Production of Clean Coal with Low Ash Content for Coal-Water Slurry by Laboratory Type Multi-Gravity Separator and Mozley Table, *Mursel Celik, Ismail Yildirim, Gunduz Atesok, Istanbul Technical University, TURKEY*

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Clean & Efficient Power with High Ash Coals Through Retrofitting, *O.P. Rao and B. Madhusudhan, Council of Scientific and Industrial Research, INDIA*

This paper was received after pagination and is located on Page 757 of these Proceedings.

DEVELOPMENT FOR PRODUCTION TECHNOLOGY OF CWM FROM LOW-RANK COALS

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ABSTRACT

The continuous upgrading tests by a small scale system were conducted using the five LRC. It was found that CWM concentration of each coal remarkably increased through the hot water drying (HWD) treatment.

A 8.4 t/d pilot plant designed through the results of continuous small-scale test was completed in November 1994. Experimental operation for a series of tests have been carried out since December using one brand of subbituminous coal. This paper presents mainly outline of the 8.4 t/d pilot plant system and demonstration test plan.

INTRODUCTION

Coal reserves are abundant among fossil fuel resources and are deposited widely throughout the world, but the coals presently being utilized are mainly high rank coals such as anthracite and bituminous coal. On the other hand, effective use of low-rank coals (LRC) is one of the most attractive project in the field of coal utilization technology. However, there are many difficulties originating from characteristics of the coals. The high moisture content incurs a large transportation cost per unit of energy and the reactivity in the air results in the danger of spontaneous ignition. Consequently, most LRCs have been limited to be consumed by local users by mine mouth power plants. Therefore, up-grading treatment of LRC is required to increase the utilization of LRC.

Against this background, Japan COM Co., Ltd. and JGC Corp. have been jointly conducting research and development of LRC upgrading technology to establish CWM production and utilization technologies from upgraded coals at lower cost and higher quality. This project began in 1991 and will continue until March 1996, financially supported by the Coal Utilization Technology Promotion Fund of the Ministry of International Trade and Industry (MITI) under the direction of the Center for Coal Utilization, Japan (CCUJ). This study finally aims at the development of upgrading technology for LRC and at production of CWM from the up-graded LRC at low cost.

After finishing construction work of the pilot plant in November 1994, the operation is now conducted.

The objectives of this project are as follows;

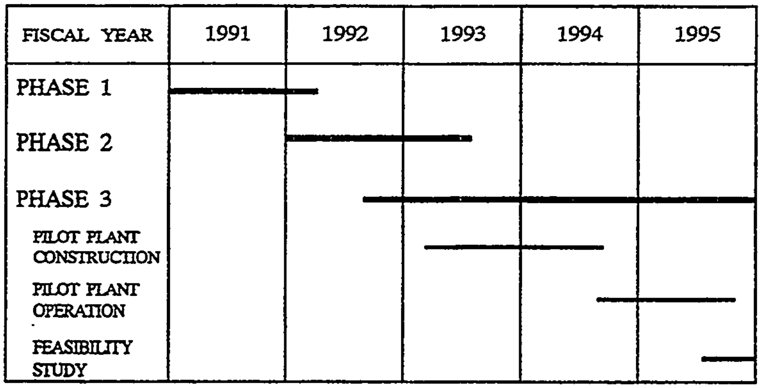
- Development of technology to upgrade subbituminous and brown coals
- Establishment of technology for producing CWM from these upgraded coals
- Evaluation of the combustibility of the CWM from the upgraded coals and their acceptability as a feed stock for a coal gasification reactor.
- Confirmation of economic feasibility for commercialization of the above technology

This paper presents mainly the outline of a pilot plant system which was designed through the results of continuous testing by a small-scaled plant (bench plant) and demonstration test plan.

OUTLINE OF THE PROJECT

Table 1 shows R&D schedule of the project.

Table 1 R/D schedule



The contents of the research and development in each phase of the following;

1) Phase 1
- Evaluation of CWM from upgraded coals in lab-scale tests
- Survey of existing coal upgrading technologies
- Investigation of low rank coal resources
- Design of a bench-scale upgrading plant

2) Phase 2
- Construction of the bench-scale plant and development of the optimum upgrading conditions
- Preparation of CWM with the upgraded coals

3) Phase 3
- Design, construction and operation of the pilot plant
- Production test of CWM from the upgraded coals
- Scale-up study on the above stated plant
- Combustion and gasification tests of the CWM
- Feasibility study of overseas large-scale CWM plant

Based upon our preliminary investigation already conducted in Phase 1, it was concluded that the hot water drying (HWD) process would be the most promising technology for the upgrading of LRC and production of CWM from them [1]. Consequently, we are conducting research and development of LRC upgrading mainly based on the HWD method [2][3]. A 8.4 t/d pilot plant in Phase 3 was completed its construction in November 1994, and is presently being operated following the bench-scale testing in Phase 2.

It is considered that the technical key points to fulfill the above objectives on upgrading LRC are to minimize the loss of volatile matter to avoid loss of calories of the coal, reduce a carboxyl group content on the surface of the coal, and reduce inherent moisture through HWD treatment.

REVIEW OF RESULTS OF BENCH TEST

Figure 1 indicates a 10 kg/h continuous bench system. HWD treatments of five low rank coals were conducted using the bench plant. Table 2 shows the results of HWD treatment of these coals and their slurryability test compared with batch tests by an autoclave [4][5]. As shown in Table 2, inherent moisture and carboxyl group content in each coal were reduced through the treatment. The effects of temperature and residence time on the concentration of CWM from upgraded coals were also considerably significant among the other parameters such as pressure and particle size [2]. However, it was noted that each concentration of CWM from upgraded subbituminous coals is slightly lower than that achieved in the batch system. As for brown coal (coal C), remarkably concentrated CWM was obtained.

Figure 2 indicates the results of additional experiments with the bench plant using coal A. As shown in the figure, solid concentration of CWM becomes slightly lower than in batch tests. Furthermore, it was observed that solid content of CWM at 330℃was lower than at 300 ℃ different from the result of batch test. The cause of this phenomenon is not clarified yet and is being investigated.

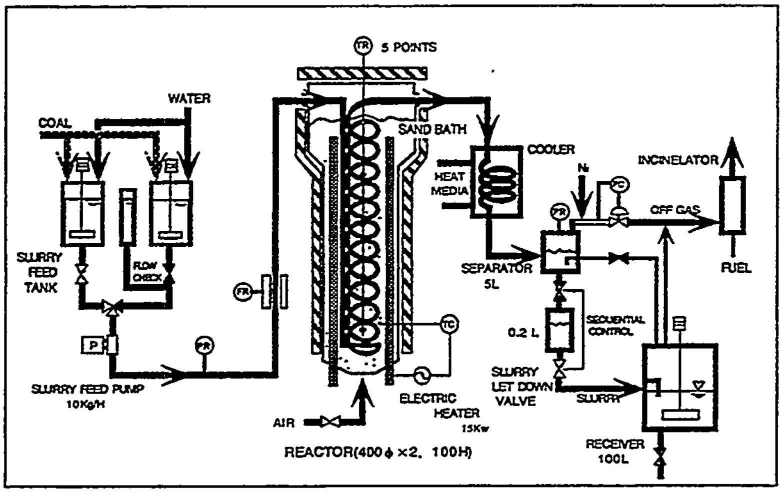


Figure 1 Schematic of benchscale plant

8.4 T/D PILOT PLANT

A pilot-scale plant (8.4 t/d dry coal) for upgrading tests was completed the construction in November 1994 at the Onahama Factory of Japan COM, Fukushima Prefecture. The operation is being carried out using one brand of coal, coal A. We will conduct testing with three coals, two subbituminous and one brown coal, in the final phase,which were selected through the bench-scale testing.

Table 2 Results of HWD treatment by a continuous bench system

coal	system	condition			property of upgraded coal			
		temperature [°C]	time [min]	pressure [kg/cm2G]	inherent moisture [%]	O content in carboxyl group [%]	volatile matter [%]	coal concentration of CWM [%]
Coal A	subbituminous				(13.7)			
	continuous	271	10.2	82	10.8	2.7	45.5	57.2
		298	10.9	111	8.7	2.4	46.6	62.8
		290	18.4	116	8.5	1.9	46.7	
	bench	330	7.3	122	7.4	1.0	45.6	66.2
Coal B	subbituminous				(18.5)			
	continuous	270	10.0	80	9.3	2.6	46.7	60.5
		300	10.8	105	7.6	1.9	47.1	64.1
		297	19.2	124	7.4	1.2	44.4	
		326	10.2	141	6.8	0.8	43.8	
		323	19.2	143	6.2	0.9	43.6	
	bench	300	11.1	120	6.7	0.7	44.3	65.7
Coal C	brown				(14.7)			
	continuous	268	10.5	81	10.8	4.5	47.0	46.9
		296	9.9	103	9.2	3.8	47.0	52.5
		295	18.7	122	7.9	2.4	46.3	
		297	30.2	120	7.4	1.1	44.0	
		300	37.0	110	7.5	1.9	45.1	
		323	10.4	144	7.2	2.6	45.2	60.4
		328	18.7	144	6.6	1.6	44.6	
		327	30.0	141	6.3	1.2	43.3	
		327	39.3	138	5.4	1.3	44.5	
	bench	300	10.2	120	6.4	1.9	48.8	59.8
Coal D	subbituminous				(19.4)			
	continuous	296	10.1	124	10.5	2.4	44.9	56.2
		328	10.7	140	7.9	1.4	43.1	61.6
	bench	303	8.5	120	7.8	0.8	43.2	61.8
Coal E	subbituminous				(21.1)			
	continuous	273	10.7	82	12.0	1.0	39.9	58.6
		329	10.2	143	8.0	0.5	39.8	62.0
	bench	303	8.7	120	8.0	0.4	40.2	65.5

( ); raw coal

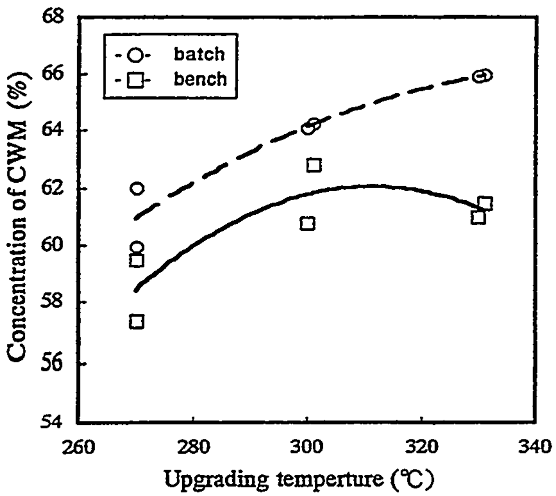


Figure 2 Effect of temperature on CWM concentration in coal A

The CWM production test from the upgraded coals with an existing 500 kg/h pilot plant will be also conducted. In addition, a combustion test with a 200 kg/h (CWM) furnace and a 6 t/d gasification test using the CWM will be conducted to evaluate its quality as a boiler fuel and gasification feedstock respectively. From the result of the batch and bench tests, the targets for quality in the pilot-scale testing were determined as shown in Table 3.

Table 3 Target for a quality of upgraded CWM

	Subbituminous coal	Brown coal
Coal concentration of CWM (at 1000cp)	64 wt% or more	58 wt% or more
Calorific value of CWM (HLV)	4400 kcal/kg or more	4000 kcal/kg or more

Pilot-scale testing aiming at a practical use on commercial scale is focused on the following;

- Design of the facilities with high temperature and high pressure equipment which allow stable, safe and continuous operation for a future commercial plant.
- Confirmation of optimum upgrading conditions giving an appropriate quality in

CWM production.

- Reduction of total CWM production costs by means of lowering plant costs and optimum operation in commercialization, based upon quantitative analysis of operating data.

Figure 3 shows the overall schematic diagram of the plant and Table 4 lists the main equipment of the plant section. Photo 1 shows the pilot plant and photo 2 indicates DCS panel in the control room. The CWM pilot plant is shown in photo 3.

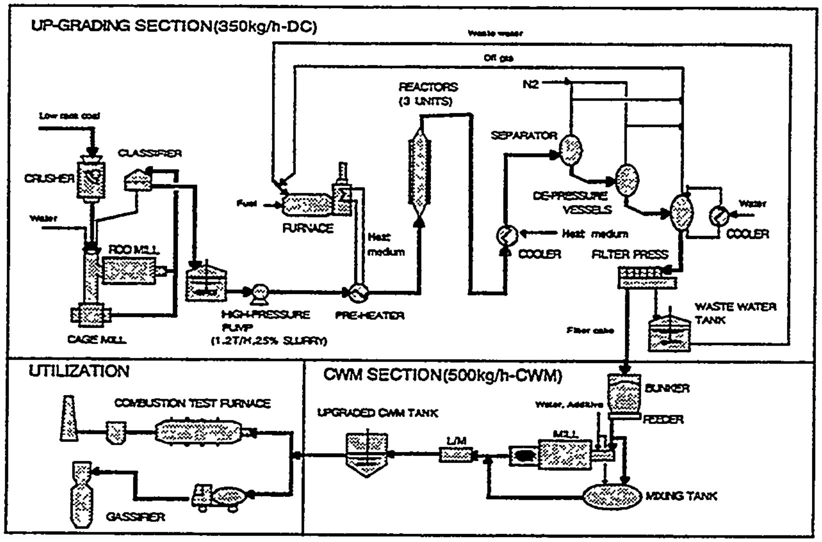


Fig 3 Process flow diagram of pilot plant

Table 4 The main equipment of the pilot plant

Equipment	Specification
Upgrading section	
Rod mill	3m/m to 0.15m/m 900 kg/h of dry coal
Cage mill	3m/m to 0.15m/m 900kg/h of dry coal
Classifier	vibration screen 0.5t/h, 1m/m separation
High pressure pump	1.6 m^3/h of slurry, 170 kg/cm^2 , hose diaphragm piston pump
Reactors	3units 207 m/m ID, 8000 m/m H, hold up 30min/unit
Slurry cooler	spiral type, 21m^2 100℃ to 60℃
Furnace	650,000 kcal/h, 900 kg/h of waste water
Filter press	420 kg/h of dry coal, 70 wt% or more of solid content in cake
CWM section	
Ball mill	500kg/h CWM, 1100m/m ID, 2000m/m L

DEMONSTRATION TEST PLAN FOR THE PILOT PLANT

1) Test schedule

Table 5 shows test schedule for the pilot plant. Test operation is now conducted with coal A.

Table 5 Test schedule

	1995												1996		
Test item	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
Upgrading test *															
coal A	▬	▬	▬												
coal B				▬	▬	▬									
coal C							▬	▬	▬						
CWM preparation for gasification and combustion test										▬	▬	▬			
Gasification										▬	▬	▬			
Combustion										▬	▬	▬			
Reporting													▬	▬	▬

* coal A and B ; subbituminous , coal C ; brown

2) Upgrading conditions

Table 6 shows standard upgrading conditions for demonstration tests.

Table 6 Upgrading conditions

Parameters	Conditions
Particle size of feed raw coal	less than 1000 μm
HWD temperature	270 ～ 330 ℃
HWD pressure	80 ～ 150 kg/cm^{2}G
HWD time	10 ～ 30 min.
Coal concentration of feed	20 ～ 30%

3) Test coal

Table 7 indicates analysis of coal A delivered in one-ton vacuum-packed plastic bags from Indonesia to Onahama. (see photo 4).

Table 7 Analysis of raw coal

Coal	Indonesian Subbituminous
Heat value * (kcal/kg)	6830
Density * (g/cc)	1.444
Proximate analysis (equilibrium basis)	
Inherent moisture (%)	17.1
Volatile matter (%)	44.2
Ash (%)	1.3
Fixed carbon (%)	37.4
Fuel racio (-) (-)	0.85
Ultimate analysis (dry ash free)	
Carbon (%)	73.8
Hydrogen (%)	5.3
Nitrogen (%)	0.8
Sulfur (%)	0.1
Oxygen (%)	20.0
Ash analysis (dry)	
SiO2 (%)	19.5
Al2O3 (%)	19.9
Fe2O3 (%)	33.6
CaO (%)	6.60
TiO2 (%)	1.20
MgO (%)	0.90
Na2O (%)	0.00
K2O (%)	0.20
SO3 (%)	5.50
Ash fusion temperature (Oxidizing)	
Deformation (℃)	1390
Hemispherical (℃)	greater than 1550
Flow (℃)	greater than 1550

* dry basis

CONCLUDING REMARKS

It was noticed that effect of temperature and residence time on degree of upgrading among other factors was the most significant for HWD in the bench system.

At present, we are in the final stage of this project over the five years and are conducting the demonstration test operation of the pilot plant using coal A, Indonesian subbituminous coal. We have already obtained some promising results through the operation. The results from the pilot plant will give confirmation of the validity and economic feasibility of the upgrading and CWM production technology to promote the use of LRC. We are convinced that this technology has great potential for the production of low cost CWM.

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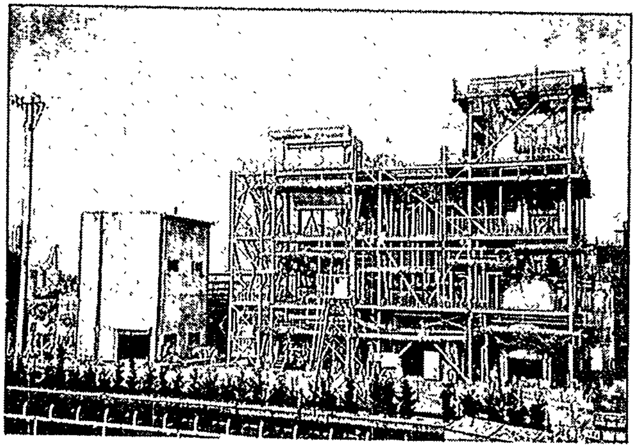

Photo 1 The pilot plant

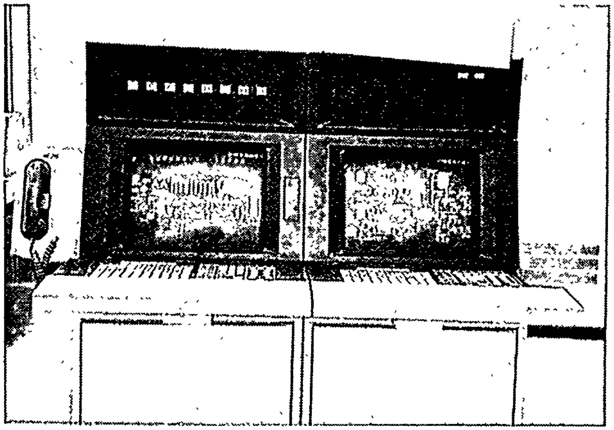

Photo 2 DCS panel

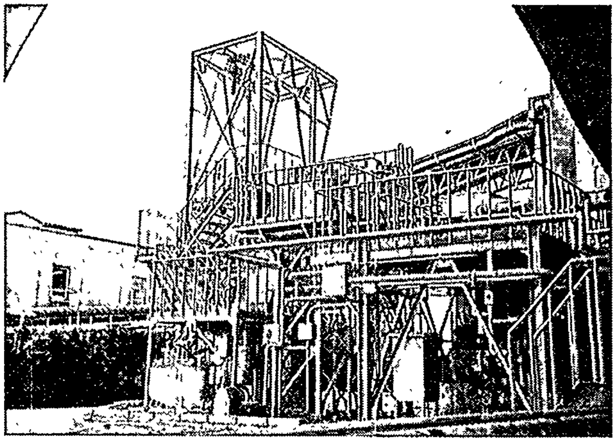

Photo 3 The CWM pilot plant

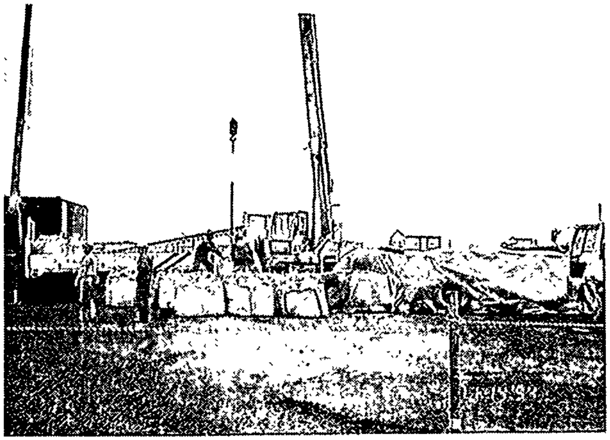

Photo 4 Storage yard of raw coal

DEVELOPMENT OF A PROCESS WHICH EMPLOYS SHEARING TO CONVERT SEWAGE SLUDGE INTO A PUMPABLE FLUID SUITABLE FOR USE AS A GASIFICATION FUEL

by

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Abstract

A process has been developed for shearing sewage sludge and transforming it from an intractable solid into a pumpable fluid which when mixed with ground coal can be converted to synthesis gas in a conventional coal gasifier. Shearing has been accomplished at temperatures ranging from ambient to 180 degF in a continuous processor equipped with a series of paddles rotating at 300 to 600 rpm operating on scales ranging from 100 to 500 pounds per hour. The process was operated continuously for five days and a prepared mixture of 16% sludge and 84% coal was converted to synthesis gas in a 15 ton per day gasifier over a four-day period. Viscosity reduction is permanent and the sheared sludge is more biologically stable than the feed sludge allowing it to be stored for longer periods than untreated sludge.

Introduction

We have previously reported on the fuel properties of sewage sludge (1) and the use of hydrothermal treatment of sludge at 400 degF under pressure to improve the fluid properties of sludge/ coal slurries and increase the amount of sludge that can be included in pumpable slurries with coal(2). Bench scale studies of various methods, including shearing, of reducing sludge viscosity and increasing the amount of sludge that can be incorporated into a pumpable slurry with coal have also been reported (3). Processing alternatives employing shearing to reduce the viscosity of sludge filter cakes have been described in patents by us (4) and others. Campbell has used shearing to reduce the viscosity of sludge(5) and Beshore has included sheared sludge in coal slurries (6).

We report here the development of an atmospheric pressure, continuous process which employs shearing at 180 degF to reduce the viscosity of sludge cake. Experience on scales ranging from 100 to 500 lb/hr is described. The neat sheared sludge is quite fluid and easily transported in closed pipe systems using progressive cavity pumps. This not only makes it easy to handle, but also reduces odors and allows a cleaner operation. Operation at atmospheric pressure affords an inexpensive and trouble-free process. Sheared sludge is mixed with finely ground coal to form a slurry which is used as a gasifier fuel to produce industrially useful synthesis gas. Process development work was conducted in Beacon, New York and Los Angeles, California using Los Angeles County sludge cake.

Shearing research was conducted in three stages. The first of these was of an exploratory nature carried out by batch in one and two-liter glass polymer kettles equipped with "Jiffy Mixer" stirrers capable of stirring at speeds up to 600 rpm which sheared the sludge. Jiffy Mixers are the laboratory equivalent of hand mixers used in home food preparation. The second and third stages of the development were conducted in nominal 100 lb/hr and 500 lb/hr "continuous processors" in which unique paddles rotating on shafts sheared the sludge.

Feedstock Properties

Most of the sludge used for this work was municipal sewage sludge from the Los Angeles County Sanitation District treatment plant in Carson, California. The sludge is anaerobically digested for 15 to 20 days and then concentrated by centrifuging to 22 to 25% solids. At this concentration, the sludge appears to be a dry amorphous solid having an unmeasurable viscosity. The solids content of the sludge received from the wastewater treatment plant was found to be about 23% - ranging from 20.5 to 26.6% solids over a one year period. The average solids content of 1000 cP pumpable slurries prepared by diluting these samples with water was found to be 12.8 %.

The coal used was a Utah Sufco bituminous coal. Analytical data for the sludge, coal and coal slurry are presented in Table 1.

Sludge used for several runs was obtained from the Passaic Valley Sewerage Commissioners plant in Newark, New Jersey. It was undigested and was used as received.

The Shearing Phenomenon

Exploratory experiments directed at shearing sludge cakes were conducted in laboratory glassware using a "Jiffy Mixer" stirrer. These stirrers, which effect the shearing, were operated at about 600 rpm and were powered by motors that allowed torque on the stirrer to be measured. This torque is linearly related to viscosity. The viscosity versus time results of preliminary shearing experiments are presented in Figure 1. Shearing reduces the viscosity of the amorphous solid sludge cake from well over 3000cP to about 1500cP in about 10 minutes at ambient temperature. The rate of shearing also increases with increasing temperature but the effect could not be demonstrated satisfactorily in the laboratory vessel because of the time needed to heat the sludge to 180degF and the need to stir, and thus shear, the sludge while heating it to prevent baking and decomposition on heat transfer surfaces. The viscosity reduction increased the amount of solids that could be included in a 1000 cP, 10% sludge/coal slurry from 55 to 58% (Figure 2). This is about 60% more sludge than could be carried in a slurry of similar solids concentration containing raw unsheared sludge. Results presented in Figure 2 indicate that coal/sludge slurries containing about 55% total solids (15% sludge) would have a 200degF viscosity of less than 1500cP which meets our target commercial specifications. The viscosity reductions were permanent, allowing the slurries to be stored for long periods with no increase in viscosity (Figure 3).

Process Development

Encouraged by the laboratory results, we sought a machine which could be used to shear sludge continuously and which offered the potential for commercial scale operation. Various mixing machines were considered but the first one evaluated was found satisfactory. This machine, shown in Figure 4, manufactured by Teledyne-Readco, is commonly referred to as a continuous processor or simply "processor". Sludge is fed by means of calibrated augers to an upstream opening in the processor barrel and is sheared by the grinding action of the unique paddles mounted on shafts that can be rotated at speeds up to 600 rpm. A steam jacket allows the sludge to be heated and sheared simultaneously.

Exploratory runs were conducted in a two-inch diameter, 20-inch long, steam-jacketed processor having a nominal capacity of about 150 pounds per hour. Shearing sludge in this machine while operating it in a batch mode, in which the unit was simply filled with sludge and sheared, afforded results similar to those obtained with the Jiffy Mixer apparatus (Figure 5). We assumed that the current draw on the motor which drives the paddle bearing shafts is a measure of the torque and consequently the viscosity. These results, which were confirmed by subsequent batch experiments, indicated that about 5 minutes were required for satisfactory viscosity reduction. Results presented in Figure 2 show that the viscosity of slurries prepared with the processor - sheared sludge are similar to those prepared with the Jiffy Mixer.

Effects of Process Variables

The processor has four controllable operating variables: weir opening, rotor rpm, paddle type and configuration and temperature. The weir is an adjustable gate valve at the downstream end of the machine which, when partially closed, increases the residence time. Different arrangements of flat and slant edged paddles affected both shearing and residence time. All of the variables affect the viscosity of the sludge but unfortunately operating at maximum speed (360rpm), temperature (180 degF), and minimum weir opening (1/32 inch) to afford maximum shearing stress did not afford consistent sufficient viscosity reduction. The 180degF viscosities of products from a number of runs over a wide of conditions fell in the range of 1800 to 2200cP. This met the 2500cP limit required by the progressive cavity pumps used for transporting the sheared sludge in the planned pilot unit but did not meet the 1500cP target specification for gasification feed slurries when mixed with coal.

It was clear that an increase in residence time was desirable. Indeed, decreasing the feed rate increases residence time but operating at a minimum practical feed rate of 25 lb/hr, corresponding to a residence time of 1.6 minutes, with other shearing conditions maximized, satisfactorily reduced the viscosity of about half the samples tested. Passing the hot sheared sludge through the processor a second time afforded satisfactory viscosity reductions in every test and resolved this difficulty. In fact, we found it possible to increase the feed rate to 85-100 lb/hr when the sheared sludge was recycled. This may be attributable to the fact that the procedures used in the recycling more than doubled the time at 185 degF. Recycling reduced the absolute 180degF viscosity by almost a factor of two from 2200 to 1200cP. Satisfactory 84/16, coal/sludge slurries having our target solids content of 54 wt% and viscosities less than 1500cP could be prepared from the 1200cP sludge. Results from a few experiments in which the sludge was recycled are presented in Table 2. Although recycling was not a realistic option in a pilot plant, increased residence time in a larger processor, or two processors in series, was. Because of time pressures in the development, we accepted the fact that two processors in series might be necessary in the larger pilot plant to allow for day-to-day variability in the feed sludge.

Shearing Sludge/ Coal Mixtures

A few experiments were carried out in the processor to determine if shearing sludge in the presence of coal would increase shearing severity. Results of runs made at 180 to 200 degF using 1/1 to 6/1 sludge/coal ratios and four different sludge samples were inconsistent. Some experiments afforded satisfactory viscosity reductions while others did not. We therefore did not pursue this option. A dramatic effect of coal addition was needed to justify the increase in the size and cost of the processor the increased amount of throughput would require.

