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**DEVELOPMENT AND TESTING OF A COMMERCIAL SCALE
COAL-FIRED COMBUSTION SYSTEM - PHASE III**

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1. INTRODUCTION AND SUMMARY

This report summarizes the results of work performed in the development and proof-of-concept (POC) testing of a coal-fired space heating system for the commercial market sector. Although coal is the most plentiful energy resource in the United States, its use has been largely restricted to utility power generation since World War II for environmental and economic reasons. Within the commercial sector, oil and natural gas are the predominant fuels for office buildings, apartment complexes, and other similar structures. Generally, these buildings require firing rates of 1 to 10 million Btu/hr. The objective of this program is to design, build and test a coal based heating system for this sector and determine the economic viability and market potential for the system.

An important consideration in meeting this objective is the fuel form to be utilized. In attempting to restore coal to the relatively small markets, it is important to recognize ease of handling and storage as important criteria. For this reason, coal water slurry (CWS) fuel has been chosen as the fuel form for this development effort. CWS eliminates the need to use dry pulverized coal with its attendant handling, metering and dusting problems as well as its explosive potential. Equally important in selecting a fuel form is the impact on emission levels and pollution control equipment requirements. CWS is amenable to coal washing since coal cleaning technologies are generally water-based processes requiring the fine grinding of the coal.

Development and demonstration of the CWS-fired space heating system is being carried out over a 39 month period. During the first stage, which covered the first 14 months, the program activities focused on component development and system integration. In this stage, an overall system heat balance was prepared, system components were designed and manufactured or purchased, the system was fully assembled and preliminary testing performed to validate component performance and identify key operating variables.

The second stage covered 10 months and involved POC testing. This testing determined the overall performance of system. The system was operated for prolonged periods to simulate a commercial application, and combustion and thermal efficiencies; tendencies to slag, foul, erode and corrode; and gaseous and particulate emissions were evaluated. Performance evaluation of the system was made using three coals: a low ash, low sulfur eastern Kentucky coal, a moderate ash and sulfur Illinois coal (Illinois No. 5) and a high ash, high sulfur Illinois coal (Illinois No. 6). Also during the second stage, an assessment of the commercial viability of the system was made. This assessment included an evaluation of the economics and market potential, including the sensitivity to fluctuations in fuel prices.

The final stage of the program, which will cover a 15 month period, will focus on testing and demonstrating the integrated system in an actual installation. Figure 1.1 gives the work breakdown structure for the overall program.

In addition to the subsystems and equipment making up the integrated space heating system, a fuel preparation system has also been included as part of the demonstration effort. It is recognized that CWS fuel is not easily obtained or widely produced at this time. To ensure a supply of CWS for the program and also to demonstrate that CWS can be economically produced, a slurry preparation facility was set up and used to supply CWS fuel for the program. It is recognized that to get CWS fuel into the commercial scale marketplace, it will take a combined effort to develop both the combustion equipment and fuel supply simultaneously.

This quarterly report describes the work carried out in the eighth quarter of the program as well as provides a complete summary of the first two stages of the development program. A brief description of the overall system design is given as well as a discussion of the unique features of the system configuration and key components. This is followed by a summary of the testing performed including a direct comparison between system performance and program goals. Finally, the results of the economic evaluation are presented along with a commercialization plan for the technology. As part of the commercialization plan, a detailed schedule of the demonstration stage is given as well as details of the demonstration facility configuration.

In summary, a fully operational prototype system has been designed, built and successfully tested. As part of the system development, the CWS combustor technology has been scaled to the commercial market size, integration of the combustor technology with a conventional firetube boiler has been demonstrated and a highly efficient, low wear slurry atomizer has been developed. Laboratory testing has demonstrated the ability to meet system performance goals utilizing three coals of varying quality, including high sulfur, high ash, Illinois No. 6 coal. Over the course of the test campaign, the system was operated for over 500 hours consuming over 18,000 gallons of slurry demonstrating both its reliability and flexibility of operation. With all three coals, emission levels were below program goals and anticipated Clean Air Act levels. Operation requirements of system turndown, automatic startup and trouble-free operation were also demonstrated.

The development of the system has progressed to the point that a commercial demonstration of the technology is justified. The laboratory testing and the associated equipment development has also demonstrated the technical competence of the program team giving confidence that a successful commercial demonstration can be conducted.

Figure 1.1 Work Breakdown Structure for Entire Project

In addition, the preliminary economic and market evaluation has revealed that at moderate differentials between premium fuel and coal water slurry fuel prices, such a system can be economically attractive with short payback periods and substantial life cycle savings. With predicted escalation in premium fuel prices and readily available CWS, the system has the potential of competing with premium fuel systems, and until that time will be available to satisfy niche markets where fuel is readily available and inexpensive such as locations near coal mines where coal fines in the form of slurry is now considered a waste product.

2. SYSTEM DESIGN

2.1 SYSTEM CONFIGURATION

A process schematic for the CWS-fired space heating system is shown in Figure 2.1. The system has been designed for a nominal firing rate of 4 million Btu/hr which is at approximately the mid-range of the commercial scale market sector. The system has been configured so that commercially available equipment and technologies are utilized wherever practicable. In particular, a fire-tube boiler typically found in installations of the commercial sector size range is used for primary heat extraction. Since only moderate changes are required to the boiler itself, the technology can be utilized to convert existing oil and natural systems to coal firing.

Figure 2.2 shows plan and elevation views of the major system components as configured for the POC testing at Tecogen's Waltham, Massachusetts facilities. Figure 2.3 is a photograph of the installation.

In the following sections, a description of the design and unique features of the major system components is given. Particular emphasis is placed on those components and subsystems specifically developed for a coal or CWS fired system.

2.2 COMPONENT DESIGN

2.2.1 Combustor

One piece of equipment that is obviously not commercially available is the combustor itself. The commercial-scale space heating system combustor is a scale-up of a combustor technology developed by Tecogen Inc. under contract to the Department of Energy (DOE), Pittsburgh Energy Technology Center for the residential scale market sector.

The combustor concept (see Figure 2.4) employs centrifugal forces combined with a staged combustion process to achieve high carbon conversion efficiencies and low nitrogen oxides (NO_x) emissions. The combustion chamber is divided into multiple zones by partitions to retard the axial flow of unburned coal particles over a given size. In this fashion, the residence time for combustion of the CWS fuel is significantly increased to enable complete carbon conversion for a wide range of particle droplet sizes. Once the particles are small enough to pass through all the partitions, they enter a secondary combustion chamber where burnout of any remaining char is completed.

Figure 2.1 Process Flow Diagram

Scale - one inch equals one foot

Figure 2.2 Plan and Elevation Views of Major System Components

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Figure 2.3 Integrated Coal-Water Slurry Fired
Space Heating System

Figure 2.4 Combustor Principle of Operation

The residential combustor developed previously had a nominal firing rate of 150,000 Btu/hr, therefore a scale-up of approximately 25 was required to meet the design firing rate of 4 million Btu/hr for the commercial scale system. Scaling laws which take into account the fluid dynamics, and chemical kinetics in the combustor were developed to extend the knowledge base that had been established on the residential unit. Of particular importance is the ability of a larger unit to separate and confine large unburned coal particles in the upper section of the combustor. Since for larger diameter combustors, higher inlet velocities are required to achieve the same particle separation a trade-off is required between inlet velocity and the associated pressure drop, particle size, and combustor temperature.

Figure 2.5 gives the results of the scale-up analysis. The commercial scale unit has an internal diameter of approximately 24 inches and an overall length of 60 inches. Inlet areas are sized for an inlet velocity of 150 ft/sec. Figure 2.6 shows a photograph of the combustor assembly. The combustor is made up of three sections: a roof, an upper section, and a lower section. Each section is a double jacketed water-cooled unit. In this photograph, the combustor is connected to an exhaust quench system which is a configuration used for initial combustor shakedown and characterization. During the course of the test program, several modifications to the combustor internal configuration were made to improve operating performance. These changes involved replacing refractory surfaces with metal liners to reduce material accumulation in the combustor, changing the size and location of partitions and varying the air inlet geometries. These changes are discussed in detail in Section 4 as part of a discussion of the test results.

The combustor is connected to the fire-tube heat recovery boiler through a transition chamber. The transition chamber turns the vertical downward flowing combustion gases and directs them to the horizontal fire tube of the boiler. In addition, the transition serves as a collection vessel for large ash agglomerates which may form in the combustor. The transition chamber is also a double jacketed water cooled unit and has 3 inches of refractory to control the heat extraction from the unit. Figure 2.7 shows the combustor/transition chamber assembly and Figure 2.8 shows the connection to the fire-tube interface. A high temperature expansion joint is used to connect the transition chamber outlet with the boiler inlet to allow for alignment flexibility and differential thermal growth of the two assemblies. This arrangement does not require any modification to the inlet of the conventional fire-tube boiler and therefore the combustor can be easily retrofitted into existing oil and gas fired installations.

Figure 2.5 Combustor Scaled From Residential Size

Figure 2.6 Photograph of the Test Setup

Figure 2.7 Combustor/Transition Chamber Assembly

Figure 2.8 Combustor/Transition Chamber Interface

2.2.2 Boiler

A conventional fire-tube boiler is used to recover the heat from the combustion gases leaving the transition chamber. To achieve the system performance goal of greater than 80% thermal efficiency, a three-pass configuration was selected. A schematic representation of the boiler configuration is shown in Figure 2.9. A 400-ft² boiler having a drum diameter of 4.5 ft and an overall length of 11 ft was chosen. Table 2.1 gives the predicted operating conditions for the boiler at various gas inlet temperatures and flowrates.

