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Lakhra Coal Mine and Power Generation Feasibility Study

Power Plant Feasibility
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Prepared by

Gilbert/Commonwealth International, Inc.

LAKHRA COAL MINE AND POWER GENERATION FEASIBILITY STUDY

POWER PLANT FEASIBILITY

VOLUME IX

Submitted to

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COMBUSTION PERFORMANCE CHARACTERIZATION OF LAKHRA BASELINE COAL

PROJECT 900029

KDL-85-F-17

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SUMMARY

INTRODUCTION

Gilbert/Commonwealth Inc. has been contracted to conduct the Lakhra Power Plant feasibility study for the Water and Power Development Authority (WAPDA) of Pakistan sponsored by the United States Agency of International Development (USAID). As part of this overall project, Combustion Engineering was subcontracted to conduct a comprehensive research program to evaluate the combustion/performance characteristics of the Lakhra coal, and to provide feedback for a successful utility furnace design to fire this fuel.

The C-E test program/design study consisted of evaluating three Lakhra coals; baseline PMDC-2, washed, and BT-11. Testing effort included both bench scale fuel analyses and pilot scale testing in C-E's Fireside Performance Test Facility (FPTF). Areas addressed include:

- Pulverization and Abrasion Characteristics
- Relative Combustion Characteristics
- Furnace Slagging
- Convective Pass Fouling
- Relative Gaseous and Particulate Emissions
- Fly Ash Erosion

Additionally, an extended 300 hour test was conducted with the baseline coal to assess its relative corrosion potential.

The following report documents the FPTF combustion performance characteristics and the corrosion potential of the Lakhra baseline coal. Results obtained from the baseline, the washed and the BT-11 coals were compared to provide inputs to design parameters for a 300 MWe Lakhra coal-fired unit.

TEST PROGRAM

Standard ASTM bench-scale techniques typically used for characterization of solid fuels were conducted on the Lakhra baseline coal sample. Analyses included total moisture, proximate and ultimate, higher heating value, ash composition, ash fusibility temperatures, forms of sulfur, and Hardgrove Grindability Index. Five special analyses were also conducted. These included Thermo-Gravimetric Analysis (TGA) and BET surface determination to assess the burn-off/combustion reactivity of the Lakhra char; Abrasion Index to assess the relative mill wear characteristics; weak acid leaching to determine the amount of "active" alkalies which are instrumental in ash fouling behavior; and Gravity Fractionation Analysis to determine the amount of segregated iron compounds which are believed to be the dominant factor influencing coal slagging behavior.

Pulverization characteristics of the Lakhra baseline coal were assessed in a C-E No. 271 bowl mill. The primary objectives were to determine the relative mill power requirements for grinding and the general comparative pulverization behavior of this coal.

Combustion/performance characteristics of the Lakhra baseline coal were evaluated in the Fireside Performance Test Facility (FPTF). The relative combustion behavior, furnace slagging, convective pass fouling, corrosion, particulate and gaseous emissions, and fly ash erosion potential were assessed for this coal.

The FPTF is a 2 to 4×10^6 Btu/hr pilot scale combustion test facility designed to simulate the radiant and convective heat transfer surfaces, temperature profiles, and the ash deposit properties in a pulverized coal fired boiler. The furnace slagging characteristics are evaluated based upon the waterwall panel deposit cleanability using a compressed air blower which simulates sootblowing conditions, the impact of deposit on waterwall heat transfer, and the deposit physical properties. The convection pass fouling is evaluated based upon the tube deposit bonding strength/cleanability, deposit accumulation rate and deposit physical characteristics. Dust loading samples are collected downstream of the facility to assess the relative particulate emission and the carbon content in the fly ash. Fly ash resistivity is measured by in-situ and by bench scale methods. Flue gas composition is measured on-line by individual analyzers for O_2, CO_2, CO, NO_x, SO_2, and SO_3 content. Fly ash erosion is measured by surface activation technique using an irradiated coupon exposed in a specially designed high velocity duct section downstream of the furnace. Corrosion potential is assessed by exposing coupons of austenitic and ferritic alloys on temperature controlled probes in the gas stream.

A total of eight tests were conducted for the subject coal. The duration of each test was approximately twelve hours. All tests were conducted at 25% excess air with fuel fineness of 70 ± 3% through 75 microns (200 mesh). The effects of fuel loading and flame temperature upon combustion/performance were evaluated during these tests. The key objective was to establish the critical conditions at which waterwall deposits developed in the FPTF could still be cleaned by sootblowing. At the conclusion of these test runs, an extended test continued for the corrosion evaluation at the established critical conditions.

Results obtained from the above tests were used as baseline data from which the performance characteristics of the washed and the BT-11 coals were compared. The overall results were interpreted for the eventual boiler design study.

BENCH SCALE CHARACTERISTICS

The volatile matter content of the Lakhra baseline coal is 55% and the higher heating value is 26.8 MJ/Kg (11,540 Btu/lb) on a moisture and ash free basis. These values are 51.7% and 17.1 MJ/Kg (7371 Btu/lb) respectively on an equilibrium moisture and mineral matter free basis. Hence per ASTM standard, this coal can be classified as a lignite A. These values, coupled with the fact that this coal is non-swelling and hence does not soften upon rapid heating, are indicative of good burning qualities. The rapid char burn-off rate from the Thermo-Gravimetric Analysis and the high BET surface area of the char, 214 M^2/g confirmed these results. The burn-off rate of this coal char is similar if not slightly better than a U.S. subbituminous A coal with known good carbon burnout in the field. This coal should not present carbon heat loss problems under normal circumstances.

Ultimate analysis of this coal indicates the sulfur is 6.1% and ash is 36.4% on a moisture free basis. Approximately 93% of the sulfur is in pyritic form. Ash fusibility temperatures were low to moderate, ranging from 1080°C (1980°F) to 1380°C (2520°F). Ash analysis shows the iron content is high, 17.2% Fe_2O_3. Gravity Fractionation Analysis shows the coal ash in the 2.9 sink contains 87.7% Fe_2O_3, indicating a high percentage of the iron is in a segregated form. The low to moderate ash fusibility temperatures and the high Fe_2O_3 content in the 2.9 sink fraction indicate this coal should exhibit severe slagging potential.

The sodium content in the ash is low, 0.7%. This would indicate low fouling. However, the high ash loading, the low to moderate ash fusibility temperatures, and the carryover of slagging phenomena can still result in fouling in the high temperature convection section.

PULVERIZATION CHARACTERISTICS

Pulverization results are in agreement with the Hardgrove Grindability Index indicating the Lakhra coal is relatively easy to pulverize. There was no apparent compaction/pasting potential with this coal. The energy required to grind this coal is 8.4 Kw-hr/tonne (7.6 Kw-hr/ton) in the FPTF bowl mill. At a mill capacity of 612 Kg/hr (1,350 lbs/hr), the mill rejection rate was 2.1 percent.

The abrasiveness of this coal was relatively high. It has a bench-scale Abrasion Index of 50. However, the potential mill wear problems can be addressed by using proper mill lining material.

COMBUSTION PERFORMANCE CHARACTERISTICS

Relative Combustion Characteristics

Observations made during testing indicated this coal ignited easily and produced a good stable flame. Analysis of the fly ash samples collected during the critical conditions test showed the carbon content was very low, corresponding to better than 99.9% carbon conversion.

Furnace Slagging

The Lakhra baseline coal has a severe slagging potential. Results show reduction in fuel load slightly reduced the amount of deposit accumulated on the waterwall panel due to the lower ash input. However, furnace temperature was the most critical parameter controlling slagging.

Furnace deposits were cleanable at flame temperature up to 1427°C (2600°F), above this temperature deposits were uncontrollable. Waterwall deposit was 12 to 20 mm (1/2 to 3/4 inch) thick, highly sintered with molten outer layer at 1427°C (2600°F). Deposits were molten and 20 to 25 mm (3/4 to 1 inch) thick above this flame temperature.

Waterall heat flux monitored during the 2.97 GJ/Hr (2.82 x 10^6 Btu/hr) firing rate at critical flame temperature test indicate heat transfer was reduced by 71.1% after a 12 hour period. Heat flux recovery after sootblowing was better than 90% when deposits were effectively removed by sootblowing.

Throughout each test firing, bottom ash accumulation rate was very high, requiring frequent handling. The ash split between the bottom ash and fly ash was approximately 40% to 60% in the FPTF.

Convective Pass Fouling

The Lakhra baseline coal has moderate fouling potential. Convective deposit accumulation was high, but deposit to tube bonding strengths were low (less than 5), thus deposits were easily cleanable for each test. Deposit accumulation increases with increasing gas temperature. Sootblowing was required every 3 to 4 hours at 1282°C (2340°F), 5 to 6 hours at 1165°C (2130°F) and 6 to 8 hours at 1115°C (2040°F). During each test run, a high deposition rate in the transition section of the furnace was also observed. This high rate was most likely due to the carryover from furnace slagging.

Particulate and Gaseous Emissions

The average mass median particle size of the fly ash collected from this coal was 5.1 microns. The fly ash resistivity measured in the FPTF was 1.76×10^{11} ohm-cm at (124°C) 255°F flue gas temperature with 15 ppm SO_3 and 8% moisture. This value is higher than the optimum 5×10^9 to 5×10^{10} ohm-cm for electrostatic precipitators operating under normal gas temperature of 149 to 177°C (300 to 350°F). It is also higher compared to the theoretical calculation of 2×10^9 ohm-cm at similar SO_3 concentration. However, its value falls within the typical range for most commercial coals and should not present any problem for electrostatic precipitator collection efficiency.

The SO_2 emission measured from the FPTF for this coal is 6340 ppm (3% O_2, dry) compared to the theoretical emission of 6960 ppm on the same basis. Sulfur retention by the ash in this coal was approximately 9%. The relative NO_x emission results from the FPTF are usually higher because of the intense, single stage combustion. The measured NO_x from the FPTF for this coal is 860 ppm.

Fly Ash Erosion

The fly ash erosion of the Lakhra baseline coal is relatively high. The normalized erosion rate is 0.91 mm (35.8 mils) per 10,000 operating hour at 18.3 m/sec (60 ft/sec). The relatively high erosion rate indicates the need for a lower gas velocity in the convective pass to reduce metal wastage rate.

Corrosion Potential

Corrosion results indicate the austenitic alloys (T_p347 and 310) exhibit very good corrosion resistance with wastage rate less than 2 mgs/cm^2. The Incoloy 800 material had minimum wastage rate of less than 1 mg/cm^2. The ferritic alloys (T-11, T-22, T-91) and carbon steel experienced significant wastage more than 20 mgs/cm^2, but should prove adequate within specified maximum metal temperatures; T-11 and T-22 up to 510°C (950°F), T-91 up to 538°C (1000°F), and carbon steel up to 427°C (800°F).

CONCLUSIONS AND RECOMMENDATIONS

FPTF results indicate the Lakhra baseline coal can be commercially fired in a properly designed furnace. Specific conclusions include:

- The Lakhra coal has very good combustion characteristics. Both bench and pilot scale results indicate this coal should not present any carbon heat loss under normal circumstances.

- Pulverization of this coal is easily accomplished requiring relatively low energy for grinding. There is no apparent compaction/pasting potential in the bowl mill. The high abrasion characteristics of this coal can be addressed with proper mill lining materials.

- From the performance standpoint, furnace slagging is the controlling factor utilizing this coal. However, the severe slagging in the FPTF can be effectively controlled by reducing furnace flame temperature below 1427°C (2600°F). This will correspond to a very large furnace design. The tangential firing system by virtue of its inherent ability to spread out the flame should provide lower flame temperatures than highly turbulent wall-fired burners. Design options such as extended windbox and concentric firing should also be considered. The high bottom ash buildup will require a large ash handling system.

- Ash fouling potential of this coal is moderate. Deposition rate is relatively rapid due to its high ash loading and furnace slag carry-over in the high gas temperature section. However, deposit to tube bonding strengths are low, indicating deposits can be easily removed by sootblowing. Convective pass deposition rate can be minimized by reducing gas temperatures to below 1149°C (2100°F).

- Fly ash resistivity of this coal falls within the typical range and should not present a problem for electrostatic precipitator collection efficiency.

- Fly ash erosion of this coal is relatively high due to its high ash loading but it can be reduced by designing commercially acceptably low gas velocities in the convective pass.

- Corrosion results indicate the austenitic alloys exhibit very good life expectancy at metal temperatures up to 704°C (1300°F). Carbon steel and ferritic alloys exhibit high corrosion at convective pass metal temperature but should prove adequate within specified maximum temperatures; carbon steel up to 427°C (800°F). T-91 up to 538°C (1000°F), and T-22 and T-11 up to 510°C (950°F).

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Section 1

INTRODUCTION

The Water and Power Development Authority (WAPDA) of Pakistan is interested in constructing a series of 300 MWe power generation stations firing the indigenous Lakhra coals as boiler fuel to meet future energy requirements. Comprehensive Lakhra Coal Mine and Power Plant facility studies are underway with sponsorship from the United States Agency for International Development (USAID). Gilbert/Commonweath, Inc. has been contracted to conduct the Lakhra Power Generation Project feasibility study.

The typical Lakhra coal has high sulfur, high ash with high iron content, and relatively low ash fusibility temperatures. Its quality can vary significantly from seam to seam within the coal field. These factors and others represent areas of concern in boiler design and operation. Combustion Engineering (C-E) was subcontracted to conduct a comprehensive test program/design study to address these concerns. It consisted of both bench and pilot scale evaluations which include:

- Pulverization and Abrasion Characteristics
- Relative Combustion Characteristics
- Furnace Slagging
- Convective Pass Fouling
- Relative Gaseous and Particulate Emission
- Fly Ash Erosion

Three Lakhra coals were evaluated under this program; the baseline PMDC 2, the washed PMDC 2, and the BT-11 coals. Results obtained from these coals were compared to provide inputs for design parameters for a 300 MWe Lakhra coal-fired unit.

The subject report provides detailed assessments of the Lakhra baseline coal characteristics. In addition, an extended 300 hour corrosion test was conducted to evaluate the effect of this coal on wastage of typical boiler tube materials under test firing conditions.

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Section 2

TEST PROCEDURES

BENCH SCALE CHARACTERIZATION OF TEST COAL SAMPLES

Standard ASTM Techniques

ASTM (American Society for Testing Materials) techniques were used to determine the proximate and ultimate analyses, Higher Heating Value, Hardgrove Grindability index, halogen contents, forms of sulfur, coal ash fusibility temperatures and compositions. These analyses were used for general assessment of coal characteristics and its relative combustion behavior.

Special Techniques

Special in-house techniques were conducted to provide more detailed information on specific coal characteristics. These techniques are briefly described in the following subsections. Detailed descriptions are provided in Appendix A.

Thermo-Gravimetric Analysis is conducted to assess char reactivity and burnout characteristics of solid fuels. Char samples are prepared by pyrolyzing the coal in a Drop Tube Furnace System in nitrogen atmosphere at 1454°C (2650°F). The relative char burnoff rate for the char is determined by measuring the sample weight loss in air at 700°C (1292°F) as a function of time.

Specific BET Surface Area Measurement is based on the principle of physical absorption of N_2 at 77°K in conjunction of the BET (Brunamer, Emmett, Teller) single or multipoint method to determine the N_2 surface area of solid fuel char. This measurement provides a relative measure of the reactivities of fuels.

Abrasion Index is a bench-scale grinding procedure used to determine the abrasiveness of a fuel. It consists of measuring the wastage from two abrasion coupons installed in a Raymond 6" screw feed pulverizer after testing. This relative index of coal abrasiveness has been successfully correlated to actual mill wear.

Weak Acid Leaching procedure consists of segregating only the "active" alkalies contained in a pulverized coal sample. The inactive alkalis are in complex mineral form which cannot be dissolved by the weak acid. The active alkalies are weakly bonded within the coal matrix. These compounds are readily vaporized during combustion and are, therefore, available to react chemically and physically downstream in the boiler. These "active" alkalies are very instrumental in ash fouling behavior because of their propensity to form very low melting compounds and act as the "glue" cementing deposits together. The weak acid soluble alkali content in a fuel has been found to reflect convection pass fouling behavior much better than the total alkali content determined by the ASTM methods.

Gravity Fractionation Technique consists of separating a pulverized coal sample into different density fractions using high specific gravity organic fluids. The gravity fractionation analysis provides information on the minerals and mineral matter distribution within the coal matrix. It can provide much more indepth information than the ASTM analysis regarding the selective deposition behavior of specific ash constituents during pulverized coal combustion process. The iron compounds in a segregated form are generally believed to play a dominant role in furnace slagging.

PILOT-SCALE PULVERIZATION

The pulverization characteristics of the Lakhra baseline coal were evaluated in a C-E Model No. 271 bowl mill. Detailed description of the pulverization system is presented in Appendix B. This mill operates in the same fashion as commercial C-E bowl mills, and can be used to determine the relative mill power consumption, as well as the general comparative pulverization characteristics of a fuel.

The test coal was pulverized at feed rate of 612 Kg/hr (1350 lbs/hr). Mill outlet temperature was controlled at 60°C (140°F) through automatic throttling adjustment of mill inlet temperature. Fuel fineness was controlled through adjustment of mill classifier vanes to obtain representative coal fineness of 70 ± 3% through 75 microns (200 mesh). Mill power consumption was measured with a wattmeter and recorded continuously during the test.

PILOT-SCALE COMBUSTION PERFORMANCE EVALUATION

The combustion performance of Lakhra baseline coal was evaluated in the Fireside Performance Test Facility (FPTF). Detailed description of the facility is in Appendix C. The FPTF is a pilot scale combustion facility used primarily to evaluate fuel properties which influence fireside boiler performance. A schematic of the test furnace is shown in Figure 2-1. Located in the radiant section of the furnace is a tri-section waterwall test panel which is used to study lower furnace ash deposition. In the convective section, four banks of air-cooled probes are used to simulate boiler superheater tubes and evaluate convective section ash deposition. Furnace gas temperature profile and residence time in the FPTF are similar to utility boiler operation. Flame temperature is controlled by varying combustion air preheat from 27 to 538°C (80 to 1000°F). Test firing in the FPTF allows direct comparison of the performance characteristics between the Lakhra baseline, washed and BT-11 coals, and provides inputs for the boiler design study.

Test Program

The key objective of the combustion testing was to establish the critical thermal loading (both flame temperature and coal feed rate) at which furnace deposits are still cleanable by sootblowing in the FPTF. The furnace conditions at which wallblowers are no longer effective in removing deposits are very important from a design standpoint as they dictate the maximum thermal loadings at which a slagging limited boiler can continuously operate. The corrosion testing was to assess the effect of this coal on wastage of typical boiler tube materials during typical firing conditions.

TABLE 2-1

LAKHRA BASELINE COAL EVALUATION TEST MATRIX

TEST NO.	FIRING RATE ($x10^6$ BTU/HR)	EXCESS AIR (%)	TARGET FLAME TEMPERATURE (°F)	ACTUAL FLAME TEMPERATURE (°F)
1	2.82	25	2850	2820
2	2.82	25	2750	2730
3	2.82	25	2650	2650
4	2.82	25	2600	2610
5	2.23	25	2550	2550
6	2.23	25	2600	2580
7	2.14	25	2600	2600
8	1.99	25	2600	2610

FIGURE 2-1

FIRESIDE PERFORMANCE TEST FURNACE

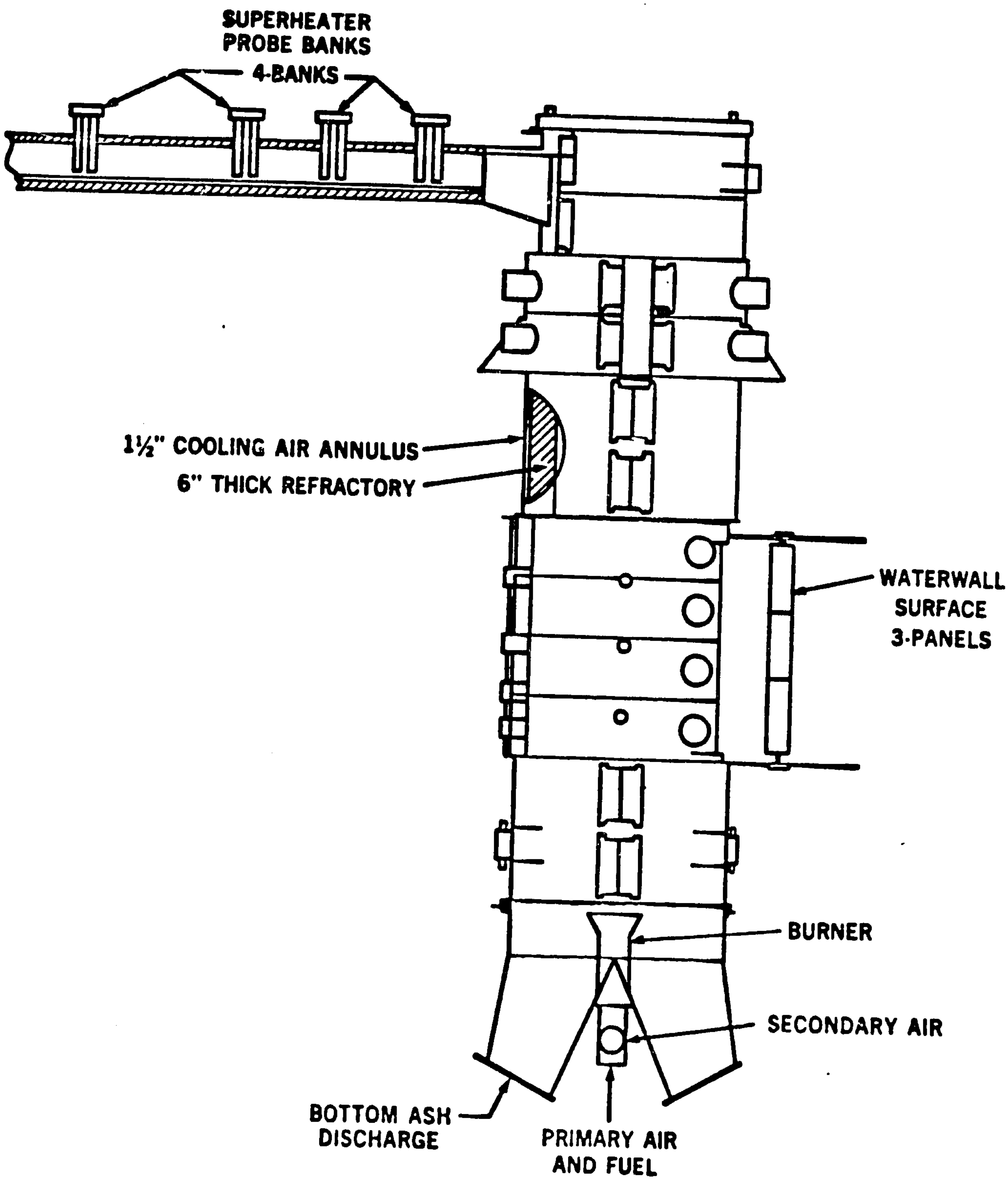

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Table 2-1 lists the eight tests conducted for the Lakhra baseline coal. Each of these tests was conducted with 70 ± 3% through 75 microns (200 mesh fuel fineness and 25% excess air level. The effects of fuel loading and flame temperature upon combustion performance in the FPTF were systematically evaluated. The initial coal feed rate and flame temperature for Test 1 were selected based upon past FPTF experience with high slagging coals, then the furnace temperature was changed and controlled at the selected level by adjusting the combustion air temperature for Tests 2 to 4. This procedure allowed testing at the desired furnace temperature which directly influences the nature of the deposits, and takes into account the effect of the change in mass input when changing loads during Tests 5 to 8. Testing was subsequently extended for corrosion evaluation.

FURNACE SLAGGING CHARACTERIZATION

The furnace slagging characteristics were assessed by determining deposit coverage and its effect on waterwall panel heat flux, deposit cleanability, deposit physical and chemical characteristics. Table 2-2 shows the criteria used to classify the slagging potential of a fuel in the FPTF based on the maximum fuel loading and critical flame temperature at which waterwall deposits are still cleanable by sootblowing.

TABLE 2-2

CRITERIA FOR FUEL SLAGGING POTENTIAL IN THE FPTF

Heat Input From Fuel (GJ/hr)	Heat Input From Fuel ($x10^6$ BTU/hr)	Flame Temperature °C	Flame Temperature (°F)	Furnace Slagging Potential
4.2	(4.0)	>1680	(>3050)	Low
3.8 to 4.2	(3.6 to 4.0)	1590 - 1680	(2900 - 3050)	Moderate
3.4 to 3.8	(3.2 to 3.6)	1510 - 1590	(2750 - 2900)	High
<3.4	(<3.2)	<1510	(<2750)	Severe

Deposit Coverage and Waterwall Panel Heat Flux

Deposit coverage on the waterwall panel is monitored and documented throughout the duration of each test run. The rate of deposit accumulation on the waterwall panel is reflected by the panel heat absorption. When deposit buildup slows and begins to approach long term characteristics, the waterwall heat absorption rate also begins to level off. In order to describe or quantify a point at which waterwall deposition has leveled off, the rate of change in heat flux was used. This was defined as the point when the average heat flux over the last three hours has not decreased more than 5% of the average for the previous three hours. The heat flux after deposit removal and its comparison to a "clean panel" heat flux along with visual observations are used as indicators of sootblower effectiveness.

Deposit Cleanability

The cleanability of deposits on two panels located at the middle and bottom of the furnace waterwall was evaluated on-line using a special sootblowing technique designed to simulate the removal forces associated with commercial sootblowing. The heat flux recovery after sootblowing and the observed deposit characteristics (physical state, thickness, percent coverage) before and after blowing were used to determine cleanability.

Deposit Physical and Chemical Characterization

The key parameter for the physical characterization is the physical state of the waterwall deposits. Dry, lightly sintered deposits are most amenable to sootblowing. Highly sintered and molten deposits usually have deleterious effect on deposit cleanability and hence on utility operation. Other physical parameters examined are deposit coverage and thickness. Desirable conditions are low panel coverage and thin friable deposits. Molten deposits are generally considered difficult to remove from waterwall panel surfaces employing conventional sootblowers. However, depending on the tenacity of the bonding between the deposit and the tube surface, thin molten deposits may be controllable with frequent sootblowing.

Waterwall deposits are separated by layer and analyzed for chemical composition. Results are used to aid interpretation of the overall slagging behavior of a coal as well as the mechanisms involved in the deposition process.

CONVECTION PASS FOULING CHARACTERIZATION

The fouling characteristics of the coals were assessed by the deposit buildup rate, deposit cleanability and deposit physical and chemical properties.

Deposit Buildup Rate

Deposit accumulation rate is determined in two manners, the sootblowing frequency requirement, and by quantitatively weighing the amount of deposits accumulated in a standard 8 hour period. Deposit buildup influences boiler tube spacing design and sootblowing requirements. Generally, a temperature exists below which deposit accumulation is minimal. Below this temperature tube spacing can be relatively close together. Above this temperature tube spacing would have to be progressively further apart to accommodate increased accumulation of deposits. It will also quantify the relative effect of overall ash reduction from coal cleaning upon sootblowing requirement in a utility unit.

Deposit Cleanability

Deposit cleanability is assessed by on-line measurements of deposit to tube bonding strength using a digital penetrometer. It provides a quantitative measurement which can be related to the ease of deposit removal by sootblowing. Table 2-3 shows the standard values established to classify the relative deposit bonding strength:

TABLE 2-3

CONVECTIVE PASS DEPOSIT TO TUBE BONDING STRENGTH MEASUREMENT

Measurement	Deposit Bonding Strength
<8	Low
8 to 15	Moderate
15 to 25	High
>25	Severe

These values were calibrated based upon the ease of deposit removal during sootblowing and against ash deposit behavior in the field. Normally, deposits yielding bonding strength measurements up to 15 are considered controllable through conventional sootblowing techniques.

Deposit Physical and Chemical Properties

The deposit physical state, internal strength, and thickness are related to cleaning effectiveness. Friable deposits, which are easy to remove, will break up into smaller pieces and will not cause pluggage downstream where tube spacing is closer together. On the other hand deposits which have high internal strength can become lodged in the more tightly spaced downstream tubes and cause pluggage which can result in outages.

As with the waterwall panel deposits, convective pass deposits were separated into layers and analyzed for ash fusibility temperatures and chemical compositions to aid the interpretation of the overall fouling behavior of each test coal.

PARTICULATE AND GASEOUS EMISSIONS

Fly ash samples were collected isokinetically downstream of the convective pass of the FPTF. These samples were analyzed for carbon and chemical composition by ASTM methods, particle size distribution by a laser diffraction technique, free quartz content by x-ray diffraction, fly ash resistivity by in-situ and by bench-scale measurements. These results were related to the relative combustion behavior, fly ash collectability and fly ash erosion results for the test coal.

Flue gas samples were analyzed periodically during each test run. A gas analysis system is used to measure the flue gas concentrations of NO_x, SO_2, SO_3, CO and O_2 on a dry basis.

FLY ASH EROSION CHARACTERIZATION

Fly ash erosion characteristics were evaluated on-line in the FPTF in a special high velocity convection section using special test probes. A surface activation technique was used to determine metal loss after exposure. It measures the changes in the intensity of emitted gamma rays to determine erosion. This requires that the object to be measured first be made radioactive by impinging a particle beam on the surface. As the surface is eroded, the level of gamma radiation emitted decreases. The detector measures the level of emitted radiation and is calibrated to relate the change in radioactivity to the depth of material loss. This technique in conjunction with high gas velocities for accelerate wear allow accurate determination of relative material wastage over a short exposure time (40 hours).

CORROSION POTENTIAL

The corrosion potential was assessed by determining the wastage rate, the type of physical attack, and the type of wastage on typical boiler tube materials after exposure in the FPTF furnace and convective pass sections at typical operating metal temperatures during Lakhra baseline coal test firing. Both ferritic and austenitic materials were used on temperature-controlled probes for evaluation. The alloys exposed included SA-210, T-11, T-22, T-91, 347 S.S., 310 S.S., and Incoloy 800. Details of the test probe system and the composition of material tested are described in Appendix D. The criteria used to classify a test material performance is based upon the metal wastage rates established from laboratory and field corrosion test results.

TABLE 2-3

CRITERIA FOR MATERIAL PERFORMANCE DURING CORROSION EVALUATION

Wastage Rate (mg/cm^2)	Corrosion Resistance
< 10	Very Good
10 to 25	Good to Transitional
25 to 40	Marginal
> 40	Poor

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Section 3

TEST RESULTS

BENCH SCALE CHARACTERIZATION

Representative samples from the Lakhra baseline coal were subjected to a series of bench scale analyses. These tests included standard ASTM analyses typically used for characterization of solid fuels, and special analyses which could provide information on the relative fuel reactivity and char burn-off rate, as well as on the mineral matters in the fuel ash.

Standard ASTM Tests

Analytical data on the Lakhra baseline coal samples are summarized in Table 3-1. The volatile matter is 55%, and the higher heating value is 26.8 MJ/kg (11,540 Btu/lb) on a moisture and ash free basis. These values are 51.7% and 17.1 MJ/kg (7,371 Btu/lb) respectively on an equilibrium moisture and mineral matter free basis. Hence, per ASTM standards, this coal can be classified as a lignite A. These values, coupled with the fact that this coal is non-swelling and hence does not soften upon rapid heating, are indicative of good burning qualities.

Results of the ultimate analysis show the sulfur content is 6.1% on a moisture free basis. Sulfur form analysis indicate 93.4% of the total sulfur is pyritic, 6.5% is sulfate and 0.1% organic. Firing this coal under complete combustion and without any sulfur removal, would yield 7.15 g SO_2/MJ (16.6 lbs/10^6 Btu).

The ash content of this coal is 36.4% on a dry basis. Ash loading of this coal would be 21.3 g/MJ (49.6 lbs/10^6 Btu). Ash composition analysis show a high percentage of iron (17.2%) and low sodium (0.7%) compounds in the ash.

Slagging characteristics of a coal is commonly evaluated by the ash fusibility temperatures, the base to acid ratio, and the iron to calcium ratio, etc. Ash fusibility temperatures of this coal were relatively low to moderate. The initial deformation temperature is 1082°C (1980°F) and the fluid temperature is 1382°C (2520°F). These results would indicate a good potential of forming fluid deposits in the furnace with this coal.

The principle of the base-to-acid ratio is based upon the tendency of ash constituents to combine according to their acidic and basic properties to form low melting salts; values of this ratio between 0.4 and 0.7 have been correlated to low melting ashes. The subject coal ash has a base to acid ratio of 0.32 which is relatively close to this problem range. It is also consistent with the low to moderate ash fusibility temperature.

The iron-to-calcium ratio is used as a slagging indicator to account for the fluxing effect of calcium upon iron. This fluxing effect is generally seen with coals having ratios between 10 and 0.2 and is generally most pronounced for ratios between 3 and 0.3. Results for the Lakhra baseline coal fell well above this range as the iron to calcium ratio was 5.21. The high iron content in the ash appears to be its most significant characteristic. Iron compounds in segregated form are known to play a dominant role in slagging behavior. In a reduced state, pyritic iron along with fluxing constituents often result in low melting temperature ash and the potential for troublesome fused/molten furnace deposits. Therefore, based primarily upon the high iron content and the ash fusibility temperatures, the standard analyses would typically indicate high slagging potential for this coal.

The primary considerations when evaluating the fouling potential of a fuel are the ash initial deformation and soften temperatures, and the alkali and alkaline earth concentrations. Sodium, in particular, can plan a major role in convective pass fouling. Sodium vaporizes during combustion and subsequently reacts chemically and physically downstream in the boiler, providing a sticky bonding matrix to build convection pass deposit. The sodium content in the subject coal was low, consisting of less than 0.7% of the total ash. Thus from the sodium standpoint, this coal should have a low fouling potential. However, the high ash loading and other factors such as slag carry-over phenomena from the lower furnace can still lead to high fouling.

TABLE 3-1

ANALYSIS OF RAW LAKHRA BASELINE COAL SAMPLES

	As Received		Moisture Free
Proximate, Wt. Percent			
Moisture (Total)	26.3		-
Volatile Matter	25.8		35.0
Fixed Carbon (Diff.)	21.1		28.6
Ash	26.8		36.4
Total	100.0		100.0
HHV, Btu/lb	5410.0		7335.0
LB Ash/mm Btu	49.6		49.6
Ultimate, Wt. Percent			
Moisture (Total)	26.3		-
Hydrogen	2.7		3.6
Carbon	29.9		40.5
Sulfur	4.5		6.1
Nitrogen	0.5		0.7
Oxygen (Diff.)	9.3		12.7
Ash	26.8		36.4
Total	100.0		100.0
Sulfur Form			
Pyritic	4.2		5.7
Sulfate	0.3		0.4
Organic	<0.1		<0.1
Ash Fusibility	Red.	Ox.	
I.T. Deg. F	1980	2100	
S.T. Deg. F	2430	2460	
H.T. Deg. F	2470	2490	
F.T. Deg. F	2520	2530	
Temp. Diff. (FT-IT)	540	430	
Ash Composition, Wt. Percent			
SiO_2	43.6		
Al_2O_3	27.2		
Fe_2O_3	17.2		
CaO	3.3		
MgO	1.3		
Na_2O	0.7		
K_2O	0.7		
TiO_2	1.9		
SO_3	3.9		
Total	99.8		
Ratios			
BASE/ACID	0.32		
Fe_2O_3/Cao	5.21		
SiO_2/Al_2O_3	1.60		
Acetic Acid Reachable, %			
Na_2O	0.7		
K_2O	0.06		
Halogens, PPM			
Cl	1265		
F	28		
Grindability	71		
Abrasiveness	50		
Free Quartz, %	1.7		

The subject coal was analyzed for halogen compounds. Chlorides are usually associated with high temperature corrosion. Results indicate the chloride content of this coal is 0.13%. Corrosion caused by chloride should not be a concern with this coal as normally chloride of 0.1 to 0.2% would not show any significant corrosion during coal firing.

