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**Preparation and Combustion of Yugoslavian
Lignite-Water Fuel, Task 7.35**

**Topical Report
July 1991 - December 1993**

**Chris M. Anderson
Ray A. DeWall
Blazo R. Ljubicic
Mark A. Musich
John J. Richter**

March 1994

Work Performed Under Cooperative Agreement No.: DE-FC21-86MC10637

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of North Dakota
Energy and Environmental Research Center
Department of Chemical Engineering
Grand Forks, North Dakota

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PREPARATION AND COMBUSTION OF YUGOSLAVIAN LIGNITE-WATER FUEL

EXECUTIVE SUMMARY

While resource-rich countries such as the U.S., Canada, and Australia have no immediate need for the widespread use of alternative sources of energy, countries that have few natural resources, such as those in western Europe, Japan, and Korea, are actively pursuing the goal of reducing their dependence upon imported oil. To achieve that objective, the energy mix in those countries is being changed to include alternative coal-water fuels as an energy option to oil. Coal-water fuels are the most promising of all alternative coal-based fuels, and the traditional coal-exporting countries of East Central Europe will have a vested interest in supplying this new market for coal, which in coal-water fuel form becomes a value-added product. Converting this coal into an easily transported liquid fuel could make it an ideal candidate to displace not only costly imported oil, but also the more polluting high-sulfur coal from other mines in Eastern Europe. The economic merits of coal-water fuels are attractive because on a heating unit basis, coal is cheaper than oil. The quasiliquid form maintains that differential, since the higher cost of dry bulk coal handling and storage is avoided. The technology opens up new markets to coal producers, while it offers price stability and security of supply for the fuel end users.

Yugoslavia's interest in lignite-water fuel (LWF) stems from its involvement in an unusual power project at Kovin in northern Serbia. In the early 1980s, Electric Power of Serbia (EPS) proposed constructing a 600-MW power plant that would be fueled by lignite found in deposits along and under the Danube River. Trial underwater mining at Kovin proved that the dredging operation is feasible. Selective mining of the lignite seams has been demonstrated with high efficiency. The disposal area for the coal and waste has been developed, with successful implementation of the hydraulic transport system. Though hampered by United Nation sanctions, almost all planned testing activities have been performed. Dredger design parameters, required capacities, system availability, process reliability, and overall productivity requirements have been met. Convinced that the trial coal-dredging operations have fulfilled their objectives, the government of Serbia and the EPS have decided to continue developing the dredging technique and investing in the mine on a gradual basis for the next six years.

The dredging method produces a coal slurry containing 85% to 90% water. Plans included draining the water from the coal, drying it, and then burning it in the pulverized coal plant. In looking for alternative ways to utilize the "wet coal" in a more efficient and economical way, a consortium of Yugoslavian companies entered into a scientific agreement with the Energy & Environmental Research Center (EERC) to assess the conversion of dredged lignite into a LWF using hot-water-drying (HWD) technology. HWD is a high-temperature, nonevaporative drying technique carried out under high pressure in water that permanently alters the structure of low-rank coals. Changes effected by the drying process include irreversible removal of moisture, micropore sealing by tar, and enhancement of heating value by removal of oxygen, thus, enhancement of the slurryability of the coal with water.

The specific objective of this agreement was to evaluate the application of physical cleaning and HWD on dredged Yugoslavian lignite. Two samples were received from the

Danube dredging test area for bench-scale testing using EERC equipment. Physical cleaning results on one sample indicated a 51 wt% reduction in ash content with a 76 wt% yield for the lignite. In addition, physical cleaning produced a cleaned slurry that had a higher attainable solids loading than a raw uncleaned coal slurry. Combustion studies were then performed on the raw and physically cleaned samples with the results indicating that both samples were very reactive, making them excellent candidates for HWD. Bench-scale results showed that HWD increased energy densities of the two raw lignite samples by approximately 63% and 81%.

An order-of-magnitude cost estimate was conducted by the EERC to evaluate the HWD and pipeline transport of Kovin LWF to domestic and export European markets. For a 20-year plant life, the HWD capital costs were estimated to range from US\$65,670,000 to US\$172,000,000, while the HWD operating costs were estimated to range from US\$32,246,000 to US\$106,224,000, depending on plant capacity. The delivered selling price of LWF per MMBtu was estimated to be US\$3.90, US\$2.90, and US\$2.55 for a 1-, 3-, and 5-MMton/yr plant, respectively. Also for these plant sizes, the delivered selling price per ton was estimated at US\$46.8, US\$34.8, and US\$30.6. The pipeline operating cost for the described plant sizes was determined to be US\$865,000 to US\$1,445,000.

PREPARATION AND COMBUSTION OF YUGOSLAVIAN LIGNITE-WATER FUEL

1.0 INTRODUCTION

To meet growing energy demands in the province of Vojvodina, Yugoslavia, plans were prepared to mine the lignitic coal deposit along the Danube River. As a consequence, Project Kovin was implemented to produce 5.5 million tons per year of raw coal, with a stripping ratio of 4.2 meters³/ton (1). Core samples collected from a nearby trial dredging area were used to establish computer maps of the coal region for the full-scale dredging operation. The coal deposit is lignite with a heating value of about 7400 kJ/kg or 3180 Btu/lb. The main coal seam is about 8 meters thick with about 20 meters of overburden, and the second seam is between 30 and 40 meters below the surface, with the maximum mining depth estimated to be 65 meters. Because of the proximity of the Danube River, open strip mining techniques or conventional mining would have to operate under complex geological and hydrological conditions, making the mining difficult and economically questionable. Therefore, plans were implemented to use underwater mining with dredgers and hydraulic transport of the coal and overburden. The underwater mining takes advantage of the natural conditions surrounding the deposit.

In the dredging process, lignite is mined as a coarse, dilute coal-water slurry, using underwater bucket-wheel excavators. Six dredgers with bucket-wheel diameters of 4.5 meters will be operating on an artificially prepared pond. Two dredgers will be used for mining the first 30 meters, the next two will be used for mining between 30 and 45 meters deep, while the remaining two dredgers will excavate the seams between 45 and 65 meters deep. The dredging will be a continuous operation, each dredger equipped with three pumps used to transfer the dredged material to storage areas via 8000 meters of pipeline.

As part of the project, the consortium is considering the integration of several new technologies, i.e., dredging operations integrated with lignite-water fuel (LWF) production, followed by direct firing. Several potential markets exist for Kovin LWFs. The commercial LWF application extends to include industrial boilers, such as cement furnaces, agriculture drying systems, and sugar-processing power plants. A market also exists in utility power, with one of the most promising being to extend the use of coal from Kovin in a LWF pipeline network that will supply fuel for seven cogenerating power plants in the province of Vojvodina (2, 3). These plants would be used to generate electricity and heat for seven towns located in an area 200 km from Kovin. Figure 1 illustrates the scenario of dredging and hot-water drying (HWD) followed by pipeline transport. The great logistic advantages offered by the LWF transport technology could open markets for Kovin lignite even in western Europe. This is particularly the case for countries such as Italy, which could become large consumers of imported coals, but have been prevented by almost saturated port facilities and railways.

2.0 PROJECT OBJECTIVES

Hydraulic transport and handling procedures for coal are not widely used, but when practiced, they result in a technically and economically successful operation. The objective of this project was to determine the response of Kovin lignite to physical cleaning and

Figure 1. Conceptual representation of the commercial LWF production and distribution system at Kovin.

hydrothermal treatment. The EERC, Grand Forks, North Dakota, with support from the U.S. Department of Energy, entered into a jointly sponsored research project with Electric Power of Serbia (EPS), Belgrade, Yugoslavia, to investigate the application of an EERC-developed nonevaporative hydrothermal drying process, commonly called hot-water drying (HWD), to lignite from the Kovin deposit. The slurry form of the Kovin lignite was presumed to lend itself to potential upgrading by water-based treatment methods. To this end, an assessment of the fuel performance was made, using an integrated scenario that included cleaning prior to HWD in order to produce premium replacement fuel for retrofitted oil-fired boiler systems. The evaluation included combustion characteristics and combustion efficiencies of the potential fuels. The prospective fuel behavior of the mixtures was also determined with respect to a review of the potential pipeline system. In addition, a preliminary technical and economic evaluation for producing HWD LWF from Kovin lignite and transporting the HWD products as LWFs or slurries in a pipeline was performed. The specific tasks are outlined below:

- Representative samples of Kovin lignite were obtained and characterized in detail.
- Bench-scale washability analysis of Kovin lignite was performed to evaluate the potential for reducing the ash and sulfur content of the coal by physical cleaning.
- Drop-tube furnace testing was performed on raw and beneficiated Kovin lignite to compare some of the combustion characteristics. Evaluation was based upon carbon conversion.

- Bench-scale tests (autoclave HWD) for the production of LWF products were performed to determine the optimum HWD temperature and particle-size distribution. The solid, liquid, and gas streams were characterized.
- Both raw and HWD fuels from Kovin lignite were analyzed using the EERC atmospheric rheology system. Viscosity and theoretical velocity profiles and their correlating power requirements were determined from pressure drop information.
- The overall process economics, including those for pipeline transportation, were developed and presented in a final report.