The only changes made to the manufacturer's standard hot water oil and natural gas fired configuration was the addition of particulate drop-out hoppers at each end of the boiler, additional connections for combustor cooling water supply and return, and a compressed air soot blowing system. The boiler was initially operated without the soot blowing system but preliminary testing revealed an increase in boiler exhaust temperature with time due to ash deposition on the boiler heat transfer surfaces. The soot blower system, as shown in Figure 2.10, consists of a nozzle in front of each boiler tube. The nozzles are connected to one of four compressed air manifolds each controlled by a solenoid valve. Figure 2.11 is a photograph of the soot blowing system external piping and control cabinet. The system is energized whenever CWS is being fired and operates with sequential pulsing of the four air manifolds every 15 minutes for a one hour cycle time. Discussion of the soot blowing system performance as related to overall system thermal efficiency can be found in Section 4.

2.2.3 Fuel Delivery System

Although the use of CWS for the commercial market sector greatly simplifies the fuel delivery system as compared to a dry, pulverized coal system, special attention must be placed on the proper design of the system to ensure proper operation of the combustor. Slurry velocities must be sufficiently high to avoid settling, piping dead-ends must be avoided, and proper flushing must be provided to clear the system during prolonged inactivity.

Figure 2.12 is a flow schematic of the fuel delivery system. A key component of the system is the atomizer. The atomizer not only defines the requirements for the handling system, i.e. required slurry pressure and filtration, but also plays a key role in the efficiency and stability of the combustion process. A variable spray angle, externally mixed twin fluid atomizer was developed to meet the needs of the system. The atomizer design is an extension of the twin fluid CWS atomizer technology developed by Tecogen Inc. under the previously funded CWS-Fired Residential Warm Air Heating System Program. The atomizer operating conditions

REAR ACCESS DOORS

TUBE BUNDLE ARRANGEMENT

FRONT ACCESS DOORS

Figure 2.9 York-Shipleley Fire-Tube Heat-Recovery Boiler Configuration

TABLE 2.1
PERFORMANCE DATA FOR 400-FT² HOT WATER BOILER

Description	Case I			Case II			Case III		
	4225	2817	1408	4225	2817	1408	4225	2817	1408
Flue Gas Flow (lb/hr)	2000	2000	2000	2300	2300	2300	2600	2600	2600
Flue Gas Inlet Temp. (°F)	1754	1704	1582	1977	1903	1728	2187	2087	1848
I Pass Outlet Temp. (°F)	608	554	458	655	587	479	699	619	496
II Pass Outlet Temp. (°F)	321.5	294	252	336	303	257	349.6	312	261
III Pass Outlet Temp. (°F)	32.8	21.8	10.94	36.81	24.5	12.27	40.81	27.2	13.6
1 Pass Inlet Velocity (ft/s)	78.4	51.1	24.1	86.2	55.8	25.82	93.69	60.1	27.23
2 Pass Inlet Velocity (ft/s)	51.2	32.37	14.65	53.4	33.43	14.99	55.5	34.45	15.25
3 Pass Inlet Velocity (ft/s)	3.33	1.47	0.36	3.38	1.49	0.36	3.43	1.5	0.37
Pressure Drop (in. w.c.)

Figure 2.10 Compressed Air Soot Blower System Configuration

Figure 2.11 Soot Blowing System External Piping and Control Cabinet

Figure 2.12 Flow Schematic of the Fuel Delivery System

can be set to provide the wide cone angle required of the radial, top center firing configuration of the commercial scale system. This atomizer uses two perpendicular atomizing streams to shear the CWS into a thin, unstable ligament sheet that breaks up into small droplets external to the atomizer. Figure 2.13 is a schematic depicting the atomizer arrangement.

The external atomization feature of this nozzle prevents erosion and allows for a large CWS passageway which minimizes the head that the CWS pump must produce. In addition to providing fine atomization due to the high shear that is imparted by the two perpendicular atomizing streams, by varying the flow rate of each of these streams, the spray angle can be changed on-line without any mechanical modifications to the atomizer. Table 2.2 lists the features of the atomizer.

Figures 2.14 through 2.16 show the variation in spray angle which can be achieved by varying the atomizing air flows. These photographs were taken with the atomizer operating with water at a flow rate equivalent to 5 MMBtu/hr. Characterization of the atomizer performance with both water and coal slurry was conducted by the University of Alabama using a Malvern Instruments particle sizer. The slurry used was produced by Jim Walter Resources, Inc. and had an apparent viscosity of 300 cp at 600 reciprocal seconds. Figure 2.17 gives the Sauter Mean Diameter (SMD) versus air liquid ratio for the two fluids. SMD is defined as the diameter of droplet whose ratio of volume to surface area is equal to that of the entire spray sample. Figure 2.18 gives the particle size distribution for two of the cases. This data are uncorrected for instrument obscuration.

The fuel system has also been simplified by the development of this atomizer because the atomizer is capable of operating on fuel oil, slurry, and fuel oil and slurry simultaneously. This eliminates the need for a separate warm-up burner and simplifies changing over from oil to slurry and back since air and/or water purging of the inactive nozzle is not required.

Also, developed specifically for the fuel delivery system was a slurry strainer. The strainer design (see Figure 2.19) eliminates the dead spots found in a conventional basket strainer. This strainer working in conjunction with the large slurry passages of the VSA has eliminated plugging difficulties commonly encountered in slurry systems due to oversized coal particles or foreign matter.

Figure 2.13 Tecogen Variable Spray Angle Atomizer

TABLE 2.2
TECOGEN VSA ATOMIZER FEATURES

- **Spray Angle Adjustable On-Line by Controlling Atomizing Air Flow – Allows Compensation for Slurry Properties**
- **Low Slurry Pressure**
- **External Mix/Low Wear**
- **Low Atomizing Air Flow**
- **Water or Air Cooled**
- **Operates on Both Slurry and Heating Oil**
- **Simple Construction/Low Cost**

TF35-292N

Figure 2.14 VSA Atomizer with Narrow Spray Angle

Figure 2.15 VSA Atomizer with Intermediate Spray Angle

TF37-292N

Figure 2.16 VSA Atomizer with Wide Spray Angle

Figure 2.17 Data Reduction for Tecogen VSA Atomizer

Figure 2.18 Droplet Size Distribution, Tecogen VSA Atomizer
Fluids: JWRI Coal Water Slurry (63.86% Solids)
and Water

Figure 2.19 Sorbent Storage, Feed, and Conveying Configuration

2.2.4 Emissions Control

To meet the targeted emission goals of no more than 1.2 lbs of SO₂ and 0.03 lbs of particulates per million Btu, the CWS fired commercial-scale space heating system must include flue gas pollution control equipment. Uncontrolled, the system will generate emissions of approximately 4 lbs of SO₂ per million Btu and 6.25 lbs of particulates per million Btu, depending on the exact coal composition. As discussed in Section 2.2, the control of NO_x to targeted levels is achieved through control of the combustion process and therefore the pollution control equipment does not include NO_x reduction capabilities.

To achieve the required goals of 70% reduction of SO₂ and 99.5% particulates capture, dry duct injection of sorbent in conjunction with a fabric filter is utilized. In the duct injection process, a dry, powdered sorbent; namely sodium bicarbonate or trona, is injected directly into the flue gas duct upstream of the particulate-control device. The sorbent undergoes rapid decomposition in the hot flue gas creating a highly porous, reactive particle. SO₂ is absorbed onto the particle initially at the point of injection and further absorption of SO₂ occurs in a baghouse as the sulfur laden gases pass through the filter cake. The baghouse is considered an integral part of the SO₂ removal equipment. Figure 2.20 illustrates the sorbent storage and injection equipment configuration.

The baghouse is a conventional pulse jet fabric filter design with a cloth surface area of 457 square ft. The unit is 4 feet by 4 feet with a height of approximately 13 feet and consists of thirty six 100-inch long bags. The bag material is P84, a nonflammable and thermostable organic fiber with a maximum use temperature of 500°F. Figure 2.21 gives a photograph of the unit. The tall, upright configuration was chosen to minimize floor area requirements since there were no overhead restrictions at either Tecogen's laboratory facility or the demonstration site.

2.2.5 Controls

The space heating system has been outfitted with a control system capable of ensuring safe, reliable and fully automatic system operation. A process and instrumentation diagram for the process is shown in Figure 2.22. The control system consists of a General Electric Fanuc Series 90-30 Programmable Logic Controller. The controller provides for complete automatic or manual control of the system including pushbutton start and stop, load following, safety interlocks, automatic fuel changeover and alarm messages. The system has six analog output channels, eight analog input channels, four thermocouple channels, 28 discrete output channels and 16 discrete input channels. Operator interface is through a

Figure 2.20 Tecogen Slurry Strainer

Figure 2.21 Baghouse Installation

Figure 2.22 Process Control and Instrumentation Diagram

CRT based operator interface terminal. This terminal has flow schematics which display key process variables and setpoints, and programmed function keys to allow complete control of the system including selection and manipulation of all proportional control loops in manual mode.

Along with termination point junction boxes for sensors and controllers, the system has two main electrical enclosures; a main control panel and an instrument panel. The main control panel is shown in Figures 2.23 and 2.24. The main control panel houses the Operator Interface Terminal, Programmable Logic Controller, relays and data acquisition boards. Figure 2.25 shows the internals of the instrument enclosure. This enclosure houses the atomizing air controllers and flowmeters, the fuel oil flowmeter and control valve and miscellaneous pressure switches, transducers and gages.

The system has also been equipped with a personal computer based data logging system to permit monitoring and data reduction of key system variables needed for the development effort.