The Hardgrove Grindability Index (HGI) is used to determine the relative ease of coal pulverization. Normally, the higher the HGI, the less energy is required to grind the coal to a desired fineness. Value obtained from this coal is 71, indicating it should be easy to grind.

Overall, standard ASTM analyses indicate this coal has good combustion qualities. It is relatively easy to grind. The slagging potential appears relatively high due to the high pyritic iron in the ash and the relatively low to moderate ash fusibility temperatures. The fouling potential appears moderate due to the high ash loading and the potential of slagging phenomena to the high temperature convective section of the furnace.

Special Bench-Scale Tests

Five special bench-scale tests were conducted for the Lakhra baseline coal. Testing included Thermo-Gravimetric analysis, specific surface area, abrasion index, weak acid leaching, and gravity fractionation analysis.

Results of the Thermo-Gravimetric Analysis is shown in Figure 3-1. Char burn-off curves obtained from various U.S. coals with known commercial experience are shown for comparison basis. The curve for the Lakhra baseline coal char shows a rapid burn-off rate. The reactivity of this char is almost identical if not slightly better than the reference U.S. Montana subbituminous coal char. These results are consistent with the standard ASTM tests indicating good burning qualities of this coal.

Table 3-2 shows the specific surface areas of the Lakhra baseline and the reference coal chars. On a dry, ash free basis, Lakhra char has a specific surface area of 214.4 m^2/g. Overall, the rapid char burn-off rate and the high surface area of this coal indicate it should not present carbon heat loss problems.

FIGURE 3-1
THERMOGRAVIMETRIC BURN-OFF OF 200 x 400 MESH DTFS CHARS AT 700°C

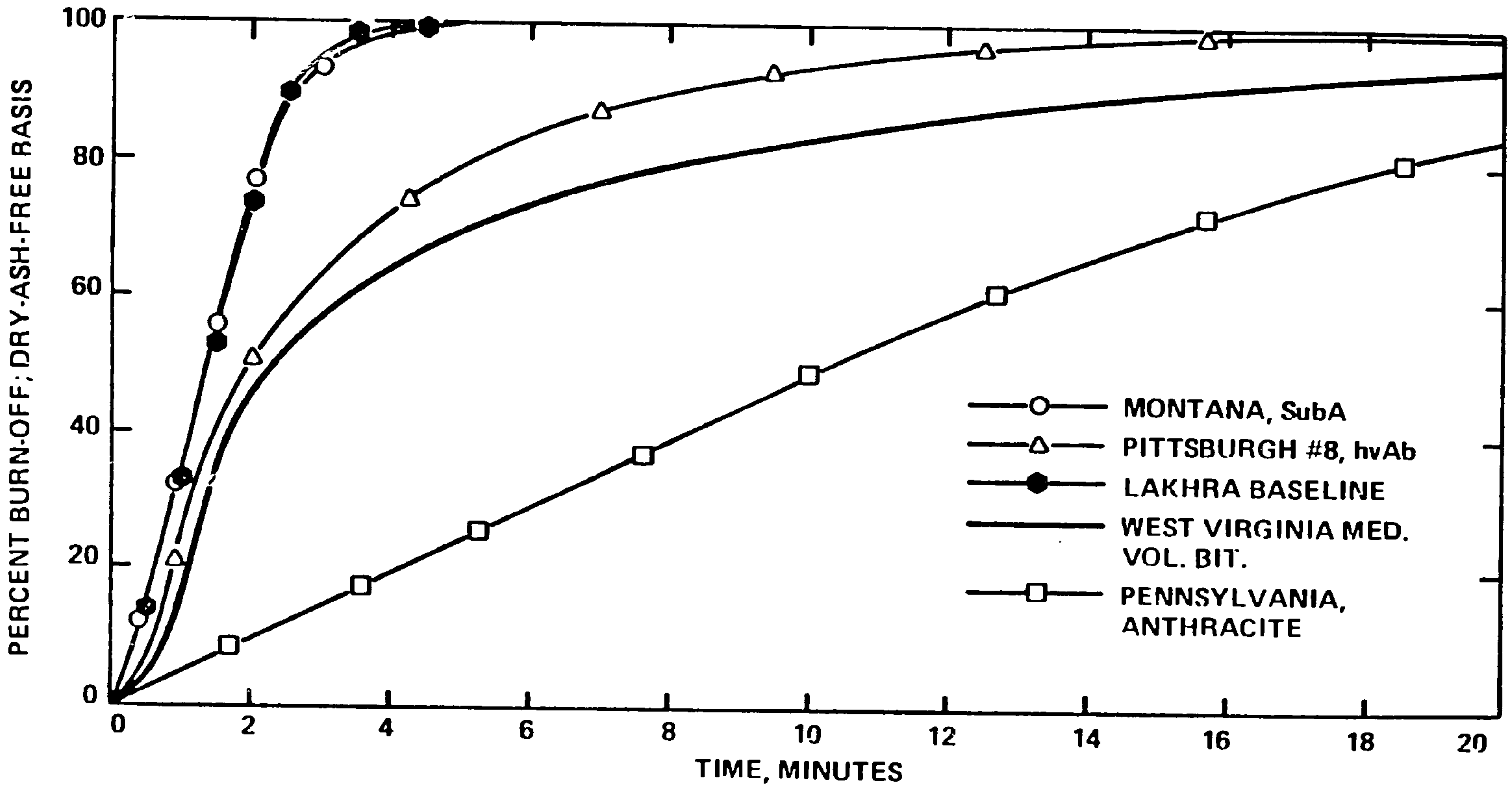


TABLE 3-2

BET SURFACE AREA OF THE 200 x 400 MESH ANALYTICAL CHAR SAMPLES

Char Origin	CHAR PROXIMATE ANALYSES, WT.%				BET Surface Area, m^2/g, dry-ash-free
	Moisture	Volatile Matter	Fixed Carbon	Ash	
Montana, SubA	1.7	3.1	79.8	15.4	64.3
Pittsburgh #8 hvAb	0.1	1.5	86.5	11.9	29.2
West Virginia Med. Vol. Bit.	0.0	0.1	70.3	29.6	12.3
Pennsylvania Anthracite	0.0	0.6	92.6	6.8	2.6
Lakhra Baseline	2.5	2.0	45.3	50.2	214.4

The abrasion index of the subject coal is high, 25 kg/1000 tonne (50 lbs/1000 tons), indicating a relatively high potential for causing mill wear. X-ray diffraction analysis shows the free quartz content in the coal ash is 1.7%. The high abrasiveness of this coal is most likely attributed to its high ash content. High mill wear potential would require proper selection of mill lining materials.

The weak acid leaching analysis provides more definitive information on the nature of the alkalies present. The technique detects "active" alkalis which are loosely bound, and are likely to volatilize during combustion and be instrumental in ash fouling. The subject test coal was leached at pH value of 3 and the leachates were subsequently analyzed for sodium, calcium and magnesium contents. Results indicate the total sodium in this coal ash is low at 0.7%, but 97% of it is in the "active" form. These results, the low to moderate ash fusibility temperature, and the high ash loading would indicate a moderate fouling for this coal.

The gravity fractionation analysis was conducted on composite pulverized coal samples obtained during the FPTF combustion performance evaluation. This analysis quantifies the amount of segregated irons presented in the coal ash. Figure 3-2 shows a good correlation between the percentage of iron in the 2.9 sink fraction and the observed slagging performance in the field units designated by numbers 1 through 16. In general, coals having greater than 70% Fe_2O_3 in the ash of 2.9 sink fractions would exhibit high slagging potential.

Four gravity fractions using organic liquids having specific gravities of 1.5, 1.9, 2.5 and 2.9 were used. Each of these cuts were subjected for ASTM ash analyses. Results are summarized in Table 3-3. The iron content in the 2.9 sink fraction was 87.7% for the subject coal. The extremely high iron concentration in the 2.9 sink fraction and the high ash content would indicate a severe slagging potential for this fuel.

In summary, the special bench-scale tests are consistent with the standard ASTM tests and provide supplemental information indicating severe slagging and moderate ash fouling potential. The gravity fractionation results show a high

FIGURE 3-2

EFFECT OF SEGREGATED IRON ON COAL ASH SLAGGING
SLAGGING POTENTIAL
VERSUS
PERCENT IRON IN 2.9 GRAVITY FRACTION

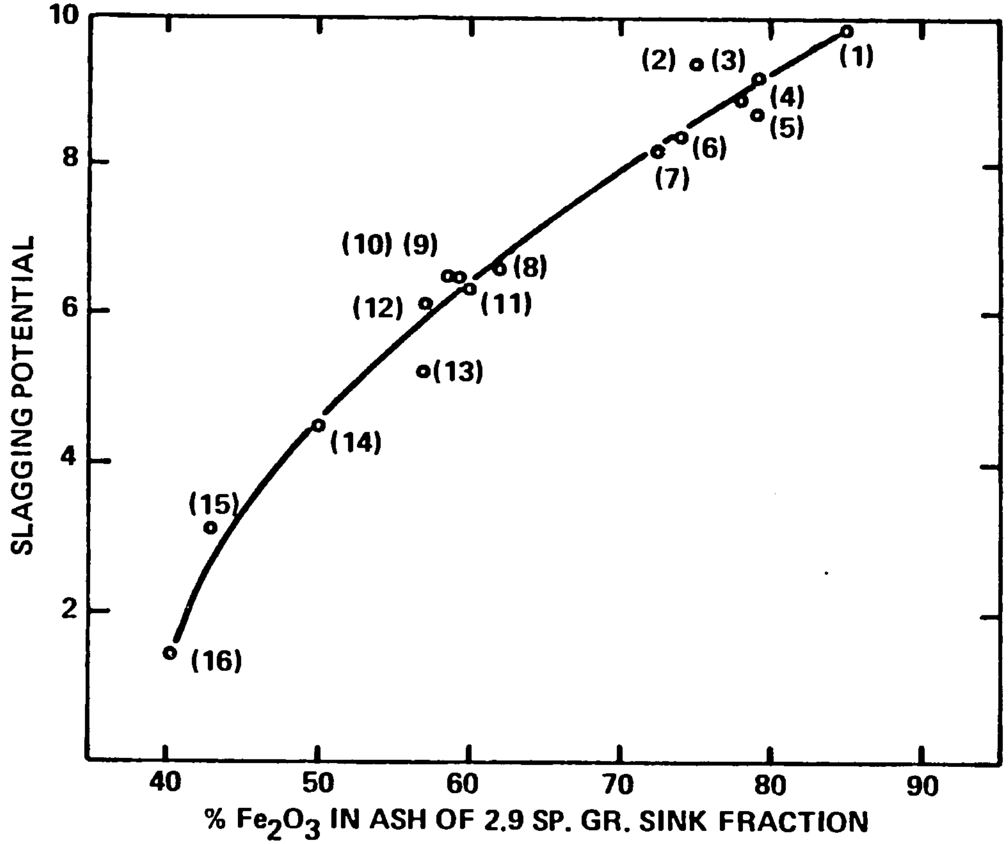


TABLE 3-3

ASH COMPOSITION OF LAKHRA BASELINE COAL GRAVITY FRACTIONS

Gravity Fraction	1.5	1.5-1.9	1.9-2.5	2.5-2.9	2.95
SiO_2	31.6	43.7	47.9	54.7	4.2
Al_2O_3	20.8	28.4	29.1	29.3	2.4
Fe_2O_3	11.9	14.5	12.9	8.3	87.7
CaO	10.0	3.4	2.6	1.9	0.3
MgO	5.4	1.9	0.8	0.6	0.1
Na_2O	2.5	1.2	0.3	0.4	0.1
K_2O	0.4	0.5	0.5	0.6	0.2
TiO_2	2.3	2.5	2.1	2.4	0.3
SO_3	13.3	3.0	2.6	1.3	3.2
TOTAL	98.2	99.1	98.8	99.5	98.4

concentration of segregated iron compounds in this coal ash. Weak acid leaching results show although the total sodium is low, but most of it is in "active" form. These results in conjunction with high ash loading and low to moderate ash fusibility temperatures indicate moderate fouling potential.

PULVERIZATION

The pulverization testing was conducted in a C-E model #271 bowl mill. Results are in agreement with the bench-scale Hardgrove Grindability Index, showing the Lakhra baseline coal is easy to pulverize. The energy required to grind this coal was 8.4 Kw-hr/tonne (7.6 Kw-hr/ton). No apparent compaction/pasting was observed during pulverization.

At a mill capacity of 612 Kg/hr (1350 lbs/hr), the amount of mill reject was 2.1% by weight of coal feed. Analysis of the composite mill reject samples is shown in Table 3-4. The ratio of the reject flow and reject composition to the coal flow and coal composition indicate rejection of 4.8% sulfur and 2.3% ash from the raw coal.

Overall, the Lakhra baseline coal exhibits good pulverization characteristics. It requires relatively low mill power consumption for grinding. Bench scale abrasion index indicate this coal has a high potential to cause mill wear, but it can be addressed with proper mill lining materials.

PILOT-SCALE COMBUSTION PERFORMANCE EVALUATION

As-Fired Fuel Analysis

Three composite samples taken hourly during the subject coal test firing in the FPTF were collected and analyzed. Overall, the as-fired fuel samples show consistent qualities. Proximate and ultimate analysis results presented in Table 3-5 indicate the ash ranges from 30.7 to 33.1%, and the sulfur ranges from 5.2 to 5.5% on a moisture free basis. These values are slightly lower compared to the raw coal bench scale results of 36.4% ash and 6.1% sulfur. The differences are mostly accounted for by the amount of mill rejects.

TABLE 3-4

ANALYSIS OF LAKHRA BASELINE COAL MILL REJECT SAMPLES

	As Received	Moisture Free
Proximate, Wt. Percent		
Moisture (Total)	9.9	-
Volatile Matter	30.3	33.6
Fixed Carbon (Diff)	23.4	26.0
Ash	36.4	40.4
Total	100.0	100.0
HHV, Btu/lb	6058	6724
LB Ash/mm Btu	60.1	66.7
Ultimate, Wt. Percent		
Moisture (Total)	9.9	-
Hydrogen	2.7	3.0
Carbon	33.6	37.3
Sulfur	12.5	13.9
Nitrogen	0.7	0.7
Oxygen (Diff)	4.2	4.7
Ash	36.4	40.4
Total	100.0	100.0
Sulfur Form		
Pyritic	10.1	
Sulfate	0.7	
Organic	1.7	
Ash Fusibility (Red.)		
I.T. Deg F	1960	
S.T. Deg F	2000	
H.T. Deg F	2130	
F.T. Deg F	2430	
Temp Diff (FT-IT)	470	
Ash Composition, Wt. Percent		
SiO_2	33.8	
Al_2O_3	17.5	
Fe_2O_3	37.4	
CaO	3.3	
MgO	1.0	
Na_2O	0.5	
K_2O	0.6	
TiO_2	1.4	
SO_3	4.2	
Total	99.7	
Ratios		
BASE/ACID	0.81	
Fe_2O_3/CaO	11.33	
SiO_2/Al_2O_3	1.93	

Ash fusibility and ash composition of the as-fired fuel show a slightly higher initial deformation temperature, 1121°C (2050°F) versus 1082°C (1980°F), and slightly lower iron content, 15.8 to 16.4% versus 17.2%, other fusibility temperatures and ash constituents are essentially the same as from the raw coal.

The particle size analysis of the as-fired fuel samples is shown in Figure 3-3. Samples were determined by sieve analysis for all materials greater than 75 mm (200 mesh) and by a laser diffraction technique for all materials less than 75 microns (200 mesh). Results show 69.8, 70.2, 70.5% through 75 microns (200 mesh) with the mass median particle diameters of 49, 47, and 48 microns for each of the composite samples.

Furnace Operating Conditions

Furnace Operating Conditions during each of the test runs are summarized in Tables 3-6 and 3-7. Each test was conducted at 25% excess air level to simulate typical field unit operating with high slagging coal. With exception for Tests 3 and 5 when furnace was shutdown for deslagging, the duration for all other tests were conducted for approximately 12 hours. The fuel heat input ranged from 2.97 to 2.10 GJ/hr (2.82 to 1.99 x 10^6 Btu/hr).

Furnace Temperature Profile

Furnace temperature profile was carefully monitored and recorded throughout each test. Results of the flame and gas temperatures are summarized in Table 3-8. Individual temperature profiles with respect to burner distance and to residence time for each of the test runs are plotted in Figures 3-4 through 3-7. Furnace temperatures were measured by using a shielded, high velocity suction pyrometer. Four traverse measurements were taken at five furnace ports located approximately 0.9m (3 ft), 1.2m (4 ft), 2.1m (7 ft), 2.4m (8 ft), and 3.7m (12 ft) above the burner during each test. Two traverse measurements were taken at each of the eight convection section ports. Adjustments were made during each test to maintain the variation of traverse

TABLE 3-5

ANALYSIS OF AS-FIRED PULVERIZED LAKHRA BASELINE COAL SAMPLES

	Sample 1		Sample 2		Sample 3	
	As Fired	Moisture Free	As Fired	Moisture Free	As Fired	Moisture Free
Proximate, Wt. Percent						
Moisture (Total)	7.8	-	7.4	-	6.6	-
Volatile Matter	35.7	38.7	34.9	37.7	36.0	38.5
Fixed Carbon (Diff)	26.0	28.2	29.3	31.6	28.4	30.4
Ash	30.5	33.1	28.4	30.7	29.0	31.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
HHV, Btu/lb	7410	8037	7715	8332	7735	8282
LB Ash/mm Btu	41.2	41.2	36.8	36.8	37.5	37.4
Ultimate, Wt. Percent						
Moisture (Total)	7.8	-	7.4	-	6.6	-
Hydrogen	3.6	3.9	3.6	3.9	4.0	4.3
Carbon	41.6	45.1	43.1	46.5	43.8	46.9
Sulfur	5.1	5.5	4.9	5.2	4.9	5.2
Nitrogen	0.7	0.8	0.8	0.9	0.8	0.8
Oxygen (Diff)	10.7	11.6	11.8	12.7	10.9	11.8
Ash	30.5	33.1	28.4	30.7	29.0	31.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
Sulfur Form						
Pyritic	2.6	2.8	2.8	3.0	2.8	3.0
Sulfate	0.5	0.5	0.5	0.5	0.5	0.5
Organic	2.0	2.2	1.6	1.7	1.6	1.7
Ash Fusibility (Red.)						
I.T. Deg F	2050		2050		2040	
S.T. Deg F	2470		2470		2460	
H.T. Deg F	2500		2500		2490	
F.T. Deg F	2550		2560		2550	
Temp Diff (FT-IT)	500		510		510	
Ash Composition, Wt. Percent						
SiO_2	44.3		44.7		43.8	
Al_2O_3	27.2		27.5		26.9	
Fe_2O_3	16.2		15.8		16.4	
CaO	3.4		3.5		3.1	
MgO	1.3		1.5		1.4	
Na_2O	0.8		0.9		0.8	
K_2O	0.6		0.5		0.7	
TiO_2	1.9		2.0		2.0	
SO_3	3.3		3.4		3.9	
Total	99.0		99.8		99.0	
Ratios						
BASE/ACID	0.3		0.3		0.3	
Fe_2O_3/CaO	4.8		4.5		5.3	
SiO_2/Al_2O_3	1.6		1.6		1.6	
Screen Analysis						
±50	1.2		1.1		1.0	
50x100	6.3		6.7		6.0	
100x200	22.7		22.0		22.5	
-200	69.8		70.2		70.5	
MMD,Microns						

temperatures within 100°F for a given radial location. The average peak flame temperature occurred in L1 and L2 throughout each of these test runs. Peak flame temperature ranged from 1549 to 1399°C (2820 to 2550°F).

The gas temperature entering the convection pass section ranged from 1282 to 816°C (2340 to 1500°F). The reduction of ash temperature from superheater banks I to IV was roughly 500°F throughout all test firings. Variations between the traverse temperatures for a given superheater section port was less than 25°F. The corresponding gas velocity entering the superheater ranged from 18.5 to 11.2 m/sec (60.7 to 36.8 ft/sec).

Furnace Residence Time

The Furnace Radiant Section Residence Time during these tests ranged from 1.39 to 2.23 seconds. These values are similar to the typical commercial pulverized coal fired units of 1.5 to 2.0 seconds.

Mass and Energy Balances

Tables 3-9 and 3-10 show the mass and energy balances which include all mass and heat flows from the burner to the first probe bank of the superheater duct during each test. Values presented were obtained by two calculation methods. Method 1 is based on the measured primary and secondary air inputs. Method 2 is based on the measured oxygen concentration in the flue gas. Both of these methods assumed a 100% carbon conversion, as the CO measured in the flue gas was negligible. The overall heat unaccounted for ranged from 0.15 to 6.35%. Since the unburned carbon contents in the fly ash for each run has approximately 0.1%, its associated heat loss was less than 0.3%. The discrepancies were most likely due to the radiation losses from the furnace exterior. The ash split for each test run was approximately 60% fly ash and 40% bottom ash in the FPTF. The rapid bottom ash buildup required frequent handling throughout the test period.

FIGURE 3-[illegible]
ROSIN-RAMMLER PLOT OF AS-FIRED LA[illegible] [illegible]INE COAL SAMPLES

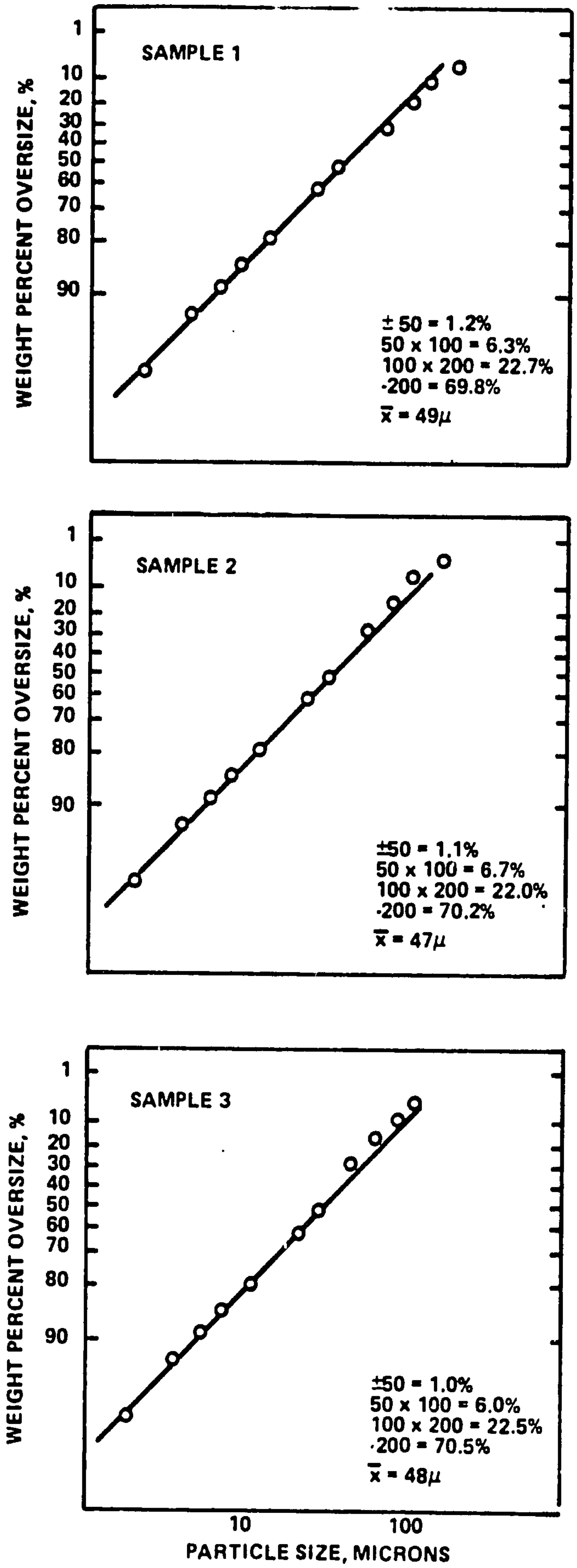


TABLE 3-6

FPTF FURNACE OPERATING CONDITIONS DURING THE
LAKHRA BASELINE COAL EVALUATION

	Test 1	Test 2	Test 3	Test 4
COMBUSTION DATA				
Fuel Feed Rate lb/hr	.238E+03	.382E+03	.282E+03	.379E+03
Fuel HHV Btu/hr	.741E+04	.741E+04	.741E+04	.772E+04
Total Heat Input Btu/hr (From Fuel and Preheated Secondary Air)	.321E+07	.323E+07	.315E+07	.304E+07
Primary Air Flow lb/hr	.262E+03	.256E+03	.266E+03	.282E+03
Primary Air Temp. F	.750E+02	.621E+02	.704E+02	.680E+02
Secondary Air Flow lb/hr	.238E+04	.256E+04	.254E+04	.258E+04
Secondary Air Temp. F	.685E+03	.660E+03	.550E+03	.253E+03
Oxygen (in flue gas)	.391E-01	.394D-01	.394E-01	.394E-01
Furnace Pressure (inches H2O)	-.350E+00	-.350E+00	-.350E+00	-.350E+00
Lower Furnace Temp. F	.282E+04	.274E+04	.265E+04	.261E+04
Lower Furnace Residence Time Sec.	.141E+01	.139E+01	.146E+01	.144E+01
WATERWALL TEST PANELS				
Panel A Surface Temp. F	.426E+03	.522E+03	.524E+03	.477E+03
Panel B Surface Temp. F	.617E+03	.649E+03	.573E+03	.638E+03
Panel C Surface Temp. F	.614E+03	.586E+03	.602E+03	.639E+03
SUPERHEATER PROBES				
Duct 1 Gas Temperature F	.234E+04	.232E+04	.213E+04	.223E+04
Duct 2 Gas Temperature F	.210E+04	.216E+04	.191E+04	.197E+04
Duct 3 Gas Temperature F	.188E+04	.193E+04	.179E+04	.197E+04
Duct 4 Gas Temperature F	.167E+04	.175E+04	.172E+04	.165E+04
Duct 1 Gas Velocity Ft/Sec	.596E+02	.607E+02	.565E+02	.597E+02
Duct 2 Gas Velocity Ft/Sec	.545E+02	.572E+02	.517E+02	.539E+02
Duct 3 Gas Velocity Ft/Sec	.498E+02	.522E+02	.491E+02	.506E+02
Duct 4 Gas Velocity Ft/Sec	.454E+02	.482E+02	.475E+02	.468E+02
ASH				
Input lb/hr	.116E+03	.116E+03	.117E+03	.108E+03
Dust Loading lb/hr	.800E+02	.805E+02	.815E+02	.750E+02

TABLE 3-7

FPTF FURNACE OPERATING CONDITIONS DURING THE
LAKHRA BASELINE COAL EVALUATION

	Test 5	Test 6	Test 7	Test 8
COMBUSTION DATA				
Fuel Feed Rate lb/hr	.301E+03	.301E+03	.278E+03	.254E+03
Fuel HHV Btu/hr	.741E+04	.772E+04	.772E+04	.772E+04
Total Heat Input Btu/hr (From Fuel and Preheated Secondary Air)	.249E+07	.261E+07	.253E+07	.226E+07
Primary Air Flow lb/hr	.289E+03	.273E+03	.268E+03	.270E+03
Primary Air Temp. F	.732E+02	.705E+02	.411E+01	.631E+02
Secondary Air Flow lb/hr	.189E+04	.192E+04	.181E+04	.163E+04
Secondary Air Temp. F	.597E+03	.651E+03	.820E+03	.770E+03
Oxygen (in flue gas)	.424E-01	.424E-01	.387E-01	.418E-01
Furnace Pressure (inches H20)	-.350E+00	-.350E+00	-.350E+00	-.350E+00
Lower Furnace Temp. F	.255E+04	.258E+04	.260E+04	.261E+04
Lower Furnace Residence Time Sec.	.194E+01	.190E+01	.202E+01	.223E+01
WATERWALL TEST PANELS				
Panel A Surface Temp. F	.475E+03	.572E+03	.547E+03	.481E+03
Panel B Surface Temp. F	.634E+03	.645E+03	.679E+03	.634E+03
Panel C Surface Temp. F	.645E+03	.693E+03	.580E+03	.621E+03
SUPERHEATER PROBES				
Duct 1 Gas Temperature F	.202E+04	.211E+04	.205E+04	.204E+04
Duct 2 Gas Temperature F	.198E+04	.193E+04	.194E+04	.183E+04
Duct 3 Gas Temperature F	.182E+04	.174E+04	.180E+04	.177E+04
Duct 4 Gas Temperature F	.170E+04	.158E+04	.161E+04	.161E+04
Duct 1 Gas Velocity Ft/Sec	.421E+02	.437E+02	.404E+02	.368E+02
Duct 2 Gas Velocity Ft/Sec	.414E+02	.407E+02	.387E+02	.337E+02
Duct 3 Gas Velocity Ft/Sec	.387E+02	.374E+02	.364E+02	.328E+02
Duct 4 Gas Velocity Ft/Sec	.366E+02	.347E+02	.334E+02	.305E+02
ASH				
Input lb/hr	.919E+02	.855E+02	.788E+02	.720E+02
Dust Loading lb/hr	.642E+02	.598E+02	.551E+02	.503E+02

TABLE 3-8

TEMPERATURE PROFILES DURING THE BASELINE LAKHRA COAL EVALUATION

Test No.	Firing Rate ($x10^6$ Btu/hr)	Radiant Section (°F) L1	L2	L3	L3A	L4	Convective Section (°F) I	II	III	IV
1	2.82	2820	2790	2730	2660	2550	2340	2100	1880	1670
2	2.82	2710	2740	2680	2630	2550	2320	2160	1930	1750
3	2.82	2650	2580	2570	2440	2340	2230	1910	1790	1620
4	2.82	2610	2560	2520	2490	2370	2130	1970	1820	1650
5	2.23	2490	2550	2460	2370	2290	2020	1980	1820	1700
6	2.23	2580	2560	2490	2410	2330	2110	1930	1740	1[illegible]
7	2.14	2600	2520	2470	2380	2310	2050	1940	1800	[illegible]10
8	1.99	2610	2500	2420	2350	2290	2040	1900	1770	1610