After completion of initial bench-scale testing, efforts were made to receive a larger and more representative sample from the proposed test region to complete the bench-scale test and progress to pilot-scale testing. Originally, the next phase of testing would have included pilot-scale LWF production and combustion studies. However, because of the political unrest in Yugoslavia, shipment of three metric tons for the program to the EERC was not possible. Since the EERC was unable to receive a large coal sample, the bench-scale program was expanded for the two on-hand samples.

3.0 EXPERIMENTAL PROCEDURES AND RESULTS

3.1 Kovin Coal Sample Characteristics

Two 10-kg samples from the Kovin lignite region were received by the EERC, the first in 1989 and the second in 1992. Analysis conducted on the raw coal samples indicated vast differences between the two test coal samples. The sample received in 1989 (Sample #1) was from a region adjacent to the Danube. This sample is currently the feedstock for several pulverized fuel boiler systems in Yugoslavia. The sample was riffled and sized for HWD and physical cleaning experiments. Sizes prepared for testing included -6 mesh and -60 mesh. The proximate and ultimate analyses for this coal are presented in Table 1.

The second sample (Sample #2) was procured by an EERC representative who visited the Kovin dredge site in 1992. Approximately 3 kg of this sample was riffled and split into two fractions. Approximately 2 kg was sized and split into three fractions for static and centrifugal washability testing. The proximate and ultimate analyses for this sample are also presented in Table 1.

The most noticeable differences between the Samples #1 and #2 were in the sulfur and ash contents: Sample #1 had a much higher ash content, 26.2 wt%, compared to only 12.5 wt% for Sample #2. Sample #2 contained 3.5 wt% sulfur, while Sample #1 contained only 0.9 wt% on a moisture-free basis. Based on analyses conducted by the Yugoslavian consortium, Sample #1, with the higher ash and lower sulfur, was more similar to a core sample from the planned dredging region. It was concluded that the dredged sample received by the EERC, Sample #2, was not a representative sample for the planned dredging area. Yugoslavian personnel had determined that Sample #2 was obtained before the dredger had reached the main coal seam. Consequently, although bench-scale testing was conducted on both samples, the emphasis was placed on Sample #1.

TABLE 1

Comparison of Proximate and Ultimate Analyses
for Kovin Raw Coal Samples

Analysis	Sample #1 (1989)	Sample #2 (1992)
Proximate, mf ¹ , wt%		
Volatile Matter	45.3	50.8
Fixed Carbon	28.5	36.7
Ash	26.2	12.5
Ultimate, mf, wt%		
Carbon	47.1	59.8
Hydrogen	4.2	4.8
Nitrogen	0.5	0.5
Sulfur	0.9	3.5
Oxygen	21.0	18.8

¹ Moisture-free.

3.2 Bench-Scale Physical Cleaning

Float-sink testing using dense media or true heavy liquids is the standard method used to determine the washability characteristics of coals. Bench-scale washability analysis was performed with Certigrav[®] solution at specific gravities ranging from 1.3 to 1.6. Testing on the 6.3 mm x 850 μ m coal was performed by placing a 100–150-gram sample in standard float-sink flasks containing 1600 mL of Certigrav[®] solution. The test was considered complete when the coal separated into distinct float and sink fractions. The sink fraction was placed in a higher specific gravity solution until all of the coal had been fractionated into specific gravity ranges. Fine coal centrifugal separation with Certigrav[®] solution was used to supplement the standard washability information and to help to predict cleaning performance when cyclone separation was used. To quantify sulfur reduction and ash reduction obtainable with the two Kovin lignites, a washability test program was completed at several different specific gravities on –3.35-mm, –6.3-mm x 850- μ m, and –250- μ m lignite samples. All specific gravities were checked with a hydrometer to verify that solution specific gravities were maintained.

To interpret the data, a cleaning efficiency index was developed to evaluate the effect of physical cleaning. It was calculated by multiplying the ash reduction by the clean coal recovery (yield). In general, cleaning efficiencies of less than 15 are indicative of poor response to physical cleaning for the coal size investigated; values from 15 to 25 are considered acceptable.

3.2.1 Results from Sample #1

The results of a washability analysis of Sample #1 sized to –3.35 mm x 0 are presented in Table 2. These results indicate the coal was cleaned to an ash content of 11.0 wt% from 26.2 wt% at 1.3 specific gravity, but the recovery was around 50 wt%. A

TABLE 2
Sample #1 Washability Analysis

Particle Size	Specific Gravity Product	Recovery, wt%	Ash Content, wt%	Ash Reduction, wt%	Cleaning Efficiency Index
-3.35 mm x 0	1.3-Float	53.6	11.0	57.9	31.1
	1.4-Float	75.8	12.9	50.8	38.5
	1.5-Float	83.1	16.0	39.1	32.5
	1.6-Float	88.1	18.2	30.5	26.8

higher recovery (75 wt%) was obtained at 1.4 specific gravity with an ash content of 12.9 wt% and a cleaning efficiency index of 38.5, compared to 31.1 at 1.3 specific gravity.

The equilibrium moisture and moisture-free (mf) proximate, ultimate, and heating value analyses for the raw and physically cleaned Kovin lignite Sample #1 are presented in Table 3. Several improvements have been made to the coal, notably a decrease in ash content and significant increases in heating value and fixed carbon content. The moisture-free heating value of the raw coal increased from 7930 to 9500 Btu/lb because of physical cleaning.

The 1.4-float fraction of Sample #1 (-3.35 mm) was submitted for analysis and considered for experimental HWD feedstock. Proximate analysis indicated an overall reduction in ash content from 26.2 to 12.9 wt%. Sulfur analysis indicated only a slight decrease, since over 60% of the raw coal sulfur is organically bound. The theoretical uncontrolled emission of SO₂ (lb/MMBtu) was 2.3 for the raw coal and 1.7 for the physically cleaned coal. The analysis of the 1.4-sink fraction (-3.35 mm) showed that physical cleaning produced major improvements in the coal, with the ash content over 65 wt%.

The ash analysis of the raw coal and the physically cleaned fractions, included in Table 3, indicates that 70 wt% of the coal ash occurred as silicon and aluminum oxide (river sand and dirt). The physically cleaned coal ash analysis indicated a reduction in the silicon and aluminum oxide concentration to approximately 60 wt%. The ash analysis of the 1.4-sink fraction for Sample #1 indicates concentrations of silica and aluminum greater than 80 wt%. Titanium and potassium oxide concentrations were slightly reduced, while the other ash components did not appear to be significant in the sink.

3.2.2 Results from Sample #2

Washability testing was conducted on 6.3-mm x 850- μ m and -250- μ m fractions of Sample #2. The results indicated that more ash was liberated by cleaning the smaller size fraction. Acceptable cleaning results were achieved at 1.3 specific gravity with both size fractions. The 6.3-mm x 850- μ m fraction ash content was reduced from 12.5 to 8.6 wt%, while the -250- μ m fraction ash content was reduced from 12.7 to 7.4 wt%. The cleaning efficiencies for these two samples, shown in Table 4, were 18.8 for the 6.3 mm x 850 μ m and 29.1 for the -250 μ m.

TABLE 3

**Equilibrium Moisture, Proximate and Ultimate Analysis, Heating Value,
and Ash Analysis for Sample #1**

Analysis	Raw Coal	1.4-Float	1.4-Sink
Equilibrium Moisture, wt%	32.4	26.7	NA ¹
Proximate, mf, wt%			
Volatile Matter	45.3	51.7	24.0
Fixed Carbon	28.5	35.3	10.6
Ash	26.2	12.9	65.4
Ultimate, mf, wt%			
Carbon	47.1	56.0	18.6
Hydrogen	4.2	4.7	1.8
Nitrogen	0.5	0.7	0.4
Sulfur	0.9	0.8	0.5
Oxygen	21.0	24.8	13.3
Higher Heating Value, Btu/lb			
Moisture-Free	7930	9500	2620
@ Equil. Moisture	5370	6960	NA
Ash Component, mf, wt%			
(as oxides)			
Silicon	48.0	40.4	58.3
Aluminum	22.1	20.6	24.7
Iron	7.7	8.3	6.8
Titanium	0.9	0.7	1.2
Phosphorous	0.3	0.3	0.2
Calcium	7.4	11.8	2.9
Magnesium	4.3	5.3	1.9
Sodium	0.3	0.2	0.2
Potassium	1.2	1.0	1.4
Sulfur	7.8	11.4	2.5

¹ Not available.

The ash analysis of the raw coal and 1.3-float fractions of Sample #2 are included in Table 5. Physical cleaning reduced the silicon, aluminum, and iron oxide concentrations, and slightly decreased the magnesium oxide concentration. High calcium concentrations in the ash of the float fraction probably indicate an increase in the inherent sulfur capture capability of the coal. High iron and sulfur oxide concentrations would mean this coal contains a significant amount of pyritic sulfur, which was verified by the sulfur forms analysis shown in Table 6.