Figure 2.23 External View of the Main Control Panel

Figure 2.24 Internals of the Instrument Enclosure

Figure 2.25 Internal Configuration of the Control Enclosure

3. SLURRY PREPARATION

3.1 SLURRY PREPARATION FACILITY

At the start of this development program, it was recognized that although CWS has great potential as an alternative fuel form for smaller scale applications, CWS fuel is not easily obtained or widely produced. Most suppliers and investigators are limited in their production capability and would be hard pressed to meet the demands of a commercial scale system with slurry firing rates of approximately 60 gph. To ensure a supply of CWS for the program and also to provide both an engineering and economic data base for slurry production at larger scales, a slurry preparation facility was set up to produce CWS for the program.

A process flow diagram for the system is given in Figure 3.1. Crushed coal (3" x 0") is received in 1-ton supersacks and fed to a hammermill via a variable speed screw feeder. The grinder has an integral aerodynamic classifier which limits the ground coal top size to under approximately 175 microns. From the classifier, the coal is conveyed to a series arrangement of primary and secondary cyclones and discharged into a mixing tank via rotary valves. The conveying air can either be operated in a closed loop configuration or in a once through, open loop configuration. It has been found that with coal moisture content of approximately 10% or greater, the system must be operated in the open loop configuration to prevent moisture build-up in the conveying lines and resulting coal deposition. A pulse jet baghouse is used to collect fines passing the cyclones, approximately 1% of the coal flow.

In the mixing tank, the pulverized coal is fully wetted with the help of tank mixers and a fluid circulation loop which takes suction from the bottom of the mixing tank and discharges the coal/water mixture (CWM) onto the surface. An air operated diaphragm pump is used to circulate the slurry and is also used as a transfer pump.

The system is operated in a batch mode by pre-filling the mixing tank with the necessary water and additives, and running the pulverizer until the CWM reaches a pre-determined starting point. The density of the slurry has proven to be a key process control variable in that it is an indirect measurement of slurry loading. Coalmaster A23, manufactured by Henkel Corporation, is used as a dispersant, and FloconC, manufactured by Pfizer Chemical, is used as a stabilizer. On a coal weight basis, their concentrations are on average 10,000 and 700 ppm, respectively.

Figure 3.1 Slurry Production Facility Flow Schematic

Figures 3.2 and 3.3 show the equipment configuration. The equipment is arranged on two independent structures: the grinding stand and mixing stand. System operation is from an operator station mounted on the mixing stand. System start and stop is via a single pushbutton and the control system ensures proper sequencing and safety interlocks.

3.2 SLURRY PRODUCTION

During the course of the laboratory test program, upwards of 50 tons of coal have been processed into approximately 18,000 gallons of slurry. Three coals have been processed: Eastern Kentucky Hazard Prince Mine, Illinois No. 5 Wabash Mine and Illinois No. 6 Delta Mine. Table 3.1 gives the proximate and ultimate analysis for the three coals. These are run of mine coals without any additional washing or beneficiation other than that performed at the mine to ensure consistent quality.

Figure 3.4 gives typical coal particle size distributions for the coals after grinding. During testing with the Illinois No. 5 coal, the pulverizer was reconditioned and an additional beater plate was added along with a larger motor. This was done mainly to increase the throughput of the unit without sacrificing the grind size. With these changes, the system throughput was increased from 300 lbs/hr to 450 lbs/hr.

Table 3.2 gives the typical slurry properties for the three coals. As can be seen in the table, coal loadings were between 55% and 60%. For each of the coals, the maximum coal loading while maintaining a viscosity of 200 cp at 60 reciprocal seconds was utilized. Figure 3.5 shows typical viscosities for the three CWS fuels.

Figure 3.2 Slurry Production Facility
Coal Grinding Stand

Figure 3.3 Slurry Production Facility
Mixing Stand

TABLE 3.1
COAL PROXIMATE AND ULTIMATE ANALYSIS

KENTUCKY HAZARD PRINCE MINE					
Proximate Analysis			Ultimate Analysis		
	As Received	Dry Basis		As Received	Dry Basis
% Moisture	2.69	xxxxx	% Moisture	2.69	xxxxx
% Ash	3.62	3.72	% Carbon	78.91	81.09
% Volatile	35.93	36.92	% Hydrogen	5.25	5.39
% Fixed Carbon	57.76	59.36	% Nitrogen	1.63	1.67
	100.00	100.00	% Sulfur	0.74	0.76
			% Ash	3.62	3.72
Btu/lb (HHV)	14144	14535	% Oxygen (diff.)	7.16	7.37
% Sulfur	0.74	0.76		100.00	100.00
MAF Btu		15097			

ILLINOIS NO. 5 WABASH MINE					
Proximate Analysis			Ultimate Analysis		
	As Received	Dry Basis		As Received	Dry Basis
% Moisture	14.94	xxxxx	% Moisture	14.94	xxxxx
% Ash	6.17	7.25	% Carbon	64.30	75.60
% Volatile	33.25	39.09	% Hydrogen	4.24	4.98
% Fixed Carbon	45.64	53.66	% Nitrogen	1.43	1.68
	100.00	100.00	% Chlorine	0.15	0.18
			% Sulfur	1.36	1.60
Btu/lb (HHV)	11439	13450	% Ash	6.17	7.25
% Sulfur	1.36	1.60	% Oxygen (diff.)	7.41	8.71
MAF Btu		14501		100.00	100.00

ILLINOIS NO. 6 DELTA MINE					
Proximate Analysis			Ultimate Analysis		
	As Received	Dry Basis		As Received	Dry Basis
% Moisture	9.44	xxxxx	% Moisture	9.44	xxxxx
% Ash	10.65	11.76	% Carbon	64.42	71.13
% Volatile	33.14	36.60	% Hydrogen	4.31	4.76
% Fixed Carbon	46.77	51.64	% Nitrogen	1.34	1.48
	100.00	100.00	% Chlorine	0.09	0.10
			% Sulfur	2.84	3.14
Btu/lb (HHV)	11592	12800	% Ash	10.65	11.76
% Sulfur	2.84	3.14	% Oxygen (diff.)	6.91	7.63
MAF Btu		14506		100.00	100.00

Figure 3.4 Typical Coal Particle Size Distributions for the Coals After Grinding

TABLE 3.2
TYPICAL SLURRY PROPERTIES

Coal	Kentucky	Illinois No. 5	Illinois No. 6
Coal Loading	59%	55%	57%
Particle Size (mmd)	30 μm	20 μm	18 μm
Specific Gravity	1.15	1.17	1.20
A23 (dry mass coal)	10,000 ppm	15,000 ppm	15,000 ppm
Flocon	700 ppm	700 ppm	700 ppm
Viscosity at 80 1/sec	200 cP	200 cP	200 cP
Heating Value	8,500 Btu/lb	7,400 Btu/lb	7,300 Btu/lb

Figure 3.5 Typical Viscosities for the Three CWS Fuels

4. TEST RESULTS

Two series of tests were completed as part of the development program. The first series of tests, component and system tests, was performed to provide preliminary evaluation of the component and system performance, identify key operating variables and their ranges, and establish appropriate operating conditions for subsequent POC testing. These tests verified that the combustor technology had been successfully scaled to the commercial market size, integration of the major system components, especially integration of the combustor with a fire-tube boiler was feasible, and the system had the potential to meet the performance goals. This testing included over 100 hours of system operation.

The second series of tests, POC tests, were performed to evaluate overall performance of the space heating system and to demonstrate that the concept is technically feasible, both from a performance standpoint and from a maintenance and reliability standpoint. Combustion and thermal efficiencies, tendencies to slag, foul, erode and corrode, and gaseous and particulate emissions were evaluated. This section of the report discusses the results of the POC testing along with anticipated system modifications and/or component upgrades needed to perform the commercial demonstration.

4.1 TEST OPERATION

During the POC test period, the integrated system was operated for over 500 hours with slurry firing making up close to 70% of these operating hours. Table 4.1 gives a summary of the test operations. During the course of the testing, approximately 7,000 gallons of Kentucky slurry, 6,500 gallons of Illinois No. 5 slurry and 3,500 gallons of Illinois No. 6 slurry were burned.

For most of this testing, the system was operated in the configuration shown in Figure 4.1. In this configuration, the heat recovery boiler was operated as a steam boiler with the steam vented to atmosphere and the combustor and transition chamber operating on a separate circulating system discharging the extracted heat to a roof mounted radiator. For the final tests, the boiler was operated as a hot water unit in the configuration shown in Figure 4.2 with the generated heat dissipated through a load compensating radiator. This configuration is identical to that to be utilized during the commercial demonstration with the exception that facility unit heaters will be utilized as the primary heat load.

