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FINAL TECHNICAL REPORT
September 1, 1991 through November 30, 1992

Project Title: **CFBC EVALUATION OF FUELS PROCESSED FROM ILLINOIS COALS**

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ABSTRACT

The fuels studied in this project are (a) three flotation slurry fuels beneficiated from coal fines at various stages of the cleaning process and (b) coal-sorbent pellets made from the flotation concentrate of the same beneficiation process using corn starch as binder, (c) a run-of-mine Illinois No. 5 coal. Combustion data such as SO_2, NO_x emissions, combustion efficiency and ash mineral matter analyses from the slurry and pellet fuels are compared with similar parameters from the reference coal burnt under similar conditions of bed temperature and fluidization velocity.

The combustion tests performed in a 4" internal diameter CFBC showed that the combustion efficiency of the slurry fuels and the pellets were quite comparable with that of the standard coal in the range of 91-98%. Sulfur dioxide emissions in lbs per million Btu from the slurry fuels were low enough to satisfy EPA emissions requirements with Ca/S ratios of 1.5 or less. At these low Ca/S ratios, the slurry fuels and the pellet emitted less SO_2 than the standard coal. Increasing the Ca/S ratios showed that the standard coal SO_2 emissions reduced at a faster rate than the SO_2 emissions from the pellet and slurry fuels, because of the more efficient dispersion and gas-solid contact of the standard coal particles.

Oxides of nitrogen emissions were generally on the order of 0.3 lbs per million Btu from the slurry fuels under the conditions of the present tests, while that from the pellets were between 0.6 to 0.75 lbs per million Btu depending on bed temperature. In comparison, the oxides of nitrogen emissions from the standard coal varied from 0.5 to 0.8 lbs per million Btu in the bed temperature range of 1475-1625°F.

The mineral matter content of the combustion-generated ash from the test fuels was investigated using EDX techniques. Trace element analysis on a representative high-ash sample was performed by a professional laboratory.

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EXECUTIVE SUMMARY

Combustion experiments were conducted in a 4-inch internal diameter circulating fluidized bed combustor on three coal-water slurry fuels, a standard reference coal and a coal-sorbent pellet fuel. The three coal-water slurry fuels were obtained by taking samples at various stages of recovery from the Galatia preparation plant of Kerr-McGee Corporation. Particle size analysis of dried coal from the slurries were made. Proximate and ultimate analyses and mineral matter distribution in the above coal samples have been investigated.

The coal-water slurry fuels were prepared by either adding or decanting water from the as-received samples such that the solids concentration of the slurries varied from 42-46%, as this solids loading was found best for injection and for slurry transport into the combustor. Using a peristaltic pump and an in-house fabricated pneumatic injection system, the three slurries were fed into the fluidized bed combustor. The combustor was operated entirely on the coal-water slurry fuel and the combustion and emissions properties of the slurry fuels investigated. The variables measured during a test included temperatures at various points within the combustor, CO, CO_2, O_2, SO_2 and NO_x emissions, coal-water slurry and air feed rates, recycle ratios and exit cyclone ash rejection rates.

Similar experiments were conducted on the standard coal and the coal-sorbent pellets made by using cornstarch as binder. Results from the combustion experiments show that the three coal-water slurry fuels and the coal-sorbent pellets are excellent fuels with combustion and emissions properties equal to or better than the standard run-of-mine coal.

Sulfur Dioxide Emissions

The SO_2 emissions of the slurry fuels were measured to be lower than those from the standard coal, except at high Ca/S ratios. At a temperature of 1550°F and a Ca/S ratio of 2.5, slurry fuel A yielded 0.8 lb/10^6 Btu, slurry fuel B emitted about 1 lb/10^6 Btu and slurry fuel C (which had the highest sulfur content) emitted about 1.15 lb/10^6 Btu.

The standard run-of-mine coal emitted 1.2 lb/10^6 Btu. These values are comparable values under the conditions of the test and are not the lowest emissions levels that can be achieved when the system is optimized. Under similar conditions of operation, the pellet fuel emitted about 1.15 lb/10^6 Btu.

Oxides of Nitrogen Emissions

Oxides of nitrogen emissions for the slurry fuels were uniformly lower than for the standard coal. For the three slurry fuels tested, NO_x emissions varied between 0.25 to 0.4 lb/10^6 Btu; and for the pellet fuel, the measured NO_x emissions were on the order of 0.6 lb/10^6 Btu. In comparison, the oxides of nitrogen emissions for the standard coal varied between 0.48 to 0.85 lb/10^6 Btu, depending on bed temperature.

Combustion Efficiency

Carbon conversion efficiencies ranging from 91 to 98% were measured for the slurry fuels and the standard coal. The pellets burnt extremely well and had a uniform carbon conversion efficiency of over 98%.

Carbon Balances

Carbon balances were made on typical test runs. Inputs to the carbon balance chemical equation were the measured coal and air feed rates, the measured volumetric percentages of CO, CO_2, O_2, NO_x, SO_2 and the carbon present in the elutriated ash. Chemical balance equations were set up to back calculate the coal feed rates from the emissions data. These calculated values were then compared with the experimentally measured coal feed rates. Agreement to within 10% was achieved for the cases investigated. Sources of error are discussed in the body of the report.

Mineral Matter Analyses

For each of the five fuels tested, the raw coal in the fuel and a representative ash sample was low temperature ashed employed oxygen plasma at 100°C, and then subjected to EDX analysis, to study mineral matter transformations. Results from the analysis show that, in general, the weight percentages of sodium, potassium and sulfur reduced on combustion. Due to limestone addition for SO_2 control, the calcium content of the combustion ash increased compared to that of the raw coal. Also, in general, the percentage of iron present in the combustion ash was greater than that in the raw coals of the five test fuels.

A typical trace element analysis of the combustion generated ash from the slurry fuel, which contained the largest percentage of ash, was made by a professional laboratory and is presented along with the above data.

It may be concluded from the results of these comparative tests that the coal-water slurry fuels processed from the preparation plant fines considered in the present tests are desirable fuels with good combustion and emissions characteristics. The coal-sorbent pellets also exhibited good carbon conversion efficiencies in the CFBC burner with emissions of SO_2 and NO_x somewhat lower than those of the standard coal.

OBJECTIVES

The overall objectives for this one-year project are:

1. to demonstrate that new fuels derived from Illinois high sulfur coal, namely (a) coal-sorbent pellets and (b) coal-water slurry produced from froth flotation feed can be effectively utilized in a circulating fluidized bed combustor,

2. to compare the carbon conversion efficiencies, SO_2 and NO_x emission levels and Ca/S ratios needed to meet EPA regulations from the above fuels with those measured under similar operating conditions with a standard IBCSP coal, and

3. to analyze ash and spent limestone residues with a view to proposing waste disposal strategies for the combustion residues resulting from these new fuel forms.

The specific goals to be achieved as stated in the proposal are as follows:

1. determination of the carbon conversion efficiency of (a) the froth flotation coal water slurry fuel developed at the ISGS under CRSC sponsorship, and (b) the coal-sorbent pelletized fuel developed by ISGS under CRSC funding.

2. determination of the Ca/S mole ratio requirements for the coal-water slurry fuel to meet EPA SO_2 emissions requirements.

3. determination of the sulfur capture efficiency of the coal-sorbent pellet fuel

4. evaluation of the mineral matter elemental distribution in the combustion residues from the above fuels when burned in a laboratory scale 4" internal diameter circulating fluidized bed combustor

5. determination of the NO_x emission levels when burning the coal-water slurry and the pelletized fuel in a CFBC unit

6. comparison of the carbon conversion efficiency, carbon balances, SO_2 and NO_x emission levels and combustion waste analyses of the coal water slurry and pelletized fuel with equivalent values obtained from a standard coal

The accomplishment of these goals involve the following tasks: (a) fuels procurement, (b) fuel testing and analysis, (c) fuels preparation, (d) installation of limestone feeder, (e) combustion testing in a 4" internal diameter circulating fluidized bed combustor, (f) combustion residues analysis using EDX, and (g) data analysis and report preparation.

INTRODUCTION AND BACKGROUND

Increased utilization of Illinois coals can be promoted by developing clean burning coal-based fuels which are low in sulfur and high in heating value. One such project, funded by CRSC, is aimed at developing coal-sorbent pellets from coal fines. A second CRSC supported project recovers fine coal from plant waste employing various flotation techniques, producing a slurry with higher solids concentration and Btu content. The market potential of these fuels will depend on the combustion and emissions characteristics of the coal/sorbent pellets and the coal slurry. This can be established only by combustion testing under conditions simulating actual boiler firing. Because of the small quantities of the fuels being produced, laboratory-scale combustors are best suited to demonstrate their utility and emissions characteristics.

There is a need to evaluate the burning characteristics of the coal-sorbent pellets and the coal water slurry to determine whether they can be burned easily and with good carbon conversion efficiencies. In the case of the coal-sorbent pellets, it is necessary to quantitatively evaluate the sulfur capture efficiency of the pellets, in comparison with the case where the coal and sorbent are fed separately, to establish the merits of the coal-sorbent pelletization process. Additionally, it is necessary to investigate how the pelletization process, namely the mixing of the sorbent with the coal matrix influences the porosity and carbon burnout histories of the coal. The sorbent Ca/S ratios needed to meet EPA requirements with the coal water slurry and its carbon conversion efficiency needs to be evaluated in comparison with standard Illinois coals to demonstrate the usefulness of the separation process.

The research currently being performed in this project addresses the above needs to improve the usefulness of fuels produced from high sulfur coals.

EXPERIMENTAL PROCEDURES

I. Equipment and Instrumentation

The experiments are being conducted in the 4" internal diameter circulating fluidized bed combustor shown schematically in Figure 1(a). The combustor is lined with a castable refractory to reduce heat losses. As shown in Figure 1(a), a blower supplies fluidizing air which is split into two streams. The main stream enters the fast fluidized bed section of the combustor through a distributor plate specially designed to provide even fluidization. This section of the air duct also houses a propane-fired preheat system, which is utilized to bring the bed solids up to temperatures required to ignite the main fuel. Unburnt fuel, limestone and ash entrained by the gases in the main bed column pass through a refractory-lined hot cyclone, which traps the larger particles and deposits them into an auxiliary bubbling bed attached to the bottom end of the hot cyclone. The second smaller air stream enters this bubbling bed into which the carry-over solids from the fast fluidized bed trapped by the hot cyclone are deposited. A non-mechanical seal ensures that this unburnt fuel and bed solids flow from the bubbling bed into the fast fluidized bed and not vice-versa. Both air streams are metered with ASME nozzles and incorporate control valves for adjusting the flow velocities in the fast fluidizing and bubbling bed sections of the combustor.

Crushed and sieved coal is fed from a pressurized hopper via a screw feeder pneumatically into the dense portion of the fast fluidized bed, using metered high pressure air. Sized limestone, stored in a separate hopper, is fed simultaneously into the air stream, conveying the coal into the bed. Both coal and limestone feed systems have been calibrated individually.

Two quartz glass-lined observation ports, one located in the dense bed at the bottom, and the other located near the top in the dilute phase or transport section of the bed, serve for visual monitoring of the combustion process. The circulating fluidized bed combustor is instrumented with chromel-alumel thermocouples at various positions for measuring temperature. The thermocouples are connected to a selector switch and, thence, to a digital readout meter.

Solids too small to be captured by the hot cyclone are trapped in a multiclone, mounted at the hot cyclone exit. In the present system, these multiclone solids are not reinjected into the bed. The multiclone solids are later analyzed for heat content, using an adiabatic calorimeter. Combustion gases are drawn off from a point at the exit of the multiclone, filtered through 2-5 micron particulate filters, and conveyed via heated lines to an instrument panel for determining gas composition. Carbon monoxide and carbon dioxide are measured with Beckman NDIR analyzers, oxygen with a Beckman 755 paramagnetic analyzer, oxides of nitrogen, NO_x, with a Thermoelectron 10 AR chemiluminescent analyzer and sulfur dioxide with a Beckman IR analyzer.