FIGURE 3-4
FPTF TEMPERATURE PROFILES DURING THE LAKHRA BASELINE COAL EVALUATION

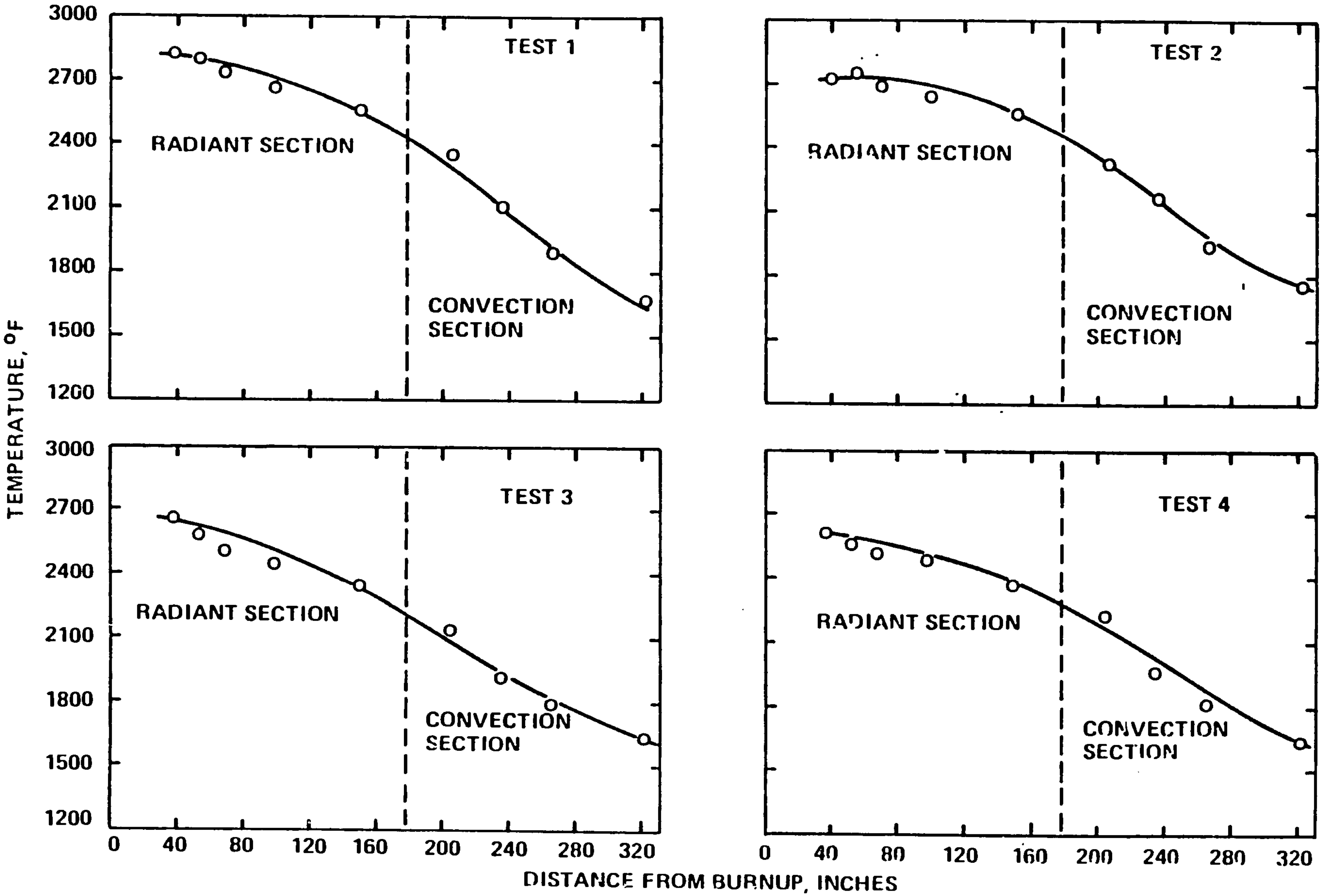


FIGURE 3-5
FPTF TEMPERATURE PROFILES DURING THE LAKHRA BASELINE COAL EVALUATION

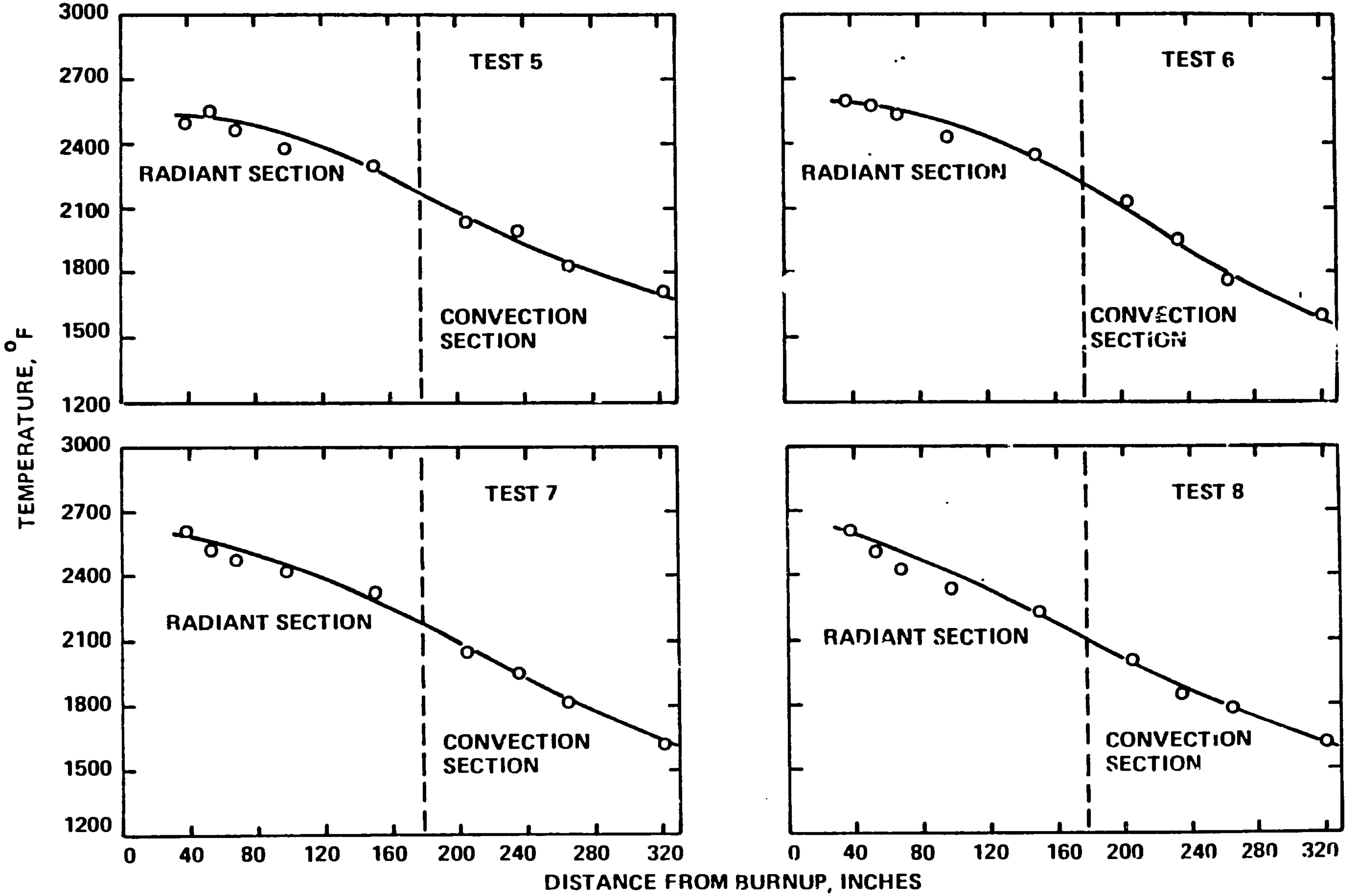


FIGURE 3-6
RESIDENCE TIME IN THE FPTF DURING THE LAKHRA BASELINE COAL EVALUATION

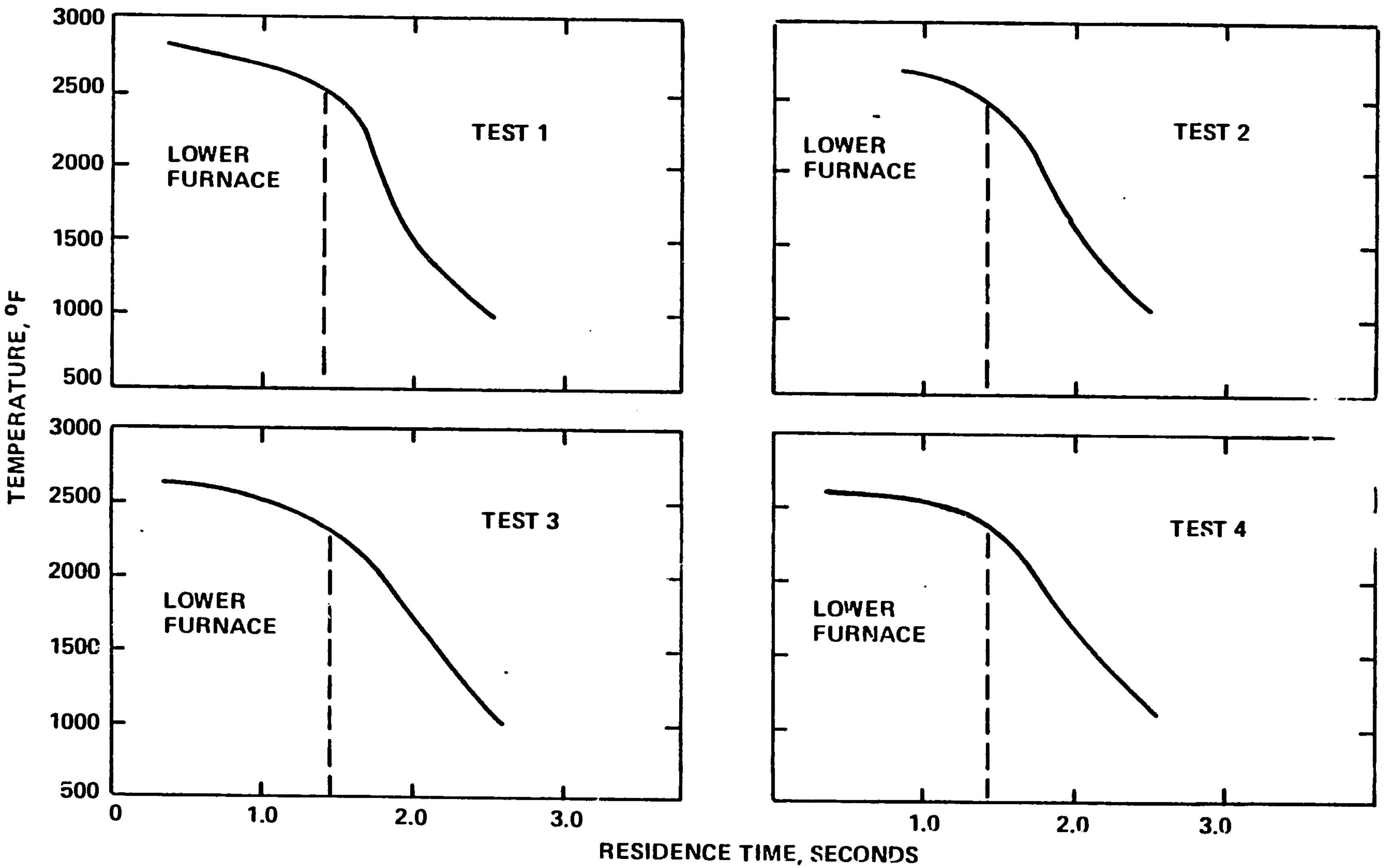


FIGURE 3-7
RESIDENCE TIME IN THE FPTF DURING THE LAKHRA BASELINE COAL EVALUATION

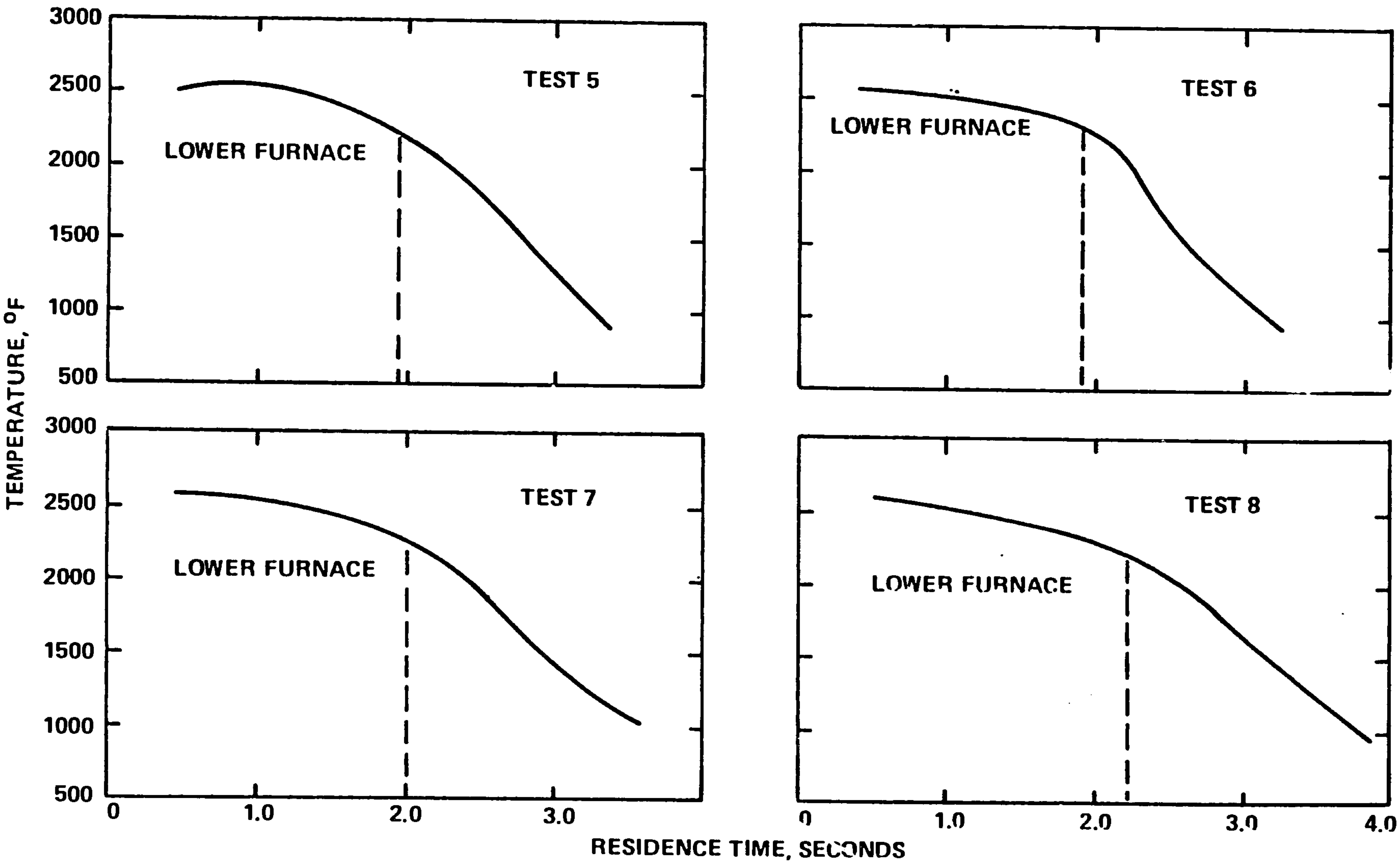


TABLE 3-9

FPTF MASS AND ENERGY BALANCES DURING THE
LAKHRA BASELINE COAL EVALUATION

	TEST 1		TEST 2		TEST 3		TEST 4	
METHOD 1-----								
FLUE GAS FLOW RATE LB/HR	.300E+04		.308E+04		.308E+04		.313E+04	
COMPOSITION IN MOLES/HR								
OXYGEN	.397E+01	3.89	.443E+01	4.24	.441E+01	4.21	.136E+02	4.31
CARBON DIOXIDE	.132E+02	12.92	.132E+02	12.65	.132E+02	12.67	.136E+02	12.82
WATER	.103E+02	10.09	.104E+02	9.92	.104E+02	9.93	.103E+02	9.64
SULFUR DIOXIDE	.606E+00	.59	.609E+00	.58	.609E+00	.58	.568E+00	.53
NITROGEN	.740E+02	72.51	.760E+02	72.61	.769E+02	72.61	.773E+02	72.70
METHOD 1-----								
HEAT LOSS FROM REFRACTORY BTU/HR	.676E+05	2.10	.145E+06	4.49	.176E+06	5.58	.160E+06	5.24
HEAT LOSS FROM PANEL	.130E+06	4.03	.105E+06	3.25	.829E+05	2.63	.103E+06	3.39
HEAT LOSS FROM WATER COOLED FRAME	.926E+05	2.88	.728E+05	2.26	.285E+05	.82	.696E+05	2.29
HEAT LOSS FROM FLY ASH	.420E+05	1.31	.430E+05	1.33	.396E+05	1.26	.372E+05	1.22
HEAT LOSS FROM FLUE GAS	.188E+07	58.66	.197E+07	60.93	.176E+07	55.93	.183E+07	60.15
HEAT LOSS FROM ROOF	.363E+05	1.13	.394E+05	1.22	.360E+05	1.14	.328E+05	1.08
HEAT LOSS FROM PROCESS HEATER	.762E+05	2.37	.715E+05	2.22	.628E+05	2.00	.399E+05	1.31
HEAT LOSS FROM S.H. TRANSITION	.153E+06	4.77	.112E+06	3.48	.893E+05	2.84	.103E+06	3.40
HEAT LOSS FROM S.H. FRAME	.606E+05	1.89	.553E+05	1.71	.399E+05	1.27	.440E+05	1.33
HEAT LOSS FROM S.H. DUCT	.326E+06	10.16	.293E+06	9.09	.251E+06	7.96	.281E+06	9.23
HEAT LOSS FROM OBS. PORT	.420E+05	1.31	.324E+05	1.00	.364E+05	1.16	.254E+05	.83
HEAT LOSS FROM BURNER	.673E+05	2.10	.791E+05	2.45	.101E+06	3.19	.344E+05	1.13
HEAT LOSS FROM FURNACE BOTTOM LEFT	.521E+05	1.62	.373E+05	1.16	.807E+05	2.56	.308E+05	1.01
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.310E+05	.97E+	.210E+05	.65	.462E+05	1.47	.222E+05	.73
METHOD 2-----								
FLUE GAS FLOW RATE LB/HR	.301E+04		.302E+04		.303E+04		.306E+04	
COMPOSITION IN MOLES/HR								
OXYGEN	.400E+01	3.91	.405E+01	3.94	.405E+01	3.94	.410E+01	3.94
CARBON DIOXIDE	.132E+02	12.90	.132E+02	12.88	.132E+02	12.88	.136E+02	13.10
WATER	.103E+02	10.08	.103E+02	10.06	.103E+02	10.06	.102E+02	9.82
SULFUR DIOXIDE	.606E+00	.59	.609E+00	.59	.609E+00	.59	.568E+00	.55
NITROGEN	.741E+02	72.52	.746E+02	72.53	.746E+02	72.53	.755E+02	72.59
METHOD 2-----								
HEAT LOSS FROM REFRACTORY BTU/HR	.676E+02	2.10	.145E+06	4.49	.176E+06	5.58	.160E+06	5.24
HEAT LOSS FROM PANEL	.130E+06	4.03	.105E+06	3.25	.829E+05	2.63	.103E+06	3.39
HEAT LOSS FROM WATER COOLED FRAME	.926E+05	2.88	.728E+05	2.26	.258E+05	.82	.696E+05	2.29
HEAT LOSS FROM FLY ASH	.420E+05	1.31	.430E+05	1.33	.396E+05	1.26	.372E+05	1.22
HEAT LOSS FROM FLUE GAS	.189E+07	58.74	.193E+07	59.88	.173E+07	55.04	.179E+07	58.87
HEAT LOSS FROM ROOF	.363E+05	1.13	.394E+05	1.22	.360E+05	1.14	.328E+05	1.08
HEAT LOSS FROM PROCESS HEATER	.762E+05	2.37	.715E+05	2.22	.628E+05	2.00	.399E+05	1.31
HEAT LOSS FROM S.H. TRANSITION	.153E+06	4.77	.112E+06	3.48	.893E+05	2.84	.103E+06	3.40
HEAT LOSS FROM S.H. FRAME	.606E+05	1.89	.553E+05	1.71	.399E+05	1.27	.404E+05	1.33
HEAT LOSS FROM S.H. DUCT	.326E+06	10.16	.293E+06	9.09	.251E+06	7.96	.281E+06	9.23
HEAT LOSS FROM OBS. PORT	.420E+05	1.31	.324E+05	1.00	.364E+05	1.16	.254E+05	.83
HEAT LOSS FROM BURNER	.673E+05	2.10	.791E+05	2.45	.101E+06	3.19	.344E+05	1.13
HEAT LOSS FROM FURNACE BOTTOM LEFT	.521E+05	1.62	.373E+05	1.16	.087E+05	2.56	.306E+05	1.01
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.310E+05	.97	.210E+05	.65	.462E+05	1.47	.222E+05	.73
METHOD 1-----TOTAL HEAT INPUT BTU/HR	.321E+07		.323E+07		.315E+07		.304E+07	
TOTAL HEAT OUTPUT BTU/HR	.321E+07		.322E+07		.298E+07		.296E+07	
HEAT UNACCOUNTED FOR	.0		.15		5.46		2.86	
METHOD 2-----TOTAL HEAT INPUT BUT/HR	.321E+07		.319E+07		.315E+07		.304E+07	
TOTAL HEAT OUTPUT BTU/HR	.321E+07		.319E+07		.295E+07		.292E+07	
HEAT UNACCOUTNED FOR	.02		1.20		6.35		4.14	
METHOD 1-----TOTAL MATERIAL INPUT LB/HR	.312E+04		.319E+04		.319E+04		.324E+04	
TOTAL MATERIAL OUTPUT LB/HR	.312E+04		.319E+04		.319E+04		.324E+04	
MATERIAL UNACCOUNTED FOR	.0		.0		.0		.0	
METHOD 2-----TOTAL MATERIAL INPUT LB/HR	.312E+04		.314E+04		.314E+04		.317E+04	
TOTAL MATERIAL OUTPUT LB/HR	.312E+04		.314E+04		.315E+04		.317E+04	
MATERIAL UNACCOUNTED FOR	.0		.0		.0		.0	

TABLE 3-10

FPTF MASS AND ENERGY BALANCES DURING THE
LAKHRA BASELINE COAL EVALUATION

	TEST 5		TEST 6		TEST 7		TEST 8	
METHOD 1-----								
FLUE GAS FLOW RATE LB/HR	.239E+04		.240E+04		.228E+04		.208E+04	
COMPOSITION IN MOLES/HR								
OXYGEN	.324E+01	3.98	.302E+01	3.70	.321E+01	4.16	.293E+01	4.15
CARBON DIOXIDE	.104E+02	12.85	.108E+02	13.29	.999E+01	12.93	.913E+01	12.94
WATER	.817E+01	10.04	.810E+01	9.93	.750E+01	9.71	.686E+01	9.72
SULFUR DIOXIDE	.479E+00	.59	.452E+00	.55	.416E+00	.54	.381E+00	.54
NITROGEN	.590E+02	72.54	.592E+02	72.53	.561E+02	72.65	.531E+02	72.65
METHOD 1-----								
HEAT LOSS FROM REFRACTORY BTU/HR	.154E+06	6.17	.177E+06	6.76	.250E+06	9.91	.175E+06	7.75
HEAT LOSS FROM PANEL	.810E+05	3.25	.102E+06	3.91	.860E+05	3.40	.816E+05	3.62
HEAT LOSS FROM WATER COOLED FRAME	.413E+05	1.66	.783E+05	3.00	.641E+05	2.54	.641E+05	2.74
HEAT LOSS FROM FLY ASH	.312E+05	1.25	.288E+05	1.10	.270E+05	1.07	.244E+05	1.08
HEAT LOSS FROM FLUE GAS	.137E+07	55.11	.136E+07	52.18	.130E+07	51.36	.118E+07	52.40
HEAT LOSS FROM ROOF	.219E+05	.88	.287E+05	1.10	.291E+05	1.15	.296E+05	1.31
HEAT LOSS FROM PROCESS HEATER	.146E+06	5.84	.456E+05	1.75	.449E+05	1.78	.476E+05	2.11
HEAT LOSS FROM S.H. TRANSITION	.931E+05	3.74	.933E+05	3.75	.665E+05	2.68	.871E+05	3.86
HEAT LOSS FROM S.H. FRAME	.387E+05	1.55	.380E+05	1.45	.281E+05	1.11	.339E+05	1.50
HEAT LOSS FROM S.H. DUCT	.180E+06	7.25	.201E+06	7.68	.174E+06	6.88	.146E+06	6.46
HEAT LOSS FROM OBS. PORT	.222E+05	.89	.392E+05	1.50	.307E+05	1.21	.386E+05	1.71
HEAT LOSS FROM BURNER	.580E+05	2.33	.809E+05	3.10	.87E+05	3.45	.952E+05	4.22
HEAT LOSS FROM FURNACE BOTTOM LEFT	.570E+05	2.29	.692E+05	2.65	.675E+05	2.68	.678E+05	3.00
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.325E+05	1.31	.506E+05	1.94	.517E+05	2.05	.542E+05	2.40
METHOD 2-----								
FLUE GAS FLOW RATE LB/HR	.243E+04		.248E+04		.224E+04		.208E+04	
COMPOSITION IN MOLES/HR								
OXYGEN	.350E+01	4.24	.357E+01	4.24	.294E+01	3.87	.295E+01	4.18
CARBON DIOXIDE	.104E+02	12.65	.108E+02	12.87	.999E+01	13.16	.913E+01	12.92
WATER	.819E+01	9.92	.815E+01	9.67	.748E+01	9.85	.686E+01	9.70
SULFUR DIOXIDE	.480E+00	.58	.452E+00	.54	.416E+00	.55	.381E+00	.54
NITROGEN	.600E+02	72.61	.612E+02	72.68	.551E+02	72.57	.514E+02	72.66
METHOD 2-----								
HEAT LOSS FROM REFRACTORY BTU/HR	.154E+06	6.17	.177E+06	6.76	.250E+06	9.91	.175E+06	7.75
HEAT LOSS FROM PANEL	.810E+05	3.25	.102E+06	3.91	.860E+05	3.40	.816E+06	3.62
HEAT LOSS FROM WATER COOLED FRAME	.413E+05	1.66	.783E+05	3.00	.641E+05	2.54	.618E+05	2.74
HEAT LOSS FROM FLY ASH	.312E+05	1.25	.288E+05	1.10	.270E+05	1.07	.244E+05	1.08
HEAT LOSS FROM FLUE GAS	.139E+07	55.95	.141E+07	53.85	.128E+07	50.50	.118E+07	52.49
HEAT LOSS FROM ROOF	.219E+05	.88	.287E+05	1.10	.291E+05	1.15	.296E+05	1.31
HEAT LOSS FROM PROCESS HEATER	.149E+06	5.84	.456E+05	1.75	.449E+05	1.78	.476E+05	2.11
HEAT LOSS FROM S.H. TRANSITION	.931E+05	3.74	.933E+05	3.57	.665E+05	2.63	.871E+05	3.86
HEAT LOSS FROM S.H. FRAME	.387E+05	1.55	.380E+05	1.45	.281E+05	1.11	.339E+05	1.50
HEAT LOSS FROM S.H. DUCT	.180E+06	7.25	.201E+06	7.68	.174E+06	6.88	.146E+06	6.48
HEAT LOSS FROM OBS. PORT	.222E+05	.89	.392E+05	1.50	.307E+05	1.21	.386E+05	1.71
HEAT LOSS FROM BURNER	.580E+05	2.33	.809E+05	3.10	.870E+05	3.45	.952E+05	4.22
HEAT LOSS FROM FURNACE BOTTOM LEFT	.570E+05	2.29	.692E+05	2.65	.675E+05	2.68	.678E+05	3.00
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.325E+05	1.31	.506E+05	1.94	.517E+05	2.05	.542E+05	2.40

	TEST 5	TEST 6	TEST 7	TEST 8
METHOD 1-----TOTAL HEAT INPUT BUT/HR	.249E+07	.261E+07	.253E+07	.226E+07
TOTAL HEAT OUTPUT BTU/HR	.245E+07	.251E+07	.241E+07	.222E+07
HEAT UNACCOUNTED FOR	1.77	3.97	4.53	1.46
METHOD 2-----TOTAL EHAT INPUT BUT/HR	.249E+07	.261E+07	.253E+07	.226E+07
TOTAL HEAT OUTPUT BTU/HR	.247E+07	.256E+07	.239E+07	.223E+07
HEAT UNACCOUNTED FOR	.93	2.20	5.39	1.37
METHOD 1-----TOTAL MATERIAL INPUT LB/HR	.248E+04	.249E+04	.235E+04	.215E+04
TOTAL MATERIAL OUTPUT LB/HR	.248E+04	.249E+04	.235E+04	.215E+04
MATERIAL UNACCOUNTED FOR	.0	.0	.0	.0
METHOD 2-----TOTAL MATERIAL INPUT LB/HR	.252E+04	.257E+04	.232E+04	.215E+04
TOTAL MATERIAL OUTPUT LB/HR	.252E+04	.257E+04	.232E+04	.215E+04
MATERIAL UNACCOUNTED FOR	.0	.0	.0	.0

Relative Combustion Characteristics

Observations made during testing indicate the Lakhra baseline coal exhibits good combustion characteristics. It burnt easily with good flame stability throughout each test condition. Fly ash analysis show the carbon content was low, 0.1%. The corresponding carbon conversion was better than 99.9%.

Furnace Slagging Characteristics

The furnace slagging was characterized by assessing the deposit buildup and its ease of removal, the interference of deposits on heat transfer through waterwall, and the physical and chemical characteristics of the waterwall deposits. The overall results show the Lakhra baseline coal has severe slagging potential. Results show reduction in fuel load slightly reduced the amount of deposit accumulated on the waterwall panel due to the lower ash input. However, furnace temperature was the most critical parameter controlling slagging. Furnace deposits were cleanable at flame temperature up to 1427°C (2600°F), above this temperature deposits were uncontrollable.

The Waterwall Heat flux Data obtained from each test run provides information on the overall effect of waterwall deposits on heat transfer and the relative deposit buildup rate. Comparison between the initial heat flux with clean panel and heat flux after sootblowing provides a quantitative indication of the ease of deposit removal and sootblower effectiveness.

The furnace conditions and slagging results during each test run are summarized in Table 3-11. Furnace deposits at two furnace elevations (panels C and B) were assessed. Panel C is located approximately 0.9m (3 ft) above the burner and panel B is approximately 1.4m (4.5 ft) above the burner.

Overall, results show the subject coal exhibits a relatively rapid deposit accumulation rate. The average heat flux through panel at the conclusion of each test ranged from 234 to 427 MJ/hr-m^2 (20,600 to 37,600 Btu/hr-ft^2), and through panel C ranged from 330 to 384 MJ/hr-m^2 (29,600 to 33,770 Btu/hr-ft^2).

TABLE 3-11

WATERWALL HEAT FLUX RECOVERY DURING THE LAKHRA BASELINE COAL EVALUATION

TEST NO.	FIRING RATE (MM BTU/HR)	FLAME TEMP. AT PANELS (°F)		INITIAL HEAT FLUX ($x10^3$ BTU/HR-FT^2)		FINAL HEAT FLUX (BTU/Hr-ft^2)		AVERAGE HEAT FLUX ($x10^3$ BTU/HR-FT^2)		HEAT FLUX RECOVERY (%)	
		B	C	B	C	B	C	B	C	B	C
1	2.82	2790	2820	87.09	82.04	22.00	19.99	37.60	31.76	0	0
2	2.82	2740	2710	77.59	86.99	13.69	16.55	25.99	33.77	0	1
3	2.82	2580	2650	59.20	69.97	12.59	11.99	29.48	27.61	17	3
4	2.82	2560	2610	65.64	64.82	17.28	18.70	25.30	33.41	99	98
5	2.23	2550	2490	53.55	55.26	13.02	20.87	20.60	27.02	100	95
6	2.23	2560	2580	59.32	65.49	12.76	26.67	22.02	32.22	100	100
7	2.14	2520	2600	60.37	56.00	11.79	20.21	22.45	29.06	100	100
8	1.99	2500	2610	56.97	57.27	24.06	27.87	21.07	29.62	94	100

Comparison between tests 4, 6, 7 and 8 at critical flame temperature of 1427°C (2600°F) indicate a heat flux reduction of 71.1, 59.3, 63.9, and 51.3% through panel C after 12 hours. The higher heat flux reduction at higher firing rate is attributed to the higher ash input from the fuel which resulted in thicker waterwall deposits.

The Cleanability of Waterwall Deposits are illustrated by the heat flux recovery values after sootblowing. The results are summarized in Table 3-11 and depicted by the heat flux plots shown in Figures 3-8 to 3-9 for each test run. The overall results from panels B and C indicate the waterwall deposits were cleanable at critical flame temperature of 1427°C (2600°F) for all firing rates. Heat flux recovery was better than 90% under these conditions. At flame temperatures above 1427°C (2600°F), deposits were uncontrollable and could not be cleaned by sootblower.

Figures 3-10 to 3-17 show photographs depicting the on-line deposit accumulated on the waterwall panels B and C, and the effect of sootblowing at the end of each test. Overall, results are in agreement with the heat flux recovery data. As shown in Figures 3-10, 3-11, and 3-12, waterwall deposits remained almost intact after sootblowing at flame temperatures above 1427°C (2600°F). Pictures from Figures 3-13 to 3-17 show the deposits were cleanable at 2600°F flame temperature for each of the firing rates tested.

The Physical Properties of the Waterwall Deposit from each test run are summarized in Table 3-12. Deposits formed on both panels B and C were molten at flame temperature above 1427°C (2600°F). Below this temperature deposits were highly sintered with molten outer layer.

Waterwall deposit thickness slightly decreased with firing rate. Tests 4, 6, 7 and 8 show at similar flame temperature of 1427°C (2600°F), the thickness decreased from 19 to 13 mm (3/4 to 1/2 inch) as firing rate decreased from 2.97 to 2.10 GJ/hr (2.82×10^6 to 1.99×10^6 Btu/hr). Deposit thickness was also affected by flame temperature. Tests 1 to 4 show at 2.97 GJ/hr (2.82×10^6 Btu/hr) firing rate, deposit decreased from 25.4 to 19 and 13 mm (1 to 3/4 and 1/2 inch) as flame temperature decreased from 1549 to 1429°C (2820 to 2610°F).

TABLE 3-12

WATERWALL DEPOSIT PHYSICAL CHARACTERISTICS OF THE LAKHRA BASELINE COAL

Test No.	Firing Rate (x10^6 Btu/hr)	Avg. Flame Temperature (°F)	Deposit Coverage (%)	Deposit Thickness (in.)	Deposit Physical State	Deposit Cleanability
1	2.82	2820	100	1	Molten	Poor
2	2.82	2740	100	1	Molten	Poor
3	2.82	2650	100	3/4	Molten	Poor
4	2.82	2610	100	1/2 - 3/4	Highly Sintered Molten Outer	Good
5	2.23	2550	100	1/2 - 3/4	Highly Sintered Molten Outer	Good
6	2.23	2580	100	1/2 - 3/4	High Sintered Molten Outer	Good
7	2.14	2600	100	1/2	Highly Sintered Molten outer	Good
8	1.99	2610	100	1/2	Highly Sintered Molten Outer	Good

FIGURE 3-8

LAKHRA BASELINE COAL EVALUATION IN THE FPTF
HEAT FLUX THROUGH WATERWALL PANELS

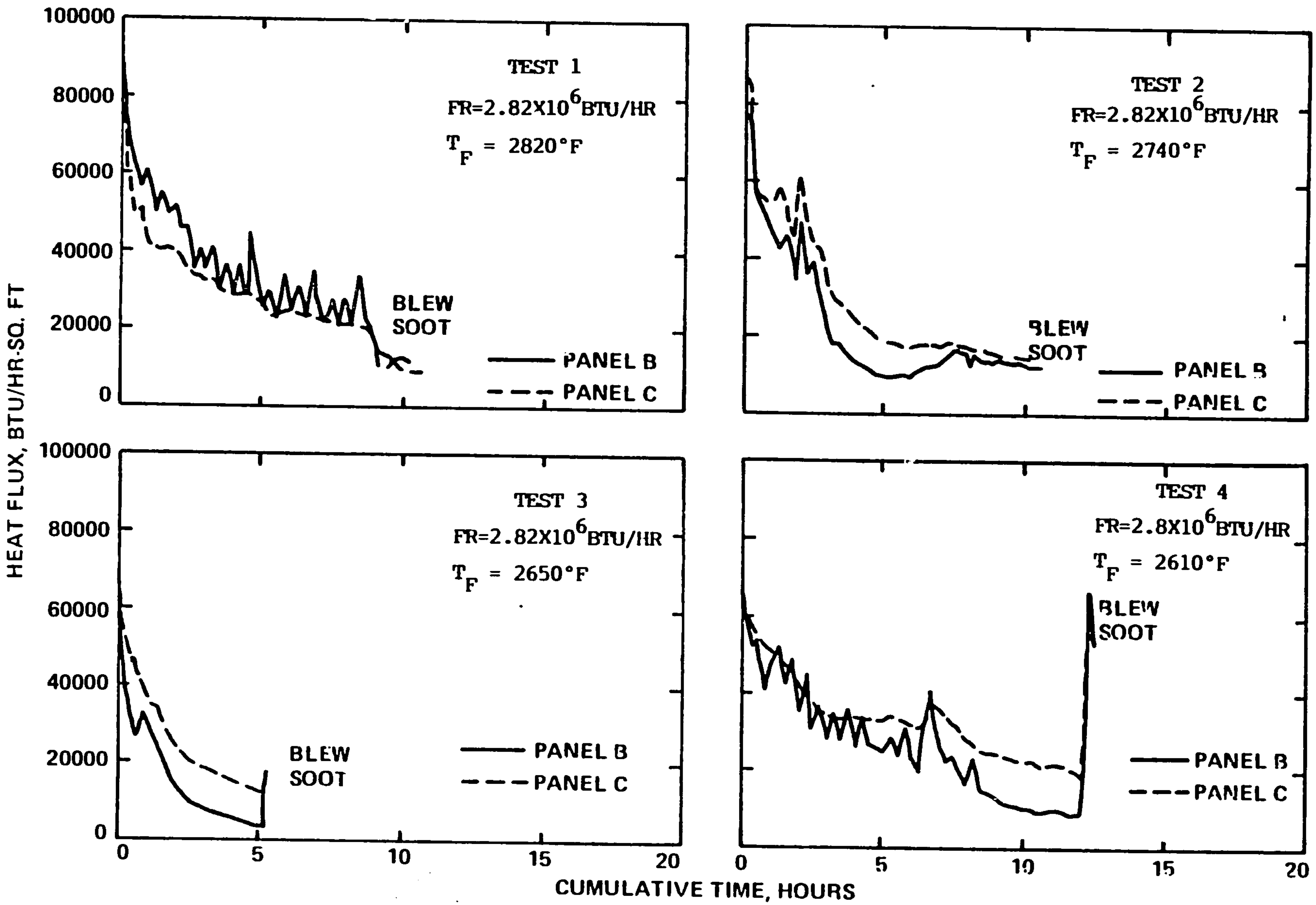
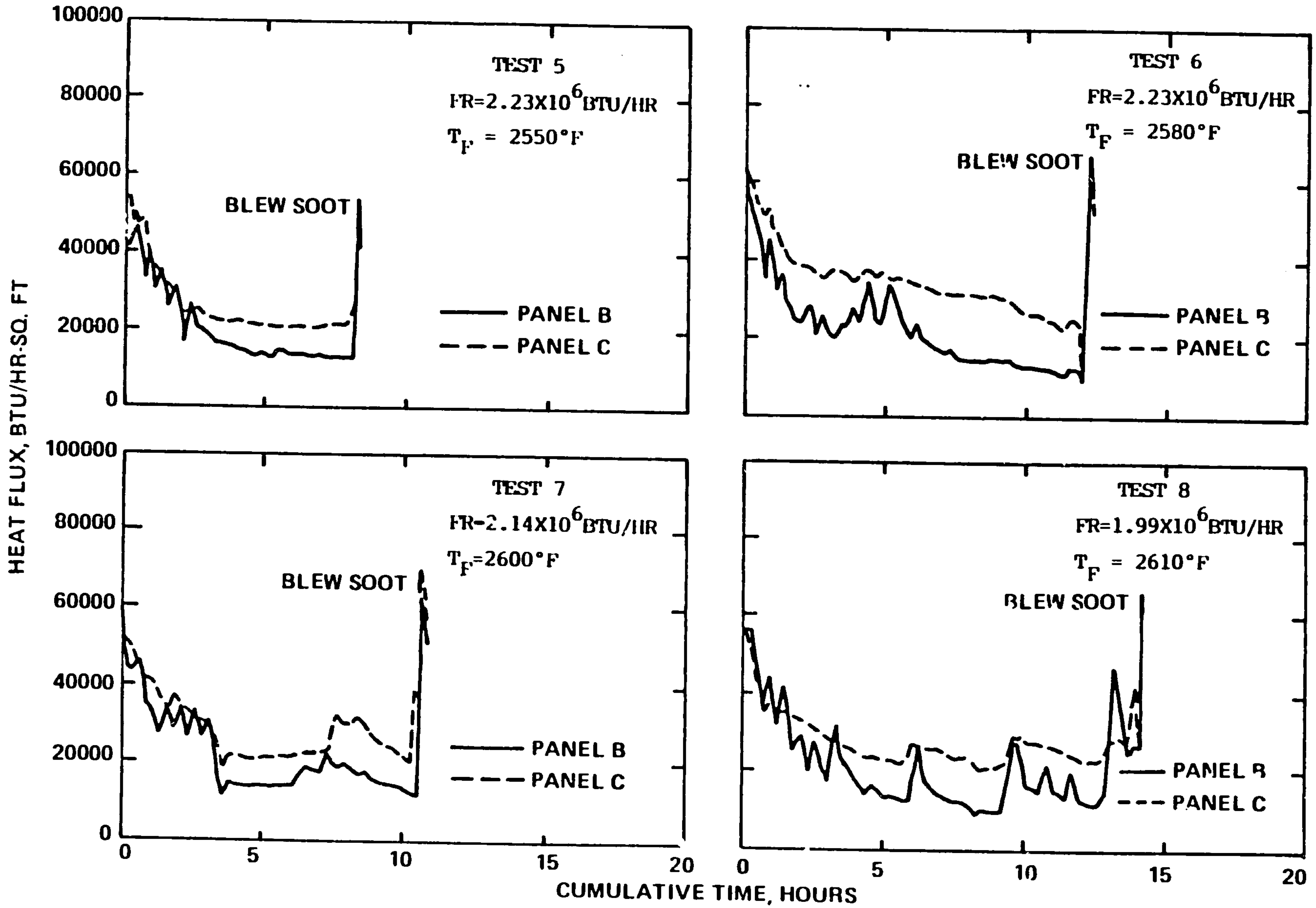