Sludge Source

Although the principal sludge used in this development effort was obtained from Los Angeles County, a few experiments were performed using sludge obtained from the Passaic Valley Sewerage Commissioners plant in Newark, New Jersey. This sludge differs from the L.A sludge in that it is undigested and contains about 10wt% paper fibers from a nearby paper recycling plant. Results presented in Figure 6 indicate that treatment of this sludge in the processor at 150degF also reduced the viscosity of this sludge. In one pass the percentage solids that can be included in a 1500cP slurry was increased by 3% and in two passes by 5.5%. This increase translates to a 3% solids concentration increase when the sludge is included in a 10% coal slurry (Figure 7). This magnitude of increase is consistent with that observed for the Los Angeles sludge.

1500 Pound/Hour Pilot Unit

A flow diagram of the 1500 lb/hr pilot unit constructed and operated at our Montebello Laboratory in California is presented in Figure 8. As received sludge cake containing about 25% solids was manually charged to a hopper mounted on an Acrison calibrated volumetric screw feeder which fed a 5 inch twin screw continuous processor at a rate of 500lb/hr. The sludge was then sheared and indirectly steam heated in the processor to about 180 degF which changed the sludge to a fluid. The sheared sludge was transported using a Bornemann progressive cavity pump to a Teledyne-Readco continuous ribbon blender (Figure 9) where it was mixed with a 120 degF coal slurry containing 65% total solids being fed at a nominal rate of 1000 pounds per hour. The 140 degF sludge/coal mixture output of this mixer was transported using a second Bornemann pump to a Bepex Twin Rotor Torusdisc Heater Dryer (Figure 10) where it was further mixed and heated indirect by steam to 180 degF. The function of the Bepex torusdisc machine is not only to heat the mixture but to remove water from it if necessary. It would be necessary to remove water from the mixture if its solids content was below 54%. This would occur if either the sludge or coal slurry contained more moisture than indicated above. The output from the Bepex unit was transferred to an insulated storage vessel by means of a Schwing KSP-17K pump through a 6-inch diameter pipeline and served as fuel for the gasifier. Air from the overhead spaces in the storage tanks was discharged through activated carbon canisters for odor control. Odor control around the storage tank area was not a problem. The target specifications and operating conditions for the pilot plant are presented in Table 3.

Except for a few minor upsets, the specified flow rates and stream composition targets were met very well. Figures 11 to 15 show trends in the data collected during the course of the feed mixture preparation run. The sludge and coal feed rates are presented in Figure 11. The accuracy of mixing was monitored by measuring the percentages of ash and carbon in the mixture and comparing them with calculated values (Figure 12 and 13). Data presented in Figure 14 shows that the mixture generally met the 1500cp specification and frequently was below it. Perhaps the most surprising aspect of the data obtained over the five days of testing is the consistency of the solids content in the as-received sludge. Over the six day test period, the solids content ranged from 23 to 25% (Figure 15). Our previous experience indicated that the expected range would be 21 to 26%.

Viscosity measurements made on samples of the product mixture withdrawn over a ten day period while waiting for the start of the gasification run are presented in Figure 16. The mixture was continuously stirred with rotating paddles and heated at 180degF. This continuous low shear treatment would be expected to cause viscosity reduction and it certainly did. Over the 14 days of storage, the viscosity of the mixture, which was maintained at 52% solids, decreased from 1600 to 600cp (measured at 122degF). The magnitude of this viscosity reduction was somewhat surprising and indicates that slow shearing for longer periods of time might allow higher concentrations of sheared sludge to be included in pumpable slurries than were used for this development. In addition to decreasing the viscosity of the sludge, the thermal/ shearing kills bacteria in the sludge and essentially pasteurizes it. This makes it storable for long periods of time without significant decomposition.

Gasification

The sheared sludge/coal mixture was transferred from the insulated storage tank into a run tank through a 14 mesh screen. The screen had to be cleaned daily because significant amounts of hair and debris accumulated on it. This debris occasionally made its way into charge pump check valves which decreased flow. The sludge/coal mixture was gasified over a four day period. Steady operating conditions were maintained throughout the run. A summary of the run conditions is presented in Table 4. Also shown for comparison in Table 4 are data from a typical gasification run with Utah-Sufco coal (7).

Acknowledgements

The authors wish to express their appreciation to the engineering, operations and support staffs at Texaco's Montebello Research Laboratory for their assistance in carrying out the large scale pilot tests at their facilities in California.

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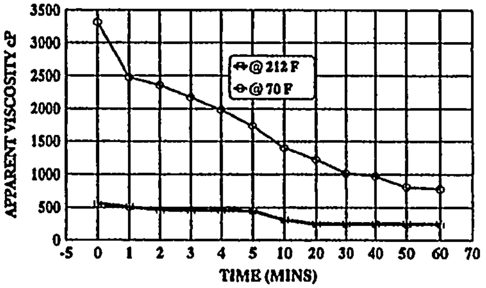

Figure 1- Effect of shearing at 700 rpm on the apparent viscosity of Los Angeles sludge at 70 deg. F and 212 Deg. F

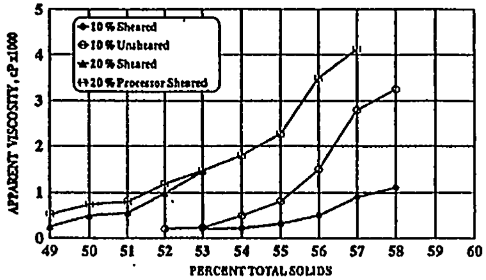

Figure 2- Relationship between total solids content and apparent viscosity of sludge/coal slurries containing varying amounts of sludge and Pittsburgh No. 8 coal at 200 deg. F

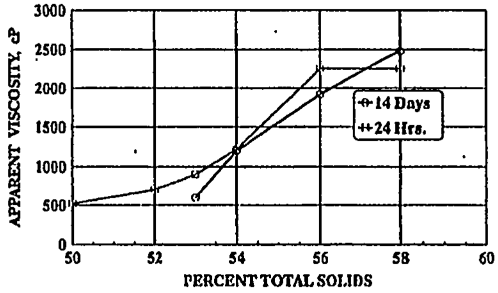

Figure 3- Effect of storage time on the viscosity of sheared sludge/coal slurries that have been stored at room temperature for varying periods of time.

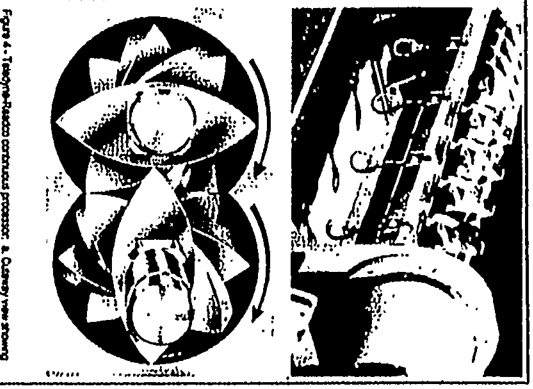

Figure 4 - Teledyne-Readco continuous processor. a. Cutaway view showing the twin shafts which bear the rotating paddles. b. Drawing of the offset paddles and their shearing motion.

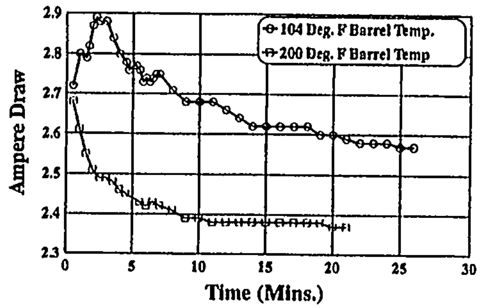

Fig. 5- Effect of time on ampere draw of the motor driving the Continuous Processer while sludge was being sheared at 104 and 200 deg. F.

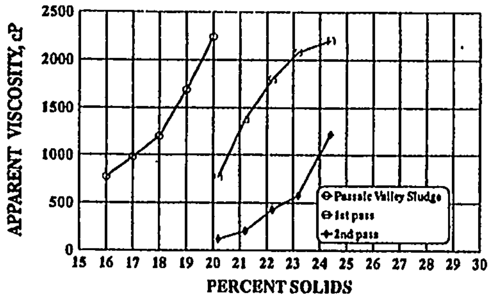

Figure 6- Effect of multiple passes of Passaic Valley sludge through the continuous processor on the apparent viscosity at 200 deg. F.

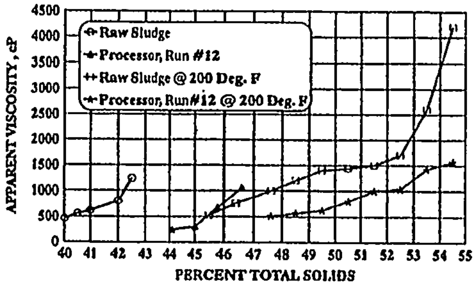

Figure 7- Effect of sheared and unsheared Passaic Valley sludge on the apparent viscosities of 10% sludge/coal slurries at 70 deg. F and 200 deg. F

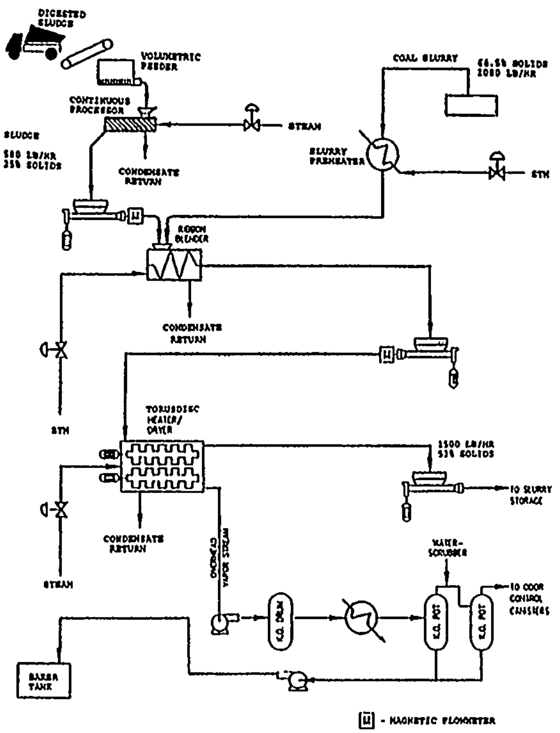

Figure 8 - Flow diagram of 1500 lb/hr pilot unit used to shear sludge and prepare sludge/coal slurries.

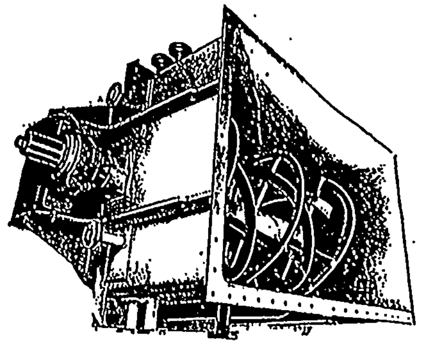

Figure 9 - Continuous Ribbon Blender

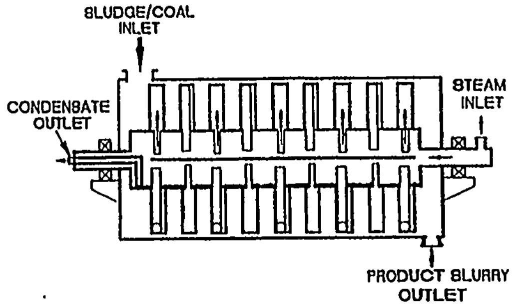

Figure 10 Schematic diagram of a Bepex Torusdisc sludge dryer.

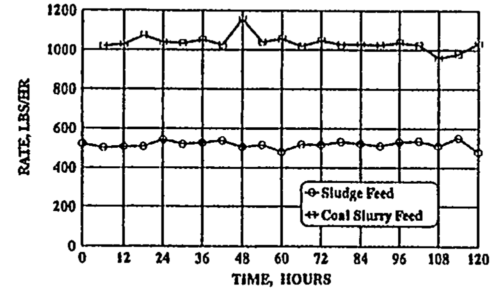

Figure 11- Measured coal slurry and sludge feed rates over a 5 day period.

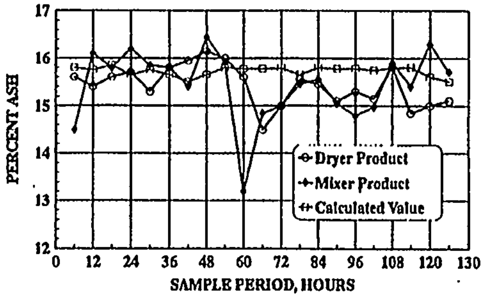

Figure 12 Percentage ash in the sludge/coal slurry at the exits of the ribbon mixer and the Bepex dryer.

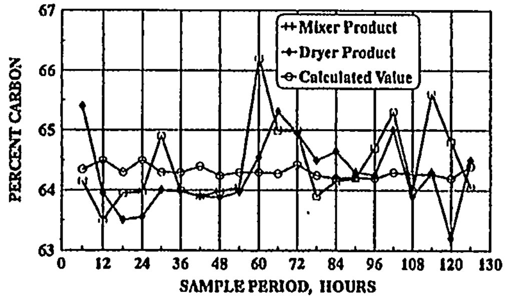

Figure 13- Percentage carbon in the sludge/coal slurry at the exits of the ribbon mixer and the Bepex dryer.

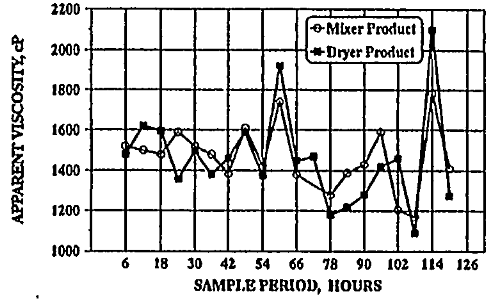

Figure 14- Apparent viscosities of sludge/coal slurries at the exits of the ribbon mixer and the Bepex dryer.

Table 1 Feedstock Analyses				
Ultimate Analysis,	Sufco Coal	L.A Cnty sldg	L.A.Cnty Sldg/Coal Slurry	Newark, Passaic Valley Sludge
Carbon, wt%	70.47	31.87	64.08	34.40
Hydrogen	4.67	4.66	4.88	5.24
Nitrogen	0.94	3.27	1.26	3.13
Sulfur	0.37	3.69	0.90	0.69
Chlorine	---	---	0.39	0.18
Oxygen	12.93	13.00	13.50	21.78
Ash	10.65	43.71	15.48	30.58
G.H.V. , Btu/lb	12653	6240	11352	7054
Slurry Heating Value	7554	1373	5983	---
Solids in Slurry, wt%	59.7	22.0	52.7	---
Ash Fusion Temps.				
Initial, degF	2070	1945	2020	2229
Softening	2115	2090	2100	2247
Hemispherical	2135	2135	2140	2261
Fluid	2330	2295	2255	2262

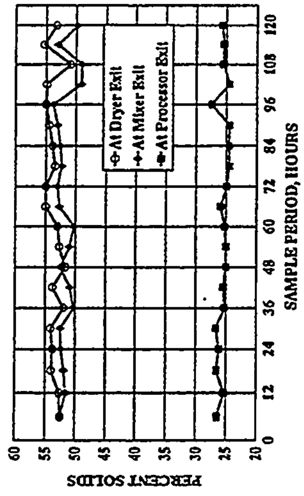

Figure 15- Percentage solids in sludge and sludge/coal slurries at various points in the slurry preparation scheme.

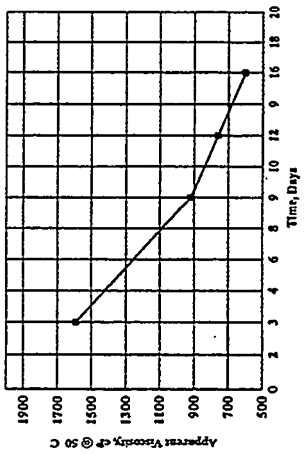

Figure 16 - Effect Of Storage At 180 DegF On The Viscosity Of An 84/16 Coal/Sludge Slurry

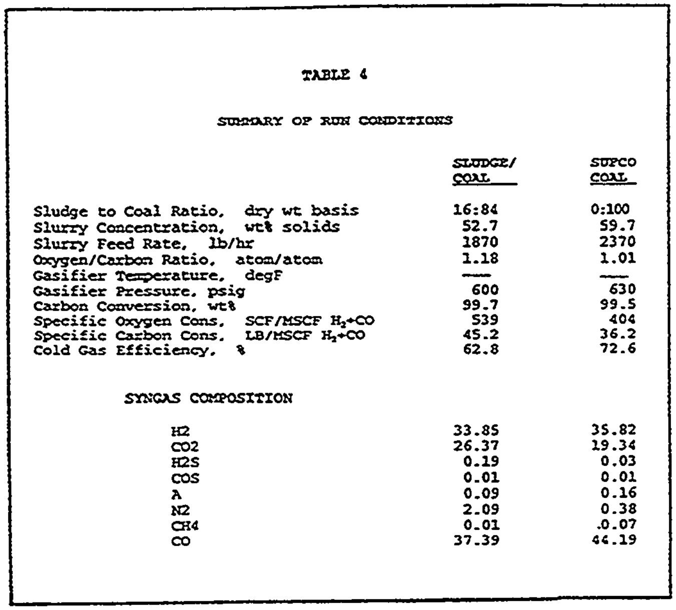

TABLE 4

SUMMARY OF RUN CONDITIONS

	SLUDGE/ COAL	SUPCO COAL
Sludge to Coal Ratio, dry wt basis	16:84	0:100
Slurry Concentration, wt% solids	52.7	59.7
Slurry Feed Rate, lb/hr	1870	2370
Oxygen/Carbon Ratio, atom/atom	1.18	1.01
Gasifier Temperature, degF	——	——
Gasifier Pressure, psig	600	630
Carbon Conversion, wt%	99.7	99.5
Specific Oxygen Cons, SCF/MSCF H_2+CO	539	404
Specific Carbon Cons, LB/MSCF H_2+CO	45.2	36.2
Cold Gas Efficiency, %	62.8	72.6
SYNGAS COMPOSITION		
H2	33.85	35.82
CO2	26.37	19.34
H2S	0.19	0.03
COS	0.01	0.01
A	0.09	0.16
N2	2.09	0.38
CH4	0.01	.0.07
CO	37.39	44.19

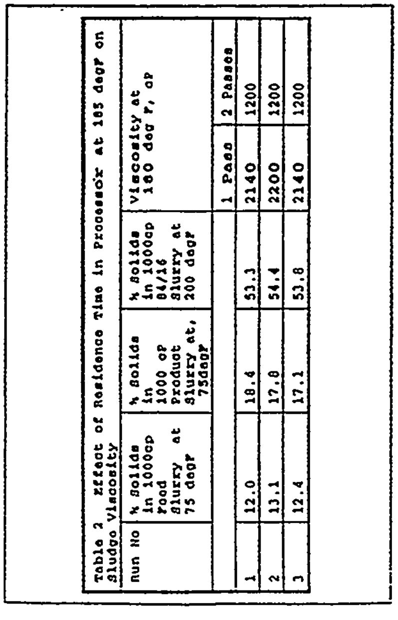

Table 2 Effect of Residence Time in Processor at 185 degF on Sludge Viscosity

Run No	% Solids in 1000cp Feed Slurry at 75 degF	% Solids in 1000 cP Product Slurry at, 75degF	% Solids in 1000cp 84/16 Slurry at 200 degF	Viscosity at 180 deg F, cP	
				1 Pass	2 Passes
1	12.0	18.4	53.3	2140	1200
2	13.1	17.8	54.4	2200	1200
3	12.4	17.1	53.8	2140	1200

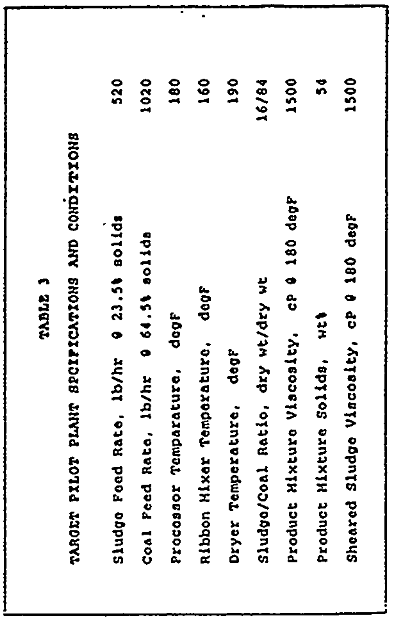

TABLE 3

TARGET PILOT PLANT SPECIFICATIONS AND CONDITIONS

Sludge Feed Rate, lb/hr @ 23.5% solids	520
Coal Feed Rate, lb/hr @ 64.5% solids	1020
Processor Temparature, degF	180
Ribbon Mixer Temperature, degF	160
Dryer Temperature, degF	190
Sludge/Coal Ratio, dry wt/dry wt	16/84
Product Mixture Viscosity, cP @ 180 degF	1500
Product Mixture Solids, wt%	54
Sheared Sludge Viscosity, cP @ 180 degF	1500

Coal Beneficiation - Organic Sulfur Removal - *A. Perkson, G. H. Wang and O. Trass, Dept. of Chemical Engineering & Applied Chemistry, University of Toronto, CANADA*

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PTBA Coal Briquette Development Project

A Status Report, March 1995.

BY :

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Heri Supriyanto, Project Manager
Teguh S Djamal, Staff

Proyek Pengembangan Briket Batubara
(Coal Briquette Development Project)
PT TAMBANG BATUBARA BUKIT ASAM (PERSERO)
INDONESIA

Paper Presented at :
The 20th International Technical Conference on
COAL UTILIZATION & FUEL SYSTEM

March 20-23 1995
Clearwater , Florida , USA

INTRODUCTION

Indonesia has a vast coal reserved amounted around 36 Billion Tons (As May 1993), of which more than 98% located in two big islands: Sumatera & Kalimantan. This reserve could fueled the nation according to current consumption and its future projection for more than 200 years ahead.
While oil also available abundant in reserve, the industry of oil mining had long been established, relatively cheap and convenient to use, it become the most preferable fuel together with natural gas in the National Energy Mix of Indonesia.

It was, then, after the world had been shocked by the World Oil Crisis in 1974, Indonesia as well as many country in the world had redirected its National Energy Policy to diversify its energy resources toward independent to oil and natural gas.

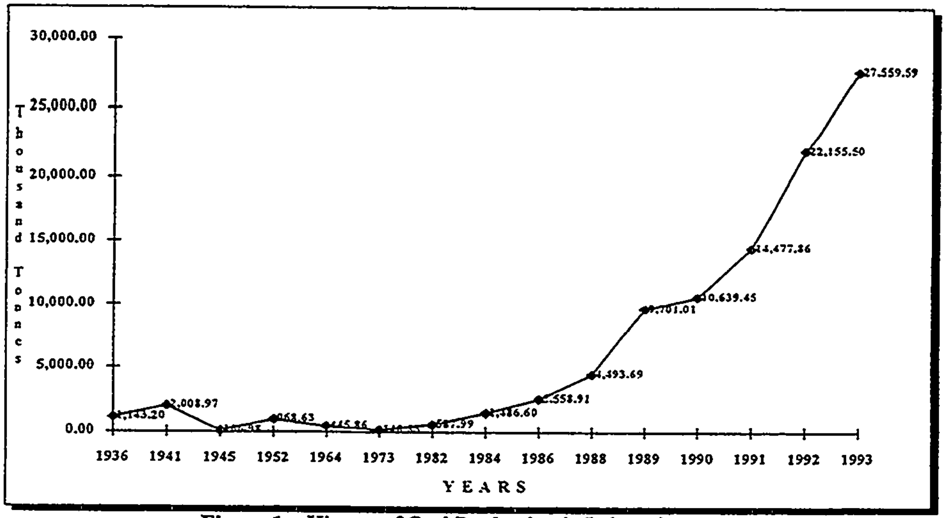


Figure 1. : History of Coal Production in Indonesia

Indonesian Energy Policy, set up in 1976 were shifting the National Energy Mix to encourage the use of other alternative energy for fulfilling the domestic energy demand. Coal, as it was available in enormous reserve become the most suitable alternative fuel. Indonesian coal mining industry was then gaining a big momentum for its resurrection since it was for long had been overlooked.
As the result of reconstruction of old mines, expanding the current mines and the opening of new mines by foreign investor (Contractors) in Kalimantan, since 1986, ten years after the set up of New National Energy Policy or 45 years after peak production level in the past, 2 million tons of coal production was regained. Afterward the coal production of Indonesian coal mine industry are increasing in an exponential rate of growth (**Figure 1**). With more than 29 million tons of coal produced in 1994, Indonesia will continue to play greater role in the world coal export market in the future. It is projected that by the year of 1998, Indonesia will rank the 3rd as the world coal exporter next to Australia and South African with around 14% of world market share.

In this paper, author would only like to report the current status of Indonesian Coal Briquette Industry of which PT Tambang Batubara Bukit Asam (Persero),PTBA, the state owned coal mining company was being appointed to pioneer the establishment of the first coal briquette industry in Indonesia. Process Technology that being compared here in this paper were based on the technical compliance to specification set by government and the techno-economic evaluation. Due to limitations and constrains, all aspects concerning the project will only be discussed in an overview.

THE BACKGROUND

As the implementation of National Energy Policy, the mayor domestic fuel consumption: Electricity, and Cement Industry of which are very suitable in using coal for their fuel are encourage to use coal replacing the current use of oil and natural gas. In January 1993, in front of the member of Parlement the President of Indonesia : Suharto as he delivered his Yearly Development Budget Plan 1993/94, declared the start of government long term planning to encourage people utilizing coal for their daily cooking fuel.

The objectives are :

- Reducing the heavy government subsidization of Kerosene, the common current fuel for daily cooking.
- Protect the deforestation from the use of wood for daily cooking fuel.
- Utilization of abundant national coal reserve.
- Create employment opportunity by the establishment of new industry (of coal briquetting).
- Improving people living standard by saving their daily cooking spending for cheaper fuel.

Kerosene are common used fuel for daily cooking for in Indonesia, since the Indonesian light Crude Oil available are not suitable to be converted to kerosene, it was imported from Arab country. The domestic price was heavily subsidy (more than 60%) by the government to be able affording by the people. The use of wood for daily cooking fuel by people living in rural area, particularly at the most populated island (more than 100 million): Java, had been at condition of serious deforestation. Each year it was calculated that 10.000 Ha of forest was diminished to be used for daily cooking fuel. Finally, with the utilization of abundant national coal reserve for fuel, amount of oil that had been replaced can intended for export, to gain more foreign currency to fund the development of the nation.

In order to reach all the objectives mentioned above, the coal to be used for daily cooking should priced cheaper than kerosene, to be able to have more advantage over its competitor. The government, than stated the mission of this program as: **"To provide the alternative fuel for people's daily cooking by utilizing the abundant coal reserve that has both comparative and competitive advantage over the Kerosene"**

Since most of Indonesian coal reserve come from the Sub/Bituminous coal that usually have relatively high volatile matter, the direct combustion of that coal will create smoke and odor, so the coal should be being processed to remove all negative properties before being used for the daily cooking: the Coal Briquette that would be smokeless and odorless in their combustion.

PTBA COAL BRIQUETTE DEVELOPMENT PROJECT

Tanjung Enim Egg Type Carbonized Coal Briquette Plant

Since the announcement from the President of Indonesia for the National Program for the use of Coal (briquette) for household and small scale industry in January 1992, a team for implementing the program was set consisted of : The Ministry of Mine & Energy as the principal, Mineral Technology Research & Development (MTRDC) as the R&D institution and PT Tambang Batubara Bukit Asam (Persero);**PTBA**, the state owned coal mining company as the pioneer for manufacturer/producer of coal briquette. Some US$ 40 million (= Rp.84 Billion) fund from National Coal Development Fund collected from Coal Production Sharing of foreign investor in coal mining Industry in Indonesian was provided to support the program. The project called: **Coal Briquette Utilization for Household & Small Industry Project**, with mission to promote and encourage people to use coal briquette for household and small industry fuel in replacing kerosene and heavy oil and pioneering the establishment of the new industry of coal briquette in Indonesia.

On 6th of February 1993, at the erection yard area of Air Laya Mine, Tanjung Enim, South Sumatera, the head quarter of PTBA marked to be the establishment of first phase of Coal Briquette Plant in Indonesia. The plant design to produce around 30,000 ton/year an Egg type Carbonized Coal Briquette from the sub/bituminous high volatile raw coal from Air Laya mine.

The technology applied was so simple, only to briquette the crushed (+/- 5mm) carbonized coal to an Egg shape of 5 Cm diameter by pressing with simple double roller pressing/briquetting machine bought from China. The ***binder*** added to the coal before being pressed is a lean (8%) starch solution in water, in order to make the coal briquette had more stability (hardness) after drying.

Volatile Matter(VM) content in the coal were the matter that responsible for the smoke and odor emitted during direct combustion of rawcoal, this VM should be remove in order to reduce the smoke and odor on its combustion. The carbonization, simplify in the purpose to reduce its VM, thus, increase the carbon content in the carbonized coal, the VM was burned and induced the carbonization process of surrounding other direct contact coal in the drums. With this process, the volatile matter of carbonized coal reduce from +/-30% in the feed coal to 10-15%.

VM in coal eventhough often regarding as an unpreferable component in coal, actually help the coal burn more easily, the removal of VM after being carbonized makes it more difficult to ignite.