Coal Water Slurry Feed System

When firing coal-water slurry (CWS) fuels, the feed system shown in Figure 1(b) is used. The CWS fuel is stored in a container fitted with a motor-driven stirrer, to maintain uniformity of slurry composition. The slurry is pumped by a speed-controlled peristaltic pump to the CFBC and injected pneumatically into the region above the dense portion of the bed, using a water-cooled injector. Due to the longer residence times in the fluidized bed, and the effective mixing of the slurry droplets and the bed material, it is not necessary to provide a finely atomized slurry to the bed. Hence, a low pressure system such as the one illustrated in Figure 1(b) has been found adequate in previous tests, and is the one used in the present tests.

Pellet Feed System

The coal-sorbent pellets are injected pneumatically into the dense bed using a vibrating feeder. Feed rates are controlled by changing the frequency of vibration. Feed rates are measured by feeding a known weight of pellets and measuring the time in which this known weight of pellets is utilized by the burner.

II. Test Procedures

CFBC Combustion and Emissions Tests

The combustion testing of the coal slurry and pellet fuels involves the following steps:

* The CO, CO_2, O_2, NO_x and SO_2 analyzers are calibrated at the beginning and at several times during a test burn.

* The CFBC combustor is filled with the proper amount of bed material (sand or limestone).

* The propane preheat system is fired the bed material and unit is brought up to about 1100-1200°F. This step takes several hours.

* Coal and limestone hoppers are filled with prepared standard coal and limestone sorbent, respectively.

* The coal feed is initiated and the CFBC unit is brought up to operating temperatures of around 1500°F on the standard coal. The operation of all sampling and control systems are checked.

* For tests with standard coal and the slurry and pellet fuels, typical values of operating variables are as follows:

fluidization velocity: 9 ft/sec
Ca/S ratio: 1-4
Bed temperature: ≈ 1450-1650°F

These parameters are kept constant with all the fuels, so that comparison of the combustion and emissions parameters can be made under identical conditions of operation.

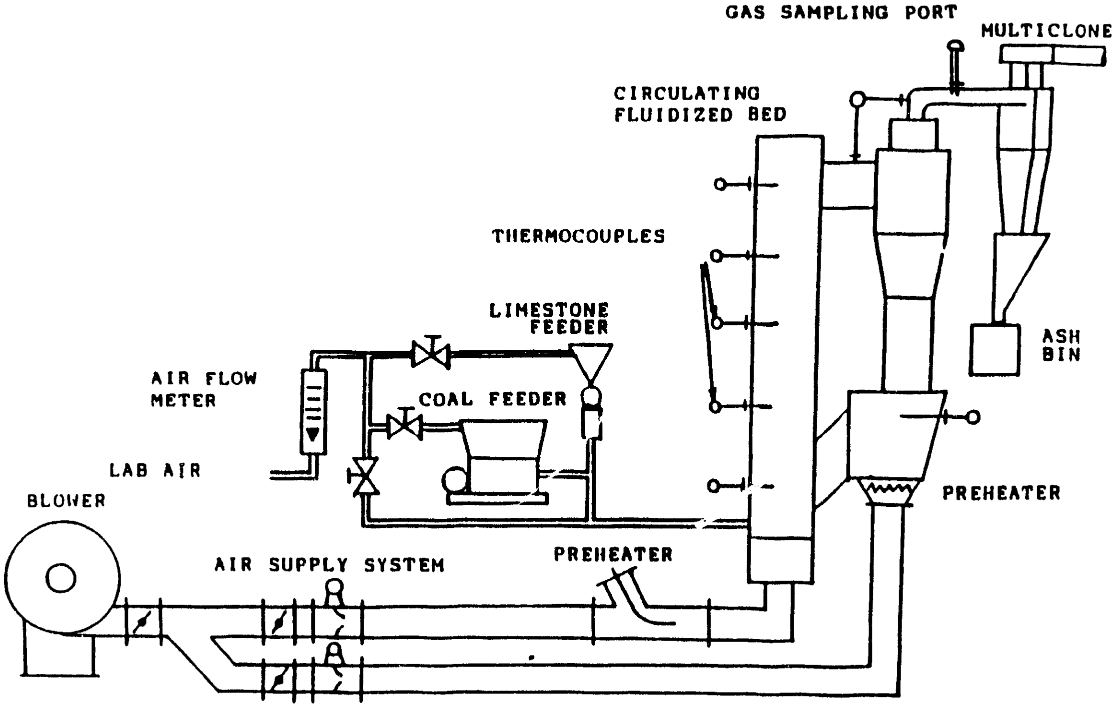

Figure 1(a). Schematic of 4-Inch Internal Diameter CFBC Facility

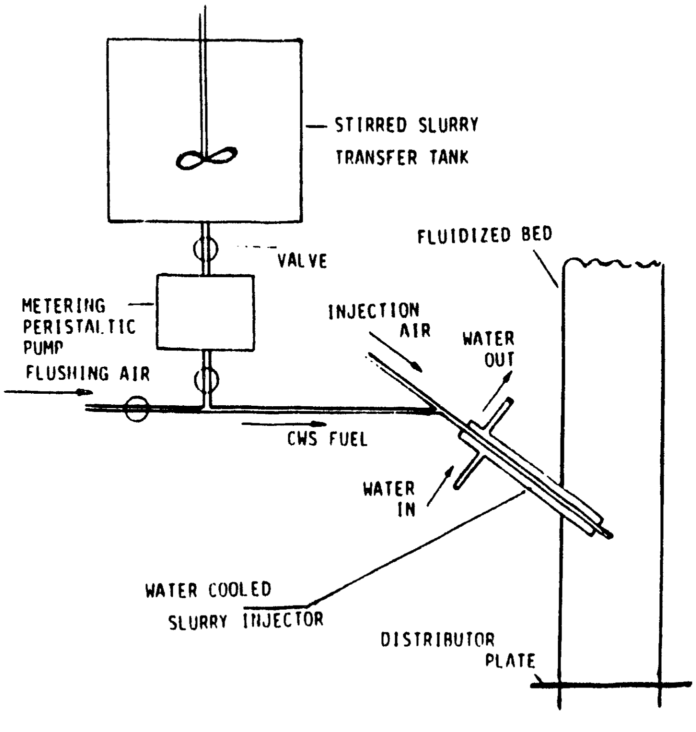

Figure 1(b). Schematic of Slurry Injection System

* During the coal-sorbent pellet tests, the pellets are injected pneumatically into the bed. No additional limestone sorbent will be injected during initial tests. If SO_2 emissions are higher than EPA limits, further tests will be conducted with limestone injection.

* With the coal-water slurry fuels, a special in-house fabricated pneumatic slurry injection system, Figure 1(b), is employed to inject the slurry fuel into the combustor.

* Each test run is made after the combustor has reached steady state conditions. Combustor steady state conditions are usually achieved after 30-48 hours of operation. Where test fuel supplies are limited, the procedure adopted is to first bring the combustor to steady state operation on the standard coal or another Illinois coal, and then change the fuel feed to the test coal, slurry or pellet fuel only for the duration of the steady state data acquisition period. The recycle ratio is controlled to be the same for each test, as far as possible.

* The variables measured during a test include:

- fuel and air mass flows
- air superficial velocity
- bed temperature
- other temperatures at various combustor locations
- combustion gas analysis comprised of CO, CO_2, O_2, NO_x and SO_2 emissions
- test duration time
- quantity of ash collected in cyclones during test period

Combustion generated ash and spent limestone from the slurry fuel, pellets and standard coal tested are analyzed. The heat content of the elutriated unburnt carbon is determined from calorimetry tests. Spent limestone and ash are prepared on metal stubs and subjected to energy dispersive x-ray (EDX) analysis to determine the elements present in the samples.

Sample Analysis

(a) Solids Concentration Determination of Slurry Samples

Three samples of slurry fuel were analyzed to determine their solids concentration. This are:

(1) the dilute coal-water stream from the flotation cell,
(2) a flotation concentrate obtained by gravity concentration, and
(3) the centrifuge product containing a high solids loading.

In each case, the solids concentration loading was determined by taking a known weight of well-mixed sample of each of the above fuels, and driving off the moisture by heating in a vacuum oven maintained at less than 100°C and measuring the weight of the dried sample at regular intervals till no weight change was detected in the dried sample.

(b) Proximate and Ultimate Analyses

Proximate and ultimate analyses of the above three slurry fuels and the size graded reference Illinois No. 5 coal were obtained using standard ASTM procedures at the Coal Technology Laboratory at Carterville, Illinois.

(c) Particle Size Analysis

Particle size analysis in the range below 125 microns was obtained utilizing a Leeds and Northrup Microtrak Model 7995-10 particle size analyzer. A schematic of the instrument is shown in Figure 2. In this version of the instrument, a laser beam is projected through a transparent cell which contains a stream of moving particles suspended in a liquid. Light rays which strike particles are scattered through angles which are inversely proportional to their sizes. The rotating optical filter transmits light at a number of predetermined angles and directs it to a photodetector. Electrical signals proportional to the transmitted light flux values are processed by a microcomputer system to form a multi-channel histogram of the particle size distribution.

(d) Mineral Matter Analysis

The mineral matter analysis of the coal in the three slurry fuels and the reference Illinois No. 5 coal was conducted with a Hitachi H-600 analytical electron microscope operating both in the transmission and the scanning-transmission electron microscopy (STEM) modes. With STEM, a Tracor-Northern energy dispersive x-ray (EDX) Model 5500 analysis system was employed. The specimen samples were mounted on adhesive copper grids and examined at 100kV in the electron microscope. The samples were uncoated.

Data Analysis

From the measured data the following parameters will be computed:

* excess-air ratios
* Ca/S mole ratios
* carbon conversion efficiency
* sulfur capture efficiency %
* SO_2 emissions levels in lb/10^6 Btu
* carbon balances

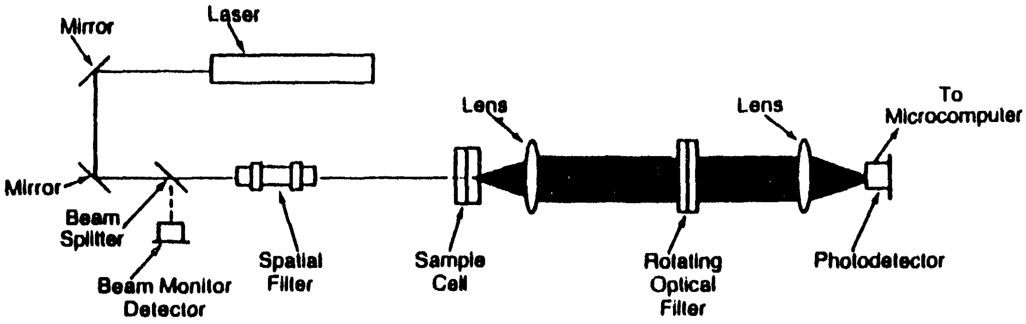

Figure 4. STANDARD RANGE ANALYZER - PARTICLE MEASURING SYSTEM

Figure 2. Schematic of Microtrak Particle Size Measurement System

RESULTS AND DISCUSSION

Solids Concentrations

The solids concentrations of the three slurry fuels (A = feed from flotation cell, B = flotation concentrate and C = centrifuge product) and the reference coal are shown in Table 1. The flotation cell coal A used as feed material for further coal recovery had only 5.6% solids, the flotation concentrate B had 46.7% solids and the centrifuge concentrate C had 79.3% solids. The run-of-mine Illinois contained 6.76% moisture.