FIGURE 3-9
LAKHRA BASELINE COAL EVALUATION IN THE FPTF
HEAT FLUX THROUGH WATERWALL PANELS



LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 1

T_B = 2790°F

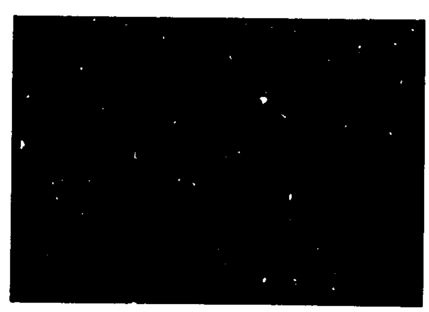
PANEL B

T_C = 2820°F

PANEL C

END OF TEST

AFTER SOOTBLOWING



LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 2

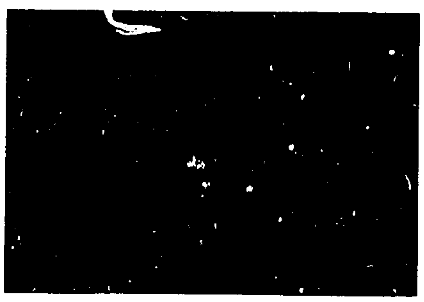
T_B = 2740°F

PANEL B

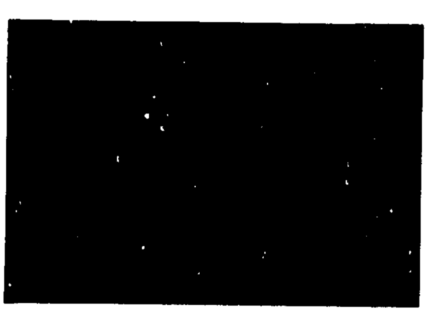
T_C = 2710°F

PANEL C

END OF TEST



AFTER SOOTBLOWING



LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 3

T_B = 2580°F

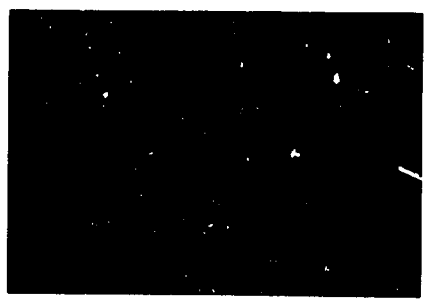
PANEL B

T_C = 2650°F

PANEL C

END OF TEST

AFTER SOOTBLOWING



LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 4

$T_B = 2560°F$

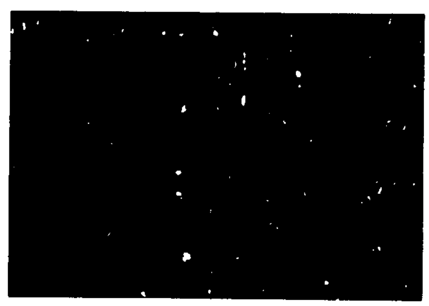
PANEL B

$T_C = 2610°F$

PANEL C

END OF TEST

AFTER SOOTBLOWING



LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 5

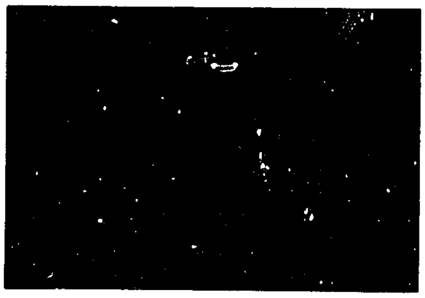
T_B = 2550°F

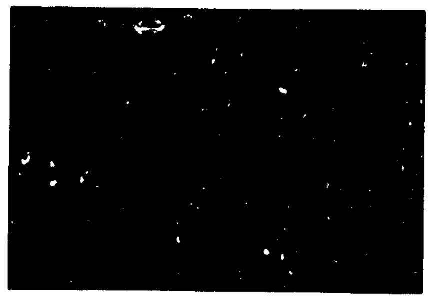
PANEL B

T_C = 2490°F

PANEL C

END OF TEST





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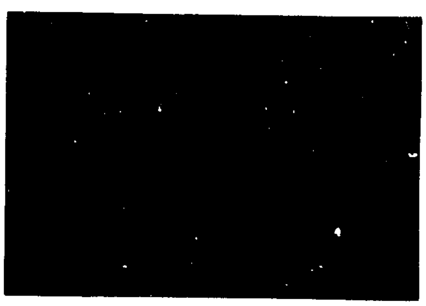


LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 6

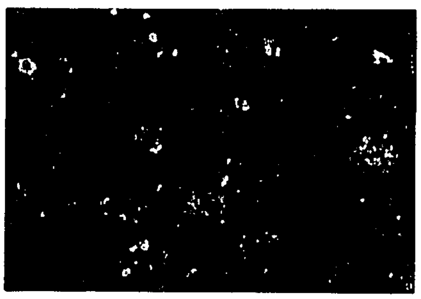
T_B = 2560°F

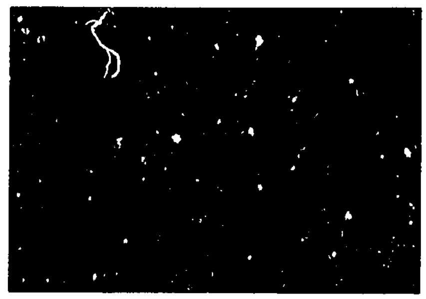
PANEL B

T_C = 2580°F

PANEL C

END OF TEST





AFTER SOOTBLOWING

LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 7

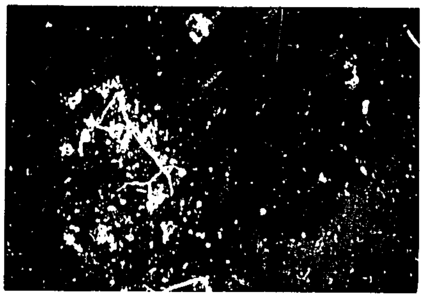
T_B = 2520°F

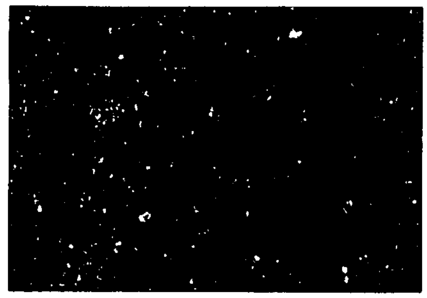
PANEL B

T_C = 2600°F

PANEL C

END OF TEST





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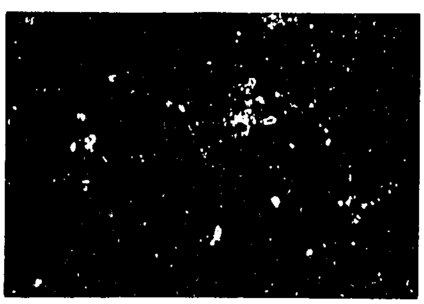


LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON WATERWALL PANELS

TEST 8

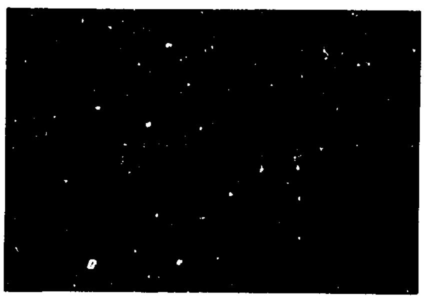
T_B = 2500°F

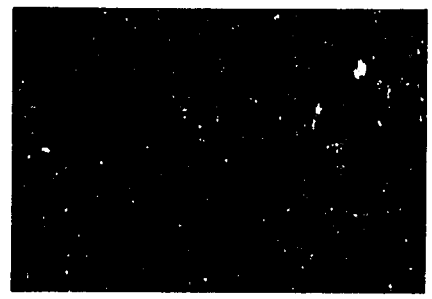
PANEL B

T_C = 2610°F

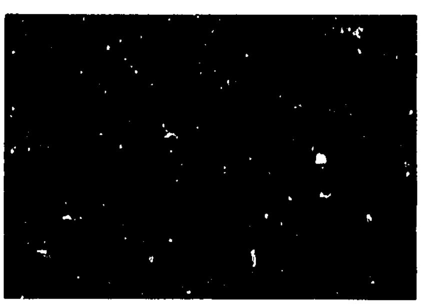
PANEL C

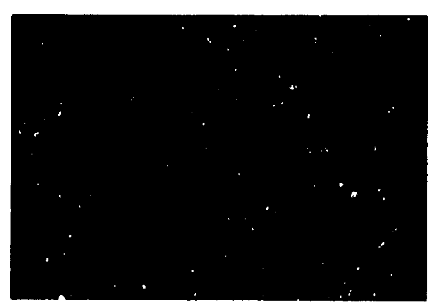
END OF TEST





AFTER SOOTBLOWING





Waterwall Deposit Chemical Analysis results are summarized in Table 3-13. In general, deposits from both panels were similar to the as-fired coal ash. Both the initial and outer deposits showed slight enrichment in iron content, with other constituents remained relatively the same. Ash fusibility temperatures of the waterwall deposits were generally lower. It ranged from 1088°C (1990°F) initial deformation temperature to 1377°C (2510°F) compared to 1121°C (2050°F) and 1404°C (2560°F) for the as-fired coal ash. The lower ash fusibility temperatures are attributed to the slight increased in iron content.

In summary, the Lakhra baseline coal exhibits severe slagging potential. Flame temperature was the most critical parameter controlling slagging. Waterwall deposits were not cleanable at flame temperature above 1427°C (2600°F). Below this temperature, deposits were controllable by sootblowing.

Convective Pass Fouling Characteristics

The convective pass deposit characteristics were assessed by the relative deposit buildup, deposit bonding strength, and deposit physical and chemical properties. Results obtained from this coal are summarized in Table 3-14. Overall, the Lakhra baseline coal has a moderate fouling potential. The rate of deposit buildup was high, but deposits were readily cleanable as deposit to tube bonding strengths were low during each of the test runs.

Convective Pass Deposit Buildup Rates are depicted by the deposit growth time sequence photographs shown in Figures 3-18 to 3-20. The effects of gas temperature, gas velocity and firing rate upon deposition rate were assessed. Overall, results show the deposit growth increases with increasing gas temperature. For the same firing rate of 2.97 GJ/hr (2.82 x 10^6 Btu/hr), sootblowing was required every 3 to 4 hours at 1282°C (2340°F), and 5 to 6 hours at 1165°C (2130°F) gas temperature. Similarly, sootblowing frequency was reduced to 6 to 8 hours at reduced firing rates, 2.35 x 10^3 and 2.10 GJ/hr (2.23 x 10^6 and 1.99 x 10^6 Btu/hr) and gas temperatures in the 1104 to 1115°C (2020 to 2040°F) range.

TABLE 3-13

ANALYSIS OF WATERWALL DEPOSITS COLLECTED FROM L HRA BASELINE COAL TESTING

	Panel C		Panel B	
	Initial	Outer	Initial	Outer
Ash Fusibility, °F				
I.T.	2010	2040	1990	2040
S.T.	2120	2350	2350	2360
H.T.	2420	2430	2430	2430
F.T.	2430	2510	2500	2490
Ash Composition, Wt %				
SiO_2	42.1	44.7	43.7	44.9
Al_2O_3	27.7	27.5	26.0	27.1
Fe_2O_3	19.7	17.5	19.6	19.8
CaO	3.5	3.6	3.4	3.2
MgO	1.1	1.3	1.5	1.3
Na_2O	0.7	0.6	0.8	0.9
F_2O	0.4	0.7	0.6	0.5
TiO_2	1.9	2.0	1.9	1.9
SO_3	2.9	2.1	2.4	0.1
Total	100.0	100.0	99.9	99.7

LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON SUPERHEATER PROBE

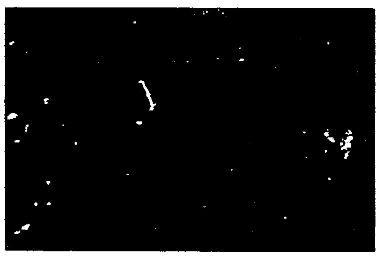
FIRING RATE = 2.82×10^6 BTU/HR   GAS TEMPERATURE = 2340°F

0 HR

2 HRS

4 HRS

FIRING RATE = 2.82×10^6 BTU/HR   GAS TEMPERATURE = 2320°F



0 HR

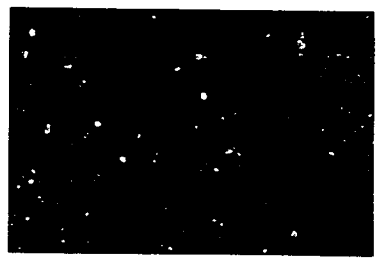
2 HRS

4 HRS

LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON SUPERHEATER PROBE

FIRING RATE = $2.82X10^6$ BTU/HR GAS TEMPERATURE = 2130°F

0 HR

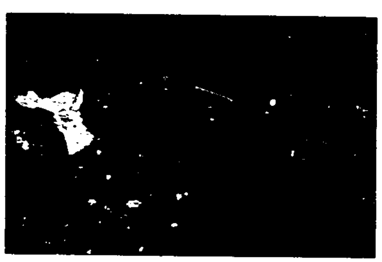


2 HRS

4 HRS

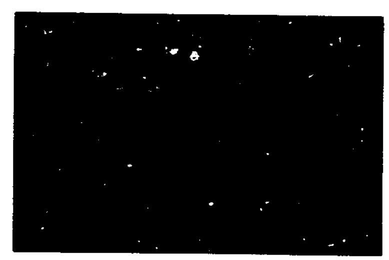
8 HRS

FIRING RATE = $2.23x10^6$ BTU/HR GAS TEMPERATURE = 2110°F



0 HR

2 HRS



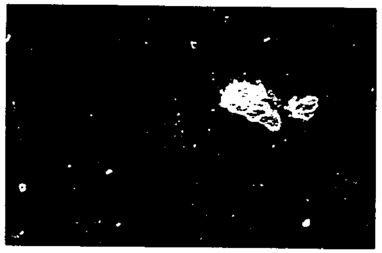
4 HRS

8 HRS

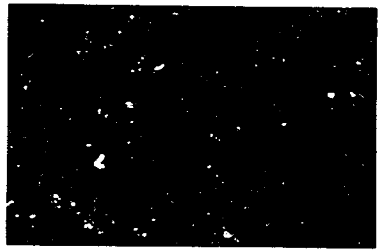
LAKHRA BASELINE COAL EVALUATION IN THE FPTF
ASH DEPOSITION ON SUPERHEATER PROBE

FIRING RATE = 2.23×10^{6} BTU/HR GAS TEMPERATURE = 2020°F

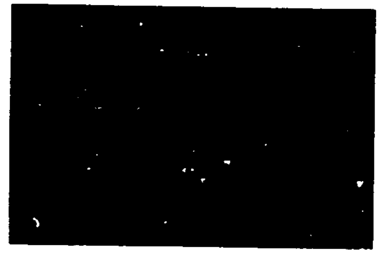
0 HR



2 HRS



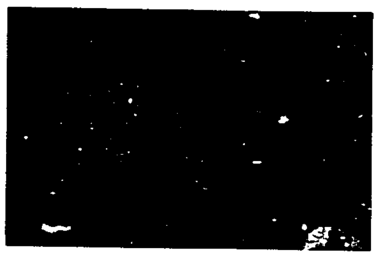
4 HRS



8 HRS

FIRING RATE = 1.99×10^{6} BTU/HR GAS TEMPERATURE = 2040°F

0 HR



2 HRS

4 HRS

8 HRS

Observations made during each of these test runs indicate there was a high amount of deposit carryover from the furnace. Deposits built up rapidly in the higher gas temperature transition, 1254 to 1399°C (2290 to 2550°F), between the furnace and the convection duct. This behavior has often been observed with high slagging fuels tested in the FPTF and in field units operating with high slagging fuels. Ample sootblower coverage will be required for the high temperature convective passes.

Deposit Bonding Strength was measured to assess the relative ease of deposit removal from the superheater tube surfaces. Measurements were taken on-line when the deposit accumulated on the convection probe surface reached a thickness of approximately 76 mm (3 inch) thick. Results show this coal has low deposit to tube bonding strength (up to 5) at flame temperatures up to 1549°C (2820°F) and gas temperature up to 1282°C (2340°F). The low bonding strength was in agreement with observations made during these tests, as small amount of deposits slough off occasionally from the superheater probe surface. Overall, because of the low bonding strength and the lightly sintered deposit, deposit removal was easily accomplished by sootblowing.

Convective Pass Deposit Physical Characteristics of this coal are summarized in Table 3-14. Results show the deposits consisted of a thin sintered scale, <3.2 mm (<1/8 in.), initial layer and a 76 to 102 mm (3 to 4 inch) outer layer. The physical state of the outer layer was lightly sintered indicating the low bonding strength characteristics of this coal throughout each test firing condition.

Chemical Analyses of the convective pass deposit samples are presented in Table 3-15. In comparison to the as-fired coal ash, both the initial and outer deposits from each probe bank showed lower ash softening temperatures, by 90 to 200°C, with other fusibility temperatures remained relatively the same. Ash composition shows while all other deposits had slight

TABLE 3-14

CONVECTIVE PASS FOULING CHARACTERISTICS OF THE LAKHRA BASELINE COAL

Firing Rate ($x10^6$ Btu/hr)	Gas Temperature (°F)	Ash Loading (lb/hr)	Gas Velocity (ft/sec)	Physical State Initial	Physical State Outer	Bonding Strength BSM	Sootblowing Frequency (Hr)
2.82	2340	80.0	59.6	Sintered/ Scale	L. Sintered	5	3-4
2.82	2130	75.0	56.5	Sintered/ Scale	L. Sintered	4	5-6
2.23	2020	64.2	42.1	Sintered/ Scale	L. Sintered	2	6-8
1.99	2040	50.3	36.8	Sintered/ Scale	L. Sintered	2	6-8

TABLE 3-15

ANALYSES OF CONVECTIVE PASS DEPOSITS COLLECTED FROM LAKHRA BASELINE COAL TESTING

	Bank I		Bank II		Bank III		Bank IV	
	Initial	Outer	Initial	Outer	Initial	Outer	Initial	Outer
Ash Fusibility, °F								
I.T.	2050	2050	2100	2100	2100	2100	2090	2090
S.T.	2110	2300	2220	2310	2230	2260	2220	2260
H.T.	2440	2460	2320	2450	2320	2450	2460	2480
F.T.	2530	2540	2520	2560	2510	2490	2490	2510
Ash Composition, wt %								
SiO_2	11.8	44.4	45.1	44.0	45.5	44.8	44.8	45.2
Al_2O_3	6.8	27.1	28.0	28.3	27.8	26.8	28.0	27.6
Fe_2O_3	58.8	17.5	16.4	16.9	17.1	16.7	16.5	16.7
CaO	10.2	4.2	3.6	2.6	3.6	2.8	2.7	2.6
MgO	0.6	1.8	1.8	1.5	1.8	1.4	1.4	1.4
Na_2O	0.1	0.9	0.9	0.9	0.8	0.8	0.8	0.9
K_2O	0.3	0.5	0.7	0.5	0.5	0.6	0.5	0.5
TiO_2	0.6	2.1	2.3	2.4	2.4	2.3	1.8	1.7
SO_3	10.8	0.2	0.4	2.9	2.9	0.5	2.1	2.3
Total	100.0	98.7	99.2	100.0	100.0	98.9	98.6	98.9

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increases in iron content, the initial deposit of the leading probe from bank I show significant enrichments in iron and calcium contents compared to the as-fired coal ash. This phenomena is attributed to the carryover effect of the furnace slagging.

In summary, the Lakhra baseline coal has moderate fouling potential. Convective deposit accumulation was high, but deposit to tube bonding strengths were low (less than 5), thus deposits were easily cleanable. Deposit accumulation increases with increasing gas temperature. Sootblowing was required every 3 to 4 hours at 1282°C (2340°F), 5 to 6 hours at 1165°C (2130°F) and 6 to 8 hours at 1115°C (2040°F). A high deposition rate in the transition section (1254 to 1399°C) of the furnace due to carryover from slagging was also observed.

EMISSIONS

Particulate Emissions

Two fly ash samples collected by isokinetic dust loading and by in-situ resistivity probe during test 4 at 2.97 x 10^3 MJ/hr (2.82 x 10^6 BTU/hr) firing rate, and 1427°C (2600°F) flame temperature were submitted for particle size distribution, chemical composition, free quartz content and fly ash resistivity analyses. Overall, results show the two samples have similar mass median particle size (5.3 and 4.9 microns). The carbon content in these samples were very low 0.1%, resulting better than 99.9% carbon conversion during this test. Isokinetic dust loading show approximately 60% of the total fuel ash input was emitted from the flue gas. In-situ fly ash resistivity was 1.76 x 10^{11} ohm-cm, indicating fly ash generated from this coal should not present problem affecting the electrostatic precipitator collection efficiency.

Chemical Analysis of the fly ash samples are summarized in Table 3-16. In general, with exception for the higher ash fluid temperatures, by 49°C (120°F) for sample 1, other ash fusibility temperatures as well as ash composition varied little from the as-fired coal ash. The carbon contents were very low, 0.1% for both samples, indicating very good combustion efficiency firing this coal in the FPTF. The resulting carbon conversion was better than 99.9%.

Fly Ash Resistivity of a fuel is affected by the ash chemical composition, flue gas temperature, SO_3 concentration, moisture content and fly ash particle size. Generally, fly ash resistivities appear to be desirable in the 10^9 to 10^{11} ohm-cm range. Values of 5×10^9 to 5×10^{10} ohm-cm are considered to be optimum for electrostatic precipitator operating at a temperature of 149 to 177°C (300 to 350°F).

Fly ash resistivity of the Lakhra baseline coal was measured by an in-situ resistivity probe system described in Appendix E and by a bench scale method. It should be noted that these measurements only provide a relative number and should not be used as an absolute value. Fly ash resistivity is highly dependent on fuel properties, the gas composition, deposition packing density on collecting surfaces, field unit design and operating conditions. Overall, results show the average in-situ fly ash resistivity measured from this coal is 1.76×10^{11} ohm-cm at gas temperature of 124°C (255°F) with 8% moisture and 15 ppm SO_3

Measurements conducted by bench scale method using fly ash samples collected from isokinetic dust loading and from in-situ resistivity probe under simulated gas environment are shown in Figure 3-21. Bench results indicate at 124°C (255°F) gas temperature, fly ash resistivity is 0.5×10^{11} ohm-cm without SO_3, and 2.5×10^9 ohm-cm with 15 ppm SO_3. These values are comparable to the theoretical calculations of 2.9×10^{11} ohm-cm without SO_3 and 1.7×10^9 with 15 ppm SO_3, but are lower compared to the in-situ results.

Overall, although there are discrepancies in the fly ash resistivity results by different measurement techniques, values obtained still fall within the typical range for most commercial coals and should not present any problem for electrostatic precipitator collection efficiency.

TABLE 3-16

ANALYSES OF FLY ASH SAMPLES FROM LAKHRA BASELINE COAL

	Sample 1	Sample 2
Carbon, %	0.1	0.1
Ash Fusibility, °F		
I.T.	2020	2090
S.T.	2440	2400
H.T.	2530	2480
F.T.	2640	2580
Ash Composition, wt %		
SiO_2	45.7	45.2
Al_2O_3	30.2	30.0
Fe_2O_3	15.8	15.7
CaO	3.3	3.5
MgO	1.5	1.7
Na_2O	0.9	1.0
K_2O	0.6	0.6
TiO_2	1.7	1.7
SO_3	1.1	1.1
Total	100.8	100.5
Mass Median Diameter, μ	5.3	4.9
Free Quartz, %	2.4	2.6

FIGURE 3-21

BENCH-SCALE FLY ASH RESISTIVITY MEASUREMENT

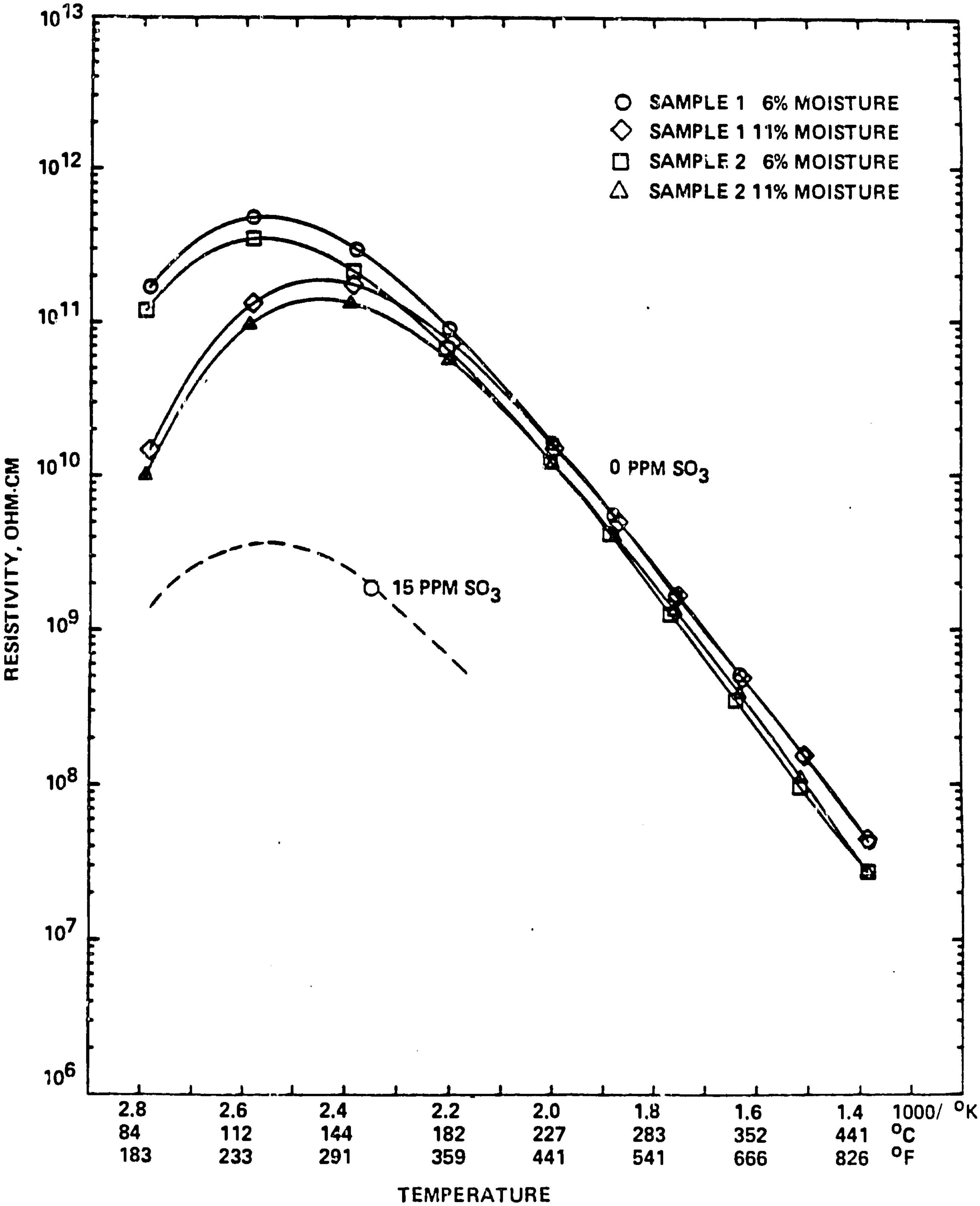


TABLE 3-17

FLY ASH RESISTIVITY MEASUREMENTS

Gas Temperature - 255°F

Moisture - 8%

	In-Situ	Bench	Theoretical
0 ppm	-	0.5×10^{11}	2.9×10^{11}
15 ppm	1.76×10^{11}	2.5×10^{9}	1.7×10^{9}

Flue Gas Emissions

Flue gas emissions measured during each test are summarized in Table 3-18. Overall, the SO_2 emission ranges from 5910 to 6340 ppm compared to the theoretical sulfur emission of 6530 to 6960 ppm on a dry, 3% O_2 basis. These results indicate only a small amount of sulfur was retained by the fly ash alkali and alkaline earths constituents, ranging from 8.4 to 9.6%.

The NO_x emissions is highly sensitive to the firing system. Values presented in Table 3-18 can only provide information on a relative basis, as the FPTF consists of a single burner which provides rapid mixing between fuel and combustion air, resulting rapid, intense combustion that tends to promote NO_x formation. The NO_x results from this coal range from 800 to 1260 ppm. The higher values correspond to tests at higher flame temperatures. Overall, based on these results and the nitrogen content of 0.9%, dry basis, NO_x emission should not be a limiting factor utilizing this coal.

In summary, SO_2 emission results show only a small amount is being retained by the fly ash. NO_x emission should not be a problem firing this coal.

TABLE 3-18

LAKHRA BASELINE COAL FLUE GAS EMISSION DURING FPTF TEST FIRING

Test No.	Firing Rate ($x10^6$ Btu/hr)	Average Flame Temperature (°F)	CO (PPM) @ 3% O_2, dry	NO_x (PPM) @ 3% O_2, dry	SO_2 (PPM) @ 3% O_2, dry	Sulfur Retained %
1	2.82	2840	60	1260	6310	9.3
2	2.82	2730	56	1130	6290	9.6
3	2.82	2650	50	950	6210	9.5
4	2.82	2610	53	860	6340	9.0
5	2.23	2550	55	870	5910	9.5
6	2.23	2580	61	800	5920	9.3
7	2.14	2600	60	870	5980	8.4
8	1.99	2610	54	800	5940	9.0

FLY ASH EROSION

Fly ash erosion for the subject coal was measured during Tests 6, 7, and 8. Results are summarized in Table 3-18. Overall, the Lakhra baseline coal exhibits a relatively high fly ash erosion rate. The average maximum wear was 3.7, 3.4 and 3.1 microns at 40.8, 39.0, and 35.7 m/sec (134, 128 and 117 ft/sec) gas velocity and 2.45, 2.26 and 2.10 GJ/hr (2.32 x 10^6, 2.14 x 10^6, and 1.99 x 10^6 Btu/hr) firing rates exposed for 8, 12, and 12 hours respectively.

To provide a comparative wear value between these tests, each erosion rate was normalized per unit mass of ash, and per heat input at typical field gas velocity of 18.3 m/sec (60 ft/sec). Results are 1.41 x 10^{-3} m/lb ash and 909.3 μ/10,000 hr (35.8 mils/10,000 hr) for each test. These data indicate while the erosion per unit weight of ash was comparable to other coals, the high ash loading results in a high erosion rate. Results from the x-ray diffraction analysis indicate the fly ash samples from these tests had the same free quartz content of 2.4%.

Overall, results show the Lakhra coal has relatively high erosion rate. The erosiveness is most likely due to its high ash content as the free quartz content in the fly ash is relatively low. The high erosiveness of this coal will require a lower gas velocity in the convective pass to reduce metal wastage.

TABLE 3-19

IN-SITU FLY ASH EROSION RESULTS DURING LAKHRA BASELINE COAL TESTING

Firing Rate ($x10^6$ Btu/hr)	Ash Loading (lbs/hr)	Gas Velocity (Ft/sec)	Free Quartz (%)	Max. Wear (μ)	Erosion Rate (μ/hr)	Norm.[1] Erosion Rate ($x10^{-3}$ μ/lb ash)	Norm.[2] Erosion Rate (mil/10^4 hr.)
2.32	85.5	134	2.4	3.7	0.417	1.41	35.9
2.14	78.8	128	2.4	3.4	0.287	1.41	35.8
1.99	72.0	117	2.4	3.1	0.258	1.41	35.8

(1) Normalized per unit mass of ash at 60 ft/sec

(2) Normalized to 3.5 x 10^6 Btu/hr, 10,000 hr exposure time at 60 ft/sec gas velocity.

CORROSION POTENTIAL

The Lakhra baseline coal was evaluated for its corrosion potential on typical boiler tube materials under firing conditions. Test probes were installed in the furnace and convective sections of the FPTF to determine the effect of location and gas temperature on metal wastage. Data obtained from weight loss, penetration, and metallographic evaluation were used to assess the overall material performance. Results indicate the austenitic alloys exhibit very good corrosion resistance at metal temperature up to 704°C (1300°F). Carbon steel and ferritic alloys exhibit high corrosion at convective pass metal temperature but should prove adequate at specified maximum metal temperatures; carbon steel up to 427°C (800°F), T91 up to 538°C (1000°F) and T-22 and T-11 up to 510°C (950°F).

Waterwall Probe

A waterwall probe was installed in the furnace section of the FPTF to assess the Lakhra baseline coal corrosion potential. The materials tested were SA-210, T-11, T-22, T-22 chromized and Incoloy 800. Figure 3-22 shows the probe prior to installation. Test rings of SA-210 and chromized T-22 were exposed at 427° to 432°C (800° to 810°F). Test rings of Incoloy 800, T-22, and T-11 were exposed at 441° to 449°C (825°F to 840°F). Weight loss data and physical measurements obtained after exposure are shown in Table 3-20. The ferritic steels exposed at these temperatures had similar wastage rates, ranging from 10.3 to 10.9 mgs/cm^2. The carbon steel ring exposed at 427 to 432°C temperature had a slightly lower wastage rate, 8.9 mgs/cm^2. The Incoloy test ring had minimal wastage, less than 0.4 mg/cm^2. These results would indicate the tested materials performed satisfactory at metal temperatures specified above.

