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RECENT COAL-OIL MIXTURE
COMBUSTION TESTS AT PETC

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RECENT COAL-OIL MIXTURE COMBUSTION TESTS AT PETC

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ABSTRACT

Coal-oil mixture combustion tests with coal concentrations of up to 50 percent were successfully conducted in a 700 horsepower watertube boiler designed originally for oil firing. A 500-hour duration test with coal-oil mixture containing 40 percent coal has also been completed. No derating of the boiler occurred, carbon-conversion efficiencies were above 98 percent, and boiler efficiencies were the same as when firing No. 6 fuel oil. All combustion tests were conducted with No. 6 fuel oil mixed with Pittsburgh Seam coal pulverized to a coal particle size of 90 percent minus 200 mesh. Test results relating to boiler performance, pollutant emissions, ash deposition, and corrosion, erosion, and fouling behavior are presented.

INTRODUCTION

Coal-oil mixtures (COM) offer the potential of a near-term retrofit technology for conserving petroleum fuel and increasing coal utilization. Technical problems associated with the application of this technology are under extensive investigation^{1,2}.

The Pittsburgh Energy Technology Center (PETC), U. S. Department of Energy (DOE), has long been active in several research areas related to coal-oil mixture combustion.³⁻⁷ A COM Combustion Test Facility was recently completed which provides DOE with an in-house technical capability to support its extensive COM program. Central to the test facility is a 700 HP watertube boiler which is a typical package industrial boiler designed originally for

firing No. 6 fuel oil. In addition, the facility has fuel storage, coal preparation, coal-oil mixture preparation and storage, a dry sorbent injection system for SO_x removal, and a baghouse for particulate control. The facility is also equipped with extensive instrumentation and a computer controlled data acquisition system.

A comprehensive test program was developed to systematically study combustion characteristics of coal-oil mixtures in this facility. The program includes baseline tests with No. 6 fuel oil, and tests on coal concentration, long duration, coal particle size, and coal type. The coal-oil mixture combustion tests with coal concentrations of 30, 40, and 50 percent by weight and a 500-hour duration test with 40 percent coal-oil mixture have been performed recently. Pittsburgh Seam coal pulverized to a coal particle size of 90 percent minus 200 mesh was used.

The objectives of the coal-concentration tests were to prepare a stable coal-oil mixture with coal concentrations up to 50 percent, to transport it through the fuel train to the burner with minimum modifications, and to fire the mixture at full and reduced boiler loads. An additional objective was to investigate quantitatively the effects of burning various concentrations of coal-oil mixtures on the performance of the boiler, the pollutant emissions (SO_x , NO_x , fly ash, etc.) from the stack, the furnace ash accumulation, and the ash deposits in the convection bank of the boiler.

The objectives of the 500-hour test were to determine the long-duration operability of the boiler using coal-oil mixtures and to investigate quantitatively the corrosion, erosion, deposition, and fouling characteristics of coal-oil mixtures in the fuel pipeline and burner, and on the heat transfer surfaces in the boiler. In addition, a study of the accumulation of furnace ash and the effectiveness of the soot blower in removing ash deposits from the convection bank was also included.

COMBUSTION TEST FACILITY

The equipment in the Combustion Test Facility is arranged as shown in Figure 1. The 700 HP boiler is a package, two-drum, "D" type watertube boiler, with a furnace size of 6.3 ft. W x 13.3 ft. L x 7.4 ft. H. It was designed by the Nebraska Boiler Company for generating 24,000 pounds of saturated steam per hour at 175 psig. The steam generated is used for process heating and to augment station steam. Excess steam is condensed in an air-cooled condenser, collected in a hot well tank, passed through a sub-cooler, and then routed back to the deaerator.

The fuel storage consists of an insulated 60,000-gallon capacity No. 6 fuel-oil-storage tank and a 26-ton coal storage bin. Coal is ground, dried, and classified by a package Williams Patent Crusher and Pulverizer Company coal pulverizer. The dry pulverized coal is stored in a 16-ton capacity coal supply hopper.

Coal-oil mixtures are prepared in a 1800-gallon capacity, steam-jacketed mix tank which incorporates an agitator comprised of two sets of turbine blades. A predetermined amount of No. 6 fuel oil is charged to the mix tank. Pulverized coal is then added to the tank from the coal supply hopper through a vertical gravimetric coal feeder at the rate of 2000 pounds per hour. The coal-oil mixture is then transferred to a 2800-gallon steam-jacketed hold tank incorporating an agitator with one set of turbine blades. The coal-oil mixture is continually recirculated from the bottom of the tank to the top by a Viking rotary pump.