Chemical Analysis of Fuels

Table 1 also shows the proximate and ultimate analyses of the fuels and their respective heating values. The flotation

TABLE 1

	Flotation Product used as feed	Flotation Concentrate	Centrifuge Product	Ref. IL #5 Coal
	A	B	C	
Solids Concentration				
Moisture %	94.4	53.3	20.7	6.76
Solids %	5.6	46.7	79.3	93.24
Dry Basis				
Proximate Analysis				
Volatile %	23.78	28.67	30.04	33.44
Ash %	31.38	5.33	9.95	13.34
Fixed Carbon	44.84	66.00	60.01	53.22
Elemental Analysis				
Carbon %	58.22	79.63	72.35	73.11
Hydrogen %	2.131	3.177	3.450	5.21
Nitrogen %	1.221	1.610	1.762	1.71
Sulfur %	1.226	0.945	1.497	1.51
Oxygen %	5.822	9.308	10.991	5.71
Heating Value				
Btu/lb	9,549	13,584	12,732	11,529

product used as feed for the recovery process is high in ash (31.4%) and low in volatiles (23.7%). Flotation concentrate B, centrifuge product C and the reference coal have about 30% volatiles. The reference Illinois No. 5 coal has a fixed carbon content of 53.22%. It also has a sulfur content of 1.51%. The flotation product A has the lowest Btu content of 9549 Btu/lb. Oxygen content of the fuels is obtained from the elemental analysis by difference after subtracting the ash and the other components of the elemental analysis from 100. The limestone used to capture SO_2 gases during the slurry and pellet fuel tests was agricultural grade limestone, obtained from the Anna Quarries, Anna, Illinois. It contained a calcium carbonate equivalent of 96.5%. It was ground to -60 mesh size and fed into the combustor.

Particle Size Distribution

Figures 3-6 illustrate the histograms of the particle size distributions. The numbers on the left indicate mean particle size in microns of a given size cut. The numbers on the far right indicate the relative volume percent of the various particle sizes.

The histogram on the right indicates similar data on a cumulative basis. The numbers on the left side of the cumulative graph are upper limits in microns of the size bin into which the particles are classified e.g. 100% less than 125 microns 97% less than 88 microns, etc., in Figure 3. Thus, Figure 3 indicates that the flotation cell product used as feed for the recovery process consists mainly of particles less than 100 microns in size. The size distribution histogram on the left reveals that they are mostly in the 7-38 micron size range. These are quite fine particles, and if emitted as dust into the atmosphere could pose as a severe environmental hazard.

Figure 4 shows that the flotation concentrate B has essentially the same particle size distribution. The centrifuge product C, however, has larger solids mixed in with the flotation concentrate solids and exhibits a different size distribution, Figure 5. The larger particles from the centrifuge product C first had to be sieved out. It contained 6.4% by weight particles which passed through a 16 mesh sieve (0.0394 inch opening). 27.45% of sample C solids by weight were in the -16+35 mesh range (0.0394-0.0165 inch range), and 66.16% were in the -35 mesh range. The particle size distribution of this last cut (-35 mesh) is shown in Figure 5, indicating that these particles are generally slightly larger than those present in Samples A and B. Figure 6 shows the particle size distribution of the -60 mesh size limestone prepared for mixing with Sample C in the manufacture of the coal-limestone pellets to be burnt in later tests in this program.

```
RELATIVE VOL. GRAPH      CUMMULATIVE GRAPH
 106  *1                  125  **********100
  75  **3                  88  *********98
  53  ****5                62  *********94
  38  ********11           44  ********88
  27  *********12          31  *******76
  19  **********13         22  ******64
  13  *******10            16  *****50
 9.4  ********10           11  ****40
 6.6  ******8             7.8  **29
 4.7  *****7              5.5  **20
 3.3  ****5               3.9  *12
 2.4  *2                  2.8  7
 1.6  *2                  1.9  4
 1.2  *1                  1.4  2
 0.8  0                   0.9  0
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Figure 3. Particle Size Distribution and Cumulative Volume Graph for Flotation Cell Product A

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RELATIVE VOL. GRAPH      CUMMULATIVE GRAPH
 106  *2                  125  **********100
  75  ****6                88  *********97
  53  ****7                62  *********91
  38  ********12           44  ********84
  27  **********14         31  *******71
  19  *********14          22  *****57
  13  *******11            16  ****42
 9.4  *******11            11  ***30
 6.6  *****8              7.8  *19
 4.7  ***5                5.5  *10
 3.3  **3                 3.9  5
 2.4  1                   2.8  2
 1.6  0                   1.9  0
 1.2  0                   1.4  0
 0.8  0                   0.9  0
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Figure 4. Particle Size Distribution and Cumulative Volume Graph for Flotation Concentrate B

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RELATIVE VOL. GRAPH        CUMMULATIVE GRAPH
 106  *3                   125  **********100
  75  ****7                 88  *********96
  53  *******12             62  ********89
  38  **********16          44  *******76
  27  ********14            31  *****59
  19  ********13            22  ****44
  13  ******10              16  ***31
 9.4  ****8                 11  **20
 6.6  **4                  7.8  *12
 4.7  **3                  5.5  7
 3.3  *2                   3.9  4
 2.4  0                    2.8  1
 1.6  0                    1.9  0
 1.2  0                    1.4  0
 0.8  0                    0.9  0
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Figure 5. Particle Size Distribution and Cumulative Volume Graph for Centrifuge Product C

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RELATIVE VOL. GRAPH        CUMMULATIVE GRAPH
 106  ****4                125  **********100
  75  ********8             88  *********95
  53  *******7              62  ********86
  38  *********9            44  *******79
  27  **********9           31  *******70
  19  *********9            22  ******60
  13  *******7              16  *****51
 9.4  ********8             11  ****43
 6.6  *******7             7.8  ***35
 4.7  ******6              5.5  **28
 3.3  ******6              3.9  **21
 2.4  ****4                2.8  *14
 1.6  ****4                1.9  *10
 1.2  ***3                 1.4  5
 0.8  **2                  0.9  2
```

Figure 6. Particle Size Distribution and Cumulative Volume Graph for -60 Mesh Limestone

Fuels Preparation

Experiments were conducted with the CFBC brought up to operating temperature to determine if the coal-water slurry fuels had the proper solids concentration loading for smooth and continuous operation. Solids concentration loading was varied between 40 to 60% by adding or decanting water from the as-received coal-water slurry samples. If the solids loading was too high, some difficulty was experienced in transporting the slurry from the pump to the injector. Also, the injector tip which was in contact with the hot combustion gases tended to clog. If the solids concentration was too low, excessive amounts of water was being fed into the bed; and bed temperature was difficult to maintain, especially at higher bed temperatures. As a result of these experiments, it was determined that a solids concentration loading of 42-46% was best suited for the comparison experiments that were being performed. Therefore, the slurry fuels solids loading was altered to fall in this range. It was also determined that a common household detergent such as Cheer added in the amount of 15gms/50kg of slurry fuel also enhanced the flow properties of the slurry fuels.

The coal-sorbent pellets were obtained from researchers at ISGS. They contained ground limestone so that the Ca/S ratio of the pellet was 2.0. The pellets were 0.125 inches in diameter and 0.375 inches long. As received, the pellets were quite moist and fragmented easily. They were dried by blowing air over them until the moisture content was less than 5%. The pellets had 15% cornstarch as binder.

Combustion Test Results

The slurry fuels, standard coal and pellets were burnt in the CFBC unit under the conditions described above. Results of the combustion tests are discussed in the following sections, under the headings of Sulfur Dioxide Emissions, Oxides of Nitrogen Emissions and Combustion Efficiency.

Sulfur Dioxide Emissions

Two types of tests were conducted with the fuels. In one series of experiments, the effect of bed temperature on SO_2 emissions were investigated. In the second series, the influence of Ca/S ratio was measured. Where supplies of the fuel were limited, only one of the tests was possible.

Figures 7 and 8 illustrate the influence of bed temperature on SO_2 emissions from slurry fuels A and B, respectively. Slurry fuel A is derived from the very low (5.6%) solids loading flotation column effluent of the preparation plant. Slurry B is the flotation concentrate fuel as developed by ISGS under CRSC sponsorship. The Ca/S mole ratios for the data of Figures 7 and 8 are 2.5 and 2.7, respectively. As

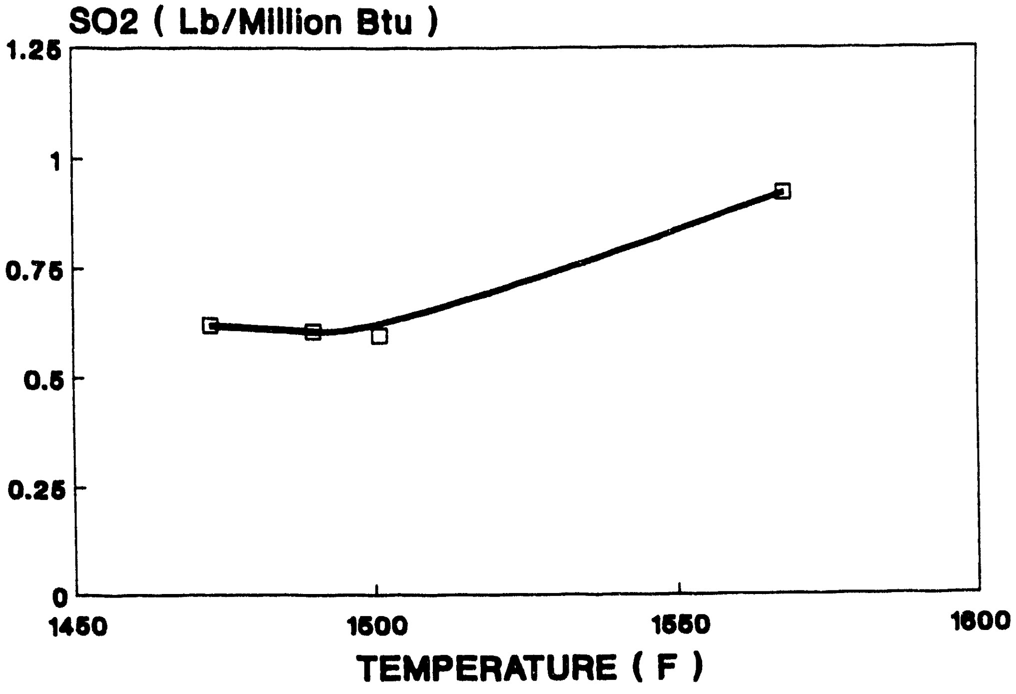


Figure 7. Variation of SO_2 Emissions with Bed Temperature; Slurry A, Ca/S = 2.5

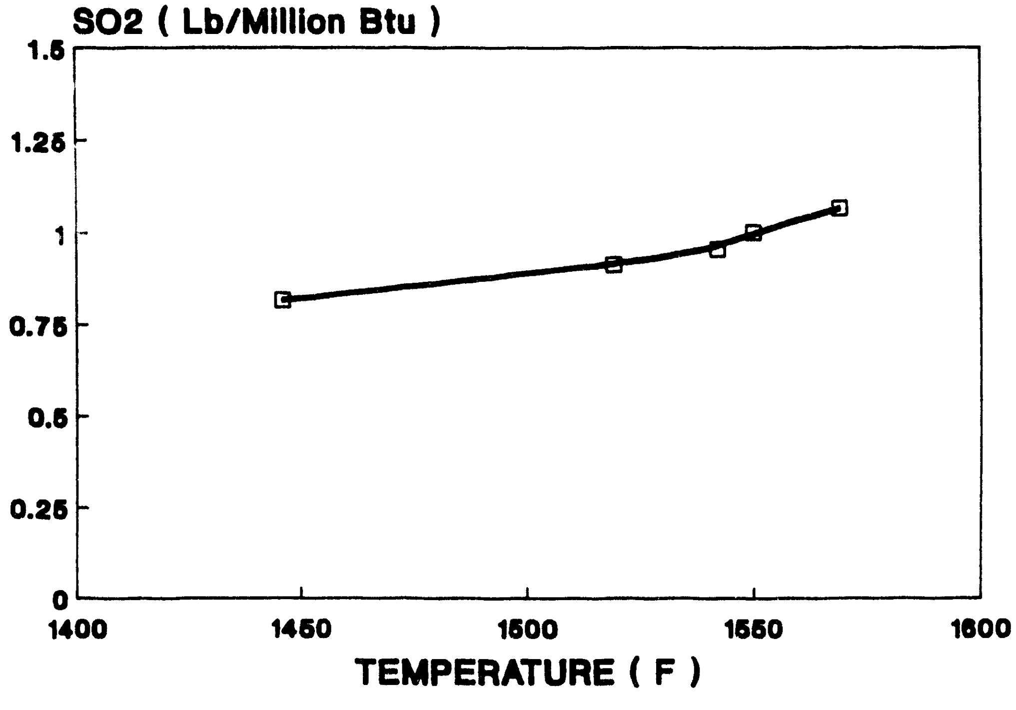


Figure 8. Variation of SO_2 Emissions with Bed Temperature Slurry B, Ca/S = 2.7

seen from the figures, the effect of bed temperature on SO_2 emissions is very similar for the two slurry fuels shown. These trends were also found to be similar for the standard coal and slurry fuel C.