To help the initial ignition of egg type carbonized coal briquette, the coal briquette comes with small portion of special coal briquette that can be easily ignite by the used of ordinary matches , the ***Ignitor***, this already ignited briquette than used for the starting fire to ordinary coal briquette which had a direct contact to it. The Ignitor made from charcoal and additives from strong oxidizing compound such KNO_3, $BaNO_3$,$KClO_4$ etc.

Coal Briquette Utilization for household and Small Scale Industry Pilot Project

The coal briquette production from Tanjung Enim plant are intended to supply for the coal briquette utilization for household and small scale industry promotion Pilot Project at three villages in rural Jawa Island. Starting April 1992, more than 3000 households in small villages of Java participating the pilot project. Each participant household was given 2 Kg of coal briquette for used in their daily cooking at no expense for three full month and its stove as well. The pilot villages was chosen according to the energy profile of the suitable target for coal briquette consumer; kerosene and wood user for daily cooking fuel of people living in rural area in Java nearby the forest of which become their sources for their cooking wood.

After the pilot project period , the villager was freed to choose whether they still would continue using coal briquette that were provided in their nearest at the price more competitive than kerosene and wood shop (Rp. 250.-/Kg = US$ 0.1 for coal briquette , while Kerosene was sold for Rp.350.-/liter = US$ 0.15) or back to their former fuel; kerosene and wood.

The method to experiment with the real acceptance from the target consumer, had been reported to be implemented also in some develop country that interested in the utilization of coal briquette such as Philippine, Vietnam, Haiti,Columbia and Zambia before.

The result of Pilot Project shown a **significant saving for daily cooking of common household consist of 5 persons (an average member for Indonesian Family) or more, by using coal briquette compare to kerosene and wood. The community that gain greatest benefit from the use of coal briquette are the small scale industry business that consume fuel for significant economic scale for long period of cooking** such as traditional cracker/snack manufacturer, small restaurants, catering services, etc.

Even at the present heavily subsidized price of domestic kerosene (Rp.350.- = US$ 0.15 per liter) coal briquette still has a comparative advantage. A group of Mineral technology Research and development Center,MTRDC in Bandung calculated the saving if the converision from the use of kerosene to coal briquette had been implemented at the Unsubcidised priced of kerosene = US$ 0.268 per liter.

However, the trade off is the consumer should be available to wait for +/- 30 minutes before the coal briquette come to fully utilize conveniently. It would also be unbeneficial to use coal briquette for a small family member household (consist of 2-3 person).

Further utilization of the Egg type carbonized coal briquette are missing parts of the original mission of the project : the household community to the small scale industry community.

In order to achieved another part of original mission, the government introduce the new type called : **Honey comb type Coal Briquette** that was intended to gain the household market segment acceptance. this new type eliminating the greatest constraint of former egg type that is: the time lag between the initial ignition to the fully convenient used of coal briquette.

With the help of China's long experience in using coal for household daily cooking and their research on coal technology, the Honey comb type coal briquette using the top ignition method is intended to be used especially for household daily cooking. This new type will produce a quick ignition (by only the help of one matches), Smokeless and Odorless in operation. Utilizing the uncarbonised rawcoal material makes the production cost for manufacturing is even lower than carbonized egg type coal briquette.

Table 1.

Comparison of cost of energy for cooking at villages in Indonesia at Unsubcidised Kerosene price US$ 0.268/liter, 1993 - 2000

YEAR	PREDICTION	NATIONAL				
		KEROSENE		COAL BRIQUETTE		SAVING
		Consumption (Bill. Liter)	Value (Bill.US$)	Consumption (Bill. Liter)	Value (Bill.US$)	(Bill.US$)
1993	LOW	18.06	4.85	26.48	3.15	1.70
	HIGH	29.64	7.97	43.47	5.17	2.79
1995	LOW	18.18	4.89	26.67	3.17	1.75
	HIGH	29.84	8.02	43.77	5.19	2.83
2000	LOW	18.09	4.86	26.54	3.15	1.70
	HIGH	29.70	5.13	43.55	5.19	2.80
1993 - 2000	LOW					13.70
	HIGH					22.47

Note: The Price of Coal Briquette : US$ 0.119/Kg
1 US$ (in 1993) = Rp. 21,00.00

Source: "The Development of Coal Briquette for Household use in Indonesia",MTRDC, 1994

Honey Comb type Uncarbonized Coal Briquette

Honey comb type Uncarbonised briquette to produce a coal briquette which has the : **Smokeless, Odorless and Quick Ignition** (by using only one match) works on a simple principles.

The combustion starts from the top part of the cylindrical briquette. As the fire makes the flame from the combustion of easily burn compound spreading on the top layer of the briquette it will completely oxidize the volatile matter evolve from the body layer of briquette. The temperature should be high enough (600-800C) to be able to combust the volatile matter completely so that no volatile matter will evolve to produce odor, the volatile matter acts similarly as a natural gas fuel to start the fire. After the volatile matter in the body layer completely burn, the flame has already set up on top of the briquette and will continue to burn the remaining coal from the body layer of the briquette.

It is very important to control the rate of emission of the volatile matter during the combustion process. The volatile matter emission rate controlled by varying the density of coal briquette by changing the pressure during briquetting and addition of some additive to retard the volatile matter emission when extreme high volatile matter raw coal material is to be used. The higher density of the coal briquette, the slower is emission rate of volatile matter.

The heat produces from the continuing combustion of the coal is concentrating to the upper part of the coal briquette by specially design stove which makes the flow of oxygen directed from the bottom of coal briquette through the ventilating hole in the bottom of the stove and passes the circulating holes of the coal briquette.

This simple principle is proven to work fine in the real situation. When all the system work accordingly, Smokeless, Odorless, Quick Ignition and high heat efficiency result can be achieved. At some cases, the smoke and odor produce cause by not enough oxygen circulating within the system due to excessive emission of the volatile matter could be controlled by changing the opening of the ventilating hole of the stove.

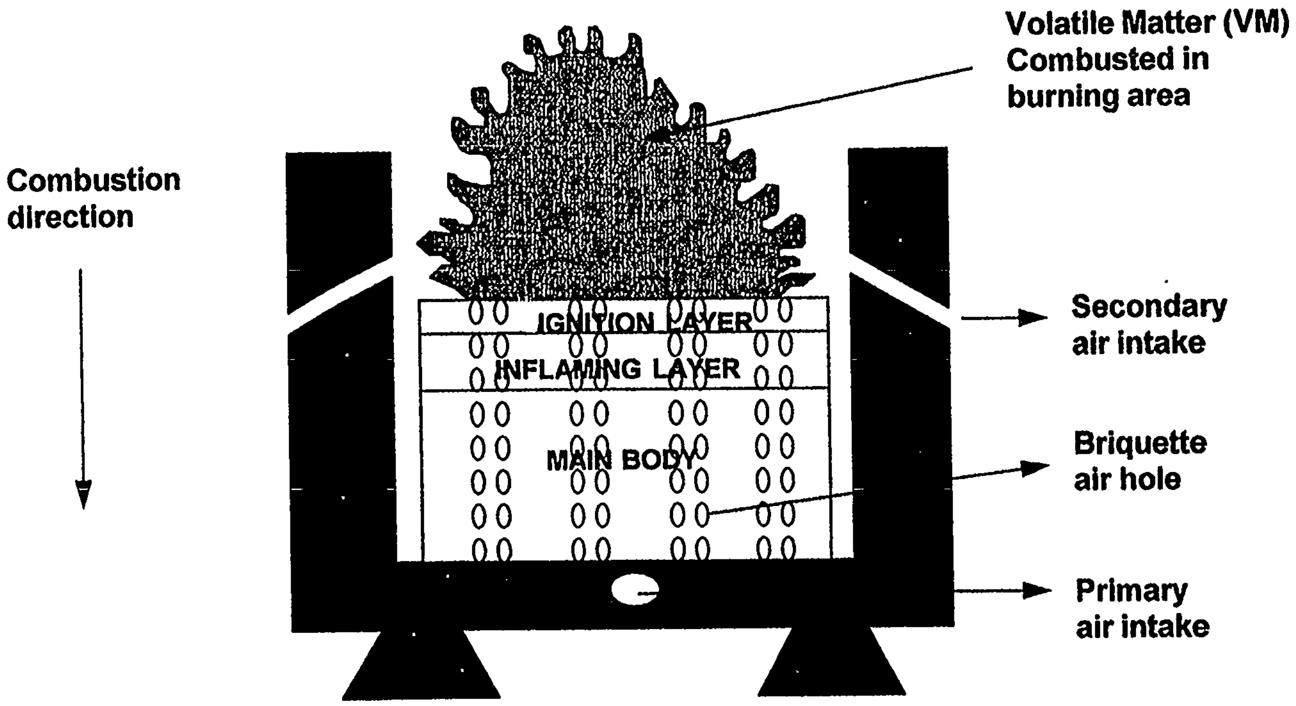
To accommodate principle of combustion mentioned above, the Honey comb uncarbonised coal briquette is design to have three layer :

- **Ignition Layer** : Consist of strong oxidizing agent (KNO3, BaNO3, KCLO4 etc.) that would produce fire when lit by matches.
- **Inflaming Layer** : from easily burned material (woodchips, charcoal etc.) that produce constant flame after the initial ignition of the first layer.
- **Body Layer** : made of coal as the combustion fuel.

The mechanism for combustion of Honey comb type uncarbonized coal briquette and the stove are illustrating at **Figure 2.**

Process Technology Comparison

Coal Utilization Department of MTRDC in Bandung had been doing some research on coal briquetting technique since early 1980's, with the technology aid from Korea, Japan, USA, Germany and Australia. Mostly in the field of utilization of the low rank Sub/Bituminous, high volatile coal of which are the majority of Indonesian coal. In Korea, coal briquette had been used in the household for heating and cooking purposes in the past. No processed applied to the coal but pressing/briquetting the coal into the form of cylindrical with ventilating hole inside to increase the combustion efficiency from high rank,low volatile matter (Anthracite) raw coal material. The coal briquette called "*Yontan Coal*" had been proven to, have higher heat efficiency and cheaper than the use of Kerosene. It become unpreferable since the coal reserve in Korea had been depleting so they should import the coal with the price higher than importing oil. In Japan the same condition happened , since they should imported every kind of energy (Coal, Oil & Natural Gas), the comparative advantage of coal briquette could not compete with the low price of oil imported from Arab country nowadays. In Australia,Germany and somehow in US also, the (usually low rank *Brown Coal*) coal was briquetted for the purpose of easier and cleaner handling during the transportation and increasing the combustion in boiler due to its uniform shape.



TOP IGNITION MECHANISM

Figure 2.

The research on coal briquetting technique usually devoted to find ***binder*** that would make coal briquette get higher stability (Hardness) while still worth economically. Some researchers are experimenting to find the ***additives*** that will reduce the negative effect of coal during its combustion such as faster ignition, reducing Sox &Nox emission, odor and higher heat efficiency.

Summary of the comparison among many Process Technology offered to PTBA for this project are given on **Table 2.**

Table 2.
PRODUCTION PROCESS TECHNOLOGY COMPARISON

PARAMETER	GERMANY	U S A	JAPAN	CHINA
1. Maximum Capacity (Tons)	1,000,000	50,000	36,000	500,000
2. Carbonization Process	Yes	Yes	Yes	No
3. Electricity Produce ,MW per Million TPY plant	83	34	--	--
4. Coal Consumption , ton per million ton briquette	2,450,000	1,700,000	1,450,000	1,000,000
5. Binder	Starch	Starch	Starch/Clay	Clay
6. Investment (Million US$) for 500,000 TPY plant	154	200	173	35
7. Operating Cost, (US$/Ton) for 500,000 TPY plant	108	---	166	82

Sources :
- LURGI Proposal 1993
- Royal Oak Briquette Plant, North Dakota
- Hashimoto Sangyo Proposal 1993
- CME proposal 1993

PTBA Honey Comb type Coal Briquette Project

PT Tambang Batubara Bukit Asam (Persero), PTBA, as the state owned coal mining company will be pioneering the first large scale of Coal Briquette industry in Indonesia. The first plant will simultaneously constructed at : Serang, West Java and Gresik, East Java to produce 165,000 ton/year **Smokeless, Odorless and Quick Ignition Honey Comb type Uncarbonised Coal Briquette** and 330,000 ton/year compound, scheduled to start in full capacity in 1996. The compound are the blending of raw material (Pulverized Coal, Ignitor and Binder) that become the mayor component of honeycomb coal briquette, will be supplied to small briquetting plants of private companies spreading in all Java island, to reduce the transportation cost of the finished product.

Technology applied at the plant come from the patented Process Technology of Professor HUANG ZHONG CHENG, China University of Mining Technology in Beijing with equipment purchased from People republic of China.

Table 3.
TECHNICAL SPECIFICATION OF PTBA HONEY COMB COAL

PARAMETER	UNIT
1. BLACKNESS OF SMOKE	< 5 Linggramm Grade
2. ODOR REMOVAL	70 % Solidified Sulfur Ratio
3. CARCINOGEN COMPOUND EMISSION	60 % decrease of B(a)P
4. SMOKE DUST	70 % decrease
5. COMPRESSIVE STRENGTH	> 400 Kg/pcs
6. IGNITION SPEED	20 minutes
7. BURNING STRENGTH	> 21 Gr/minutes
8. SIZE	125mm Diameter, 100mm Height
9. WEIGHT	+/- 1 KG/pcs

Sources: CME proposal, Prof. Huang Zhong Cheng, CUMT,Beijing,1993

PTBA other Coal Briquette Project.

Beside the commercial plant mentioned above, at Tanjung Enim,South Sumatera, the head quarter of PTBA, is planning to become the center of coal briquetting technology pilot-research plant in Indonesia. Pilot-research plant for Fluidised Bed Carbonization Plant to produce 10,000 ton/year carbonized coal briquette egg type and honey comb is scheduled to be constructed in 1996, funded by the grant from New Energy Development Organization (NEDO) of Japan.

Currently in operation an egg type carbonized coal briquette plants with capacity of 30,000 ton/year constructed and design by PTBA engineers and an unit of honey comb briquetting plant of 3,000 ton/year capacity purchased from China in 1994, intended for supplying the existing market demand for domestic coal demand in Java.

CONCLUSION

The development of Indonesian Coal Briquette Industry based on the mission to utilize abundant of Indonesian coal reserve, reducing government subsidy on common household cooking , by offering people an alternative fuel that have both competitive and comparative advantages over kerosene.

Coal Briquette (for all kind; egg type, honeycomb type , carbonized or uncarbonised) seems to be an attractive energy alternative for household and small scale industry as well.

Some socio-psycologic constraint for people to use coal briquette is the willingness to change to new habit ,such as to handle a solid fuel, as they were accustomed to use liquid fuel.

As an alternative new fuel, the new customer asks for more value added of the product, cost saving by using the coal briquette should significant enough to make customer willing to change from their former fuel.

To push the unit cost for coal briquette as low as possible, the uncarbonize coal briquette will has more competitiveness over the cost additional for carbonization of the rawcoal are relatively high plus the energy losses during the process.

With regard to compliance on environmental regulation, the lowest investment & operation cost of any method will be the best choice.

Interfacial Properties of Coal-Water Slurry Fuels
-on the effect of coal particle sizes-

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ABSTRACT

Experiments were conducted to investigate the effect of particle size on coal-water slurry (CWS) surface tension properties. Two different coal powder samples of different size ranges were obtained through sieving of coal from the Upper Elkhorn Seam. Two anionic surfactants, DDBS-soft (dodecylbenzene sulfonic acid) and 1840-x (sodium salt of sulfonated fatty acid), were selected for this test. The surfactant concentration varied from 0 to 1.0% in weight while the coal loading remained at 40% in weight for all the cases. A du Nouy ring tensiometer and a maximum bubble pressure tensiometer measured the static and dynamic surface tensions, respectively. The results show that both static and dynamic surface tensions tend to increase with decreasing coal particle sizes suspended in CWS fuels.

INTRODUCTION

Coal-water slurry atomization involves interactions between three different phases: solid (coal particles), liquid (water and additives), and gas (air or steam). Surface or interfacial tension is one of the significant properties in determining atomization characteristics of liquid or slurry fuels. Under the quasi-equilibrium conditions of low shear-rates of excessively slow atomization, the static surface tension of the fluid is an appropriate measure of the fluid's ability to form small radius droplets. However, the surfactants, additives or wetting agents presented in the CWS formulation do not reach an equilibrium concentration throughout the solid-liquid or liquid-vapor interfaces at higher shear rates. Therefore, dynamic surface tension should be a more appropriate measure in assessing the atomization that usually occurs at high shear rates.

The dynamic surface tension of a fluid is simply a measurement of the surface tension at a particular rate of surface formation or shear rate. The static and dynamic surface tension values are the same for pure fluids, such as water. The values of dynamic surface tension for slurry mixtures containing solid particles and various additives may be much higher than the corresponding static surface tension because insufficient time exists for the migration of surfactant additives to the atomized interface from the bulk mixture. The difference between the two surface tension values enlarges at higher shear rates that allows less time for the surfactant migration.

It is the intention of the present work to examine the effect of coal particle sizes on CWS static and dynamic surface tension properties. Rheology shows that the slurry viscosity generally increases with decreasing mean particle size [1]. When particles are suspended in the solution dispersed with additives and/or solvents, adsorption or solvation layers are formed on the particle surface which increases the effective volume (ϕ) of the particle. This effective volume increase is particularly significant for small particles which can explain the increase of the slurry viscosity with decreasing mean particle size. To the extent of our literature survey, no such a correlation for surface tension, whether static or dynamic, has been published. Examination of particle size effect on interfacial properties of CWS fuels is attempted using a specially prepared coal particle samples.

EXPERIMENTAL PROCEDURE

Dynamic Surface Tension Measurement Technique

Figure 1 illustrates the operating principle of the maximum bubble pressure tensiometer technique [2]. A capillary is inserted vertically to a depth of h into the vessel holding the CWS sample. The capillary is formed from Teflon orifice that is not wetted by CWS and has an outer radius of 0.49 mm, which is small enough to nullify the effect of hydrostatic deformation of the bubble as it emerges from the orifice [3]. As the bubble starts, grows, and detaches from the tube orifice, the bubble pressure varies due to changes in bubble radius. The maximum pressure is reached as the bubble radius is at a minimum at the outer orifice radius.

The dynamic surface tension is calculated from measurements of the maximum bubble pressure and evaluating the relation over a range of bubble frequencies: $\sigma = (p_{\max} - \rho g h)\, r_c/2$. Here σ is the dynamic surface tension, $p_{\max}$ is the maximum bubble pressure, ρ is the fluid (CWS) density, g is the gravitational constant, h is the height of the fluid above the orifice (h = 10 mm), and r_c is the capillary outer radius. The KRUSS Model BP-10 tensiometer was adopted for the dynamic surface tension measurements and proved to be effective over a range of 2 to 10 bubbles/sec. The bubble formation frequency is directly related to the surface expansion rate or shear rate. The accuracy of the tensiometer was tested by measuring the surface tension for distilled and deionized water. The result ensured a satisfactory accuracy showing less than a ±1 % deviation from the surface tension values listed in the CRC Handbook [4].

Preparation of CWS Fuel Samples of Different Coal Particle Size Ranges

Coarsely ground Upper Elkhorn Seam coal provided by DOE-PETC was classified into several different size ranges using a sieve shaker. To minimize the coal oxidation during the sieving, the sieve array was sealed with tape and the duration of sieve shaking was kept at a minimal necessary level. In most cases, the sieving was completed within thirty minutes. Two samples containing the largest and the finest particles were selected for testing so the effect of particle size on surface tension values could be distinctively observed. Figure 2 shows electron microscope photographs of the two selected coal powder samples. The coarse sample contains coal particles in the range of 180 to 250 mm, and the fine sample contains coal particles less than 63 mm.

The coal and water was completely mixed by a rotating mixer running for twelve to twenty-four hours. The specified amount of surfactant was then added and mixed by a magnetic stirrer for thirty minutes. All the present experiment used 40% weight CWS fuels. The slurry viscosity increases with increasing ratio of the packing density which is defined as the ratio of the solid volume fraction to the maximum attainable solid volume fraction, i.e., ϕ/ϕ_m [1]. The relatively uniform size distribution of the sieved coal particles tends to reduce the maximum attainable solid volume fraction and increases the packing density compared with coal powder of a wide size distribution. 50% or higher weight CWS fuel samples were too viscous and the tensiometers were not able to function with acceptable accuracy.

RESULTS AND DISCUSSION

Static Surface Tension

A du Nouy ring tensiometer measured static surface tension for the coarse and fine CWS samples. Results are shown for 1840-x in Fig. 3 and for DDBS-soft in Fig. 4. For both surfactants, the static surface tension decreases with increasing surfactant concentration and approaches a saturated value beyond a certain surfactant concentration. Before reaching this certain concentration, which is called a critical micelle concentration (CMC), the fine CWS sample shows larger surface tension values than the coarse sample and the CMC of the fine CWS is higher than the coarse CWS.

The dashed arrows indicate the CMC of the fine sample, the solid arrows represent the CMC of the coarse sample, and the empty arrows are for the CMC of an aqueous solution of the specified surfactant. The CMC values for CWS fuels are higher than their aqueous counterparts. The primary reason for this is believed to be the surfactant adsorption on the coal particle surfaces which requires more amount of surfactant than the aqueous solution (Fig. 5). The higher CMC of the fine CWS compared with the coarse CWS can also be explained by the surface adsorption. Smaller coal particles create more total surface area than larger particles for the same coal loading, which causes the overall surface adsorption of surfactant to increase. This needs higher surfactant concentration for the saturated surface tension level and higher CMC.

Dynamic Surface Tension

All CMC values of static surface tension are higher than 0.1% surfactant concentration for both fine and coarse CWS samples. The dynamic surface tension measurement was carried out for 0.1% or higher surfactant concentrations so that the dynamic surface tension behavior could be pronounced, providing the static surface tension level was already saturated. Since CWS fuels containing surfactant concentrations beyond 1% would not be commercially practical, the maximum surfactant concentration for the reported dynamic surface tension measurement was limited up to 1% in weight.

Figure 6 shows dynamic surface tension versus bubble frequency for the two selected CWS samples of 40% coal weight containing 1840-x surfactant. The family of curves in each plot, from the top to the bottom, correspond to 0, 0.1%, 0.5% and 1.0% concentrations. At each surfactant concentration, the fine CWS fuel shows consistently higher dynamic surface tension values than the coarse CWS under the same bubble frequency. Two reasons can be listed for the distinction: (1) smaller coal particles of higher number density contained in the fine CWS sample enhance the physical blockings against the surfactant migration to the bubble-created surface and reduce the surfactant diffusion into the bubble surface (Fig. 5), and (2) the increased total particle surface areas of the fine CWS sample increase the surfactant adsorption.

For the case with no surfactant mixed, the top curve in each plot, the higher surface tension for the fine CWS is attributed to the different bubble surface characteristics depending on the particle size. When the surfactant concentrations are zero or close to the static CMC level of 0.1%, the dynamic surface tension is nearly independent of the bubble frequency, which shows that the dynamic effect on surface tension is not pronounced for low surfactant concentrations. With increasing surfactant concentration, however, the dynamic surface tension shows a gradual increase with increasing bubble frequency, as the increased bubble frequency does not allow sufficient migration time for the surfactant.

Figure 7 shows similar results when DDBS-soft is mixed with the selected CWS samples. The previous observation of CWS with 1840-x is qualitatively consistent with the findings for DDBS-soft. The dynamic surface tension values for DDBS-soft shows a faster increase with increasing bubble frequency and approaches nearly the surface tension value of pure water near the bubble frequency of 10/s. As the bubble frequency increases, the effectiveness of surfactant more rapidly decreases. This shows that DDBS-soft should diffuse relatively slowly than 1840-x. For low bubble frequencies, the DDBS-soft results in slightly higher values of dynamic surface tension than the 1840-x results. This finding suggests that DDBS-soft is more readily adsorbed than 1840-x.

CONCLUSION

Examination of interfacial properties of CWS fuel samples of different coal particle size ranges shows that the CWS static and dynamic surface tensions tend to increase with decreasing coal particle sizes.

ACKNOWLEDGMENT

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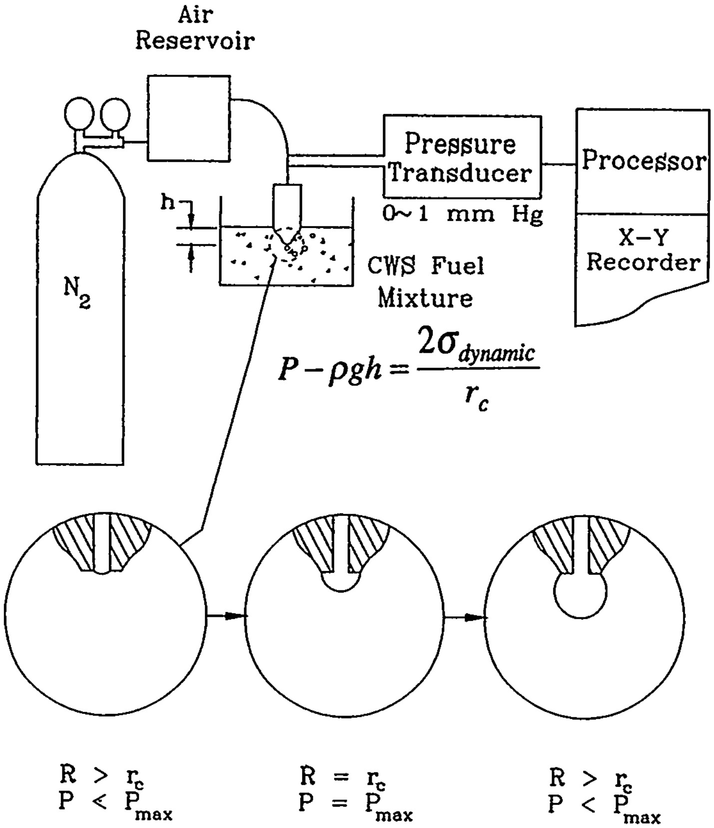
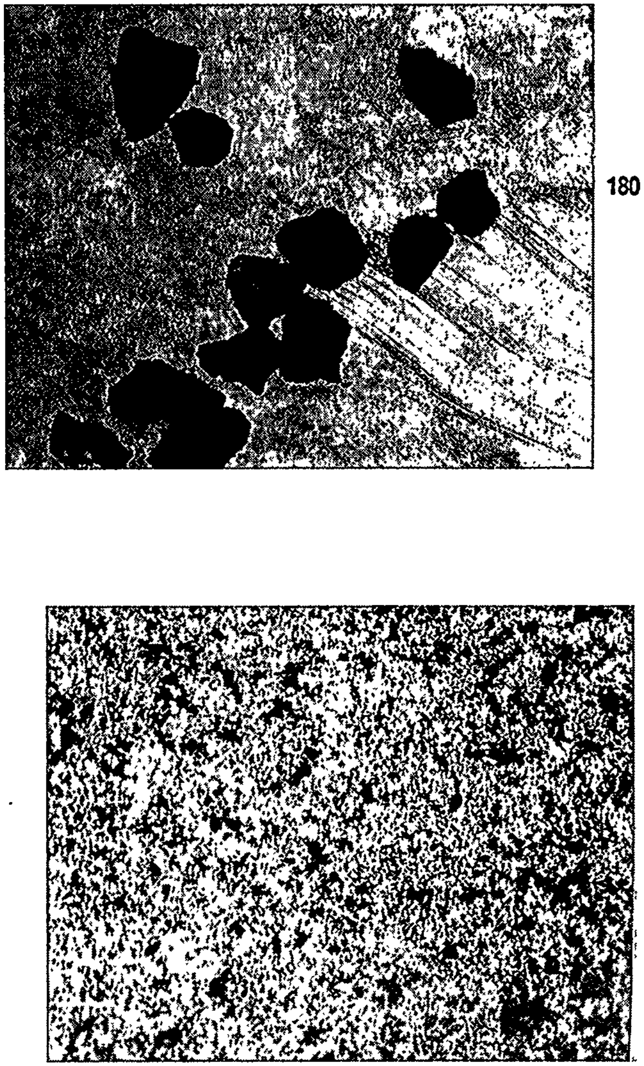


Fig. 1 Schematic illustration of maximum bubble pressure technique.



180 µm < d < 250 µm

d < 63 µm

Fig. 2 Electron microscope photographs of coarse and fine coal particle samples.

