Interpolation Algorithm (SENINAL), though it is preferable to have the specific SEM information.

Transport phenomena are described to determine the flight of fly ash particles and their interaction with heat transfer surfaces. Particle deposition is then described; various processes constitute the overall deposition process, as shown in Figure 2.

The boiler has been divided into specific regions, some of which are best described by slagging phenomena, addressed by PSI PowerServe, and other regions that are best described by fouling phenomena, addressed by UNDEERC. Figure 3 depicts the various regions of the boiler as; PSI PowerServe has addressed regions 1 through 5 and UNDEERC has addressed regions 6 through 10.

SLAGGING MODEL (SLAGGO)

Slagging Prediction Approach

PSI PowerServe has combined the bench, pilot scale and field testing in the CQE program, in concert with their previous experience, to improve the prediction of utility furnace slagging. This improvement, termed SLAGGO, is comprised of a combination of previous models and new models which have been based on the experimental results of the CQE program. This approach has allowed the establishment of links among coal (and ash) properties, furnace design, and operating conditions.

The indices created by SLAGGO are relative indices to be compared to a baseline (reference) case for each boiler. The baseline case will ideally include a coal and a set of operating conditions for which the boiler performance is known in detail. Once the baseline case is established, the predicted performance for a new candidate coal can be comparatively evaluated. If the predicted performance is unacceptable, a number of parameters can be changed in the model to determine the best combination of fuel and operating conditions, in terms of the slagging performance, including:

- Fuel properties
- Excess air
- Maximum continuous boiler rating
- Sootblower frequency and location
- Time at maximum continuous rating (or time before a load drop is required)

The CQE boiler performance model will then be used to evaluate the effect of the above changes on overall boiler performance and economics. Operating conditions will likely be chosen by the plant manager based on the predicted economic and operating impacts. In this manner the plant operator or manager can assess which operational changes are best, given his constraints.

As the number of coals, boiler designs, and operating conditions that are utilized by any user increase, the confidence level in the predictions will increase. This confidence factor is not just familiarity with the software, but also experience in terms of the predictions and the correlation of the predictions while varying parameters at a particular unit. SLAGGO is designed for the prediction of the behavior in all major furnace configurations.

Description of Submodels

SLAGGO has several components to simulate the entire cycle of ash formation, deposit initiation, growth, and removal processes. An overall schematic of the process is shown in Figure 4. The overall model is comprised of a number of submodels to describe the formation and deposition of fly ash:

- Ash Formation Model (AFM)
- Ash Transport Model (ATM)
- Deposit Growth Model (DGM)
- Thermal Properties Model (TPM)
- Deposit Removal Model (DRM)

The ash formation model (AFM) starts with the coal CCSEM data and calculates the fly ash particle size and composition distribution (PSCD). Each of the submodels has a number of components, but the AFM is the most complicated with several elements:

- Mineral Matter Transformation code (MMT)
- A preprocessor that renders MMT applicable to cyclone combustors
- Alkali Vaporization Model (ALKAVAP)
- Excluded pyrite kinetics model (PYRKIN)

Mineral Matter Transformation

The driver for the SLAGGO model is the MMT model which is a fundamentally-based model initially developed under DOE AR&TD funding. MMT takes as input the mineral analysis data for a given coal, follows the transformation process of coal mineral matter during combustion, and produces as output the fly ash particle size and composition data required for the prediction of slagging. ALKAVAP uses the ASTM ash analysis data, the temperature and the oxygen concentration in the burner zone, and calculates the vaporized fractions of alkali (sodium and potassium) and alkaline earth (calcium) metals as oxides. The inputs for PYRKIN are the size distribution of the excluded pyrites as produced from MMT and the temperature and the oxygen concentration in the burner zone; the output is the time for a melt phase to appear in an excluded pyrite particle of a given size and the time for the melt phase to disappear due to iron oxide crystallization. These times are reported for all the excluded particles in the size distribution, and are used by the DGM.