The effect of bed temperature on the SO_2 emissions from the pellet fuel for a Ca/S ratio of 2.0 is shown in Figure 9. Figure 10 depicts the comparative emissions levels of SO_2 from the standard coal, slurry fuel A and slurry fuel C at a bed temperature of 1575°F and a Ca/S ratio of 2.5. Generally, the slurry fuels yielded lower levels of SO_2 emissions than the standard coals, especially at lower Ca/S ratios.

The effect of Ca/S ratio on the slurry fuels and the pellets is shown in Figures 11 and 12 for a bed temperature of 1550°F. Slurry A coal contained about 1.2% sulfur, while slurry C coal contained 1.5% sulfur. The standard coal and the coal used in the pellets also contained 1.5% sulfur. At low Ca/S ratios less than Ca/S = 2.5, the slurry fuels emit lower levels of SO_2 in lbs per million Btu. Thus, with slurries of this type, and with fuel and operating conditions optimized, it may be possible to meet EPA emissions limits on SO_2 with very small Ca/S ratios.

With higher Ca/S ratios, it was found that the standard coal exhibited a more rapid decline in SO_2 emissions than the slurry fuels. For these tests, the limestone feed rate was varied. This is seen in Figure 11 by comparing the levels from the standard coal and slurry C which has the same percentage of sulfur in the coal. This is attributed to the dispersion characteristics of the fuel and limestone in the fluidized bed. The slurry fuel is in the form of larger droplets than the standard coal. As the Ca/S ratio is increased, more limestone particles are dispersed in the bed; and since the coal particles are also more dispersed, the probability of SO_2 capture increases. This effect is not so strong for the slurry fuels, and the rate of decrease of SO_2 emissions with increasing Ca/S ratios is slower. Figure 12 shows the influence of Ca/S ratios on the pelletized coal fuel. The pellet has limestone incorporated in it such that the Ca/S ratio is 2:1. In these pellet tests, additional limestone was also fed separately to investigate the influence of increasing the Ca/S ratio in the bed beyond the 2:1 ratio already inherent in the pellets. Again, the decrease of SO_2 emissions with increasing Ca/S ratios is not as prominent as with the standard coal for similar reasons. However, the SO_2 release and absorption characteristics and histories are different for the slurries, standard coal and pellet fuels, and is evidenced by the lower SO_2 emissions levels for the pellets and slurry fuels at lower Ca/S ratios.

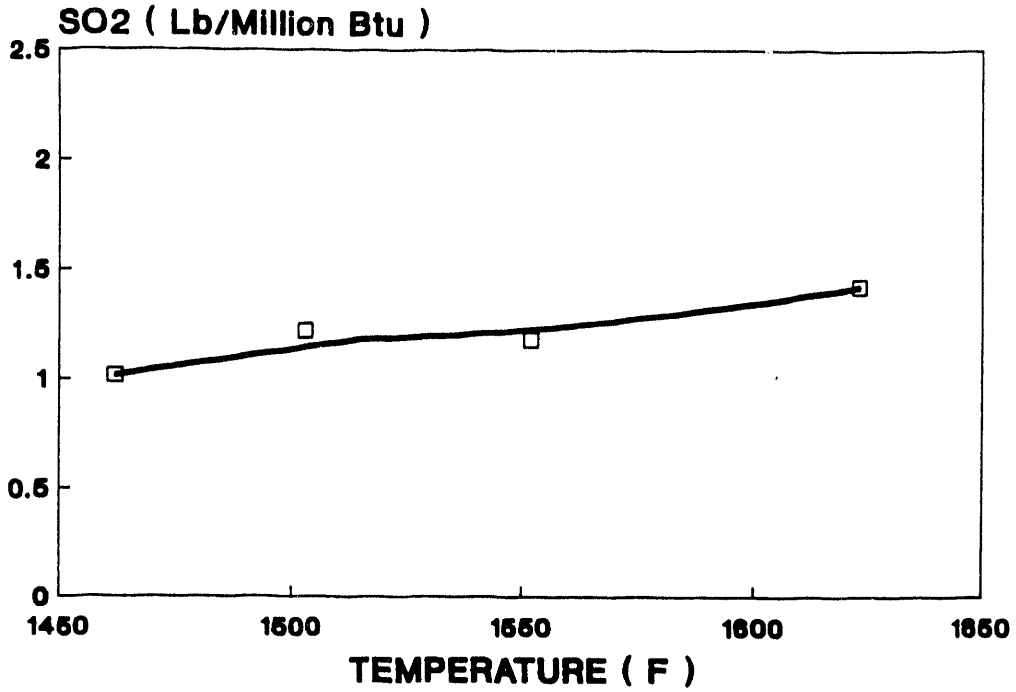


Figure 9. Effect of Bed Temperature on SO_2 Emissions; Coal-Sorbent Pellets, Ca/S = 2.0

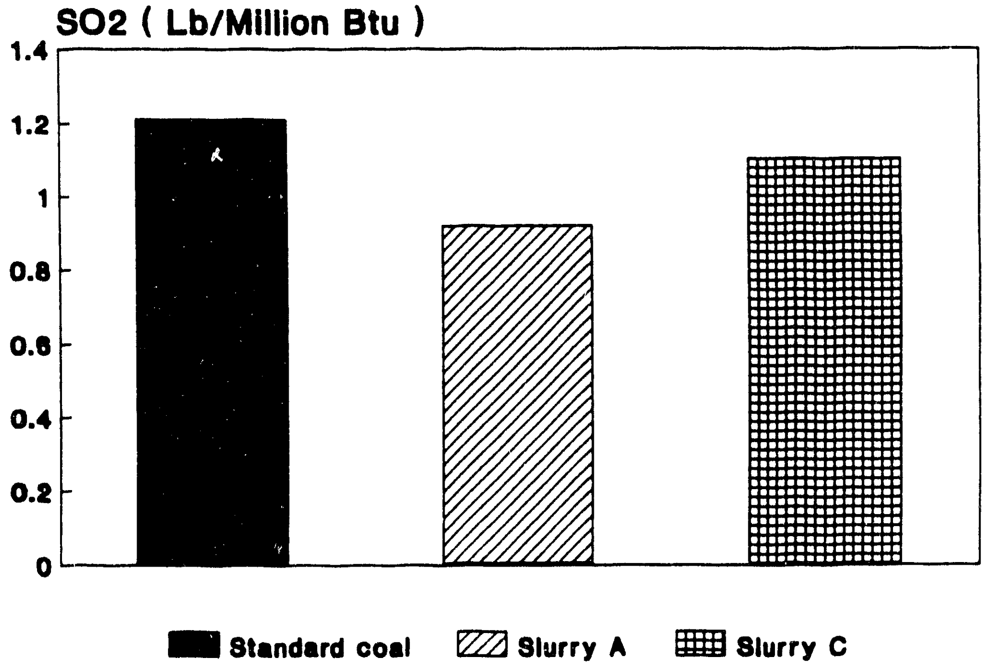


Figure 10. Comparative SO_2 Emissions for Standard Coal, Slurry A and Slurry C; Bed Temperature 1575°F, Ca/S = 2.5

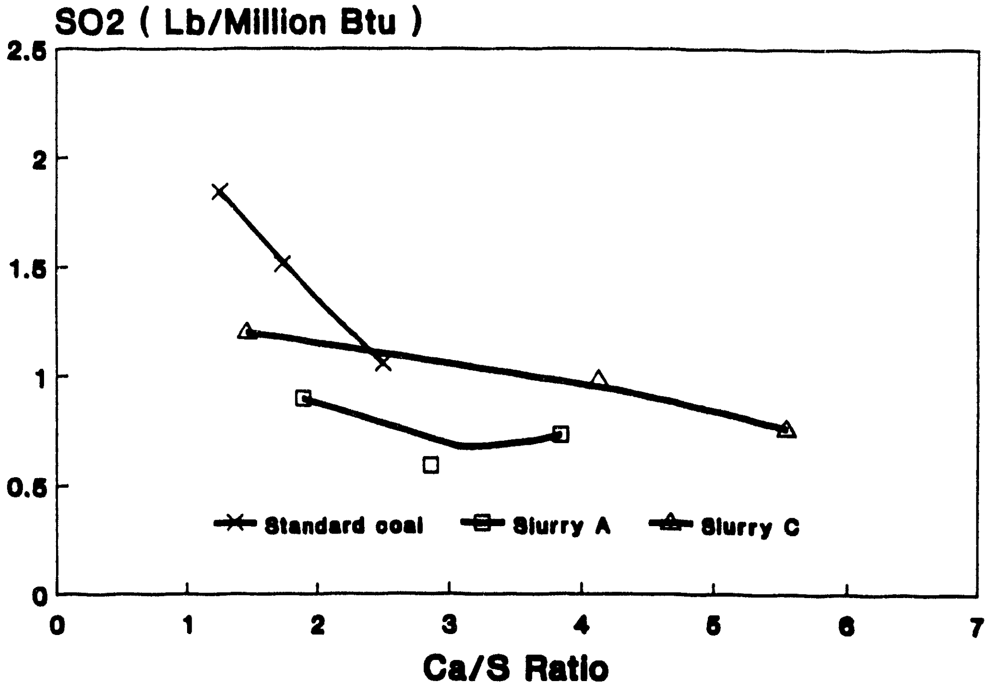


Figure 11. Influence of Ca/S Ratio on SO_2 Emissions for Slurry Fuels

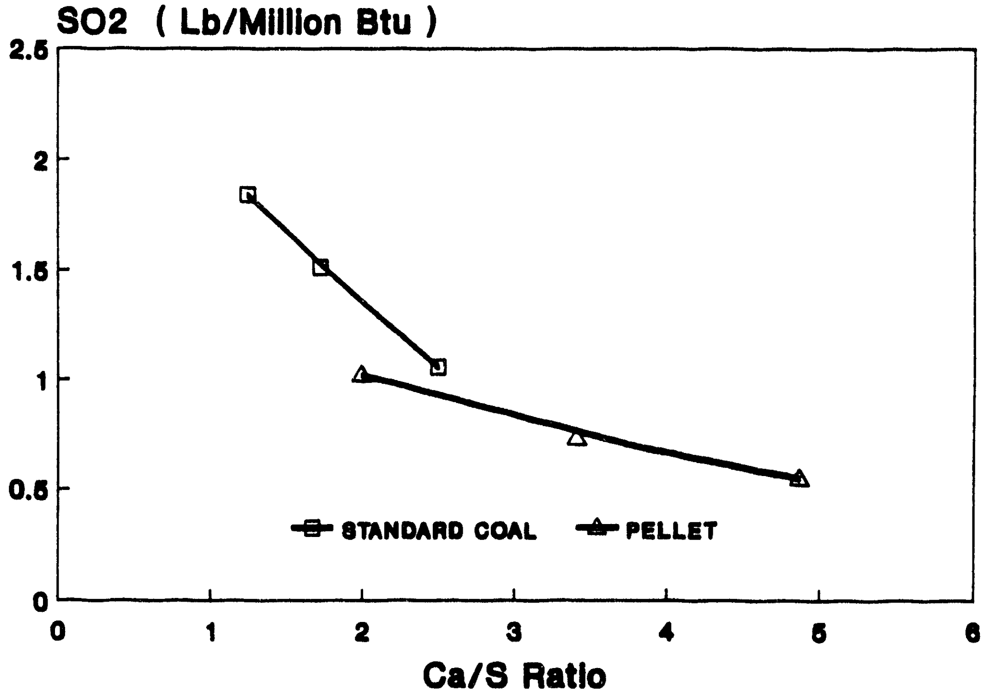


Figure 12. Influence of Ca/S Ratio on SO_2 Emissions for Pellets with Additional Limestone Injection