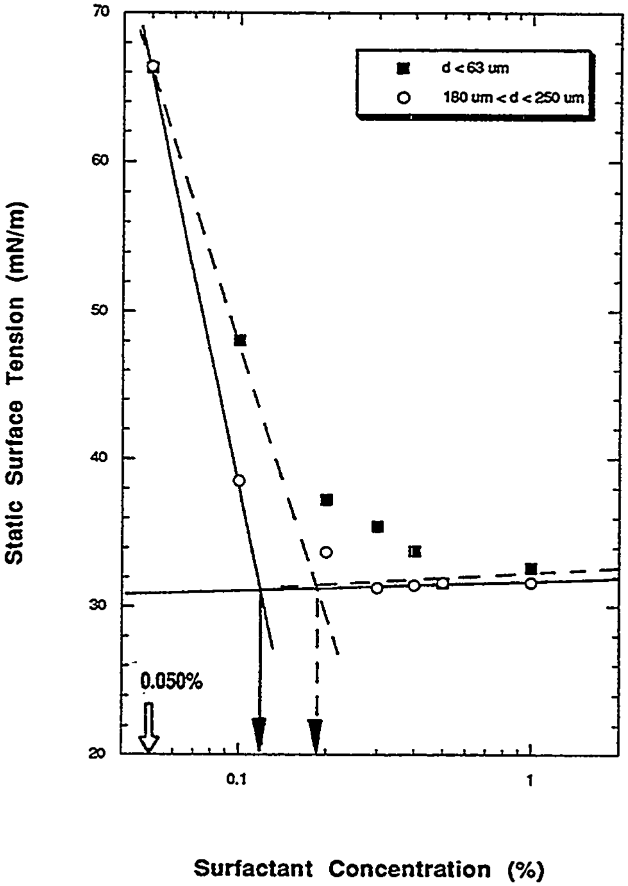


Fig. 3 Static surface tension versus concentration of 1840-x for 40% coal weight CWS fuels containing different particle sizes.

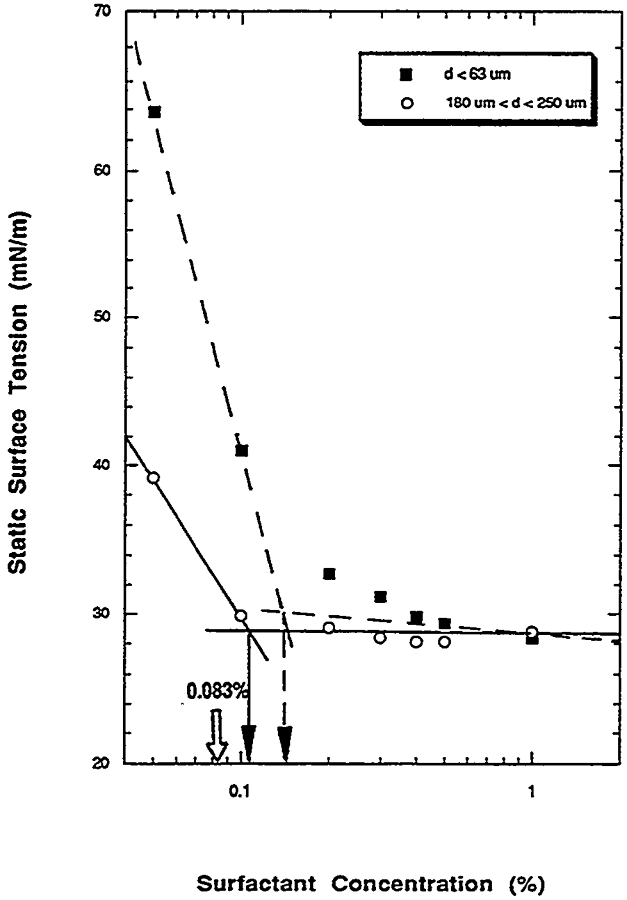


Fig. 4 Static surface tension versus concentration of DDBS-soft for 40% coal weight CWS fuels containing different particle sizes.

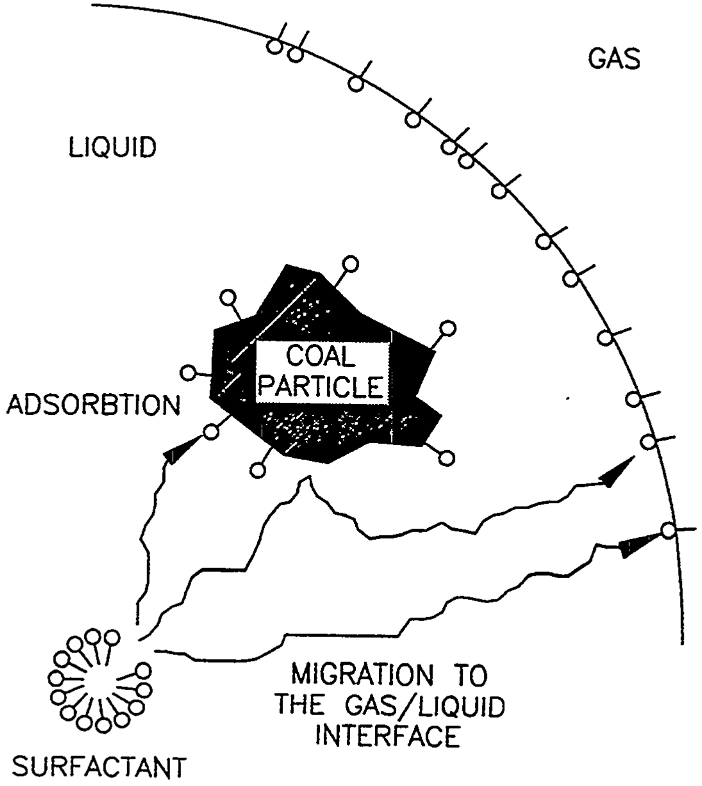


Fig. 5 Illustration of surfactant adsorption at coal surfaces an reduced diffusion of surfactant due to particle blocking.

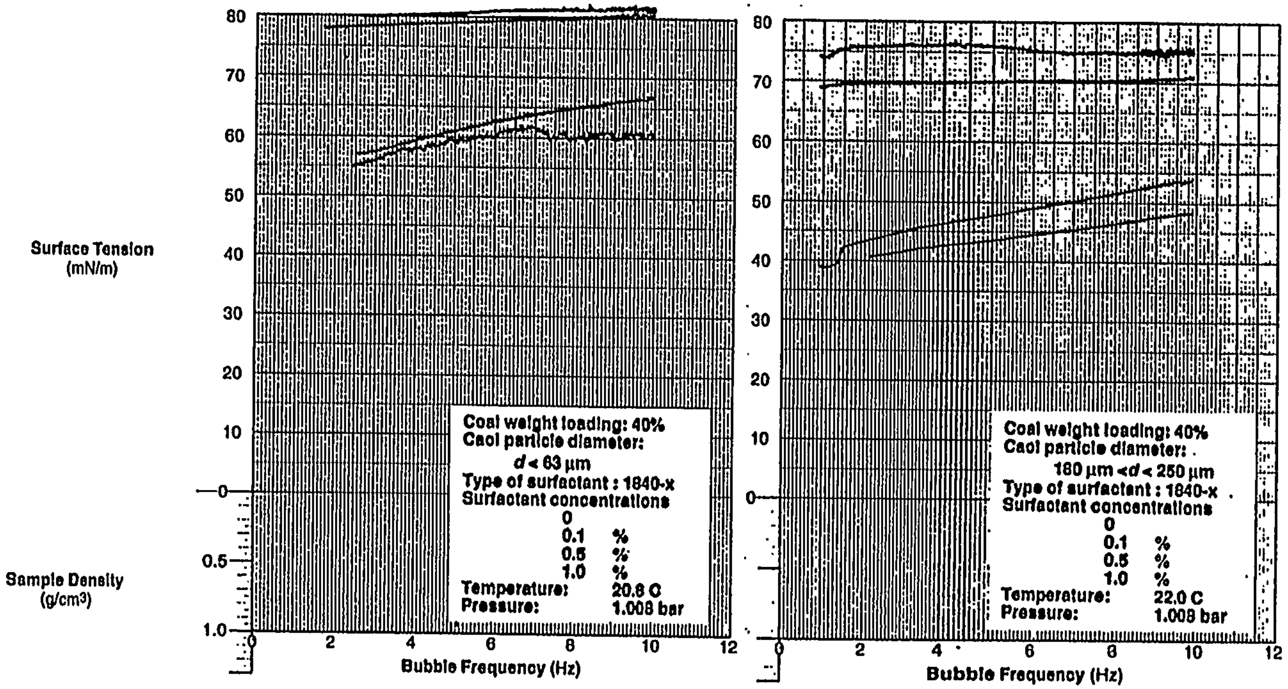


Fig. 6 Dyanmic surface tension versus bubble frequency for different surfactant concentrations.

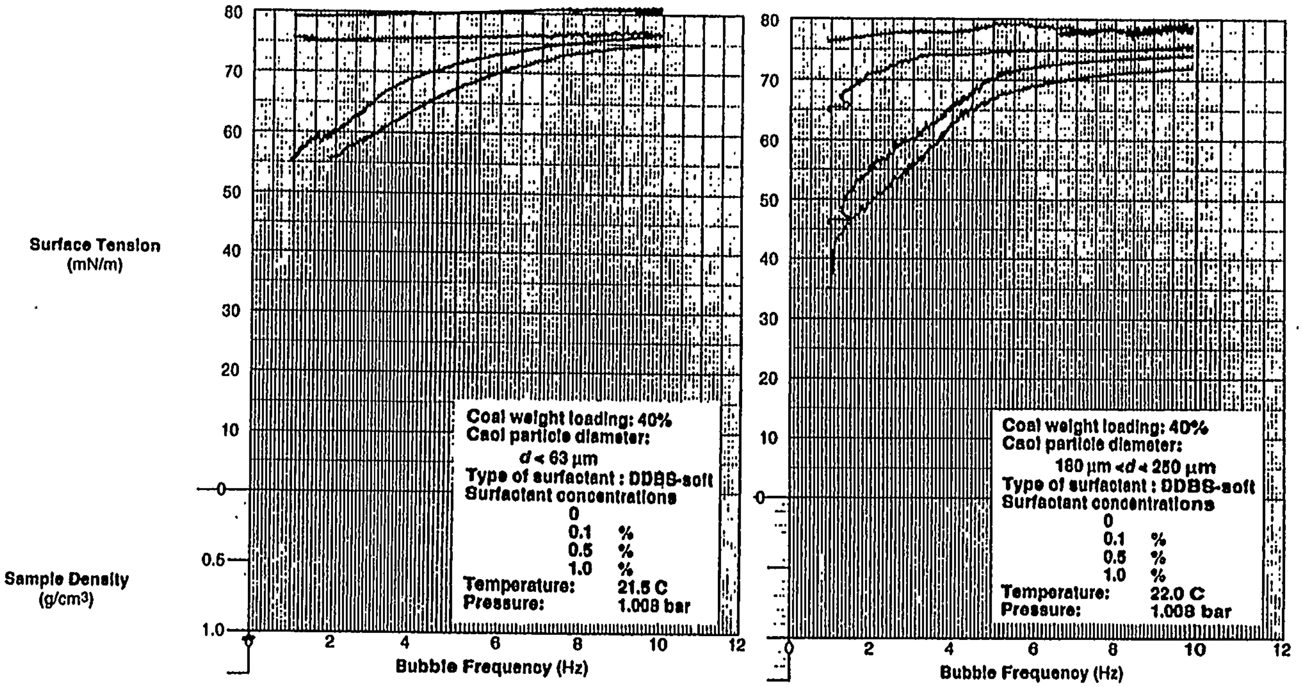


Fig. 7 Dyanmic surface tension versus bubble frequency for different surfactant concentrations.

FULL UTILIZATION OF MINED COAL

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SUMMARY

This paper makes a case for the installation of cost effective processing capability for fines, middlings and waste on coal wash plant sites for BTU recovery. The product mix leaving the wash plant would comprise very high quality coal, power and a cement byproduct.

The paper reviews the combustion of coal and the release of volatiles from coal as a function of thermal treatment. The treatment of coal and coal waste in a plasma environment is reviewed as a logical consequence and it is suggested that plasma technology can provide the cost effective mine site process tool needed. Coal and coal wastes have been successfully treated in plasma in tonnage quantities requiring moderate power input (176 kWh/ton @ 200 kW plasma power) while producing high quality cement products and thermal energy. The published results are used to verify the conclusions of this paper and form the basis for the estimates of process economics.

Calculations show that the profitability per ton mined coal can increase from a few dollars to the $ 10 to $ 30 range as all mined energy values are either converted to power or exported as high quality coal. The higher profitability numbers also assume sale of byproduct cement from the plasma process. The coal fraction leaving the site may be either dry coal or a highly loaded coal water slurry fuel with its inherent down stream advantages. As a not insignificant additional benefit, the environmental burden associated with the storage of coal mining waste fractions is eliminated.

The paper is not intended to convey the impression that any available plasma technology is ideally suitable. It suggests the urgency of further investigation of both suitable technologies and site specific economic optimization of wash plant operations and product mix.

COAL COMBUSTION

The combustion of coal is highly complex and discussed in great detail in the relevant literature. It can be divided into two separate processes - the combustion of volatile species evolving from the coal involved in the combustion process and the combustion of the remaining solid char. The more volatiles are evolved, the faster the combustion proceeds. The oxidation of the evolved gaseous species is rapid, and the more volatiles escape, the greater the remaining char surface area to mass ratio becomes. The porosity of the char increases with the temperature of its formation[1)]. A discussion of the process of volatiles evolution upon heating is very essential to this paper, with its subsequent conclusions.

As stated, the rate of combustion depends on the combustion kinetics of the gaseous species and the rate of combustion of remaining fixed carbon[2)]. The attainment of complete fixed carbon burn-out is normally the rate limiting step. The ultimate rate of combustion is thus determined by the presence of oxygen (or other oxidizing agents), the temperature, the specific surface area of the remaining skeletal carbon and oxygen access to the carbon surfaces.

The inorganic matter included in the coal particles may inhibit total carbon burn-out by melting and coating combustible remains with a slag layer precluding the access of oxygen. Such effects are likely to be minimized in processes employing very rapid heating and devolatilization, as rapid evolution of gas pries the coal particle apart, separating inorganic matter from burning organic matter.

VOLATILE MATTER IN COAL

Volatile matter is expressed from coals as the coal is heated. The internal molecular structure of coal begins to decompose as a result of heating to temperatures exceeding 350°C. The volatiles given off, mostly oxides of carbon, methane, ethane, hydrogen and other light hydrocarbons, leave a high carbon content residual, a char, which is referred to as the fixed carbon in the proximate analysis procedure. After volatile matter release, the remainder of the coal sample consists of this char and mineral matter.

The amount of volatile matter in any specific coal as measured in accordance with ASTM procedures indicates the coal rank. Hence, the amount of volatiles released according to the standard test procedure, using relatively low temperatures and heating rates, constitutes a coal classification measure. Whereas the standardized test is useful in the way that it helps to classify the coal, it is also clear that the ultimately attainable content of volatile, combustible species in any coal is in no way described by the ASTM proximate analysis.

Coal composition, testing apparatus, heating rate and final temperature determine the measured amount of volatiles. It is not advisable to use the proximate analysis data in order to assess the actual extent of coal volatile content for practical purposes. It cannot be assumed that a coal of a certain rank has a specific amount of volatile matter - the amount of volatile matter participating in the process of firing the coal is dependent on the combustion process.

The relative amounts of volatiles expressed will enhance the rate of combustion and total burn-out of the coal. This is true for all ranks, from lignite to the anthracites. Hawksley and Badzioch[3)] determined that the mass loss of a coal being heated prior to combustion may be up to twice that predicted by the ASTM determination of coal volatile content. They defined the "Q factor", the value of "Q" being that of actual weight loss of the coal upon heating in any given process divided by the ASTM determined content of volatile matter in the coal. The value of "Q" has been established at 1.35 to 2.00[3)], at heating rates on the order of 1,000°C to 10,000°C sec^{-1}.

The "Q factor" is particularly high in "dilute" combustion of coal, i.e. where volatiles are removed with sufficient speed and do not undergo cracking reactions, leaving solid carbon in the pores of the coal particle undergoing heating prior to ignition and during combustion. The "Q factor" is further enhanced by diminished coal particle size. It should be below 100 μm in diameter in a pulverized coal flame to allow char burn-out in under one second at the actual heating rate at or above 10,000° C per second[2)].

Ultimately Available Volatile Matter.

The "Q factor" is well established. It appears to limit the expected volatiles formation to twice the ASTM determined number. Theoretically, the total amount of volatile matter which can be formed depends largely on the amount of available hydrogen in the coal macerals. Anthracitic coals and low volatile bituminous coals, having undergone the decarboxylation process for too long in their formation, contain far too little hydrogen to yield substantial amounts of volatile hydrocarbons upon heating. High volatile bituminous coals and coals ranked lower, however, do. In fact, the hydrogen content of medium and low rank coals is theoretically sufficient to volatilize the entire organic content of those coals, leaving virtually no char at all[4).

In standard measurements of volatile matter at the low heating rates employed, and the low final temperatures aspired for, the indigenous hydroxyl groups absorb the available hydrogen in the coal macerals to form water vapor. Formation of methane and ethane claims more hydrogen than can support the possibility of volatilizing the whole body of the coal matrix. If the formation of these hydrogen rich compounds could be abated, more of the macerals would be volatilized.

The hydroxyl groups limit coal volatilization at temperatures well below 700°C where the formation of water vapor is thermodynamically favored. Above that temperature carbon monoxide is stabler and hydroxyl groups are destabilized, leaving additional hydrogen to combine with carbon. At further elevated temperatures, the hydrogen consumption in the formation of methane and ethane becomes increasingly limited in favor of the formation of stabler compounds. Acetylene, readily formed in contacting coal with plasma5), consumes only one hydrogen atom per carbon atom, rather than the four required for methane. Therefore, it may be argued, if higher "Q factors" than about 1.35 to 2.0 are to be found, both higher heating rates and higher final temperatures than used in the bodies of work reporting these values, are required.

Based on work at heating rates ranging from 650°C to 10,000°C $\sec^{-1}$, Anthony et al6) concluded that the heating rate in itself does not affect the evolution of volatiles. Differences in measured amounts were ascribed to cracking reactions, obscuring the "true" volatile matter content. This was contradicted by Kimber and Gray7). They concluded that increased volatiles yield resulted when the heating rates were extended to 100,000°C $\sec^{-1}$, employing final temperatures up to 2,000°C, higher than those reported by Anthony et al. This may lend some support to the speculation above.

PLASMA AS THE HEATING MEDIUM.

Pulverized coal passed through a plasma undergoes extremely rapid heating. Reaction times are on the order of milliseconds and the products formed are mostly soot and gas5).

Plasma environments provide heating rates on the order of 10^6 °C $\sec^{-1}$. This is given both by heat transfer from ions and neutral species at elevated temperature and particularly the condensation of electrons and ions species on all available sufaces, releasing the ionization energy as heat.

In addition, the presence of ionized species is believed to enhance chemical reaction rates by means of e.g. electron attachment mechanisms. Speculatively, there are other mechanisms involved as well, such as interaction between the plasma and multipole moments in the coal and inorganic matter, caused by strong and transient microfields resulting from charge separations in the plasma near the surfaces of immersed particles.

The plasma environment differs radically from what a coal particle would experience in a conventional pulverized coal flame. The Q factor should reach a maximum under these circumstances and the other specific plasma/particle interactions may further accelerate the volatilization and structural collapse of the particles. The plasma features thought to be essential in the treatment of coal, i.e. heat flux, heating rate, electron attachment and microfield interaction are discussed below.

High Temperature Plasma

Plasmas are created by using shockwaves, high temperatures or strong electric or magnetic fields. Industrial plasmas, used for tonnage throughputs, are established using plasma guns or simple consumable graphite electrodes. The resulting plasmas are referred to as hot plasmas, defined as plasmas where the electron density, n_e, is at least 10^{22} m^{-3}, the electron and ion temperatures are in the range of 5,000 to 50,000 K, and the plasma is roughly in thermal equilibrium, i.e. the electron temperature, T_e, and ion temperature, T_i, are approximately the same:

$$T_e \simeq T_i$$

Whether or not the thermal equilibrium is in place locally at any given time appears to be a matter of considerable debate. It has been claimed by some workers in the field that the local deviations from equilibrium contribute to special effects in the interaction between an established plasma and matter introduced into it. Such interactions have not been quantified.

Heat Flux and Heating Rate

The heat flux from a plasma, assuming a Maxwellian electron energy distribution, can be written as[8]:

$$q = 1/2 n_e \, [2kT_e/\pi m_e]^{1/2} kT_e$$

In an atmospheric arc plasma whith a typical electron density is about 10^{22} m^{-3} and an electron temperature of 2 eV, or 15,466 K, the corresponding heat flux is about 411 MW/m². This is at the low end of the scale - values of 500 to 800 MW/m² are typical for these plasmas.

The following expression can be used for a rough estimate of the vaporization of mass given the plasma heat flux:

$$\Delta m/m = 3qtM/\rho H_v r$$

Applying this to an example of treating coal particles of 8 mm diameter in the plasma, inserting the following values:

q:	411 MW/m²; the heat flux
t:	.05 seconds; the time of plasma contact
ρ:	1,200 kg/m³; the density of the coal particle
H_v:	50 kJ/mole; heat of vaporization of coal - this value is questionable and quite possibly rather low for high volatile bituminous coals, considering the very low net heat of pyrolysis reactions.
M:	100 grams per mole; assumed effective molecular weight of the coal
r:	.004 meters
$\Delta m/m$:	The dimensionless instantaneous mass loss at radius r

one finds the magnitude of $\Delta m/m$ to be about 25. In other words, in the given example with the given assumed values, a coal particle of 8 millimeters diameter would vaporize more than 25 times over, assuming a residence time of 50 milliseconds in the plasma.

The uncertainty of this estimate is very considerable. First, the assumption of a Maxwellian energy distribution is incorrect for most industrially applied plasmas and, in addition, the plasma is significantly disturbed by the coal. The energy transfer is influenced by the endothermic or exothermic reactions in the interface between the plasma and the coal particle. The development of a protective hot gas layer between the plasma and the particle surface further impedes the heat transfer. Furthermore, the estimate does not allow for the charge accumulation on the particles/droplets, which will alter their trajectories in the plasma. The mass loss equation is of course another simplification, and is true only for the immediate loss, assuming no change in particle diameter. The discussion does, however, indicate the magnitude of available heat flux and therefore the high rates of heating attainable.

Electron Attachment

At temperatures as high as 5,000 K only simple molecular structures can be created and naturally complex structures can be destroyed. Low temperature and low pressure plasmas are used to both synthesize and selectively destroy molecular species.
They are defined as plasmas where:

$$T_e >> T_i$$

An interesting application of low temperature plasmas is in the selective decomposition of organic molecules. The energy required for the decomposition of a dilute stream of organic substance in a carrier gas, air for example, using a low temperature non-equilibrium plasma, is much less than a thermal process requires, simply since electrons of sufficient energy level selectively attack bonds of a corresponding energy level in the organic molecules and the entire body of gas does not need to be heated to reaction temperature. The attachment process in such cases occurs as a dissociative two body reaction between electrons and the organic molecules.

This mechanism also occurs in the high temperature plasmas as defined above, but at far higher electron densities and therefore much higher frequency.

Charge Separation and Microfields

The existence of transient microfields in a plasma as a result of introducing particles is not in question. The phenomenon is not well quantified, and certain results of plasma treatment on matter can only speculatively be attributed to the interaction between these microfields and multipole moments in the material treated. Such multipoles exist in the inorganic matter of coal as well as the coal macerals themselves until fully charred.

The microfields are established as a result of the affinity of electrons and ions to the cold surfaces introduced. Electrons, being three orders of magnitude lighter reach the surfaces first, leaving heavy ions behind, thus creating very strong, but transient fields.

EXPERIMENTAL VERIFICATION

The theories advanced above regarding the expected reactivity of coal in a plasma environment have been verified experimentally. Particularly significant work was reported by Tetrosem Ltd. and Rugby Portland Cement, Ltd[9], both of the U.K., as early as 1978. In trial campaigns over a long period of time using a so called Expanded Precessive Plasma reactor (EPP) reactor, coal and coal mining waste were processed on tonnage scale at 200 kW plasma power, with a specific energy input of no more than 176 kWh per ton of coal mining waste processed. Energy requirements of 100 - 130 kWh/ton were expected in scaled -up reactors, limiting thermal losses.

The EPP process was developed in the U.K. some 20 years ago. It was originally intended for use in the metallurgical industry, which is where the technology is in commercial use today. The plasma reactor consisted of a vertical shaft where combustion air could be injected at various levels and a top mounted plasma gun. The plasma gun could be orbited and the issuing plasma jet was directed downwards towards a circular anode. This entire assembly was mounted above the reactor shaft. By orbiting the plasma gun, a cone shaped plasma volume was established, through which feedstock material could be inserted into the reactor. The coal was treated in the plasma under reducing conditions and then entered the shaft where it was combusted.

The tests regularly achieved complete burn-out of the coal macerals, providing significant exothermic energy release. Coal and coal waste, with particle size of 90% below 1 mm diameter and with varying ash content were used, from a high of 80% to a low of 20%, all with essentially the same result. At the time, the main focus of the effort seems to have been the manufacture of hydraulic cements from the carbon free residue, rather than energy recovery and other issues more directly associated with the economics of coal production and use. The inorganic residue collected from the reported tests displayed excellent cementitious or pozzolanic properties, in many instances superior to ordinary portland cement. The final composition of the inorganic residue could be modified by externally administered mineral matter prior to plasma treatment.

SIGNIFICANCE OF THE FINDINGS

For the purposes of this paper, the particular importance of the published EPP work is twofold:

1. Irrespective of ash content, all organic content of the coal could be converted to hot exhaust gas, suitable for steam raising, in the very short residence time of less than 0.5 seconds.

2. The plasma energy requirement in this reactor and on this small scale was as low as 176 kWh per ton material; indicating an actual requirement of some 100 kWh/ton.

There is every reason to expect better performance yet from equipment specifically developed for the treatment of coal and coal wastes, scale-up to commercial size and taking advantage of the further development of plasma technology which has taken place in the intervening years.

This opens the very interesting possibility of establishing dedicated plasma based processing facilities to be operated on mine site, alongside the coal wash plant. Such an arrangement permits the reoptimization of the coal wash plant operation and product mix. Instead of removing high ash fractions and fines from the mined coal, and exporting the remainder by rail, the plasma operation could convert a majority of the low and medium BTU product for export as power on the grid, providing a very low ash, high quality coal product for export as such, or as a coal water slurry fuel. The slurry alternative offers considerable potential advantages over lump coal:

1. The coal cleaning is carried out at the mine site to the extent that a slurry can be directly fired in oil or coal based conversion units. The washing operation can be carried out at finer particle sizes to yield a lower ash product, especially if it is to be used as a slurry fuel.

2. Washing to very low remaining ash levels will yield a wet product. By converting it to a slurry fuel, the dewatering step is eliminated.

3. The slurry fuel has considerable advantages in transportation and storage over coal.

4. Even if the resulting coal contains residual sulphur levels requiring SO_2 scrubbing, the slurry fuels can be provided with small amounts of low cost sulphur capturing agents, rendering it a compliance fuel or better. It can then be co-fired with higher sulphur fuels.

The treatment of large volumes of coal mining waste deposited on operating or abandoned mine sites may become a necessity for environmental reasons in the USA as it has elsewhere. This future mining cost could be avoided by the proposed strategy. The byproducts of the combined plant would be mined rock and inert solids recovered from the plasma process. The latter are suitable as cement raw material - not as a filler material, but on its own merits.

ECONOMICS

It is possible to make reasonable estimates of the costs and benefits involved in establishing an integrated mining/washing/plasma processing facility on mine site. The following model is based on many generalizations and is solely intended to provide indications and to facilitate a sensitivity analysis.

Simplified Basic Model for Overall Process Profitability Estimates

I. Materials Balance

Basis for the model:
1,000 kg run of mine coal
a % organic matter in r.o.m. coal; 10a kg
b % of r.o.m. coal remains after washing process; 10b kg.
c % organic matter in clean coal fraction.

Simplifying assumptions: 20 weight percent of the material removed from the clean coal stream in the washing operation can be removed as rock and shale with no calorific content and no environmental penalty associated with its disposal. The resulting middlings and coal fines stream is further processed in a plasma reactor. The influence of coal moisture has been neglected, as has the heat loss to inorganic material in the plasma processing step.

Coal washability: The washability is chosen to be represented by the following equation; approximated from data published for a high volatile bituminous A coal from West Virginia:

$$c = 95 - 0.1278\,(b - 25)^{1.3}$$

wherein

$$25 \leq b \leq 100 \ \ [\text{and } a = 60\,]$$

Actual washability influences the results significantly and dictates the particle sizes at which the desired degree of separation is achieved.

II. Revenue Calculations

The revenue streams, based on one metric ton of coal mined and processed through the wash plant and plasma treatment facility, are the following:

1. Revenue from sale of clean coal as delivered from the washery.

The revenue from sale of clean coal is based on the mined amount of 1,000 kg of run of mine coal and a sale price f.o.b. wash plant which varies with the degree of mineral matter removal. Coal with less than 10% mineral matter is assumed to be compliance coal. The coal sale revenue is given below, where Q stands for BTU/lb dmmf coal:

% wash plant recovery; cleaned coal [b]	% organic matter in clean coal [c]	$/MBTU	Revenue; $/ton mined coal at Q = 13,000	Revenue; $/ton mined coal at Q = 15,000
100	60.0	.95	16.32	19.82
90	65.9	.95	16.13	19.59
80	71.6	1.00	16.40	18.92
70	77.0	1.10	16.97	19.58
60	82.0	1.20	17.60	20.31
50	86.6	1.25	17.35	20.02
40	90.7	1.50	15.58	17.97
30	94.0	1.70	13.72	15.83
25	95.0	1.70	11.56	13.34

2. Revenue from sale of power generated from the plasma treatment of fines and middlings product from the washing process.