The main fuel train for the boiler includes a variable-speed COM feed pump, fuel preheaters, and manual control valves which are arranged as shown in Figure 2. The COM feed pump is a progressing-cavity Moyno pump driven by an adjustable-speed-drive DC motor. The coal-oil mixture flow rate at the

FIGURE 1 700 HP COMBUSTION TEST FACILITY FLOW DIAGRAM

FIGURE 2 COAL-OIL MIXTURE FUEL TRAIN

burner is regulated by the variable speed feed pump. The fuel flow rate is measured by a Micro-Motion mass flow meter and also by a positive displacement ITT Floco meter.

The firing equipment consists of a packaged, single-burner, Model Fyr-Compak, manufactured by the Coen Company. The original Coen Model No. 2 mV, inside-mix, steam-atomized burner was designed to fire No. 6 fuel oil. All coal-oil mixture tests were performed using slightly different Model No. 2 mV burners supplied by Coen Company for abrasive service. The changes included materials of construction and an optional pintle in the burner body. Figure 3 shows the fuel injection nozzle assembly.

The four valves originally installed in the fuel train of the packaged burner were removed or replaced to avoid clogging with coal particles. The oil pressure differential regulator and oil control valve were removed and fuel flow rate was controlled by adjusting the variable-speed-drive COM feed pump. The safety shut-off solenoid valve and oil-return solenoid valve were replaced by pneumatically actuated stainless steel full-ported one-inch ball valves. The packaged burner incorporates an automatic air register louver control that closes in on the register louvers at low fire to maintain air velocity and swirl. Combustion air is supplied by a remote forced-draft fan.

The flue gas leaving the boiler passes through an air-cooled heat exchanger to control the flue-gas temperature entering the baghouse. To reduce the SO₂ emissions to an acceptable level, the SO₂ is reacted with a dry sorbent, sodium bicarbonate, which is introduced into the flue gas duct upstream of the baghouse. The reaction product (sodium sulfate) is collected on the filter bags along with the fly ash. The bags are periodically pulsed with compressed air to shake the filter cake and ash from the bags. The dry powder mixture of

FIGURE 3 FUEL INJECTION NOZZLE ASSEMBLY

fly ash and sulfate is conveyed from the baghouse for subsequent disposal at a commercial land-fill site. The cleaned flue gas is discharged to the atmosphere by an induced-draft fan.

Instrumentation in the test facility includes both continuous on-line and periodic in-flow measurements. Most measurements are transmitted to a data acquisition system that includes a Digital Equipment Corporation PDP-11/40 computer and a central data acquisition cabinet. The cabinet contains a 100-point scanner for electrical signals and a 64-point scanner for pneumatic signals; both scanners are controlled remotely by the PDP-11/40 computer.

COMBUSTION TESTS

Coal-Concentration Tests

A total of 13 oil and coal-oil mixture combustion tests with three different coal concentrations were performed at different boiler loads and at different excess-oxygen levels (see Table 1 for details). Full-load tests were conducted to assess the possibility of derating of the boiler when firing coal-oil mixtures. To compare the characteristics of the boiler at different loads, tests at 3/4 load were conducted with No. 6 fuel oil and also with a 50 percent coal-oil mixture. Since the boiler was originally designed to burn No. 6 fuel oil at 12.5 percent excess air (corresponding approximately to 2.4 percent excess oxygen), tests were conducted with No. 6 fuel oil and 30, 40, and 50 percent coal-oil mixtures at 2.4 percent excess oxygen. Since efficient combustion of coal-oil mixtures requires more excess air than when burning No. 6 oil, tests were performed at excess-oxygen levels that provided satisfactory operation at each coal concentration. For comparison, the No. 6 fuel oil was also run at 3.0 percent excess oxygen.

COM (%)	Load	Excess-Oxygen Level (%)			
0 (#6 Oil)	Full	-	3.0	-	2.4
	3/4	-	3.0	-	-
30	Full	-	-	2.8	2.4
40	Full	3.3	-	2.8	2.4
50	Full*	-	3.0		2.4
	3/4	-	3.0	-	-

*Both washed and unwashed coal were used.