Oxides of Nitrogen Emissions

Oxides of nitrogen emissions in lbs per million Btu are shown in Figures 13-16 as a function of bed temperature. Nitrogen content of the slurry coals varied from 1.22 to 1.76% while that of the standard coal and the pellet coal was 1.71%. Regardless of fuel nitrogen content, the NO_x emissions of the slurry fuels were uniformly lower than those from the standard coal. This can clearly be attributed to the lower temperature environment of the burning coal-water slurry droplet, especially in the preliminary combustion stages encompassing the volatiles release phase. For the slurry fuels, NO_x levels were on the order of 0.3 lbs/10^6 Btu. Oxides of nitrogen levels for the pellet fuel did not vary much with bed temperature in the range of 1460 to 1625°F and were on the order of 0.55 lbs/10^6 Btu. NO_x emissions for the standard coal at lower temperatures were similar in magnitude for the standard coal and pellet fuel. For the standard coal, they increased somewhat more rapidly with bed temperature increase to a value of 0.85 lb/10^6 Btu at a bed temperature of 1625°F.

Combustion Efficiency

Figures 17-19 show the range of combustion efficiencies measured in the present experiments. Slurry A coal had the lowest heating value of 9550 Btu/lb, but yielded the highest efficiency among the slurry fuels, Figures 17 and 18. The longer residence time of the slurry droplets in the hotter regions of the bed generally results in higher combustion efficiencies for the slurries. Figures 18 and 19 show that the combustion efficiency varies almost linearly with bed temperature under the conditions of the present tests. Very good efficiencies were also measured for the pellet fuels, on the order of 98% as seen from Figure 19.

Mineral Matter Analysis

Carbon Balances

Carbon balances were made on selected test runs. The proximate and ultimate analyses of the coal were used to write a chemical balance equation with the reactants on one side which included the elements C, H, N, S and O_2 and N_2. The product included the compounds CO, CO_2, SO_2, NO_x and the elements O_2 and N_2. Unburnt carbon in the fly ash was accounted for as a product of the reaction. Using the measured concentrations of CO, CO_2, O_2, NO_x and SO_2, gases in the exhaust and the mass of unburnt carbon in the fly ash, the feed rate of carbon to the combustor was calculated from the balanced chemical reaction equation. These calculated carbon feed rates were compared with the ones actually measured as found from the measured coal feed rate.