TABLE 4.1
TEST SUMMARY

Date	Length of Test (Hours)	Length of Slurry Firing (%)	Coal
<u>January</u>			
15	8	62	Kentucky
<u>February</u>			
4	8	62	Kentucky
9	7	71	Kentucky
14	4	50	Kentucky
20	7	57	Kentucky
<u>March</u>			
6	6	67	Kentucky
11	4	50	Kentucky
17	8	75	Kentucky
25	4	50	Kentucky
30	6	66	Kentucky
<u>April</u>			
9	6	66	Kentucky
16	7	71	Kentucky
23	8	75	Kentucky
<u>May</u>			
14	3	0	Kentucky
15	4	75	Kentucky
22	7	57	Kentucky
<u>June</u>			
25	14	86	Kentucky
26	8	87	Kentucky
<u>July</u>			
1	16	87	Kentucky
7	6	66	Illinois No. 5
10	7	71	Illinois No. 5
15	7	71	Illinois No. 5
16	8	75	Illinois No. 5
21	7	71	Illinois No. 5
22	10	90	Illinois No. 5
<u>August</u>			
3	5	60	Illinois No. 5
5/6	26	92	Illinois No. 5
24	11	73	Illinois No. 5
25	10	90	Illinois No. 5
<u>September</u>			
2/3	34	94	Illinois No. 5
9	12	83	Illinois No. 5
10	6	83	Illinois No. 5
11	9	89	Illinois No. 5
15	7	71	Illinois No. 6
16/17/18	44	73	Illinois No. 5 & 6
29	7	57	Illinois No. 6
<u>October</u>			
30/1/2	60	50	Illinois No. 6
5-8	100	40	Illinois No. 6
TOTAL	511	66	94 Hours Kentucky 145 Hours Illinois No. 5 99 Hours Illinois No. 6

Figure 4.1 Schematic of System Test Configuration

Figure 4.2 System Tests Configuration
Integrated System Test Series - 10/7/92

4.2 SYSTEM PERFORMANCE

The system performance goals for space and water heating requirements of commercial buildings are listed below:

Ignition:	Fully automatic startup with system purge and ignition verification
Turndown Ratio:	3:1
Reliability/Safety: Thermal Efficiency:	Comparable to oil-fired commercial boilers >80%
Combustion Efficiency:	>99%
Routine Operating/ Maintenance Labor:	Less than one dedicated man-hour per day and an additional two man-hours per week
Ash Removal:	Dust-free and automatic or semiautomatic
Scheduled Maintenance:	≤ twice a year
Service Life:	Overall system ≥ 20 years
Emissions:	1.2 lb SO ₂ /10 ⁶ Btu 0.3 lb NO _x /10 ⁶ Btu 0.03 lb particulates/10 ⁶ Btu

There are wide variations in state and local air pollution control regulations for commercial-scale space heating systems. In addition, these regulations are all subject to change. Therefore, the aforementioned emissions specifications chosen as the program goals by the DOE are those that are expected to be achieved based on the present state of development of coal cleaning, combustion, and flue gas cleanup technologies. These goals are consistent with Title IV of the Clean Air Act Amendments of 1990 which will limit SO₂ emissions to 1.2 lbs/MMBtu and NO_x emissions to between 0.45 and 0.5 lbs/MMBtu from coal-fired utility boilers. For coal-fired systems to become environmentally, and hence commercially acceptable, for this market sector, however, emissions levels will ultimately need to be comparable to those produced by fuel oil-fired commercial-scale units, namely:

0.4 lb SO₂/10⁶ Btu
0.2 lb NO_x/10⁶ Btu
0.02 lb particulates/10⁶ Btu

In designing the emissions control strategy for the system and evaluating system performance, close attention was paid to the likelihood that the emission levels from the system may need to be lower than those of the program goals.

Following is a discussion of the system performance as related to the system performance goals. Since system performance in general and emissions in particular are both dependent on coal properties, variations in system performance encountered with each of the three coals utilized are addressed.

4.2.1 Ignition

The combustion system has been successfully ignited over 100 times without incident. For laboratory testing, the system was ignited with a natural gas pilot. This pilot consists of a Honeywell Flame Safeguard System with an ultraviolet flame sensor. The pilot is interlocked with the fuel to ensure safe operation. A second safety interlock is triggered by combustion chamber temperature. Once fuel is introduced to the combustor, if the combustion chamber temperature does not reach a pre-set temperature in the prescribed time period, the fuel flow will automatically be stopped. In addition, fuel flow will be interrupted whenever the combustor temperature drops below this value. Before re-starting the system, a purge sequence is automatically initiated. The pilot can be operated on either a continuous or intermittent basis.

From a cold start, the system is operated on fuel oil for approximately 2 hours at a firing rate of 1.5 MMBtu/hr to bring the boiler water up to temperature and the baghouse temperature above the dew point before switching to slurry. With the boiler water at temperature, fuel switch over can occur in approximately 15 minutes.

For the commercial demonstration, propane will be utilized as the pilot fuel and the pilot will be operated on an intermittent basis.

4.2.2 Combustor

System tests performed during the component development stage of the program revealed that material accumulation in the combustor occurred during prolonged combustor operation at high loads. During the POC tests, several design modifications were implemented to eliminate this material accumulation. The final combustor configuration results from a thorough investigation of design and operating parameters including: combustor wall material, partition location and size, atomizer spray angle and combustion air staging. The combustor design evolution was influenced strongly by the need to burn progressively higher ash coals with changing ash properties. Table 4.2 gives the ash fusion temperatures for the three coals.

TABLE 4.2
ASH FUSION TEMPERATURE

Fusion Temperature	Kentucky		Illinois No. 5		Illinois No. 6	
	Red.	Oxid.	Red.	Oxid.	Red.	Oxid.
Initial Deformation	2700+	2700+	2053	2475	2052	2468
Softening	2700+	2700+	2163	2528	2152	2508
Hemispherical	2700+	2700+	2258	2570	2283	2549
Fluid	2700+	2700+	2360	2613	2389	2595
Ash (% Dry)	3.7		7.2		11.7	

Figures 4.3 through 4.6 illustrate the progression of changes made to the internal combustor geometry. Although refractory surfaces could be used in the lower regions of the combustor when burning the high fusion temperature Kentucky coal, ash attachment to the refractory surfaces was problematic for the lower fusion temperature Illinois coals. Best results were obtained with all three coals, with metal liners and water cooled partitions making up the combustor internal surfaces. Various arrangements were investigated to control metal liner temperatures while at the same time controlling heat extraction from the combustor and allow for liner growth. The final arrangement as shown in the combustor sketches is to allow the liners to operate as floating shields. In this configuration, rather than having a refractory material between the liner and water cooled shell, and controlling liner temperature through conduction, the liner is offset from the water-cooled shell by a quarter inch air gap and is allowed to radiate back to the shell. This configuration allows for unrestrained circumferential expansion of the liner and eliminates the possibility of hot spots which can develop if the liner separates from the refractory in the contact arrangement.

In addition to eliminating material accumulation in the combustor, the combustor modifications also resulted in a reduction in the NO_x produced allowing performance goals to be met. Figure 4.7 shows the reduction in NO_x achieved in going from the baseline refractory lined combustion chamber (Figure 4.3) to the metal lined/water cooled upper chamber configuration (Figure 4.4). The NO_x reductions realized with the metal liner/water cooled partition configuration can be attributed to more uniform devolatilization and burning of the coal particles, a reduction in wall temperatures where the bulk of particle burnout occurs, and a slight reduction in the bulk gas temperature resulting from increased heat extraction. As can be seen in the figure, NO_x emission goals were met over the full range of combustor load.

When Illinois No. 5 CWS was burned in the metal liner/water cooled partition upper chamber configuration (Figure 4.4), NO_x formation, as shown in Figure 4.8, was greater than that for the Kentucky CWS and well above the performance goal. This higher NO_x formation was a result of material deposition on the remaining refractory within the combustor. Whereas the Kentucky coal with an ash fusion temperature in excess of 2700°F did not stick to this refractory, the lower fusion temperature Illinois coal readily attached to these surfaces. To eliminate this material accumulation and also reduce NO_x , the lower chamber refractory was replaced with a metal liner and water cooled partition similar to that utilized in the upper combustion chamber.

Figure 4.3 Refractory Lined Combustor Configuration

Figure 4.4 Metal Liner/Water Cooled Partition - Upper Chamber Combustor Configuration

Figure 4.5 Combustor Configuration With Full Length Metal Liner Water Cooled Partitions

Figure 4.6 Bare Wall - Water Cooled Lower Combustor

Metal Lined Upper Chamber Refractory Lined Upper Chamber

Figure 4.7 NOx Emissions With Refractory and Metal Lined Upper Combustor Chamber - Kentucky CWS

Figure 4.8 NOx Emissions With Refractory, Metal Lined and Bare Wall Lower Combustor Chamber - Illinois No. 5 and 6 CWS

This arrangement reduced the material accumulation on the lower chamber walls but did not entirely eliminate it and as a result NO_x formation was only slightly reduced (see Figure 4.8). The final set of data on Figure 4.8 shows the NO_x levels for the final combustor configuration. This configuration with water cooled metal surfaces below the lower partition entirely eliminated material accumulation in the lower combustor and also significantly reduced NO_x formation. Although the investigated load range for this configuration utilizing Illinois No. 5 CWS was limited, due to complete utilization of the programs Illinois No. 5 coal supply, operation on Illinois No. 6 coal further characterized the NO_x levels with this combustor geometry. Figure 4.9 shows the NO_x versus load data for the Illinois No. 6 CWS and Figure 4.10 plots the actual NO_x data for a portion of a test run. The performance goal of 0.3 lbs NO_x per MMBtu was achieved throughout the entire load range.

For the refractory lined combustor, combustion efficiencies greater than 99% were achieved while burning Kentucky CWS. Combustion efficiencies for the various deposition management combustor configurations utilizing Illinois No. 5 CWS are given in Table 4.3. (Laboratory analysis of ash samples for Illinois No. 6 tests were not available at the time of report preparation.) There was a slight drop in combustion efficiency from the baseline, refractory lined, combustor configuration. This reduction can be attributed to the lower heating value of the Illinois CWS and to the slightly lower bulk temperature in these configurations due to the additional heat extraction. Table 4.4 summarizes the heat extraction data for the different configurations.

