WRI 09-R025R

TESTING OF FMI'S COAL UPGRADING PROCESS

Topical Report

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For
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DISCLAIMER

ABSTRACT

WRI and FMI have collaborated to develop and test a novel coal upgrading technology. Proprietary coal upgrading technology is a fluidized bed-based continuous process which allows high through-puts, reducing the coal processing costs. Processing is carried out under controlled oxidizing conditions at mild enough conditions that compared to other coal upgrading technologies; the produced water is not as difficult to treat. All the energy required for coal drying and upgrading is derived from the coal itself.

Under the auspices of the Jointly Sponsored Research Program, Cooperative Agreement DE-FC26-98FT40323, a nominal 400 lbs/hour PDU was constructed and operated. Over the course of this project, several low-rank coals were successfully tested in the PDU. In all cases, a higher Btu, low moisture content, stable product was produced and subsequently analyzed. Stack emissions were monitored and produced water samples were analyzed. Product stability was established by performing moisture readsorption testing. Product pyrophobicity was demonstrated by instrumenting a coal pile.

EXECUTIVE SUMMARY

Fuels Management Inc. (FMI) and Western Research Institute (WRI) began the development of a proprietary concept for upgrading low-rank Western US coals. A nominal 400 lbs/hour PDU was constructed at the WRI's Advanced Technology Center to optimize the process. For the early development of the technology, nearly all of the tests were conducted with coal obtained from the Wyodak mine located in Gillette, Wyoming. However, over the course of this development effort, several different coals from Montana, South Dakota, North Dakota, Colorado, Alaska and Indonesia have been successfully processed.

The FMI coal upgrading process involves heating the coal in a bubbling fluidized bed-based reactor operating at near ambient pressures. The process heat required is derived from the coal itself. Upgrading process being a fluidized bed-based technology is a continuous process that allows high throughputs thereby reducing the processing costs. Maintenance costs are also expected to be low since the only moving parts are in the blowers. The FMI approach to coal upgrading is the only one using an oxidizing environment. The oxidative environment removes the more active oxygen components of the coal, thereby contributing to the stability of the product. Similarly, since the processing is carried out in air at conditions mild enough that compared to other coal upgrading technologies, the produced water is not as difficult to treat.

The PDU test facility constructed at WRI consists of a 12-inch diameter fluidized bed reactor where all coal-drying reactions occur. The fluidized bed reactor was assembled from flanged spool pieces such that the fluidized-bed aspect ratio could be changed. The reactor was well instrumented so that temperature of the bed could be monitored at every 3 inches. Similarly, pressures and differential pressures could be monitored at several locations in the reactor. The reactor was also equipped with a 3-inch diameter feed port, whereby a screw feeder could feed coal into the reactor at rates up to 400 lbs/hour. Several drain ports were installed on the reactor at elevations ranging from 18 inches down to 6 inches. These ports were used for withdrawing the dry coal, and/or for collecting samples. By changing the height of the drain port, active fluidized-bed volume was changed which in turn changed the average particle residence time in the bed. A refractory-lined propane-fired burner was used for start up. The burner heated the fluidizing gas to the desired temperature to start the drying process.

Over the course of the development project, variables investigated were bed operating temperature (400 – 675 F), bed residence time (3 – 10 minutes), feed-rate (50 – 400 lbs/hr), oxygen content of the fluidizing gas controlled by recycle (13 – 21%) and coal types (lignite and sub-bituminous). In all cases, while working with ¼ x ⅛-inch feed, a near-zero moisture content, higher Btu upgraded product exited the reactor.

Ultimate and Proximate analyses of the parent coal and the dried product showed that the process also removes some of the mercury present in the parent coal. Based on the solids analyses, indications are that the product contained only about 1/3 of the mercury present in the parent coal.

Subsequent testing and characterization of the product has established the pyrophobicity of the product and that the equilibrium moisture content of the product is in the 9 -12 % range.

INTRODUCTION

There are four primary types of coal. Anthracite, bituminous, subbituminous, and lignite, all four types of these coals principally contain carbon, hydrogen, nitrogen, oxygen, and sulfur, as well as moisture. However, actual concentrations of these elements and moisture vary widely from rank-to-rank. For example, anthracite, the highest ranking coals contain about 98 % carbon, while lignite, the lowest ranking coals may only contain about 30 % carbon. The amount of moisture in anthracite and bituminous coals can be less than 1%, but for subbituminous and lignite coals the moisture content can be in the 25 – 40%, range. The high-moisture subbituminous and lignite coals have lower heating values and their high moisture content adversely affects coal-fired power plant performance and emissions. High moisture content results in significantly lower boiler efficiencies and higher unit heat rates. The high moisture content of the coal can also raise fuel handling, and fuel preparation issues.

Eighty-nine percent of the coal mined in the US is used for electricity production. Bituminous coals have been the most widely used rank of coal because of their abundance and relatively high heating value. However, these coals contain high levels of sulfur. Low-rank coals account for about 50% of coal reserves and their use is limited due to low heating value and concerns regarding spontaneous combustion. Many of the low-rank coals, however, contain lower sulfur and lower ash than the bituminous coals. So if these coals could be efficiently and economically processed to yield a higher-grade, high-heating value product, there will be a beneficial impact not only on the energy supply side but also on the environmental side as well. A successful coal upgrading process has to be economical and address the issues of spontaneous combustion, decrepitation, and equilibrium moisture.

Over the years several technologies have been tested to reduce the moisture content of sub-bituminous and lignite coals. Notable attempts at developing such an upgrading technology include ENCOAL, Western SynCoal and KFx processes. However, the cost of processing the coal remains high. Viability of a simple, cost effective and efficient process has not yet been demonstrated.

During the mid-1997 through mid-1999 period, WRI worked closely with Fuels Management Inc. (FMI) in the verification of a new coal upgrading concept. With FMI's support, a nominal 400 lbs/hour test facility was constructed at the WRI's Advanced Technology Center. A control strategy was devised and implemented for processing coal in controlled oxidizing environment. Several successful tests were conducted in the pilot facility to define the optimum processing conditions.