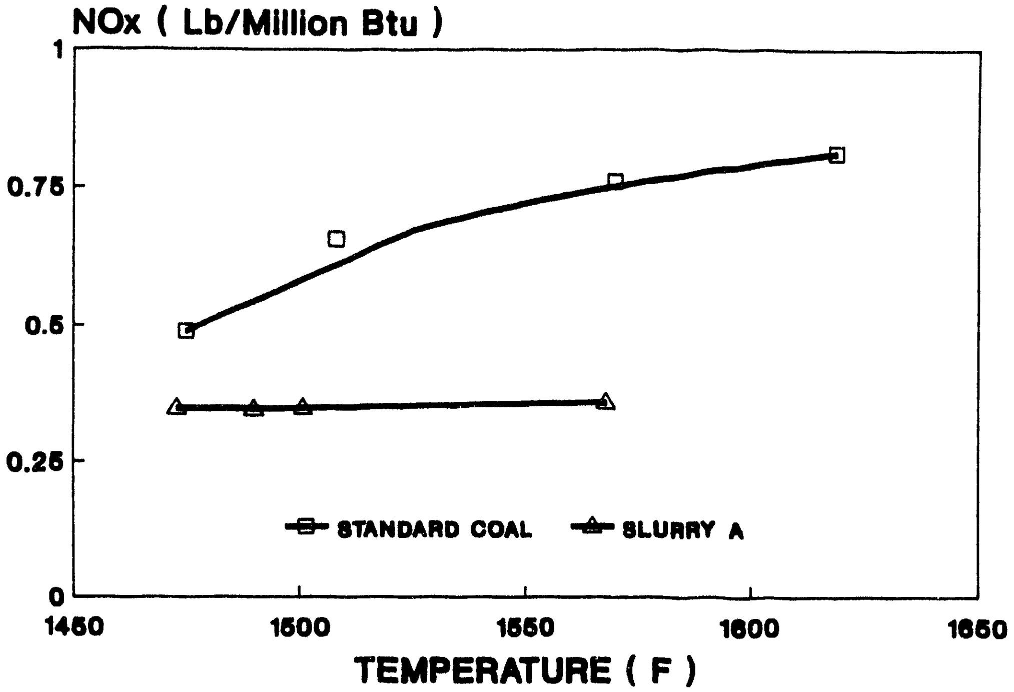


Figure 13. Comparison of NO_x Emissions for Standard Coal and Slurry A

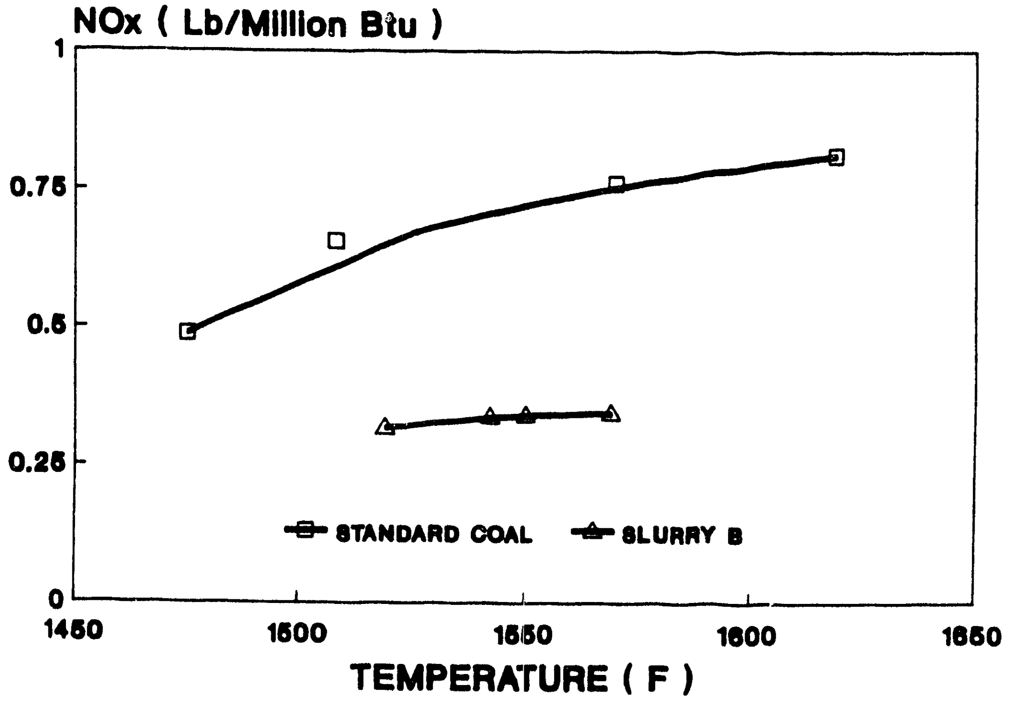


Figure 14. Comparison of NO_x Emissions for Standard Coal and Slurry B

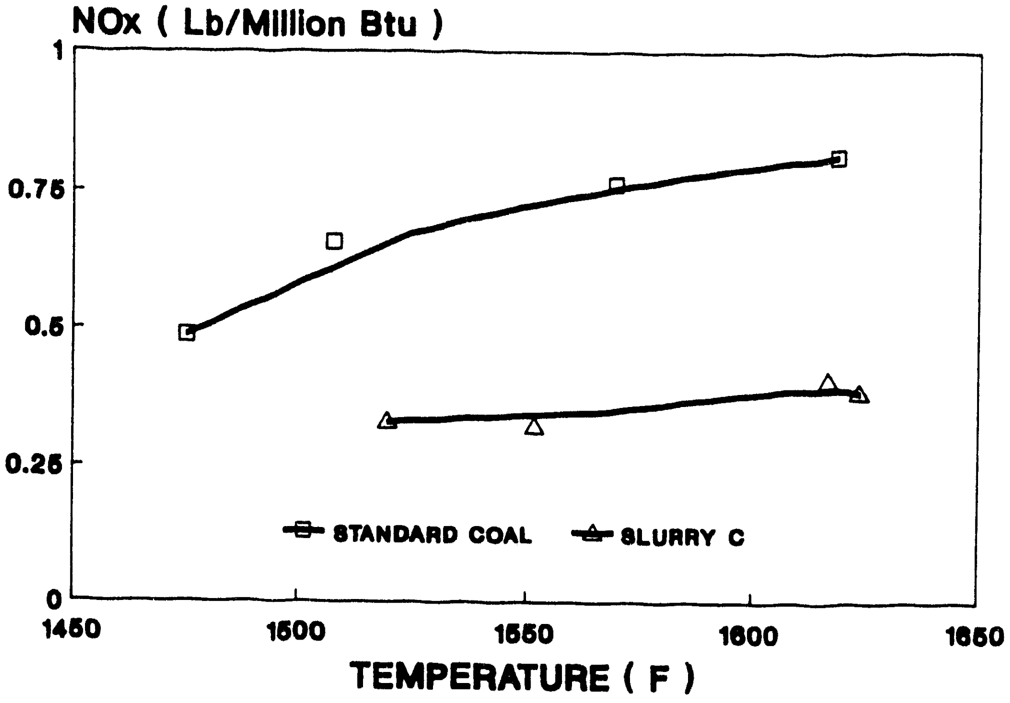


Figure 15. Comparison of NO_x Emissions for Standard Coal and Slurry C

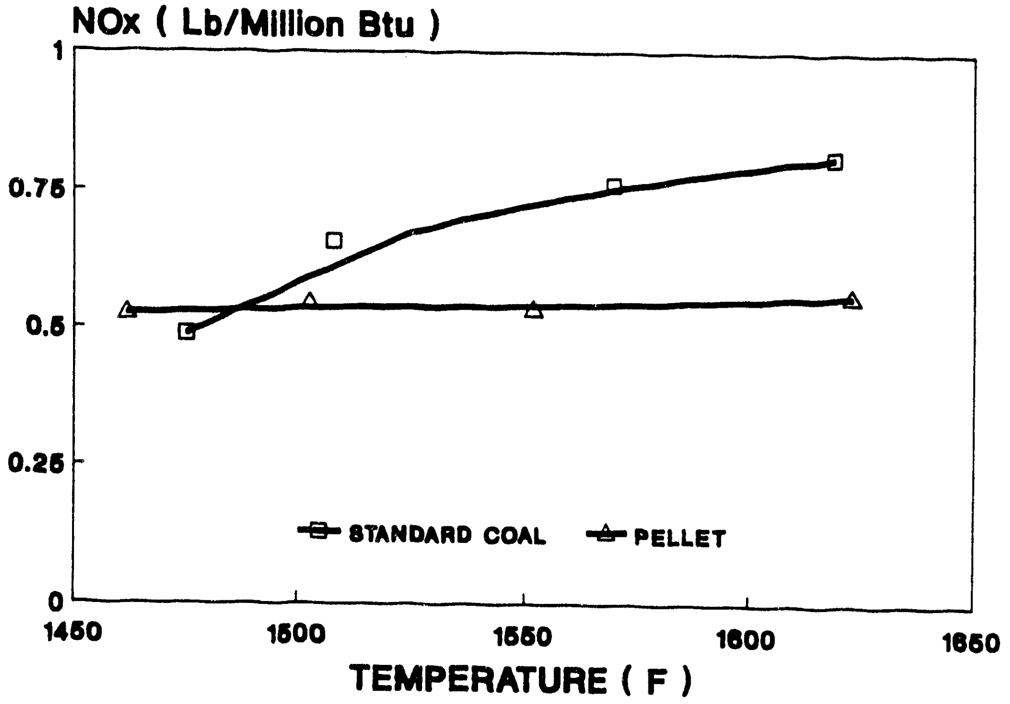


Figure 16. Comparison of NO_x Emissions for Standard Coal and the Pellets

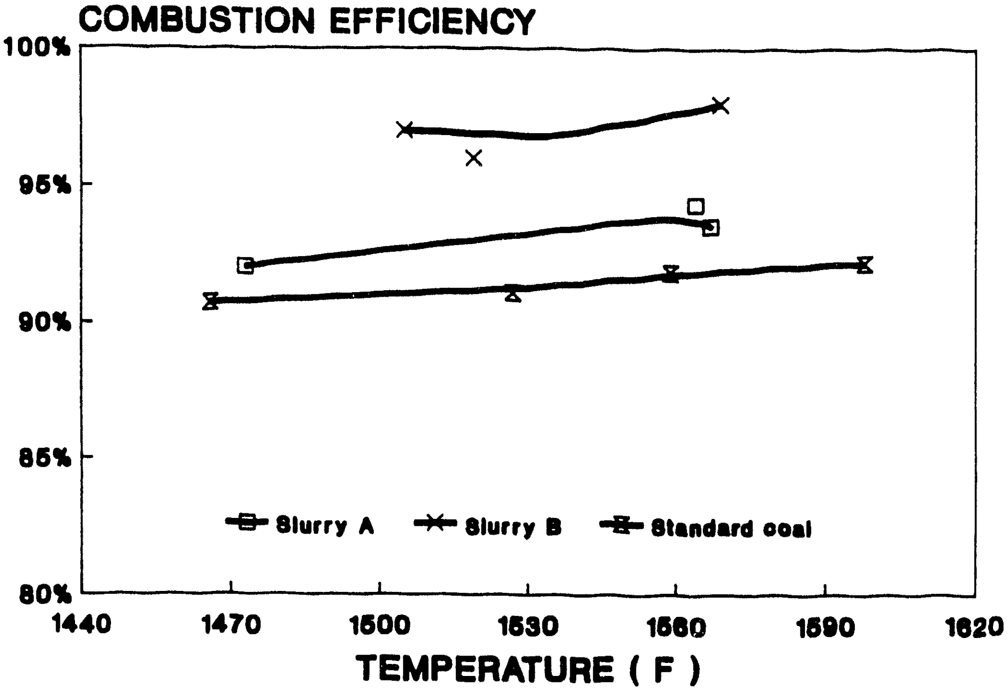


Figure 17. Influence of Bed Temperature on Combustion Efficiency for Slurry Fuels

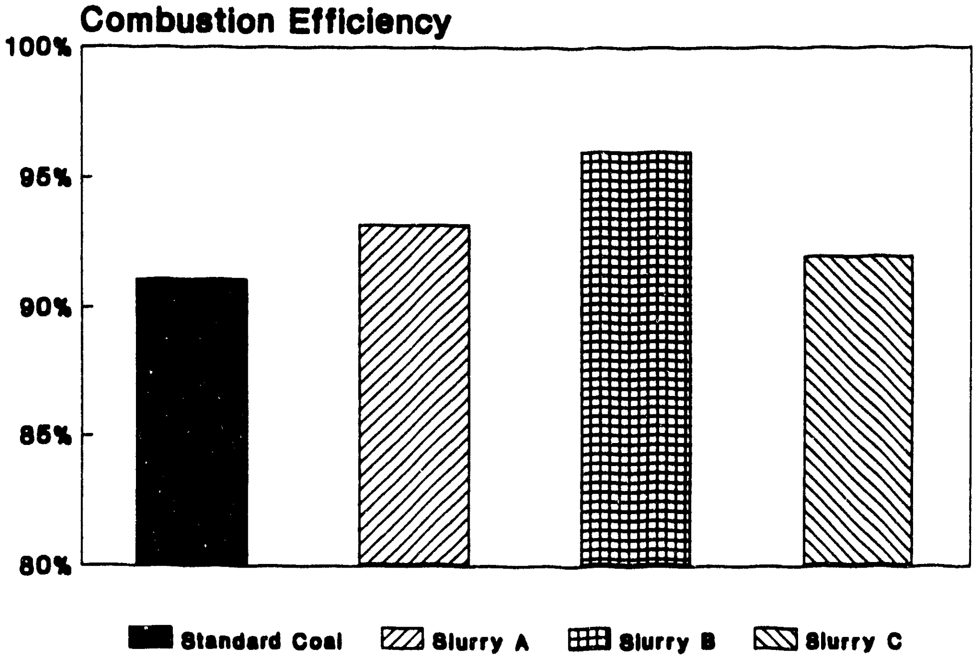


Figure 18. Comparison of Combustion Efficiencies at Bed Temperature of 1550°F

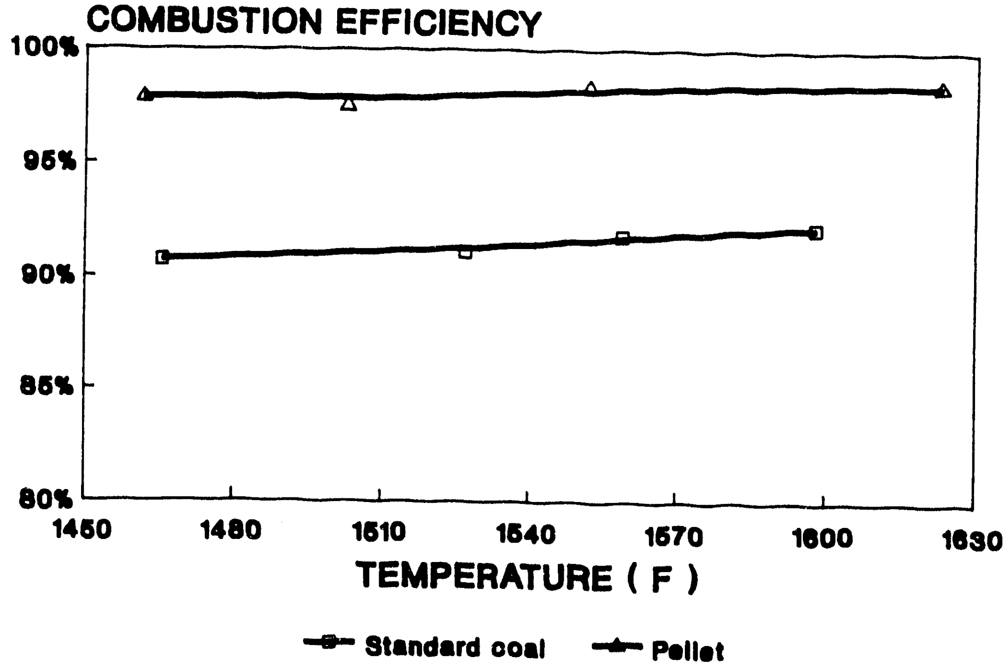


Figure 19. Effect of Bed Temperature on Combustion Efficiency of the Pellet Fuel

Generally, agreement between the calculated and measured carbon feed rates was within 10%. The sources of error in the carbon balance are (a) the error introduced in the coal feed rate measurement from the calibration of the coal feeder, and (b) the compounding of small errors in the measurements of the exhaust gas composition and the fly ash mass and composition. The errors in (a) are largely the result of back pressure transmission from the fluidized bed combustor to the coal feeder. A large number of measured variables enter into the carbon balance calculations. For some of the calculations the error was less than the 10% mentioned above.

Mineral Matter and Trace Element Analyses

The coal-water slurries, the standard coal and the coal-sorbent pellets all had various amounts of ash or mineral matter in them. The transformations in the inorganic content of the coals comprising the slurry fuels, run-of-mine fuel and pellets was investigated. The combustion generated ash of a typical test run from the slurry fuel which had the largest amount of inorganic matter in the coal (Slurry A coal) was also analyzed for trace elements by a professional laboratory. The results of this trace elemental analysis is given in Table 2. The histogram shows the ppm or percentage levels of trace elements in the ash. A bar opposite the element listed indicates that the element is present in the list of trace elements measured using x-ray spectroscopy. Elements listed in Table 2 in brackets e.g. platinum Pt [33.49ppm] indicate that platinum was not present in the ash and its detection limit for this analysis was 33.49ppm.

Energy dispersive x-ray analysis was also conducted to examine the mineral matter transformations. For each fuel tested, the raw coal and a representative ash from the combustion tests were selected and the samples subjected to a low temperature ashing process using oxygen plasma at 100°C. This process removed any remaining organic matter in the coal. EDX spectra were then taken of the raw coal ash and the ash from the CFBC combustor. A typical comparison is made in Figure 20. The top spectrum for Slurry C coal is for the raw coal, and the bottom spectrum is for the corresponding burnt coal ash. The major portion of these ash samples are aluminum, silicon and iron.

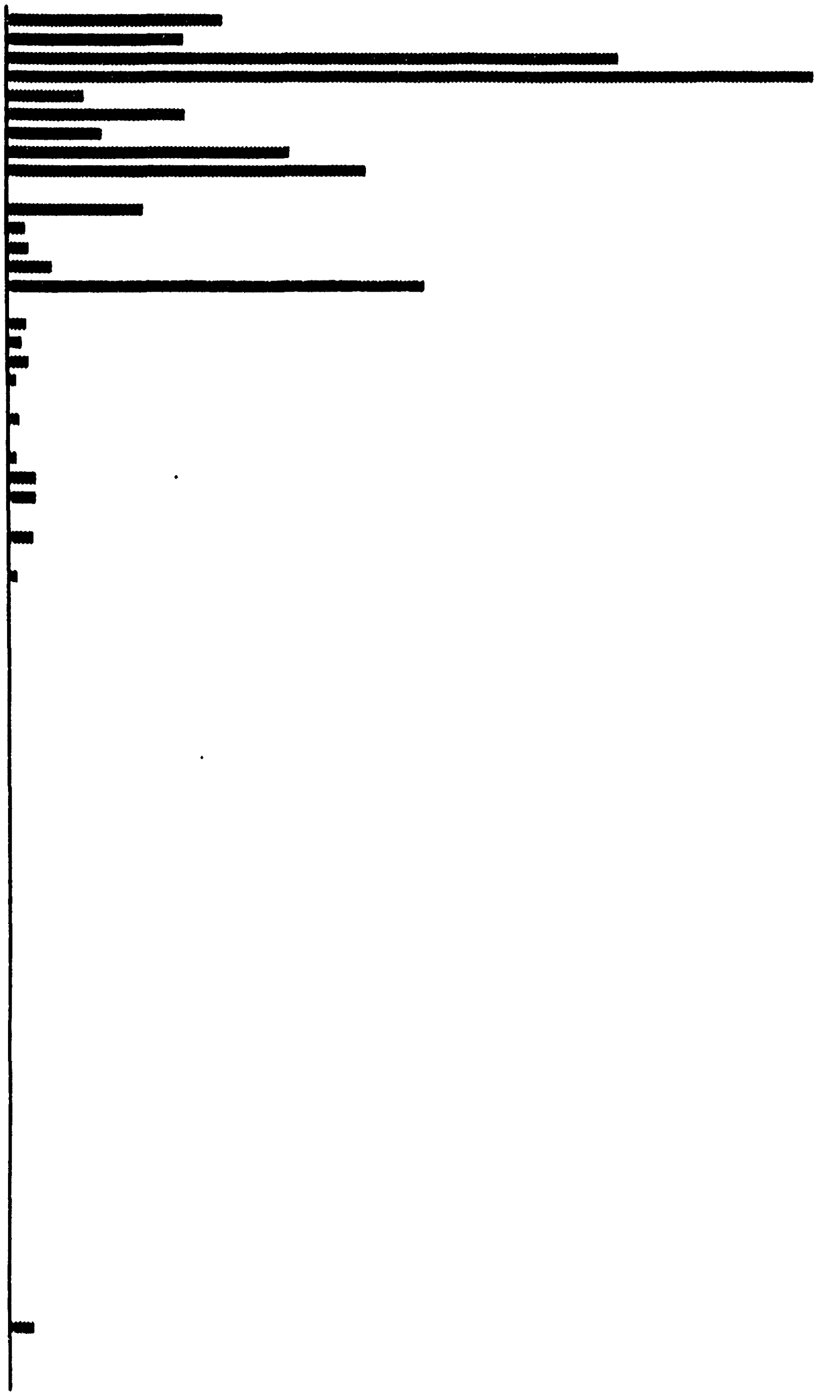
Figures 21-25 show the transformations in the elements sodium, potassium, sulfur, calcium and iron, respectively. The element sodium is a component of compounds corrosive to the boiler tube environment. The highest percentage of sodium was about 4.8 weight percent of the ash in the raw coal for slurries A and B. Upon combustion, some of this sodium is converted into volatile compounds, causing a reduction in the weight percent of sodium in the fly ash for most of the fuels tested as seen in Figure 21. For Slurry C, there is a

Table 2

Histogram of Elements Present in Slurry A Ash (Elements printed as symbols are below the detection limits shown in brackets.)