The thermal energy released in the exothermic oxidation reaction is converted to steam with a thermal efficiency of 72%. The turbine efficiency is assumed to be 40% and the credit for power delivered to the grid is assumed to be 5.5 cents per kWh. The revenue stream can be written as:

$$1.02\cdot10^{-5}\,Q\,(600 - 9.5b + 1.278\cdot10^{-2}b(b - 25)^{1.3})\ [\$] \qquad (2)$$

3. Revenue from the sale of inorganic residue from the plasma treatment process as a cement precursor material.

This revenue stream is assumed to contribute up to $ 40.00 per ton of the inorganic residue produced. The sale price of cement, f.o.b. plant site is currently about $ 70 per ton. The revenue contribution can be written as:

$$(0 \text{ to } 40)\cdot(0.2 + 1.5\cdot10^{-3}b - 1.278\cdot10^{-5}b(b-25)^{1.3})\ [\$] \tag{3}$$

4. Revenue resulting from not paying environmental penalties for acceptable storage of middlings and fines product resulting from the separation of the clean coal product.

It was assumed that the rock and slate removed from the washing operation would not require additional disposal cost. On the other hand, the disposal of waste, middlings and fines streams which contribute to groundwater and atmospheric pollution is likely to attract legislative attention in this country as it has in other coal producing regions. It is not unreasonable to assess an environmental penalty to these streams in the range of up to $ 5 per ton of such waste. This revenue can then be written as:

$$(0 \text{ to } 5)\cdot(800 - 8b)\cdot10^{-5}\ [\$] \tag{4}$$

III. The Costs Incurred:

5. The coal mining cost.

The mining cost is assumed constant at $ 13.00 per ton r.o.m. coal.

6. The capital and operating cost of the wash plant.

The present model is merely established in order to indicate the potential value of installing a plasma treatment facility to operate in parallel with the washplant in terms of optimizing the utilization of all mined energy values with minimum environmental expenditure. The cost of washing, W, expressed as a cost per ton of r.o.m. coal is thus simply assumed to be directly related to the capital cost and the operating cost; the latter being introduced as a linear function of the amount of material removed from the stream of r.o.m. coal.

$$W = 4 - .02b\ [\$] \tag{6}$$

7. The capital and operating cost of the plasma processing installation.

The investment required for a plasma treatment installation, including comminution, plasma reactors, flue gas treatment and a boiler/turbine system capable of treating 3 tons of 20% ash coal per hour at a power consumption of 170 kWh per ton has been established at $ 24 million. The costs involved in operating at 30 tons of feedstock per hour have been extrapolated from this basis.

The operating cost is assumed to be 18% of the capital cost for maintenance, labor and consumables at 100 to 170 kWh electric power per ton material treated at 6.5 cents/kWh.

The assumptions provide a total plasma treatment cost ranging from a low of $ 43 per ton material to a high of $ 70 per ton as shown:

COST CATEGORIES	170 kWh required per ton - proven	100 kWh required per ton - estimated
Investment requirement per annual ton	$ 316	$ 186
Capital cost per ton	$ 47.40	$ 27.88
Maintenance, consumables and labor, per ton	$ 7.10	$ 4.18
Plasma power, per ton	$ 11.05	$ 6.50
Auxiliary power, 70 kWh/ton	$ 4.55	$ 4.55
COST PER TON MATERIAL TREATED IN PLASMA:	**$ 70.10**	**$ 43.11**

The cost of the plasma treatment can then be represented as:

$$(43 \text{ to } 70)\cdot(0.8 - 8\cdot10^{-3}b)\ [\$] \qquad (7)$$

This equation is based on the treatment of 240,000 metric tons of material per year with a high combustible content (80%). The estimate range is conservative for the same throughput with less combustible matter. It is also conservative for larger throughputs as a result of further scale-up.

IV. Net Profitability Calculations.

The technical feasibility is not in doubt, based on the review above. The economic feasibility is indicated in two tables below. In order to arrive at harder numbers the calculations need further refinement and application on actual situations.

Net profitability estimates are given for eight separate scenarios, both assuming no credits from landfill cost savings or byproducts and assessing various credit levels for these items as indicated in the table headings. The two tables differ only in that the assumed calorific value of the coal has been varied from 13,000 to 15,000 BTU/lb DMMF.

The capital and operating cost assumptions introduce a significant difference between the high and low estimates. This cost has been selected at $ 60 per ton material treated in the plasma facility. Assuming a realistic actual plasma energy consumption of 120 kWh per ton, the investment cost will include a buffer of 30 % for contingencies.

The resulting net costs indicate profitability if over 50% of the mined material is separated in the washing process. This cut-off point is directly related to the coal washability and BTU content. Higher profitabilities are indicated if the cost and sale price of power increase beyond the 6.5 and 5.5 cents per kWh assumed in the given example.

1. **Q = 13,000 BTU/lb; Net Profitability Expressed as $/ton Mined Coal.**

b % wash plant recovery; cleaned coal	Scenario A - Plasma treatment : $ 60 ton^{-1} - No revenue from cement precursor - No credit for elimination of landfill costs	Scenario B - Plasma treatment : $ 60 ton^{-1} - No revenue from cement precursor - $ 5.00 ton^{-1} credit for elimination of landfill costs	Scenario C - Plasma treatment : $ 60 ton^{-1} - $ 20 ton^{-1} revenue from cement precursor - $ 5.00 ton^{-1} credit for elimination of landfill costs	Scenario D -Plasma treatment : $ 60 ton^{-1} - $ 40 ton^{-1} revenue from cement precursor - $ 5.00 ton^{-1} credit for elimination of landfill costs
100	$ 3.32	$ 3.32	$ 3.32	$ 3.32
90	$ (2.76)	$ (2.36)	$ (.88)	$ .60
80	$ (4.39)	$ (3.20)	$ (.54)	$ 2.12
70	$ (4.94)	$ (3.74)	$ (.14)	$ 3.46
60	$ (4.91)	$ (4.31)	$ .83	$ 5.07
50	$ (.55)	$ 1.45	$ 6.53	$ 10.77
40	$ 1.73	$ 4.13	$ 8.99	$ 13.85
30	$ 5.82	$ 8.62	$ 13.46	$ 18.30
25	$ 8.12	$ 11.12	$ 16.08	$ 20.64

2. **Q = 15,000 BTU/lb; Net Profitability Expressed as $/ton Mined Coal.**

100	$ 6.82	$ 6.82	$ 6.82	$ 6.82
90	$ 1.47	$ 2.05	$ 3.53	$ 5.01
80	$ (.32)	$ .48	$ 3.14	$ 5.80
70	$ 1.32	$ 2.52	$ 6.12	$ 9.72
60	$ 2.87	$ 4.47	$ 8.61	$ 15.75
50	$ 9.30	$ 11.30	$ 15.96	$ 20.62
40	$ 13.96	$ 16.35	$ 21.21	$ 26.07
30	$ 20.03	$ 22.83	$ 27.67	$ 32.51
25	$ 22.30	$ 25.30	$ 30.26	$ 34.82

CONCLUSIONS

The tables above indicate significant profitability if 50% or more of the mined material is separated from the clean coal stream in the wash plant. This is especially true when the BTU value is high, even if potential credits for byproduct values and eliminated landfill costs are neglected. As a consequence of the low yield in the washing operation, the resulting clean coal will be of higher quality and the coal mining operation profitability increases. In some cases, currently unprofitable coal mines could become viable with the addition of the plasma processing capability.

It is clearly shown that the potential revenues from producing a saleable cement precursor material, which can be transported to cement plants to supplement and be interground with the clinker produced there, provides a dramatic profitability increase. The more material that can be separated in the washing process, the more cement precursor material and power can be sold, and the better the quality of the clean coal stream.

The coal mining profitability can increase to $15 to $ 30 per ton coal mined. That compares very favorably with current levels.

What is needed now is:

1. Identification and development of a dedicated plasma processing system with an investment cost below some $ 200 per annual ton. Given reported results, this is feasible.
2. Further research to establish reliable databases for the process based on a wide variety of coals and coal mining wastes.
3. Further verification of cement precursor properties as well as final cement quality on a case by case basis to establish market value. The work done by Rugby Cement, Ltd. needs to be followed up and placed into a broader perspective.
4. Optimization studies are required, based on real scenarios, including the option of exporting the coal as a slurry fuel from the wash plant site.

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Proposed Shanxi to Shangdong Coal Slurry Pipeline,
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UTILIZATION OF COAL-WATER FUEL IN HEAT POWER INDUSTRY AND BY PUBLIC UTILITIES OF UKRAINE

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1.0 INTRODUCTION

One of the major problems of the fuel and energy balance of Ukraine is acute shortage of its own resources of organic fuel.

At present the steam coal output in Ukraine approaches 100 mln t, oil production makes up about 5 mln t and that of gas reaches 22 bln. m^3, which in terms of equivalent fuel (e.f.) totals 94 mln t, the annual demand being approximately 300 mln t e.f.

To make up for fuel deficiency Ukraine has to annually import 120 bln. m^3 of gas, 50 mln t of oil and about 10 mln t of coal, their approximate cost being U.S.$ 15.6 bln.

At the same time coal reserves in developed fields only make up 10 bln. t, the total reserves of this fuel being 100 bln. t.

Thus the whole burden of meeting the requirements of Ukraine in power resources when nuclear power plants capacities are being reduced and expected to be reducing in the nearest future falls on coal.

Under existing conditions a problem of today is to develop and introduce new technologies of coal mining and utilization with due regard for technical, economic and ecological aspects which are particularly important for densely populated industrial regions.

Ecological problems associated with a dramatic increase in the volume of coal combustion can be solved by developing new methods and means for flue gas cleaning in the first place and by wide-scale introduction of coal-water fuel (CWF) in the second place.

Investigations have shown that the second way is more preferable since it is based on the integrated technology for original coal demineralization and CWF production, advantages of each process being used in full measure.

Demineralization of coal increases the heat value of CWF, ensures stability of its qualitative characteristics and improves combustion ecology.

The necessity of coal demineralization is also called forth due to a continuous quality deterioration of solid fuel supplied to the heat power industry, which is explained by the lack of new development techniques for difficult mining and geological conditions and insufficient productive capacities of cleaning plants.

Thus demineralization of coal is among major requirements to development of a CWF production technology.

2.0 INVESTIGATIONS OF ASH CONTENT IMPACT ON CWF PARAMETERS

Depending on quality of the original coal a CWF production technology can be complicated in case of long-distance hydrotransportation with subsequent CWF combustion in boiler untis of large thermal power stations (TPS). It can also be quite simple if CWF is to be supplied to power-and-heat generation units of utilities.

The problem of a practicable level and methods of coal cleaning, therefore, gains primary importance.

With that end in view there have been carried out investigations aimed at the following:

- determination of the optimum level of cleaning (estimated by dry ash) on the basis of physical and chemical properties of coal;
- determination of special features of key units and elements of a CWF production technology proceeding from the adopted scheme and balance of cleaning products;
- assessment of main factors that ensure obtaining specified properties of CWF, their study and search for process control methods.

The investigations were conducted on coal ranked "G" (gas coal) with a density of ρ_s = = 1460 kg/m^3, dry ash of A^d = 14.7-21.7%, moisture as-received of W_t^r = 8%.

To begin with, the study of operating conditions and parameters of grinding facilities yielded the particle size consist of ground coal that ensured the best rheological and sedimentation properties of CWF (Fig. 1). The plot of Fig. 1 gives a cumulative curve of the particle size distribution, where the log-log of cumulative weight percent retained is plotted on the ordinate and the logarithm of particle size (or mesh dimension) is laid off as abscissa.

The effect of the original coal ash on the size consist of the ball mill product is illustrated by curves of Fig. 2.

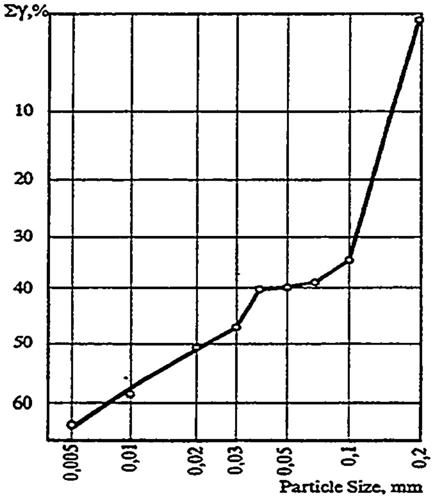

Fig. 1. Particle size consist that ensures the best rheological properties of CWF

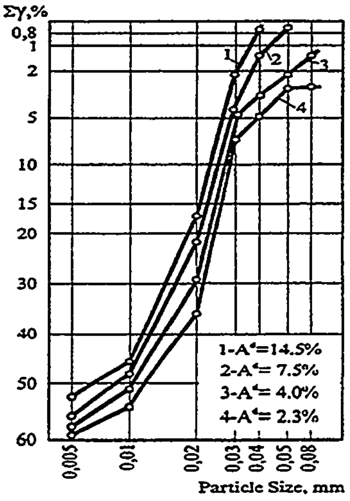

Fig. 2. Effect of ash content on coal grinding

Fig. 3 shows the impact of the coal ash content on the effective viscosity of CWF.

The graphs of Fig. 4 give variations of the CWF concentration, rheological properties being satisfactory.

Fig. 5 shows the CWF effective viscosity at a shear rate of $\hat{\varepsilon} = 9\ s^{-1}$ as a function of storage time.

Technical-and-economic indices of CWF depending on the ash content can be to a certain degree characterized by the data listed in table 1.

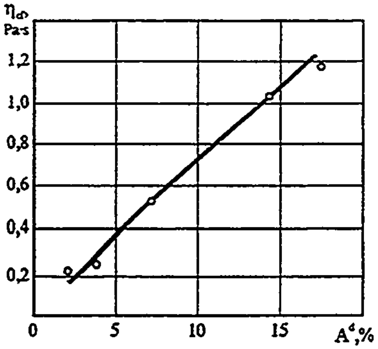

Fig. 3. Impact of coal ash on effective viscosity of CWF

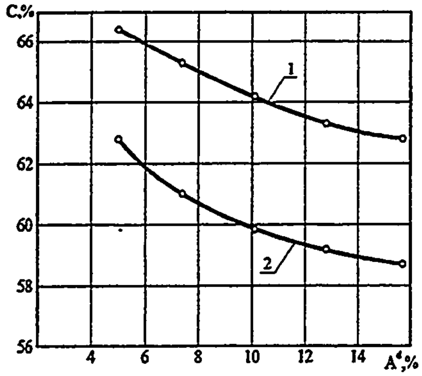

Fig. 4. CWF concentration as a function of coal ash:
1 — CWF viscosity at $\hat{\varepsilon} = 9\ s^{-1}$, $\eta = 1.0$ Pa·s;
2 — CWF viscosity at $\hat{\varepsilon} = 9\ s^{-1}$, $\eta = 0.5$ Pa·s

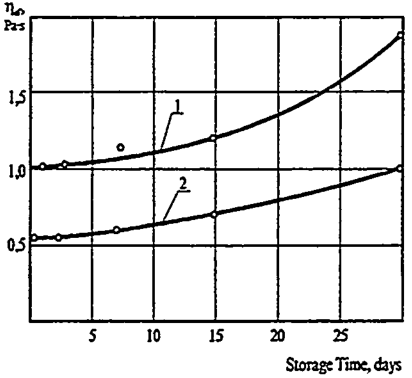

Fig. 5. Changes in CWF viscosity during storage:
1 — CWF produced from coal with 14.5% ash;
2 — CWF produced from coal with 7.5% ash

Table 1.

CWF properties at constant rheological parameters related to coal ash

Original coal ash, A^d, %	CWF concentration by weight, C, %	CWF heat value, Q_i^r, kcal/kg	CWF quantity, equivalent to 1000 ths t e.f., ths t
15	62	3845.9	1820
8	62	4273.5	1638
4	64	4632.7	1511
2	64	4733.4	1479

The above data indicate that the original coal ash content has a considerable impact upon CWF properties.

3.0 INVESTIGATIONS OF COAL DEMINERALIZATION

The diffractometer analysis of inherent ash has revealed that the latter is mostly represented by clay matter (65-70%): caslinite (4-24%), disordered compound laminated hydromica-montmorilonite formations (4-54%), hydromica (10-27%), chlorites (1-6%) and montmorilonites. Non-clay mineral inclusions are quartz and feldspar.

Mineral inclusions (clay matter, quartz and carbonate) can be basically found in free state and less frequently in aggregations with coal. Coal grains are mainly clean.

The microelements in terms of clean coal subdivide into vitrinite (71-88%), inertinite (14-26%) and liptinite (3-5%).

The experimental procedure is illustrated in Fig. 6. CWF was produced in accordance with a full technological cycle. There were subsequently determined rheological and sedimentation properties.

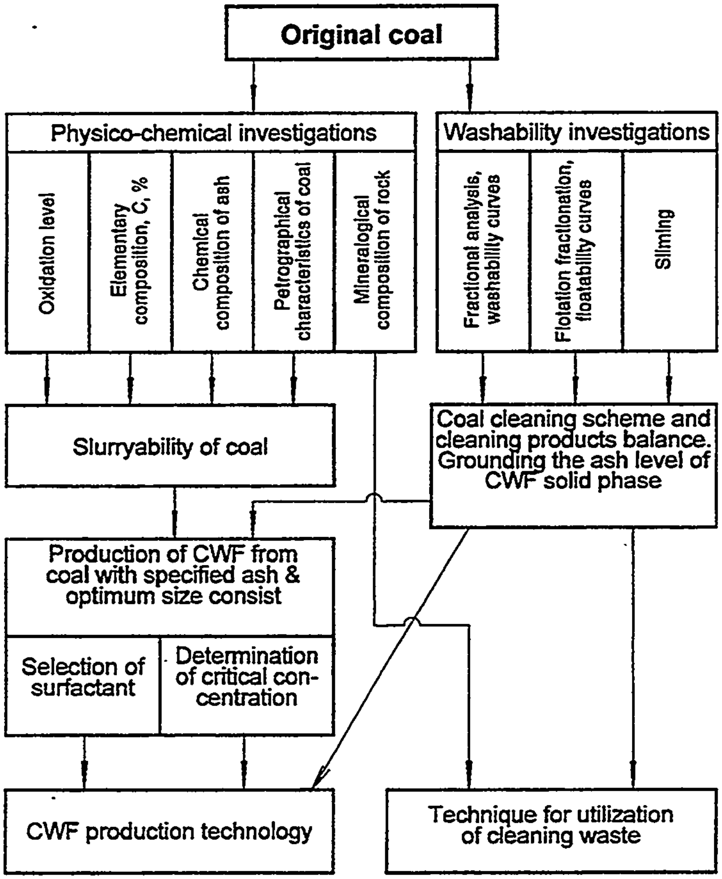

Fig. 6. Scheme of investigations on CWF production

In the course of the investigations there were made proximate and ultimate analyses of coal and there was determined the chemical composition of ash.

Chemical properties of coal under investigation were estimated by the presence of functional groups and heat of wetting by ethanol.

As cleaning techniques there were investigated gravity separation and flotation.

4.0 INVESTIGATIONS RESULTS

Analysis of the investigations results allows to draw the following conclusions:

4.1. To determine the optimum level of coal cleaning (or the limiting value of ash) one should proceed from the following considerations:

The reduced content of minerals belonging to montmorilonite and hydromica groups in the CWF solid phase results in lower viscosity and increases the maximum achievable concentration. The presence of quartz and kaolinite does not actually effect the CWF viscosity. However, certain contents of quartz particles in coal may lead to destabilization of CWF.

The study of the combined effect of different minerals on rheological properties of CWF has shown that satisfactory rheological parameters of CWF can be achieved in a very narrow range of mineral components ratios. This range expands at lower concentrations or reduced ash of the original coal.

A practicable level of coal cleaning in the CWF production that ensures satisfactory rheological properties as well as static and dynamic sedimentation stability can be determined based on the complex assessment of expenditures on production, transportation and combustion of CWF.

Proceeding from the above-stated the lower limit of the original coal ash can be considered as $A^d = 7\%$ and the upper one as $A^d = 29\%$. If CWF is not to be pipelined through a long-distance hydrotransport system, the above range can be reduced to 13-18%.

4.2. The CWF viscosity is increased with the content of functional oxygen, which makes this factor very important when estimating coal as raw material for making CWF.

4.3. The content and ash of fine size coal are considerably increased with decreasing hardness and increasing maceration ability of dirty inclusions. The greater part of rock goes over into a size of < 0.05 mm ($A^d = 80\%$).

4.4. The most efficient cleaning technique for coals of medium washability is gravity separation (jigging) without yielding middlings, which considerably simplifies the process control. The concentrate yield in our case made up γ_k = 89.96% at a dry ash of A^d = 4.6%. The rejects had an ash content of 80.2%.

4.5. Flotation is practicable in case of coals that are difficult to clean, provided it is proceded by separation and grinding of middlings in the course of jigging.

4.6. Partial cleaning of high-ash slimes can be carried out by means of hydrocyclones with sizing to 0.05 mm.

5.0 FLOW DIAGRAMS OF CWF PRODUCTION

Having summerized and analyzed the investigations results, we worked out some technical solutions that underlied a production technique of CWF for different applications.

The most complicated scheme is illustrated in Fig. 7. It incorporates the receipt of difficult-to-clean coal from mines or opencast collieries, hydrotransport and combustion in boiler units of a TPS.

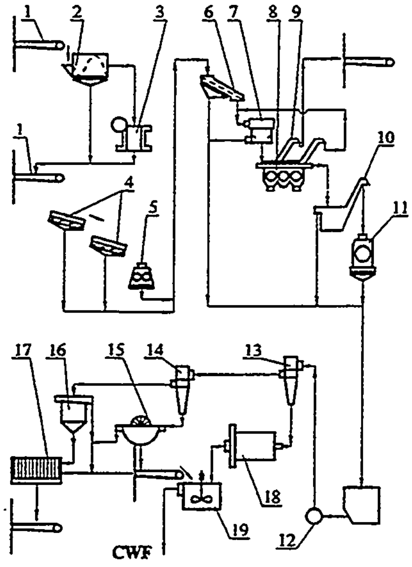

Fig. 7. Equipment circuit arrangement of CWF production terminal

In accordance with this scheme the run-of-mine coal is fed by conveyer 1 to cylindrical screen 2 that is close-circuited with jaw crusher 3. There the coal is crushed to a size of 0-100 mm and then moved to screen 4 for classifying into a size of 0-13 mm. The oversize (+13 mm) is recrushed in crusher 5. Hydroscreen 6 separates the coal under 13 mm from slime, the 0-1 mm fraction fed to a storage tank. The oversize is moved to conical screen 7 and then to jig 8. The jigging rejects are dewatered and go to waste (9). The middlings after dewatering are returned to the conical screen for the control classification into a size of 0-1 mm. The jigging concentrate is classified and dewatered on bucket elevator 10. The underflow goes into a finished product tank. The latter is also fed with the concentrate after crushing. Further, slurry pump 12 moves the cleaned product from the storage tank to hydrocyclones 13 and 14. The hydrocyclones underflow (size fraction 0-0.04 mm) is thickened in cylindrical thickener 16 and size fraction +0.04 mm is fed to vacuum filter 15.

The thickened product from hydrocyclones is moved to ball mills 18 to be ground to a size under 0.07 mm. It is then mixed with the dewatered product of vacuum filters 15 in apparatus 19. The thickener filtrate is used in the circulating water system. The thickened product of the cylindrical thickener is first dewatered in filter press 17 and then goes to the dump. The filtrate is fed to the circulating water system. The normal operation of the proposed scheme requires strick weighing of the materials feed, which necessitates the incorporation of the appropriate equipment into the automated process control system.

The above technology enables to produce low-ash CWF with the minimum power consumption. This is achieved through utilization of coal slimes obtained in the process of cleaning and classification as well as associated 30% reduction in the volume of coal ground in the ball mill and exclusion of a highly power-intensive ultrafine grinding operation.

The effective viscosity of CWF produced by the proposed technique corresponding to a shear rate of $\dot{\varepsilon} = 9\ s^{-1}$ at concentrations of $C = 65\%$ and $C = 67\%$ by weight is 0.5 Pa·s and 0.7 Pa·s respectively.

6.0 SIMPLIFIED TECHNOLOGY FOR CWF PRODUCTION

The simplest flow diagram of producing CWF intended for combustion in power-and-heat generating units for industrial and utilities purposes is represented in Fig. 8.

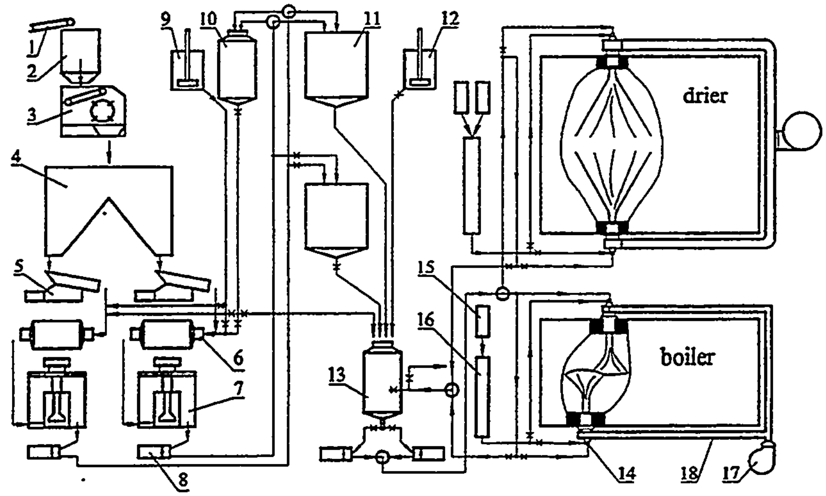

Fig. 8. Flow diagram of pilot-commercial plant for CWF production and combustion:

1 — belt conveyer; 2 — storage vessel (10 m^3); 3 — sampling apparatus МПЛ-150 (crusher with feeder); 4 — hopper; 5 — feeder КЛ8-0; 6 — ball mill CM 6007A; 7 — mixer (homogenizer); 8 — pump CO-5A; 9 — mixer for feeding chemical additives; 10 — tank for off-grade CWF (5 m^3); 11 — storage tank (14 m^3); 12 — mixer for feeding additives (i.e. lime); 13 — operation vessel (5 m^3); 14 — boiler burner; 15 — compressor K-5M; 16 — receiver; 17 — fan BBCM-IV; 18 — air conduit

This scheme has been introduced in a pilot-commercial installation for CWF production and combustion at a cleaning plant of the Donbas (Donets coal-fields). To produce CWF they use the concentrate of coals ranked "C" (cannel coal) and "G" with an average dry ash of $A^d =$ $= 15\%$.

The scheme can be further simplified by grinding coal in one mill, the ground material quality being ensured by grading the grinding bodies (Fig. 9).

7.0 CHEMICAL ADDITIVES

There has become the usual practice to employ various chemical additives in CWF production, i.e. plasticizers as well as desulfurizers, denitrificators, corrosion inhibitors etc. used to improve CWF utilization ecology.

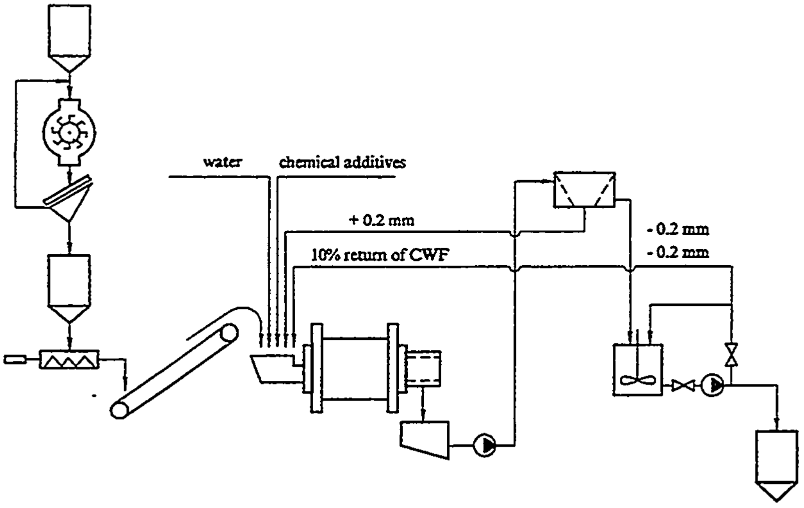

Fig. 9. Schematic flow diagram of CWF production

In choosing chemical additives preference is given to the most inexpensive, efficient, environmentally safe agents made of raw materials that are in good supply.