TABLE 1 COMBUSTION TESTS WITH DIFFERENT COAL-OIL MIXTURES

Since ash deposition could affect boiler performance when burning coal-oil mixtures, an unwashed Pittsburgh Seam coal was used during most coal-concentration tests to experience a more severe deposition problem. The main difference between the washed and unwashed coals was in the ash contents. The ash content of the washed coal was about 9.2 percent, whereas that of the unwashed coal was in the range of 11.0 to 14.8 percent. To compare the combustion characteristics of the washed and unwashed coals, the washed Pittsburgh Seam coal was also used in two of the 50 percent coal-oil mixture full-load tests. Both coals were pulverized to a coal particle size of 90 percent minus 200 mesh.

Prior to each coal-concentration test, the furnace was first cleaned, then brought up to a proper firing rate overnight with No. 6 fuel oil to allow the boiler skin temperature to reach its steady-state value. The heat-transfer surface of the convection bank of the boiler was cleaned by applying the soot blower several times. During a test, the soot blower was not applied, to avoid its interference with data acquisition.

At the start of a test, the fuel supply was switched from No. 6 oil to COM. The boiler was operated at steady-state test conditions for at least one hour before acquisition of test data was initiated. The duration of each test was about six hours.

After completion of a test, the boiler was switched back to No. 6 oil and brought down with minimum disturbance to the furnace ash accumulation. The furnace was allowed to cool, then was opened and inspected. Furnace ash was collected, weighed, and analyzed.

Long-Duration Test

The 500-hour duration test was performed after the completion of the coal-concentration tests. The boiler was fired with a 40 percent coal-oil

mixture and operated at full capacity with 3 percent excess oxygen. Washed Pittsburgh Seam coal, pulverized to a coal particle size of 90 percent minus 200 mesh, was used.

The test period was divided into five weeks with continuous testing each week. The boiler was brought up to full load with No. 6 fuel oil at the beginning of each week and then switched to the prepared coal-oil mixture. At the completion of each weekly segment of the test, the boiler was switched to No. 6 oil and was brought down. After cooling the furnace, the depths of the accumulated furnace ash at several selected locations were measured.

After completion of the 500-hour test, the total accumulated ash inside the furnace was collected and weighed. Samples were obtained from different locations and analyzed. Boiler tubes were inspected and test coupons installed prior to the test were removed for metallographic analysis. The major components in both the burner nozzle and fuel feed pump, and test sections in the fuel pipeline were measured to determine their wear characteristics.

COAL-CONCENTRATION TEST RESULTS

Test Conditions

Both washed and unwashed coals were used during the series of coal-concentration tests. Typical analyses of the coal are given in Table 2. Each coal was pulverized to a particle size of 90 percent minus 200 mesh; a typical coal particle size distribution is shown in Figure 4.

The coal concentration of the fuel, and its ultimate analysis, heating value, and specific gravity in each combustion test are given in Table 3. The measured coal concentrations in the coal-oil mixtures tested were generally quite close to the values planned; however, the coal concentration was 54.3 percent during the 50 percent COM test in Run No. 4.

	Washed Coal	Unwashed Coal
Proximate Analysis		
Moisture	1.2	1.9
Volatile Matter	37.5	32.9
Fixed Carbon	52.1	50.4
Ash	9.2	14.8*
Ultimate Analysis		
Hydrogen	5.0	4.9
Carbon	73.9	69.3
Nitrogen	1.5	1.5
Sulfur	1.8	1.8
Oxygen	8.6	7.7
Ash	9.2	14.8*
Heating Value (Btu/lb)	13417	12338
Ash		
Initial Deformation (°F)	2020	2140
Softening Temp (°F)	2110	2250
Fluid Temp (°F)	2240	2460