Ash Transport Model

The ash transport model (ATM) calculates the ash flux transported to the waterwall surfaces by turbulent diffusion. The ATM accounts for aerodynamics in wall-fired, T-fired, and cyclone furnaces. With respect to slagging, there are two regions with differing transport mechanisms. These regions are (1) the radiant region bounded by the walls of the furnace, and (2) the superheater tubes. The radiant region may be further subdivided into zones, for example burner, lower furnace, and upper furnace. The main transport mechanism for ash particles to the wall in the radiant zone is by turbulent diffusion; the main mechanism for the superheater tubes is inertial impaction.

Deposit Growth Model

The deposit growth model (DGM) simulates three main sequential events: (1) deposit initiation by small ash particles arriving by turbulent diffusion and adhering by van der Waals force; (2) deposit growth by sticky ash particles impacting on the existing ash deposits; and (3) deposit maturation.

The stickiness of ash particles arriving at waterwalls is determined by the viscosity model previously developed by PowerServe. The viscosity model predicts particle viscosity at a given temperature from the composition of the individual ash particles. The strength of a deposit at a given time is determined from the density of the deposit which is calculated by the sintering rate of spherical ash particles. The primary goal of the DGM is to predict the change in the cleanliness factor with time in six different regions of a furnace.

The cleanliness factor is defined as the ratio of the heat transmitted across the waterwall tubes with deposit on them to the heat transmitted across the "clean" waterwall tubes; "clean" refers to the state of cleanliness after effective commercial sootblowing. The cleanliness factor decreases with time until it reaches an equilibrium value and reflects the effect of slagging on boiler thermal performance. The cleanliness factor can be used to estimate the optimal sootblowing frequencies for economical operation. Since the DGM keeps track of the porosity change of the initial layer, it also forms the basis for computing deposit strength and it relates deposit strength to deposit removability by sootblowing.

Thermal Properties Model

The DGM requires knowledge of the thermal properties of the ash deposit, such as thermal conductivities and emissivities, under different deposit conditions. The thermal properties model (TPM) calculates these thermal properties. The emissivity and thermal conductivity of an ash deposit are functions of temperature, porosity (sintering), and chemical composition; the model calculates thermal conductivity and emissivity using data from models described above.

Deposit Removal Model

The deposit removal model (DRM) simulates deposit removal by sootblowers. Sootblower efficiency is initially determined from the performance data provided by users for the baseline coals. The sootblower characterization curve, thus determined, and the deposit strength from the DGM, are used in concert to predict deposit removability. Change in the cleanliness factor following sootblowing is determined as the final output.

SLAGGO Inputs and Outputs

The exact nature of the input and output screens for SLAGGO is still being formulated. Additionally, default values will be provided for virtually all input information. Although use of the default values is discouraged, the program will operate without most inputs. The input information will be organized into three main topics: coal properties, boiler design, and boiler operation parameters as follows.

Coal Properties

- Coal name and rank
- Ultimate and Proximate analysis
- ASTM ash analysis
- CCSEM data
- Coal Particle Size Distribution (PSD) data

Boiler Design

- Boiler name
- Boiler type
- Boiler dimensions (so that a cross sectional area can be calculated)
- Air and fuel injection information
- The number of sootblowers in each furnace zone (1 through 5)
- Type of sootblowers - air, steam, or waterlance.
- Single wall fired

- Opposed wall fired
- Tangentially fired
- Cyclone fired

Boiler Operation

- Load level
- Load mode of operation
- Air feed rate and distribution
- Fuel feed rate and distribution
- Furnace exit gas temperature
- Maximum time at full load
- The frequency of sootblower use by furnace section

Additionally, options will be provided for low NOx firing systems and for the corresponding variation in slagging behavior as a function of furnace location.

In SLAGGO a particular boiler load will be specified as an input. If there is a slag-related problem at full boiler load, then the user can specify a reduced load as one means to address a slagging problem, i.e., slag shedding. The use of reduced load to control slagging is handled by a prediction of the maximum time at full load. The program predicts the continual deterioration of conditions that occurs in cases where load drop is necessary, and a prediction is made for the time it takes to reach the minimum cleanliness factor level; this time defines the maximum time at full load.

Output Information - The key output will be a cleanliness factor diagram as a function of furnace location (see Figure 5). This diagram will be compared to diagrams from other cases, including the base case, so that a decision can be made regarding the choice of fuel and operating condition.