Since Ukraine does not dispose of its own developed wood-pulp and paper industry, lignites mined in Alexandria coal field can be used as such a raw material. This problem is attacked by combined efforts of the Scientific Industrial Corporation HYMEC and a number of institutes of the Academy of Sciences of Ukraine. The objective of the research work is to use salts of sulphurized humic acids as plasticizers for CWF. These are natural substituted alkylakrylic acids that exhibit anion-active surfactant properties. To enhance their plasticizing ability sulpho groups are added to the macromolcules' structure of humic acids, a familiar technique of mechano-chemical activation of mixture being employed for the purpose.

This technique has been improved by the activation process in a high-powered vibroattritor. To prepare a fraction of more low-molecular humic acids the extraction process was run at a temperature of 20°C.

As seen from the table given below, the plasticizer obtained by the proposed technique is the most effective one.

Table 2.

Rheological properties of CWF treated with
humic acids-based plasticizers at a weight concentration of $C = 60\%$

Plasticizer	t_{extr}, °C	η_{ef}, Pa·s	τ_0,Pa
1. No plasticizer	—	1.38	14.07
2. Unmodified humate (humic acid salt)	100	0.79	10.06
3. Modified humate	100	0.69	6.62
4. Humate modified according to the improved technique	20	0.17	1.13

The use of such a plasticizer allows to produce CWF with a flow approaching the Newtonian one, having a weight concentration of $C = 65\%$, effective viscosity of $\eta_{ef} = 0.46$ Pa·s and shear stress of $\tau_0 = 2.0$ Pa.

The consumption of this plasticizer makes up 1% relative to dry coal weight.

The investigations have revealed that the plasticizing action of humic acids salts in coal-water systems is bound up with the state of macromolecules of this natural polyelectrolyte. The configuration of these molecules can be changed with acid-alkaline properties of the medium.

The maximum plasticizing effect is exhibited by salts of sulphurized humic acids, the solution of which has a *pH* value of 13. The reason is that in alkaline medium a molecule of humic acid is gradually unrolling as available carboxyl and then hydroxyl groups are being ionized.

8.0 CONCLUSION

Ukraine has no developed oil and gas production industries of its own today but disposes of considerable coal resources. This creates the necessary prerequisites for a wide-scale introduction of CWF into the heat power industry of the country.

The conducted investigations as well as experience of Ukraine and other countries confirm technical and economic feasibility of substituting CWF for natural gas, liquid petroleum products and coal in the heat power industry and utilities.

With that end in view there have been worked out and included into the National Program "Power Resources" of Ukraine a number of projects that presuppose development of fuel and energy systems (mine — TPS) as well as heat power systems (CWF production terminal — industrial and residential consumers).

The first step in that direction will be construction of pilot-commercial plants for CWF production and combustion, including a full-scale unit. The plants will be used for trying out the technology, testing new equipment and instrumentation.

The Program also includes development and finally commercialization of a production technique for chemical additives-plasticizers based on lignites.

In prospect it is planned to develop production techniques for CWF with improved environmental safety on the basis of sewage water and liquid combustible waste of chemical processes as well as for low-ash CWF to be used as fuel for diesels and other transport engines.

NOMENCLATURE

ρ_S, kg/m^3 — density of solids
A^d, % — dry ash
W_t^r, % — integral moisture content
Q_i^r, kcal/kg — low heat value
γ_k, % — yield of cleaned concentrate
$\Sigma\gamma$, % — cumulative weight percent retained
C, % — weight concentration
η_{ef}, Pa·s — effective viscosity
$\dot{\varepsilon}$, s^{-1} — shear rate
τ_0,· — shear stress
t, °C — temperature

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Utilization of Czech Black Coal for Clean Coal Technology, *Pavel Noskievic and Vaclav Roubicek, Technical University of Ostrava, CZECH REPUBLIC*

This paper was received after pagination and is located on Page 767 of these Proceedings.

OUTLOOK OF DEVELOPMENT OF CLEAN COAL TECHNOLOGIES IN JAPAN

Center for Coal Utilization, Japan
Sadayuki Shinozaki

1. Introduction

Japan's energy consumption is assumed to increase along with her economic growth as shown in Table 1. Although, increases of coal consumption as for Japan's primary energy is being controlled, coal fired power generation capacity is planned to expand by large.

Utility companies are planning to construct a number of coal-fired power plants in Japan as shown in Table 2. Then, coal is positioned as a very important energy source for Japan's power generation. Consumption of steaming coal in 2010 is estimated to increase to about double of that of 1992.

Table 1 Prediction of Japan's primary energy supply[1)]

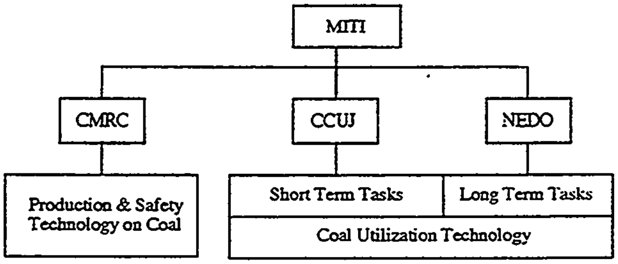
	1992	2000	2010
Total (10^6 Kl)	541	582	635
Coal demand (10^6 t)	116.3	130~134	134~140
Stare of Coal (%)	16.1	16.5	15.4

Table 2 Power supply target (installed capacity)[2)]

	1992	2000	2010
Total Electric Power (10^6 KW)	183.8	239.3	285.1
Coal fired power generation capacity (10^6 KW)	14.67	32.6	44.0
Share of Coal Fired Power Plant (%)	8.0	14.0	15.0

But coal has handicaps of both high ash content and CO_2 emission among other fossil fuels.

As shown in Figure 1, the Center for Coal Utilization, Japan (CCUJ) is working on the development of clean coal technology with a support of the Ministry of International Trade and Industry (MITI) to produce clean energy from coal.



CMRC: Coal Mining Research Center
NEDO: New Energy and International Technology Development Organization

Fig. 1 Organization of CCT research and development in Japan

2. Development System of Japan's Clean Coal Technologies

After the first oil crisis (1974),Japan realized once again the importance of coal for its abundant reserves, stable supply and price. Therefore, intensive fuel consuming industries started to convert from petroleum to coal, and the use of overseas coal as steaming coal increased. However, environmental regulations became stricter in 1975 although regulation values differed by each area. As a result, as shown in Table 3, newly installed boilers became advanced types that satisfied the toughened environmental regulations. The more advanced of these boilers has a service life of fifteen years enabling a high power gross thermal efficiency of 38 to 40%; fundamentally, these boilers are low pollution types fit for high-efficiency power generation systems.

	Regulation value3) (daily average value)	Example in strict areas (emission density)	Main flue gas processing equipment
SOx ppm	Less than 0.04	Less than 50~60	Lime gypsum method Magnesium gypsum method, etc.
NOx ppm	Less than 0.04~0.06	Less than 50~60 * Less than 30	SCR, low NOx burner, flue gas circulation method, etc.
Smoke and dust (mg/Nm^3)	Less than 50~100	Less than 10	High temperature EP, 2-stage EP, bag filters, etc.

* Mark: An example of the most severe case.

Table 3 Typical Emission Regulations SOx and NOx for Large Capacity Boilers

However, global environmental awareness has increased, and further cleaner use of coal was required. Therefore, the government and private sectors have been jointly working on the development of clean coal technologies.

Under these circumstances, Japan has established the following key items for the development of coal technology in order to both maintain stable supply of energy and make coal a clean and environment-friendly source of energy:

○ Development of coal utilization technologies which are more efficient and cleaner than the present ones
○ Development of newly and highly efficient utilization technologies to expand the scope of coal utilization
  ・New technologies to convert coal into a different type alternative energy
  ・Technologies to increase the usable types of coal, including low rank coal
○ Development of technologies for using large volume of coal ash
○ Development of technologies which ensure clean and efficient use of coal in developing countries in the future

Clean coal technologies are also under development in the following areas:

Area 1: Coal preparation
Area 2: Coal distribution
Area 3: Coal energy conversion and processing
Area 4: Coal combustion
Area 5: Flue gas processing
Area 6: Coal ash utilization

Table 4 shows the major themes both under development and research being conducted in each area. When considering global environmental measures in Japan, measures for improving efficiency of her electric power generation are most important for the power generation will dominantly use coal in the future. Current developments to improve this efficiency are shown in Figure 2.

Table 5 outlines the main themes of Table 4 and the stage of development.

The following technologies have relatively few reports in Table 5 and are considered unique in Japan:

○Advanced PFBC
○P-IFBC, P-CPC
○ High efficient cement production technology by fluidized bed
○Coal direct use metal melting system
○Low grade coal improvement/CWM technology
○New thermal decomposition technology - Flash pyrolisis

The underlined themes will be presented by other Japanese presenters.

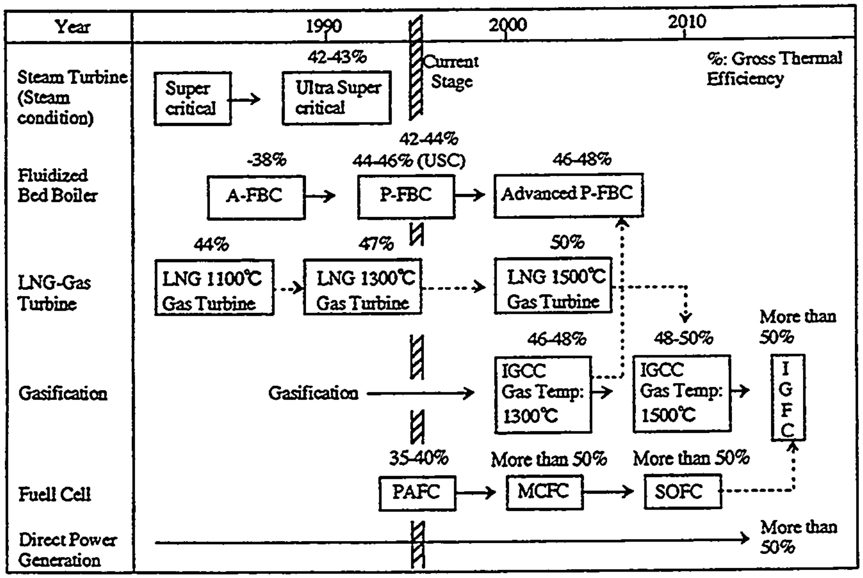


Fig. 2 Development Concept of High Efficient Power Generation

3. Targets of Clean Coal Technology Development in Japan

3-1. Measures upto 2010

Japan has agreed to stabilize its CO_2 emissions on a per capita basis in the year 2000 to the level of 1990, which is an emission level of 2.6 t/person/year. Therefore she is now developing the required technology in the aforementioned categories.

Since new technology development requires huge time and cost, it is difficult to accurately predict when the technologies will be commercialized. Table 6 shows the progress of seeds and the expected needs[5].

Power generation technology with USC steam conditions shown in Table 6 has minor restrictions in its boiler materials. However, the Hekinan No. 3 Unit (700 MW, 246 kg/cm^2, 538℃/593℃) of Chubu Electric Power Co. uses this type for generating power, and Chugoku Electric Power Co. will construct a 1,000 MW coal-fired power station with an up-graded steam condition of 250 kg/cm^2 and 600℃ in 1998[4].

Although PFBC is currently at the demonstration test stage, each one unit of 85 MW, 350 MW, and 250 MW are being constructed or designed for commercial power generation, and they are scheduled for commercial operation in the early next century.

In the industrial sector, the development of CCS (Coal Cartrige) technology and CWM technology has been completed and already commercialized. One point which should not be overlooked is development of an effective way to use the ash discharged by coal combustion. In Japan, the discharging ash volume is estimated to be about 10 million tons in 2010. Since there are quantitative and qualitative limits to using the ash for cement, development of effective using methods of a large volume of ash is extremely important, though there are environmental restrictions. Figure 3 introduces a systematic outline of the bulk-use technology that is now being developed. The key to effective ash utilization in Japan is primarily to develop the technology and conduct many demonstrations, because ash has for each purpose, to be approved by the government, otherwise it cannot be used in public works there. Therefore, a series of work is underway to obtain the approvals.

3-2. Measures after 2010

Although most of the new technologies, currently being developed, fatally depend on the price of petroleum, these technologies can be put to practical use between 2000 and 2010 as long as there are social needs due to the global environmental issues, and that is our goal. Concerning the types of clean coal technologies required after 2010, overall energy systems must be constructed based not limitedly on an extension of our current concept, but rather on a world-wide global basis.

One concept is to construct an ecological, environmental, and economical energy supply system by integrating various types of clean technology currently under development. Another important issue is the conversion of daily domestic refuse and industrial wastes (approximately 50 million tons) into a fuel resource, although this is simply an idea at present. In terms of oil, refuse and industrial wastes amount to about 8 million KL (based on 1991 emissions), and are a potential energy resource within the naturally circulating system rather than using underground reserves. Thus, the construction of highly efficient technologies that utilize these energy resources and low cost coal on a long-term basis are considered to be vital.

5. Conclusion

Coal will undoubtedly become a more important energy source in the 21st century than today due to its abundant reserves. However, there are also many disadvantages in the use of coal, which means that coal exists in solid form, coal contains more ash than other fossil fuels, and its CO_2 generation per unit is large during combustion. The development of clean coal technologies is important for both energy stability and global environment preservation. Since much time is required to develop the technology, we believe that the developed countries must exchange technical information and proceed for further development.

This paper reports the status of Japanese CCT development themes, which we hope will be of use for other countries.

Thus far, very few new technologies have been put to practical use. However, we will continue to develop clean coal technologies to contribute to the preservation of the global environment.

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Table 4 Items of Clean Coal Technologies Development in Japan

Preparation	Coal Handling system	Coal Conversion system	Combustion	Flue Gas Treatement	Ash Utilization
1.1 Preparation * De-Ash Technology * De-Sulfurization Tech. 1.2 Advanced Coal Cleaning Technologies · Ultra-Conductive Magnetic Separation · Fine Particles Dense Medium Tech. · Column Flotation Tech. · Improved oil agglomeration · Micro-Biological treatment (De-sulfur, De-ash) 1.3 Manufacturing Ultra-clean coal · Ultra Violet and Alkali leaching · Selected Agglomeration 1.4 Up-Grading Technology of Low Rank Coals (HWD-Dewatering etc.)	2.1 C.C.S. Technology 2.2 CWM Technology · Stability by Mixing of different CWMs · CWN manufacturing from Low Rank Coals * CWM manufacturing * CWM Combustion 2.3 * COM 2.4 Storage Technology for Coals * Preventive Tech. for flying Coal Dusts · Preventive Technology for spontanous Ignition of coals.	3.1 Coal Liquifaction tech. ★Bituminous Coal ★Brown Coal 3.2 Gasification ★Entrained bed system : For IGCC : For Manufacturing H_2 · Fluidized Bed System · CPC System ★Hydro-Gasification system (Manufacturing High Calorific Value's Gas) 3.3 Mild Gasification (Flash Pyrolysis Technology) · Medium Calorific Value's Gas (4000 Kcal/Nm^3) · Light oil (BTX) · Tars of good quality 3.4 Cokes Manufacturing Tec. · Advanced Cokes manufacturing Technology 3.5 DIOS Process 3.6 * Briquet manufacturing Technology	4.1 Steam Turbine System * USC Boiler Tech. * FBC Boiler Tech. * ICFBC Boiler Tech. * CPC Boiler Tech. 4.2 O_2/CO_2 Combustion Technology - For CO_2 Recovery - 4.3 Advanced Electric Power Generation system · P-FBC · P-CFBC · P-ICFBC · P-CPC · Advanced P-FBC ★[IGCC] · IGFC 4.4 Metal Fusion System directly using coal Fire 4.5 High eff. Cement manufacturing by FBC Technology 4.6 ★Fuel Cell 4.7 ★Closed cycle MHD system	5.1 DeSOx Technologies * Wet system * Dry system * Semi-Dry system * DeSOx in inner furnace 5.2 De-NOx Technologies * Low NOx Burner * SCR * SNCR *NH_3 or Urea Injection 5.3 Dust Removal Technology in Flue Gases * High Temperature EP · Ceramic Filter · [Granular bed system] 5.4 Innovative Flue gas treatment Technology · Flue Gas Treatment system to deal with High efficiency and Low cost. · High temperature dust removal technology	6.1 Using tech. as materials for cement * For Raw Materals * For Cement Admixture 6.2 Using tech. as materials for construction · Pelletizing Technology of Fly Ash * Roof tiles, Bricks * Road construction materials · Surface course materials · ALA · Back filling Materials * Reclamation Materials 6.3 Using tech. as materials for Agriculture · Fertizers · Soil Improving agents 6.4 Using tech. as materials for Fisheries · Fish reef · A sea tangles reef

* Mark P/J are already commercialized. ★Mark P/J means: now developed by NEDO Tech: Technology

Table 5 Outline of Japan's Clean Coal Technology Development

Development item	Technology outline	Plant size/development plant
[Practical technology] 1. Combustion Technologies (1) Coal fired Boiler a) A-FBC	○ 350 MW FBC power generation plant: A scaled up version of a 160 t/h FBC demonstraion plant that was completed several years ago. It is compact and can be installed in the vacant space of an existing heavy oil-fired boiler.	· 350 MW FBC power generation plant - under test operation
b) PFBC[6]	○ This PFBC achieves campact combustion equipment through pressurized fluidized bed combustion and an improved gross thermal efficiency (42-44%) through the combined cycle power generation method. Compared with pulverized coal boilers, the PFBC offers better furnace desulfurization, and the denitrification load can be reduced as combustion temperature is low. The power generation rate of gas turbine is approximately 20%.	· 71 MW demonstration plant in operation '93-'98 · 85 MW, 350 MW, and 250 MW commercial equipment are being constructed.
c) Advanced PFBC	○ This system combines a fluidized bed as a partially gasified furnace and a pressurized fluidized bed as an oxidized furnace for char and CaS. The temperature of the gasified gas (1,000 Kcal/Nm^3) is raised to 1,300℃ in a gas turbine power generator, and the heat of the exhaust gas from the turbine is recovered by an exhaust heat recovery boiler to be supplied through a steam turbine power generator. The power generation rate of turbine is approximately 50%. The gross thermal efficiency can be improved (46～48%) through such compound power generation. Furthermore, it can be combined with a USC to improve efficiency significantly.	· A 4 MW pilot plant is schduled. (Construction period has not been determined.) · Commercial equipment is in operation.
d) ICFBC[7]	· This is an atmospheric pressure type internal circulating fluidized boiler that can use various types of fuel with excellent environmental characteristics and has an excellent load response and DSS operatability. Combustion efficiency: more than 99% Desulfurizing rate: more than 95% Exhaust gas characteristics: SOx: less than 50 ppm (at 0.5 S% coal) NOx: less than 50 ppm CO: less than 100 ppm	
e) P-ICFBC	○ This is a pressurized type of the above-mentioned internal circulating fluidized bed boiler. A combustion system that is more efficient with better environmental characteristics and dedusting equipment for high temperature use must be developed.	· A 4 MW pilot plant is scheduled.
(2) Cement[2] manufacturing plants by using FBC Technology.	○ This is a cement calcining technology that is a combination of a entrained bed type granulating furnace, a fluidized bed type kiln, and a fluidized bed and movable bed coolers. This is an energy saving type cement production techology that can use various types of coal, with reduced NOx emissions (less than 50% of conventional type), and lower energy consumption (about 15% saving). · Features: · Cement calcining temperature: 1,400℃ (flame temperature) (In case of kiln type, flame temperature of 1,800℃ is required) · Heat consumption: 700→680-690 Kcal/kg Clinker · Capable of highly efficient heat recovery (an improvement of 20%) using a fluidized bed cooler · Plant heat efficiency: More than 60% (kiln type plant efficiency: 54-56%) · Reduces final crushing power by 7-8% by reducing clinker diameter · Cement production cost: Cost reduction of about 18% · Service life of furnace refractories can be extended · CO_2 generation: 65 kg/t (kiln type: 73 kg/t)	· A 20 t/day pilot plant is in operation. · A 200 t/day scale up plant is under construction and is schedued for operation in 1996.

Development item	Technology outline	Plant size/development plant
(3) Coal direct utilization Metal melting system Metal fusion system by coal directly oxy-combustion	○A highly efficient utilization technology to melt metals by using high temperature (2,400-2,500 ℃) energy obtainable from combusting pulverized coal with directly oxy by using (heat efficiency target: 60%). This is an alternative technology for electric furnaces and is effective for recycling. ● Heat efficiency ● Product yield: 90-93% Conventional type / IT/ch P-P / Target type Iron: 25% / 45～50% / 60% Nonferrous metal: 30～40% / 40～47% / 60% ・This technology will be presented by Nihon Oxygen Co. separately.	・Bench scale test completed ・5 t/charge pilot plant under construction, scheduled to be completed in 1995.
2. Coal slurry technology		
(1) Low rank coal improvement CWM production technology (HWD process)	○This is a CWM production technology that is capable of efficiently dehydrating and improving low grade coal such as brown coal and sub-bituminous coal of which there are huge reserves (equivalent to that of bituminous coal) using critical pressure steam. The method is suitable for transportation as well as stable storage, and offers very low cost combustion. Depending on the selection of raw materials, this technology can produce ultra clean CWM (extremely low ash content). ・This technology will be presented by Japan COM Co. separately.	・350 kg/hr (7 t/d) pilot plant in operation
3. Coal handling technology		
(1) CCS technology	○This system processes coal to pulverized coal, supplies it to users using bulk lorries, and recovers coal ash after combustion for recycling. This is a total closed cycle type system having an excellent load response and is clean.	・200,000 t/year commercial terminal is in operation (Presently supplying to 2 users)
4. Coal partial combustion furnace technology (CPC technology and P-CPC technology)	○This technology partially combusts coal under atmospheric or pressurized condition at high temperature in a reducing atmosphere to remove about 80% of ash through melting. Generated gas (about 1,000 Kcal) is secondarily combusted in a boiler furnace. Through this process, combustibility is improved, NOx is reduced (i.e. 150-200 ppm→100 ppm), and the boiler furnace is lighter. This technology is applicable to unique technologies such as highly efficient combustion and power generation through reducing the ash deposit in the rear boiler stage by removing most of the ash as melting slag in a CPC furnace. DCFT power generation utilizing this technology will be presented by KHI separately.	・7 t/day bench plant is under study for operation. ・25 t/day pilot plant is under study, and scale-up is scheduled. This plant is scheduled for completion in 1995.

Development item	Technology outline	Plant size/development plant
3. Oxy combustion technolgy (O_2/CO_2)	○This technology combusts coal with a gas mixture of O_2 and CO_2 in a pulverized coal boiler at higher efficiency than conventional boilers and produces high CO_2 concentration (more than 90%) in the exhaust gas to facilitate the recovery of CO_2 from the combustion exhaust gas. This technology ensures extremely low NOx emission combustion (emission equivalent to about 10% of pulverized combustion) and low SOx combustion. • Compared with the power generation system in which the amin absorbing method is combined as a CO_2 recovery method, gross thermal efficiency is expected to increase by 8.2%.	• A study is being carried out on a 100 kg/h bench plant. • A pilot plant study has not been determined.
4. New coal thermal decomposition technology[11] (Flash pyrolysis) (Mild Gasification)	○This is a multi-function type thermal decomposition, high efficiency technology (heat efficiency: 87%, gasification efficiency: 95%) that rapidly performs thermal decomposition at low temperatures (600-800℃) and produces both medium calory gas (about 4,000 Kcal/Nm^3) and high value-added acid tar. This technology may be used as a core technology for a coal complex system that includes industrial gas supply, coal chemicals, and power generation.	• A study is being carried out on a 7 t/day bench plant. • A 100 t/day pilot plant is scheduled.
5. Advanced Coal Cleaning Technology	• This is a hybrid coal cleaning process in which coal is desulfurized and deashed prior to combustion to produce quality coal for consumers while also being environment-friendly (combination of physical, chemical, and biological cleaning technologies). • Product quality targets: Mild clean coal: Ash content: 5-7% Ultra clean coal: Ash content: less then 1% Sulfur content: less than 0.1%	• Elementary technologies are being studied on small scale devices. • A pilot plant study has not been determined.
[Effective technology for recycling ash]		
1. Technologies for bulk-ash recycling	• FGC, FSC concrete, Pozo-tech production technology, grouting method, artificial light-weight aggregate, ALC, fluidized bed cured road bed materials, fish reef, kelp reef, and slurry technologies are being developed in order to use ash for road bed materials, civil engineering materials, and marine development materials by taking advantages of its characteristics such as light-weight, self-hardening and formability.	
2. Demonstration survey on use of coal ash	• Technologies are being developed to utilize light-weight, self-hardening coal ash as an alternative material for sand, crushed stone, and cement that are used for revetment backfilling of harbors and airports, surface layer treatment to ensure trafficability of heavy equipment, weak ground improvement, and roadbed/subgrade materials. These are potential large users of coal ash. After these technologies have been demonstrated in actual construction works and their environmental effects have been evaluated, approvals will be obtained from the authorities and user manuals prepared in order to diffuse these technologies.	• Demonstration test until 1995.

Development item	Technoloty outline	Plant size/development plant
5. Direct coal use for steel-making technology9) Direct iron ore smelting reduction process	○This process produces pig iron by by directly using ordinary coal without pretreatment such as charging the coal to cokes and sintering iron ore. Ordinary coal is charged into a molten reducing furnace directly or after devolatile treatment while iron ore is charged into a molten reducing furnace after pre-reduction in the fluidized bed. Compared with the blast furnace method, this DIOS process uses ordinary coal, increases production speed per furnace volume, saves 10% energy, and has excellent load response. Example of total retention time in all processes: Blast furnace method→48 hours DIOS process→10-12 hours	• 500 t/day pilot plant is under study for operation until 1995.
[Next-generation technology]		
1. Entrained bed coal gasification technology (NEDO)	○IGCC This is a highly efficient combined cycle power generation system, in which pulverized coal is first gasified (1,000 Kcal/Nm^3) using air as an oxidizing agent under high temperature and high pressure, washed by gas, then the temperature is raised to 1,300℃ in a gas turbine combustor before sending to a gas turbine power generator for power generation. At the same time, heat is recovered from the exhaust gas and power is generated in a steam turbine power generator. • Power generation ratio (%) of gas turbine and steam turbine = 50:50 ○Manufacturing hydrogen technology10) This technology produces highly concentrated hydrogen by gasifying pulverized coal (about 2,700 Kcal/Nm^3) in a entrained bed furnace using oxygen as an oxidizing agent under high temperature and high pressure. Hydrogen is refined and used for fuel cells, petroleum refining, and as a source for petroleum and chemicals. At the same time, this gasification technology can also be utilized for IGCC. Development target of 98% carbon conversion rate and 78% gasification efficiency target were achieved by the pilot plant, and 1,000 hours of continuous operation confirmed its operational stability.	• 200 t/day pilot plant is under study for operation until 1996. • 50 t/day pilot plant operation Study was completed in 1994. • Scale up plant is scheduled.
2. Coal liquefaction technology (NEDO) - Bituminous coal liquefaction and brown coal liquefaction	○This technology liquefies solid coal by adding hydrogen to crushed coal molecules under high temperature and high pressure and produces clean fuel, mainly fuel for transportation. Liquefied oil is upgraded through blended refining with petroleum at petroleum refineries to obtain quality fuels for transportation.	• A pilot for converting to brown coal (50 t/day) Completed in 1992. • A pilot plant for liquifying bituminous coal (150 t/day) is under construction and is scheduled for completion in 1997.