*Ash content in unwashed coal varied in the range of 11 to 14.8%

TABLE 2 TYPICAL COAL ANALYSES

Test	50% COM		50% COM			40% COM			30% COM		No. 6 Fuel Oil		
Run Number	(Washed Coal)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Coal Concentration (%)	49.0	48.5	49.0	54.3	46.7	40.5	40.0	40.5	29.0	29.9	0	0	0
Ultimate Analysis (%)													
Hydrogen	7.9	8.0	8.3	7.8	8.3	8.9	8.7	8.8	9.4	9.3	10.8	11.0	11.0
Carbon	80.0	80.7	80.4	78.91	79.2	79.9	81.6	82.7	82.8	82.8	87.3	86.7	86.7
Nitrogen	1.0	0.9	0.7	0.8	0.7	0.6	0.8	0.7	0.5	0.6	0.3	0.1	0.1
Sulfur	1.3	1.3	1.2	1.4	1.2	1.1	1.1	1.3	1.0	0.9	0.8	0.7	0.7
Oxygen	5.4	4.6	3.9	4.1	4.5	4.5	3.5	2.2	2.6	2.6	0.8	1.4	1.4
Ash	4.5	4.5	5.6	7.0	6.1	5.0	4.4	4.6	3.7	3.9	0	0	0
Heating Value (Btu/lb)	16188	16161	16135	15652	16058	16523	16851	16759	17186	17309	18551	18642	18642
Specific Gravity at 140°F	1.1015	1.1022	1.0998	1.1185	1.1051	1.064	1.0621	1.0638	1.0406	1.0638	0.953	0.939	0.939

TABLE 3 FUEL ANALYSES FOR COAL-CONCENTRATION TESTS

FIGURE 4

COAL-PARTICLE SIZE DISTRIBUTION

Test conditions for the coal-concentration tests are given in Table 4. The excess air was calculated from the measurement of flue gas and fuel analyses as described in the ASME Power Test Codes⁸. The steam flow was set at the respective load condition of each test; i.e. 24,000 lb/hr at full load and 18,000 lb/hr at 3/4 load. The atomizing-steam pressure, atomizing-steam flow, and fuel temperature were set based on the best boiler operating conditions for good flame stability and appearance.

Boiler Performance

The flue-gas temperature, the carbon-conversion efficiency, and the boiler efficiency for each test are listed in the bottom part of Table 4. The flue-gas temperature is an indication of the general combustion and heat-transfer characteristics inside the boiler. The flue-gas temperature increased with an increase in boiler load. In the 50 percent COM tests, the firing of higher ash COM (unwashed coal) increased flue-gas temperatures.

Boiler performance is expressed by the carbon-conversion efficiency and the boiler efficiency. The carbon-conversion efficiency indicates the completeness of combustion in the boiler, whereas the boiler efficiency measures the effectiveness of useful energy transfer in the boiler. The carbon-conversion efficiency for the washed coal is slightly higher than that for unwashed coal. The carbon-conversion efficiency decreased with a decrease in the excess-air level. All carbon-conversion efficiencies were generally above 98 percent. The only exception is the 50 percent coal-oil mixture test with unwashed coal at an excess-air level of 8.31 percent, which resulted in a carbon-conversion efficiency of 97.3 percent.

Based on the ASME Power Test Code⁸, there are two methods of calculating the boiler efficiency: the input-output method and the heat-loss method. In this paper, the heat-loss method is used because this method not only provides

Test	50% COM		50% COM			40% COM			30% COM		No. 6 Fuel Oil		
Run Number	(Washed Coal)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Load	Full	Full	Full	Full	3/4	Full	Full	Full	Full	Full	Full	Full	3/4
Excess O ₂ (%)	3.01	2.40	2.99	2.35	2.97	3.33	2.75	2.40	2.76	2.39	3.00	2.43	3.02
Excess Air (%)	14.55	10.82	13.95	8.31	14.37	16.76	12.60	10.30	12.87	10.50	15.71	12.24	15.76
Steam Flow (lb/hr)	23560	24110	23460	23920	17280	23570	23640	23800	23400	24150	23820	23510	17880
Fuel Flow (lb/hr)	1757	1737	1758	1895	1290	1734	1698	1732	1670	1674	1542	1488	1140
Thermal Input (MBtu/hr)	28.44	28.07	28.37	29.66	20.71	28.65	28.61	29.03	28.70	28.98	28.61	27.74	21.25
Atomizing Press. (psig)	80	80	80	81	65	70	71	70	68	66	65	66	60
Atomizing steam flow (lb/hr)	354	364	333	364	302	326	333	331	325	326	235	238	231
Fuel Temp. (°F)	268	265	271	270	268	218	230	226	214	214	213	206	220
Flue Gas Temp. (°F)	529	535	556	557	490	518	530	552	529	525	530	526	496
Carbon Conversion Efficiency (%)	99.0	98.8	98.4	97.3	98.8	99.0	98.7	98.5	98.9	98.6	100	100	100
Boiler Efficiency (%) (Heat Loss Method)	82.7	82.6	81.2	80.7	82.8	82.2	82.4	81.5	82.1	82.4	82.3	82.6	82.8