The cleanliness factor diagram is illustrated in Figure 5 shows two modes of behavior. In both cases, the beginning of the graph represents a time when the furnace has been thoroughly cleaned. The "stable case" represents a situation where sootblowing can adequately remove deposits and the minimum cleanliness factor does not change significantly. In this case, the local cleanliness factor drops until sootblowing occurs which causes an immediate recovery. The degrading case represents a situation where sootblowing is inadequate, and the cleanliness factor continually drops until a critical condition is reached. At this point the utility must respond with a change in operating conditions to prevent severe slagging. By using the cleanliness factor diagram in this manner, the following, targeted slagging areas of concern can be addressed:

- The furnace operational limits
- The required sootblower frequency
- The effect of load drop
- The effect on thermal resistance caused by slagging

Many different cleanliness factor behaviors are possible, depending on the input conditions, and the furnace location being considered. Under some conditions, the cleanliness factor will not decrease significantly, corresponding to very low slag buildup. Under other conditions, the cleanliness factor decrease will be more rapid and the recovery due to sootblowing lower. In some furnace locations, no sootblowers exist; therefore, there will be no recovery. The cleanliness factor can be evaluated (compared) as a function of different coals and/or changes in input conditions to obtain acceptable slagging conditions.

In addition to the cleanliness diagrams, the output of a wide variety of more detailed information is possible. The exact level of detail available in the final version of CQE is presently being discussed, but the data attainable include:

- Coal mineral particle composition and particle size distributions
- Fly ash composition and particle size distributions
- The slag layer composition, thickness, porosity and sintering rate as a function of time and location

The slag emissivity and thermal conductivity as a function of time and location

Code Operation and Interfacing

SLAGGO utilizes the above mentioned algorithms to predict ash deposition in the radiative section of the utility boiler. The lower and upper sections of the furnace are divided into several zones: one zone for the ash hopper region, a zone for each burner level, two zones between the top burner and the nose, and two zones for the upper furnace, if no tube banks are present, from the nose to the roof. Boiler operational conditions and dimensions for each zone and the fly ash particle size and composition distributions are received as input from the boiler model and user input.

The code is set up so that a sequence of procedures is implemented for each of the zones described above as follows:

- The initial deposit layer is calculated from the amount of ash particles which stick to the bare metal heat transfer surfaces.
- After the initial deposit layer reaches a thickness of 100 microns, the bulk layer ash deposition rate is calculated.
- The thickness of the ash deposit layer increases until the deposit surface exceeds the temperature at which the deposit is assumed to be running slag.
- The amount of deposit removed by sootblowing is calculated from the strength of the existing deposit and a sootblowing calibration curve which is generated from full-scale data entered in by the user of the program.
- Thermal properties of the deposit are calculated for all the zones based on sintered state, thickness and radiative properties.

Fly ash particle size and composition distributions for the SLAGGO code are predicted from the initial coal properties as measured by ASTM analysis or preferably CCSEM analysis, or as measured directly from an entrained ash sample should one be available. The CQE code utilizes the mineral matter transformation (MMT) code to predict the particle size and composition distribution (PSCD) of the entrained ash as a function of the original coal properties. The PSCD of the ash is divided into vapor species, pyritic species and residual ash. The residual ash is divided into 512 bins based on calculated ash viscosity.

Experimental Data Input/Validation

The coding of SLAGGO and integration with CQE is currently being finalized. Validation of the entire model will occur in the near future. However, the DGM and the TPM have been verified using data provided by the ABB Combustion Engineering Fireside Performance Test Facility using two HVA Bituminous coals.

A detailed description of the FPTF can be found elsewhere [3]. In brief, the FPTF is an up-fired furnace with a firing rate of 3 to 4 MBtu/hr. Permanent panels are used to study the heat transfer reduction as slag builds up. Single-use, sacrificial ash deposition probes were also used to collect slag deposits for in-depth analysis. In order to obtain a general understanding of the deposition characteristics of the two coals, the deposits were cross-sectioned along the direction of the deposit growth and were examined under CCSEM. The changes of the chemical composition and porosity along the deposit growth direction were examined. Additionally, the heat flux across the wall panel was monitored continuously throughout the test run by measuring the heat absorption with a cooling fluid.