The raw -250- μ m 1.3-float fraction and a 6.3-mm x 850- μ m 1.3-float fraction were also submitted for sulfur forms analysis. The results are presented in Table 6. The analysis indicated the raw coal contained 3.9 wt% total sulfur with 53.8 wt% organic, 38.5 wt% pyritic, and 7.7 wt% sulfatic sulfur. Physical cleaning reduced total sulfur to

TABLE 4

Sample #2 Washability Analysis

Particle Size	Specific Gravity Product	Recovery, wt%	Ash Content, wt%	Ash Reduction, wt%	Cleaning Efficiency Index
-6.3 mm x 850 μ m	1.3-Float	60.2	8.6	31.2	18.8
	1.4-Float	64.7	9.1	27.2	17.6
	1.5-Float	75.8	10.3	17.6	13.3
	1.6-Float	88.9	11.1	11.2	10.0
-250 μ m x 0	1.3-Float	69.0	7.4	42.2	29.1
	1.4-Float	72.7	7.6	40.2	29.3
	1.5-Float	82.2	8.4	34.2	28.1
	1.6-Float	91.8	9.5	25.2	23.2

TABLE 5

Ash Analysis for Sample #2 Physically Cleaned Fractions

Sample	Raw Coal	1.3-Float, -250 μ m	1.3-Float, 6.3 mm x 850 μ m
Ash Content, mf, wt%	12.5	7.4	8.6
Ash Component, mf, wt% (as oxides)			
Silicon	12.6	8.5	6.7
Aluminum	7.0	6.0	5.6
Iron	28.4	22.2	26.5
Titanium	0.3	0.1	0.1
Phosphorous	1.1	0.6	1.1
Calcium	19.6	28.0	26.0
Magnesium	4.2	3.4	3.1
Sodium	0.1	0.2	0.1
Potassium	0.5	0.1	0.1
Sulfur	26.2	30.9	30.8

2.9 wt% for the 6.3-mm x 850- μ m fraction, with the pyritic sulfur being reduced to 0.8 wt% (28% of the total sulfur); yet the organic sulfur remained relatively unchanged. For the -250- μ m fraction, the total sulfur was reduced to 2.1 wt% (46.2 wt% reduction) and the pyritic sulfur reduced to 0.4 wt% (19% of the total sulfur). The organic sulfur component was reduced by 19 wt% for the -250- μ m sample. Because of high sulfur concentrations,

TABLE 6

Sulfur Forms for Sample #2

Analysis	Raw Coal	1.3-Float, -250 μm	1-3 Float, 6.3 mm x 850 μm
Total Sulfur, % (moisture-free)	3.9	2.1	2.9
Organic Sulfur, %	2.1	1.7	2.0
Pyritic Sulfur, %	1.5	0.4	0.8
Sulfate Sulfur, %	0.3	0.1	0.1

Sample #2 products were not considered suitable feedstock for HWD. Therefore, a complete analysis of the physically cleaned fractions was not performed.

3.3 Atmospheric Drop-Tube Furnace Testing

Two fuels were tested in the atmospheric drop-tube furnace (ADTF): raw and 1.4-float (physically cleaned) Kovin lignite. The raw and clean coals were pulverized in a lab-scale hammer mill and then air-dried to ensure uniform and unhindered coal feed. The proximate, ultimate, and heating value analysis, mean particle size, and particle density of the as-tested fuels are presented in Table 7. Particle-size analysis was performed by Malvern laser diffraction; particle density analysis was determined by dividing the bulk fuel density by $(1 - 0.45)$, where 0.45 was the assumed void fraction of the pulverized coals. Bulk density was calculated from the volume of a graduated cylinder occupied by a specific mass of coal. The mean size and density of the fuels were used in calculating required coal feed rates to achieve the specified average particle residence times.

ADTF testing was performed to compare the combustion performance of the raw and cleaned Kovin coals under similar combustion conditions and to observe the effects of physical cleaning on carbon conversions. The two fuels were fired in the drop-tube furnace at nominal temperatures of 800°, 900°, and 1000°C and at particle residence times of 0.2, 0.5, 0.8, and 1.1 seconds. Fixed parameters from test to test included oxygen concentration (20.9% atmospheric air), primary and secondary air flow rates (0.8 and 4.2 L/min, respectively), nitrogen quench flow rate (3.0 L/min), and total gas flow rate (8.2 L/min). Atmospheric pressure ranged from 0.963 to 0.979 atm, and sample gas temperature ranged from 28° to 31°C. The recorded variables included total coal fed, coal feed duration, and product gas composition; the calculated variables included average coal feed rate, molar rate of carbon in coal feed, molar rate of carbon in product gas, and carbon conversion. Table 8 presents the run conditions for each test and the primary recorded variables.

Carbon conversion was calculated from the molar rates of carbon in the fuel and product gas (CO and CO_2); calculation of molar rates of carbon (feed and product gas) and carbon conversion are presented in Appendix A. Molar rates of carbon in feed and product gas and carbon conversion results for each test are presented in Table 9. Plots of carbon conversion versus residence time at 800°, 900°, and 1000°C furnace wall temperatures for the raw and physically cleaned Kovin coals are shown in Figures 2 and 3.

TABLE 7

**Analyses for Raw and 1.4-Float Kovin Lignite Fuels
(ADTF-normalized)**

	Raw Coal	1.4-Float
Proximate, wt%		
Moisture	15.32	12.63
Volatile Matter	38.36	45.20
Fixed Carbon	24.13	30.87
Ash	22.18	11.31
Ultimate, wt%		
Hydrogen	5.24	5.47
Carbon	39.92	48.96
Nitrogen	0.45	0.64
Sulfur	0.77	0.73
Oxygen (difference)	31.44	32.91
Ash	22.18	11.31
Heating Value, Btu/lb	6720	8290
Mean Particle Diameter, μm	25.9	24.1
Particle Density, g/cm^3	0.89	0.87

Carbon conversion results indicated that within the accuracy of the ADTF test system, the raw Kovin lignite was very reactive, requiring relatively low combustion temperatures to achieve complete combustible burnout. Compared to several United States lignites tested in the ADTF, including those from North Dakota and Texas, comparable carbon conversions were achieved at temperatures 100°–200°C lower with the Kovin lignite. The physically cleaned coal had a more rapid burnout at up to 0.8 seconds residence time at 800°C, compared to the raw coal. The relatively few ADTF tests performed on the physically cleaned Kovin lignite limit conclusions regarding the effect of mineral reduction on combustion performance.

3.4 Bench-Scale HWD Test on Kovin Coal

The HWD tests with Kovin lignite were performed in the EERC 7.6-liter batch autoclave, shown in Figure 4. The bolted closure autoclave is externally heated and equipped with an automatic temperature controller and a variable-speed magnetically driven stirrer. The autoclave is instrumented to continuously measure and trend pressure plus slurry and vapor temperatures.

Approximately 4000 grams of a 50 wt% coal/50 wt% water slurry were used in each test. After slurry was charged to the autoclave, residual air was evacuated and the external heaters turned on. Heatup to the desired temperature took approximately 2.0 to 2.5 hours, after which the slurry and vapor temperature were allowed to stabilize. After a

TABLE 8

Run Conditions and Variables for Atmospheric Drop-Tube Furnace Testing

Particle Residence Time, s	T_w , ¹ °C	Coal Feed Rate, g/min		Product Gas Composition, vol% CO ₂ + CO	
		Raw	1.4-Float	Raw	1.4-Float
1.10	1000	0.104	---	1.11	---
0.80	1000	0.101	---	1.04	---
0.50	1000	0.104	---	1.06	---
0.20	1000	0.100	---	0.13	---
1.10	900	0.104	---	1.19	---
0.80	900	0.098	---	1.10	---
0.50	900	0.100	---	0.50	---
0.20	900	0.097	---	0.08	---
1.10	800	0.100	0.101	0.95	1.21
0.80	800	0.100	0.101	0.34	1.04
0.50	800	0.104	0.104	0.11	0.12
0.20	800	---	---	---	---

¹ Nominal furnace wall temperature.

TABLE 9

Results from Drop-Tube Furnace Testing

Particle Residence Times, s	T_w , ¹ °C	Carbon Feed Rate, g-moles/min (x1000)		CO + CO ₂ Flow Rate, g-moles/min 3(x1000)		Carbon Conversion, mol%	
		Raw	1.4-Float	Raw	1.4-Float	Raw	1.4-Float
1.10	1000	3.46	---	3.60	---	103	---
0.80	1000	3.36	---	3.31	---	100	---
0.50	1000	3.46	---	3.41	---	99	---
0.20	1000	3.33	---	0.43	---	12	---
1.10	900	3.46	---	3.91	---	112	---
0.80	900	3.26	---	3.57	---	109	---
0.50	900	3.33	---	1.60	---	48	---
0.20	900	3.23	---	0.24	---	8	---
1.10	800	3.33	4.12	3.02	3.84	92	94
0.80	800	3.33	4.12	1.07	3.31	32	82
0.50	800	3.46	4.25	0.39	0.34	10	9
0.20	800	---	---	---	---	---	---

¹ Nominal furnace wall temperature.

Figure 2. Carbon conversions of raw and physically cleaned (1.4-float) Kovin coals combusted at 800°C.

Figure 3. Carbon conversions of raw Kovin coal.

Figure 4. Schematic diagram of autoclave HWD system.