TABLE 4 CONDITIONS AND BOILER PERFORMANCE FOR COAL-CONCENTRATION TESTS

the boiler efficiency but also gives detailed information regarding each individual heat loss. Moreover, the boiler efficiencies based on the heat-loss method are less dependent on a few flow measurements, the required accuracies of which are difficult to obtain. The accuracy of the boiler efficiency based on the heat-loss method depends strongly upon the accurate measurements of the flue-gas temperature and the CO₂ concentration in the flue gas. The accuracy of the boiler efficiency presented here is about ± 0.40 percent. As shown in Table 4, the boiler efficiencies for coal-oil mixtures are about the same as those for No. 6 fuel oil. However, when the 50 percent coal-oil mixture test data for the washed coal and the unwashed coal are compared, the boiler efficiencies for washed coal are slightly higher than those achieved with unwashed coal, mainly due to the difference in carbon conversion.

To assess the overall balances of energy, carbon, sulfur, and ash in the boiler system, their imbalances are given in Table 5. The imbalance of a quantity is defined by the difference between the input and the output of this quantity divided by the input of this quantity (expressed as a percentage). Therefore, the imbalances also assess the overall accuracy of the combustion tests. Data presented in Table 5 show that the total energy imbalances are less than 2.14 percent, and the carbon and sulfur imbalances are less than 0.54 and 3.25 percent, respectively. The imbalances of ash are large; the unaccounted ash is assumed to be the deposition in the convection bank of the boiler. The absolute amount of ash deposition per hour in each test is presented in the next section.

Ash Deposition

The rates of fly ash emission and furnace ash accumulation are given in Table 6, along with the compositions (carbon, sulfur, and ash) of the fly ash and furnace ash. The amount of ash apparently deposited in the boiler

Test	50% COM		50% COM			40% COM			30% COM		No. 6 Fuel Oil		
Run Number	(Washed Coal)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Energy Imbalance (%)	0.90	-2.09	-0.19	1.26	0.79	1.55	0.76	0.36	-0.43	-0.15	0.19	-0.95	-2.14
Carbon Imbalance (%)	-0.28	-0.29	-0.49	-0.54	0.39	0.36	-0.29	-0.28	-0.22	-0.29	0	0	0
Sulfur Imbalance (%)	-1.66	-1.37	-0.81	0.19	-1.16	1.36	-1.61	-2.08	-1.56	-3.25	-0.6	-1.06	-0.38
Ash Imbalance (%)	31.04	33.26	10.83	25.34	23.01	23.85	28.47	37.22	20.18	21.3	-	-	-

TABLE 5 OVERALL ENERGY AND MATERIAL BALANCE FOR COAL-CONCENTRATION TESTS

Test	50% COM		50% COM			40% COM			30% COM		No. 6 Fuel Oil		
Run Number	(Washed Coal)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Fly Ash													
Loading (lb/hr)	63.86	64.09	105.9	132.3	67.45	77.4	68.09	59.63	62.18	67.42	0.196	-	-
Analysis													
Carbon (%)	23.1	26.2	20.6	30.4	16.7	17.0	26.3	31.5	24.7	27.7	-	-	-
Sulfur (%)	0.5	0.4	0.3	0.4	0.3	0.4	0.4	0.6	0.4	0.7	-	-	-
Ash (%)	75.0	71.2	76.3	67.0	81.0	80.2	70.2	64.4	72.3	69.8	-	-	-
Furnace Ash													
Accumulated (lb/hr)	7.98	6.81	7.04	10.52	6.72	4.39	6.0	5.47	4.5	4.1	-	-	-
Analysis													
Carbon (%)	5.1	2.9	5.3	5.5	8.8	8.1	4.7	4.3	3.9	4.5	-	-	-
Sulfur (%)	0.7	0.4	0.4	0.4	0.6	0.6	0.3	0.4	0.5	0.5	-	-	-
Ash (%)	93.1	96.0	93.9	93.6	88.5	89.8	94.0	94.7	94.6	94.0	-	-	-
Ash Deposition in Convection Bank (lb/hr)	24.54	26.0	11.06	34.11	18.11	20.60	21.27	29.66	12.47	13.91	-	-	-

TABLE 6 ASH ANALYSES FOR COAL-CONCENTRATION TESTS

convection bank during each combustion test was also calculated by an ash balance and is listed. The amount of fly ash emitted during the No. 6 fuel oil tests was extremely small in comparison with that of the coal-oil mixture tests; the isokinetic samples were not large enough for composition analysis. Furthermore, there were no noticeable ash accumulations in the boiler.