To increase the combustion efficiency the 1 or 2 percentage points needed to meet the combustion efficiency goals with the higher ash, lower Btu value Illinois coals, additional residence time at combustor temperature is required. This can be easily achieved by reducing the heat extraction from the transition chamber. As shown in Table 4.4, the transition chamber heat extraction accounts for approximately one-quarter of the total heat extraction from the combustor/transition chamber assembly. By simply increasing the refractory lining thickness in this chamber, the heat extraction can be drastically reduced.

A second method to reduce the overall assembly heat loss is to return to the metal lined lower chamber configuration instead of the bare wall configuration. Although there was ash accumulation on the lower chamber liner during POC testing, a change in liner material may eliminate this build-up. The liner utilized in this region was made of 310 stainless steel. At the high temperatures in this region, the metal was heavily oxidized which contributed to it serving as an attachment point for ash deposition. Installation of a nickel based alloy liner with a higher service temperature will minimize this oxidation and resultant ash

Figure 4.9 NO_x versus Load Data for the Illinois No. 6 CWS

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Figure 4.10 Actual NO_x Data for a Portion of a Test Run

TABLE 4.3
COMBUSTION EFFICIENCIES FOR THE VARIOUS DEPOSITION MANAGEMENT
COMBUSTOR CONFIGURATIONS UTILIZING ILLINOIS NO. 5

Run Date Thermal Input	Refractory Lower Chamber			Metal Lined Lower Chamber				Bare Wall Lower Chamber		Transition Chamber Deposit
	7/16/92 4.0 MM	7/16/92 2.5 MM	7/16/92 4.0 MM	8/5/92 3.0 MM	9/2/92 2.7 MM	9/3/92 3.2 MM	9/10/92 3.6 MM	9/15/92 2.6 MM	9/16/92 3.5 MM	
Combustion Efficiency	98.7	98.7	98.0	99.6	96.3	98.8	97.3	96.8	97.7	100.0

TABLE 4.4
COMBUSTOR/TRANSITION CHAMBER HEAT EXTRACTION (Btu/hr)

Configuration	A	B	C	D
	Refractory Lined Combustor	Refractory Lined Lower Combustor	Metal Lined Lower Combustor	Bare Wall Lower Combustor
Upper Chamber	127,000	204,000*	183,000*	115,000*
Lower Chamber	212,000	156,000	309,000*	620,000*
COMBUSTOR TOTAL	339,000	444,000	492,000	735,000
Transition Chamber	260,000	250,000	230,000	240,000
TOTAL	599,000	694,000	722,000	975,000

*Includes water-cooled partition.

build-up. These changes will reduce the heat extraction from the combustor/transition chamber so that the total assembly heat loss more closely matches the earlier refractory lined combustor values.

In addition to the above mentioned modifications, one further combustor upgrade is planned to further enhance system performance for the commercial demonstration. In several tests, especially those with the higher ash content Illinois No. 6 CWS, material deposition on the refractory surfaces of the combustor roof has effected system performance. Based on our experience with the floating liner, metal walls, a similar construction will be utilized for the combustor roof. Figure 4.11 illustrates the configuration. With such an arrangement, material attachment will be minimized and what material, if any, attaches will be easily removed. If necessary, a pulse jet cleaning system can easily be installed.

4.2.3 Boiler

As discussed in Section 2.2.2, initial testing with the boiler revealed the need for on-line cleaning of the boiler heat transfer surfaces. A compressed air soot blower system was, therefore, installed. Figure 4.12 is a plot of the boiler exit temperature with and without the soot blowing system and Figure 4.13 shows the boiler exit temperature as a function of load and operating hours. These curves clearly show the effectiveness of the soot blowing system in keeping the tubes clean.

One area which is not covered by the soot blowing system and is prone to ash deposition is the entrance to boiler. Figure 4.14 is a schematic of this area. Ash deposition onto the refractory surfaces in this area, although not sufficient to impact system performance for the length of tests conducted during the POC testing, will need to be eliminated to allow for long term commercial operation. To minimize the deposition in this region and to assure that the deposits, if any, can be easily removed by means of an air lance, a water-cooled transition sleeve (see Figure 4.15) will be installed in this region to eliminate all refractory surfaces. It has been demonstrated that ash accumulating in the water-cooled portion of the mortise tube can be readily removed with the use of an air lance. It is anticipated that cleaning of the transition sleeve and mortison tube will be part of a weekly maintenance schedule.

No corrosion or erosion of the boiler tube sheets or tubes has been detected throughout the course of the test campaign.

Figure 4.11 Metal Lined Combustor Roof Configuration
With Ash Management System

Figure 4.12 Boiler Exit Temperature

Figure 4.13 Boiler Performance

Figure 4.14 Transition Chamber/Boiler Connection (Refractory Lined)

Figure 4.15 Transition Chamber/Boiler Connection (Refractory Lined)

4.2.4 Emissions Control

Unregulated SO₂ emissions for the Kentucky Hazard, Illinois No. 5 and Illinois No. 6 coals are 1.0, 2.4, and 4.9 lbs/MMBtu, respectively. Corresponding uncontrolled particulate emissions for these coals are 2.5, 5.4, and 9.1 lbs/MMBtu.

During POC testing, the ability to control SO₂ emissions levels below the performance goal of 1.2 lbs/MMBtu was demonstrated for the Illinois coals. Since the Kentucky coal is a compliance coal as far as sulfur emissions are concerned, sulfur removal from the exhaust gas was not necessary. Figure 4.16 shows a typical plot of SO₂ emissions for Illinois No. 5. SO₂ emissions were reduced to below the design goal at a sodium to sulfur stoichiometric ratio of approximately 0.65. A similar plot for Illinois No. 6 operation is given in Figure 4.17.

As discussed in Section 2.2.4, particulate emissions are controlled through the use of a conventional pulse jet baghouse filter. The performance goal of 0.03 lbs/MMBtu is well within the performance specifications of the Flex Kleen unit. For the ash and sorbent particle sizes encountered, the manufacturer, based on historical design data and operating experience, guarantees an exit dust loading of 0.013 grains per standard cubic foot throughout the operating range of the system. Table 4.5 summarizes the operating conditions for both average (3 MMBtu/hr) and maximum design conditions (5 MMBtu/hr). As can be seen from this table, the outlet dust flow is extremely low and therefore prolonged operation at steady operating conditions will be required to reliably determine the performance of the unit. Complete EPA Method 5 testing of the exhaust emissions will be carried out as part of the commercial demonstration.

4.3 PERFORMANCE SUMMARY

Table 4.6 summarizes the overall system performance on each of the three coals evaluated during POC testing and compares achieved performance to the program goals. Best performance results were obtained with the low ash Eastern Kentucky coal but even with the higher ash, lower heating value, Illinois coals performance goals were met. With the Illinois coals, especially Illinois No. 6 with greater than 10% ash, system operation was more sensitive to slight changes in coal loading, slurry viscosity and operating setpoints.

Figure 4.18 illustrates the turn down capability, ability to follow load and operating flexibility of the system using Illinois No. 6 slurry. This figure plots the slurry flowrate and corresponding thermal input to the system over a three and one-half hour period. Figure 4.19 shows the corresponding combustor upper chamber gas temperature. Although this temperature which is adjacent to the

Figure 4.16 SO₂ Concentration at Baghouse Exit - Illinois No. 5 CWS

Figure 4.17 SO₂ Emissions With Illinois No. 6 CWS

TABLE 4.5
OPERATING CONDITIONS FOR
AVERAGE AND MAXIMUM FIRE CONDITIONS

Thermal Input	Average	Maximum
Inlet Temperature (°F)	375	425
Inlet Gas Flow (acfm)	1136	2022
Inlet Dust Flow (lbs/hr)	47	80
Air to Cloth Ratio	2.49	4.4
Inlet Gas Loading (gr/scf)	7.75	7.86
Outlet Gas Loading (gr/scf)	0.013	0.013
Outlet Dust Flow (lbs/hr)	0.079	0.132
Capture Efficiency	99.83	99.84

TABLE 4.6
PERFORMANCE GOALS

	Goal	Kentucky	Illinois No. 5	Illinois No. 6
Ignition	Safe and Reliable	30 Successful Starts	10 Successful Starts	30 Successful Starts
Turndown	3:1	4:1	3:1	3:1
Thermal Efficiency (percent)	>80	85 Clean 75 Dirty	85 with Soot Blower	85 with Soot Blower
Combustion Efficiency (percent)	>99	Baghouse Ash Burnout >99	Baghouse Ash Burnout >98	Baghouse Ash Burnout >98
Emissions (lb/mil Btu)				
NO _x	<0.3	0.26	0.30	0.27
SO _x	<1.2	1.03 lb/MMBtu (Compliance)	0.68	0.80
Particulates	<0.02	Baghouse Control	Baghouse Control	Baghouse Control

Figure 4.18 Thermal Input Versus Time With Illinois No. 6

Figure 4.19 Combustor Upper Chamber Gas Temperature

primary air inlet varies slightly with changes in primary combustion air flow resulting from load changes and changes in stoichiometry, it illustrates the stability of the combustion process over the full load range. Table 4.7 gives the NO_x levels for this operating range.

In summary, the proof-of-concept testing demonstrated the technical viability of the integrated system. The CWS combustor technology was scaled to the commercial market size, integration of the combustor technology with a conventional firetube boiler was demonstrated and a highly efficient, low wear slurry nozzle was developed. The laboratory testing demonstrated the ability to meet system performance goals utilizing three coals of varying quality, including high sulfur, high ash, Illinois No. 6 coal. Over the course of the test campaign, the system was operated for over 500 hours consuming over 18,000 gallons of slurry demonstrating both its reliability and flexibility of operation. With all three coals, emission levels were below program goals and anticipated Clean Air Act levels. Operation requirements of system turndown, automatic startup and trouble free operation were also demonstrated.