In FY 1999, FY 2001, FY 2003, FY 2005, and FY 2006, a JSR project was approved by USDOE to further develop and test the technology in an attempt to prepare it for the demonstration phase. This report describes the results of the technology development and verification activities concluded under this project.

400 lbs/hr PDU

The FMI coal upgrading process involves heating the coal in a near atmospheric pressure, bubbling fluidized bed-based reactor. Coal processing occurs at about 600 °F and the process heat required is derived from the coal itself. Upgrading process being a fluidized bed-based technology allows high through-puts, reducing the processing costs. Processing is carried out under controlled oxidizing conditions at mild enough conditions that compared to other coal upgrading technologies; the produced water is not as difficult to treat. Nevertheless, as shown in Table 1, a premium product is indeed produced by the process.

Table 1. Coal Quality Parameters for Raw and Processed Wyodak Coal

	Raw Coal	Product
Moisture, wt %	29.32	0.43
Ash, wt %	6.35	11.32
HHV, Btu/lb	8269	11847
Sulfur, wt %	0.69	1.09

The 400 lbs/hr test facility (see Figure 1) consists of a 12-inch diameter fluidized bed reactor where all coal drying reactions occur. The fluidized bed reactor is assembled from flanged spool pieces such that the bed aspect ratio can be changed. The reactor is well instrumented so that temperature of the bed can be monitored at every 3 inches of bed height. Similarly, pressures and differential pressures can be monitored at several locations in the reactor. The reactor is also equipped with a 3-inch diameter feed port, whereby a screw feeder can feed coal into the reactor at rates up to 400 lbs/hr. Four drain ports are installed on the reactor. Two ports are at an elevation of 18 inches, and the other two one each at 12 inch and 6 inch bed height. These ports are used for withdrawing the dry coal, and/or for sampling. These ports are used for withdrawing the dry coal, and/or for collecting samples. By changing the height of the drain port, active fluidized-bed volume can be changed which in turn changes the average particle residence time in the fluidized bed.

Figure 1. A photograph of the FMI Pilot Facility

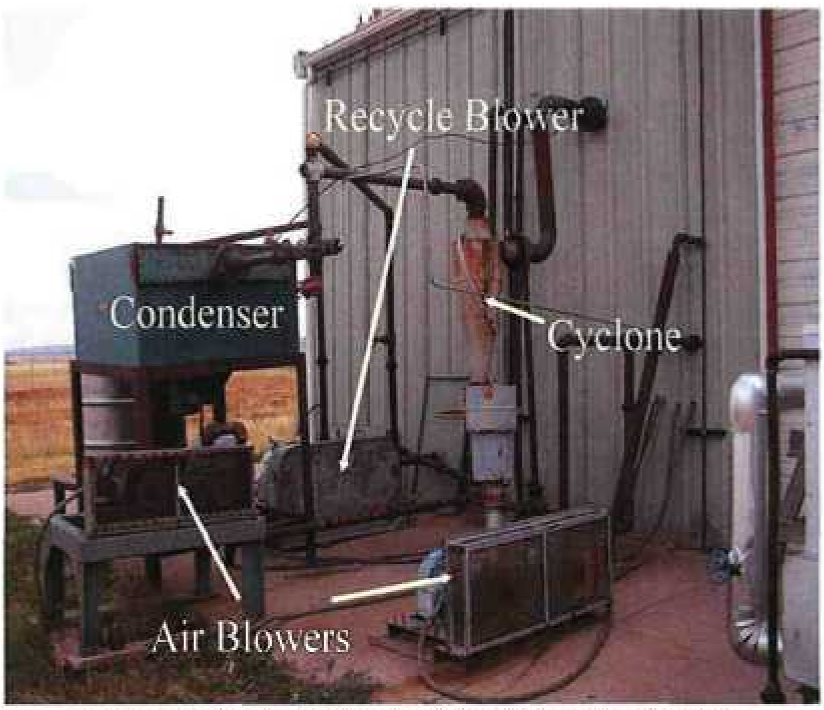

Figure 2. A photograph of the FMI Pilot Facility

A refractory-lined propane-fired burner is used for start up. The burner heats the fluidizing gas to the desired temperature. As the bed of coal is heated, exothermic oxidative reactions ensue and bed temperature increases beyond that of the fluidizing gas. By adding coal to the bed a constant temperature in the 450 to 675°F is maintained during the steady-state operation.

A 3-inch screw feeder transports the coal from a hopper into the reactor. A variable speed motor drives the screw. The feed-rate can be controlled by a PC-based logic control loop to maintain the bed temperature.

Off-gases from the reactor are sent to a cyclone separator, and then to a forced-air condenser. The water removed from the coal is condensed and drains into a storage drum. A blower is used to recycle a portion of the gases back to the reactor. A second blower provides air for the process. This air is heated by the propane burner and then mixed with the recycle gas to fluidize the bed of coal.

The FMI coal drying process requires a precise control of the bed temperature, and of the amount of oxygen present in the fluidizing gas. A PC-based control system employing LabTech Control software is used to control the process temperature, partial pressure of oxygen, and the coal feed-rate. The system also serves as a data logger whereby all flows, temperatures, and pressures are logged every five seconds. A photograph of the PC-based control system is displayed in Figure 3.

Figure 3. A photograph of the PC-based Controls for FMI Pilot Facility

The reactor is also equipped with provisions for spraying water in the bed. Water injection is also controlled by the PC to maintain a pre-selected bed temperature.

TESTING and RESULTS

A typical test involves reactor warm-up by lighting the propane burner and by starting the air blower. Recycle blower is then started. The system controls are then transferred to an Auto mode and the fluidizing gas volume set to 100 scfm. The propane firing rate is slowly increased until the onset of exothermic reactions in the reactor. This is typified by a sudden drop in the oxygen concentration in the off gases from the reactor, and depending upon the coal, occurs in the 325 - 400°F range. At this time, coal feed is initiated and slowly increased as the reactor temperature increases. When the desired coal feed rate and bed temperature are achieved, the system oxygen level controls are also transferred to the Auto mode. Under these conditions, any temperature excursions are compensated by either the coal feed rate adjustment and/or by water injection. The bed can be fluidized with a recycle gas/air ratio from zero (no recycle) to about four. As the recycle gas/air ratio is increased, the amount of throughput through the reactor decreases. The control system accommodates slight mismatches in the amount of heat produced in the reactor and that needed to evaporate the water from coal by injecting small amounts of water.