Simulation of the ash deposition process for a hvA bituminous coal was carried out with a simplified version of the SLAGGO algorithm; only the deposit growth portion of the code was considered. Figure 6 shows the calculated $q_{dirty}/q_{initial}$ compared against the measured values for this coal. The measured q_d/q_i rapidly decreased in the first 2 hours and then leveled off approaching the equilibrium value after 12 hours. The trend of the change of the thermal degradation with time suggests that the effective thermal conductivity of the ash deposit formed in the first 2 hours is lower than that formed over the 12 hour period. The effective thermal conductivity increases with increased sintering of the deposit, and will result in a flattening of the curve; this shows more clearly the effect of the deposit sintering on the thermal degradation. The heat flux ratio, q_d/q_i, for the first 2 hours shows a better agreement with the thermal conductivity of 0.2 W/m C, whereas that for the last 4 hours shows a better agreement with the thermal conductivity of 0.8 W/m C. In this initial version of the DGM, a constant value for the thermal conductivity was used. In the final version the thermal conductivity will vary with porosity as the deposit matures.

Figure 7 shows the deposit composition profiles for the same two hvA bituminous coal. Comparison of the calculated with the measured composition profiles shows good agreement. The composition change with deposit thickness is minimal indicating that most of the ash particles are sticky at the temperature at which the testing was performed.

FOULING MODEL (FOULER)

Fouling Prediction Approach

Fouling refers to the deposition of ash in the convective pass region of a utility boiler. Deposit characteristics throughout the convective pass can change dramatically in morphology, varying form strong, highly molten deposits to weak, powdery deposits. The prediction of fouling and its effects on heat transfer is a complex process that requires information about the coal properties and operational parameters. Fouler, is a code developed by the Energy and Environmental Research Center, EERC, to predict the convective pass fouling of a coal-fired facility.

The fouler code receives the required input information from the CQE heat transfer module, interface shell, and the mineral matter transformation (MMT) code as mentioned in the previous section. The heat transfer module supplies the temperature and fluid flow properties of the system prior to deposition. The interface shell supplies the operational parameters such as sootblower configurations and mass loadings as entered by the user. The MMT algorithm supplies the necessary ash particle size and composition information.

In general, fouling deposit formation can be described as two interacting mechanisms: deposit growth and strength development. As the deposit grows, the temperature profile throughout the deposit changes, which affects the strength development and future deposit growth. The deposit growth is influenced by both transport to the heat-exchange surface and adhesion to the surface. The effects of deposit growth and strength development can then be applied to the thermal properties of the deposit and the deposit removability.

Description of Submodels

Fouler is comprised of over 25 different subroutines which can be grouped together as four general algorithms: (1) Deposit Growth, (2) Strength Development, (3) Thermal Properties, and (4) Deposit Removability.

Deposit Growth

The three primary methods of deposit growth which are accounted for in the fouling model are: (1) inertial impaction and eddy impaction, (2) vapor-phase and small particle diffusion, and (3) thermophoresis/electrophoresis. The initial upstream layers around a tube are generally deposited by vapor-phase and small particle diffusion and by thermophoretic/electrophoretic forces. The inner layer is composed primarily of condensed vapors and particles less than 5 microns that traverse the boundary layer surrounding the tube and deposit. The actual particles that deposit are dependent upon the flow characteristics around the heat-exchange tubes. At higher temperatures, which result in faster gas velocities, the inner layer is enriched condensed in vapor-phase species and remains loosely bound, while at lower temperatures (and lower velocities) the enrichment tends to shift to particles in the less than five micron range which become sulfated and produce a high strength layer. In both cases, the inner layer serves as the foundation for the eventual formation of massive upstream deposits.

The massive upstream deposits are primarily formed from inertial impaction into the sintered/molten surface of the deposit. This molten surface is often referred to as a captive surface. The larger particles, (greater than 10 microns), become separated from the gas stream as it flows around the tubes as shown in Figure 8. The particles impact the surface and either stick or deflect off depending upon their stickiness as well as that of the captive surface of the tube. As massive deposits grow, the surface temperature of the deposit increases, developing a highly captive surface which will capture most of the impacting particles. As the deposit grows, it also becomes more aerodynamic thus minimizing the amount of ash which impacts the surface.