The development of the system has progressed to the point that an actual demonstration, wherein the system is used to heat an actual commercial facility through a heating season, is justified. The laboratory testing and the associated equipment development has also demonstrated the technical competence of the program team giving confidence that a successful commercial demonstration can be conducted.

As discussed above, several equipment upgrades are planned to enhance performance during the demonstration phase of the program. In summary, heat extraction from the transition chamber will be reduced to improve combustion efficiency, a metal lined combustor roof will be installed to eliminate material deposition, and a metal sleeve will be installed at the boiler inlet to reduce ash build-up at this point and allow compressed air lance cleaning of the entire morrison tube. Also planned for the demonstration site is the addition of an automatic ash removal system for the baghouse.

TABLE 4.7
NO_x EMISSIONS VERSUS LOAD

Slurry Flow (lbs/hr)	Thermal Input (MMBtu/hr)	NO_x (ppm @ 3% O₂)	NO_x (lb/MMBtu)
150	1.1	214	0.20
250	1.8	199	0.19
350	2.6	198	0.19
450	3.3	136	0.13
550	4.0	129	0.12
650	4.8	206	0.19
450	3.3	126	0.12
250	1.8	142	0.13
150	1.1	179	0.7
500	3.7	202	0.19

5. ECONOMIC EVALUATION

The commercial-scale coal slurry fired space heating system needs to be economically competitive in addition to being technically sound and environmentally acceptable if it is going to successfully penetrate the market now dominated by oil and natural gas systems. The economic feasibility of the system is determined by capital investment and operating cost considerations. Due to the need for pollution control equipment, capital investment for a coal-fired system is greater than oil and natural gas systems, and therefore, total operating costs including the cost for sorbent materials and ash disposal must be lower for the coal based system. A summary follows of the economic evaluation including an assessment of the delivered slurry cost based on historical projections and the information gained in the design and operation of the slurry production facility for the program.

5.1 DIRECT INVESTMENT

The total direct investment required to install the heating system includes equipment, engineering, installation, and capital costs. These costs have been determined for the CWS-fired system and premium fuel (oil and natural gas) systems. The direct investment cost variation between oil and natural gas systems is small and therefore are treated as one as far as direct investment is concerned. Although there is a slight increase in equipment and installed costs for steam systems as compared to hot water systems, this variation was deemed small and therefore a hot water system is used for the economic evaluation.

Figure 5.1 shows the equipment costs for premium fuel (fuel oil and natural gas) and CWS-fired systems. For the premium fuel system, the equipment costs are based on current York-Shipley pricing and includes all equipment with a typical "boiler island" including all necessary instruments and controls. The main connection points are: forced draft fan inlet, boiler outlet, burner fuel inlet, circulating water supply and return flanges, boiler connections for blowdown, drain, vent and boiler water make-up, and electrical enclosure terminal strips. The range in costs presented for the premium fuel systems is a result of the small difference in price for fuel oil, natural gas and dual fuel equipment. More significantly, the reduction in price per unit thermal output is associated with less conservative boiler sizing at the expense of thermal efficiency.

For the CWS-fired system, the high volume manufacturing cost for CWS-fired space heating systems was determined based on the equipment costs for the development unit and the experience of Tecogen Inc. and York-Shipley in performing similar scale-up and commercialization. Table 5.1 summarizes the

Figure 5.1 CWS and Premium Fuel Hot Water Boiler Equipment Costs

TABLE 5.1

EQUIPMENT COST ESTIMATE FOR 3.2 MMBTU/HR THERMAL OUTPUT CWS SYSTEM

SYSTEM COMPONENTS	DEVELOPMENT UNIT COST (\$)	HIGH VOLUME SYSTEM COST (\$)
COMBUSTOR/BOILER		
Combustor/Transition Chamber	20,790	3,500
Expansion Joint	1,075	1,075
Boiler	19,230	19,230
Combustor Cooling Water Pump	679	679
Soot Blower	4,330	3,000
Exhaust Piping	1,909	NA
Combustor Cooling Water Piping	2,000	800
Structure	1,000	600
Subtotal	51,013	28,684
COMBUSTION AIR SYSTEM		
FD Fan	2,060	1,500
Air Control Valves	1,896	1,200
Air Piping	500	NA
Subtotal	4,456	2,700
EMISSIONS CONTROL SYSTEM		
ID Fan	1,165	800
Exhaust Damper	1,650	NA
Baghouse	7,879	6,000
Sorbent Feeder	3,860	3,000
SO ₂ Reactor	3,300	2,000
Sorbent Storage Hopper	2,000	2,000
Ash Collection System	NA	3,000
Subtotal	20,819	16,800
FUEL SYSTEM		
Fuel Oil Pump	321	321
Fuel Oil Flow Meter	720	NA
Fuel Oil Control Valve	969	969
Slurry Pump & Controller	1,456	1,000
Slurry Flow Meter	5,590	NA
Threeway Valves	1,569	520
Atomizer	1,600	2,500
Pilot System & Flame Safety	572	572
Subtotal	12,797	5,882
CONTROLS		
Controller	11,000	2,500
Relays, Breakers & Starters	2,170	2,170
Enclosures	2,037	1,000
Pressure Transmitters	2,595	500
Cooling Water Flow Meter	1,670	NA
Circulation Water Flow Meter	1,670	NA
Combustor Water Flow Meters	990	NA
Subtotal	22,132	6,170
TOTAL	106,887	60,236

NA = Not Applicable

development unit equipment costs and the predicted high volume costs for a 3.2 MMBtu/hr thermal output unit. The range in costs presented for the CWS-fired system is mainly a result of the uncertainty in high volume production cost pricing and variation in scope of supply especially regarding instrumentation and controls to achieve fully automatic operation. As seen in Figure 5.1, the equipment costs for the CWS system is on average two to three times that of the premium fuel system depending on the size of the unit. This difference is mainly a result of the added pollution control equipment required of the coal-based system. The costs can be reduced, if low sulfur CWS fuel is utilized, by eliminating the need for the equipment associated with post combustion sulfur removal. It is unlikely, even with the most aggressive coal cleaning techniques, that particulate control equipment will not be necessary because even with zero ash in the CWS fuel at 99% combustion efficiency, particulate emissions would exceed standards.

Figure 5.2 gives the corresponding installation costs for the systems. The installation costs include placement of the equipment at the site, all plumbing and stack connections, and all electrical hook-ups. It does not include the piping and equipment associated with the building's heating system; 50 feet of circulating water piping in the boiler room is included for interface with the system. Also not included is the cost of the fuel storage tanks for either the oil or CWS systems.

Finally, Figure 5.3 gives the total investment costs for the premium fuel and CWS-fired systems. The total investment cost or capital cost is the sum of the equipment and installation costs along with costs associated with site engineering and design, permit procurement, and system start-up. In summary, the total capital investment for a CWS-fired space heating system is estimated to be approximately 2 to 2 1/2 times higher than a premium fuel system.

5.2 OPERATING COSTS

Since the total investment required for a CWS-fired space heating system is significantly higher than a premium fuel system, operating costs must be less to justify the greater initial investment. Operating costs consists of fixed and variable types. Fixed costs are independent of capacity factor, while variable costs are mostly made up of consumables and maintenance charges. Operating costs include operating and maintenance labor, spare parts, and consumables. Consumable costs can include fuel, water, electricity, chemicals and waste disposal.

Operating costs for both premium fuel and CWS-fired systems were determined for a wide range of operating conditions and baseline assumptions. Since the difference in energy costs between the premium fuels and CWS is the

Figure 5.2 CWS and Premium Fuel Hot Water Boiler System Installation Costs

Figure 5.3 CWS and Premium Fuel Hot Water Boiler
Total Capital Investment

economic driver making the use of CWS attractive, the economic comparison is made on the basis of the differential fuel cost. This also simplifies the comparison because it enables the results to be compared independent of fuel price projections. Price projections can be made independently and the resultant differential fuel cost utilized to evaluate the economic benefit of the CWS based system. In Section 5.3, the projected fuel cost differential between CWS fuels and oil and natural gas is discussed.

Two economic indicators are utilized to assess the attractiveness of the CWS based heating system: simple payback and total life cycle savings. In evaluating alternate technologies which require additional up-front capital expenditures such as the CWS-fired space heating system, commercial and industrial users typically are most interested in how soon the equipment will pay for itself, simple payback, and the accepted time period for payback is influenced by the total savings potential of the alternative system for the life of the equipment, total life cycle savings.

Figures 5.4 through 5.6 show the results for the simple payback analysis for each of the program coals. Table 5.2 summarizes the assumptions made in determining the system payback. It is evident from these results that CWS quality, i.e. sulfur and ash content, strongly influences the payback period. This is more clearly illustrated in Figure 5.7, where the payback period versus fuel cost differential is plotted for five coals of varying sulfur and ash content for a 6 MMBtu/hr system. Three of the coals are the coals utilized in the test program, Eastern Kentucky Hazard, Illinois No. 5 and Illinois No. 6 and the two additional coals, a low ash (3.7%), high sulfur (3.14%) coal and a high ash (11.8%), low sulfur (0.76%) coal are utilized to demonstrate the sensitivity of the payback period to coal quality. It is evident from the plot that sulfur content of the coal strongly influences the payback period through increased sorbent cost and correspondingly higher disposal costs.