WATERWALL CORROSION TEST PROBE

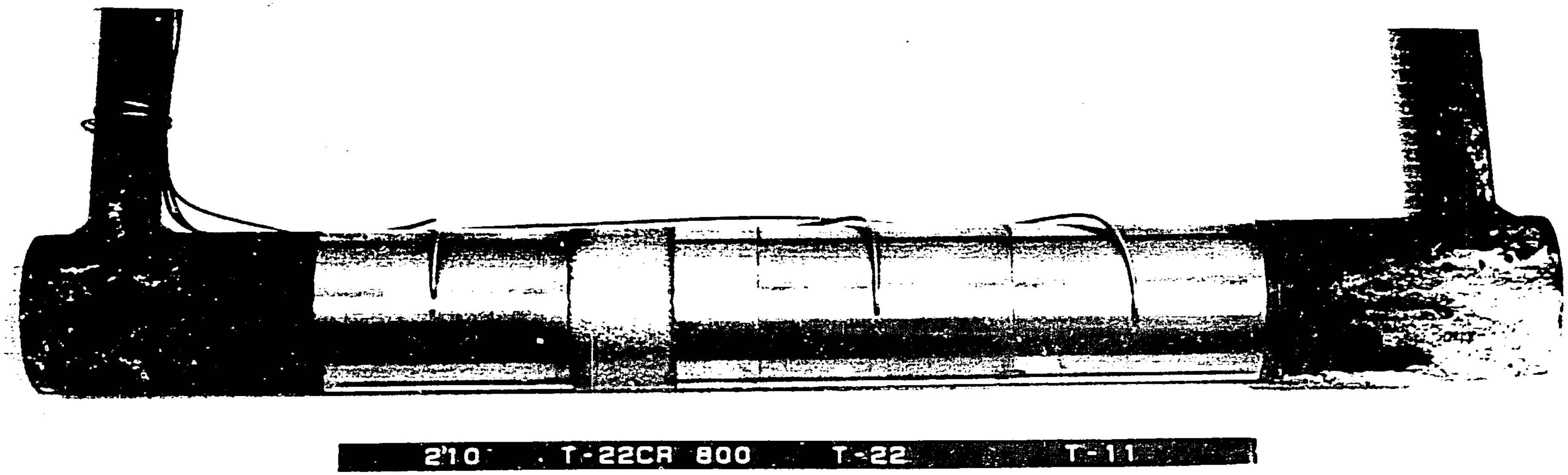


FIGURE 3-22

TABLE 3-20
WATERWALL PROBE PHYSICAL MEASUREMENTS

		WALL THICKNESS BEFORE								WALL THICKNESS AFTER							
Sample No.	Material	A	B	C	D	E	F	G	H	A	B	C	D	E	F	G	H
756	SA-210	.236	.235	.234	.236	.240	.241	.241	.236	.235	.235	.234	.236	.240	.241	.240	.235
757	T-22(CR)	.251	.250	.249	.248	.248	.248	.250	.250	.250	.249	.249	.248	.248	.248	.250	.250
758	In 800	.237	.242	.254	.255	.258	.252	.251	.239	.237	.242	.254	.255	.258	.252	.251	.239
759	T-22	.237	.239	.240	.241	.242	.241	.239	.237	.236	.239	.239	.240	.241	.240	.238	.237
760	T-11	.237	.235	.230	.224	.220	.222	.225	.233	.236	.235	.229	.222	.220	.222	.225	.233

WALL THICKNESS LOSS (PENETRATION IN INCHES)

Sample No.	Material	A	B	C	D	E	F	G	H
756	SA-210	.001	----	----	----	----	----	.001	.001
757	T-22(CR)	.001	.001	----	----	----	----	----	----
758	In 800	----	----	----	----	----	----	----	----
759	T-22	.001	----	.001	.001	.001	.001	.001	----
760	T-11	.001	----	.001	.002	----	----	----	----

---- NO CHANGE

WEIGHT LOSS DATA

Sample No.	Material	Location	Initial Weight-Grams	Weight After Test-Grams	Weight Loss-Grams	Loss mgs/cm^2
756	SA-210	Waterwall	486.5648	486.0294	0.5354	8.9800
757	T-22(CR)	"	212.5673	212.0177	0.5496	01.9800
758	In 800	"	170.2893	170.2707	0.0186	0.37825
759	T-22	"	493.0149	492.3875	0.6274	10.4840
760	T-11	"	463.3835	462.7705	0.6130	10.3840

Convection Probes

Eight test probes were installed in the FPTF convection section to determine the effect of location and gas temperature on corrosion when firing the subject coal. The probe location and materials tested are shown in Appendix D. Results of weight loss and wall thickness measurement from each test probe are presented in Tables 3-21 through 3-23. The overall results are summarized in Table 3-24.

1st Door - Probe A was composed of T-91, 310 s.s., 374 s.s., and Incoloy 800. It was controlled at 593°C (1100°F) metal temperature. Figure 3-23 shows the probe prior to installation and upon removal after completion of the test. The test pieces were cleaned in inhibited hydrochloric acid and weight loss data was collected. The austentitic pieces including the Incoloy material had very low wastage rates, 0.6 to 1.7 mg/cm^2. The ferritic T-91 material had a wastage rate of 25.3 mgs/cm^2.

Probe B was composed of T-22, T-91, 347 s.s., and Incoloy 800. These materials were exposed on the probe controlled at 593°C (1100°F) metal temperature. Figure 3-24 shows the probe prior to installation and upon removal. THe ferritic materials, T-22 and T-91, had significant wastage both as weight loss and also in wall thickness loss. The austenitic and the Incoloy materials had low rates of wastage, approximately 1 mg/cm^2.

2nd Door - Probe C was composed of T-22, chromized T-22, T-91, and 347 s.s. materials and controlled at 538°C (1000°F) metal temperature. Figure 3-25 shows the probe prior to installation and after removal. The T-22 material had experienced significant wastage, 53 mgs/cm^2, but this rate was lower than the piece exposed at higher metal temperature on Probe B. The chromized T-22 piece had less wastage (32 mgs/cm^2) than the unprotected T-22 piece (53 mgs/cm^2). This was still a significant rate of wastage. The T-91 piece had a wastage rate of 14.6 mgs/cm^2 at this metal temperature compared to the wastage rate of the same material exposed at higher temperature on Probe A. Again, the austenitic material had minimum wastage, less than 1 mg/cm^2. Only the T-22 material had measurable wall thickness loss.

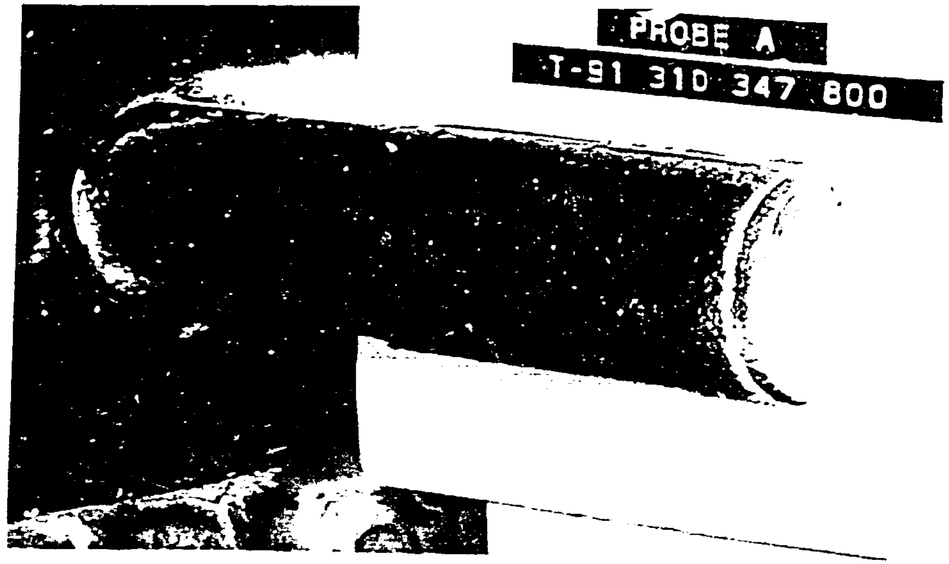
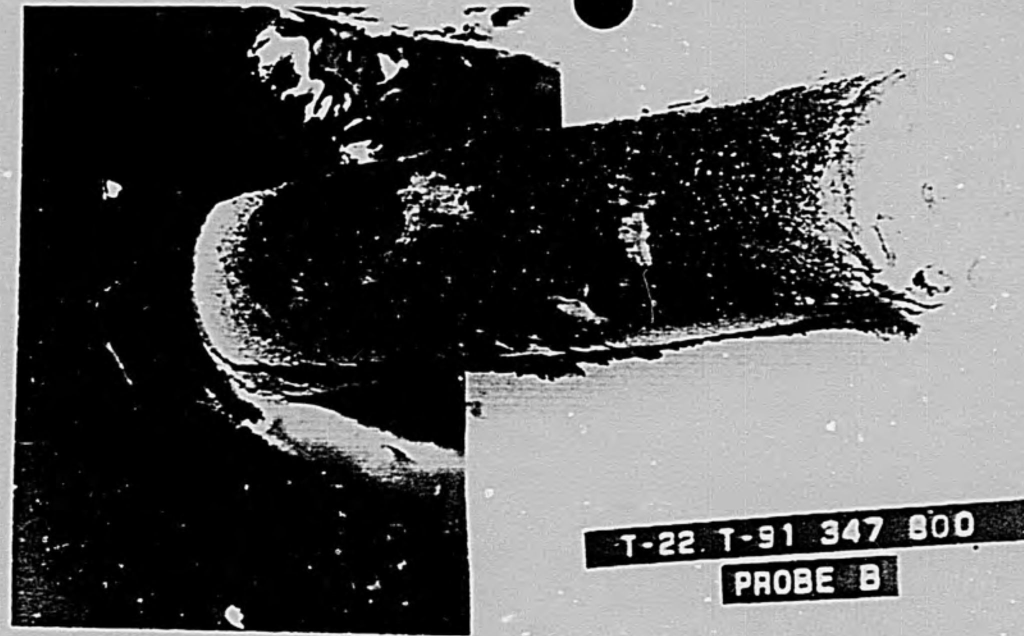


FIGURE 3-23



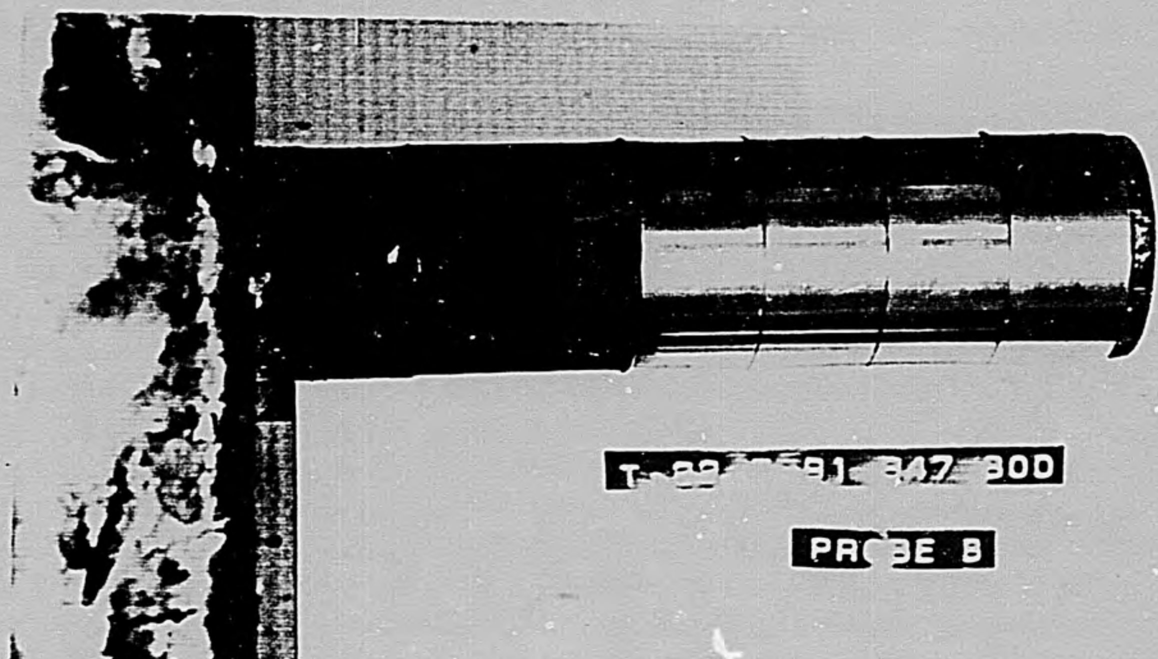


FIGURE 3-24

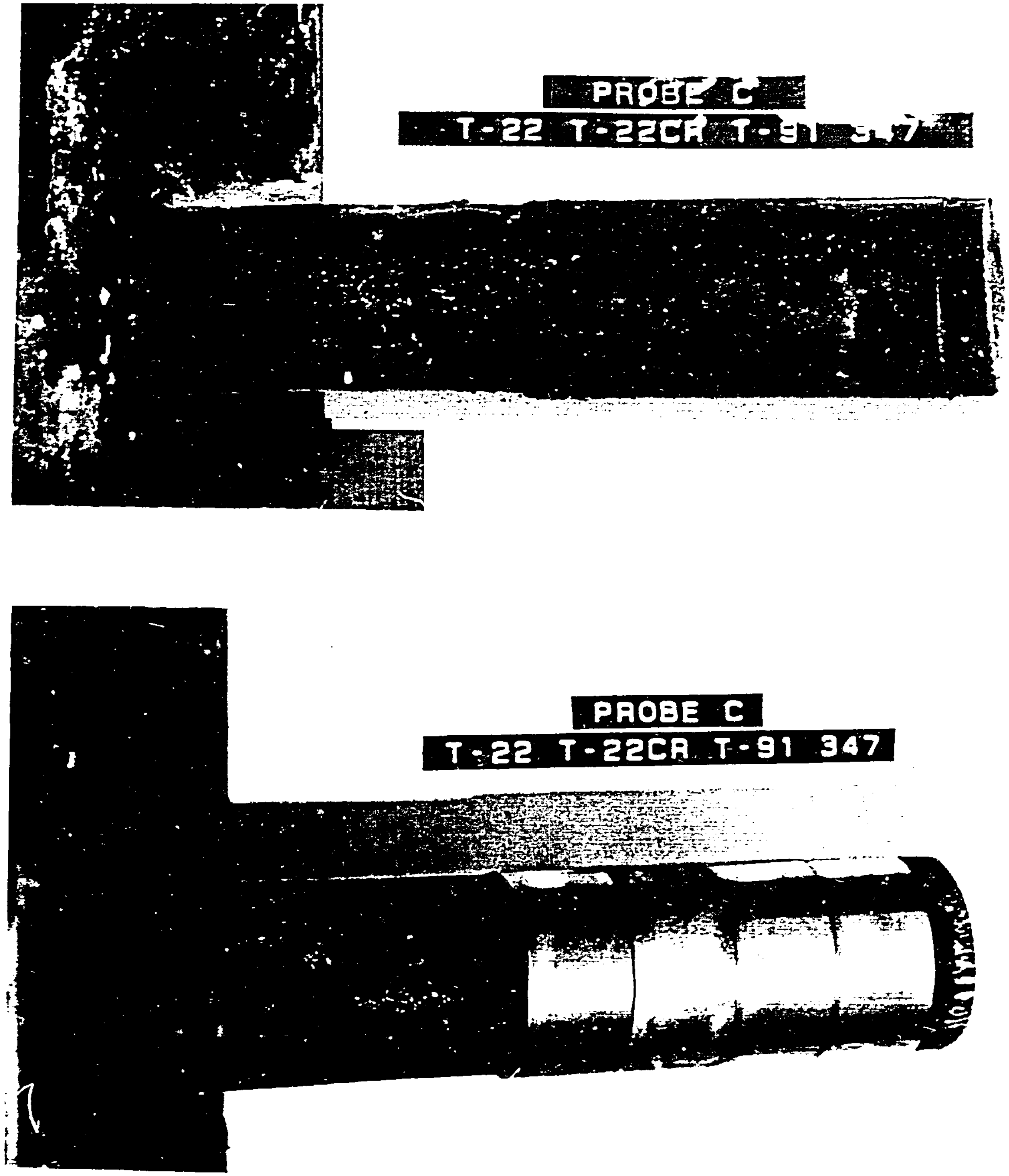


FIGURE 3-25

Probe D consisted of SA-210, T-11, T-22, and 347 s.s. materials. The metal temperature was controlled at 538°C (1000°F). Figure 3-26 shows the probe prior to installation and after removal. The carbon steel material, SA-210, had a very high wastage rate of 144 mgs/cm^2. This was confirmed by the physical measurements taken about the circumference of the test piece. T-11 and T-22 materials had lesser rates of wastage at 67 mgs/cm^2 and 48 mgs/cm^2, respectively. Physical measurements confirmed these wastage rates. The austenitic material had minimal weight loss measured.

3rd Door - Probe E was composed of T-22, T-91, 310 S.S., and 347 S.S. materials and controlled at 593°C (1100°F) metal temperature. Figure 3-27 shows the probe prior to installation and after removal. The T-22 piece had a significant wastage rate of 67 mgs/cm^2, but is slightly lower than the rate established on Probe B, exposed in the higher gas temperature zone of the duct. The T-91 material did not demonstrate this effect with a wastage rate of 21 mgs/cm^2. Both austenitic pieces had insignificant wastage rates at about 1 mg/cm^2.

Probe F was composed of T-22 chromized, T-91, 310 s.s., and 347 s.s. materials were exposed on this probe was controlled at 593°C (1100°F) metal temperature. Figure 3-28 shows the probe prior to installation and removal. The chromized T-22 piece experienced significant wastage (96 mgs/cm^2) due to a defective application of the chromizing process. The T-91 piece was submitted, in total, for metalographic evaluation and electron microprobe analyses of the deposit. Both pieces of austenitic materials had insignificant wastage rates.

4th Door - Probe G consisted of SA-210, T-11, T-22 chromized, and 347 s.s. materials were exposed at 538°C (1000 °F) metal temperature. This zone of the duct has the lowest gas temperatures prior to leaving the test facility. Figure 3-29 shows the probe prior to installation and after removal. The carbon steel material has a very substantial reduction in the wastage rate, 32 mgs/cm^2, as compared to the piece exposed on Probe D in a higher gas temperature but the same metal temperature. Similar results were established on the T-11 material with a wastage rate of 23 mgs/cm^2. The chromized T-22 was a defective piece as previously described. The austenitic material has insignificant wastage.

Probe H was composed of SA-210, T-11, T-22 and 347 s.s. materials controlled at 538°C (1000°F) metal temperature. Figure 3-30 shows the probe prior to installation and upon removal. The ferritic materials had similar wastage rates on both this probe and on Probe G. The same was evident for the austenitic material.

Metallographic Evaluation

In addition to the physical measurements, five selective coupons representing exposures from different locations, gas temperatures, and metal temperatures were submitted for metallographic evaluation. The purpose of this analysis is to determine the type of corrosion attack on these materials. The coupons selected are listed below.

Coupon No.	Material	Probe
724	T-91	A
726	347SS	A
728	T-22	B
745	T-91 w/deposit	F
738	T-22	D

Figure 3-31 shows the results obtained from the two T-22 coupons. The OD surfaces of these two coupons, after cleaning, were generally smooth with little evidence of deterioration. Only shallow indications of intergranular attack, 12 microns (0.5 mils) or less were found at 500X magnification on both coupons. The microstructures exhibited by the specimens consisted of spheroidized carbides in a ferrite matrix, typical of T-22.

Figure 3-32 upper shows the 347SS coupon. The OD surface showed little evidence of exposure except for a few slightly tarnished areas that remained after acid cleaning. A metallographic specimen through one of these areas revealed no apparent surface oxide penetration, although slight carbide precipitation was noted in the grain boundary twin lines and along

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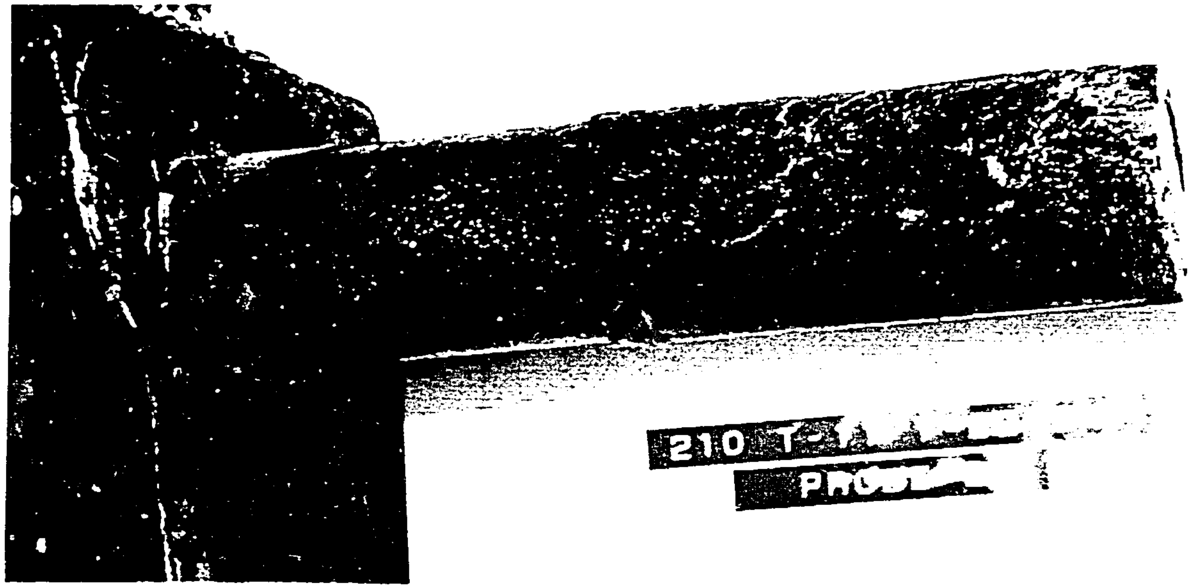
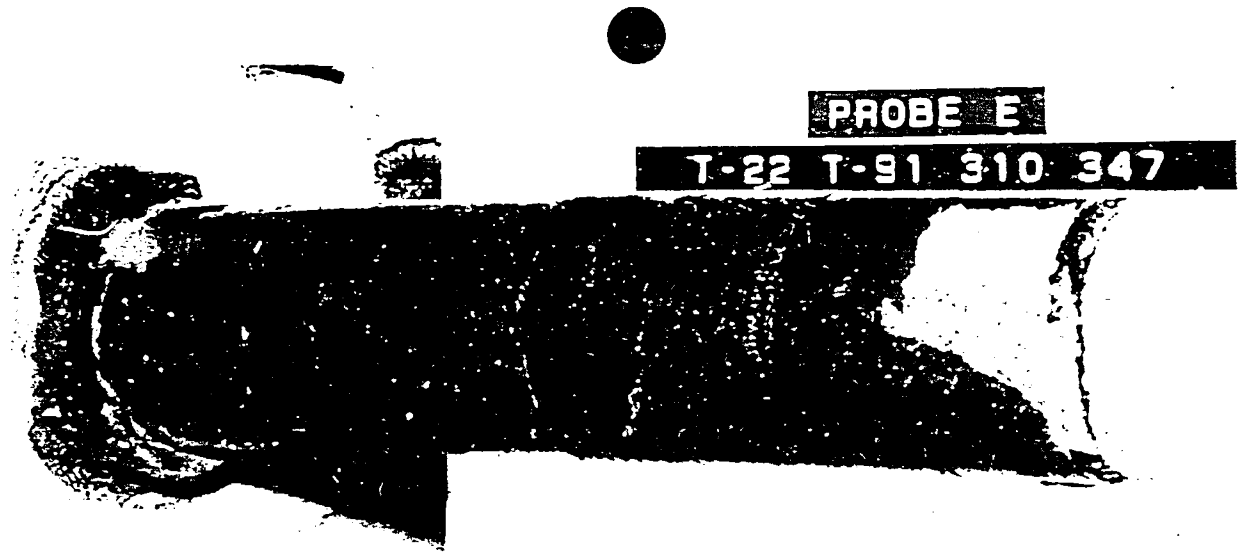


FIGURE 3-26



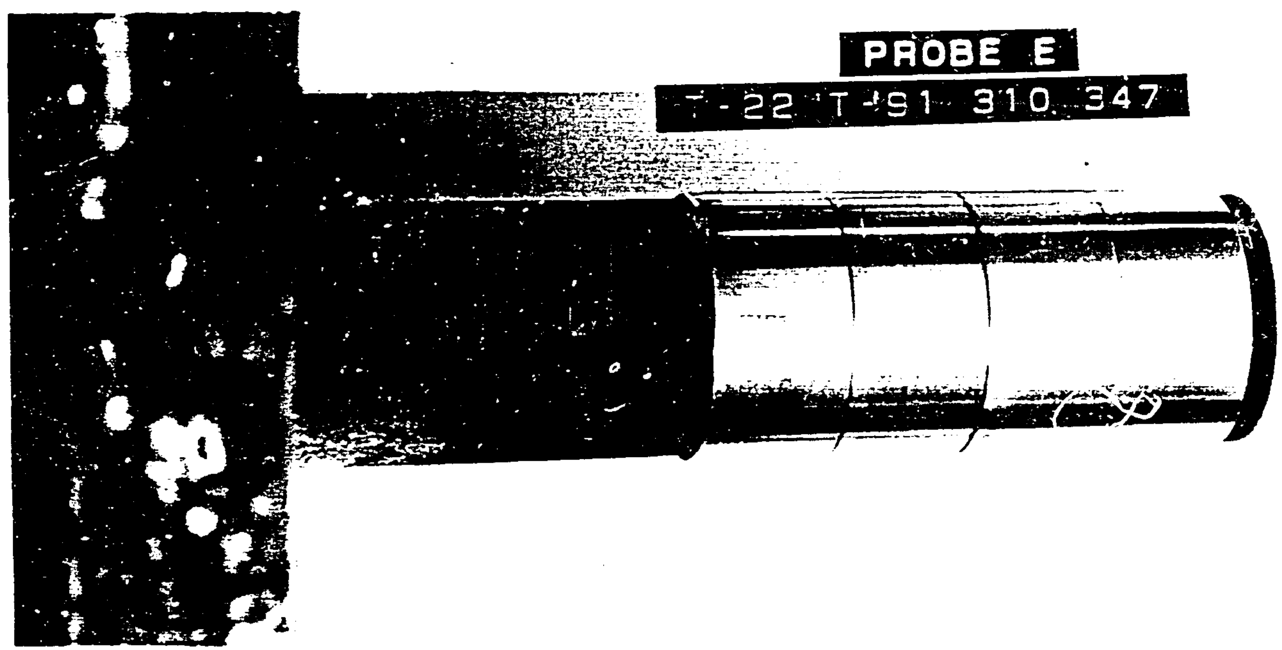
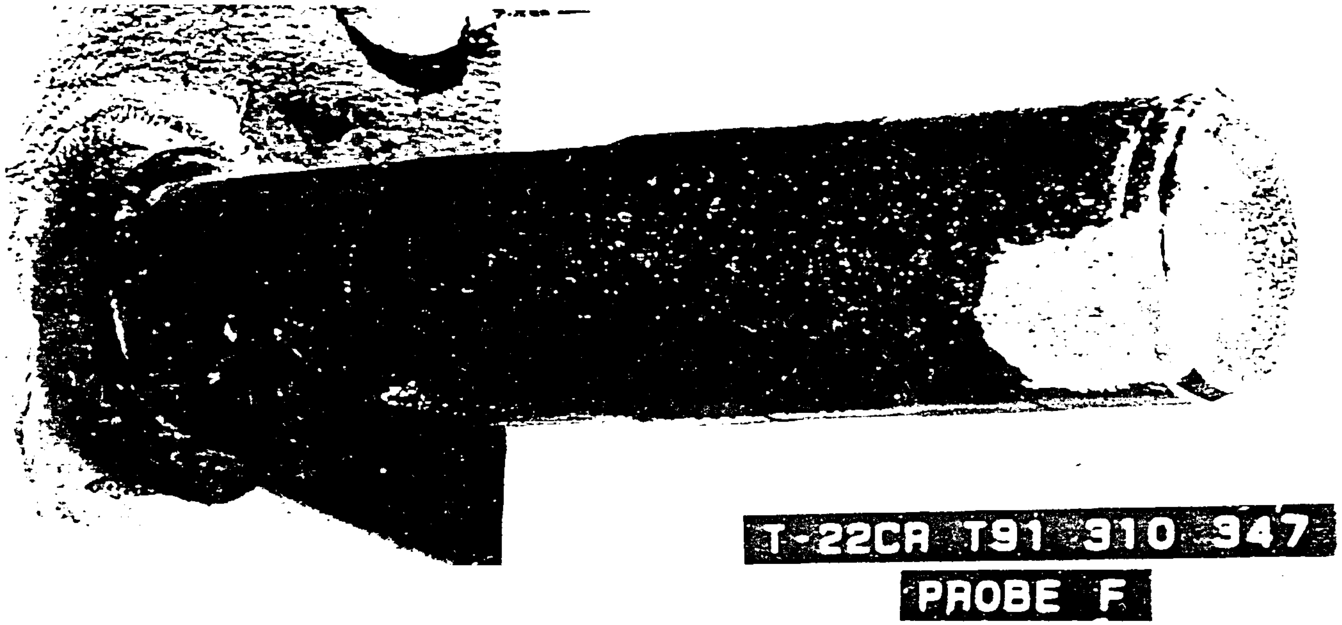


FIGURE 3-27



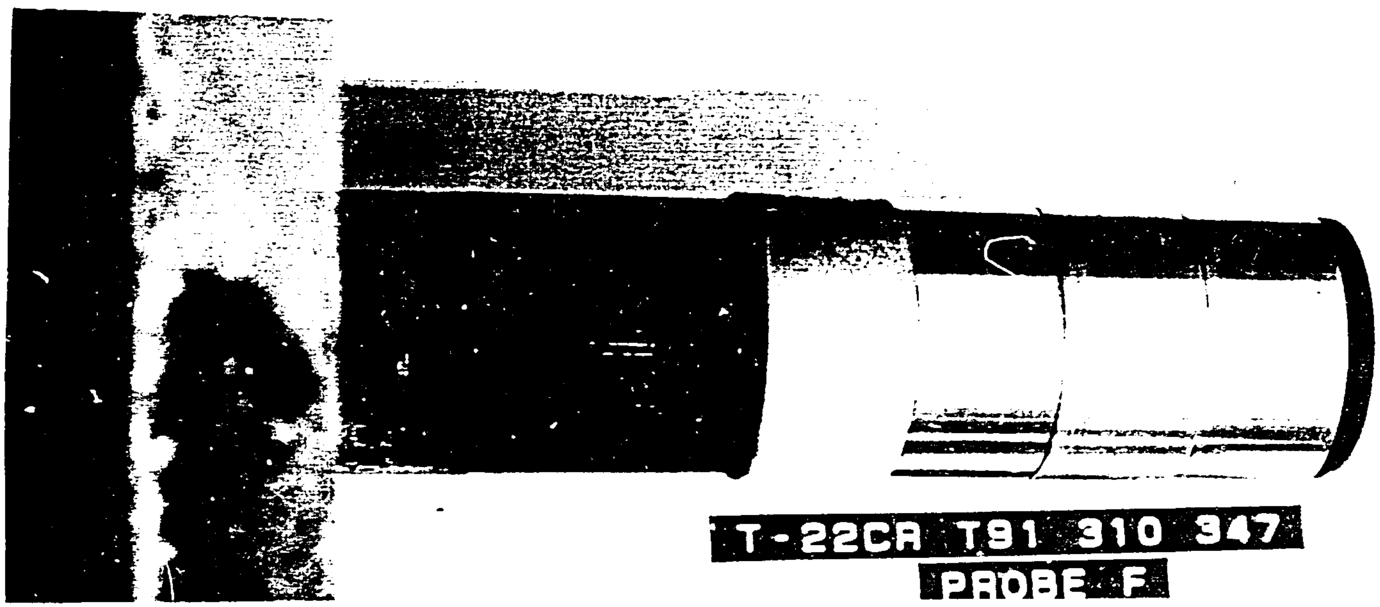
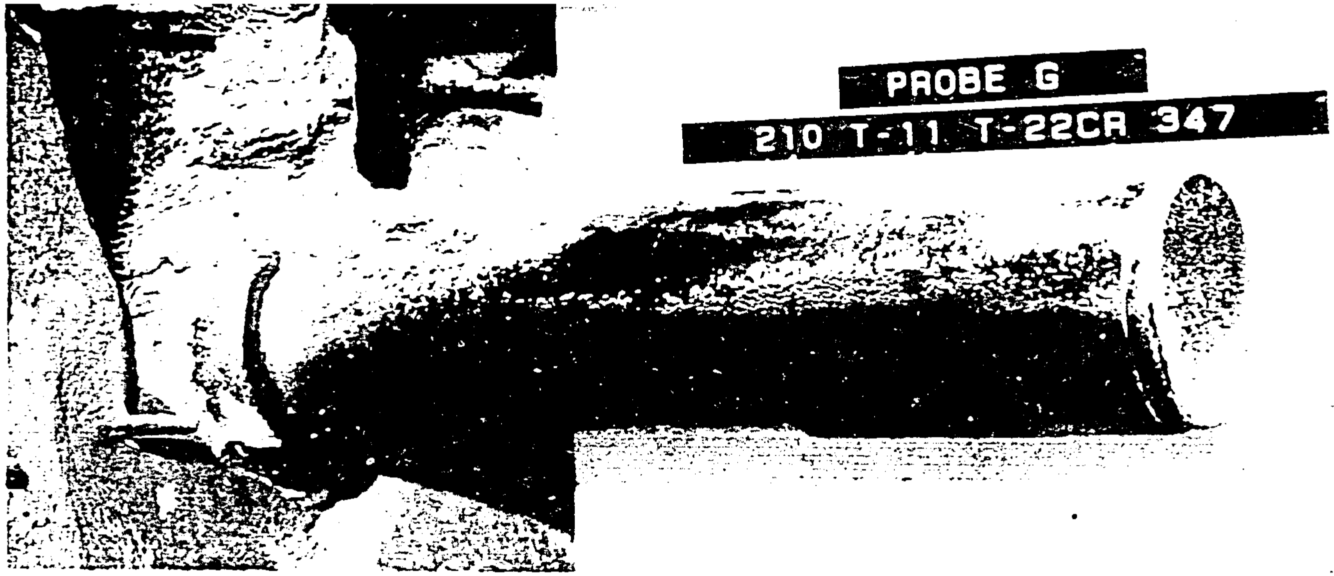