Bed temperature 1550°F; Ca/S = 2.5

Sodium	1.5879	%	±	0.338
Magnesium	1.0563	%	±	0.195
Aluminum	12.9397	%	±	0.866
Silicon	23.5674	%	±	1.552
Phosphorus	0.1958	%	±	0.040
Sulfur	1.0750	%	±	0.078
Chlorine	0.3030	%	±	0.026
Potassium	2.7439	%	±	0.183
Calcium	4.4340	%	±	0.294
Sc	[326.200	ppm	]	
Titanium	0.6285	%	±	0.043
Vanadium	92.9351	ppm	±	44.516
Chromium	128.696	ppm	±	19.690
Manganese	641.258	ppm	±	46.171
Iron	6.0211	%	±	0.396
Co	[102.200	ppm	]	
Nickel	94.9023	ppm	±	8.873
Copper	52.7848	ppm	±	6.456
Zinc	124.324	ppm	±	10.754
Gallium	11.6342	ppm	±	4.086
Ge	[8.5090	ppm	]	
Arsenic	30.6974	ppm	±	10.241
Se	[7.5400	ppm	]	
Bromine	14.1277	ppm	±	5.590
Rubidium	231.385	ppm	±	23.000
Strontium	238.674	ppm	±	26.135
Y	[47.2700	ppm	]	
Zirconium	176.989	ppm	±	28.389
Nb	[42.1000	ppm	]	
Molybdenum	13.1056	ppm	±	18.506
Tc	[38.2000	ppm	]	
Ru	[38.9600	ppm	]	
Rh	[59.2700	ppm	]	
Pd	[30.3200	ppm	]	
Ag	[105.200	ppm	]	
Cd	[93.1400	ppm	]	
In	[139.200	ppm	]	
Sn	[185.000	ppm	]	
Sb	[208.300	ppm	]	
Te	[0.2970	%	]	
I	[0.1425	%	]	
Cs	[406.700	ppm	]	
Ba	[791.100	ppm	]	
La	[572.600	ppm	]	
Ce	[302.500	ppm	]	
Pr	[232.400	ppm	]	
Nd	[129.000	ppm	]	
Pm	[122.300	ppm	]	
Sm	[98.7700	ppm	]	
Eu	[140.300	ppm	]	
Gd	[158.400	ppm	]	
Tb	[947.300	ppm	]	
Dy	[0.1011	%	]	
Ho	[164.100	ppm	]	
Er	[398.000	ppm	]	
Tm	[477.100	ppm	]	
Yb	[75.0000	ppm	]	
Lu	[48.4500	ppm	]	
Hf	[44.1000	ppm	]	
Ta	[47.5100	ppm	]	
W	[42.1200	ppm	]	
Re	[62.2500	ppm	]	
Os	[34.2600	ppm	]	
Ir	[32.9800	ppm	]	
Pt	[33.4900	ppm	]	
Au	[33.2900	ppm	]	
Hg	[26.9200	ppm	]	
Tl	[35.0700	ppm	]	
Lead	178.363	ppm	±	26.059
Bi	[28.8800	ppm	]	
Th	[104.300	ppm	]	
U	[112.900	ppm	]	



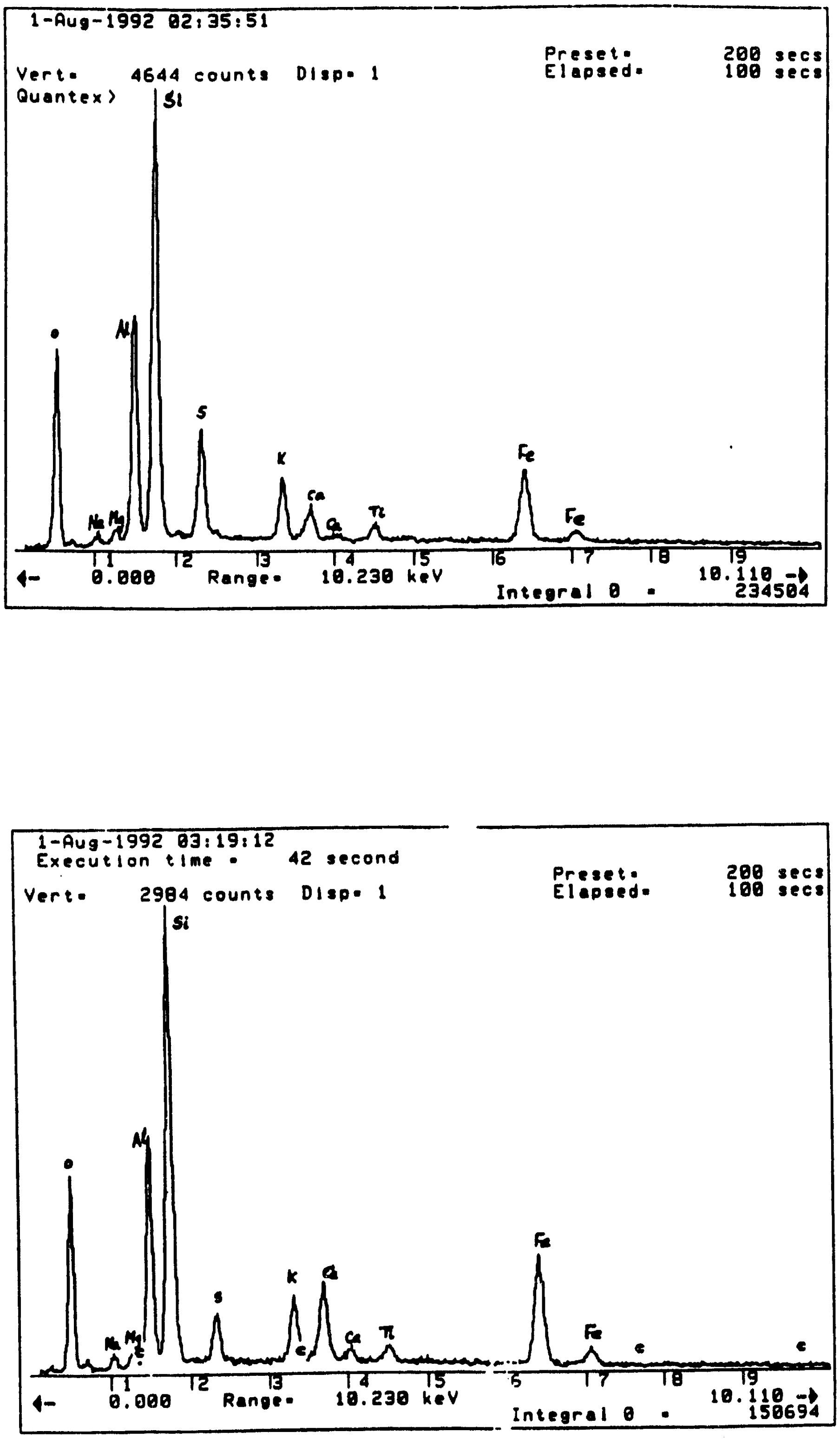


Figure 20. EDX Spectra of Ash from Unburnt and Burnt Coal (Slurry C Coal)

very small increase in the weight percent of sodium. This does not mean that the sodium content has actually increased. Rather, it means that the ash composition has changed to reflect a larger percentage of sodium compared to the whole ash content.

The element potassium also exhibits a similar trend on combustion. Generally, the potassium percentage in the ash decreases with combustion, Figure 22. These changes are not as pronounced as with pulverized coal combustion where the temperatures are higher. Potassium compounds provide a corrosive environment around the heat transfer tubes. Other corrosive compounds contain sulfur. The sulfur transformations are shown in Figure 23, indicating a reduction in sulfur content of the ash in each case. Most of the remaining sulfur is found with the calcium in the ash shown in Figure 24. The increase in calcium in Figure 24 is brought about by the addition of limestone.

Iron transformations are shown in Figure 25. The weight percentages of iron in the burnt ash samples were found to be higher than in the raw coal samples for all the fuels tested. Iron compounds are quite volatile and are some of the first particles to adhere to boiler heat transfer tubes, causing deposit buildup.

CONCLUSIONS

Evaluation of the combustion and emissions properties of three coal-water slurry fuels processed from preparation plant waste streams have been performed. Compared with similar performance from a standard run-of-mine coal, the coal-water slurry fuels generally emit lower levels of SO_2 emissions. The advantage of the slurry fuels over the run-of-mine coal, in respect to SO_2 emissions, appears greater at low levels of Ca/S ratio because of the SO_2 release history from the slurry fuels. For the size of standard coal and limestone employed in these experiments, dispersion of the fuel particles/droplets and the limestone particles in the bed influences SO emissions from the standard coal more strongly as Ca/S ratio is increased, in comparison to that from the slurries and the pellet fuel.

Oxides of nitrogen emissions from the slurry fuels are markedly lower than from the standard coal as measured in the present tests. The coal-sorbent pellet also emits lower NO_x levels, especially at the typical FBC operation temperature of 1500-1550°F. Combustion efficiencies measured with the slurry fuels and the coal-sorbent pellets were generally 2-5 percentage points higher than with the standard coal.