Emission of Pollutants

Flue-gas compositions and opacity for each combustion test are presented in Table 7. The measurements of CO, THC (total hydrocarbon), and opacity showed that they were generally higher at lower excess-oxygen levels. Note that the CO emission (615 ppm) and the opacity (54 percent) during the 50 percent COM test Run No. 4 were both very high; this indicates that the specified excess oxygen (2.35 percent) and the corresponding excess air (8.3 percent) were probably too low to provide satisfactory conditions. The emission of SO_x depended mainly on the sulfur content in the fuel. The emission of NO_x showed that it increased with the increase of nitrogen content in the fuel and also with the increase of excess oxygen during boiler operations.

LONG-DURATION TEST RESULTS

Test Conditions

Typical coal and 40% COM analyses for the 500-hour duration test are given in Table 8. The coal-particle size distribution was about the same as that shown in Figure 4. During the test, the excess oxygen was set at 3 percent which corresponds to approximately 16.5 percent excess air. The fuel flow was set to generate a steam rate of 24,000 lb/hr and was maintained constant at 1720 lb/hr throughout the test. The corresponding thermal input was about 28.9 MBtu/hr. For good boiler operation, the following conditions were set: 81 psig atomizing-steam pressure, 370 lb/hr atomizing-steam flow,

Test	50% COM		50% COM			40% COM			30% COM		No. 6 Fuel Oil		
Run Number	(Washed Coal)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Flue-Gas Analysis													
O ₂ (%)	3.01	2.40	2.99	2.35	2.97	3.33	2.75	2.40	2.76	2.39	3.00	2.43	3.02
CO ₂ (%)	14.67	15.11	14.49	15.14	14.48	14.02	14.59	14.82	14.36	14.68	13.84	14.22	13.77
CO (ppm)	44	58	7.7	615	25.3	35	52	91	37.4	71	17.8	119	69
SO _x (ppm)	902	922	813	1000	825	725	745	677	655	605	472	429	418
NO _x (ppm)	499	479	414	366	344	363	366	350	321	305	223	207	209
THC (ppm)	3.8	3.2	3.0	14.1	1.1	0.88	3.3	11.0	0.6	2.7	0.94	2.34	4.05
Opacity (%)	29	-	36.5	54	32.5	27.7	29.5	33.5	29.5	31.5	20.2	20	9

TABLE 7 FLUE GAS MEASUREMENTS FOR COAL-CONCENTRATION TESTS

	Coal	40% COM
Proximate Analysis		
Moisture	1.1	
Volatile Matter	37.4	
Fixed Carbon	53.1	
Ash	8.4	
Ultimate Analysis		
Hydrogen	5.0	8.7
Carbon	75.5	83.0
Nitrogen	1.3	0.8
Sulfur	1.7	1.1
Oxygen	8.0	3.3
Ash	8.4	3.1
Heating Value (Btu/lb)	13548	16822

TABLE 8 TYPICAL COAL AND COM ANALYSES FOR LONG-DURATION TEST

and a fuel temperature of 230°F. Figure 5 shows the variations of steam generation and fuel flow throughout the test. Each data point represents an average of test data for at least 4 hours.

Boiler Performance

During the 500-hour duration test, the coal-oil mixture preparation, delivery, and injection systems performed without difficulties. However, due to continuing accumulation of ash inside the furnace, the ash deposition, after 370 hours, blocked a large portion of the entrance to the convection bank of the boiler. As a result, difficulties were encountered in maintaining a steady furnace pressure. The accumulated ash had to be removed before the remaining 130 hours of the combustion test could be completed. In spite of the ash accumulation, there was no derating of the boiler throughout the entire test period. Ash deposits in the convection bank of the boiler were effectively removed by the soot blower, thereby maintaining the flue-gas temperature around 530°F (Figure 6).

By assuming a linear ash accumulation with time in the furnace and an average of 0.2 percent carbon content in the furnace ash, the carbon-conversion efficiencies were calculated to be above 99 percent throughout the entire test. The boiler efficiencies computed by the heat-loss method were found to vary between 82.1 and 83.2 percent (Figure 7), which are about the same as when firing No. 6 fuel oil.