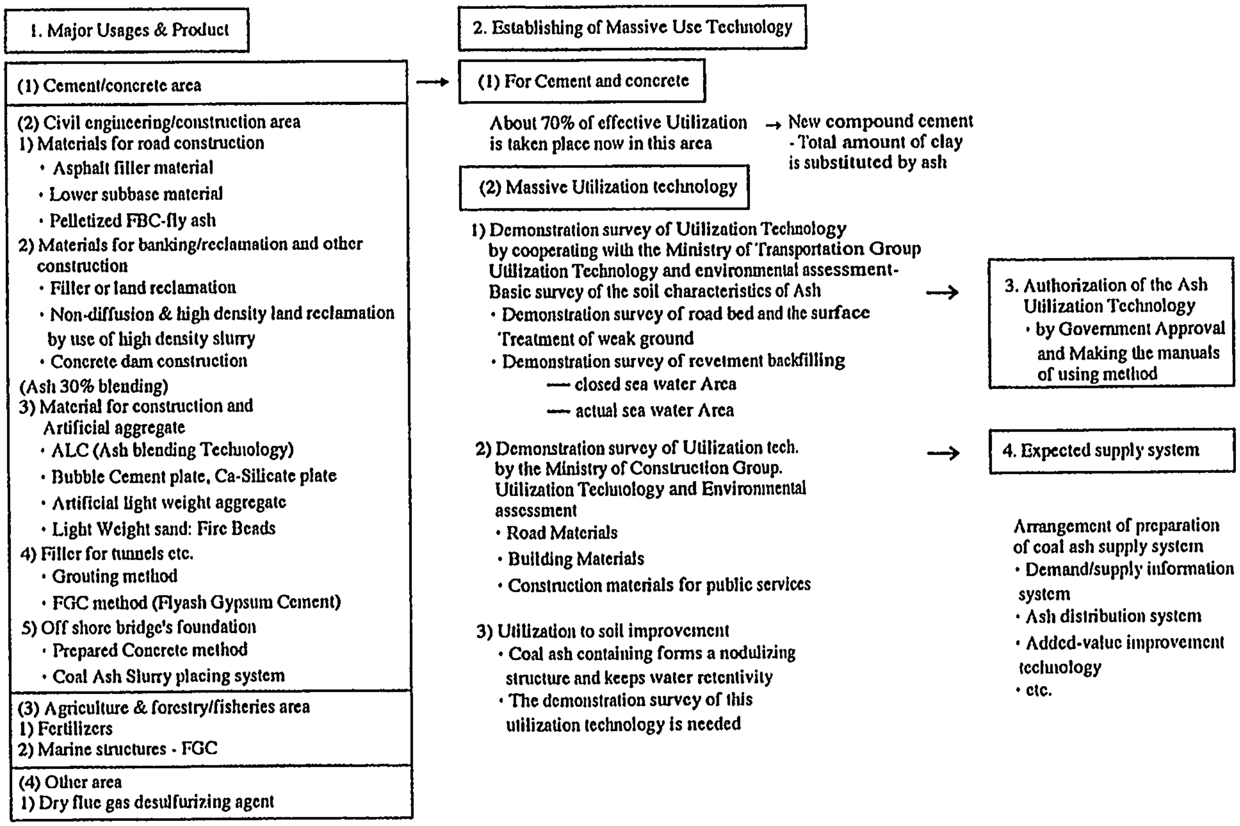
Table 6 SCENARIO OF NEW TECHNOLOGY DEVELOPMENT REGARDING GLOBAL ENVIRONMENTAL ISSUES

CCUJ

	To stabilize Emission of CO_2 on per Capita basis by the 2000 at about the same Level as in 1990		CO_2 Level: 2.6 t/Person/year
	'92~	~2000~	~2010~ Year
Whole Items	○To introduce existing clean coal Technologies ○To develop new high efficency CCT ○To develop new technologies for coal uses	○To introduce existing clean coal Technologies ○To introduce new developed higher efficiency CCT	○To promote New sunshine projects • Eco - Energy Supply System, etc. ○To develop innovative environmental technologies under way at RITE
For Power Generation	○To introduce USC System Power generation ○To introduce large scale FBC boiler (350 MW) ○To develop and introduce PFBC combined cycle power generation, and to develop Advanced PFBC combined power generation △To develop coal gasification technologies • IGCC • Manufacturing Hydrogen	△To actually use IGCC ○To actually use Advanced PFBC combined cycle power generation △To develop MHD power generation system ○To develop oxy-combustion system(O_2/CO_2)	○To introduce fuel cell system ○To introduce IGFC ○To introduce MHD power generation system ○To introduce coal complex system ○To introduce CO_2 Fixation technologies
For Industries (Ind: Industry)	○To spread CWM Tech. and CCS Technologies ○To develop high efficient cement manufacturing technology by FBC technology. ○To develop metal fusion technology by oxy-combustion of coal ○To develop mild gasification technologies (Manufacturing Medium calorific value gas and Tars) ○To develop DIOS process ★To research effective combined combustion system using combustible wastes and coals	○To introduce DIOS' ○To develop high eff. cokes manufacturing Tech. ○To introduce Mild gasification technology. (Manufacturing medium calorific value gas and Tars) ○To introduce • High efficient Cement manufacturing tech. by FBC technology • Metal fusion tech. by oxy-combustion of coal ★To develop and introduce higher efficient power generation by using combustible wastes	△To develop innovative energy utilization system • Global energy net-work system Urban system with good ecology and energy system △WE-NET system for Hydrogen gasification for manufacturing Hydrogen as a supplement role △Coal complex system in harmony with economic and environmental problems example: Mild gasification - coal complex system Hydro-gasification 〃 • A complex system, etc. of coal-fired thermal power generation with super-power generation using municiple refuses
For reducing environmental loads	○To develop and demonstrate Ash utilization as materials for constructions and roads ○To develop newer flue gas treatment tech.	○Making whole manuals for Ash Utilization ○To construct Ash delivery center ○To introduce Flue gas Treatment technologies	
※[1] Target of Power Generation's efficiency	(38~40%)	~(42~44%)~	~(45~48%)~ ~50%
Consumption of coal in Japan	116 Million Tons	~130 Million Tons~	~134 Million Tons~
※[2] Crude oil price	14~17 $/B1	18~23 $/B1 18~28 $/B1~	28 $/B1~

※[1] Energy efficiency target of new developing technologies ※[2] Crude Oil Price: Prediction by IEA (1994-4) △Mark: developing by NEDO ★Mark: expected themes

Fig. 3 Current Situation and Development of Effective Utilization Technology of Coal Ash



1. Major Usages & Product

(1) Cement/concrete area

(2) Civil engineering/construction area
1) Materials for road construction
- Asphalt filler material
- Lower subbase material
- Pelletized FBC-fly ash

2) Materials for banking/reclamation and other construction
- Filler or land reclamation
- Non-diffusion & high density land reclamation by use of high density slurry
- Concrete dam construction

(Ash 30% blending)
3) Material for construction and Artificial aggregate
- ALC (Ash blending Technology)
- Bubble Cement plate, Ca-Silicate plate
- Artificial light weight aggregate
- Light Weight sand: Fire Beads

4) Filler for tunnels etc.
- Grouting method
- FGC method (Flyash Gypsum Cement)

5) Off shore bridge's foundation
- Prepared Concrete method
- Coal Ash Slurry placing system

(3) Agriculture & forestry/fisheries area
1) Fertilizers
2) Marine structures - FGC

(4) Other area
1) Dry flue gas desulfurizing agent

2. Establishing of Massive Use Technology

(1) For Cement and concrete

About 70% of effective Utilization is taken place now in this area → New compound cement - Total amount of clay is substituted by ash

(2) Massive Utilization technology

1) Demonstration survey of Utilization Technology by cooperating with the Ministry of Transportation Group Utilization Technology and environmental assessment-
Basic survey of the soil characteristics of Ash
- Demonstration survey of road bed and the surface Treatment of weak ground
- Demonstration survey of revetment backfilling
  — closed sea water Area
  — actual sea water Area

2) Demonstration survey of Utilization tech. by the Ministry of Construction Group. Utilization Technology and Environmental assessment
- Road Materials
- Building Materials
- Construction materials for public services

3) Utilization to soil improvement
- Coal ash containing forms a nodulizing structure and keeps water retentivity
- The demonstration survey of this utilization technology is needed

3. Authorization of the Ash Utilization Technology
- by Government Approval and Making the manuals of using method

4. Expected supply system

Arrangement of preparation of coal ash supply system
- Demand/supply information system
- Ash distribution system
- Added-value improvement technology
- etc.

Underground Coal Gasification, *Alan H. Singleton, Energy International Corporation, USA*

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This paper was unavailable at the time of publication and may be obtained directly from the author.

Recent Development of CWS Combustion Technology in China, *Cen Kefa, Yao Qiang, Cao Xinyu, Zhao Xiang and Huang Zhenyu, Institute of CWS Combustion Technology, Zhejiang University; and Hao Fenying, Zan Rong, Chen Fengying, Huang Xiuyu and Lu Hualiaang, National Coal Ministry, PEOPLE'S REPUBLIC OF CHINA*

This paper was received after pagination and is located on Page 729 of these Proceedings.

Cofiring Conventional and Upgraded Coal-Water Slurries in Utility Boilers, *Donald K. Morrison, Todd A. Melick, Dr. Roy Payne and Todd M. Sommer, Energy and Environmental Research Corporation; Joseph J. Battista, GPU GENCO; Rick Carson, Tennessee Valley Authority; and Bill Weber, EPRI, USA*

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EXPERIMENTAL TESTING OF A RETROFIT INDUSTRIAL SIZED BURNER USING MICROFINE COAL

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ABSTRACT

This paper summarizes recent progress on the development of a micro-fine coal fired burner for retrofit application in an industrial scale boiler designed for gas/oil. The work has been carried out under DOE-PETC support, in a joint project between the Energy and Fuels Research Center of The Pennsylvania State University (Penn State) and ABB Power Plant Laboratories. The primary focus of this program was to carry out a long term test under steady state operation on micro-fine coal while maximizing carbon conversion efficiency and maintaining NOx emissions below a target goal. Specific experimental results discussed here include a summary of the approximately 500 hour testing of the burner in a 15,000 lb/hr package boiler located at Penn State. All program goals were met except carbon conversion efficiency. The results have shown very good performance especially considering the very small size and short residence time in the boiler. In addition to burner performance/boiler test results the paper presents an economic evaluation of the burner system for retrofit applications.

BACKGROUND

Under U.S. Department of Energy, Pittsburgh Energy Technology Center (PETC) support, the development of a High Efficiency Advanced Coal Combustor (HEACC) has been in progress since 1987 at the ABB Power Plant Laboratories (Rini, et al., 1987, 1988). The initial work on this concept produced an advanced coal firing system that was capable of firing both water-based and dry pulverized coal in an industrial boiler environment (Rini, et al., 1990).

Economics may one day dictate that it makes sense to replace oil or natural gas with coal in boilers that were originally designed to burn these fuels. In recognition of this future possibility, the U.S. Department of Energy, Pittsburgh Energy Technology Center (PETC) has continued to support this program led by ABB Power Plant Laboratories and the Fuels Research Center of Penn State University to develop the HEACC concept. The objective of the current program is to demonstrate the technical and economic feasibility of retrofitting a gas/oil designed boiler to burn micronized coal. In support of this overall objective, the following specific areas were targeted:

- A coal handling/preparation system that can meet the technical requirements for retrofitting microfine coal on a boiler designed for burning oil or natural gas
- Maintaining boiler thermal performance in accordance with specifications when burning oil or natural gas
- Maintaining NOx emissions at or below 0.6 lb/MBtu (~450 ppm)
- Achieving combustion efficiencies of 98% or higher
- Calculating economic payback periods as a function of key variables

The overall program has consisted of five major tasks:

1.0 A review of current state-of-the-art coal firing system components.
2.0 Design and experimental testing of a prototype HEACC burner.
3.0 Installation and testing of a HEACC system in a commercial retrofit application.
4.0 Economic evaluation of the HEACC concept for retrofit applications.
5.0 Long term demonstration under commercial user demand conditions

The results of Tasks 1 and 2 have been summarized in previous technical publications (Rini, et al., 1993, Jennings, et al., 1993). This paper summarizes the work in Task 3, the 400 hour proof-of-concept testing of the HEACC system in an gas/oil - designed package boiler at Penn State, and Task 4, the economic evaluation of the HEACC concept for retrofit applications. Task 5, a 1000 hr long term demonstration is planned to start in mid-1995.

INTRODUCTION

An objective of the work in Task 3 has been to assess the technical and economic viability of displacing premium fuels with micro-fine coal by retrofitting the previously developed High Efficiency Advanced Coal Combustor (HEACC) to a standard gas/oil designed industrial boiler. This paper summarizes the work involving the retrofit of a complete micro-fine pulverized coal milling and firing system to an existing 15,000 lb/hr package boiler located in the East Steam Plant of Penn State University. Combustion performance-related objectives included steady state operation on 100% coal while achieving a carbon conversion efficiency of 98%, without increasing NOx emissions above 0.6 lb/MBtu (~450 ppm). The testing was also designed to show that consistent reliable operation of entire coal storage/handling and pulverization system could be achieved. Reliable operation of the coal preparation system in concert with satisfactory burner performance would serve as a prerequisite to the demonstration phase of the project.

A Prototype HEACC burner was previously tested in the Industrial Scale Burner Facility (ISBF) located at Combustion Engineering's ABB Power Plant Laboratories (PPL) in Windsor, Connecticut. A key objective of the 100 hour burner validation tests at PPL was to confirm burner operating characteristics and demonstrate operation over the range of conditions expected for the field boiler tests. This modified HEACC configuration successfully achieved the project performance goals during these performance verification tests on standard grind coal. The successful testing at PPL demonstrated the technical validity of the design improvements incorporated into the second generation HEACC. This burner was then installed as part of a complete coal handling and firing system in Penn State's commercial boiler for a 400 hour proof-of-concept test program (Task 3).

A schematic of the micronized coal preparation/firing system at Penn State is shown in Figure 1. As can be seen, the cleaned coal comes on site and is stored in a large hopper. The coal is crushed and sent via a screw feeder to a micronized coal mill (TCS system). The coal is then micronized to ~80% through 325 mesh (~18 microns MMD) in the TCS mill and pneumatically conveyed to the HEACC burner where it is then burned in the boiler. This boiler is an oil/gas designed Tampella Keeler Model DS-15; a packaged D-type watertube boiler capable of producing 15,000 lb/hr of saturated steam at 300 psig. It represents a typical gas/oil - designed system with a furnace volumetric heat release of 50,000 Btu/hr ft^3, standard for this class of boiler. Furthermore, its design is similar to that of many other manufacturers' (including Combustion Engineering) models.

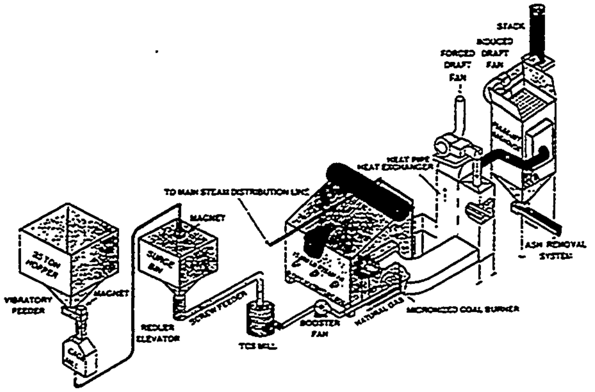


Figure 1 Micronized Coal Combustion System at Penn State

EXPERIMENTAL TESTING RESULTS

A) OVERVIEW

During the long term test period, the boiler system was operated over a range of operating conditions. Specifically, he boiler was tested over a variety of load ranges, excess air, combustion air damper settings and burner swirl levels. Two coals Brookville Seam and Kentucky were used. Their analyses are summarized in Table 1. During the test period, boiler performance data, emissions data, electric parasitic power and house compressed air consumption data, as well as other data required for the technical and economical analysis of the system were obtained.

Table 1 Selected Analyses of the Brookville and Kentucky Coals

	Brookville Seam	Kentucky
Proximate, wt%		
Moisture	8.2	6.8
Volatile Matter	33.1	33.3
Fixed Carbon	55.8	55.4
Ash	2.9	4.5
HHV, Btu/lb	13,260	13,010
Ash Fusion Temp, °F		
IDT	2,820	2,803
ST	+3,000	+3,000
FT	+3,000	+3,000

The initial burner tests included a shakedown series of runs using natural gas firing (Jennings, et al., 1994a, 1994b). At the conclusion of baseline natural gas firing, the boiler operation was directed towards hardware optimization (e.g., coal handling/preparation, burner settings) and testing with 100% coal firing. During this phase of the work, a major objective was to obtain consistent, repeatable 100% coal fired runs. This goal, along with minor modifications to the system (discussed in the next section) to increase boiler and carbon conversion efficiency resulted in several short term tests. Subsequently, the chosen hardware configuration was then used during the long term test program.

B) SYSTEM CHARACTERIZATION/MODIFICATIONS

A key objective of the proof of concept testing was to determine the operating characteristics of the complete, integrated system in contrast to the operation of the individual components. Although all of the system components installed at the demonstration boiler host site were proven in either commercial operation or prior testing, the complete system from micro-fine coal production to steam production at this scale had not been previously demonstrated/proven.

The testing at Penn State indicated areas that should be carefully engineered in a commercial design. Furthermore, it was anticipated that if any problems occurred, they would likely be related to the burner (the least developed system component). However, the coal handling/feeding sub-system as it related to boiler system operability proved to be a critical component during initial testing. Some of the key system modifications and operational problems relating to the Penn State boiler are discussed below.

TCS Mill

The TCS mill and booster fan operated well without constant supervision. Initial system testing, however, revealed a coal settling problem in the mill outlet duct. This problem was corrected by a specially designed diffuser/transition section fitted to the mill exit. In addition, a detailed experimental study was carried out to characterize the effect of mill air flow rate and mill speed, on coal particle size distribution (PSD) and top size for the two coals tested. This was done as part of an effort to determine the milling conditions necessary to reduce the coal PSD and top size in order to achieve maximum coal combustion efficiency. In addition, the results were used to evaluate the feasibility for external classification to reduce the coal top size. Selected results from this characterization study are shown in Fig. 2. This figure shows the Brookville Seam coal particle size distribution for a near constant mill air flow rate and the two values of mill speed. As can be seen, the mill speed was a most important parameter to obtain the desired coal PSD. The results from these tests were used to optimize the mill settings for coal fineness during the experimental test program. Table 2 presents typical optimized mill operating conditions.

Table 2 Mill Performance Summary

Typical mill air flow rate: 370-400 acfm
Typical coal feed rate: 16.5- 18.5 lb/min

Particle Size (microns)	Brookville Seam Coal	Kentucky Coal
Top Size	190-300	250-275
D_{80}	50-70	50-70
D_{50}	25-30	25-30

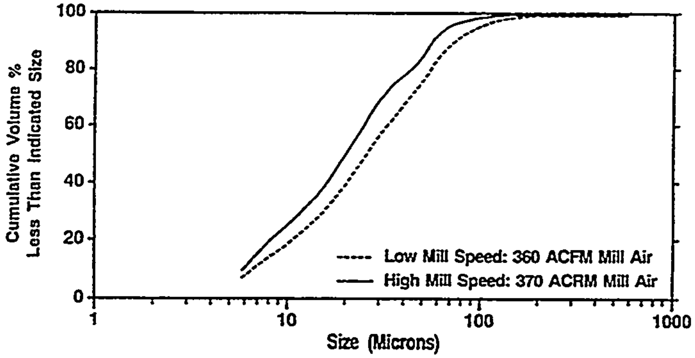


Figure 2 Brookville Seam Coal PSDs (Fixed coal feed rate)

Furnace Modifications

The furnace geometry was slightly altered during the test program by installing an ceramic wall at the exit of the radiant section of the boiler. The basic idea was to improve carbon burnout by making better use of the entire boiler volume through changing the gas patterns and temperature profile in the boiler. This was done because analytical (CFD) modeling showed that the flame was skewed from the burner to the furnace outlet and that the entire furnace volume was not being used (Model results were subsequently verified by suction pyrometry).

Boiler System Operability

During the initial testing period, a number of operational problems involving the coal handling and boiler system were encountered. They were primarily related to the weather (cold, snow), the coal (particle size, moisture content), the burner/boiler system (unstable/ low u.v. signal), or mechanical difficulties (feedwater pump, steam valves). With the exception of the coal handling problems caused by high moisture, these problems were all addressed and solved during the shakedown test series. The coal moisture problems will be fully addressed prior to beginning 1000 hour demonstration test (Task 5).

C) SUMMARY OF EXPERIMENTAL RESULTS

Under the 400 hour test program, Brookville Seam and Kentucky coals were evaluated, the furnace geometry was modified by installing a ceramic wall, two coal guns (the RO-II with and without a coal deflector/accelerator and the I -Jet) were tested, and the operating conditions (excess air and firing rate) were varied. During the course of the long term coal only tests, no support fuel was required and the burner operated with excellent ignition stability. A typical summary of the microfine coal firing (both coal) is given in Table 3.

Table 3 Microfine Coal Firing Results

Boiler Operation:	
Steam Flow Rate (lb/hr)	13,240
Boiler Efficiency (%)	84.1 (3% O_2)
Combustion Performance	
Carbon Conversion Efficiency (%)	95.3
NOx at 3% O_2 (ppm)	413 (0.56 lb/MBtu)
Burner Pressure Drop (in H_2O)	8

During this test program, key performance variables were monitored in detail: boiler efficiency, combustion efficiency, and NOx emissions. A summary of the results involving these parameters follows.

Boiler Thermal Performance

Boiler thermal performance when firing micro-fine coal was essentially comparable to that achieved when firing natural gas. In fact, because of the greater latent heat loss when burning natural gas (greater formation of water due to higher hydrogen content), firing micro-fine coal actually gave slightly higher boiler efficiencies despite the need to run at higher excess air levels.

During the relatively short operating periods, usually less than 16 hours, ash deposits did not cause significant changes to the boiler thermal performance. It is recognized, however, that longer term operation could result in greater build-up of ash deposits which could impact heat transfer. Because of the relatively short duration of the tests, any build-up of ash deposits would slough off when the boiler was shut down. A better test of the possible impact of ash deposits will occur during the long term demonstration phase of the work (Task 5.0).

Combustion Efficiency

The target for combustion efficiency was 98%. The highest combustion efficiency obtained during the test program was slightly over 96%. However, this value was not compatible with meeting the NOx target, and was not able to be routinely repeated. As shown in Figure 3, a value of 95% combustion efficiency was able to be routinely achieved, and was compatible with meeting the NOx target.

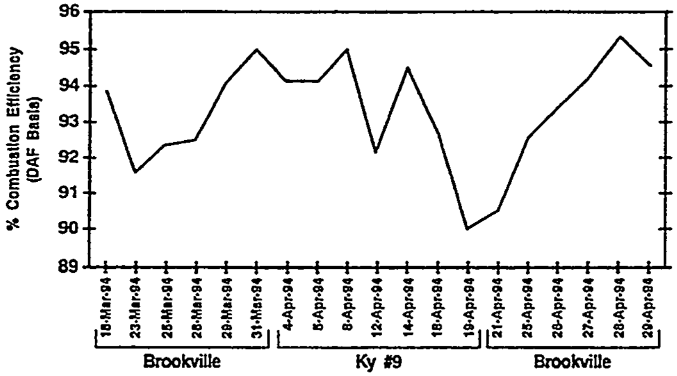


Figure 3 Combustion Efficiency During 400 Hour Test Period

NOx Emissions

The NOx emissions target was 0.6 lb NOx per million Btu fired; this translates to about 450 ppm at 3% O_2. As shown in Figure 4, testing with 100% microfine coal showed that this target was achieved (in general a NOx emissions value of 0.56 lb NOx per million Btu was routinely met) while meeting nearly all other required conditions. It is acknowledged that the optimum conditions for low NOx will generally exacerbate carbon conversion efficiencies. Indeed, this was the case with the HEACC burner and the challenge was to find a reasonable balance between meeting the NOx target while not aggravating the carbon conversion efficiency.

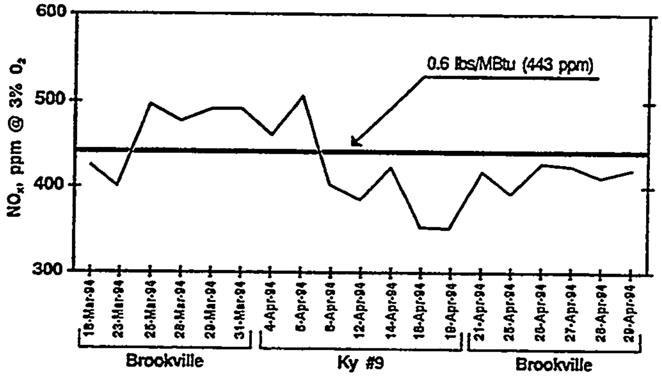


Figure 4 NOx Emissions During 400 Hour Test Period

D) ANALYTICAL MODELING CONSIDERATIONS

One of the technical goals during the 400 hour testing period under Task 3 was to achieve 98% combustion efficiency with 100% micronized coal firing. As previously discussed, results from the 400 hour testing segment show that the highest average steady state combustion efficiency that could be reached in the Penn State boiler was around 95%. Data from the 400 hour testing period were evaluated to understand which of the key parameters might be adjusted to achieve the desired burnout. It was difficult to pinpoint any cause and effect relationships which would help explain the primary controlling independent variables which might improve the combustion efficiency.

In order to identify reasons for the lower combustion efficiency than the original goal (95% vs. 98%), and to evaluate which key parameters (i.e, coal fineness, residence time, coal reactivities etc.) are important for maximizing the combustion efficiency, ABB CE's proprietary mathematical model known as the Lower Furnace Program-Slice Kinetic Model (LFP-SKM) was used for simulating the combustion process in the Penn State boiler (at full load firing rate). Fuel kinetic information for this study was selected on a surrogate basis from ABB CE's extensive in-house data base.

The Penn State Boiler is considerably smaller and a different boiler type compared to the typical LFP-SKM application. Thus, some simplified assumptions were required for application of LFP-SKM. Based on the size and operating conditions (i.e., volumetric flows, temperature) of the Penn State boiler, the calculated bulk residence time up to the convective section entrance varies from 0.6 to 0.7 seconds. Assuming that the coal particle residence times could be greater than bulk residence times, gas residence time simulations were made for residence times of up to 1.0 second by intentionally increasing the boiler length (~8 ft to ~ 13 ft.).

A typical LFP-SKM result from this work is shown in Fig. 5. This figure shows predicted combustion efficiency as a function of bulk residence time for two different coal fineness values. The results clearly show the effect of residence time and fineness (especially top size) on combustion efficiency. Specifically, combustion efficiency can increase by 1% as either residence time increases from 0.7 to 1.0 second or as coal fineness increases from 75% -325M and 0.1% +100 M to 75% -325M and 0.01% +100 M.

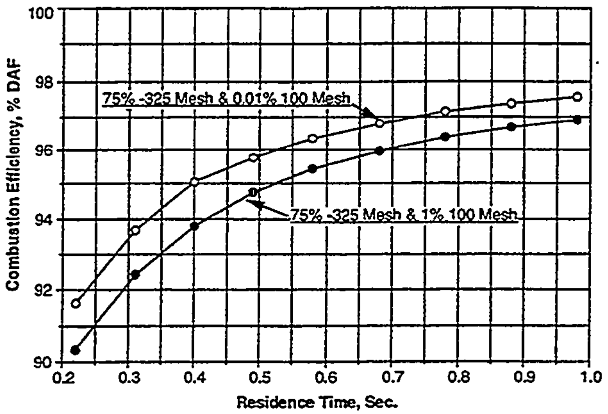


Figure 5 Combustion Efficiency vs. Residence Time (2 Values of Coal Fineness)

In general, the experimental tests showed less sensitivity to particle size than the analytical results from the LFP-SKM model. Although it was difficult to pinpoint any cause and effect relationship from the experimental data, the LFP-SKM simulations clearly show the effects of residence time and coal particle top size on combustion efficiency. Both the experimental and analytical work show that the Penn State boiler (with residence time of about 0.65 sec. represents a definite challenge for burning coal at high combustion efficiency.

SYSTEM ECONOMICS

This phase of the work involved an economic evaluation of coal firing for existing small industrial boiler installations. In addition to a Base Case evaluation (the 15,000 lbm/hr natural gas fired Penn State boiler), various economic sensitivity studies which provide insight into the economics for other unit sizes, fuel price scenarios, capacity factors and other variables were carried out. The primary objective of this analysis was to determine how the coal option compares with natural gas firing on an annual basis. With coal firing the capital costs for the retrofit modifications as well as some additional operating and maintenance costs must be justified by the savings in fuel costs. The evaluation summarized here defines the incremental costs and savings on an annual basis as a result of the use of coal as a substitute for natural gas firing. The first year incremental operation and maintenance cost savings and the total retrofit capital requirement were then used to determine a simplified payback period.

A) CAPITAL COSTS

Cost data were compiled for three components: 1) Direct Investment Expenditures, 2) Boiler Retrofit Costs, and 3)Fuel Preparation Facility Costs which includes site modifications and installation. The Direct Investment Expenditures include materials, fabrication, assembly, and shipment. The Direct Investment Expenditures are shown below.

Direct Investment Expenditures (1992 $)

Feeder	6,600.00
Crusher	42,000.00
Truck Dump Bin	60,000.00
Magnet	1,200.00
Conveyor	48,000.00
Surge Bin	9,000.00
Screw Feeder	8,400.00
Mill	160,000.00
Dust Collector	14,400.00
Sump Pump	2,250.00
Interconnecting Piping, etc.	48,448.00
Power and Controls	32,299.00
Booster Fan	11,337.00
Sales Tax	16,380.00
Performance Bond	11,324.00
Total Direct Investment Expenditures	471,638.00

The Boiler Retrofit Cost category included the costs required to modify the boiler to fire micronized coal. This cost includes the boiler balanced draft conversion, ductwork modifications, air preheater installation, baghouse installation and flyash hopper installation. These costs were determined using engineering estimates and actual costs incurred by Pennsylvania State University during the retrofit. These costs are shown below.

Boiler Retrofit Costs (1992 $)

Combustion Air Preheat/Duct Modifications	99,139.00
Baghouse	151,612.00
Fans	36,793.00
Ash Hopper/Removal	59,000.00
HEACC Burner	70,000.00
Total Boiler Retrofit Costs	416,544.00

Fuel Preparation Facility Costs were based on the actual costs incurred by Pennsylvania State University to construct, install and provide site modifications to the existing facility. This facility was also be used to prepare Coal Water Slurry Fuel, a percentages of the total building costs were used for this analysis. The total resulting costs under this category were estimated to be $1,045,391.