15-minute hold time, the heaters were shut off and the autoclave and contents allowed to cool overnight. The product recovery for each test was conducted approximately 16 hours after the sample was loaded into the autoclave. The slurries were continuously stirred from charging to recovery.

After cooldown, product gas was vented through a diaphragm meter to quantify production of noncondensable HWD products. A gas sample was taken and analyzed by off-line gas chromatography. The product slurry was recovered, weighed, and then separated into a damp HWD cake and a water stream via Büchner filtration. The mass of the HWD product and water fractions was determined for subsequent material balances. Fuels for rheological evaluation were prepared by blending damp cake and water at the desired solid concentration. The moisture concentration of the feed and products was determined by ASTM methods.

3.4.1 Results from Sample #1

Hot-water drying was performed on four samples of Kovin lignite. The $-250\text{-}\mu\text{m}$ raw coal was HWD at 275° , 300° , and 325°C , and a sample of physically cleaned coal was HWD at 300°C . The solids loading for feed slurries in the four tests ranged from 31.3 to 35.1 wt%, with viscosity ranging from 25 to 100 cP. Samples were collected of the product slurry, gas, and water for further evaluation. The product slurries were dewatered by Büchner filtration.

Tests were performed on the HWD process water to evaluate the amount of carbonaceous material, the recyclability of the stream, and best treatment methods. Water

analysis indicated that the total organic carbon (TOC), chemical oxygen demand (COD), and biological oxygen demand (BOD) concentrations increased as the temperature increased. The concentrations of these components in the condensate increased to a greater extent than in the filtrate upon temperature increase. The water analyses for these HWD tests are summarized in Table 10.

Gas analysis was performed using a Hewlett-Packard 5880a gas chromatograph to identify the gases produced during HWD. The results in Table 11 indicate that 95 wt% of the gas evolved as CO₂, which slightly decreases the reactivity of the coal. In addition, the results indicate that as the temperature increased, the amount of hydrogen, methane, hydrogen sulfide, ethane, and calculated heating value increased. Details of the instrumentation and techniques performed on the water and gas can be located in Appendix A.

Table 12 contains a summary of the results from the autoclave tests performed on Kovin Sample #1. The table contains the solids recovery and material converted to the gas and water phases. Energy recoveries for each of the four samples were above 90%. Table 13 summarizes the proximate, ultimate, and heating value for the raw and the HWD samples. The results indicated that HWD made several improvements in the coal, notably increases in heating value and carbon content and reductions in equilibrium moisture and oxygen content. The equilibrium moisture content decreased from 32.4 wt% for the raw coal to less than 20 wt% for the HWD coals. The test performed at 300°C produced the best HWD fuel, based on the heating value. The moisture-free heating value of the raw coal, 7930 Btu/lb, increased to 10,020 Btu/lb after hot-water drying at 300°C, and hot-water drying the physically cleaned coal increased the heating value to near 10,800 Btu/lb. The increase in heating value upon HWD was caused primarily by the reduction in oxygen

TABLE 10

Water Analysis for HWD Sample #1

Parameter ¹ , mg/L	HWD, 275°C		HWD, 300°C		HWD, 325°C	
	Filtrate	Condensate	Filtrate	Condensate	Filtrate	Condensate
SS	100	<20	330	<20	290	NA ²
TC	2,600	1,570	3,600	4,920	4,480	NA
TOC	2,900	1,850	4,100	5,640	5,120	NA
BOD	2,100	1,930	6,750	9,800	8,100	NA
COD	14,900	13,600	19,600	20,200	25,900	NA

¹ SS = suspended solids.

TC = total carbon.

TOC = total organic carbon.

BOD = biological oxygen demand.

COD = chemical oxygen demand.

² Not available.

TABLE 11

Gas Analysis for HWD Sample #1

	HWD, 275°C	HWD, 300°C	HWD, 325°C
Gas Generated, g	63.8	74.7	87.9
Gas Component, mol% (air-free basis)			
Hydrogen	0.2	0.2	0.4
Carbon Dioxide	96.1	95.6	94.8
Propylene	0.1	0.1	0.2
Hydrogen Sulfide	0.2	0.3	0.4
<i>iso</i> -Butylene	0.1	0.1	0.1
Ethylene	0.1	0.1	0.1
Ethane	0.0	0.1	0.2
Methane	0.7	1.1	1.7
Carbon Monoxide	2.5	2.3	2.0
Calculated Btu/scf			
Saturated	13.0	15.3	37.2
Dry	13.3	15.5	37.9
Calculated Specific Gravity	1.3	1.2	1.5
Calculated Average Mole Wt.	37.8	36.1	41.9

TABLE 12

Autoclave Test Summary for HWD Sample #1

Component	275°C	300°C	1.4-Float 300°C	325°C
Material Converted to Gas, %	6.8	7.9	9.7	9.4
Material Converted to Process Water and/or Process Losses, % (by difference)	4.5	4.5	11.9	6.9
Solids Recovery, %	88.8	87.6	78.5	83.8

content from decarboxylation and mild pyrolysis (4). The increase in heating value for physically cleaned HWD coal was because of the lower ash content. The theoretical uncontrolled sulfur dioxide emissions for these HWD samples were 2.2, 1.8, 1.7, and 2.3 pounds of SO₂/MMBtu for 275°, 300°, physically cleaned 300°, and 325°C samples, respectively.

TABLE 13

Equilibrium Moisture, Proximate and Ultimate Analysis, Heating Value,
and Ash Analysis for Sample #1 Raw Coal and HWD Coal

Analysis	Raw Coal	HWD, 275°C	HWD, 300°C	1.4-Float HWD, 300°C	HWD, 325°C
Equilibrium Moisture, wt%	32.4	14.5	18.7	12.6	19.9
Proximate, mf, wt%					
Volatile Matter	45.3	41.7	40.5	45.4	40.6
Fixed Carbon	28.5	31.7	33.6	40.9	32.5
Ash	26.2	26.6	25.9	13.7	26.9
Ultimate, mf, wt%					
Carbon	47.1	52.7	52.7	63.9	53.4
Hydrogen	4.2	4.4	4.1	4.8	4.1
Nitrogen	0.5	1.2	0.9	0.8	0.8
Sulfur	0.9	1.0	0.9	0.9	1.1
Oxygen	21.0	14.1	15.5	16.0	13.7
Higher Heating Value, Btu/lb					
Moisture-Free	7,930	9,190	10,020	10,780	9,520
@ Equil. Moisture	5,370	7,860	8,150	9,690	7,630
Ash Component, mf, wt% (as oxides)					
Silicon	48.0	50.7	49.0	43.5	51.3
Aluminum	22.1	23.6	22.2	21.3	24.0
Iron	7.7	7.5	11.8	6.6	7.8
Titanium	0.9	0.9	0.8	0.7	0.8
Phosphorous	0.3	0.3	0.3	0.1	0.2
Calcium	7.4	6.0	5.2	12.7	5.7
Magnesium	4.3	3.3	2.7	6.3	3.3
Sodium	0.3	0.2	0.2	0.5	0.2
Potassium	1.2	1.1	1.3	0.9	1.2
Sulfur	7.8	6.4	6.5	7.5	5.4

Ash analysis for the HWD Kovin samples is also included in Table 13. The results indicated no substantial differences in the ash for the raw and three HWD temperature samples, except for a slightly higher iron oxide concentration in the 300°C sample. This discrepancy was believed to be caused by sample variance or experimental error.

3.4.2 Results from Sample #2

Only a single HWD test was performed at 330°C on Sample #2. The results indicated 10.2 wt% of the coal solids was converted to the gas phase, and 6.8 wt% was converted to the water phase with a solids and energy recovery of 83.0 and 89.0 wt%, respectively. Table 14 summarizes the proximate, ultimate, heating value, and ash

TABLE 14

**Equilibrium Moisture, Proximate and Ultimate Analysis, Heating Value,
and Ash Analysis of Sample #2 Raw and HWD Coal**

Analysis	Raw Coal	HWD, 330°C
Equilibrium Moisture, wt%	30.3	7.6
Proximate, mf, wt%		
Volatile Matter	50.8	40.1
Fixed Carbon	36.7	45.8
Ash	12.5	14.1
Ultimate, mf, wt%		
Carbon	59.8	65.9
Hydrogen	4.8	4.2
Nitrogen	0.5	0.6
Sulfur	3.5	4.1
Oxygen	18.8	11.2
Higher Heating Value, Btu/lb		
Moisture-Free	10,430	11,800
@ Equil. Moisture	7,270	10,900
Ash Component, mf, wt%		
(as oxides)		
Silicon	12.6	13.2
Aluminum	7.0	7.8
Iron	28.4	31.2
Titanium	0.3	0.1
Phosphorous	1.1	1.2
Calcium	19.6	17.2
Magnesium	4.2	4.1
Sodium	0.1	0.0
Potassium	0.5	0.4
Sulfur	26.2	24.8

analysis for the raw and HWD sample. The equilibrium moisture content was reduced from 30.3 to 7.6 wt%, fixed carbon increased from 36.7 to 45.8 wt%, and oxygen decreased from 18.8 to 11.2 wt%, the latter because of decarboxylation. Although these fuel properties show sufficient improvements with HWD, the high sulfur concentration still makes this an unsuitable fuel. In fact, the theoretical uncontrolled SO₂ emissions were 6.7 and 6.9 lb/MMBtu for the raw coal and HWD coal, respectively, which is much above any allowable standards.