Figures 4 - 7 show typical time-base plots of the test conditions. For the data displayed, the coal used was provided by Arch Coal from their Thunder Basin Coal mine. Figure 4 shows the typical bed-temperature profile whereby all bed thermocouples show nearly the same temperature confirming a well-mixed coal-bed. Figure 5 shows the sustained coal feed in the reactor at a rate of about 100 pph. Figure 6 shows the fluidizing gas flow-rates whereas oxygen content of the gases exiting the fluidized bed is shown in Figure 7.

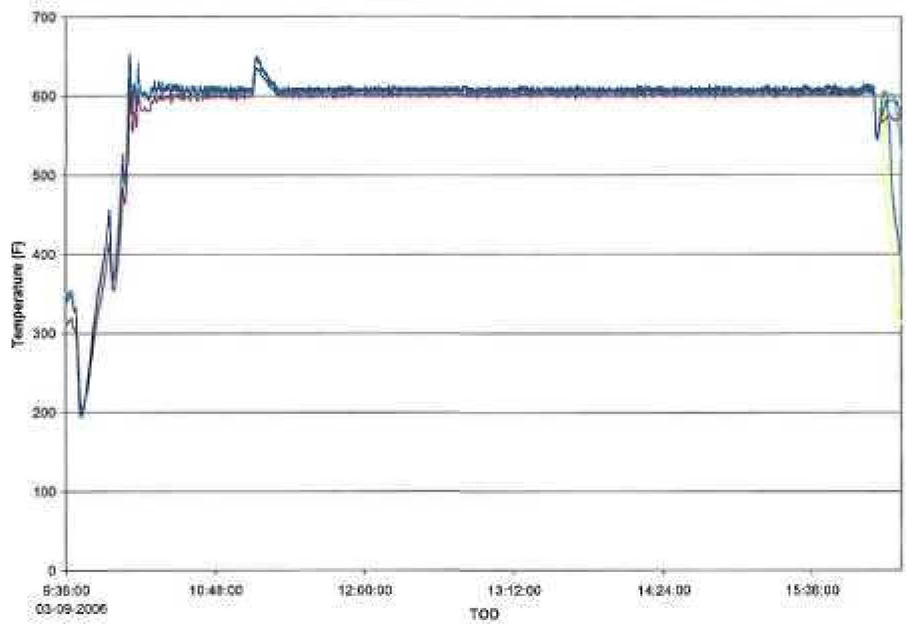

Figure 4. Bed temperature during a typical 600F test

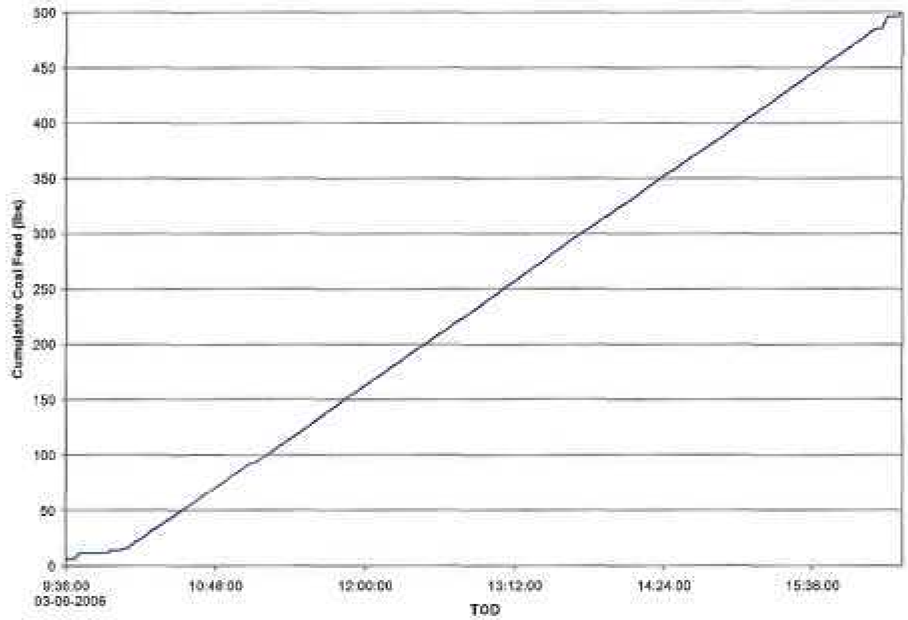

Figure 5. Cumulative coal feed into the reactor during a typical test

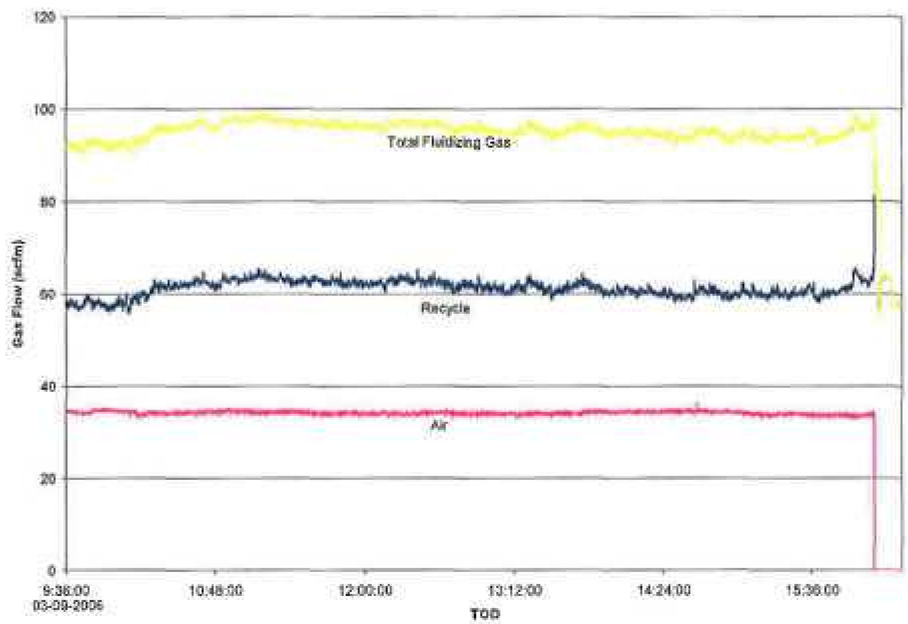

Figure 6. Fluidizing gas flows during a typical test

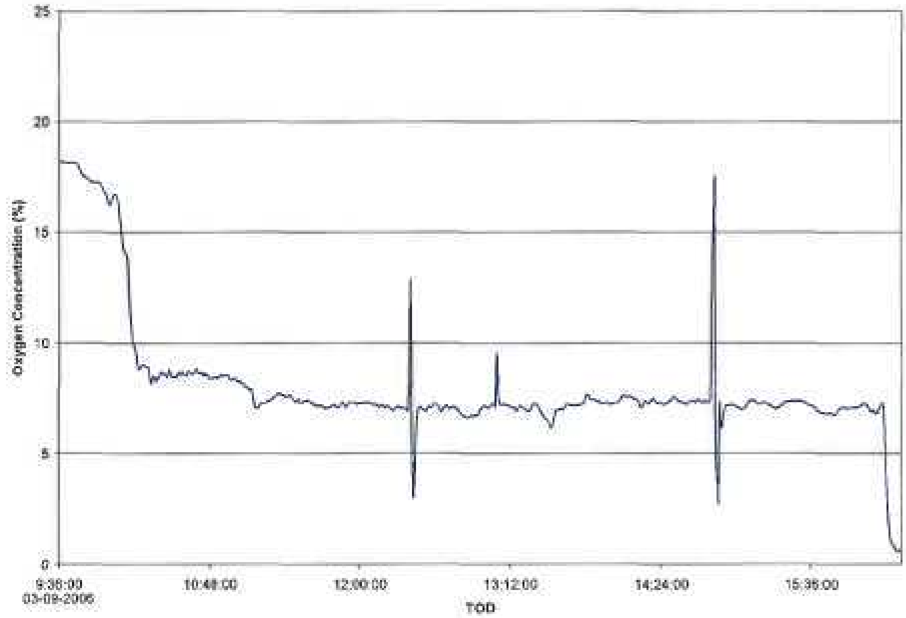

Figure 7. Oxygen content of gases leaving the reactor during a typical test

Samples of raw feed and product were analyzed by an independent analytical laboratory. Typical feed and product analyses are displayed in Tables and 3 and. Data presented clearly show a dramatic increased in the heating value of the coal because of the removal of the moisture and a substantial reduction in the mercury content of the coal. Bulk density of the product has been determined from small samples and is typically about 88 - 90 % that of the raw coal.

Table 2. Ultimate and Proximate Analysis of Coal

	AS RECEIVED wt.%	MOISTURE FREE wt.%	MOISTURE & ASH FREE wt.%
PROXIMATE:			
MOISTURE	25.20		
ASH	5.36	7.17	
VOLATILE MATTER	32.68	43.69	47.06
FIXED CARBON	36.76	49.14	52.94
TOTAL	100.00	100.00	100.00
HEATING VALUE (Btu/lb.)	8,952	11,968	12,892
ULTIMATE:			
MOISTURE	25.20		
HYDROGEN	2.80	3.74	4.03
CARBON	54.07	72.29	77.87
NITROGEN	0.98	1.31	1.41
SULFUR	0.33	0.44	0.47
OXYGEN	11.26	15.05	16.21
ASH	5.36	7.17	
TOTAL	100.00	100.00	100.00

Mercury, ug/kg 150

Table 3. Ultimate and Proximate Analysis of Product

	AS RECEIVED wt.%	MOISTURE FREE wt.%	MOISTURE & ASH FREE wt.%