FIGURE 3-28



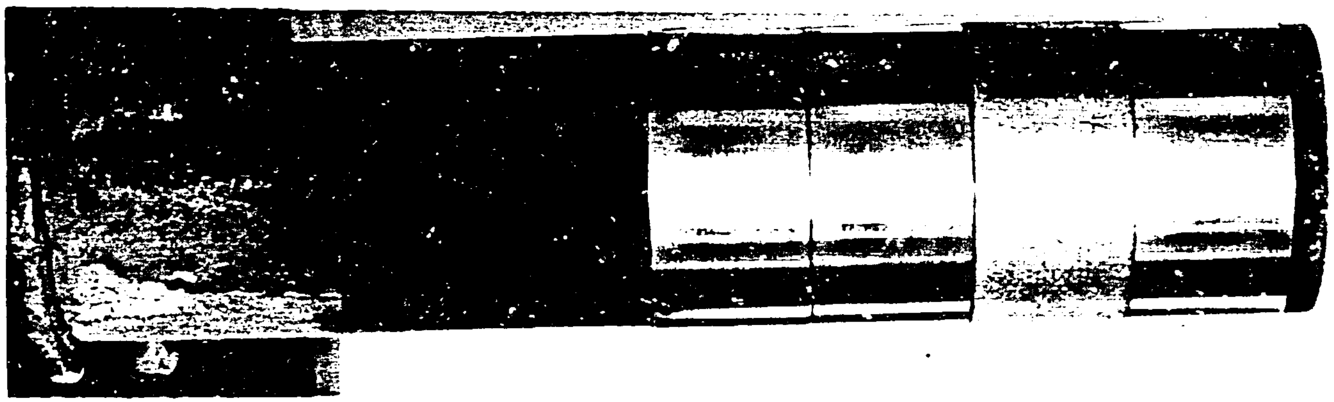
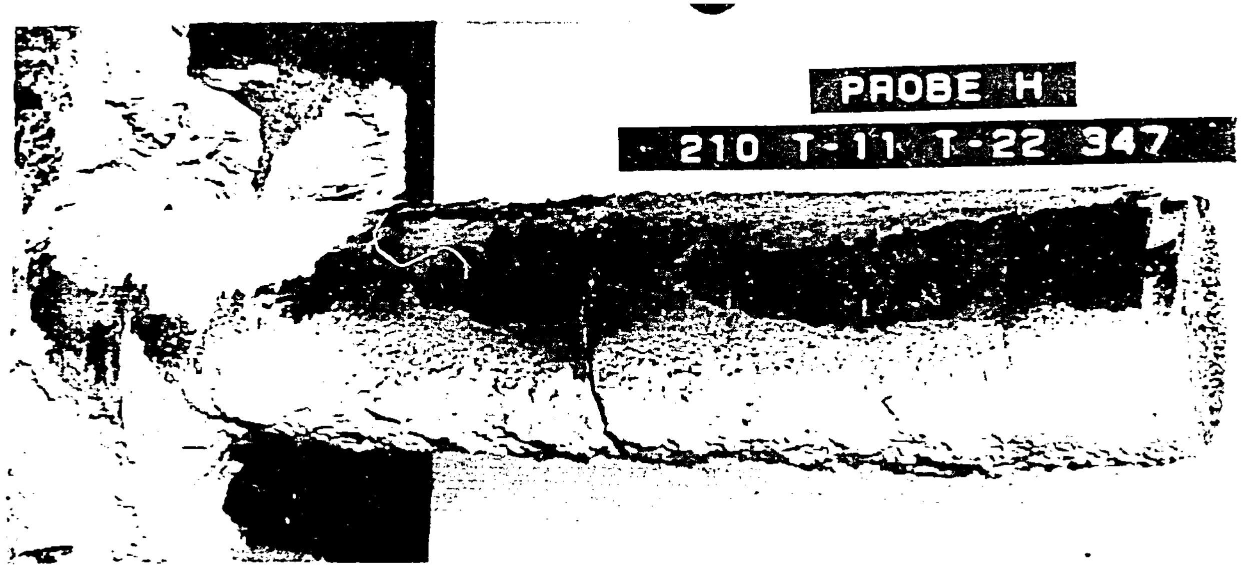


FIGURE 3-29



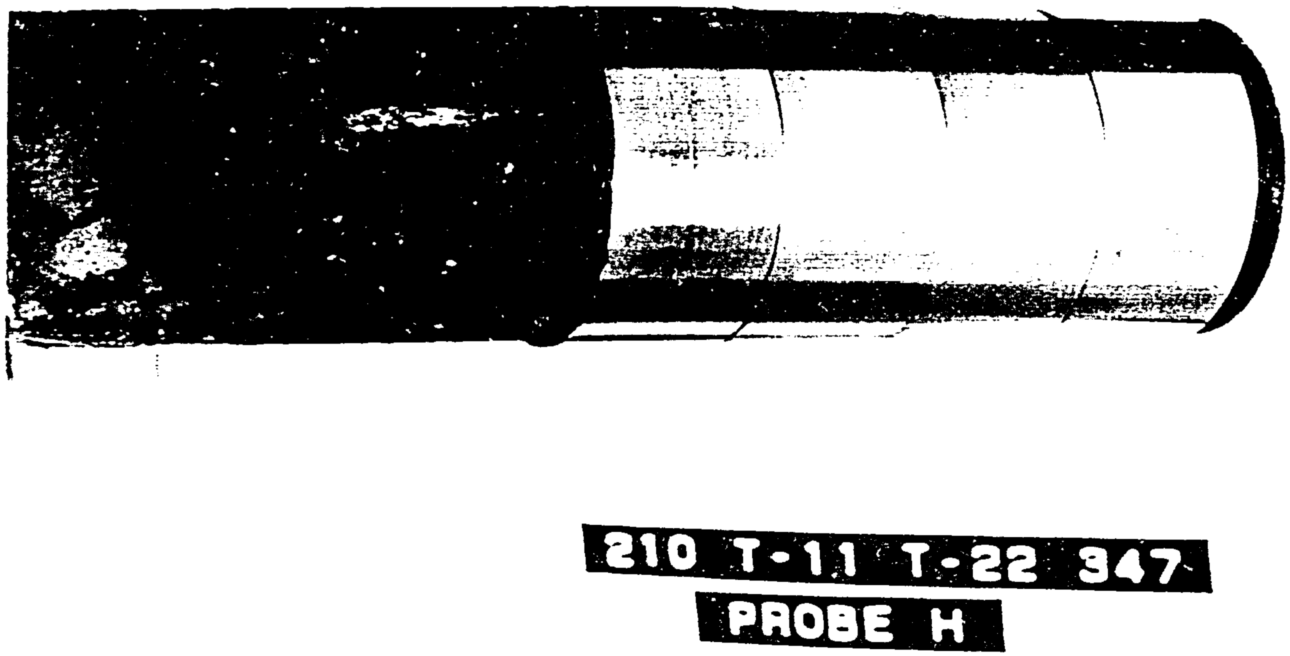


FIGURE 3-30

TABLE 3-21
MATERIAL WEIGHT LOSS DATA FROM LAKHRA BASELINE COAL CORROSION TEST

Probe	Sample No.	Material	Temp °F	Location	Initial Weight-Grams	After Test Weight-Grams	Weight Loss-Grams	Loss mg/cm^2
A	724	T-91	1100	Door 1	156.5897	155.5713	1.0184	25.3
A	725	310 S.S.	1100	"	154.8038	154.7521	0.0517	1.3
A	726	347 S.S.	1100	"	157.0623	156.9938	0.0685	1.7
A	727	In 800	1100	"	158.5635	158.5410	0.0225	0.56
B	728	T-22	1100	Door 1	153.8662.	150.6394	3.2268	80.5
B	729	T-91	1100	"	152.1434	151.6371	0.5063	12.6
B	730	347 S.S.	1100	"	157.5496	157.5082	0.0414	1.0
B	731	In 800	1100	"	160.6906	160.6549	0.0357	0.89
C	732	T-22	1000	Door 2	154.7259	152.5965	2.1294	53.1
C	733	T-22 (CR)	1000	"	160.5053	159.2271	1.2782	31.7
C	734	T-91	1000	"	152.4229	151.8373	0.5856	14.6
C	735	347 S.S.	1000	"	152.5389	152.5074	0.0315	0.79
D	736	SA-210	1000	Door 2	152.8638	147.0933	5.7705	143.8
D	737	T-11	1000	"	151.0531	148.3526	2.7005	67.3
D	738	T-22	1000	"	154.4426	152.5223	1.9203	47.9
D	739	347 S.S.	1000	"	157.5413	157.4942	0.0471	1.2
E	740	T-22	1100	Door 3	152.3028	150.5993	2.7035	67.4
E	741	T-91	1100	"	152.8569	152.0066	0.8503	21.2
E	742	310 S.S.	1100	"	157.8600	157.8255	0.0345	0.86
E	743	347 S.S.	1100	"	155.3726	155.3201	0.0525	1.3
F	744	T-22 (CR)	1100	Door 3	160.7667	156.8850	3.8817	96.1
F	745	T-91	1100	"	152.8134	MML	----	----
F	746	310 S.S.	1100	"	158.5869	158.5396	0.0473	1.2
F	747	347 S.S.	1100	"	157.0104	156.9426	0.0578	1.4
G	748	SA-210	1000	Door 4	153.5662	152.2675	1.2987	32.4
G	749	T-11	1000	"	152.2873	151.3829	0.9044	22.6
G	750	T-22 (CR)	1000	"	160.1255	158.2992	1.8263	45.3
G	751	347 S.S.	1000	"	154.1426	154.1114	0.0312	0.78
H	752	SA-210	1000	Door 4	153.2260	151.9614	1.2646	31.5
H	753	T-11	1000	"	153.8756	153.0638	0.8118	20.2
H	754	T-22	1000	"	145.1808	144.2731	0.9077	22.8
H	755	347 S.S.	1000	"	156.3408	156.3167	0.0241	0.60

TABLE 3-22
MATERIAL PHYSICAL MEASUREMENTS BEFORE AND AFTER EXPOSURE FROM THE LAKHRA BASELINE COOL CORROSION TEST

			WALL THICKNESS BEFORE								WALL THICKNESS AFTER							
Probe	Sample No.	Material	A	B	C	D	E	F	G	H	A	B	C	D	E	F	G	H
A	724	T-91	.244	.241	.239	.240	.241	.244	.245	.245	.243	.240	.238	.239	.240	.243	.244	.244
A	725	310 S.S.	.246	.244	.242	.241	.241	.243	.245	.246	.246	.244	.242	.240	.241	.243	.245	.246
A	726	347 S.S.	.239	.240	.241	.239	.238	.237	.236	.237	.239	.240	.241	.240	.238	.236	.239	.236
A	727	In 800	.242	.248	.244	.243	.242	.241	.235	.235	.241	.247	.245	.243	.241	.241	.235	.235
B	728	T-22	.238	.238	.237	.237	.238	.238	.238	.238	.237	.235	.235	.232	.233	.233	.236	.237
B	729	T-91	.250	.247	.241	.235	.231	.238	.244	.246	.249	.247	.241	.235	.230	.232	.238	.245
B	730	347 S.S.	.241	.242	.241	.241	.238	.238	.238	.238	.241	.242	.242	.241	.238	.237	.238	.238
B	731	In 800	.245	.242	.241	.242	.238	.239	.246	.246	.245	.242	.241	.242	.238	.239	.246	.246
C	732	T-22	.239	.240	.241	.240	.240	.238	.237	.239	.238	.238	.237	.237	.238	.237	.236	.238
C	733	T-22 (CR)	.248	.247	.247	.247	.249	.250	.250	.248	.247	.247	.246	.247	.248	.250	.249	.247
C	734	T-91	.237	.242	.246	.246	.243	.236	.233	.233	.237	.242	.245	.245	.242	.236	.232	.232
C	735	347 S.S.	.238	.238	.236	.232	.230	.230	.231	.234	.238	.237	.235	.232	.230	.230	.230	.233
D	736	SA-210	.240	.242	.242	.244	.242	.234	.235	.238	.237	.239	.237	.230	.238	.230	.232	.235
D	737	T-11	.238	.238	.238	.237	.237	.237	.237	.237	.237	.237	.235	.232	.233	.234	.235	.236
D	738	T-22	.243	.243	.241	.238	.235	.235	.237	.240	.242	.242	.240	.235	.233	.233	.235	.239
D	739	347 S.S.	.241	.242	.241	.241	.240	.238	.238	.239	.241	.241	.241	.240	.239	.238	.238	.239
E	740	T-22	.239	.237	.234	.234	.235	.239	.241	.241	.236	.234	.233	.233	.234	.238	.240	.239
E	741	T-91	.243	.245	.246	.243	.237	.234	.233	.236	.241	.245	.245	.242	.237	.233	.232	.234
E	742	310 S.S.	.245	.247	.247	.246	.243	.241	.241	.243	.245	.247	.247	.243	.241	.240	.240	.242
E	743	347 S.S.	.235	.239	.242	.242	.241	.238	.236	.235	.235	.239	.241	.242	.241	.238	.236	.235
F	744	T-22 (CR)	.249	.249	.249	.249	.249	.250	.249	.249	.245	.235	.245	.245	.246	.245	.245	.245
F	745	T-91	.240	.243	.243	.241	.238	.235	.234	.236								
F	746	310 S.S.	.244	.243	.243	.243	.244	.246	.246	.245	.244	.243	.243	.243	.244	.245	.244	.244
F	747	347 S.S.	.242	.243	.243	.242	.240	.238	.238	.240	.242	.243	.243	.241	.240	.238	.238	.239
G	748	SA-210	.232	.231	.233	.239	.243	.244	.243	.237	.231	.230	.231	.237	.242	.244	.241	.237
G	749	T-11	.241	.241	.241	.240	.240	.238	.239	.238	.240	.240	.240	.239	.238	.237	.238	.238
G	750	T-22 (CR)	.248	.247	.248	.249	.250	.250	.250	.249	.248	.247	.248	.249	.250	.249	.249	.248
G	751	347 S.S.	.238	.237	.235	.234	.234	.236	.238	.237	.237	.237	.236	.234	.234	.236	.237	.237
H	752	SA-210	.237	.234	.235	.237	.239	.241	.241	.239	.236	.233	.234	.236	.239	.241	.241	.239
H	753	T-11	.241	.241	.241	.240	.240	.240	.240	.240	.240	.240	.240	.240	.240	.239	.239	.239
H	754	T-22	.233	.237	.241	.239	.234	.228	.227	.228	.232	.237	.240	.237	.233	.228	.226	.228
H	755	347 S.S.	.241	.239	.237	.236	.236	.238	.241	.241	.241	.239	.237	.236	.236	.238	.241	.240

TABLE 3-23

CORROSION PENETRATION FROM THE LAKHRA BASELINE COAL CORROSION TEST

WALL THICKNESS BASIS*

Probe	Sample No.	Material	A	B	C	D	E	F	G	H
A	724	T-91	.001	.001	.001	.001	.001	.001	.001	.001
A	725	310 s.s.	----	----	----	.001	.001	----	----	----
A	726	347 s.s.	----	----	----	----	----	.001	----	.001
A	727	In 800	.001	.001	+.001	----	.001	----	----	----
B	728	T-22	.001	.003	.002	.005	.005	.005	.002	.001
B	729	T-91	.001	----	----	----	.001	[illegible]	[illegible]	.001
B	730	347 s.s.	----	----	----	----	----	.001	.001	----
B	731	In 800	----	----	----	----	----	----	----	----
C	732	T-22	.001	.002	.004	.003	.002	.001	.001	.001
C	733	T-22 (CR)	.001	----	.001	.001	.001	----	.001	.001
C	734	T-91	----	----	.001	.001	.001	----	.001	.001
C	735	347 s.s.	----	.001	.001	----	----	----	.001	.001
D	736	SA-210	.003	.003	.005	.014	.014	.004	.003	.003
D	737	T-11	.001	.001	.003	.005	.004	.003	.002	.001
D	738	T-22	.001	.001	.001	.003	.002	.002	.002	.001
D	739	347 s.s	----	.001	----	.001	.001	----	----	----
E	740	T-22	.003	.003	.001	.001	.001	.001	.001	.002
E	741	T-91	.002	.001	.001	.001	----	.001	.001	.002
E	742	310 s.s.	----	----	----	.003	.002	.001	.001	.001
E	743	347 s.s.	----	----	.001	----	----	----	----	----
F	744	T-22 (CR)	.004	.004	.004	.004	.003	.005	.004	.004
F	745	T-91				MML				
F	746	310 s.s.	----	----	----	----	----	.001	.002	.001
F	747	347 s.s	---	----	----	.001	----	----	----	.001
G	748	SA-210	.001	.001	.002	.002	.001	----	.002	----
G	749	T-11	.001	.001	.001	.001	.002	.001	.001	----
G	750	T-22 (CR)	---	----	----	----	----	.001	----	----
G	751	347 s.s.	.001	----	----	----	----	----	.001	----
H	752	SA-210	.001	.001	.001	.001	----	----	----	----
H	753	T-11	.001	.001	.001	----	----	.001	.001	.001
H	754	T-22	.001	----	.001	.002	.001	----	.001	----
H	755	347 s.s.	----	----	----	----	----	----	----	.001

*Penetration in inches.

TABLE 3-24
SUMMARY OF LAKHRA BASELINE COAL CORROSION RESULTS

DOOR 1- 1100°F			DOOR 3 - 1100°F		
PROBE A	WT. LOSS mgs/cm^2	PENETRATION EST (MM/YEAR)	PROBE E	WT. LOSS mgs/cm^2	PENETRATION EST (MM/YEAR)
T-91	25.3	0.33	T-22	67.4	0.88
310 s.s.	1.3	0.03	T-91	21.2	0.28
347 s.s.	1.7	0.04	310 s.s.	0.9	0.02
In 800	0.6	0.02	347 s.s.	1.3	0.03
PROBE B			PROBE F		
T-22	80.5	1.05	T-22 (CR)	96.1	1.25
T-91	12.6	0.16	T-91	---------MML---------	
347 s.s.	1.0	0.03	310 s.s.	1.2	0.03
In 800	0.9	0.02	347 s.s.	1.4	0.03

DOOR 1- 1100°F			DOOR 3 - 1100°F		
PROBE C			PROBE G		
T-22	53.1	0.69	SA-210	32.4	0.42
T-22 (CR)	31.7	0.41	T-11	22.5	0.29
T-91	14.6	0.19	T-22 (CR)	45.3	0.61
347 s.s.	0.8	0.02	347 s.s.	0.8	0.02
PROBE D					
SA-210	143.8	1.90	SA-210	31.5	0.41
T-11	67.3	0.87	T-11	20.2	0.26
T-22	47.9	0.62	T-22	22.8	0.29
347 s.s.	1.2	0.03	347 s.s.	0.6	0.02

superficially cold-worked areas on the OD. Microstructural features were typical of 347 stainless steel, and displayed no apparent effects from the exposure.

Figures 3-32 lower and 3-33 show the T-91 and T-91 with the tightly bonded initial scale deposit. Slight roughening of the OD surface was exhibited by both samples of this alloy. Intergranualar attack was not detected on these specimens. The deposit on the coupon with initial deposit generally appeared as a porous scale except at the deposit-metal interface; here a dense, thin, uniform layer separated the two materials. Since the deposit had been reported to be hard and tenacious, an EDX scan (energy dispersive x-ray) was made to qualitatively characterize the material. The major peak in the deposit was identified as iron, with small amounts of calcium and sulfur.

Microstructures of the two T-91 coupons appeared to vary slightly as depicted in the lower right views of Figures 3-32 and 3-33. Grain structure in coupon no. 724 appeared to be more spheroidized with better grain boundary delineation than in coupon no. 745. However, the differences might be traced back to original unexposed (archive) T-91, since it is doubtful the test temperature (1100°F) could produce this variation.

Overall, results from the metallographic evaluation show only shallow indications of intergranular attack to the T-22 material. The T-91 material exhibits slight surface roughening with no evidence of intergranular attack. The 347 s.s. material shows no surface oxide penetration although slight carbide precipitation is noted in the grain boundary twin lines and along superficially cold-worked areas.

Based on the physical measurements and the metallographic results, the individual material performances can be concluded as follows:

SA-210, carbon steel material, exposed on the lower temperature probes, experienced significant wastage. The material could be utilized at metal temperatures below 427°C (800°F).

T-11 material, 1-1/4% chromium - 1/2% molybdenum, exposed at different gas temperatures, but the same 538°C (1000°F) metal temperature, shows less wastage at lower gas temperature. This material could be utilized at metal temperatures up to 510°C (950°F).

T-22 material, 2-1/4% chromium - 1% molybdenum, had similar results as the T-11 materials and could be utilized at metal temperature up to 510°C (950°F).

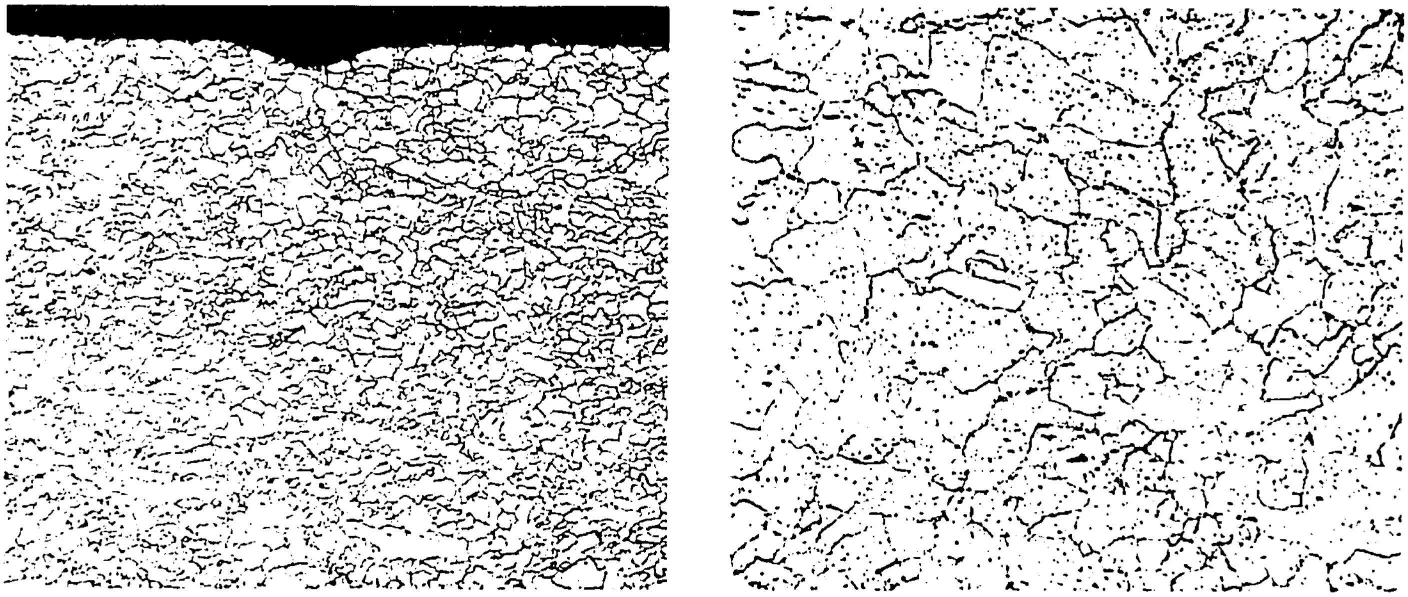
T-91 material, 9% chromium - 1% molybdenum, vanadium - niobium stabilized, had lower wastage rates at lower metal temperatures. This material could be utilized up to 538°C (1000°F) metal temperatures.

347 s.s., 18% chromium - 10% nickel, experienced minimal wastage at all temperatures. This material could be utilized up to 704°C (1300°F) metal temperature.

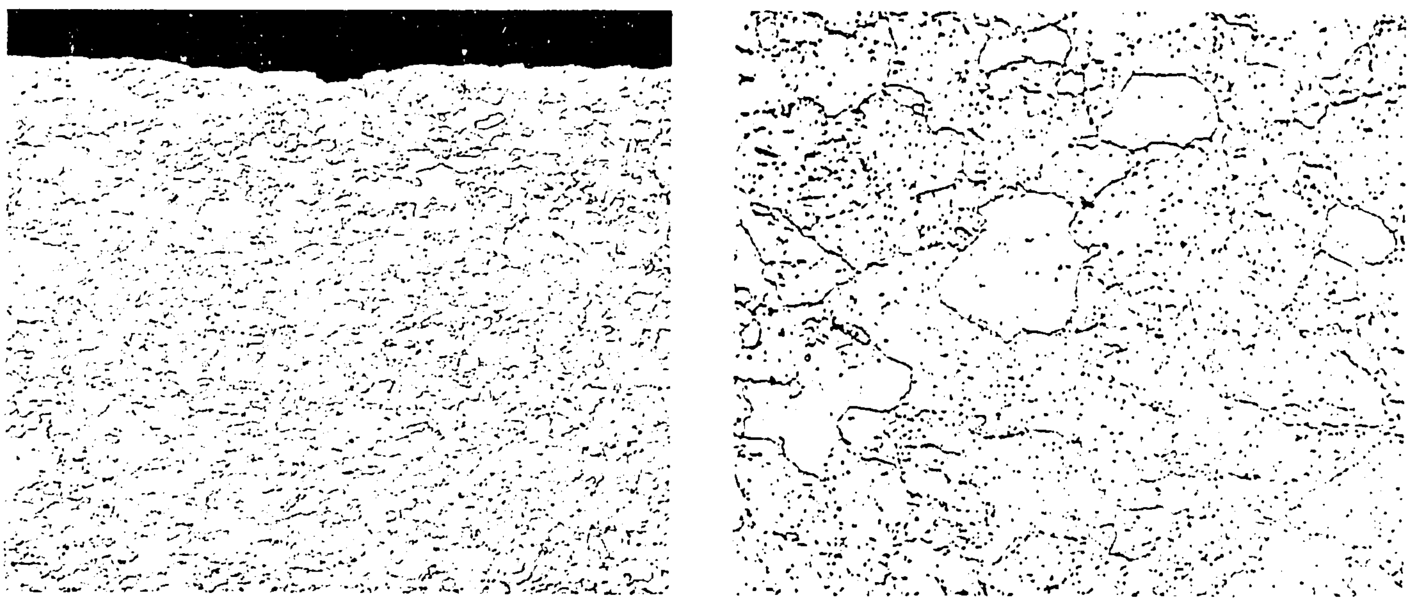
310 s.s., 25% chromium - 20% nickel, the same results were evident for this material as with 347 s.s.

Incoloy 800, 21% chromium - 32% nickel, had similar results to 310 s.s. and 347 s.s. in this test.

In summary, the wastage rates for the austenitic materials were very low and would provide satisfactory life expectancy in this application. The ferritic materials would also be satisfactory provided they are utilized within the temperature limitations indicated.



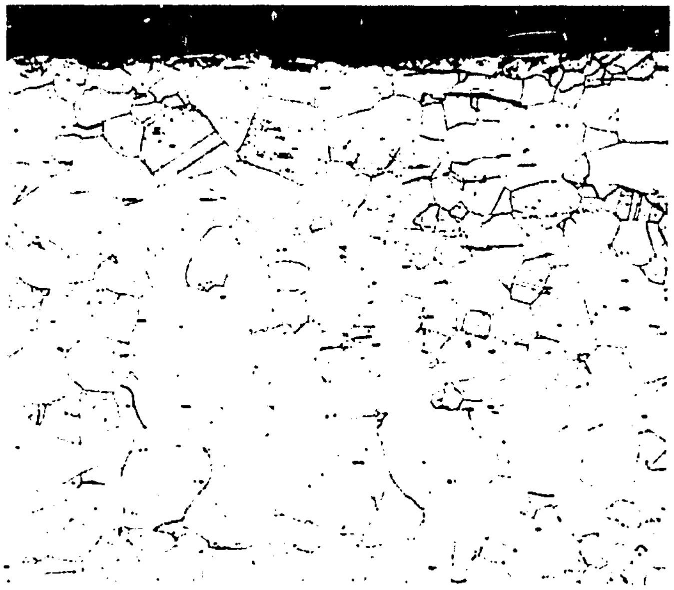
100X mag. No. 728, 9406-C, nital etch 500X mag.



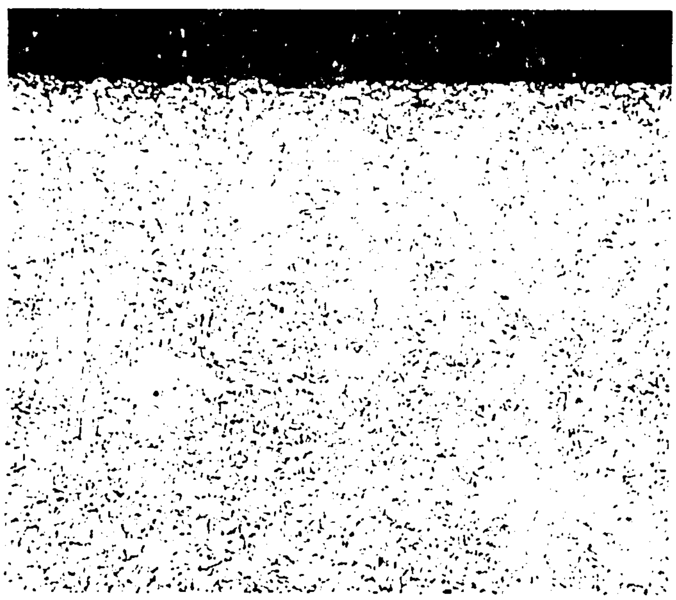
100X mag. No. 738, 9406-E, nital etch 500X

FIGURE 3-31

Surface features and microstructures of the T-22 coupons.




100X mag. No. 726, 9406-B, Elec. HNO_3 500X

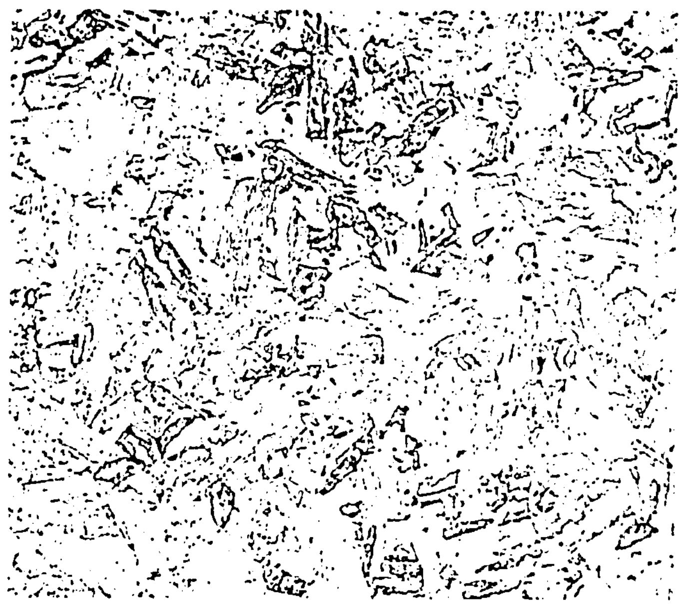



100X mag. No. 724, 9406-A, Hcl & Picric 500X mag.

FIGURE 3-32

Upper View: 347 stainless steel coupon
Lower View: T-91 coupon after acid cleaning.

No. 745
9406-D
Hcl & Picric
15X



100X mag. 9406-D Hcl & Picric 500X mag.

FIGURE 3-33

T-91, coupon no. 745 with OD deposit intact.

APPENDIX A

SPECIAL BENCH SCALE TESTS

Appendix A

SPECIAL BENCH SCALE TESTS

THERMO-GRAVIMETRIC ANALYSIS

The pyrolysis rate and char reactivity of the Lakhra coal will be assessed in a Thermo-Gravimetric system. A 200x400 mesh size fraction will be obtained from the sample fuel. A small amount of the sample will be pyrolyzed in the TGS in nitrogen atmosphere at a heating rate of 10°C/min. The remaining sample will be pyrolyzed in nitrogen at 2650°F in the Drop Tube Furnace System, and a 200x400 mesh size fraction will be subsequently obtained from the resulting char. This char sample will be tested in the TGS to determine the reactivity of the size graded char in air at an isothermal temperature of 700°C. The pyrolysis rate and char reactivity results are interpreted by comparing to the results generated from a wide range of fuels which have known commercial performance data.

SPECIFIC SURFACE AREA

The principal physical adsorption of gases is used to determine the specific areas of solid fuels. The BET (Brunaner, Emmett, Teller) single or multipoint method is used in conjunction with N_2 adsorption at 77°K to determine the sample's N_2 specific surface area. These surface area measurements give a relative measure of the reactivities of the fuels. A Quantasorb Surface Area Analyzer is used to make the N_2 specific surface area measurements of the sample. It involves passing mixture of the helium (used as a carrier) and adsorbate (N_2) through a U-shaped cell containing the sample. The amount of adsorbate physically adsorbed at various partial pressures on the sample (adsorbent) surface can then be used to calibrate the sample's surface area and other pore structural parameters (average pore size, pore size distributions).

ABRASION INDEX

The Abrasion Index test is developed by C-E to predict the relative potential of a given coal to cause mill wear and erosion of fuel transport lines.

The apparatus essentially consists of a Raymond 6" (15 cm), screw feed pulverizer, with peripheral screen to classify the coal according to size and to serve as a liner for the grinding chamber. The pulverizer has a steel rotor to which two cold rolled steel hammers are attached. Two iron wearing blades (abrasion coupons) can be screwed onto the two hammers such that a constant clearance is maintained between the wearing blades and the peripheral screen. The steel rotor can be rotated at a constant speed. The test procedure involves the following. The wear blades are cleaned, dried, weighed very accurately, and attached to the two steel hammers. About a 1,000 gram sample of coal is prepared to 16 x 30 mesh size and weighed. It is fed at a constant rate to the pulverizer. After the test, the wear blades are cleaned and weighed. The weight loss of the metal is then calculated as pounds metal lost per thousand tons of coal processed. The laboratory test data have been found to correlate with the field results on large mills.

GRAVITY FRACTIONATION ANALYSIS

The extraneous mineral matter in coal can exist as a blend of coal and minerals or as discrete particles. The gravity fractionation technique represents a way of taking coal apart into different gravity fractions to explore the impact of mineral matter within the coal matrix, particularly the selective deposition of segregated low melting pyrite minerals which cause slagging problems. This analysis can also aid in determining the concentration and size distribution of free quartz particles which may impact on fuel and fly ash erosion.

The Gravity Fractionation test procedure consists of grinding the subject fuel to a typical boiler grind (about 70% through 200 mesh); even density "cuts" are then prepared from the coal through the float/sink techniques using organic liquids of various specific gravities. Each density cut is subsequently analyzed for percent ash, ash compositions, ash fusibility, and percent sulfur. Selected fractions will be further analyzed by SEM and X-ray diffraction techniques for more detailed information on particular minerals.

ACETIC ACID LEACHING ANALYSIS

The weak acid leaching procedure is designed to segregate only the loosely held alkalis (either organic or as simple inorganic compounds) contained in coal. Alkalis present in these forms are those which readily vaporize during combustion, and are, therefore, available to react chemically and physically downstream in the boiler. These "active alkalis" are very instrumental in ash fouling behavior because of their propensity to form very low melting compounds and act as the "glue" cementing deposits together.

The leaching procedure consists of dispersing a 20 gm sample of pulverized coal in 100 ml of deionized distilled water. The slurry is rigorously and continuously agitated during the leaching procedure. A pH meter is utilized to monitor the acidity of the slurry. A solution of acetic acid is carefully added to bring the pH to the required level. The pH of the slurry is continuously monitored and carefully maintained at the desired level over a 30 minute leaching period. Additional acid solution is utilized as required (pH of the slurry drifts upward; substantially at first). At conclusion of the leaching interval, the slurry is filtered. The concentration of soluble alkali in the leachate is then determined by atomic absorption spectophotometry.

APPENDIX B

C-E BOWL MILL MODEL 271

Appendix B

PULVERIZER FACILITY DESCRIPTION AND TEST PROCEDURES

Evaluation of pulverization characteristics of the coals is performed in a Model 271 bowl mill. The C-E Raymond Model 271 Pulverizer utilizes one spring loaded grinding roll, which is free to rotate, and a bowl driven by an external source. The roll is located adjacent to the bowl so that there is no metal to metal contact. When coal is fed into the pulverizer, it is directed to the small gap between the bowl and the roll, causing the roll to turn and the material to be ground. The pulverized coal is dried by heated air entering below the bowl. The hot air carries the pulverized coal up through the classifier and into the fuel piping system. The coal laden air is then passed through a cyclone which removes most of the coal particles. The air is then passed through a bag filter which removes any atmosphere (Figure B-1).