This is further illustrated in Figures 5.8 through 5.10 which gives the breakdown in annual operating costs for the various size systems and coals. For the high sulfur Illinois No. 6 coal, the combined cost for sorbent and disposal of the spent sorbent/ash mixture exceeds the cost of the slurry, drastically increasing the payback period. The annual fuel costs are calculated for a baseline slurry price of \$2/MMBtu and therefore depending on transportation charges associated with fuel delivery, the CWS fuel costs will be correspondingly a greater percentage of the total annual costs.

The payback period and annual operating costs shown in Figures 5.1 through 5.10 were based on an overall annual system utilization of only 20%.

Figure 5.4 CWS-Fired System Capital Payback Utilizing Eastern Kentucky CWS

Figure 5.5 CWS-Fired System Capital Payback Utilizing Illinois No. 5 CWS

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Figure 5.6 CWS-Fired System Capital Payback Utilizing Illinois No. 6 CWS

TABLE 5.2
SYSTEM PAYBACK ANALYSIS ASSUMPTIONS

Operating Hours	3600
Load Factor	50%
Sorbent Cost	\$270/ton
Disposal Cost	\$64/ton
Sorbent Utilization	80%
Baseline CWS Cost	\$2/MMBtu
Maintenance Labor Oil/Gas CWS Spare Parts	1 hr/wk 7 hr/wk 5% of Equipment Cost Annually

Figure 5.7 Coal Quality Effect on Payback Period

Figure 5.8 Annual Operating Cost Utilizing Eastern Kentucky CWS

Figure 5.9 Annual Operating Cost Utilizing Illinois No. 5

Figure 5.10 Annual Operating Cost Utilizing Illinois No. 6

This 20% utilization was based on a five month heating season and an average load factor of 50%. Payback periods can be drastically reduced if the CWS system is operated as a baseload system which would increase the average load factor to closer to 100%, or if the system is utilized year round for non-space heating applications such as domestic hot water or process heating. Figure 5.11 gives the required payback period for a system utilizing Illinois No. 5 CWS operating for the five month heating season as a baseload unit (3600 hours, load factor = 1.0). Since maintenance costs are fixed, the payback period is less than half the baseline case of Figure 5.2.

Total life cycle savings for the corresponding cases of Figures 5.1 through 5.3 are given in Figures 5.12 through 5.14. Since the life cycle savings are incurred over the entire 20 year operating life of the equipment, the following escalation factors were utilized: a general interest rate of 5% was used for the cost of money, a price increase of 3% a year for sorbent, a price increase of 10% a year for ash disposal, and an escalation rate of 8% per year for maintenance. An annual price escalation of 5% was used for the premium fuels and a 1% escalation was used for the CWS fuels (see Figure 5.15).

These figures show that for the low and moderate sulfur fuels present value life cycle savings of millions of dollars are predicted at moderate CWS to premium fuel price differentials. For the higher sulfur Illinois No. 6, slightly higher differentials are required to achieve this level of savings but especially for the larger size units (8 to 10 MMBtu/hr), significant saving can be obtained at fuel cost differentials of \$4/MMBtu.

5.3 CWS FUEL COST

As demonstrated in the above economic evaluation, the price differential between premium fuels and CWS strongly influences the economic viability of a coal-based heating system technology for the commercial scale market sector. This differential is a function of current and projected premium fuel prices and the cost of CWS production and transportation. Since the production of CWS is not currently being carried out commercially and a distribution infrastructure for the fuel is non-existent, introduction of CWS based combustion systems will require the co-development and commercialization of a CWS based production and distribution network. At today's coal price of \$30 per ton or \$1.2/MMBtu and premium fuel prices of \$4.0 and \$5.3/MMBtu for natural gas and home heating oil, respectively, there is a significant margin to enable CWS to be cost effective in selective market areas. With the differential between coal and premium fuel prices predicted to increase as shown in Figure 5.15, the CWS market will most certainly grow.

Figure 5.11 Capital Payback Period for System Load Factor of 1.0 - Illinois No. 5 CWS

Figure 5.12 Life Cycle (20 Year) Savings Utilizing Eastern Kentucky CWS

Figure 5.13 Life Cycle (20 Year) Savings Utilizing Illinois No. 5

Figure 5.14 Life Cycle (20 Year) Savings Utilizing Illinois No. 6

Annual Energy Outlook 1993, January 1993, Table A3, Commercial Sector (1991 Dollars)

Figure 5.15 Fossil Fuel Price Projections

A recent study by Science Applications International Corporation projects a plant gate cost of \$1.85/MMBtu for CWS. This projection is for slurry produced at the coal mine and includes a small degree of beneficiation. Non-beneficiated slurry costs may be as low as \$1.65/MMBtu. Similar cost projections have been made by the Japan COM Company, Ltd, a joint venture company established to provide CWS produced in China to Japanese users. This is the first project to sell CWS in the international energy market as an alternative to premium fuels. They predict a slurry cost of \$1.82/MMBtu for slurry made in China and shipped to Japan and \$2.11/MMBtu for slurry made in Australia and shipped to Japan. Figure 5.16 gives the cost breakdowns for these two cases at a production rate of 1,000,000 tons per year.

With plant gate cost of CWS established, the cost of distributing the fuel to commercial users must be predicted. Since a distribution system is not currently available, distribution cost projections can vary widely. Assuming no dedicated distribution network with transport by common bulk carrier, CWS costs quickly become uncompetitively high moving further from the mine mouth slurry production facility or major relay station. Figure 5.17 shows the projected delivered costs for this scenario. On the other hand, if one assumes a complete distribution infrastructure has been developed for CWS allowing tank car or slurry pipeline transport to regional centers, the delivery costs for CWS can be on a par with current fuel oil delivery costs. Transportation and handling costs for home heating oil from refinery to commercial user is approximately \$2.5/MMBtu. This is the difference in price between the cost of home heating oil at the refinery and that paid by the residential or commercial user. Table 5.3 gives a breakdown of these prices for various regions of the country and the national average. Assuming 50% of this cost is attributed to overhead and profit and accounting for the difference in heating value on a volume basis between fuel oil and CWS, a transportation and handling cost of \$3.5/MMBtu can be expected resulting in a delivered slurry cost of \$5.35/MMBtu throughout the country.

The above discussion and previous economic evaluation of the CWS-fired space heating system leads to the conclusion that in the future, when a CWS distribution network is established, CWS-based heating systems for the commercial market sector will be economically justified with short payback periods and substantial annual and total life cycle savings as compared to premium fuel systems. The establishment of a national CWS distribution network will certainly require a parallel growth of the demand side. This growth must be through an increase in the use of slurry in the utility and industrial sectors as well as the commercial market sector. Until that time, niche markets are available which can take advantage of their proximity to the coal mines or utilities with slurry production capabilities.

Source: "Annual 250,000 tons of CWM Production by a China-Japan Joint Venture Company at Shiuiu, Shantong, China," Noboru Hashimoto, et. al., Proceedings of the 17th International Conference on Coal Utilization

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Figure 5.17 CWS Delivered Cost Versus Miles From Plant

TABLE 5.3
1991 AVERAGE NO. 2 FUEL OIL PRICES

	Price at Refinery (\$/MMBtu)	Price Paid by Residential User (\$/MMBtu)	Handling and Transportation Cost (\$/MMBtu)
Massachusetts	4.7	7.2	2.5
Pennsylvania	4.5	7.0	2.5
Illinois	4.2	6.5	2.3
Idaho	4.4	6.7	2.3
California	4.7	7.0	2.3
National Average	4.4	7.2	2.8

Source: Energy Information Administration.

6. COMMERCIALIZATION

Introducing the commercial-scale coal combustor as a new product to the marketplace is a complicated process. Tecogen Inc. and its parent corporation, Thermo Electron, have learned through commercialization of a wide range of products, that most often this involves the interaction of several subsidiaries or divisions within the organization and usually the involvement of companies outside of the corporate organization, each one specializing in certain aspects of development, marketing, etc. Tecogen Inc. has assembled a strong development and commercialization team which through synergism of their individual capabilities and specialization, is poised to bring the technology to the market place. Figure 6.1 shows the product development, manufacturing, and marketing organization structure.

Throughout the course of the prototype system design and testing, Tecogen Inc. has worked closely with York-Shipley, a world leader in the manufacture of fire-tube boilers for the commercial market sector, and AMAX, a large coal company with experience in CWS science, production, and sales. This relationship will continue through the commercial demonstration and into commercialization.

A site has been chosen for the commercial demonstration and preliminary engineering has been completed. The demonstration will take place at Southern Illinois University's Illinois Coal Development Park. The prototype system will be utilized to heat the High Bay Building at the site. This building contains offices, classrooms and laboratories. Southern Illinois University personnel will assess the performance and operation of the unit and be involved with slurry production and system operation.

Commercialization of the technology will involve a number of companies, including York-Shipley, who is currently involved in supplying heating equipment to residential, commercial and industrial users. Also, two sister subsidiaries of the Thermo Electron family will be involved, Holcroft/Loftus and Energy Systems. The commercialization marketing structure is shown in Figure 6.2.

We have divided the application of the CWS combustion technology into two groups: direct heating and indirect heating. Each of these groups is further divided. In the direct heating group, Frame Engineering will market the system at thermal inputs less than 10×10^6 Btu/hr. Thermal duties greater than that are reserved for further development by Tecogen Inc. in conjunction with Thermo Electron's Energy Systems Division. With these larger size units, Tecogen Inc. may utilize the manufacturing capabilities of Holcroft/Loftus, a manufacturer of industrial heat treating furnaces. Frame Engineering has identified asphalt plant

Figure 6.1 Product Development - Manufacturing Organization Structure

Figure 6.2 Commercialization Structure

aggregate dryers as a target area within the direct heating group for initial market penetration.