PROXIMATE:			
MOISTURE	0.26		
ASH	6.49	6.51	
VOLATILE MATTER	36.98	37.08	39.66
FIXED CARBON	56.27	56.41	60.34
TOTAL	100.00	100.00	100.00
HEATING VALUE (Btu/lb.)	11,962	11,993	12,828
ULTIMATE:			
MOISTURE	0.26		
HYDROGEN	3.29	3.30	3.53
CARBON	72.27	72.46	77.51
NITROGEN	1.26	1.26	1.35
SULFUR	0.47	0.47	0.50
OXYGEN	15.96	16.00	17.11
ASH	6.49	6.51	
TOTAL	100.00	100.00	100.00
Mercury, ug/kg	52		

Equilibrium moisture content of the product was determined by exposing a small sample to saturated air for approximately 48 hours while recording the weight gain. The material was then allowed to stand in room air while periodically monitoring the weight loss. Typically, within 24 hours, a stable weight is achieved. Moisture content associated with this stable weight is reported as the equilibrium moisture content of the product. Such weight gain/loss data for the material produced during the test described above are displayed in Figure 8. From the data displayed it is evident that the equilibrium moisture content of the product is about 9 percent.

An alternate approach to determining the equilibrium moisture content is to expose the dried coal product to room air for a long time and then determine the moisture content of the coal. Figure 9 shows the test data for several samples, where percent weight gain by product exposed to room air in Laramie, WY is plotted as a function of exposure time. The data plot show that nearly all the weight gain (moisture pick-up) occurs in the first 24 hours or so. The rate of weight change after that slows down considerably. From the data presented in Figure 9 one can deduce that the equilibrium moisture for the product is in the 6 percent range.

During the course of this project, tests were concluded with coals received from Montana, South Dakota, North Dakota, Colorado, Alaska and Indonesia. In all cases, a bone-dry product exited the reactor. Equilibrium moisture content varied from coal-to-coal and with drying conditions.