A quantitative determination of ash accumulation and the effect of ash on boiler operation were among the primary objectives of the long-duration test. After each weekly segment of the test, the depths of furnace ash accumulated were measured. Table 9 gives the depth of ash at nine locations on the furnace floor; the nine locations are identified in Figure 8. The measurements show that ash accumulation increased with boiler operating time, and apparently no

FIGURE 5 VARIATION OF STEAM GENERATION AND FUEL FLOW DURING LONG-DURATION TEST

FIGURE 6 VARIATION OF FLUE-GAS TEMPERATURE DURING LONG-DURATION TEST

FIGURE 7 VARIATION OF CARBON-CONVERSION AND BOILER EFFICIENCIES DURING LONG-DURATION TEST

Locations	Ash Accumulation in Inches (after hours of testing)			
	100 hr	200 hr	370 hr	500 hr*
1	15	22	21	7.5
2	4.5	5	8	3.5
3	11	12.7	13	7.5
4	18	23	23	12
5	4.5	6	8.5	6.5
6	11	14.5	16	8
7	1.5	4.7	7	3
8	0	4.5	2.5	0
9	0	0	8.7	0

*130 hours after removal of the furnace ash and new start.

TABLE 9 ASH ACCUMULATION ON FURNACE FLOOR

FIGURE 8 IDENTIFICATION OF LOCATIONS IN FURNACE

steady-state layer was reached. However in most of the locations, the major portion of the accumulation occurred during the first 100 hours. Photographs of the furnace interior, Figures 9 and 10, show the ash accumulation after 200 and 370 hours of operation.

After 370 hours of operation, ash samples were taken from different locations in the furnace for analyses. Ash samples exhibited different colors and structures depending upon the location of the sample taken. Ash formed in layers on the furnace side walls and floor. In general, the ash closest to a tube was soft and brown, whereas the ash farthest from the tube was black or grey and in the form of either a hard crust or porous hard slag. A total of 4,830 pounds of ash was collected after 370 hours of operation; during the same period, 636,400 pounds of 40 percent COM was burned.

Table 10 gives the compositions of the ash samples taken from locations identified in Figure 8 and also of one composite sample of ash brushed off the furnace walls. Compositions do not show significant variations at different locations. It may be noted that the carbon contents in the accumulated furnace ash are much lower than those measured during the short-duration coal-concentration tests (see Table 6). The iron content of the composite ash sample brushed off the furnace wall (last row of Table 10) is higher than that of the other samples. Comparisons will be made later with the corrosion and erosion data obtained from the test tubes, which are not available at the time of writing.

Erosion and Corrosion

Prior to the long-duration test, three boiler-tube test coupons were specially prepared and installed in the furnace and in the convection bank. Several test sections in the fuel pipeline were also selected for erosion studies. Relevant dimensions of the test sections, Moyno pump rotor and rotor drive components, and burner nozzles were measured before and after the test.

FIGURE 9 FURNACE ASH ACCUMULATION AFTER 200 HCURS OF OPERATION

FIGURE 10 FURNACE ASH ACCUMULATION AFTER 370 HOURS OF OPERATION

Sample Locations	Weight Percentage										
	C	Si	Al	Fe	Ca	Mg	Na	K	S	V	Ti
1	0.2	19.8	10.7	13.2	1.2	0.4	0.3	0.2	≤0.1	<0.1	0.8
2											
Flame side	0.3	19.5	9.2	14.9	1.1	0.4	0.5	0.2	1.1	0.1	1.2
Tube side	0.1	18.7	10.8	12.0	1.3	0.4	0.4	0.2	0.5	<0.1	0.8
3	0.2	21.0	10.8	17.7	1.4	0.4	0.4	0.3	0.2	0.1	1.2
4	0.2	21.6	8.9	15.0	1.2	0.4	0.3	0.4	0.1	0.1	0.7
5	1.0	21.9	9.7	18.0	1.3	0.4	0.3	0.5	0.1	0.1	0.8
6	0.4	21.7	10.6	13.9	1.1	0.4	0.5	0.4	0.6	0.1	1.1
7	0.1	21.9	10.6	13.3	1.3	0.4	0.4	0.2	0.1	<0.1	1.2
8	0.1	22.3	11.4	15.3	1.2	0.3	0.2	0.7	≤0.1	0.1	0.6
9	0.1	19.9	11.6	15.2	1.6	0.4	0.4	0.5	0.2	0.1	1.3
10	0.1	22.7	11.2	15.9	1.2	0.4	0.3	0.6	≤0.1	<0.1	0.8
11	<0.1	20.9	11.2	16.4	1.2	0.4	0.4	0.2	≤0.1	0.1	1.3
12	0.3	23.3	11.7	15.1	1.5	0.5	0.3	0.4	≤0.1	0.1	0.7
13	0.2	20.3	10.8	17.6	1.2	0.4	0.4	0.4	0.4	0.1	1.1
Ash brushed off furnace wall	0.1	17.6	8.8	25.0	1.3	0.4	0.3	0.3	-	0.1	0.7