3.5 Rheological Analysis

The evaluation of the viability of a prospective liquid fuel relies on its particle-size distribution and the rheological or flow behavior of the fuel. The particle-size distribution contributes particle packing efficiency to the fuel and overall particle size. The packing

efficiency is important, because if the particles are too large, there will be more void spaces and lower packing efficiency, resulting in a decreased fuel solids concentration. The presence of smaller particles in the fuel causes the void spaces to be occupied, resulting in a better packing efficiency, which increases the fuel solids concentration. More information on the instrumentation used to perform particle-size analysis is described in Appendix A.

The rheological behavior for the lignite-liquid mixture, specifically the apparent viscosity, was determined as a function of shear rate and LWF solids concentrations using a HAAKE RV 100 viscometer. Figure 5 is a diagram of the rheological instrumentation used to measure the viscosity of the lignite-water slurries and LWFs. The HAAKE concentric cylinder viscometer shears the slurry sample in the annular space between a rotating cylinder and a stationary cup. The torque necessary to rotate the cylinder at a given speed is measured by a torsion spring. The stationary cup (stator) is surrounded by a tempering vessel, which is maintained at 25°C. More information on viscosity measurement can be found in Appendix A.

3.5.1 Results from Sample #1

Table 15 contains the results for particle-size distribution analysis on raw coal, physically cleaned 1.4-float coal, 300°C LWF, and the two physically cleaned 300°C LWF samples. Size degradation was observed following hot-water drying, with the fuel average particle size being 75% smaller than that of the raw coal. This same effect was observed with the physically cleaned 300°C LWF, which had an average particle size 66% smaller

Figure 5. HAAKE rheological measuring equipment.

TABLE 15

Particle-Size Distribution Analysis for Sample #1 Raw Coal, 1.4-Float, and LWFs

Particle Size, μm	Cumulative wt% under Size				
	Raw Coal	1.4-Float	300°C LWF	1.4-Float, 300°C LWF (A)	1.4-Float, 300°C LWF (B)
564	100.0	100.0	100.0	100.0	100.0
312	94.5	98.7	100.0	100.0	100.0
173	81.0	90.3	99.8	100.0	100.0
96	61.7	73.5	91.8	96.1	97.6
53	41.9	54.6	79.2	85.6	91.1
29	26.8	37.7	65.8	72.0	79.0
16	14.7	24.4	48.3	52.5	62.2
9	7.9	15.9	31.2	30.8	40.8
7	5.3	11.9	26.1	26.8	36.3
5	3.1	7.2	15.9	15.2	22.1
3	1.8	4.7	8.8	6.9	11.9
Estimated MMD ¹	67.7	45.8	17.4	15.3	11.4

¹ Mass mean diameter or average particle size.

than the physically cleaned coal. The rheology analysis, summarized in Figure 6, indicated that for the two physically cleaned LWF samples, the sample with a mass mean diameter (MMD) of 11.4 μm was preferred, yielding a fuel 4 wt% higher in solids concentration than the sample with a MMD of 15.3 μm . This was attributed to a broader particle-size distribution resulting in more efficient particle packing and reduced void spaces.

Figure 6 presents the viscosity profiles for the raw coal, physically cleaned coal, and LWF samples for Sample #1. The viscosities determined at a shear rate of 100 Hz indicated that slurries made from the raw coal contain 30 to 34 wt% solids with an increase in solids loading of 3 to 4 wt% achievable from physical cleaning alone. The increase in solids concentration was because of a reduction in silicon and aluminum contents and concentration of the calcium.

The rheological profiles in Figure 6 show significant improvements in the viscosity and solids concentration with HWD at 300°C. The solids concentration ranged from 42 to 48 wt% over a viscosity range of 100 to greater than 1500 cP. A significant difference observed between LWFs prepared from raw coal and physically cleaned LWFs was that a higher solids concentration was achievable with the physically cleaned LWF. The solids content for the first physically cleaned LWF (A) ranged from 45 to 50 wt% at viscosities of 100 to 1200 cP. At a viscosity of 500 cP, the solids concentration for the first physically cleaned LWF was 48 wt%, and the 300°C LWF was 45.6 wt%, the variance caused by physical cleaning. A similar increase was observed when the particle size was reduced. The second physically cleaned LWF (B) solids concentration ranged from 48 to 55 wt% solids at viscosities of 100 to 1500 cP. At 500 cP, this fuel has a solids concentration of 52 wt%, 4% higher than the first physically cleaned LWF.

Figure 6. Rheological results for Sample #1 raw, physically cleaned 1.4-float, 300°C and physically cleaned 300°C LWFs.

The rheological profiles in Figure 7 show the effect of HWD temperature on LWF solids concentration and viscosity. The results indicated that HWD definitely improves the solids concentration of the fuel. The differences that are observed at 275° and 325°C are attributed to decarboxylation, a greater amount occurring at the higher temperature. There is a definite improvement from HWD at 300°C in comparison to 275°C; however, only slight improvement between 300° and 325°C.

3.5.2 Results from Sample #2

Table 16 contains the particle-size distribution analysis for Sample #2 raw coal and 330°C LWF. These results indicate similar effects to those observed with Sample #1. The average particle size of the 300°C LWF was 66% smaller than that of the raw coal. The rheological results, summarized in Figure 8, reflect the particle size and HWD effects. Figure 8 contains the viscosity profiles for Sample #2, which achieved a greater benefit from HWD than the Sample #1 coals. Viscosities for raw coal, at 32 to 37 wt% solids, ranged from less than 100 to 800 cP, and for the HWD coal the solids ranged from 53 to 61 wt%, with viscosities from less than 100 to 1300 cP. At 500 cP, the solids concentration increased from 36 to 58.4 wt%, a greater than 12 wt% solids increase with HWD.

3.6 Pipeline Transport of Kovin LWF

One of the most carefully researched areas of dense-phase flow involves the hydraulic transportation of coal. It has been shown that very high concentrations of finely divided particles can be transported at reasonably low velocities (<1 m/sec) using a relatively high

Figure 7. Rheological results for raw and HWD Sample #1 fuels.

TABLE 16

Particle-Size Distribution Analysis for Sample #2 Raw Coal and 330°C LWF

Particle Size, μm	Cumulative wt% under Size	
	Raw Coal	330°C LWF
564	100.0	100.0
312	86.8	100.0
173	60.3	99.8
96	44.2	90.1
53	29.3	76.2
29	17.8	58.8
16	9.8	40.2
9	4.4	23.2
7	2.9	19.7
5	1.9	11.3
3	0.9	5.3
Estimated MMD	67.7	22.7

operating pressure. High-density coal slurries with several hundred centipoise apparent viscosity can be pipelined basically because laminar flow is acceptable, provided the homogeneity and stability observed in static tests holds true in pipelines.

Figure 8. Rheological results for raw and HWD Sample #2 fuels.

A computer program for non-Newtonian fluids developed at the EERC was used to analyze a frictional pressure drop. Inputs for the program are yield stress, consistency, and flow factor results from HAAKE viscometer analysis. Other inputs include pipe diameter, pipe roughness, length, solids loading, capacity, and slurry density. The program determines the total pressure drop, velocity profiles, and the amount of solids transported. The information is then used to determine an optimum slurry concentration (5).

The pumping pressure requirements of a slurry pipeline system are a function of slurry flow rate, slurry solids loading, density, particle-size distribution, pipe size, distance of transport, and transport route. The computer presents results from the analysis in a form that relates pump station power requirements to energy required for slurry transportation. These results are presented in Figures 9 and 10 for the various types of fuels.

Pump stations have to be located at various places along the pipeline. The positioning of these pump stations will depend upon terrain crossed, line size, and the economic balance between multiple pump stations and high-pressure design. Generally, pump stations are spaced at 100- to 150-km intervals, which means that acceptable energy input requirements would be in a range of 14 to 21 kW/mile or 0.04 to 0.06 kWh/ton-mile.

3.7 Conceptual Process Flow Sheets

The diagram in Figure 1 illustrates the conceptual scenario of dredging, HWD processing, and pipeline transportation. These unit operations are summarized in six distinct areas illustrated in Figure 11:

Area 100: Coal Dredging Operation
 Area 200: Coal Cleaning and Slurry Preparation
 Area 300: Slurry Heating and Product Separation
 Area 400: Fuel Recovery and Storage
 Area 500: Water Treatment and Storage
 Area 600: LWF Pipeline Terminal

3.7.1 Areas 100 and 200

The coal and overburden are dredged to the surface using an O&K Libek UCW 450 dredger. Six dredgers with bucket-wheel diameters of 4.5 meters will be operating on an artificially prepared pond. Two dredgers will be used for mining the first 30 meters, the next two will be used for mining between 30 and 45 meters, while the remaining two dredgers will excavate the seams between 45 and 65 meters deep. The dredging will be a continuous operation, each dredger equipped with 3 pumps used to transfer the dredged material to storage areas via 8000 meters of pipeline. The pumps will transport the coal slurry material through pipelines to the first separation section where most of the sand and gravel is removed from the coal and the slurry is concentrated to approximately 35 wt%. The coal is then crushed, sampled, and sized prior to being transferred to Area 200. In Area 200, coarse coal is sent to the dense-media vessel, while the finer coal is cleaned using a dense-media cyclone. The sink, or refuse, material from the separations are reconcentrated and sent to the refuse loadout station.