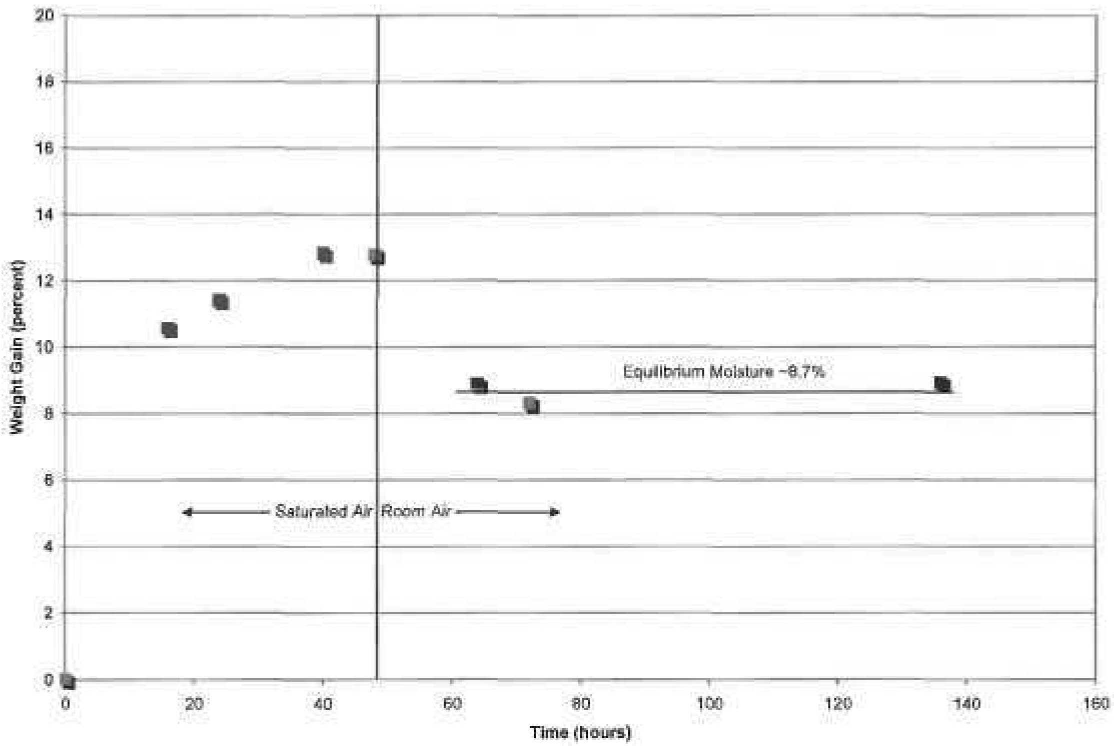

Figure 8. Graphical representation of equilibrium moisture data

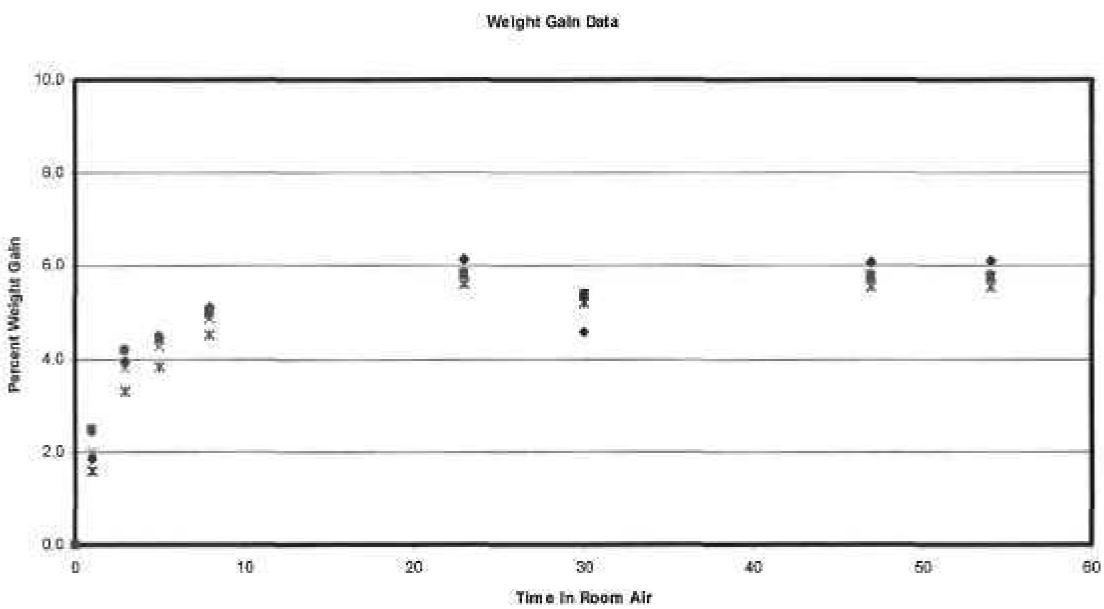

Figure 9. Graphical representation of equilibrium moisture data

Under a separate project funded by Headwaters Inc., a drum each of the raw feed and product were sent to Hazen Research in Golden, Colorado for pulverizing to 80% minus 200 mesh. Both the materials were then fired in the WRI's Combustion Test Facility. During the combustion tests, stack emissions with respect to mercury, SO_2 and NOx were continuously monitored. Preliminary indications are that consistent with reports from other upgraded product producers that there might indeed be a beneficial effect of coal upgrading on the power plant emissions.

FATE OF MERCURY

A series of tests tests and analyses were performed to determine the fate of mercury present in the parent coal during fluidized-bed-based coal upgrading process.

Over a four hour period of plant operations, nearly 900 lbs of Wyodak coal was processed at standard coal upgrading conditions developed earlier for PRB coals. Figures 10 - 11 show plots of operating conditions (temperatures and coal feed rate) during the tests. Samples of feed coal, product, fines, and produced water were collected and submitted for analyses. Concurrently, Air Pollution Testing Inc. (APT) performed stack gas sampling to determine the amount of mercury present in the gaseous streams. The test times for the Air Pollution Testing are illustrated in Figure 10 by two blue arrows. The results of various analyses are described below.