TABLE 10 COMPOSITION OF FURNACE ASH SAMPLES

After the test, the coupons were sent to laboratories for metallographic analysis. At the time of this writing, however, laboratory analyses are not yet available.

Table 11 indicates the wear of several burner nozzles made of different materials. Burner nozzles made of tool steel (Latrobe Steel Co., type A2) and stainless steel had significant wear; the rate of wear seems to decrease with the increase in operating hours. The steel cap with tungsten-carbide inserts exhibited no measurable wear over a period of 40 hours.

No measurable wear was found in the carbon steel fuel-line test sections. No measurable wear was found on the hardened-steel rotor of the Moyno pump which had a BUNA-N synthetic rubber stator. The BUNA-N double thread helical stator exhibited abrasion marks on the first helical thread on the suction side that proved too difficult to measure accurately. However, there was no change in pump output due to this wear. There was significant wear of the connecting rod and pins between the drive shaft and the pump rotor. In all progressing cavity pumps, the rotor describes a circle around the centerline of the drive shaft as it rotates. This eccentric action causes wear on the rotor connecting rod and pins that is aggravated at the pump rotor end by erosion caused by exposure to the fluid being pumped. The wear of the holes in the connecting rod was 0.003 to 0.016 inches on the drive-shaft end and 0.007 to 0.015 inches on the pump rotor end (the original hole size being 0.466 inches). The connecting rod pins showed a maximum wear of 0.015 inches only in the area that is contained in the connecting rod. The pump manufacturer has recognized this problem and has changed the connecting rod design to a sealed-gear type, universal joint design for new pumps.

Burner Nozzle Material	Hours of Operation	Wear	
		Inch	Inch/Hour
Tool Steel	72.5	0.0245	0.00034
Tool Steel, Chromed	42.8	0.016	0.00038
440C SS	70	0.0267	0.00038
440C SS	105.5	0.034	0.00032
Steel Cap With:			
Tool Steel Inserts	10	0.008	0.0008
Tool Steel Inserts	34.3	0.022	0.00064
Inconel X-750 Inserts	37.5	0.021	0.00056
Tungsten-Carbide Inserts	15.8	0	0
Tungsten-Carbide Inserts	39.8	0	0

TABLE 11 WEAR CHARACTERISTICS OF BURNER NOZZLE

CONCLUSION

Coal-oil mixture combustion tests with coal concentrations of 30, 40, and 50 percent by weight were conducted successfully in the PETC 700 HP watertube boiler originally designed for oil-firing. A 500-hour duration test with 40 percent coal-oil mixture has also been completed recently at PETC.

Analyses of test results showed that there was no derating of the oil-fired boiler using coal-oil mixtures of up to 50 percent coal concentration. Carbon-conversion efficiencies were generally above 98 percent and boiler efficiencies were about the same as those when firing No. 6 fuel oil. The emission of NO_x increased with the increase of nitrogen content due to the coal content in the fuel and the operating excess-air level. The emission of SO_x was dependent on the sulfur content in the fuel. The fly ash emission and furnace ash accumulation were dependent on the ash content in the fuel; however, there appeared to be no relation between the ash deposition in the convection bank of the boiler and the ash content in the fuel.

Long-duration test data showed that the continuing furnace ash accumulation could interrupt the boiler operation. However, early furnace ash deposition can be handled with soot blowers which are now being retrofitted in the PETC 700 HP boiler. In spite of the large amount of furnace ash accumulation, no boiler derating occurred throughout the test. The carbon-conversion efficiencies were above 99 percent and the boiler efficiencies were the same as when firing oil. Wear at the burner nozzles was significant; however, the problem can be remedied by selecting proper materials. Information on the corrosion and erosion characteristics of the boiler tubes was not available at the time of writing.

Coal-oil mixture combustion tests are continuing at PETC. Currently, tests with different coal particle size consists are being conducted. Future

tests will include investigations of different coal types, different type burners, and NO_x control techniques.

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