The cleaned coal float fraction is sent to four parallel rod mills to reduce the coal to an approximate average size of 75 μm . The rod mills are sized to accommodate a wide range of coal particle size and tonnage. The product from the rod mill is transferred to a series of mixing stations where particle size and solids concentration are further modified to ready

Figure 9. Comparison of pump requirements for Kovin LWFs.

Figure 10. Comparison of energy requirements for Kovin LWFs.

the coal slurry for the high-pressure pump system. Mass and magnetic flowmeters are located throughout Area 200 to quantify the amount of slurry being transferred. High-pressure pumps increase the slurry pressure from 1.5 to approximately 140 bars.

3.7.2 Areas 300 and 400

Pressurized slurry is transferred to Area 300, where it is heated to the selected temperature. The main heating zone heats a pressurized mixture of coal and water from 20° to near 300°C. Various heat-exchange options were reviewed based on pressure drop through the heating zone, thermal efficiencies, and cost of heat exchangers. Shell-tube heat exchangers were selected to be aligned in series to accommodate heating the slurry to approximately 300°C. Coal slurry will be sent through the tube side, while the heat-transfer medium is circulated through the shell.

After the slurry has been heated, it is then sent through reactors that provide residence time and additional slurry blending. The slurry is then transferred to vertical gas-liquid separators to remove a portion of the gas generated during slurry heating. This separation is to reduce the volume expansion, minimize foaming, and reduce erosion at pressure letdown stations located in Area 400. The pressurized gas removed is fired with supplemental natural gas to meet some of the in-house electricity needs. For the Kovin sample, it is estimated that approximately 12% of moisture- and ash-free (maf) coal is converted to gas during HWD via decarboxylation.

From the separators, product slurry heats the circulating heat-transfer medium to an intermediate temperature of approximately 260°C through a series of heat exchangers

EERC RD09941.CDR

Figure 11. Conceptual plant design.

before it is transferred to the booster heat section, a retrofitted oil-fired system fired on product LWF. Product coal slurry from Area 300 is sent to Area 400, where the recovery of the pressure letdown product occurs. Letdown valves reduce the pressure systematically to atmospheric conditions. The valves are selected based on their ability to handle flashing conditions with minimal erosion problems. After initial letdown, the slurry is transferred to hold tank separators equipped with a pressure or gas relief system. The slurry is then dewatered using a solid bowl centrifuge, and the product is transferred to a slurry tank where the cake is remixed to final fuel form with sufficient makeup water supplied from Area 500. The final product is assumed to have a solids content of 52 wt% and a viscosity of approximately 500 cP.

3.7.3 Areas 500 and 600

Area 500 is the main area of water treatment and storage for the plant. All of the process water from the plant is treated before being recycled back to the various process areas. The main unit operations for the plant are a cooling tower followed by systems for belt filtration, activated sludge treatment, and finally reverse osmosis (6).

Area 600 in Figure 11 shows a schematic of typical facilities disposition at the front terminal. Following preparation, LWF is transferred to tanks with a storage capacity of ten days of production. A collapsible bladder within the fuel storage tank eliminates air pockets above the LWF. As fuel is withdrawn from the bladder, it collapses onto the LWF surface, preventing any evaporation from the fuel surface. Before reaching the main pipeline, the fuel can be pumped through a safety, or test, loop with the same diameter as the main pipeline. The purpose is to monitor the main parameters of the fuel (flow rate, density, viscosity, and friction losses) that act on the pipeline control system, in case the characteristics of the fuel deviate from established operating parameters.

4.0 ECONOMIC EVALUATION OF LWF PROCESS SCENARIO

An order-of-magnitude economics study was performed on a 1-, 3-, and 5-million ton/yr LWF preparation plant and pipeline system. The process scenario was the delivery of LWF to the province of Vojvodina and to the seven cogeneration systems. The study was conducted using bench-scale data, previous cost data, vendor information, and reference handbooks (7-14). The estimated accuracy of about $\pm 30\%$ is considered suitable for preliminary screening of the HWD production. This type of estimate can yield sufficient information to establish the relative economics of a process and can be used to identify the key constraints in the development of the technology. However, it must be noted that the accuracy of each such estimate is highly dependent on the type, quality, and age of the original cost estimate. In addition to coal-specific variations, different site requirements, such as criteria for emission controls, waste treatment and disposal, and water use and discharge, can have significant effects on process economics.

One assumption made in preparing the cost evaluation was that the processing plant was to be located near the mining operation, with transport of the LWF by pipeline to the user. Based on bench-scale information, a physical separation at 1.4 specific gravity and HWD at 300°C were selected for the conceptual plant. The particle-size distribution was selected to be $-150\ \mu\text{m}$ for the final fuel. In addition, it was assumed that for the main unit operations, four parallel trains will be used to give the plant the flexibility to meet changing market demands.

4.1 Dredging Operation

As part of the review, Yugoslavian consortium members conducted a thorough review of the dredging technology versus a conventional mining system. Because of the complex geological and hydrological conditions, it was determined the dredging operation would require half the capital costs of conventional mining. The major cost savings for dredging is in the proximity of the coal to the river; underwater mining eliminates the need for clay curtains. The open pit operation would contribute 54.9% of the cost per kWh, compared to 45% for dredging. Table 17 summarizes the capital expenditures for a dredging operation.

Based on the capital expenditures, 30-year life, and the anticipated operating costs, the cost of the coal is estimated to be US\$15–US\$20 per ton (15).

4.2 LWF Preparation

The solids loading and heating value of the LWF, the total working days of the facility, and the capacity of the plant were the basis for determining the annual operating cost of the plant. Operating costs for the plant, listed in Table 18, were established by adding together the fixed costs, the variable costs, and all of the costs entailed in completing the manufactured product, plus the labor costs. The variable cost includes the raw materials costs, labor estimations, and the yearly utilities cost. Most of the operating costs are from the coal cost, estimated to be near US\$20 per ton. Cleaning results ensure that the product yields are approximately 70 wt%, while yields for HWD were assumed to

TABLE 17

Dredging Capital Costs (US\$K)

Mining Construction	3,325
Hydro-Civil Installations	8,524
Building Construction	18,694
Domestic and Imported Equipment	172,750
Working Capital	38,880
Contingency	<u>8,827</u>
Total Capital Cost	US\$251,000

TABLE 18

Operating Cost for Conceptual 3-MMton/year LWF Plant

	US\$/MMBtu in LWF	US\$/ton of LWF	US\$K/year
Variable Costs			
Coal Preparation	1.15	13.75	41,250
Labor	0.09	1.06	3,322
Utilities	0.08	0.97	2,905
Miscellaneous	<u>0.01</u>	<u>0.13</u>	<u>393</u>
	1.33	15.91	47,870
Fixed Costs			
Depreciation(12% for 20 y)	0.38	4.53	13,587
Maintenance (4% of total capital)	0.14	1.71	5,064
Overhead (2% of total capital)	<u>0.07</u>	<u>0.85</u>	<u>2,532</u>
	0.59	7.09	21,183
Total Operating Cost	US\$1.92	US\$23.00	US\$69,053

be 85 wt%. The overall product yields are approximately 60 wt% of the initial coal fed to the process unit. Estimated labor requirements for the LWF plant were determined using Yugoslavian employee wage rates and benefits. A miscellaneous category includes magnetite, heat-transfer medium, and various reagents and chemicals needed for water treatment.

Fixed charges are made up of the following principal items: depreciation, interest, maintenance, taxes and insurance, and overhead. Each was chosen based on chemical engineering reference materials and the process description. The maintenance and materials costs include a general maintenance cost for replacement parts and coal grinding supplies, estimated at 4% of the total capital cost. The overhead or annual plant upkeep cost was estimated at 2% of the total capital costs. Interest and depreciation are totalled by straight-line depreciation plus average interest of 12% over 20 years for current Yugoslavian conditions, assuming a salvage value of 15% of the capital investment. Taxes were not included in this cost analysis of fixed charges, but were considered for return on investment evaluations.

Total capital cost, summarized in Table 19, was made up of total plant cost and working capital. The factors used to determine installation, piping, electrical, engineering and fees, construction, contingency, etc., are also presented in Table 19. Current prices for the major equipment items were obtained as either written or verbal quotations from suppliers. Other equipment prices were obtained from internal files and published sources. The current cost estimations for various capacity plants were determined using the 0.6 scaleup rule and yearly cost indices.