Mineral matter analysis of the combustion ash from selected test runs were made and compared with the mineral content of

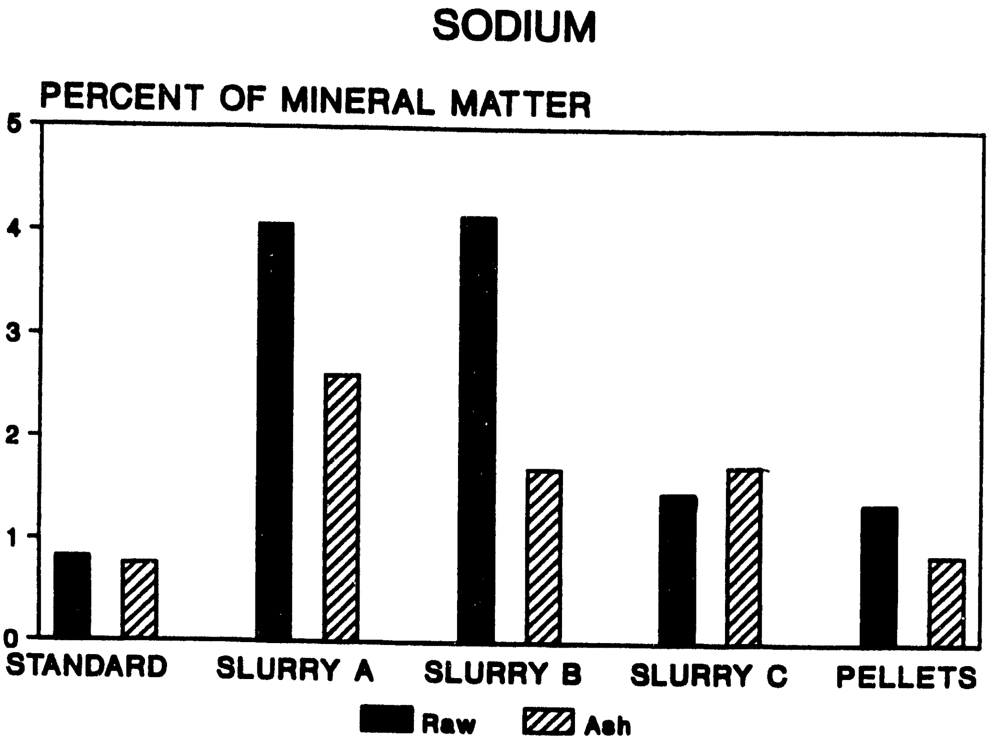


Figure 21. Sodium Transformations During CFBC Tests

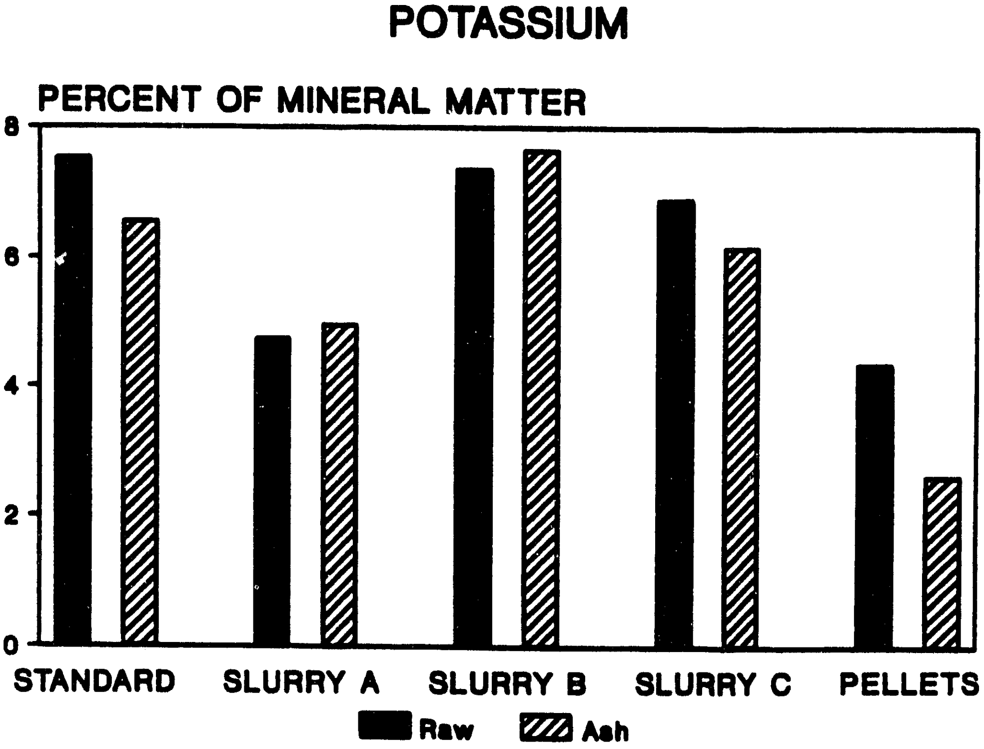


Figure 22. Potassium Transformations During CFBC Tests

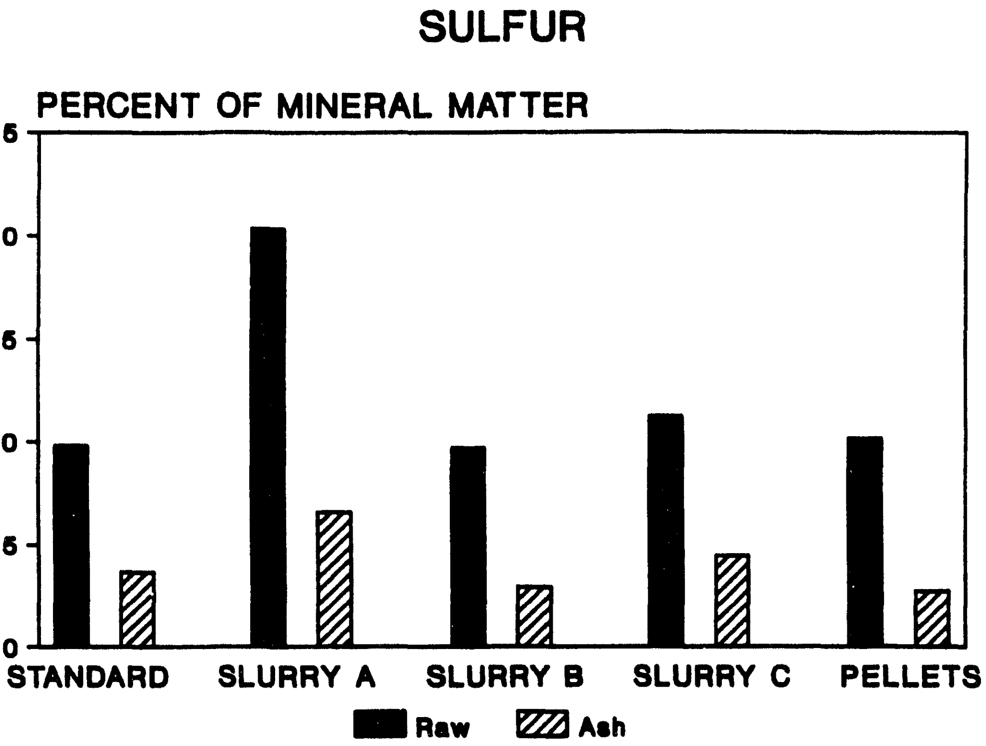


Figure 23. Sulfur Transformations During CFBC Tests

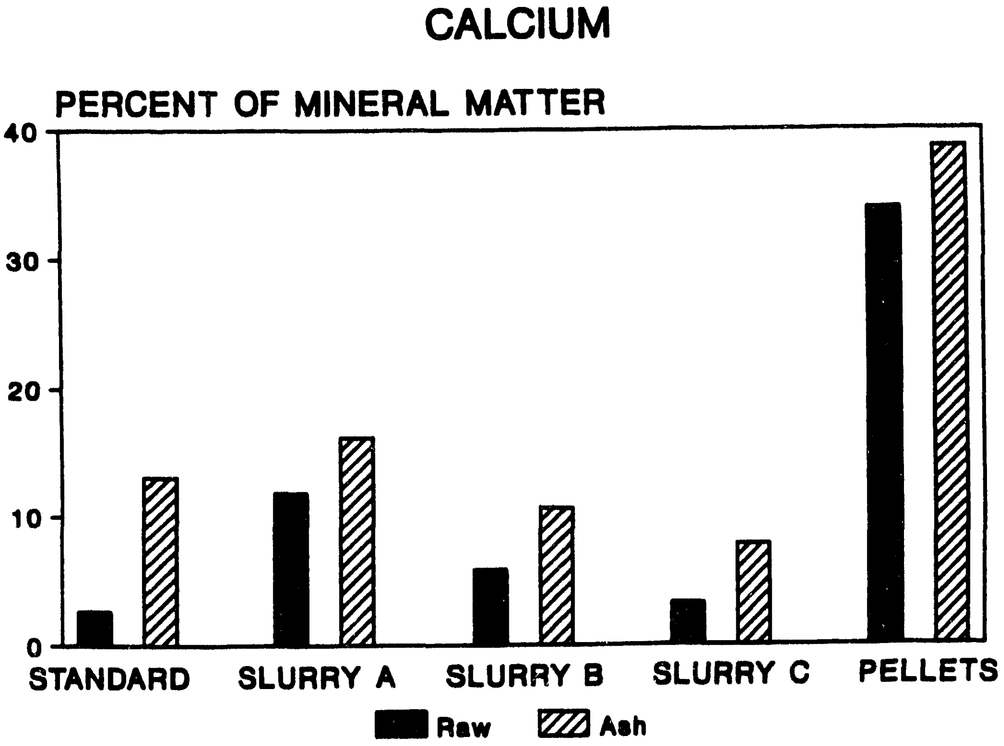


Figure 24. Calcium Transformations During CFBC Tests

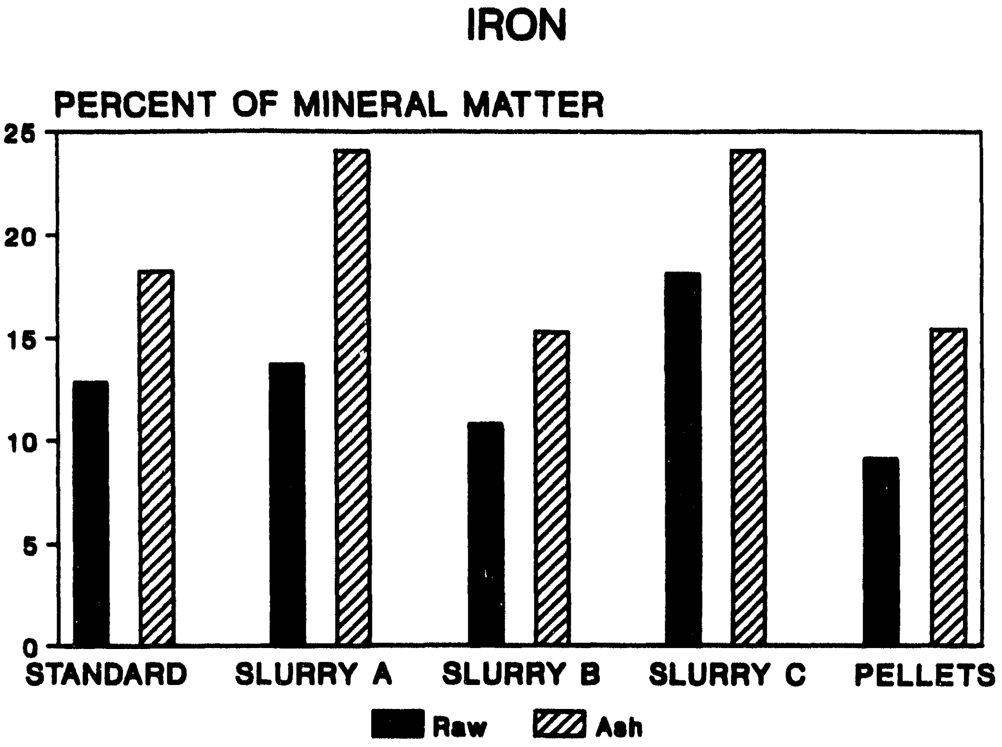


Figure 25. Iron Transformations During CFBC Tests

the parent coals in the slurry, pellet and reference coal, respectively. It was found that the main components of the ash were aluminosilicates or clays, as indicated by the large percentages of aluminum and silicon in the ash. Test results show that the weight percentage or sodium, potassium and sulfur in the combustion ash are less than in the raw coal. The weight percent of iron, on the other hand, was found to increase in the combustion ash compared to that in the raw coal.

PAPERS PRESENTED

The following paper has been accepted for presentation as a poster at the 12th International Conference on Fluidized Bed Combustion, San Diego, May 1993.

Rajan, S. and Bruyns, H., "CFBC Combustion and Emissions Properties of Processed Preparation Plant Slurry Fuels."

EQUIPMENT PURCHASED

No equipment was purchased in the period of duration of this project.

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