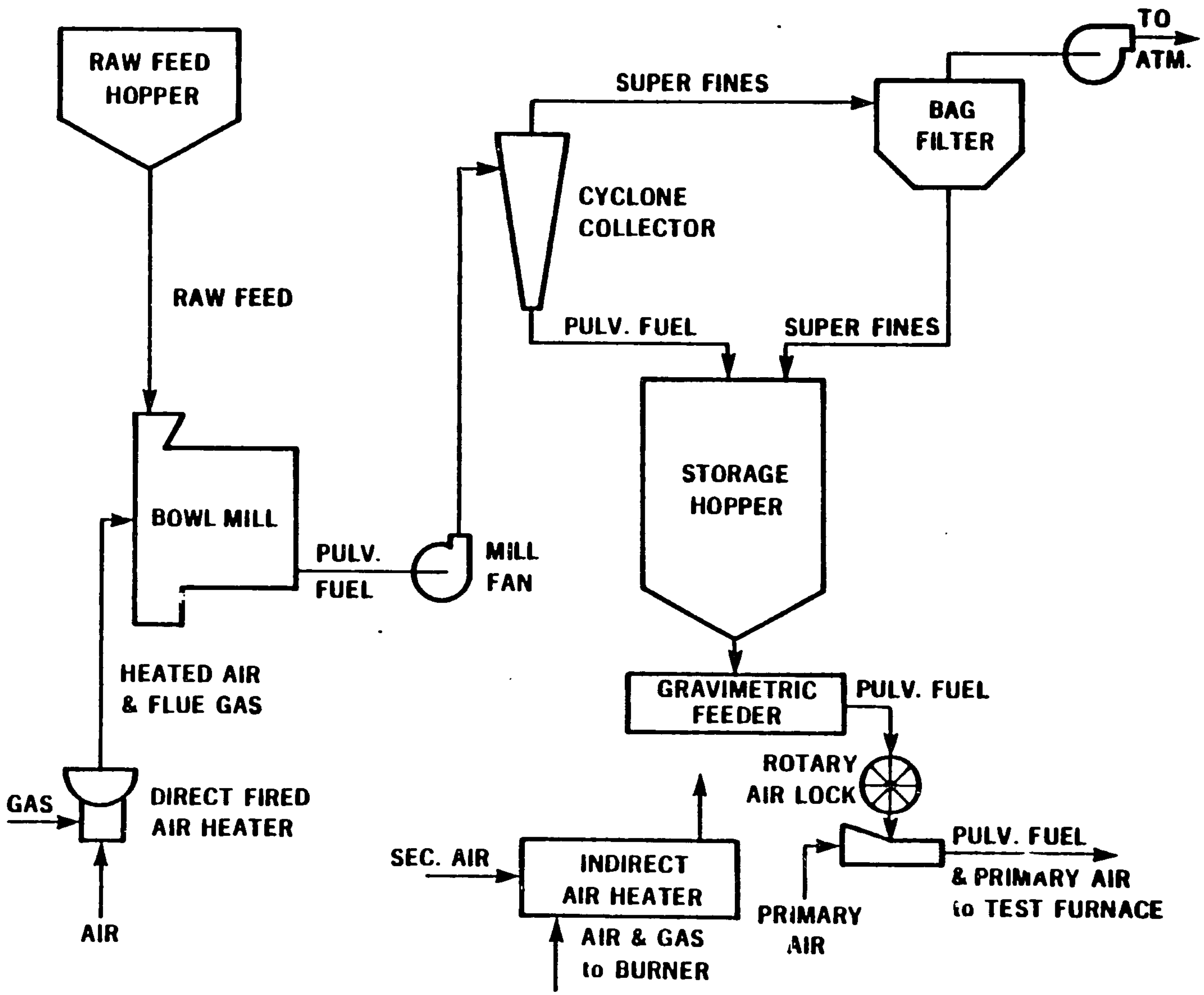
The coal is fed from a large storage hopper to the bowl mill by a weight belt feeder. The feeder is used to meter and measure the coal going into the bowl mill. The mill was allowed to pulverize for 15 minutes and at that point a test was begun. A test consisted of taking a 5 minute spillage sample, along with a reading from the wattmeter on power consumption.

A pulverized coal sample was taken and screened for size. The vanes were adjusted as necessary and a spillage sample, a pulverized coal sample and the power consumption requirements were taken at the maximum capacity with the correct coal fineness.

The outlet temperature of the bowl mill was held at a constant 150°F for all pulverization testing. The grinding roll to grinding ring distance and the spring compression were varied as necessary to obtain the optimum pulverization capacities for all the coals and blends.

FIGURE B-1

FIRESIDE PERFORMANCE TEST FURNACE
Fuel Preparation and Feed System



APPENDIX C

FIRESIDE PERFORMANCE TEST FACILITY

Appendix C

FIRESIDE PERFORMANCE TEST FACILITY DESCRIPTION

The Fireside Performance Test Facility (FPTF) is a pilot-scale combustion facility used primarily to assess fuel properties which influence fireside (ash deposition, external corrosion, etc.) boiler performance. It is comprised of a complete fuel handling system, air preheater, and a vertically-fired test furnace (Figure C-1).

Crushed coal (1-1/2" top size) is fed from a 5-Ton capacity outside-storage hopper to a C-E Model 271 bowl Mill where it is pulverized to the desired fineness. The small, deep bowl, single-journal (roller) mill is equipped with a direct gas fired air heater to provide mill drying air. The pulverized coal is pneumatically transported to a cyclone collector where most of the coal is dropped into a 3-ton capacity storage hopper. Fines in the cyclone effluent are collected in a bag filter and returned to the storage hopper. Pulverized coal is fed by a belt type gravimetric feeder from the hopper into a rotary air lock, from which it is pneumatically transported into the furnace.

The test furnace basically consists of a refractory-lined 36 inch I.D. cylinder, 18 ft. in height. A six inch thick refractory lining minimizes the potentially high heat losses associated with the large surface-to-volume ratio inherent with small scale units. Cooling air is drawn through the 1-1/2 inch annulus surrounding the refractory lining providing the necessary cooling for the furnace structural shell, as well as control of the heat absorption by the lower furnace.

The furnace is fired from the bottom through a single, swirl-type burner. Either a conventional burner for pulverized coal testing or a specially designed burner for CWM testing can be used. The maximum capacity of the furnace is approximately 5.0×10^6 Btu/hr which corresponds to roughly 350 lb/hr of pulverized coal feed. Firing in the test furnace is designed to simulate commercial boiler time-temperature history. Firing rate can be varied to obtain a wide range of conditions (Flame temperatures from 1900 to 3000°F and residence times from 1 to 2.5 seconds).

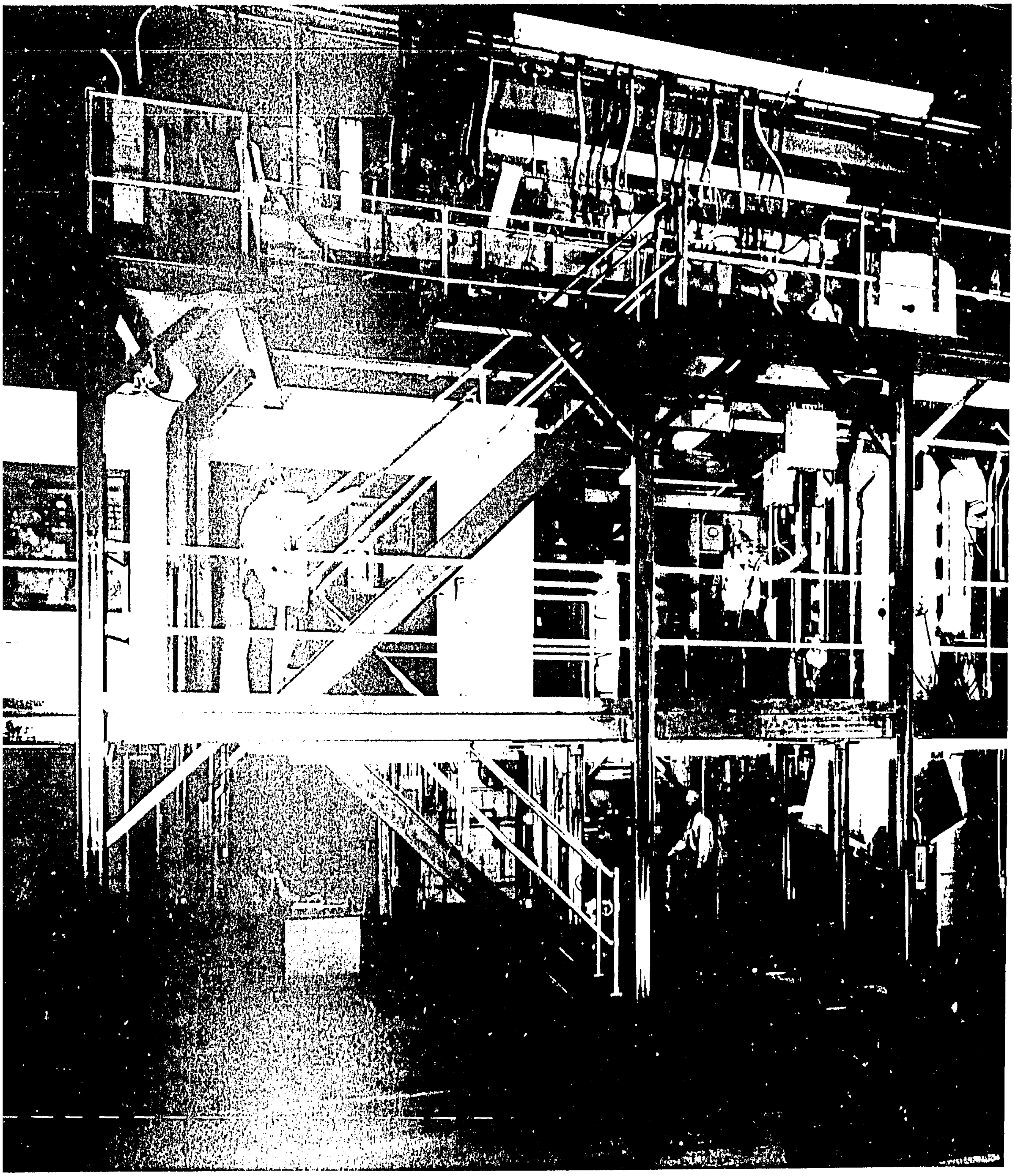
Secondary air can be heated up to 1100°F in an indirect gas fired air heater. The preheated secondary air may be injected through each of the three rings. The middle overfire ring bisects the waterwall panel surface and may be used to achieve slagging data on the panel in both reducing (lower panel surface) and oxidizing (upper panel surface) environments. Combustion air can also be introduced tangentially through four 2" dia. nozzles located approximately 6" above the burner to simulate tangentially fired conditions.

Located in the radiant section of the furnace (approximately 3 ft. above the burner) is a simulated water wall test furnace (Figure C-2). This waterwall test panel is used for the study of lower furnace ash deposition and is capable of providing detailed data on the slagging characteristics of the test fuel. A water-cooled frame surrounds the panel to reduce interference from slag generated on hot refractory surfaces. The panel is relatively large (approximately 4.7 square feet surface area), and actually consist of three separate panels. Each panel section is cooled by fluid passing through serpentine tubing. The panel is designed to simulate the conditions in the lower furnace of a commercial boiler. Metal temperature of the panel is typically controlled at 700°F. Syltherm, a high boiler point organic liquid, is utilized as the coolant and flows in a closed cycle through the panel. The heat absorption rate of the panel is continuously monitored by recording the coolant flow rate and temperature changes through the panel.

Flue gas leaves the combustion zone at a right angle through a horizontal water cooled superheater duct (Figure C-3). A water-cooled transition section surrounds the entrance of the superheater duct. The duct section of the furnace can be designed to simulate the convection sections of a commercial pulverized coal or oil fired units, and consists of five sections totaling 13 feet in length. Air-cooled probes are used to simulate superheater tubes. Each bank contains two rows of probes. Probe metal temperatures are typically controlled at 1100°F. Typical gas temperatures and gas velocities at the probe banks range from 2300-1600°F and 70-30 ft/sec, respectively.

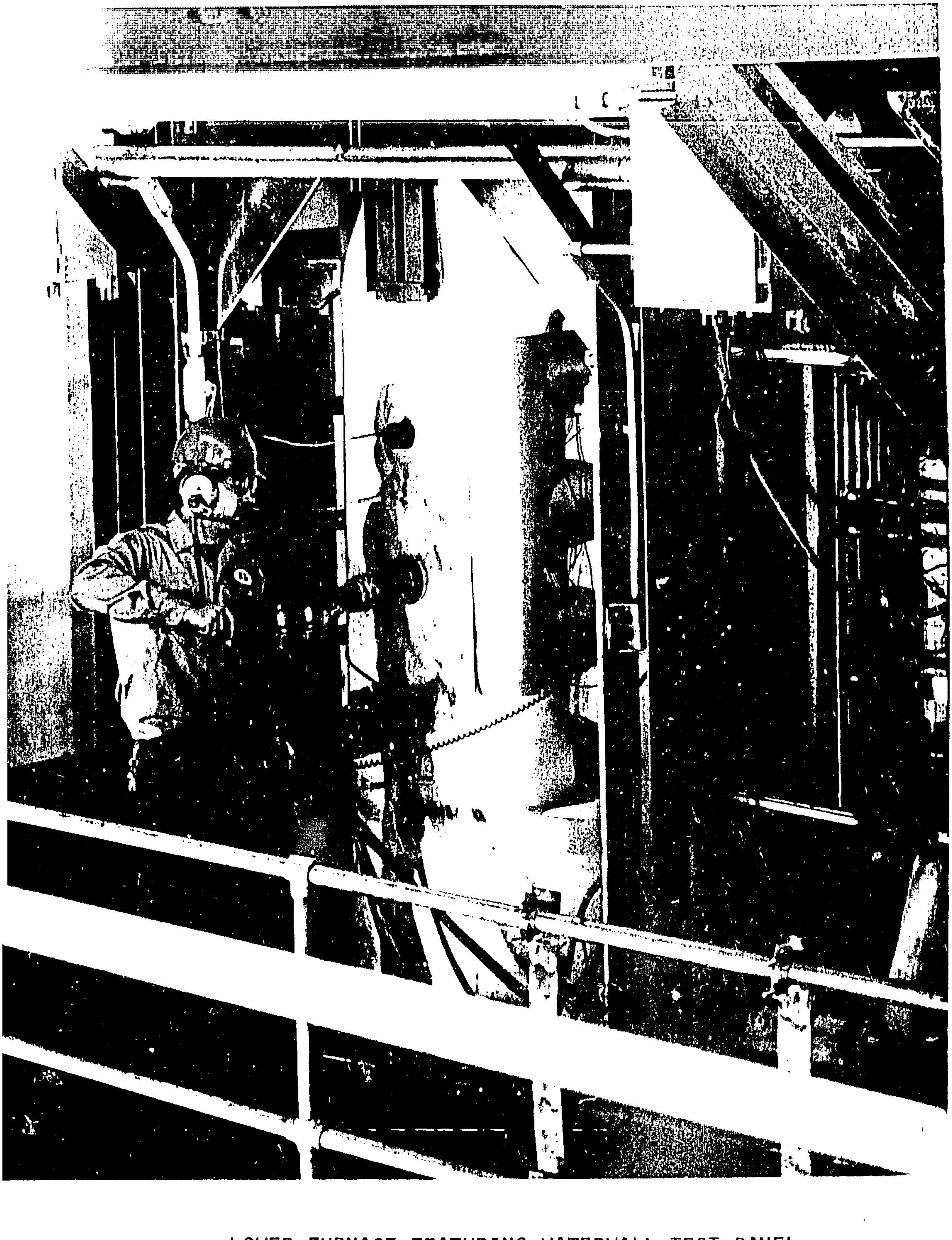
A specially designed high velocity section is located downstream of the convection superheater duct. This section is used for the erosion study. A probe made out of removable compounds is installed in this section. Metal temperature is controlled at 800°F. The coupons are carefully measured and weight at the beginning and conclusion of the test to obtain the relative metal wastage rate.

The facility is fully instrumented and accurately monitor and record all fuel and air inputs. Cooling flows and temperatures are measured to obtain mass and energy balances around the furnace. A gas analysis system allows periodic measurement of O_2, CO_2, CO, NO_x, and SO_2 concentrations in the flue gas (Figure C-4). The flue gas sample is obtained downstream of the FPTF convective pass probes (1000°F). The sample is conditioned to remove fly ash and water vapor before being introduced into the individual dedicated gas analyzers.



THE FIRESIDE PERFORMANCE TEST FACILITY (FPTF)

FIGURE C-1



LOWER FURNACE FEATURING WATERWALL TEST PANEL

FIGURE C-2

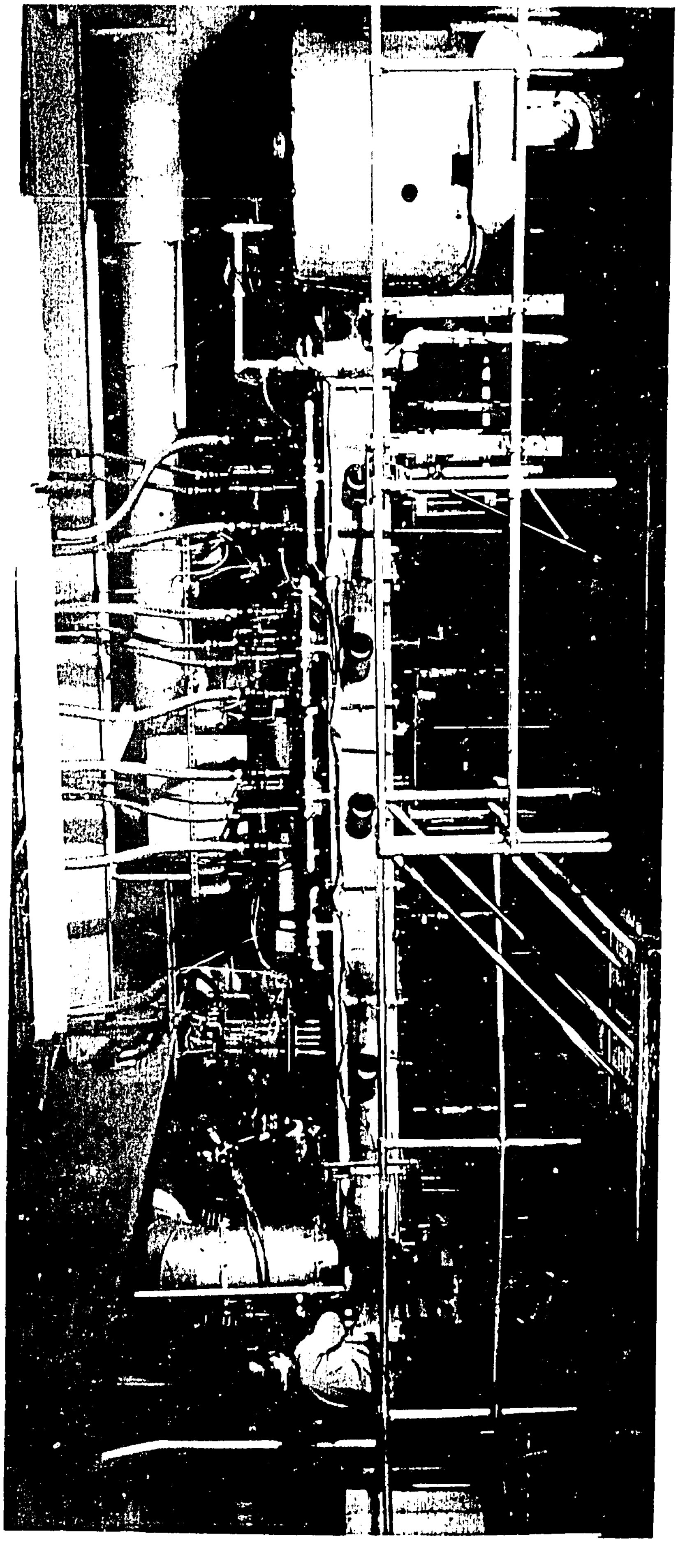
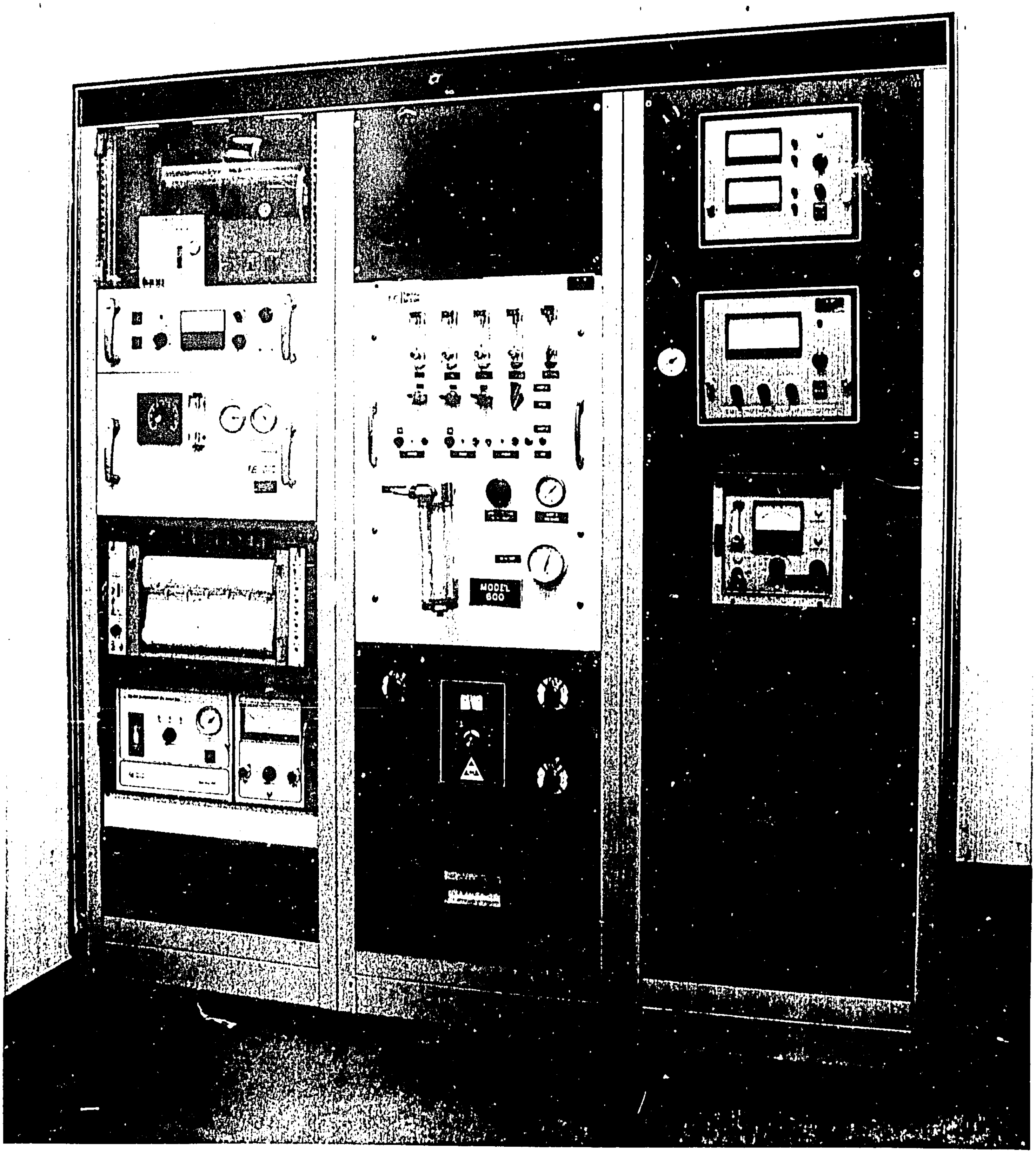


FIGURE 7 UPPER FURNACE SECTION OF FPTF AND SUPERHEATER DUCT

FIGURE C-3



GAS ANALYSIS SYSTEM

FIGURE C-4

APPENDIX D

CORROSION TEST SYSTEM

Appendix D

CORROSION TEST SYSTEM

TEST PROBE SYSTEM

A corrosion test probe consisted of 4 specimens of typical boiler tube materials machined into threaded rings, which were screwed into each other to form the surface exposed to the gas stream. An additional reusable piece was manufactured in the shape of an end cap, which was not used to evaluate wastage. Two of the rings had 1/16" holes drilled into the ring toward the outside diameter (O.D.). Stainless sheathed thermocouples (T.C.) were inserted through a hole at the cap of each probe external to the superheater duct. These T.C.'s were retained within the probe and the sensing end inserted in the 1/16" holes. The probes were controlled from one T.C. in each probe, while the other T.C. was used to monitor test ring metal temperatures. A 5/8" O.D. air line ran through both the shank and test rings, distributing cooling air along the line to the inside of the probe. The air entered through 1/16" holes located around the periphery of the air line, turns 180° and exited through the top of the probe. The whole assembly was screwed onto a 2" nipple welded to the superheater duct door at the cap and mounted vertically. T.C.'s were connected to lead wire at the probe outlet and run to recorders and controllers. The test probes were located in the water-cooled superheater duct. The probe locations utilized in this test are shown in Figure D-1.

TEST MATERIAL COMPOSITION

Several alloys were exposed on the probes. The alloys exposed included SA-210, T-11, T-22, T-91, 347 s.s., 310 s.s., and Incoloy 800. The material composition of each alloy is shown in Table D-1. A total of 32 test rings were exposed for the corrosion test.

FIGURE D-1
SUPERHEATER DUCTS SHOWING PROBE LOCATIONS

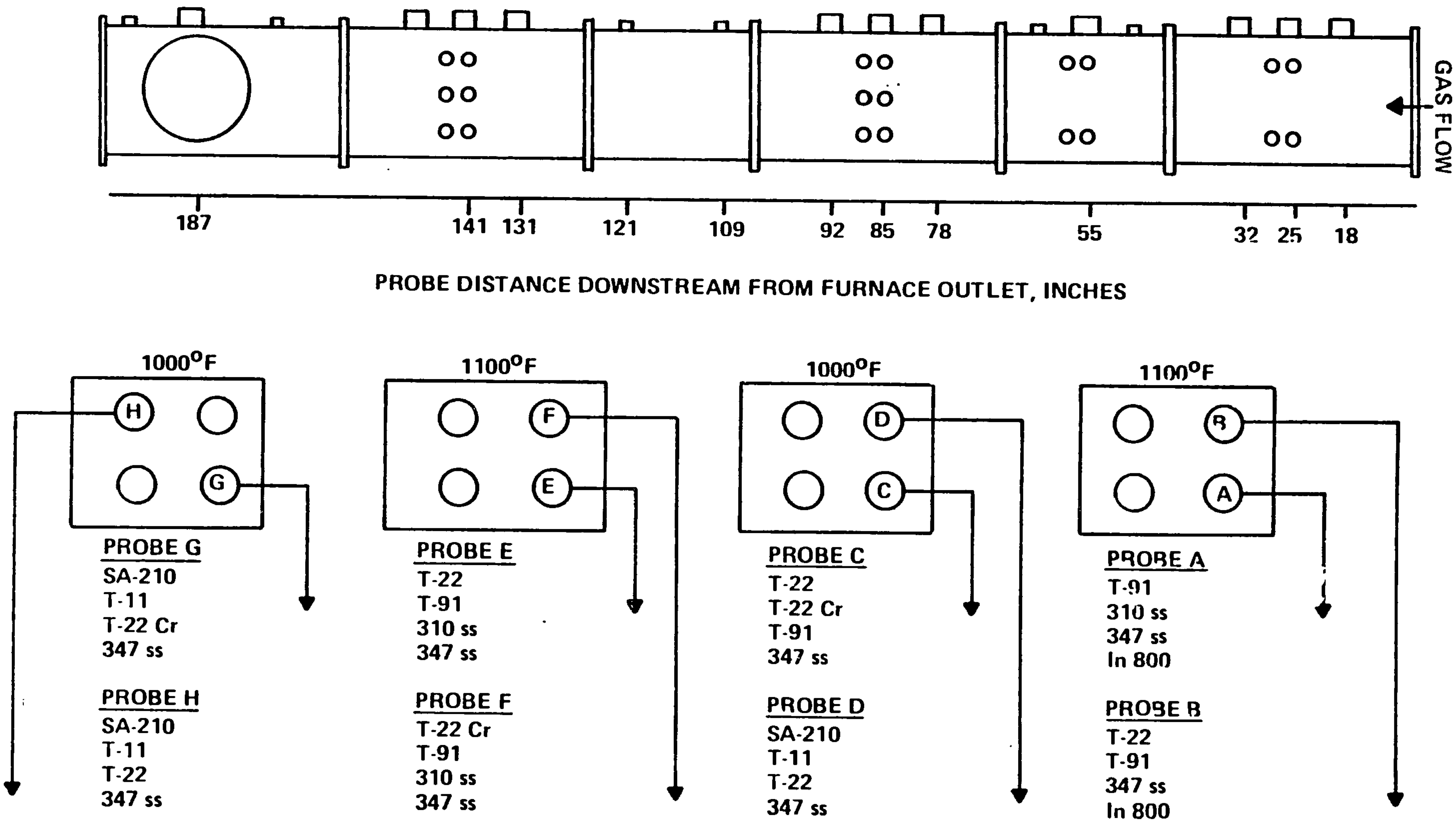


TABLE D-1

CORROSION TEST MATERIAL COMPOSITION

MATERIAL	C	MN	P(MAX.)	S(MAX.)	SI	NI	CR	MO	FE	OTHER
SA-210 CARBON STEEL	0.25 MAX.								99	
T-11	0.15 MAX.	0.3-0.6	0.030	0.030	0.5-1.00	-	1.0-1.5	0.44-0.65	96	
T-22	0.15 MAX.	0.3-0.6	0.030	0.030	0.5 MAX.	-	1.9-2.6	0.87-1.13	95	
T-91	0.08-0.12	0.03-0.6	0.02	0.01	0.2-0.5	0.4 MAX.	8.0-9.5	0.85-1.05	87.5	V 0.18-0.25 NB 0.06-0.10
347 S.S.	0.08 MAX.	2.0	-	-	1.0 MAX.	9-12	17-19	-	66	NB STABILIZED
310 S.S.	0.25 MAX.	2.0 MAX.	-	-	1.5 MAX.	19-21	24-26	-	49	
IN 800	0.08	0.08	-	0.008	0.5	32	21	-	46	AL 0.4 CU 0.4
T-22 (CHROMIZED) 15 MILS							80 2-1/4			

APPENDIX E

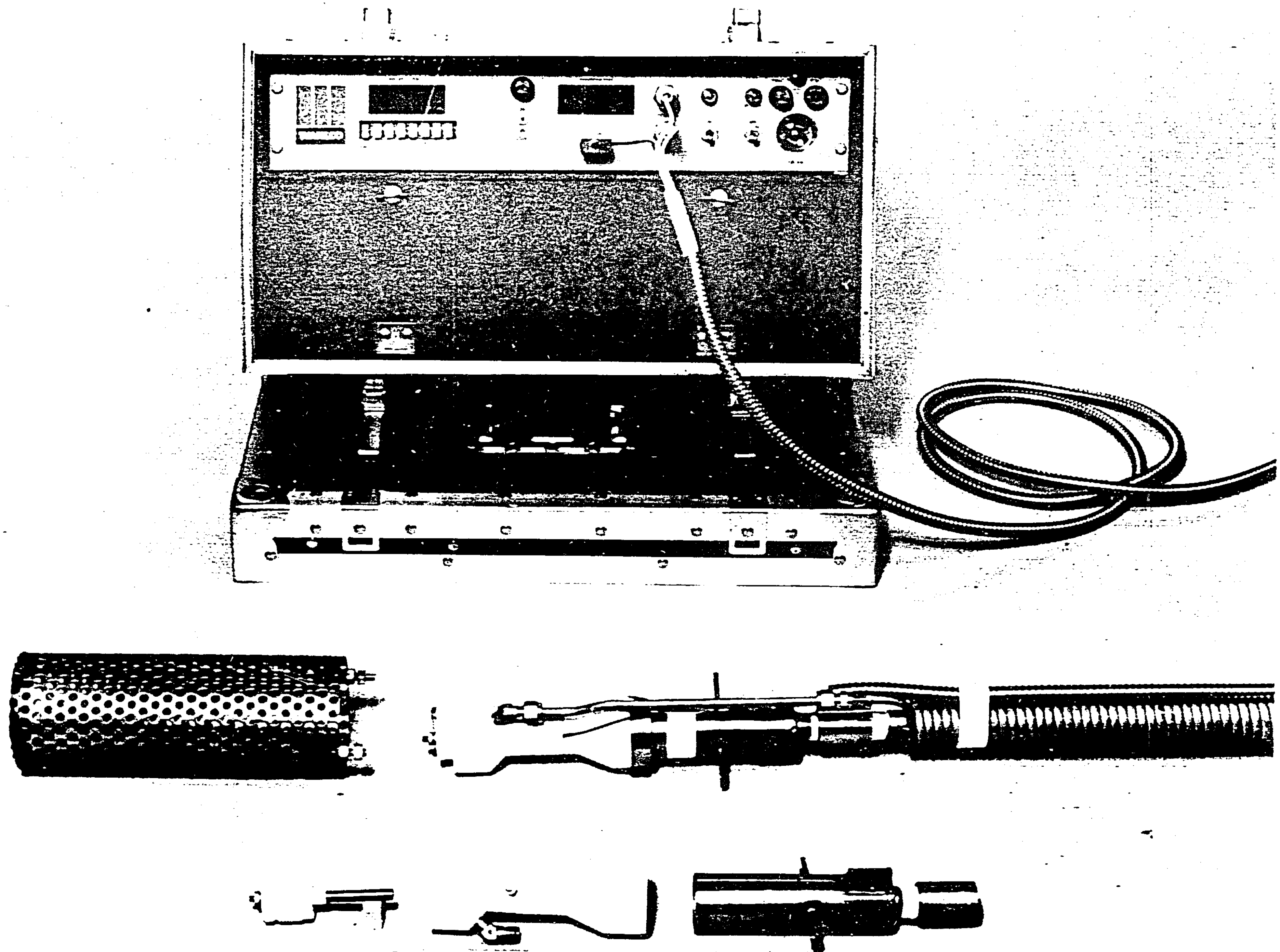
IN-SITU FLY ASH RESISTIVITY MEASUREMENT PROBE

Appendix E

IN-SITU FLY ASH RESISTIVITY MEASUREMENT SYSTEM

The system shown in Figure E-1 is used for fly ash resistivity measurement. It consists of a cyclone used to extract an ash sample from the flue gas. The ash drops into a teflon (non-conductive) thimble which is fitted with a steel circumferential ring. A steel point is screwed into the thimble and protrudes through the ring. This design basically fixes the gap between the high voltage ring and grounded pin, thereby eliminating measurement of the ash layer thickness as in the point plant method.

This in-situ meter was inserted into the flue gas and a sample of ash extracted using an aspirator. To completely cover the pin in the teflon thimble approximately 7.0 grams of ash are required. Initial measurements indicated that as the ash sample was compacted by rapping the probe top, the resistivity measurement would decrease. Based on this and the inability to measure or gauge compactness, the remaining samples were taken and consistently rapped down to the point at which the measurement reached a steady state.



IN-SITU FLY ASH RESISTIVITY MEASUREMENT PROBE
FIGURE E-1

COMBUSTION PERFORMANCE CHARACTERIZATION
OF LAKHRA WASHED COAL

Project 900029

KDL-85-F-20

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EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVES

This phase of the Lakhra project is aimed at quantifying the fuel performance characteristics of the Lakhra Washed Coal. The goal is to generate detailed data to assess beneficiation and the commercial impact of the washed versus baseline coal. This work is part of a contract in which Gilbert/Commonwealth, Inc. is conducting a Lakhra Power Plant feasibility study for the Pakistan Water and Power Development Authority (WAPDA) sponsored by the United States Agency for International Development (USAID). Combustion Engineering, Inc (C-E) has been subcontracted to conduct a comprehensive research program to evaluate the combustion/performance characteristics of the Lakhra coals and to provide feedback for an effective utility furnace design.

The test plan was devised to provide detailed assessment of fuel performance characteristics in key unit design and operating areas. The testing effort consisted of both special bench-scale fuel analysis and comprehensive pilot-scale testing in C-E's Fireside Performance Test Facility. Areas addressed included:

- Pulverization
- Combustion
- Ash Slagging
- Ash Fouling
- Fly Ash Erosion
- Flue Gas and Particulate Emissions

KEY RESULTS

The most obvious effect of cleaning Lathra coal was the reduction in ash and sulfur content and the corresponding increase in calorific value. Reduction of ash content lowers mass throughout, this will result in lower mill wear and tube erosion as well as decreased ash handling requirements and slightly decreased convection pass sootblowing requirements. Lower sulfur content will favorably impact SO_2 emissions. Higher calorific value will lower mill power requirements. Although the washed coal reduced sulfur and ash levels, ash quality did not change significantly. The coal ash characteristics for the washed coal are very similar to those for the baseline yielding comparable combustion, severe slagging and moderate fouling for both coals.