TABLE 19

Capital Costs for Conceptual LWF Plant in Yugoslavia (US\$K)

Plant Size, MMton/year:	1	3	5
Direct Cost			
Delivered Equipment Costs (DEC)	23,500		61,550
Installation (10% of DEC)	2,350	4,530	6,155
Instrumentation (30% of DEC)	7,050	13,590	18,465
Piping and Elec. (25% of DEC)	5,875	11,325	15,388
Process Bldg. and Land (15% of DEC)	3,525	6,795	9,233
Total Direct Cost (TDC)	42,300	81,540	110,791
Indirect Costs			
Engineering and Fees (5% of TDC)	2,115	4,077	5,540
Process Contingency (30% of TDC)	12,690	24,462	33,237
Total Indirect Costs	14,805	28,539	38,777
Total Plant Cost (TPC)	57,105	110,079	149,567
Working Capital (15% of TPC)	<u>8,566</u>	<u>16,512</u>	<u>22,435</u>
Total Capital Cost	US\$65,671	US\$126,591	US\$172,002

The remaining other direct costs listed in Table 19 were approximated by referring to chemical engineering handbooks and other plant start-up costs in Yugoslavia (12, 13). The type of process, the cost of a high-temperature and high-pressure system, and location of plant were considered when rates for piping, installation, and instrumentation were determined. Indirect costs for the plant were estimated from chemical engineering reference material and based on direct cost information.

4.3 Pipeline Costs

The basic framework used to estimate coal slurry pipeline cost was adopted from work done by J.A. Warner (16). Although developed for freight pipelines, the method may be used as a guide or checklist for coal slurry pipelines. Since the Black Mesa pipeline is the only currently operating coal slurry pipeline, its cost experience provides the only reliable database available. However, Black Mesa cost experience could not be applied directly, and data pertaining to petroleum and natural gas pipeline were used as the basis for cost estimates in this study (17).

Pipelines are economically advantageous over other methods of transportation because, once constructed, they would be less subject to unpredictable, potentially rapid inflation and rapid escalation of total unit cost. Table 20 summarizes the results for estimated capital and operating costs for pipelines of various capacities. In the cost structure of pipelines, construction accounts for three-quarters of the total unit cost of coal transportation, while operating costs account for less than one-quarter, in contrast to railroads, which have substantially greater operating costs than capital costs (18). As the pipeline throughput capacity increases, the unit costs tend to decline. Therefore, the economic competitiveness of pipelines depends in part on their ability to take advantage of the economics of scale, i.e., to build larger and longer pipelines and to carry coal at their maximum capacity.

The basis for the delivered price was calculated using pressure-drop information and various pipe diameters. The evaluation indicated that the pressure drop for HWD LWF containing 52 wt% solids would actually be lower than for a conventional coal slurry pipeline containing less than 32 wt% solids. The economic results also indicated that the cost per ton-kilometer for 120-kilometer pipeline delivery from various capacity LWF plants is as follows: US\$0.244 for 1 MMton/year, US\$0.16 for 3 MMton/year, and US\$0.121 for 5 MMton/year.

4.4 Summary

Table 21 gives an approximate breakdown of the projected operating and capital costs for various plant preparation capacities. These costs have been based on using lignite from Yugoslavia and are relevant only for plant construction in that region. The criteria for financial analysis of the HWD process plant included 100% equity financing, 20-year plant life, declining rate depreciation switching over to straight line, 15% salvage value, and 10% after-tax rate of return. Also listed in Table 21 is the selling price for transporting the LWF 120 km to the user station via pipeline.

TABLE 20

Summary of Kovin Pipeline Economics

	1	3	5
Plant Size, MMton/year:			
Pipe Diameter, in.:	10	16	20
Capital Cost, US\$K			
Construction	12,468	30,000	38,940
Pump Station	389	648	907
Slurry Storage	4,554	8,558	9,506
Communication Facility	180	180	180
Miscellaneous	630	1,300	2,000
	US\$18,221	US\$40,686	US\$51,533
Operating Cost, US\$K			
Labor	540	540	540
Energy	96	160	224
Water	50	150	250
Repair and Supply	100	200	300
Miscellaneous	79	105	131
	US\$865	US\$1,155	US\$1,445
Estimated Unit Cost (US\$/ton-km)	0.244	0.160	0.121

TABLE 21

Costs for Conceptual Kovin LWF Plant and Delivered Prices

Plant Size, MMton/year:	1	3	5
HWD Capital Costs, US\$K	65,670	126,590	172,000
HWD Operating Cost, US\$K/yr	32,246	69,052	106,224
Selling Price, del., US\$/MMBtu	3.90	2.90	2.55
Selling Price, del., US\$/ton	46.8	34.8	30.6

5.0 CONCLUSIONS

In summary, Kovin LWF slurry pipelines may indeed reduce the delivered cost of coal and thus provide substantial savings to electric utilities and, ultimately, to electricity consumers. The successful introduction of the Kovin coal slurry technology into the European marketplace as a replacement for oil has significant advantages. New technology is capable of solving most logistic problems related to the use of coal. This could be accomplished by adopting the principles for transport of any liquid fuel and by obtaining the same combustion performance for LWF as for dry pulverized coal. The intent of implementing LWF as a primary fuel and developing a clean use of coal with reduced environmental impact during handling, transportation, and combustion is to diversify

Yugoslavia's primary energy sources and reduce Yugoslavian dependence on oil. Developing a fuel with a mixture of lignite and water solves the stability problems by producing a safe, easily transported, liquid fuel that can be handled and used like oil. This process offers an efficient method to "dewater" low-rank coals and permanently alter the coal surface to allow formulation of an environmentally benign, easily transportable liquid fuel.

The Yugoslavian energy sector has been devastated by ongoing war, reshuffling energy flows into several separate zones. War damage, closure of the Adria-Trans Yugoslav oil pipeline, United Nations sanctions, and the collapsing economy are the most influential parameters in the Yugoslavian energy equation at the moment. But whatever the outcome of the civil war, major concerns will be, again, imported oil and increasing environmental restrictions on conventional power plants. These factors are going to drive the Yugoslavian postwar energy sector reintegration and development of alternative energy sources. According to Electric Power of Serbia, as dredging technology becomes more widely accepted, more focus will be placed on the technology's performance. With the technology's maturity, corresponding improvements will be realized in the overall process economics. Because of this, dredging and HWD now make LWF a viable electric utility power generation option in Yugoslavia.

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APPENDIX A:
ANALYTICAL EQUIPMENT
AND PROCEDURES

ANALYTICAL EQUIPMENT AND PROCEDURES

The Energy & Environmental Research Center (EERC) has researched numerous drying and conversion technologies that can be applied to lignite and subbituminous coals to upgrade the quality of the coal. Table A-1 summarizes the test procedures used to analyze the coal samples for this project.

PROXIMATE AND ULTIMATE ANALYSIS

Proximate analysis (moisture, ash, volatile matter, fixed carbon) was performed on the raw and treated coal using a Fisher® coal analyzer. The instrument determines

TABLE A-1

Analytical Equipment and Procedures

<u>Analysis</u>	<u>Equipment</u>	<u>Procedure</u>
Hot-Water Drying	Two-Gallon Autoclave	NA ¹
Fuel Viscosity	HAAKE® Rotoviscometer RV 100	NA
Particle Size	Malvern® 2600c Laser Diffraction Analyzer	NA
Gas Analysis	Hewlett-Packard® 5880a Gas Chromatograph	NA
Carbon	Leco® CHN 600 Analyzer	NA
Hydrogen	Leco® CHN 600 Analyzer	NA
Nitrogen	Leco® CHN 600 Analyzer	NA
Sulfur	Leco® Induction Furnace	ASTM D3177
Sulfur Forms	NA	ASTM D2492
Heating Value	Parr® Adiabatic Calorimeter	ASTM D2015
Equilibrium Moisture	NA	ASTM D1412
Moisture	Fisher® Coal Analyzer	ASTM D3175
Volatile Matter	Fisher® Coal Analyzer	ASTM D3175
Ash	Fisher® Coal Analyzer	ASTM D3174
Ash Characterization	KeveX® Energy-Dispersive X-Ray Spectrometer	NA
Combustion Behavior	Drop-Tube Furnace (DTF)	NA

¹ Not applicable.

moisture at conditions specified in ASTM D3175. Volatile matter is determined by heating the dried sample to 950°C in a nitrogen atmosphere at conditions specified in ASTM 3175. The sample is covered during this process in order to exclude oxygen and prevent the sample from being ashed. Following the volatile matter determination, the sample is uncovered and combusted, and the ash is determined at conditions specified by ASTM D3174. Fixed carbon is determined by difference, following the previously described methods.

Ultimate analysis determines carbon, hydrogen, nitrogen, sulfur, oxygen, and ash content in a sample. Carbon, hydrogen, and nitrogen (CHN) content are determined using a Leco® CHN-600 analyzer. Carbon and hydrogen are determined by infrared cells, and elemental nitrogen is measured by a thermal conductivity cell. This method gives the total percentages of CHN in the organic sample as analyzed and includes the carbon in carbonates and the hydrogen in the moisture and in the water of hydration of minerals. Sulfur is determined using a Leco® SC-132 sulfur analyzer in which a sample is combusted in oxygen, forming sulfur dioxide, which is determined by an infrared cell detector. Ash is determined by the ASTM method described under proximate analysis. Oxygen is determined by difference in order to achieve a balance of the ultimate analysis. Forms of sulfur are determined according to ASTM D2492. Ash characterization is determined using x-ray fluorescence techniques using the equipment in Table A-1.