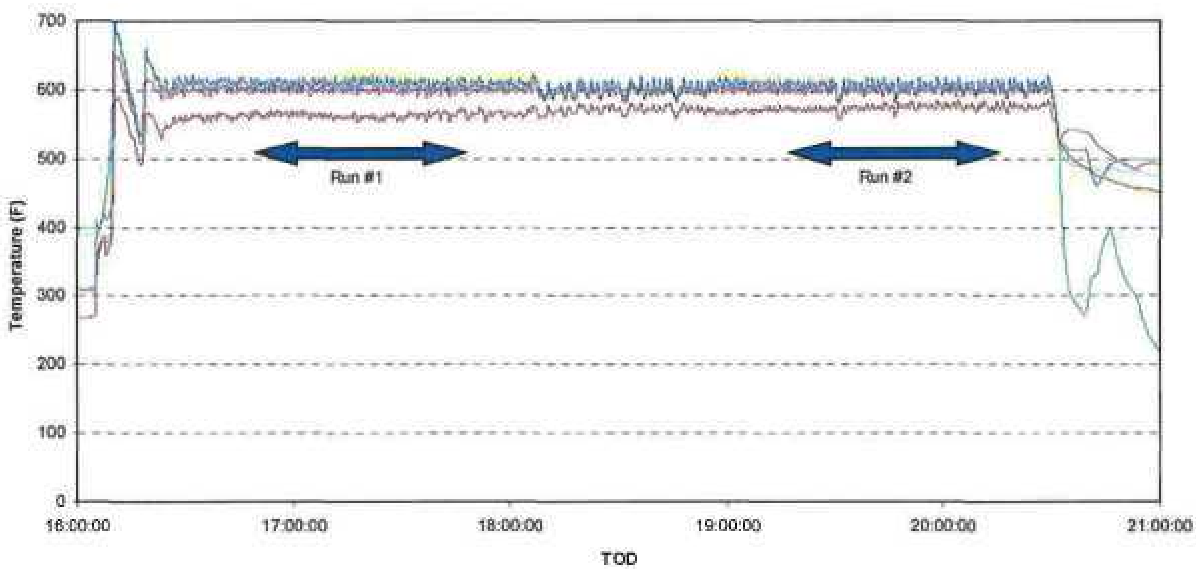

Figure 10. Bed temperature during coal upgrading test

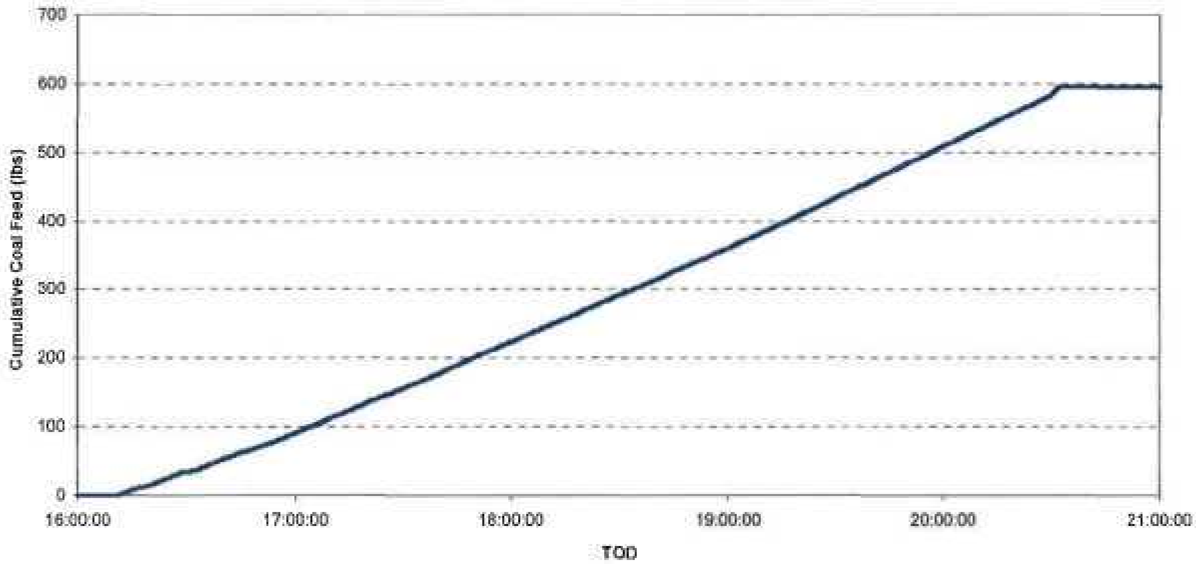

Figure 11. Cumulative coal feed during the test. Feed rate used was about 170 pph.

Solids Analyses

A total of five samples were submitted for mercury analysis. These included one sample of feed coal, three product samples and one sample of fines collected in the cyclone. Samples were analyzed using a LECO AMA 254 mercury analyzer. Following a standard procedure, the coal samples were dried in an oven at 140°C for at least 24 hours in order to determine moisture content. The "dried" samples were then analyzed for Hg content using a drying time of 60 seconds, a decomposition time of 250 seconds, and a wait time of 45 seconds. These analytical conditions have been found to be optimum for samples in other work. The results are displayed in Table 4.

Table 4. Hg content of coal samples

Sample ID	Hg Concentration As Received ppm	Moisture %	Hg Concentration Dry-Basis ppm
Feed	0.0504	23.23	0.0657
Fines	0.0561	<0	0.0561
Prod. #1	0.0258	<0	0.0258
Prod. #2	0.0213	<0	0.0213
Prod. #3	0.0240	<0	0.0240

From the data displayed in Table 4, it is clear that the FMI coal upgrading process not only removes the water from coal but in the process nearly 70 percent of the mercury present in the coal is also removed.

Stack Sampling

Air Pollution Testing, Inc. (APT) was contracted to perform the stack gas sampling. Two locations, fluidized-bed reactor outlet, and stack were selected for emissions monitoring. Simultaneous sampling was performed to determine the concentrations of oxygen (O_2), carbon dioxide (CO_2), moisture (H_2O), particulate matter (PM), elemental, oxidized, particle-bound and total Hg. The gas samples were withdrawn from each duct through a Swagelock fitting and though a Method 5 sampling train with a series of eight impingers immersed in an ice bath. Quartz, borosilicate glass or Teflon probes, filter holders, fittings, etc., were used as warranted.

Particle bound mercury was collected in the front half of the sampling trains. PM was determined gravimetrically from the front half filter and acetone probe wash at the APT laboratory in Wheat Ridge, Colorado. The filter and PM (or an aliquot) were then digested for further Hg analysis. Oxidized mercury was collected in the impingers containing a potassium chloride solution. Elemental mercury was collected in the subsequent impingers (one impinger containing an acidic solution of hydrogen peroxide and three impingers containing solutions of potassium permanganate).