Downstream deposits on the tube are formed by impaction of particles in the recirculation eddies passing around the tubes. As the gas stream passes around the tube, those particles that do not inertially impact (generally less than 10 microns) get caught in the recirculation eddies of the gas stream and are impacted into the downstream side of the tube surface as shown in Figure 9.

Strength Development

As mentioned previously, strength development is generally due to one of two sintering mechanisms: silicate- or sulfate -based. The general temperature of crossover from sulfate- to silicate-based sintering is 1850°F (1000°C) due to the instability of sulfates above that temperature. Silicate-based sintering is attributed to the viscous flow of amorphous material during and after deposition. The low viscosities responsible for silicate-based sintering are commonly attributed to higher temperatures and lower melting point phases such as sodium and potassium aluminosilicates. Some of the low melting phases are formed after deposition because of the interaction of the deposited material and gas phase species.

Sulfate-based sintering is attributed to the filling of deposit pores by the sulfation of the alkali-alkaline earth components in the deposit, primarily calcium, sodium, and potassium. Sulfates are generally unstable and decompose above 1850°F (1000°C), but form rapidly at temperatures slightly below the decomposition temperature. The crossover temperature range from rapid sulfation to decomposition is narrow and can be crossed in some areas of the boiler as a result of load swings.

Thermal Properties and Deposit Removability

The thermal properties of the deposit are primarily dependent upon the thickness, temperature, and physical sintered state of the deposit. Correlations have been developed for lightly sintered and highly sintered deposits as a function of temperature. The sintered state of the deposit can be indirectly estimated from the strength of the deposit. Due to the temperature change and sintered state change, throughout the thickness of a deposit as well as during its growth, the thermal properties are not constant and require multiple iterations to calculate.

The deposit removability algorithm accounts for thermal shedding, sootblowing and gravity shedding. Thermal shedding occurs when a utility drops load which results in a temperature change in the boiler. The change in temperature causes a difference between the thermal contraction of deposit versus tube which results in a shear fracture in the deposit; this can be correlated to the apparent density of the deposit. The sootblowing process accounts for the shear stress applied to a deposit by a retractable sootblower as a function of the blowing media, pressure, nozzle angle and other parameters. The sootblowing removal efficiency is calculated from the strength of the deposit. Gravity shedding is common in the back pass regions of a utility boiler where strength development is low but deposition is high. This form of deposit removal is correlated to a function of the strength/mass ratio of the deposit.

Fouler Inputs and Outputs

The inputs to the Fouler code are far too numerous to be listed here but they can generalized into four categories: (1) design parameters, (2) temperature and gas distributions, (3) ash size and composition distributions, and (4) sootblowing and load drop parameters. The primary outputs from the code are thermal resistivity as a function of time for each heat exchanger, and the sootblower effectiveness for each bank of heat exchange tubes. Other outputs such as deposit strength development, deposit growth (mass), and deposit composition can also be outputed if desired.

The thermal resistivity of each heat exchange section is returned to the CQE heat transfer module for calculation of the new temperature profile of the boiler. A cleanliness factor can then be calculated for each heat exchange section from the difference in heat transfer between the dirty and clean state of the tubes. The sootblower effectiveness curve is a prediction of the amount of deposit that will be removed depending on the time interval between sootblowing cycles. This curve will allow the user to better optimize their sootblowing cycles.

Code Operation and Interfacing

The fouling model, Fouler, utilizes the above-mentioned algorithms to predict the heat-transfer effects of a particular coal on the convective pass of a boiler. The convective pass of a boiler is divided into as many as twelve individual heat-exchange sections (within the primary superheater, reheater, economizer) for the fouling predictions. Fouler receives, as input, the boiler operational parameters for each section of tube banks (temperatures, velocities, tube spacings) and a fly ash particle-size and composition distribution. The code then separately executes the following calculations for each section of the convective pass. Particle sizes participating in the upstream, downstream and inner layer deposition for each bank are calculated. An inner layer deposit of approximately 100 microns is assumed as the initial tube cleanliness for the first iteration of the test using a two-hour or smaller time increments, the program calculates the amounts of upstream and downstream deposition. The upstream deposition algorithm first determines an impaction efficiency for a given group of particles from particle size and gas velocity. The sticking efficiency is then calculated to determine if the particle will adhere to the surface of the deposit/tube. The downstream deposition is based on the turbulence of the gas as it passes around a tube.