RHEOLOGICAL CHARACTERIZATION

The rheological properties are determined based on the Yield Power Law equation for fluids. The HAAKE® RV 100 viscometer is used to measure the flow properties of various liquid fuels from shear rates of near zero to 1100 sec⁻¹ (Hz), over a temperature range of 4° to 95°C. Results from the HAAKE® are logged and compiled using a computer network system. The computer indicates the independent flow behavior, viscosity, and yield stress values for the fluid as each correlates to the Yield Power Law. The HAAKE® viscometer shears the slurry in the annular space between the rotating cylinder and a stationary cup. The torque necessary to rotate the cylinder at a given speed is measured by a torsion spring. Various rotor assemblies allow the user a complete profile of the rheological characteristics. Rheological data are used to assess the effect of the hot-water drying (HWD) process variables on the relationship between viscosity and dry solids concentrations.

PARTICLE SIZE

The particle-size distribution of the raw and HWD coal are determined using a Malvern® 2600c laser diffraction particle-size analyzer, capable of measuring particle sizes from 0.5 to 564 microns. Figure A-1 depicts the Malvern® instrument setup. The basic principle of the Malvern® involves a He-Ne low-power visible wavelength laser that is first expanded and spatially filtered to provide a clean parallel beam. As particles pass through the beam, they scatter or diffract the light at different angles, depending upon their diameter; large particles scatter at small angles and vice versa. The scattered light is collected by a lens and brought to focus on a multielement solid-state detector that simultaneously measures the light at a number of angles. During analysis, the sample

Figure A-1. Malvern® instrument setup.

particles move rapidly through the laser beam. The results indicate the volume percentage distribution, as well as reporting the average particle size.

EQUILIBRIUM MOISTURE

The moisture contents of the raw and HWD coals as a function of incubation time are determined using a standard or modified ASTM equilibrium moisture method. The standard equilibrium moisture tests use an incubation time of 3 or 4 days, while the modified test uses incubation times of 2 to 30 days. The extended time period is used because the standard 3 or 4 days is often too short to allow the raw and HWD low-rank coals to attain an equilibrium moisture.

PROCESS WATER ANALYSIS

Various tests are performed on the process water produced during HWD to evaluate the amount of carbonaceous material, the recyclability of the stream, and treatability. The most widely used parameter of organic pollution applied to both wastewater and surface water is the 5-day biochemical oxygen demand (BOD). The BOD test is completed on the water sample to measure the oxygen required for the biochemical degradation of organic material and the oxygen used to oxidize inorganic material. The BOD is computed from the difference between initial and final dissolved oxygen. The chemical oxygen demand (COD) test is used to measure the content of organic matter of both wastewater and natural waters. The COD of a waste is, in general, higher than the BOD because more compounds can be chemically oxidized than can be biologically oxidized.

For many types of wastes, it is possible to correlate COD with BOD. This can be very useful because the COD can be determined in three hours, compared to five days for the BOD. Once the correlation has been established, COD measurements can be used to good advantage for treatment plant control and operation. Total organic carbon (TOC), another means for measuring the organic matter present in water, is especially applicable to small concentrations of organic matter. To determine the quantity of TOC, the organic molecules must be broken down to single carbon units and converted to a single molecular form that can be measured quantitatively. TOC methods utilize heat and oxygen, ultraviolet irradiation, chemical oxidants, or combinations of these oxidants to convert organic carbon to carbon dioxide. Total carbon (TC) is determined by taking a quantity of sample and analyzing directly using an infrared carbon analyzer. In order to determine TOC, the sample must be sparged of the inorganic carbon (IC). Total solids determination is also performed on the sample. This includes total dissolved solids (TDS) and total suspended solids (TSS). TSS includes the portion of total solids retained by a filter, and TDS is the portion of the total solids that passes through the filter.

GAS ANALYSIS

Gas analysis is evaluated using a Hewlett-Packard® Model 5880a gas chromatograph with a refinery gas analyzer package used to detect selected gases in process gas samples. The method of detection is based upon relationships of thermal conductivity of the various gas compounds. The refinery package consists of five different absorbing columns and four heated valves for column switching. The instrument uses two carrier gases, and hydrogen is used for the determination of CO₂, CO, O₂, N₂, H₂S, and carbon chains C₁ through C₆ hydrocarbons. Argon is used for the determination of helium and hydrogen.

BENCH-SCALE COMBUSTION CHARACTERIZATION

The atmospheric drop-tube furnace (ADTF), shown in Figure A-2, is a laboratory-scale, entrained flow, tube furnace designed to combust coal and produce ash under closely controlled conditions. The ADTF can be configured using key operational parameters to produce results similar to those that would be observed in a full-scale boiler. Key parameters include gas temperature, gas velocity, particle residence time, and excess air.

The drop-tube furnace system consists of coal feed, primary air injection, secondary air preheat and injection, main furnace, gas sampling and analysis, and particulate collection subsystems. The coal feed system is designed to feed particles of various sizes in the pulverized coal range at rates of 0.05 to 0.5 g/min. The apparatus shown in Figure A-3 consists of a pressurized cylinder housing a container filled with coal. A rotating brush and stirrer driven by a variable-speed motor feeds the coal from the container into a funnel, where it is transported by the primary air (1 L/min) through tubing into the furnace injector. The coal feeder is mounted on a top-loading balance that is digitally interfaced with a personal computer to record and store real-time coal feed rates.

Figure A-2. Drop-tube furnace test facility.

Figure A-3. Drop-tube furnace coal feeder.

The furnace assembly consists of a series of vertical tube furnaces, illustrated in Figure A-4, which possess a total of four independently controlled, electrically heated zones. The furnaces are mounted on support bars and can be moved to accommodate specific furnace configurations. Maximum flexibility and control of combustion conditions are achieved by operating the furnaces separately or in conjunction with adjacent furnaces.

Coal, primary air, and secondary air are introduced into the top of the furnace system via a preheat injector. This system injects ambient primary air and coal through a water-cooled probe assembly positioned at the center of the tube. Secondary air, typically heated to 1000°C, is introduced into the furnace through a mullite flow straightener. The coal, primary air, and secondary air descend the length of the furnace in a laminar flow regime. Combustion air is added in excess to provide sufficient oxygen for coal combustion.

An alumina-insulated, short residence time probe (Figure A-5), inserted a predetermined distance into the bottom of the furnace, is used to collect char and residue samples. The probe insertion distance is calculated based on the desired particle residence time and the linear velocity of the particles descending under laminar flow. The probe consists of a series of four concentric steel tubes with combustion products passing through the innermost shell. Further coal combustion is inhibited by two quick quench

Figure A-4. Drop-tube furnace cross-sectional illustration.

Figure A-5. Drop-tube furnace short residence time probe.

methods: injecting room temperature nitrogen directly into the gas stream at the top of the probe and indirect heat exchange with cooling water. The char and residue are collected on a filter attached to the innermost shell of the probe.

Downstream of the sampling probe and collection filter, the combustion gas is cooled further and passes through a secondary filter before entering a diaphragm pump. The pump is designed to eliminate air leakage into the sampled gas. The pressurized gas exhausted from the pump passes through a flowmeter that measures the volume of gas being drawn through the probe. A gas slipstream is directed through carbon monoxide, carbon dioxide, and oxygen analyzers. The volume concentrations of these gases can be read directly from the analyzer digital readouts. The gas concentrations are logged by the PC and a chart recorder for subsequent data interpretation. The configuration of this system is shown in Figure A-6.

ADTF CARBON CONVERSION METHODOLOGY

Determination of carbon conversion by direct on-line analysis of the gaseous combustion products (CO and CO_2) offers an accurate, real-time indication of the viability of individual tests. The molar feed rate of carbon is calculated from the coal feed rate and the ultimate analysis carbon content of the as tested in the drop-tube furnace (DTF). The molar flow rates of combustion products (CO_2 and CO) are calculated from the product gas

Figure A-6. ADTF gas sampling and analysis system configuration.

flow rate and the ideal gas law ($PV = nRT$). The carbon feed rate and the molar flow rates of CO_2 and CO are defined by:

$$C_{\text{influent rate}} = \frac{C_c}{100} \cdot (\text{coal feed rate}) \cdot \frac{1 \text{ mole C}}{12.0 \text{ grams C}}$$

$$\text{CO}_2 \text{ effluent rate} = (\text{gas flow rate}) \cdot \frac{\text{CO}_2}{100} \cdot \left(\frac{P}{760 \text{ mmHg}} \right) \cdot \frac{1}{(R \cdot T_K)}$$

$$\text{CO effluent rate} = (\text{gas flow rate}) \cdot \frac{\text{CO}}{100} \cdot \left(\frac{P}{760 \text{ mmHg}} \right) \cdot \frac{1}{(R \cdot T_K)}$$

where C_c is the as-DTF-tested coal carbon content (wt%), P is the barometric pressure (mmHg), R is the universal gas constant (0.0821 L-atm/mole-K), T_K is the average as-analyzed gas temperature (K), and CO_2 and CO are the quench-nitrogen-free product gas concentrations (vol%).

The percent carbon conversion is defined by:

$$\text{Carbon conversion} = \frac{CO_2 + CO_{\text{effluent rate}}}{C_{\text{influent rate}}} \cdot 100\%$$

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