All of the sampling data was combined with flow data to calculate the elemental, oxidized, particle-bound and total Hg concentration and emission rate in units of micrograms per dry standard (1 atmosphere and 68°F) cubic meter (µg/dscm), and pounds per hour (lb/hr). The results are summarized in Tables 5 and 6.

Table 5. Hg Emissions Data at Reactor Outlet

	Run #1	Run #2	Average
Particulate Emissions (lb/hr)	2.1	1.7	1.9
Particulate-bound Hg emissions (lb/hr)	1.01E-07	1.16E-07	1.09E-07
Oxidized Hg emissions (lb/hr)	5.29E-07	4.08E-08	2.85E-07
Elemental Hg emissions (lb/hr)	1.85E-05	1.46E-05	1.66E-05
Total Hg emissions (lb/hr)	1.91E-05	1.48E-05	1.70E-05

Table 6. Hg Emissions Data at the Stack

	Run #1	Run #2	Average
Particulate Emissions (lb/hr)	0.1	0.1	0.1
Particulate-bound Hg emissions (lb/hr)	6.15E-08	1.68E-08	3.91E-08
Oxidized Hg emissions (lb/hr)	5.38E-08	4.37E-08	4.88E-08
Elemental Hg emissions (lb/hr)	7.72E-06	5.83E-06	6.78E-06
Total Hg emissions (lb/hr)	7.83E-06	5.89E-06	6.86E-06

Water Analysis

One sample of produced water condensed during the test was submitted to Wyoming Analytical Laboratories for Wyoming DEQ Guideline 8 analysis. The results are displayed in Table 7 below. The data show that the Hg content of the produced water is 0.04 ppm.

Table 7. Report of Wyoming DEQ Guideline 8 Analysis

	Result	Reporting Limit
Aluminum, mg/L	3.37	0.01
Arsenic, mg/L	ND	0.02
Barium, mg/L	0.3	0.0003
Boron, mg/L	1	0.02
Cadmium, mg/L	ND	0.007
Calcium, mg/L	52.8	0.01
Chromium, mg/L	ND	0.02
Copper, mg/L	1.9	0.02
Iron, mg/L	2.3	0.01
Lead, mg/L	ND	0.02
Magnesium, mg/L	9.38	0.01
Molybdenum, mg/L	0.3	0.01
Manganese, mg/L	0.5	0.01
Mercury, mg/L	0.04	0.01
Nickel, mg/L	ND	0.01
Potassium, mg/L	15	0.01
Selenium, mg/L	ND	0.01
Sodium, mg/L	45.7	0.01
Zinc, mg/L	1	0.01
Chloride, mg/L	579	0.2
Fluoride, mg/L	ND	0.1
Sulfates, mg/L	927	0.1
Total Dissolved Solids, mg/L	3.01	NA
Total Recoverable Petrolium HCs, mg/L	830	0.1
Cations, me/L	125	
Anions, me/L	1506	

From the data presented above, it is clear that the FMI technology while producing an upgraded product from low-rank coals can also reduce the Hg content of the coals. A reduction of Hg content by nearly 70% was with a Powder River Basin subbituminous coal. The data also show that a large proportion of the mercury is retained in the process itself and does not report to the stack.

SPONTANEOUS COMBUSTION

Ever since coal drying research began, there have been concerns that dried coal has a propensity for self heating. The dried coal, when exposed to the atmosphere, rapidly adsorbs water vapor and oxygen and subsequently heats up and ignites. The adsorption of water vapor or oxygen and resultant oxidation is an exothermic reaction. This reaction can have an ultimate heat release that if not dissipated will promote self accelerating oxidation process and cause coal temperature to rise until it spontaneously ignites. In the case of FMI coal upgrading technology, the coal upgrading is carried out at a high temperature under oxidizing conditions. Therefore, once cooled, the likelihood of spontaneous combustion of the product at ambient conditions is reduced. In order to demonstrate the stability of the product, nearly two tons of product that was produced from Wyodak coal under standard operating conditions. A 4'x4'x4' pile was assembled and instrumented with thermocouples. A photograph of the assembly as it was being filled with upgraded coal product is displayed in Figure 12. A total of eight thermocouples (TCs) were installed in the coal pile. Five TCs were spatially distributed at the mid elevation (2 ft from ground), as shown in Figure 13. In addition there were two more TCs at the center at 1 foot and 3 foot elevation. One TC measured the ambient temperature above the coal pile.

Figure 12. Assembly of a 4'x4'x4' product pile

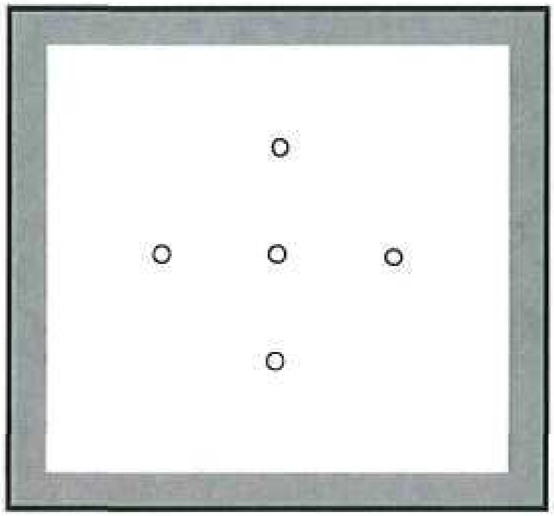

Figure 13. A schematic of the coal pile with TC locations

The temperature signals from the TCs were logged on a PC-based data logger for a period of 31 days. The temperature data are displayed in Figure 14. It is evident from the data logs in presented in the figure that the pile temperature at the locations being monitored did not exceed 100 F. All TCs installed in the pile showed a slow early rise in temperature for the first nine-to-ten days and then a steady decline. From the data it is quite clear that the coal pile was in no danger of spontaneous ignition.