B) OPERATING AND MAINTENANCE COSTS/ PAYBACK PERIOD CALCULATIONS

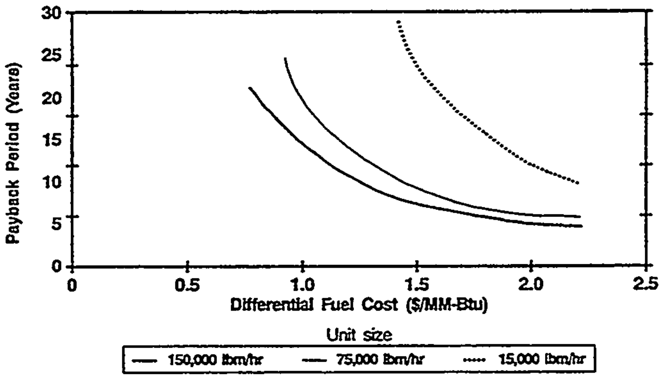
The only savings incurred with coal firing is a result of the lower cost of coal as compared to natural gas (per unit of heat input to the boiler). There are also several additional costs due to coal firing which reduce the annual net savings. The annual ash disposal cost is calculated based on 10.00 $/Ton of ash. The incremental annual electrical cost with coal firing is based on the additional electrical usage for auxiliary equipment (fans, coal mill, crusher, conveyor) and a cost of electricity of 0.0424 $/kwhr. The additional annual operating and maintenance cost with coal firing is made up of two components. First, the annual maintenance cost for the additional equipment added during the retrofit is calculated as 4 percent of the total retrofit cost. The second component is the additional operating labor required. For this analysis it was assumed that an additional half a man per shift would be required for three shifts per day. The annual labor rate was assumed to be

30,000 $/yr. Startup costs for this retrofit were based on an additional one man per shift for a period of three weeks.

The primary calculated outputs from this study were the annual net savings and the simplified payback period. The annual net savings is simply the annual fuel cost savings due to coal firing minus any additional annual costs associated with the firing of coal (such as ash disposal costs, additional electrical auxiliary usage, and additional operation and maintenance requirements). The simplified payback period is calculated as the required total cost for the retrofit divided by the annual net savings with coal firing.

C) RESULTS

A series of economic comparisons (spreadsheet based) were carried out for the base case and other systems involving different economic input parameters. For these studies a range of differential fuel costs were used, and other sensitivity studies were carried out to determine the effect of unit size, annual operating time, and carbon heat loss on simplified pay back time. Figures 6 to 8 show the results of these sensitivity studies. In addition to differential fuel costs (see Fig. 6), other sensitivity variables studied were shown to have significant effects on payback period. As shown in Fig. 6, increasing unit size is shown to quickly improve the economics. Also, as shown in Fig. 7, changes in the annual operating time from 4000 to 8000 hrs/yr showed significant effects on payback period. Typically industrial boilers have very high capacity factors (the base Case for this study used 7000 Hrs/yr (equivalent to an 80 percent capacity factor)). Fig. 8 is of most interest as it shows that variations in carbon heat loss (combustion efficiency) have no significant effect on payback period for the range studied (2 to 6%).



(Annual Operating Time = 7,000 hrs/yr)

Figure 6 Payback Period as a function of Differential Fuel Cost and Unit Size

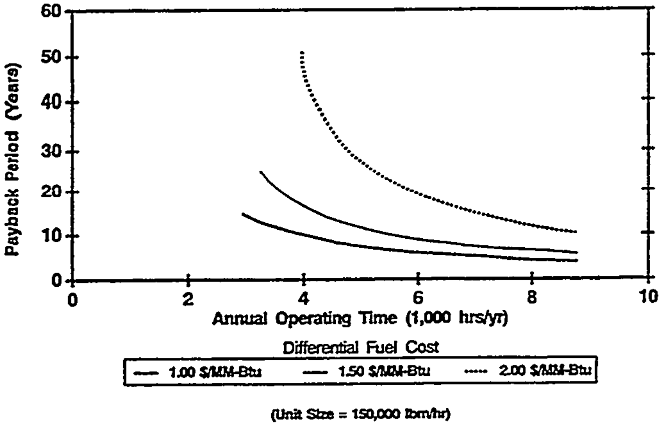


Figure 7 Payback Period as a function of Annual Operating Time

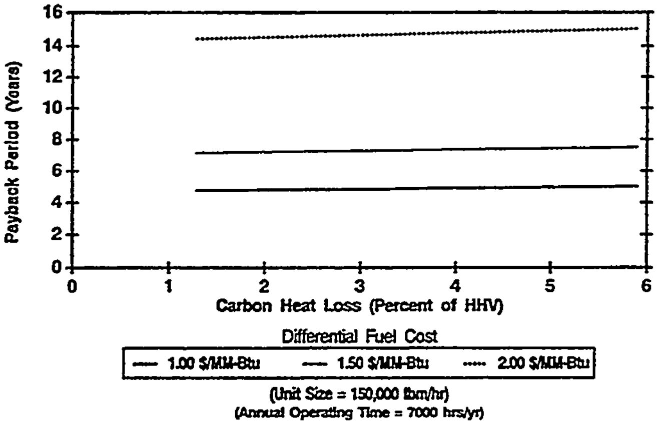


Figure 8 Payback Period as a function of Carbon Heat Loss

Although this analysis was done relative to natural gas as the base fuel, the results can also be generally applied to oil firing as well. By knowing the differential fuel cost the payback period can be approximated from the attached curves. Although boiler efficiency with oil firing is typically about 5 percent better than with natural gas, the effect on payback period is relatively insignificant as was shown by the results of the carbon heat loss sensitivity study.

CONCLUSIONS/ RECOMMENDATIONS

The following specific conclusions are based on the results of the coal fired testing at Penn State and the initial economic evaluation of the HEACC system:

- A coal handling/ preparation system can be designed to meet technical requirements for retrofitting micro-fine pulverized coal.
- The boiler thermal performance met requirements
- Combustion efficiencies of 95% could be met on a daily average basis, somewhat below target of 98%
- NOx emissions can meet target of 0.6 lb/million Btu
- The economic payback was very sensitive to fuel differential cost, unit size, and annual operating hours

As a result of recent long term tests using micronized coal, Penn State has experienced some convective pass ash deposition problems. To alleviate this problem they are planning to install additional soot blowers. Also, as a result of problems encountered during the 400 hour testing, the following modifications are planned for the Penn State system:

Coal feeding improvements
a) Installation of a gravimetric feeder
b) Redesign/installation of a surge bin bottom
c) Improved raw coal/ storage and transport
Monitoring of ash deposit effects
a) Ash deposition probes
b) Air sparge system
c) Monitoring effects on heat transfer in the furnace and the convective pass

In addition, ABB CE plans to modify the burner for more precise aerodynamic control of the fuel and air streams to improve the combustion efficiency and NOx emissions. Based on the results summarized in this paper the ABB/Penn State team and DOE/PETC have concluded that a 1000 hr demonstration program is warranted. Thus, the demonstration phase (Task 5.0) of this program is scheduled to begin in June 1995.

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PRESSURIZED FLUID-BED COMBUSTION OF DRY AND COAL-WATER FUELS

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INTRODUCTION

One of the overall goals of the U.S. Department of Energy (DOE) is the development of the technology necessary to provide for a secure, reliable, affordable, and environmentally sound source of energy. This is important in order to ensure economic stability and growth in the next century as well as to reduce current and minimize future environmental impacts associated with power generation in the United States and the world as a whole. The continued and potentially expanded use of abundant coal reserves is one key to a secure and affordable source of energy in the United States.

In order for coal to play a key role in the U.S. energy mix, technologies must be developed and commercialized that are capable of producing electricity at significantly higher overall system efficiencies than the 30%–35% levels currently observed in conventional coal-fired systems. Also, the production of liquid and gaseous fuels from coal will be necessary in order to effectively meet the broad spectrum of future energy needs. In order to achieve overall system efficiencies of 40% to 60% in an environmentally acceptable manner, development and demonstration of advanced second-generation utilization and conversion technology will be necessary. Examples include 1) advanced pulverized coal-fired combustion systems; 2) high-temperature heat exchangers for indirect firing of gas turbines; 3) pressurized combustion in staged, entrained, slagging, and fluidized-bed modes; and 4) integrated gasification and direct gas-fired turbines. A number of barrier issues exist that are not unique to individual technologies but are in some manner common to all advanced power system processes for both oxidizing and reducing environments. Examples include materials issues, specifically ceramic and refractory components, and operational issues unique to high-temperature pressurized systems. These operational issues include a comparison of pressurized fluidized-bed combustion (PFBC) performance utilizing dry (powdered) versus wet (slurry) coal feed systems (1).

OBJECTIVES

The goal of the PFBC program is to generate fundamental process information that will further the development of an economical and environmentally acceptable second-generation PFBC. A great deal of PFBC performance relates to the chemistry of the bed and the gas–solids contacting that occurs during combustion. These factors can be studied in a suitably designed bench-scale reactor. The focus of the work reported here was the difference in PFBC operation caused by the use of different types of feed systems (i.e., powdered versus slurry).

ACCOMPLISHMENTS

Description of Pressurized Fluidized-Bed Reactor

A pressurized fluidized-bed reactor (PFBR) has been constructed at the Energy & Environmental Research Center (EERC) to simulate the bed chemistry, ash interactions, and emissions from a PFB under closely controlled conditions. This reactor is used for sorbent characterization, gaseous emissions including trace elements, agglomeration, and hot-gas cleanup testing in a cost-effective manner over a wide range of operational conditions. The 55-in.-tall reactor is constructed of 3-in. Schedule 80 pipe and is externally heated with three ceramic heaters. A hot cyclone collects the ash and bed material that is carried out of the reactor. The preheated fluidizing gas can be a mixture of air and nitrogen or just air; in addition, one additional gas such as carbon dioxide, carbon monoxide, sulfur dioxide, or a nitrogen oxide can be added to result in a fuel gas similar to that generated in a full-scale FBC. Preheated gas at temperatures of up to 1400°F and pressures of up to 200 psig are supplied at the bottom of the reactor through a 1-in. Schedule 40 pipe. The fluidizing gas is supplied at sufficiently high velocities to prevent the sized bed material from dropping out during operation. The use of both air and nitrogen as fluidizing gas allows excess air and gas velocity to be matched to any design condition.

The fluidizing gas enters the 3-in. Schedule 80 main section of the reactor through a conical transition. This conical section was designed without a distributor plate to allow quick removal and quench of the bed material after completion of a test. Bed material can be sampled or collected using a lock hopper system located at the bottom of the reactor. Ports for alkali-sampling probes or, alternatively, solid-sampling or gas-sampling probes are located at the top of the reactor and the top of the cyclone. An air-cooled deposition probe is located at the top of the reactor. Alternatively, a sight port at the top of the reactor can be installed with a color videocamera for on-line observation of the bed during either high-pressure or atmospheric operation. Figure 2 is a schematic of the PFBR showing the feed port, hot cyclone, fluidizing gas inlet, and the sampling ports on the top of the reactor and cyclone. Figure 2 is a photograph of the actual reactor vessel, cyclone, air preheater, reactor collection pot, and fuel feed hopper.

The use of electric heaters provides the capability to match the fuel feed rate to the amount of bed material in the reactor. External heaters are used for heating and maintaining the reactor and hot cyclone at temperatures of up to 2000°F for atmospheric operation and up to 1700°F for operation at 150 psig. The high heat losses through the reactor walls inherent to small-scale systems also require either good insulation or reactor heating. This type of heating system provides very good control of the reactor temperature.

The bench-scale PFBR is equipped to feed either dry fuel or slurry. Slurry feed is metered with a variable-speed progressive cavity pump. The suction end of the progressive cavity pump is attached to the outlet of the feed tank which is continuously stirred to keep the solid particles suspended. The slurry fuel is then fed through 1/4-in. tubing into the PFBR, which necessitated that the fuel particle size be kept small. Also included in the slurry fuel feed piping are provisions for circulating the fuel back to the feed tank, a water purge for flushing the feed lines with water, and a nitrogen purge for keeping the feed line into the PFBR clear of bed material. The slurry feed pump is capable of delivering 3- to 8-lb/hr of fuel against a reactor pressure of 150 psig.

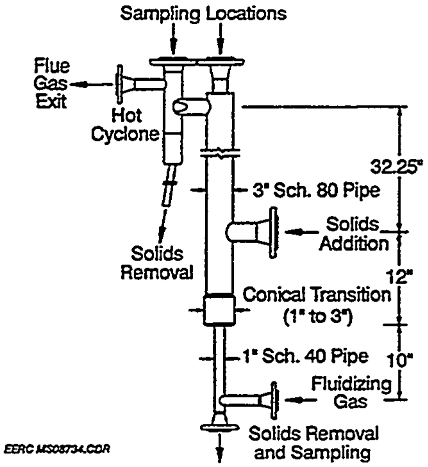

Figure 1. Schematic of PFBR pressure vessel.

Dry coal and sorbent are metered with separate augers that feed into a common water-cooled auger, which in turn carries the material into the reactor. A bed material hopper empties directly into the common auger, without flow control. Each hopper is maintained at a pressure slightly higher than that in the combustor during operation. The hoppers can be isolated from the pressurized system so that they can be refilled during a test. At the bottom of each hopper are sensors to alert the operator when the hoppers are empty and need to be refilled.

A data acquisition and control system is used to monitor and record all critical pressures, temperatures, flow rates, and emissions. These critical data include the gas flow rates, bed static pressure and differential pressures across the bed and cyclone, and eleven different internal reactor temperatures. The reactor thermocouples are located at 0.25, 1.75, 3.5, 5, 7, 9, 11, 15, 23, 31, and 43.25 in. above the conical transition section. The air and nitrogen flow rates are controlled automatically to flow rate set points. The reactor pressure is automatically controlled to a pressure set point. Continuous emission sampling of the flue gas measures the levels of O_2, SO_2, NO_x, N_2O, HC, CO, and CO_2. Solid samples include fly ash and bottom ash, which were analyzed for unburned carbon.

Experimental Results

The two hydrothermally treated (HTT) slurries were made from a Little Tonzona subbituminous coal and a North Dakota lignite. These slurries and the −1/4 in. as-received powders of these two fuels were then tested in the PFBR. A combustion test was also performed with a lump powder feed of the hydrothermally treated Little Tonzona coal, referred to in this report as dried HTT, as opposed to HTT slurries. The analyses of these fuels are shown in Table 1. This table shows that the as-received Little Tonzona coal had higher sulfur levels than the HTT Little Tonzona fuels.

The fluidizing gas was a mixture of air and nitrogen preheated to about 650° to 800°F. Table 2 shows the operating data for the combustion tests with Knife River lignite and the Little Tonzona fuels. The heat input for the Knife River slurry was about 38,000 Btu/hr as compared to 31,000 Btu/hr

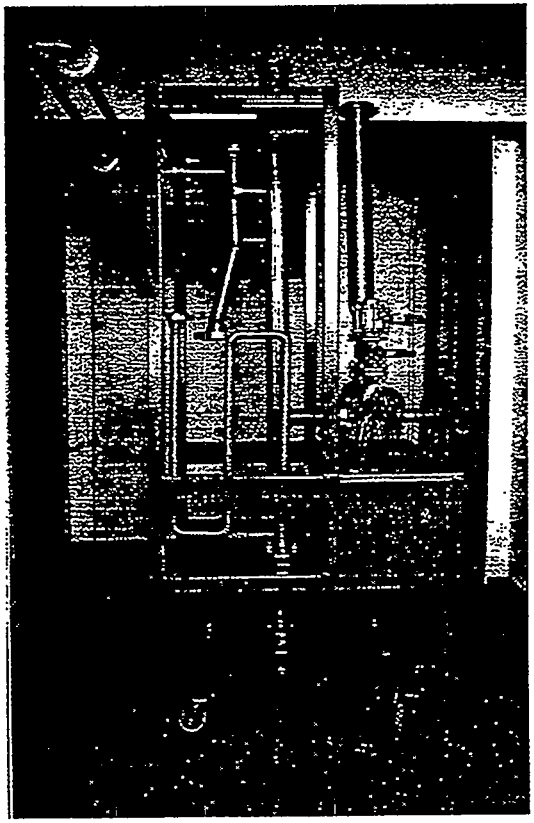

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Figure 2. Photograph of PFBR pressure vessel.

for the dry Knife River fuel. The heat input for the Little Tonzona fuels ranged from 28,000 Btu/hr for the Little Tonzona slurry and as-received dry fuel to approximately 33,600 Btu/hr for the Little Tonzona dried HTT fuel. All five tests were operated at similar temperature, velocity, and excess air levels. Figure 3 shows the temperature distributions for the five tests. The Little Tonzona dry fuels had very similar temperature distributions, while the slurry fuel had a lower bed temperature and similar freeboard temperatures as the dry fuels. The Knife River slurry fuel had a very similar temperature distribution as the Little Tonzona dry fuels, while the Knife River dry fuel had a much lower bed temperature with

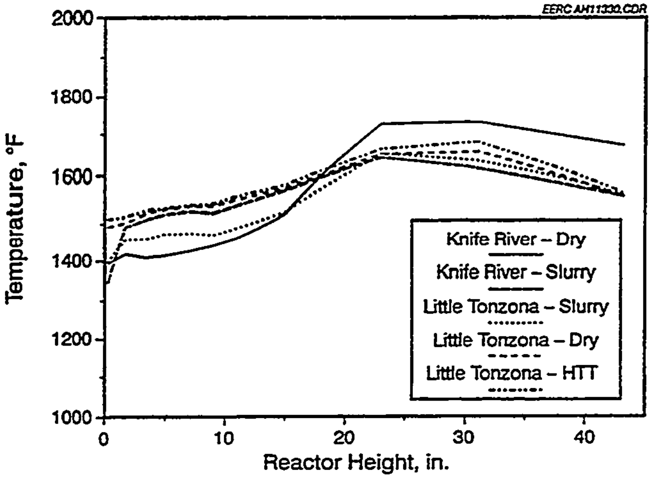

Figure 3. Temperature distributions for Knife River and Little Tonzona combustion tests.

higher freeboard temperatures than the other fuels tested. This indicates that substantial combustion of the fuel was taking place in the freeboard region of the combustor.

Table 3 shows the gaseous emissions data for the five combustion tests. Included in this table are the as-measured emission levels as well as the emission levels corrected to take out the makeup nitrogen and corrected to 3% O_2. Also included in Table 4 are the gas emissions converted to a lb/MMBtu basis. Figure 4 compares the emissions, in lb/MMBtu, for the five tests. The SO_2 emissions were highest for the Little Tonzona as-received coal followed by the dried HTT Little Tonzona fuel. A sulfur-compliant fuel was achieved with the Little Tonzona HTT slurry. The Knife River slurry had higher SO_2 emissions than the as-received fuel because of the removal of inherent alkali (sodium) from the coal's inorganic constituents. This is also reflected in the alkali utilization of the inherent alkali for sulfur capture. The alkali utilization was about 57% for the Little Tonzona slurry, 65% for the Knife River slurry, and 78% for the dry Knife River lignite. However, the alkali utilization dropped to 38% for the dried HTT Little Tonzona and to 28% for the as-received Little Tonzona fuels. The reason for the lower sulfur retention for these powdered Little Tonzona fuels as compared to the slurry fuel can be partially explained by the differences in the bed temperatures between these tests and partially by slight differences in the alkali-to-sulfur ratios for these fuels; however, these differences do not completely explain the large differences in SO_2 emissions seen in these tests. Preliminary results from computer-controlled scanning electron microscopy (CCSEM) and chemical fractionation (CF) indicate the presence of substantially more calcite ($CaCO_3$) and a gypsum/aluminosilicate in the HTT fuel as compared to the as-received fuel. The presence of these compounds indicates that some of the calcium from the as-received fuel is being converted to calcite or gypsum in the HTT process.

NO_x and N_2O emissions are influenced by reactor temperature, with NO_x emissions increasing and N_2O emissions decreasing with increasing reactor temperatures; thus the relatively high freeboard temperature for the powdered test resulted in higher NO_x and lower N_2O emissions than either slurry test. Hydrocarbon and CO emissions were quite low for all five tests. The low loss on ignition (LOI) numbers shown in Table 3 for the cyclone ashes for these tests indicate that high carbon burnout was achieved in all tests.

TABLE 1

Fuel Analyses

	Knife River (as-received)	Knife River (slurry)	Little Tonzona (slurry)	Little Tonzona (as-received)	Little Tonzona (dried HTT)
Proximate Analysis, moisture-free, wt%					
Volatile Matter	47.35	42.74	49.71	52.34	44.34
Fixed Carbon	41.23	46.99	40.05	37.42	44.43
Ash	11.42	10.27	10.24	10.24	11.23
Ultimate Analysis, moisture-free, wt%					
Carbon	61.1	66.0	63.7	59.7	65.6
Hydrogen	4.4	4.6	4.4	4.8	4.5
Nitrogen	0.9	0.9	0.8	0.8	0.6
Sulfur	1.6	1.5	1.4	1.6	1.5
Oxygen	20.5	16.7	19.5	23.0	16.6
Ash	11.4	10.3	10.2	10.2	11.2
Ash Composition, % as oxides					
Calcium, CaO	22.6	23.5	25.3	26.8	25.3
Magnesium, MgO	9.1	11.2	2.7	6.3	2.7
Sodium, Na_2O	3.2	0.9	0.2	0.2	0.2
Silica, SiO_2	25.1	22.3	27.6	25.5	27.6
Aluminum, Al_2O_3	9.7	10.7	20.5	16.4	20.5
Ferric, Fe_2O_3	3.6	5.3	7.2	5.4	7.2
Titanium, TiO_2	0.5	0.4	0.2	0.6	0.2
Phosphorous, P_2O_5	0.4	0.4	0.5	0.3	0.5
Potassium, K_2O	0.3	0.3	0.2	0.4	0.2
Sulfur, SO_3	25.4	24.9	15.5	18.1	15.5
Heating Value, Btu/lb	10,543	11,691	10,863	10,189	11,286
Solids Content, %	NA[1]	55.5	53.7	NA	NA
Viscosity, cP	NA	500	500	NA	NA
Moisture Content, %	31.7	NA	NA	25.5	12.2

[1] Not applicable.

TABLE 2

Summary of Process Data

	Knife River	Knife River	Little Tonzona	Little Tonzona	Little Tonzona
Fuel Form	As-Rec.	Slurry	Slurry	As-Rec.	Dried HTT
Fuel Feed Rate, lb/hr	4.34	5.88	4.96	4.02	3.45
Fuel Feed Rate, Btu/hr	31,265	38,138	28,629	27,847	33,638
Reactor Pressure, psig	150.4	153.1	151.2	150.4	148.2
Reactor Pressure Drop, in. H_2O	13.9	11.4	11.5	14.1	14.3
Fluidizing Gas, scfm					
Air	11.0	11.3	10.2	10.0	10.0
Nitrogen	11.5	11.0	12.3	12.5	12.0
Total	22.5	22.3	22.5	22.5	22.0
Excess Air, %	25.0	23.3	24.7	24.4	25.7
Sulfur Retention, %	80.0	65.0	60.0	27.7	38.2
FG SGV,[1] ft/sec	2.95	2.94	2.91	3.03	2.97
Reactor Temperatures, °F					
Preheater Exit	662	649	652	797	807
Plenum	927	813	943	1006	1026
0.25"	1394	1345	1396	1493	1511
1.75"	1419	1493	1459	1503	1517
3.5"	1409	1511	1461	1525	1530
5.0"	1415	1522	1474	1532	1534
7.0"	1426	1529	1476	1537	1540
9.0"	1442	1524	1472	1539	1543
11.0"	1462	NA[2]	NA	1550	1557
15.0"	1522	1568	1526	1573	1580
23.0"	1728	1642	1650	1650	1663
31.0"	1733	1616	1634	1657	1681
43.25"	1672	1556	1559	1555	1561
Average	1523	1551	1523	1562	1571
Cyclone Exit Temperature	1428	1432	1392	1386	1399

[1] Flue gas superficial gas velocity.

[2] Not available - slurry feed enters the reactor through this thermocouple port.

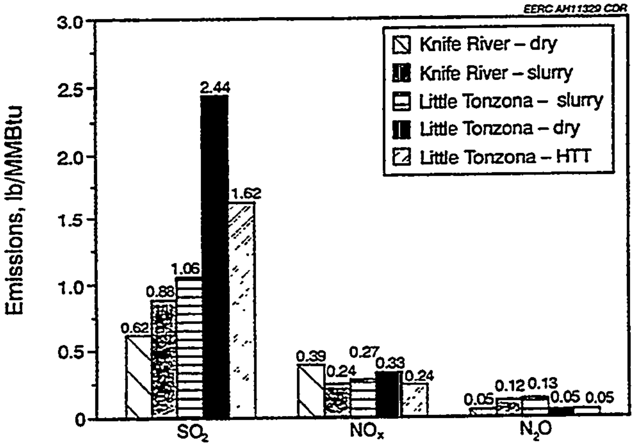

Figure 4. Comparison of flue gas emissions for five combustion tests using Knife River lignite and Little Tonzona subbituminous fuels.

CONCLUSIONS

The 3-in. pressurized fluid-bed reactor was successfully operated using both powdered and slurry forms of the same fuel. Combustion efficiencies of both fuel forms were very high. In general, slurry fuels had more even temperature distributions than the same powdered fuels. It appears that hydrothermally treating the lignite fuel slightly decreased the sulfur retention of the coal ash because of the reduction of the sodium in the coal ash; however, hydrothermally treating the subbituminous fuel increased the sulfur retention of the coal ash because of the presence of increased amounts of calcium-based compounds such as calcite and gypsum. As compared to a combustion test using the same fuel under pulverized coal combustion tests (2), the NO_x emissions from the PFBR combustion test were 1/3 to ½ of the emissions from the PC-fired unit. This is the result of the lower combustion temperatures achieved in a fluid-bed combustor as compared to a PC-fired combustor. The SO_2 emissions were approximately ½ of the emissions from the PC-fired unit, again indicative that the lower combustion temperature from a fluid-bed combustor is more conducive to sulfur capture.

TABLE 3
Emissions Data

	Knife River As-Received	Knife River HTT slurry	Little Tonzona HTT slurry	Little Tonzona As-Received	Little Tonzona Dried HTT
O_2, %	4.80	4.52	4.79	4.76	4.95
Excess Air, %	24.96	23.26	24.71	24.37	25.66
CO Content, actual ppm	2	1	3	21	22
CO Content, undiluted[1] ppm	5	1	6	47	48
CO Content, corrected[2] ppm	7	2	10	83	86
CO Emission, lb/MMBtu	0.007	0.001	0.010	0.097	0.093
CO_2 Content, %	4.2	4.7	3.7	3.2	3.2
CO_2 Content, undiluted[1] %	8.5	9.4	8.0	7.3	7.1
CO_2 Content, corrected[2] ppm	13.7	14.0	13.8	12.7	12.7
NO_x Content, ppm	73	53	44	43	34
NO_x Content, undiluted[1] ppm	149	105	97	97	75
NO_x content, corrected[2] ppm	240	156	166	169	133
NO_x Emission, lb/MMBtu	0.387	0.242	0.273	0.326	0.238
N_2O Content, ppm	10	27	22	7	8
N_2O Content, undiluted[1] ppm	21	53	48	16	18
N_2O content, corrected[2] ppm	34	80	83	28	31
N_2O Emission, lb/MMBtu	0.053	0.118	0.131	0.051	0.053
HC Content, ppm	1	1	0.3	1.3	0.8
HC Content, undiluted[1] ppm	1	2	1	3	2
HC Content, corrected[2] ppm	2	3	1	5	3
HC Emission, lb/MMBtu	0.0010	0.0013	0.0005	0.0028	0.0016
SO_2 Content, ppm	83	139	122	231	167
SO_2 Content, undiluted[1] ppm	170	275	268	520	367
SO_2 Content, corrected[2] ppm	274	410	462	909	653
SO_2 Emission, lb/MMBtu	0.617	0.883	1.055	2.437	1.623
Sulfur Retention, %	80.0	65.0	60.0	27.7	38.2
Alkali-to-Sulfur	1.02	0.97	1.05	0.95	1.12
Alkali Utilization	78.5	67.3	57.1	29.1	34.1
Avg. Reactor Temperature, °F	1523	1551	1523	1562	1571
Loss on Ignition, %	6.5	NA[3]	2.5	7.7	2.4

[1] Emissions assuming no nitrogen dilution:

$$\text{Undiluted Emission} = \frac{\text{Actual Emission}}{1 - \left(\dfrac{\text{Total Flow} - \text{Air Flow}}{\text{Total Flow}}\right)}$$

[2] Undiluted emissions corrected to 3% 0_2

$$\text{Corrected Emission} = \text{Undiluted Emissions} \times \frac{(3 - 21)}{(\text{Undiluted } O_2 - 21)}$$

[3] Not available

FUTURE WORK

Future testing with the PFBR will include sorbent characterization, evaluation of gaseous emissions including trace elements, bed agglomeration, and hot-gas cleanup testing. Sorbents to be tested include sulfur sorbents and in-bed sorbents for controlling the formation of vapor-phase alkali species.

DISCLAIMER

ACKNOWLEDGMENT

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