The indirect heating group is further divided. Hot air space heating applications are reserved for Yukon Energy Systems at firing rates less than 0.25×10^6 Btu/hr. Donlee Technologies, through its York-Shipley division, will market the system for water and steam-based space and process heating needs at firing rates up to 10×10^6 Btu/hr. Tecogen Inc. has worked with Yukon in the development of an air-cooled residential CWS unit for the Pittsburgh Energy Technology Center, and will continue to work with them up to this size.

Our plan joins together such companies. We have a technology development company with many years of developing and introducing new products into the marketplace. Also, we have two companies that supply products of this type into the direct and indirect heating system markets. In addition, we have the interested participation of a large coal company, which is capable of producing the necessary fuel for this system. Finally, we have the willing participation of a host site to demonstrate the operation of the facility under normal demands in a real environment.

While at this time, the market introduction of this technology in the U.S. is presently limited by the availability of coal slurry fuels, Tecogen Inc. is actively pursuing markets in eastern Europe where coal is still a predominant fuel in the commercial/industrial market sectors. In particular, Tecogen Inc. has visited a number of boiler companies in Poland, Czechoslovakia, and Germany and is presently negotiating a technology transfer agreement with First Brno in Czechoslovakia.

The cost to commercialize a product of this type is often many times the initial development costs. The manufacturer must be willing to stand behind the product for many years because it can represent substantial risk to the customer (loss of product revenue from inadequate operation). In addition, there is usually a one- to two-year time period between initial discussions and closing of additional sales. This represents a considerable marketing investment before any revenue is seen. Nevertheless, Tecogen Inc., in conjunction with the Thermo Electron Corporation, has an exceptional track record of bringing new products to the market, and we are confident that, with the help of our team members, this new combustion system will also prove to be a commercial success.

6.1 COMMERCIAL DEMONSTRATION

As discussed above, Southern Illinois University's High Bay Building at the Illinois Coal Development Park will be the host site for the commercial demonstration of the technology. Significant work has been conducted during the component development stage of the program to ensure a meaningful and successful demonstration effort.

Preliminary engineering including equipment layout and definition of facility requirements has been completed. Figure 6.3 shows the site layout at the Coal Development Park. As can be seen in the layout drawing, the commercial demonstration will include on-site slurry production.

Figure 6.4 gives a preliminary program schedule for the demonstration effort. A construction and operating permit for the space heating system has already been granted by the Illinois Environmental Protection Agency. Appendix A contains a copy of the permit. A site agreement detailing responsibilities, rights and access privileges to the SIU facility by Tecogen Inc. personnel has been prepared. This agreement will help ensure the demonstration will be carried out on schedule without interference.

6.2 BOILER MARKET

Since World War II, the US commercial boiler market has been limited to using predominantly "premium" fuels such as natural gas or petroleum distillate fuels. The predicted price escalation of premium fuels, especially petroleum distillates, along with the predicted price stability of domestically produced coal based fuels, represents an attractive fuel option for the commercial market sector. For coal to be attractive, it must offer the ease of operation now afforded by premium fuels, be capable of meeting ever more stringent emission regulations and competitively-priced technologies must be available to take advantage of the fuel price differential.

Historically, boiler selection is generally accomplished by parochial applications of local boiler technologies or, more frequently, first cost considerations. As shown in Figure 6.5, cast iron boilers dominate the selection of commercial sizes below 4 MMBtu/hr. Fire-tube boilers are the predominant choice for hot water and low to medium steam pressure below (300 psig) in the size range of 4 to 35 MMBtu/hr. Of these fire-tube boilers, 58% of them fall in the commercial market sector, having a capacity of 10 MMBtu/hr or less. Water-tube boilers representing the largest firing capacity, are the choice for medium pressure (up to 900 psig) or higher capacity requirements. As shown in Figure 6.6, coal accounts

Figure 6.3 Host Site Layout

Figure 6.4 Demonstration Schedule

Figure 6.5 Relative Distribution of Industrial/Commercial Boiler Population by Type, Size, and Number

Figure 6.6 Relative Distribution of Industrial/Commercial Boiler Population by Size and Fuel Type

for only about 10% of the total energy utilized in the commercial/industrial market, with very little coal currently being used in the commercial sector (<10 MMBtu/hr). The joint development of CWS technology capable of providing a beneficial, easy to handle, low cost coal fuel, and low cost, maintenance free, environmentally compatible combustion equipment capable of utilizing these fuels can help to stimulate and consolidate the fragmented boiler industry while increasing the utilization of domestic coal.

A detailed market analysis has shown that fire-tube boilers have an annual oil and gas consumption of 2.0 quads, which is approximately 12% of the total energy used in the combined industrial and commercial markets (Burns and Roe, 1986). According to this study, the greatest opportunity for market penetration of CWS appears to be in fire-tube boilers with capacities of 10 MMBtu/hr or less. This includes packaged systems for new facilities and replacement of old equipment.

Forces are presently at work to displace the premium, oil and gas fuels from their position as the fuel of choice in the commercial and industrial market sectors. Commercial and industrial users are increasingly evaluating or specifying coal as an economical option for future boiler capacity. In addition, the shift to coal is encouraged by federal energy policies promoting conservation and alternative fuels and regulations restricting the use of certain traditional energy forms. In the future, technological advancements in coal combustion systems will serve to curtail unlimited consumption of natural gas and petroleum distillates which are acknowledged to be in limited supply. These premium fuels can then be reserved for use in the residential and transportation sectors.

7. SUMMARY

During the component development and proof-of-concept stages of the development program, a complete integrated, prototype coal water slurry fired space heating system for the commercial market sector was designed, built, and tested. The system has achieved the following program requirements:

- Successful operation with input rates ranging from 1 to 5 million Btu's per hour.
- Combustion efficiencies in excess of 99% with Eastern Kentucky coal and 98% with Illinois coals.
- Response time to full-load operation on CWS from an idle condition in less than 15 minutes.
- Steady state thermal efficiencies of greater than 80%.
- Completely automated operation.
- Integration with conventional fire-tube boilers for retrofit capability.
- Safe and reliable operation.

Additionally, the system is capable of meeting the program emission goals with coals of varying quality including high ash, high sulfur Illinois No. 6 coal.

Successful long-term and cyclic operation has demonstrated the technical viability of the system. Equipment upgrades are planned to enhance system performance with respect to combustion efficiency with the lower heating value Illinois CWS and to control material deposition at the boiler entrance.

Analysis of the system economics has determined that the CWS-fired system can be competitive with conventional fuel oil and natural gas systems at moderate differential fuel costs between CWS and premium fuels. The high volume manufacturing cost of the system is predicted to be two to three times greater than conventional fuel systems with total installation costs two to two and one-half times greater, depending on thermal output. Payback periods and total life cycle savings are highly dependent on coal sulfur levels due to sorbent and disposal costs. However, with a fuel price differential of four dollars per million Btu, simple payback periods of four years or less can be attained utilizing a moderate sulfur content coal such as Illinois No. 5. With predicted escalation in premium fuel

prices and readily available CWS, the system has the potential of competing with premium fuel systems in the near future, and until that time will be available to satisfy niche markets where fuel is readily available and inexpensive such as locations near coal mines where coal fines in the form of slurry is now considered a waste product.

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APPENDIX A

**ILLINOIS ENVIRONMENTAL PROTECTION AGENCY
JOINT CONSTRUCTION AND OPERATING PERMIT**

217/782-2113

JOINT CONSTRUCTION AND OPERATING PERMIT

PERMITTEE

Tecogen, Inc.
Attn: Anthony F. Litka
45 First Avenue
Waltham, MA 02254

Application No.: 92070078 I.D. No.: 199862AAK
Applicant's Designation: SIU-CRL-01 Date Received: July 21, 1992
Subject: Coal Water Slurry Fired Space Heating System
Date Issued: October 13, 1992 Expiration Date: April 30, 1994
Location: Box 4 Illinois Coal Development Park

Permit is hereby granted to the above-designated Permittee to CONSTRUCT and OPERATE emission source(s) and/or air pollution control equipment consisting of coal water slurry fired space heating system with dry sorbent (sodium bicarbonate) injection system and fabric filter as described in the above-referenced application. This Permit is subject to standard conditions attached hereto and the following special condition(s):

1. The allowable limit for particulate matter and sulfur dioxide from coal water slurry fired space heating system shall be 0.1 and 1.8 pound per million BTU.
2. Emissions and operation of equipment shall not exceed the following limits:

<u>Item of Equipment</u>	<u>Maximum Operating Hours (Hour/Year)</u>	<u>Maximum Emissions</u>	
		<u>Particulate Matter Lb/Hour</u>	<u>Sulfur Dioxide Lb/Hour</u>
Space heating system	1000	0.5	9.0

These limits are based on the maximum firing rate and the information provided in the permit application. Compliance with annual limits shall be determined from a running total of 12 months of data.

3. The use of coal water slurry fuel system shall not be allowed during malfunction and breakdown of the control equipment.
4. The Permittee shall keep the following records of operation for the demonstration test.
 - a. The periods when the unit failed to function normally, an explanation as to why the unit malfunctioned and steps taken to resume normal operation.
 - b. Flue gas opacity.

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5. The Permittee shall notify the Agency of date of start-up of the operation of the demonstration test.

If you have any questions on this, please call Shashi Shah at 217/782-2113.

Donald E. Sutton

Donald E. Sutton, P.E.
Manager, Permit Section
Division of Air Pollution Control

DES:SRS:ds:0506N/15-16

cc: Region 3

**DATE
FILMED**

9/15/93

END