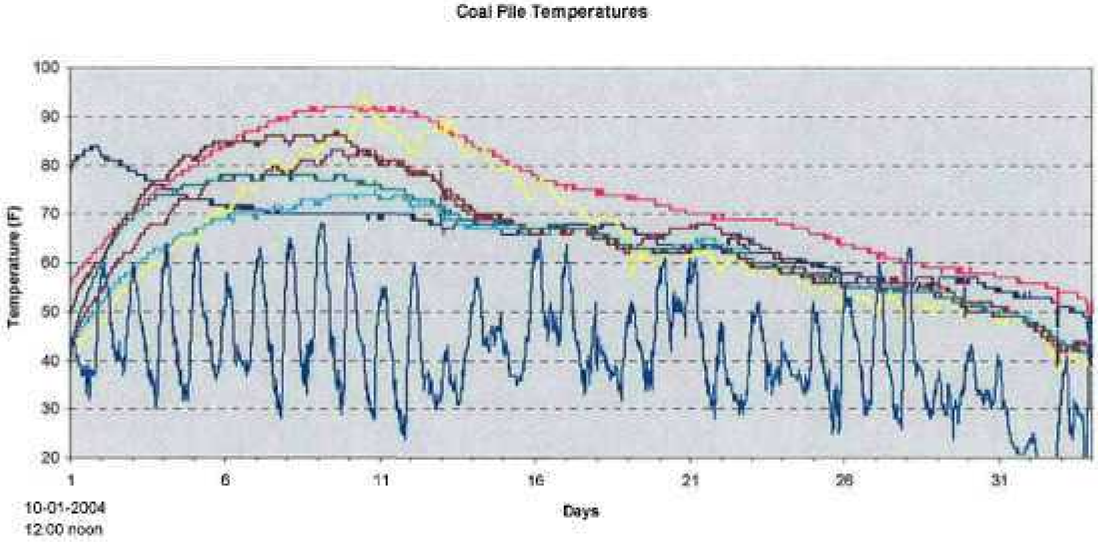

Figure 14. Temperature logs of a coal pile. Blue line shows ambient temperature

TECHNOLOGY STATUS

Based on the bench-scale data produced under this project, FMI contracted with Carrier Vibrating Equipment Inc., Louisville, Kentucky to build and test a 100-tpd plant at their facilities. A nominal 3-feet diameter fluidized bed was proposed. Figure 15 depicts a PFD for the plant. Working closely with WRI staff, plant fabrication and equipment shakedown was completed by Carrier Vibrating Equipment during the FY 2007. Photographs of the assembled plant are displayed in Figure 16.

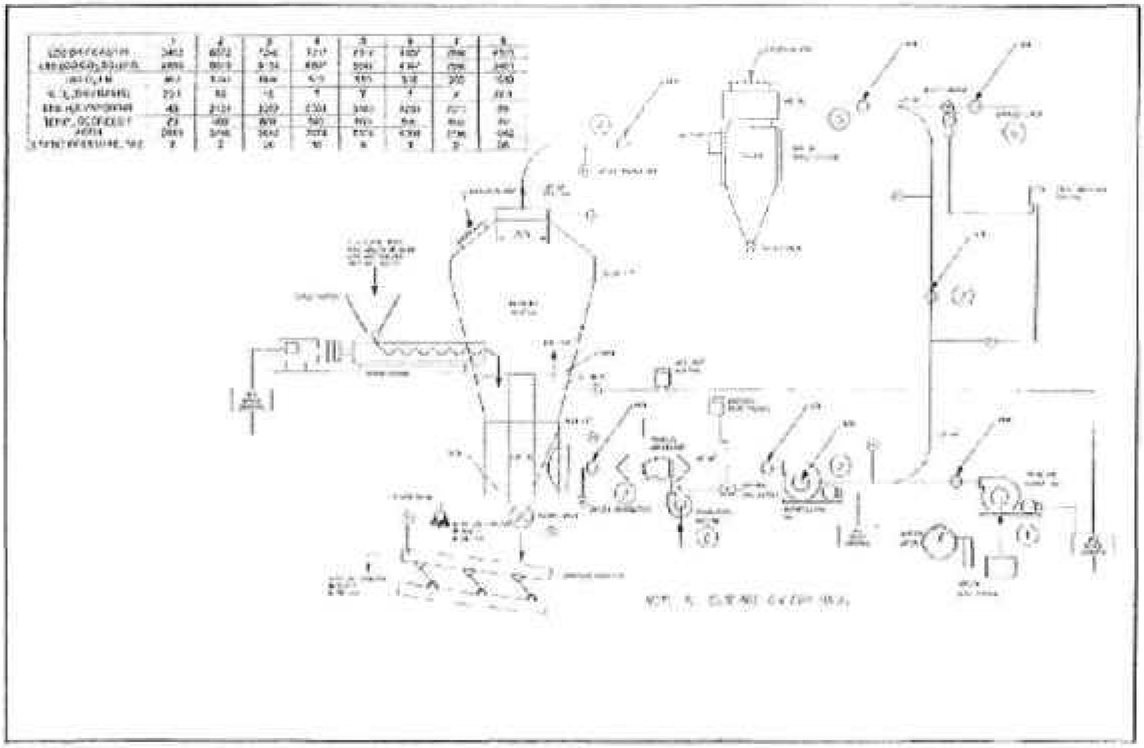

Figure 15. A process flow diagram for a nominal 100 tpd plant

Shakedown testing at Carrier identified some design issues including, turn-down. The plant as assembled uses a cyclone for particulate cleanup. Cyclone separation efficiency drops considerably when plant operations are attempted at less than the design conditions causing the fines to be entrained in the recycle gas stream thereby creating a potential hazard after extended operations. As a means to rectify the situation, among other modifications, a baghouse will replace the cyclone.

Figure 16. A photograph of the 100-ton per day plant

SUMMARY

WRI and FMI have collaborated to develop and test a novel coal upgrading technology. Proprietary coal upgrading technology is a fluidized bed-based continuous process which allows high through-puts, reducing the coal processing costs. Processing is carried out under controlled oxidizing conditions at mild enough conditions that compared to other coal upgrading technologies; the produced water is not as difficult to treat. All the energy required for coal drying and upgrading is derived from the coal itself.

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