Both silicate-based and sulfate-based strengths are determined for each of the deposits. The silicate strengths are a function of the viscosity and particle size of the deposited materials and the time duration of deposition. The sulfate strength is a function of composition and time. Sulfation strengths above 1850°F (1000°C) are set to zero, since sulfates are unstable above that temperature. The greatest strength as determined from the two algorithms is chosen as the strength for the deposit at that given time.

The removability and heat-transfer characteristics of the deposit are calculated from the deposit mass and strength. Each of the removability algorithms are applied over their user-entered time increments. After a fraction of the deposit has been removed, the heat-transfer properties of the deposit are calculated for each layer of the deposit using correlations derived from various literature sources. The amount and strength of the deposit remaining is then used as the basis for the calculations during the next two-hour time increment. This process is continued for a specified number of time increments.

The particle size and composition distributions for the Fouler code can be predicted from the initial coal properties or measured, by computer controlled scanning electron microscopy, CCSEM, from entrained ash samples. The CQE code utilizes the mineral matter transformation (MMT) code created by Physical Sciences Incorporated (PSI) to predict the particle-size and composition distribution (PSCD) of the entrained ash as a function of the original coal properties. The PSCD of the ash is divided into six size and seven composition bins for a total of 42 different sets of particle information.

Experimental Data Input/Validation

The prediction of deposit compositions for high and low temperature deposits has been compared to pilot-scale experimental results. Pilot scale upstream deposits were collected on a water cooled sacrificial probes in the ABB-CE Fireside Performance Test Facility (FPTF) firing HVA a bituminous coal. The deposits were collected at a gas temperature of 2320°F (1270°C). The current fouling algorithms are designed to predict the potential for a given particle to impact and deposit on the leading edge of a heat exchange surface in the absence of a captive surface. Since the deposit formed from the HVA coal produced a highly liquid layer after significant deposition the predicted results are only compared to the initial non-liquid layer. Input to the fouling code was generated from the mineral matter transformations (MMT) code as predicted from the initial coal properties. Figure 10 compares the deposit before the captive surface formation, predicted deposit and the initial coal inorganic components. The predicted results compare well with the experimentally measured results with the exception of the calcium content.

Full scale downstream deposits were sampled from Northern States Power Sherco Unit #1 as part of Project Calcium. The feed coal was a Wyoming subituminous. Input to the Fouler code in this case was generated from analysis of entrained ash sampled from the same location as the deposits. The deposits were collected at a gas temperature of approximately 1800°F (980°C). Figure 11 compares the deposit, predicted deposit, and original coal inorganic components. The predicted values compare well with those measured from the full-scale sampling.

SUMMARY

Coal quality can significantly affect the performance, reliability and economics of a coal fired power plant. Arguably, the most difficult of all coal properties to accurately predict has been the behavior and impact of the mineral matter during the combustion process, specifically the formation of ash deposits, usually termed slagging and fouling.

A key part of this U. S. Clean Coal Technology Program, sponsored by the DOE and EPRI, has been the development of algorithms to predict coal ash slagging and fouling behavior in utility boilers for inclusion in the Coal Quality Expert. SLAGGO and FOULER, developed for predicting slagging and fouling, respectively, have been based on a combination of fundamental information from theory and bench scale laboratory experiments together with results from pilot and full scale test results. The slagging and fouling algorithms represent an advanced methodology which recognizes the importance of boiler operating conditions as well as coal properties for the accurate prediction of coal ash behavior and its impacts on boiler operation. By virtue of being part of the Coal Quality Expert which contains, among other things, a boiler performance model the necessary interaction between boiler operating conditions and ash deposit characteristics will occur. Version 1.0 of the FOULER code has been entered into the CQE program; coding of the slagging algorithm is nearing completion. Validation of certain elements within the algorithms has occurred, but overall validation will be undertaken later this year and early next year.

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