BENCH SCALE CHARACTERISTICS

The ASTM volatile matter content of the Lakhra washed and baseline coals is 51 and 55% respectively on a dry ash-free basis. The Thermo-Gravimetric Analysis for both coal chars had a rapid burn-off rate. The burn-off rate of these coal chars is similar if not slightly better than a U.S. subbituminous, a coal with known good carbon burnout in the field. High BET surface areas of the chars confirmed these results with 159 m^2/g for the washed coal and 214 m^2/g for the baseline. This coal should not present carbon heat loss problems under normal circumstances.

Lakhra washed coal showed reduction in ash and sulfur content, however, ash composition and fusibility temperatures remained generally unchanged. The ash content for the washed coal was approximately one-half of the baseline, 19.1 vs. 36.4% (dry basis) respectively. Sulfur and pyritic sulfur content was similarly reduced by coal cleaning. The washed coal had 4.7% sulfur content (dry basis) one half of it present as pyritic sulfur whereas the baseline coal contained 6.1% sulfur, 93% of it being in pyritic form. Higher heating value increased by one third on a dry basis due to the reduction in ash content. Ash composition remained approximately the same for the two coals. Iron content remained high at 19.3% compared to 17.2% of the baseline coal. Ash fusibility temperature ranged from 1120°C IDT to 1340°C FT (2040 to 2440°F) for the washed coal. This was within the range found for the baseline coal. Gravity Fractionation Analysis indicate that the ash in the 2.9 sink contains 89.8% Fe_2O_3 for the washed coal and 87.7% for the baseline. The low to moderate ash fusibility temperatures and high Fe_2O_3 content in the 2.9 sink fraction indicate that both coals should exhibit severe slagging potential.

Sodium content in the ash for both coals was low, less than 1.2%. Weak acid leaching test results for the washed coal indicate that 100% of the sodium in the ash is in active form. Lakhra baseline yielded slightly higher results. The overall concentration of active sodium in the coal are low to moderate coupled with the high ash loading and low to moderate fusibility temperatures indicate a moderate fouling potential for both washed and baseline coals.

PULVERIZATION CHARACTERISTICS

The overall pulverization characteristics of washed coal was similar to the baseline coal. The grindability indices for the coals were 67 and 71 for washed and baseline respectively. Both coals HGI's indicate that they should be relatively easy to grind. Mill power requirements in the FPTF bowl mill were 7.8 kw-hr/tonne (7.1 kw-hr/Ton) for the washed coal compared to 8.4 kw-hr/tonne (7.6 kw-hr/Ton) for the baseline coal. However, on a per heat input basis, power consumption decreased with the washed coal, 0.31 to 0.49 kw-hr/MJ (.33 vs. 52 kw-hr/10^6 Btu) (dry) due to its higher heating value. The mill reject rate at a coal feedrate of 613 kg/hr (1350 lb/hr) was lower than that for the baseline coal, 0.8% versus 2.1% respectively. This decline in reject can be attributed to the decrease in ash and pyrite content. The FPTF mill characteristics provide a comparative basis by which to compare coals.

The abrasiveness of the washed coal was relatively low. It had a benchscale abrasion index of 12. This is substantially lower than the baseline coal with an abrasion index of 50. The washed coal should not result in mill wear problems.

COMBUSTION PERFORMANCE CHARACTERISTICS

Six tests consisting of 12 hour waterwall cleanability cycles were conducted in the FPTF. Test conditions were established based on the Lakhra baseline coal results. Effects of flame temperature at a 856 kw (2.92 10^6Btu/hr) firing rate on combustion and performance in the FPTF were evaluated during these tests.

RELATIVE COMBUSTION CHARACTERISTICS

The combustion characteristics during each of the Lakhra washed coal tests were good. Good intense stable flame was obtained, indicating there should be no potential turndown/stability problems firing this coal. Combustion efficiency indicated better than 99.8% carbon burnout in the FPTF using the ash-tracer method.

FURNACE SLAGGING

Overall slagging results indicate that both the washed Lakhra and baseline coals exhibited severe slagging potential. Slagging characteristics of both coals were highly dependent on furnace temperatures. Radiant section waterwall deposits were evaluated during each test at different flame temperatures with the objective of establishing the maximum or "critical" furnace conditions at which deposits are still cleanable by sootblowing. Results indicate the maximum or "critical" furnace conditions at which deposits could be effectively cleaned by sootblower corresponds to a flame temperature range of 1427 to 1444°C (2600 to 2630°F) for the washed coal and a flame temperature less than 1427°C (2600°F) for the baseline. Deposits for Lakhra washed coal at 1466°C (2670°F) were molten 0.3 to 1.3 cm (1/8 to 1/2 inch) thick; they were not removable and exhibited poor cleanability. Deposits formed at 1427 to 1444°C(2600 to 2630°F) were similar in thickness but were highly sintered with a molten outer layer. These deposits were removable and had good to marginal cleanability. Deposits formed with flame temperatures of 1382 to 1410°C (2520 to 2570°F) were highly sintered .3 to 1.3 cm (1/8 to 1/2 inch) thick and exhibited good cleanability. Bottom ash accumulation rates were high requiring frequent handling, however, it was significantly lower compared to the baseline coal.

The effects of deposits on waterwall heat transfer were continuously monitored by the heat flux through waterwall panels at two elevations. Heat flux recovery after sootblowing was better than 90% for each of the cases when deposits were effectively removed at FPTF flame temperatures up to 1444°C (2630°F). Heat flux recovery at temperatures above 1455°C (2650°F) were 50%, exhibiting partially unremovable deposits.

CONVECTIVE PASS FOULING

The Lakhra washed and baseline coals both have a moderate fouling potential. Convection pass fouling was primarily assessed by determining the convective deposit cleanability (bonding strength measurements) and deposit build-up rate. Deposit bonding strength was less than 5 (values less than 15 are considered acceptable by commercial sootblowing). Deposit cleanability was good for Lakhra baseline and washed coals with the washed coal having a slightly lower accumulation rate. Although deposit accumulation rate was slightly lower compared to the baseline, it remained moderate to high over the temperature range tested 1155 to 1238°C (2110 to 2260°F). Deposition occurred rapidly with 3-4 inch deposits building up in 4 to 6 hours compared to the baseline 3 to 4 hours at 1282°C (2340°F), 5 to 6 hours at 1170°C (2140°F) and 6 to 8 hours at 1121°C (2050°F). Despite the deposit build-up rate, deposits were easily removable and caused no operating difficulty in the FPTF. The majority of ash build-up occurred in duct I 1155°C (2110°F) and the transition section 1277°C (2330°F). This is due to carryover from the lower furnace. Overall the fouling characteristics of Lakhra washed were similar to baseline results showing moderate fouling potential.

FLY ASH EROSION

A significant reduction in fly ash erosiveness was observed with the reduced ash loading of the washed coal. The normalized erosion rate is 0.55 mm (21.6 mils) per 10,000 hrs. at 183m/s (60 ft/s) compared to the higher rate for the baseline coal, 0.91 mm (36.8 mils) per 10,000 hrs. Erosion was found to increase linearly with ash loading. Ash content, quartz content and mass median diameter effects being similar showed little influence on tube wear and were overshadowed by the large difference in ash loading between the fuels.

PARTICULATE AND GASEOUS EMISSIONS

The fly ash resistivity measured in the FPTF in-situ was 7.6 x 10^{11} ohm-cm at 308°F flue gas temperature with 3 ppm SO_3. This value is higher than the optimum 5 x 10^9 to 5 x 10^{10} ohm-cm for electrostatic precipitators operating under normal gas temperature of 149 to 177°C (300 to 350°F). Bench-scale resistivity testing on fly ash collected isokinetically measured 3.0 x 10^9 ohm-cm at 6% H_2O and 3ppm SO_3 at 153°C (308°F). This laboratory resistivity measurement is slightly lower than the theoretical value of 6.9 x 10^{10} ohm-cm at 153°C (308°F), 5% H_2O and 3ppm SO_3 concentrations. The washed coal generally produced a higher resistance fly ash than the baseline. The fly ash for the washed coal may be more difficult to collect than the baseline and would correspondingly have a lower electrostatic precipitator collection efficiency.

The effect of coal beneficiation on sulfur emissions was significant due to the reduction of sulfur in the coal. Sulfur emissions for the washed coal were reduced by 30% with coal beneficiation. The theoretical SO_x for washed and baseline fuels are 4730 and 6960 ppm on a 3% O_2 dry basis, respectively. Measured SO_2 concentrations were very similar (within 13%) of the theoretical sulfur measurements and average values (3% O_2 dry basis) for washed and baseline tests were 4283 and 6000 ppm respectively. NO_x emissions were not affected by fuel changes but the firing conditions did affect NO_x values. The NO_x results at 3% O_2 dry basis from the Lakhra washed coal tests ranged from 1025 to 1375 ppm. The variation in NO_x values is attributed to the high rate of burner deposition and slagging potential of the coal.

CONCLUSIONS AND RECOMMENDATIONS

FPTF results indicate the Lakhra washed coal can be commercially fired in a properly designed furnace. Specific conclusions include:

- The Lakhra washed coal has very good combustion characteristics. Both bench and pilot scale results indicate this coal should not present any carbon heat loss under normal circumstances.

- Pulverization of both washed and baseline coals is easily accomplished requiring relatively low energy for grinding. Power requirements per unit heat input are less with the washed coal due to its higher heating value. There is no apparent compaction/pasting potential in the bowl mill. The abrasiveness of the washed coal was significantly reduced compared to the baseline coal. The low abrasion characteristics of the washed coal should not pose any potential difficulties in mill operation. The baseline coal will require proper mill lining materials.

- Lower furnace performance characteristics indicate that the physical waterwall deposits were highly dependent on flame temperature. Critical conditions for the washed coal were flame temperatures below 1427 - 1444°C (2600 - 2630°F) and for the baseline were 1427°C, (2600°F). The critical conditions for the two Lakhra coals are close and showed similar performance characteristics indicating severe slagging potential. In the FPTF this can be controlled by reducing temperature below critical conditions, for a commercial scale unit it will correspond to a large unit design. The high rate of bottom ash accumulation will require a large handling system.

- The Lakhra washed coal exhibited moderate fouling potential. Convection tube deposits were weakly bonded and readily cleanable with sootblowers. Deposit buildup rates were moderate to high with gas temperatures in the 1150 to 1240°C (2110 to 2260°F) range. Deposit cleanability for the baseline coal was similar, however, due to increased ash loading baseline deposit accumulation rates were higher. Commercial design for both coals should include low furnace outlet temperatures to reduce convection pass deposit accumulation. The higher temperature convective passes should have wide tube spacing to deal with the relatively high accumulation rates in these regions. These rates for the washed coal will be somewhat less than those for the baseline.

- Fly ash erosion for the washed coal was moderate. Baseline erosion values were much higher due to increased ash loading. Commercial units firing the baseline coal will require relatively low convection pass velocities. Units firing the washed coal can accommodate somewhat higher velocities than the baseline coal or will have longer tube life than the baseline if fired at similar velocities.

- Fly ash resistivity of the washed coal is slightly higher than the typical range for most commercial coals. The washed coal may be more difficult to collect than the baseline and have a lower electrostatic precipitator collection efficiency.

SECTION 1

INTRODUCTION

Interest in the effects of coal cleaning on the performance and design of utility boilers has increased significantly due to higher unit capital and operating costs and diminishing coal quality. Coal cleaning can provide potential benefits due to its reduction of mineral matter and sulfur content in a coal. Reduction of such compounds can influence the performance, availability and life of pulverizer firing systems and radiant and convective heat transfer surfaces. The cleaning of coal is likely to produce some benefits to the various parameters listed above. Therefore, the accurate prediction of fuel performance parameters is critical to assess the benefits of coal cleaning.

To generate a sufficient data base to permit assesement of the coal cleaning, Combustion Engineering, Inc. (C-E) has performed detailed combustion testing to compare the behavior of baseline and washed coals and define their impact on unit design and operations. This work is part of a contract in which Gilbert/Commonwealth, Inc. is conducting the Lakhra Power Plant feasibility study for the Pakistan Water and Power Development Authority (WAPDA) sponsored by the United States Agency for International Development (USAID). Combustion Engineering was subcontracted to conduct a comprehensive research program to evaluate the combustion/performance characteristics of the Lakhra coals and to provide feedback for an effective utility furnace design.

C-E test program consisted of test firing the Lakhra baseline (PMDC2), washed, and BT-11 coals. Testing effort for each coal consisted of both bench and pilot scale evaluation. Areas addressed include:

- o Pulverization and abrasion characteristics
- o Relative combustion characteristics
- o Furnace slagging

- Convective pass fouling
- Relative gaseous and particulate emission
- Fly ash erosion

This report presents the evaluation of Lakhra washed coal and its characteristics in comparison to the baseline coal data.

SECTION 2

OBJECTIVES

The ultimate objectives of this study are (1) to obtain bench-scale and pilot-scale test data on Lakhra washed coal for analysis of performance impacts on full-scale equipment and (2) the comparison of Lakhra washed and Lakhra baseline coal. The goal of this test work is to provide the detailed fuel performance data necessary to estimate and compare the commercial impacts of cleaning Lakhra coal.

Specific test objectives included:

- To determine pulverization characteristics through mill capacity, power requirement and abrasion wear rates.
- To assess the relative flame stability, carbon burnout and the overall combustion characteristics of the beneficiated coal.
- To characterize the relative ash slagging and fouling tendencies of the coal through evaluation of deposit buildup rate, bonding strength, cleanability and deposit physical and chemical properties.
- To determine the effect of ash deposition on heat absorption rate through lower furnace waterwalls.
- To assess fly ash erosion characteristics.
- To characterize the gaseous and particulate emissions of the coal during combustion.

SECTION 3

TEST PROCEDURES, COMBUSTION TEST MATRIX AND CONDITIONS

TEST PROCEDURES

This effort was designed to utilize both special bench-scale tests and comprehensive pilot-scale tests addressing various boiler sections and auxiliary equipment in order to accurately define key fuel performance characteristics of Lakhra washed coal. The procedures for the special bench and pilot scale tests are the same for washed and baseline tests. For detailed information on test procedures refer to Section 3 in the Lakhra Baseline Report.

COMBUSTION TEST MATRIX AND CONDITIONS

A total of six tests were performed with the Lakhra washed coal. Each test was performed at a firing rate of 856 kW (2.92 x 10^6 BTU/hr) with varying flame temperature. The objective of testing at one firing rate and several temperatures was to allow evaluation of flame temperature without influence by firing rate. To simulate commercial conditions a high firing rate was chosen (highest value run for Lakhra baseline) and flame temperature was varied to assess ash deposition characteristics. Testing the baseline coal prior to this provided a basis for comparison for the washed coal and allows for a more adequate commercial application of the cleaned coals combustion characteristics. Table 3-1 summarizes key test variables. All tests were conducted with 25% excess air in order to better simulate commercial unit operating conditions for high slagging coals. Units are often operated at 25% excess air or higher when firing severe slagging coals similar in performance to the Lakhra coals.

Initial test conditions were selected based upon results from the baseline testing. Test conditions were maintained at constant levels during a given test run. Testing focused on establishing the flame temperature at which

TABLE 3-1

LAKHRA WASHED TEST MATRIX

TEST NO.	FUEL FEED RATE: LBS/HR	FIRING RATE 10^6 BTU/HR	EXCESS AIR (%)	AVERAGE PEAK FLAME (°F)
1	319	2.92	25	2630
2	319	2.92	25	2710
3	319	2.92	25	2670
4	319	2.92	25	2670
5	319	2.92	25	2650
6	319	2.92	25	2610

waterwall deposits become molten/fused and no longer respond to wallblowers. This was defined as the critical temperature (T_{crit}). The furnace conditions at which wallblowers lose effectiveness is very important from a design standpoint as it dictates the maximum thermal loadings at which a slagging limited boiler can continuously operate.

The duration of the testing period prior to sootblowing was dictated by the slagging behavior of the fuel. Because of the high slagging characteristics of the Lakhra coals, the time period required for deposits to approach long term conditions was approximately 12 hours.

After the panel deposits and heat flux stabilized waterwall cleanability was determined and furnace conditions adjusted based upon these results in order to approach slagging limited "critical" temperature. After stabilizing at these new conditions another test was conducted. After this second test, furnace conditions were again adjusted to approach the estimated "critical" temperature. Testing was conducted over 6 cycles each approximately 12 hours in length. Convective section deposit bonding strength measurements were performed after 2 to 3 inches of deposit accumulated. The sootblowing frequency for all tests was 5 to 6 hours which allowed 2 sootblowing cycles to occur during each test.

FPTF Operating Conditions

The total heat input from each test was calculated from the fuel feed rate, fuel calorific value and the average energy contained in the preheated secondary air. Secondary air temperature was adjusted to maintain desired flame temperature. The fuel feed rate was 145 kg/hr (319 lb/hr) during the tests. The FPTF operating conditions during the Lakhra washed coal tests are summarized in Appendix F.

Furnace Temperature Profiles

Average peak flame temperatures ranged from 1432 to 1488°C (2610 to 2710°F). The furnace temperatures were kept low, less than 1488°C (2710°F), for all of the tests - as a result of the high slagging potential of the Lakhra washed

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coals. Convection temperatures varied from 894 to 1238°C (1640 to 2260°F) over the length of the superheater duct. Table 3-2 presents the flame and gas temperature during the Lakhra washed coal tests. Individual temperature profiles with respect to burner distance are plotted in Appendix G. Furnace temperatures were measured by using a single shield, high velocity suction pyrometer. Four traverse measurements were taken at five furnace ports located approximately .9m [3 ft(L1)], 1.2m [4 ft(L2)], 2.1 m [7 ft(L3)], 2.4 m [8 ft(L3.5)] and 3.6 m [12 ft(L4)] above the burner during each test. The furnace residence times from each of the subject tests were similar to typical commercial fired units. Values for tests are summarized in Table 3-3 and presented in Appendix H.

Furnace Mass and Energy Balances

Furnace mass and heat flows were measured during each test. Tables in Appendix I provide data and calculation methods for mass and heat balances during each test. The heat flux distributions for the Lakhra washed coal tests show that approximately 40 to 50% of the heat is absorbed in the lower furnace, (burner through superheater duct I). The waterwall panel absorbed roughly 2% of the heat input. The unaccounted heat ranged from 0.78 to 5.89% during the Lakhra washed coal tests. These values are consistent with typical FPTF results (less than 10.0%).

The ash distribution was approximately 60/40 fly ash to bottom ash for all of the tests. Utility units typically exhibit an 80/20 fly to bottom ash split. The higher percentage of bottom ash in the test furnace is attributed to the higher surface to volume ratio for the FPTF.

As-Fired Fuel Analysis

A composite sample of the Lakhra washed pulverized coal was collected and analyzed. The as-fired fuel analysis was very similar to the as-received sample. This is expected due to the small amount of reject from the bowl mill. The as-fired washed coal had a moisture of 10.2%, this is somewhat higher than the baseline coal. The higher moisture level for the washed coal

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TABLE 3-2

FURNACE TEMPERATURE PROFILE DURING

LAKHRA WASHED COAL EVALUATION

TEST NO.	AVE. PEAK TEMP. (°F)	FURNACE TEMPERATURE					ENTERING S.H. TEMPERATURES			
		L_1(3ft)	L_2(4ft)	L_3(7ft)	$L_{3.5}$(8ft)	L_4(12ft)	I	II	III	IV
1	2630	2630	2550	2510	2470	2360	2190	2000	1940	1640
2	2710	2710	2630	2580	2510	2410	2260	2170	1960	1800
3	2670	2670	2610	2570	2500	2420	2220	2030	1920	1720
4	2670	2670	2560	2520	2450	2370	2240	2170	2000	1770
5	2650	2650	2570	2520	2460	2450	2210	2150	2030	1790
6	2610	2610	2520	2450	2360	2280	2110	2030	1920	1720

TABLE 3-3

LAKHRA WASHED COALS
FURNACE RADIANT SECTION RESIDENCE TIME

TEST NO.	AVE. PEAK FLAME TEMP. °F	LOWER FURNACE RESIDENCE TIME (SEC)
1	2630	1.42
2	2710	1.41
3	2670	1.41
4	2670	1.42
5	2650	1.43
6	2610	1.47

is attributed to the cleaning process. Due to the lower ash content the HHV for the washed coal was significantly higher than that of baseline coal. Ash composition and fusibilities remained approximately the same. See Table 3.4.

Particle size analysis of the as-fired pulverized samples for the washed and baseline coal samples are illustrated in Figure 3-1. Size was determined by seive analysis for all particles greater than 45 microns (325 mesh) and by a laser diffraction technique for all particles less than 45 microns (325 mesh). Results show that washed and pulverized samples were 70.8% and 70.2% through 75 microns (200 mesh). The mass median particle diameters were 54 and 47 microns respectively. The slight amount of difference in mass median diameter (MMD) can be attributed to the increased carbon content in the washed coal.

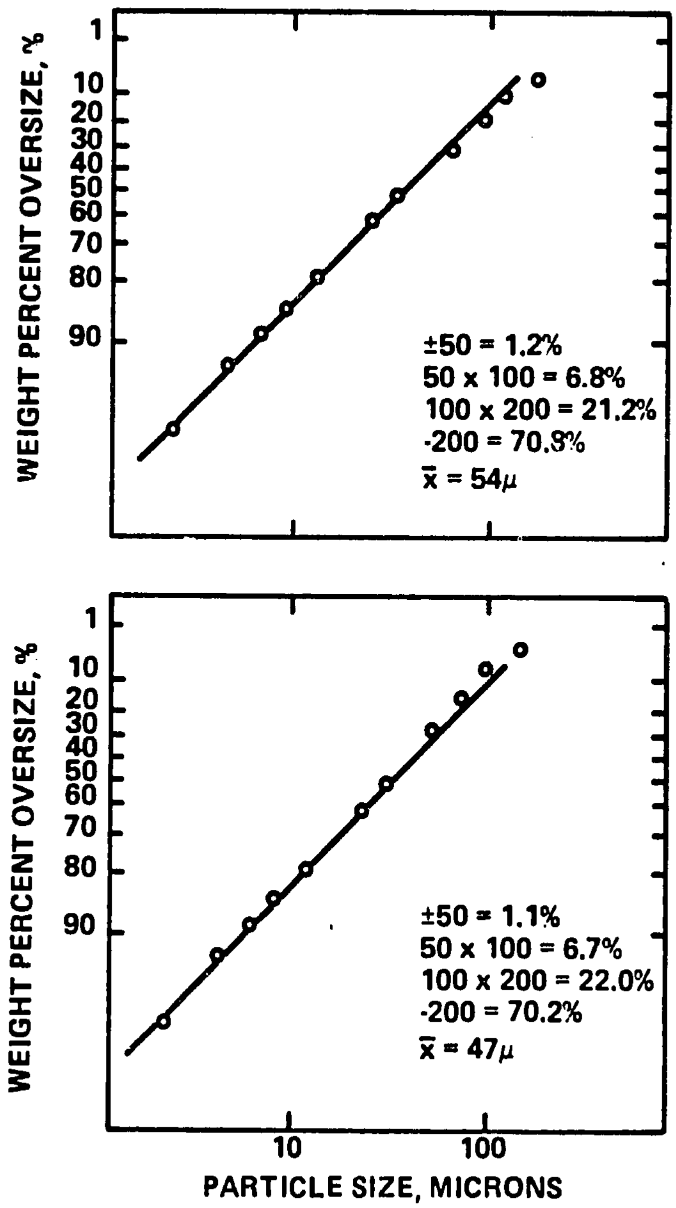
TABLE 3-4

ANALYSIS OF AS-FIRED PULVERIZED LAKHRA WASHED BASELINE COAL SAMPLES

	Lakhra Washed		Lakhra Baseline	
	As Fired	Moisture Free	As Fired	Moisture Free
Proximate, Wt. Percent				
Moisture (Total)	10.2	-	7.4	-
Volatile Matter	37.8	42.1	34.9	37.7
Fixed Carbon (Diff)	34.8	38.8	29.3	31.6
Ash	17.2	19.1	28.4	30.7
Total	100.0	100.0	100.0	100.0
HHV, Btu/lb	9250	10300	7715	8332
LB Ash/mm Btu				
Ultimate, Wt. Percent				
Moisture (Total)	10.2	-	7.4	-
Hydrogen	4.2	4.7	3.6	3.9
Carbon	51.4	57.2	43.1	46.5
Sulfur	4.2	4.7	4.9	5.2
Nitrogen	1.1	1.2	0.8	0.9
Oxygen (Diff)	11.8	13.1	11.8	12.7
Ash	17.2	19.1	28.4	30.7
Total	100.0	100.0	100.0	100.0
Ash Fusibility (Red.)				
I.T. Deg F	2120		2050	
S.T. Deg F	2340		2470	
H.T. Deg F	2420		2500	
F.T. Deg F	2470		2560	
Temp Diff (FT-IT)	350		510	
Ash Composition, Wt. Percent				
SiO_2	39.2		44.7	
Al_2O_3	23.1		27.5	
Fe_2O_3	19.0		15.8	
CaO	5.2		3.5	
MgO	2.3		1.5	
Na_2O	1.1		0.9	
K_2O	0.7		0.5	
TiO_2	1.4		2.0	
SO_3	6.4		3.4	
Total	98.4		99.8	
Ratios				
BASE/ACID	0.3		0.3	
Fe_2O_3/CaO	4.8		4.5	
$SiO_2$7Al_2O_3	1.6		1.6	
Screen Analysis				
±50	1.2		1.1	
50x100	6.8		6.7	
100x200	21.2		22.0	
-200	70.8		70.2	
MMD,Microns	54		47	

FIGURE 3-1

ROSIN-RAMMLER PLOT OF AS-FIRED LAKHRA WASHED AND BASELINE COAL SAMPLES



SECTION 4

TEST RESULTS

BENCH-SCALE RESULTS

ASTM Fuel Analysis

The Lakhra washed fuel was produced from the baseline coal at a coal cleaning test facility. The parent coal, Lakhra baseline was mined from Sind Province, Pakistan and can be classified as a lignite A rank coal using the ASTM ranking system. The process of coal cleaning acts to reduce ash content and hence silica, alumina, iron and sulfur constituents within a fuel. Heating value subsequently increases.

Results from bench-scale testing for both as received coals are summarized in Table 4-1. The most obvious effect of cleaning Lakhra coal was the reduction in ash content and the corresponding increase in calorific value. The ash content for the washed coal was approximately one half of the baseline, 19.1 vs. 36.4% (dry basis) respectively. Sulfur contents were 4.7 and 6.1% (dry basis) for the washed and baseline coals, respectively with one half and 90% of the sulfur for each coal being present in pyritic form. In general, the washed coal exhibited low initial deformation temperature, high iron content and low alkali/alkaline earth constituents, similar to the baseline coal.

The reduction in ash content appears to be primarily the result of removal of silica and alumina based constituents (clays, quartz, etc.). Only a small percentage of the pyrite in the raw coal was removed and sulfur contents remained almost unchanged. Selective removal of the silicon and alumina constituents resulted in the enrichment of iron, calcium, magnesium and sulfur in the coal ash. This change in ash chemistry resulted in a significant decrease in ash softening from 1332 to 1282°C (2430 to 2340°F) through fluid from 1382 to 1349°C (2520 to 2460°F) fusibility temperatures for the washed coal. Initial deformation temperatures for the washed coal were slightly higher than the baseline 1155 to 1082°C (2110 to 1980°F). The reducing atmosphere ash fusibilities ranged from 1154 to 1316°C (2110 to 2400°F) for the washed coal and 1082 to 1382°C (1980 to 2520°F) for the baseline coal.

TABLE 4-1

FUEL ANALYSIS FOR LAKHRA WASHED AND BASELINE COALS AS-RECEIVED

	LAKHRA BASELINE		LAKHRA WASHED	
	AS RECEIVED	MOISTURE FREE	AS RECEIVED	MOISTURE FREE
PROXIMATE, WT. PERCENT				
MOISTURE (TOTAL)	26.3		36.6	
VOLATILE MATTER	25.8	35.0	26.6	41.6
FIXED CARBON (DIFF)	21.1	28.6	24.9	39.3
ASH	26.8	36.4	12.1	19.1
TOTAL	100.0	100.0	100.0	100.0
HHV, BTU/LB	5,410	7,340	6,550	10,330
ULTIMATE, WT. PERCENT				
MOISTURE (TOTAL)	26.3		36.6	
HYDROGEN	2.7	3.6	3.0	4.7
CARBON	29.9	40.6	36.3	57.2
SULFUR	4.5	6.1	3.0	4.7
NITROGEN	0.5	0.7	0.8	1.2
OXYGEN (DIFF)	9.3	12.6	8.2	13.1
ASH	26.8	36.4	12.1	19.1
TOTAL	100.0	100.0	100.0	100.0
ASH FUSIBILITY RED ATM				
I.T. DEG F	1980		2110	
S.T. DEG F	2430		2340	
H.T. DEG F	2470		2420	
F.T. DEG F	2520		2460	
TEMP DIFF (FT-IT)	540		350	
ASH COMPOSITION, WT. PERCENT				
SIO2	43.6		39.0	
AL2O3	27.2		22.9	
FE2O3	17.2		19.3	
CAO	3.3		5.3	
MGO	1.3		2.2	
NA2O	0.7		1.2	
K2O	0.7		0.6	
TIO2	1.9		1.5	
P2O5	N/A		N/A	
SO3	3.9		6.4	
TOTAL	99.8		98.4	
BASE/ACID	0.32		0.45	
FE2O3/CAO	5.21		3.64	
FUEL RATIO (FC/VM)	0.82		0.95	
FORMS OF SULFUR				
SULFATE AS S	0.1		< 0.1	
PYRITE AS S	4.2		1.5	
ORGANIC AS S	0.3		1.4	

The combustion characteristics of the test coals appear similar based upon the proximate analyses. Volatile matter content of each coal was similar on a dry, ash-free basis and the fuel ratio; fixed carbon/volatile matter, was also similar indicating little change in organic composition due to cleaning. The fuel ratios for coals ranged between 0.8 and 1.0 which is typically considered good from a combustion standpoint. Coals having fuel ratios greater than 2.2 are often considered to have potentially low reactivity. However, these analyses do not provide sufficient information to reach definitive assessment of combustion characteristics.

Coal ash slagging potentials are conventionally assessed by comparing ash fusibility characteristics, and other slagging indices such as base/acid ratio and Fe_2O_3/CaO ratio. Ash fusibility temperatures in a reducing atmosphere are typically the most heavily weighed bench-scale test used in assessing slagging characteristics. Fusibility temperatures in a reducing atmosphere are expected to be more representative of the melting characteristics of ash particles in the high temperature zones of a boiler where slagging is most severe. In these zones, combustion is generally still in progress and the local environment (within the particle where the minerals undergo transformation) should be reducing. Ash fusibility temperatures in an oxidizing atmosphere are generally higher than in a reducing atmosphere particularly if significant iron concentration is present in the ash. Iron in the reduced oxidation state generally forms much lower melting compounds than in higher oxidation states. The ash fusibility temperatures for both coals would be considered moderate, except for the initial deformation temperatures. These low initial deformation temperatures indicate high to severe slagging potential for both washed and baseline coals.

Base/acid ratios for these ashes (commonly used indicator of ash melting characteristics) are in good agreement with the fusibility data. Base/acid ratio between 0.4 and 0.6 are considered indicative of low melting behavior and high slagging potential. The washed and baseline coals which exhibited the low melting ashes had base/acid ratios (0.45, 0.32) close to the predicted low melting range of 0.4 to 0.6. Iron/calcium ratios between 0.3 and 3.0 are considered indicative of low melting behavior. Washed and baseline coals had values 3.6 and 5.2, respectively.

The iron contents in these ashes appear to be the dominant factor responsible for overall melting characteristics. Iron contents for the washed and baseline coals are 19.3 and 17.2% Fe_2O_3 in the ash. The difference in ash levels of these fuels are also significant, 19.1% and 36.4% respectively. Overall, based upon the analytical data contained in Table 5-1, the relative slagging potential of the washed coal would be considered high to severe similar to the baseline coal high-to-severe slagging potential.

Fouling potential is typically assessed by considering sodium content in the coal ash, and ash initial deformation and softening temperatures along with ash content. The sodium contents of both coals are low. Ash fusibility temperatures are moderate for both coals. Ash content is relatively high.

Based upon the traditional parameters, the relative fouling potential of Lakhra washed coal would typically be considered moderate despite the low sodium concentrations due to the moderate fusibility temperatures and moderate to high ash content. Fouling should be somewhat lower for the washed coal than the baseline due to its lower ash content.

Fouling behavior is frequently induced by two mechanisms. The first is a sodium vaporization/condensation mechanism. Most sodium compounds melt at temperatures below 816°C (1500°F) and some compounds volatilize at relatively low temperatures 1371°C (2500°F). Volatilized sodium from the high temperature zone can condense on ash particles and on metal surfaces as heat is absorbed and gas temperature decreases. The condensed sodium provides a low melting material which can provide a bonding matrix for ash particles to fuse together and build up on tube surfaces. The second mechanism is the direct impaction of low melting ash particles. This mechanism is essentially a carryover of slagging phenomena into high temperature convection sections and is generally indicated by low fusibility ash. This second mechanism is expected to be the primary concern from a fouling standpoint given the relatively low sodium content and high ash content.

In summary, the standard ASTM analyses indicate good combustion characteristics for both coals. Ash slagging potential for the washed and baseline coals is considered high-to-severe. Ash fouling potential is considered moderate for both fuels. The carryover of slagging phenomena into high temperature convective sections is an important factor in evaluating fouling potential for the coals which have low initial deformation fusibility temperatures. In general the coal ash characteristics for the washed coal are very similar to those for the baseline yielding comparable combustion, slagging and fouling potentials.

Special Bench-Scale Analysis

As part of this study seven special bench-scale performance tests were conducted to obtain greater insight on fuel performance properties than obtained from ASTM tests. These tests included: Abrasion Index, Gravity Fractionation Analysis, Weak Acid Leaching, Thermo-Gravimetric Analysis, Quartz Content, Flammability Index and Pore Surface Area. (Description of these tests are provided in Appendix A). Results of the special tests are summarized in Table 4-2 and Figure 4-1.

The relative abrasiveness of the coal decreased with coal cleaning. Abrasion indexes for the washed coal was 6.25 g metal loss/ tonne (12 metal loss /1000 tons) indicating very low abrasion potential. This is significantly lower than the baseline coals moderate to high value of 25 g metal loss/ tonne (50 lb metal loss/1000 tons). The washed coal abrasiveness indicates normal mill life expectancy and normal maintenance.

The Thermo-Gravimetric Analysis burn-off curves (a measure of relative fuel reactivity) of the 200x400 mesh size of the chars in air at an isothermal temperature of 700°C (1292°F) are shown in Figure 4-1. Four chars prepared from U.S. coals of various rank and known reactivity have also been illustrated for comparison. Lakhra washed and baseline coals fall to the left of the Sub A coal indicating increased reactivity and good carbon burnout potential. The washed coal reactivity is consistent with the flammability index results.

TABLE 4-2

BENCH-SCALE AND SPECIAL BENCH-SCALE TEST RESULTS FOR LAKHRA BASELINE AND LAKHRA WASHED COALS

	BASELINE	WASHED
ABRASION INDEX (LBS METAL LOSS/1000T)	50	12.5
QUARTZ CONTENT (%)	1.7	0.4
WEAK ACID LEACHING:		
Na_2O (ppm Coal)	1870	2390
K_2O (ppm Coal)	160	145
Na_2O (% Ash)[1]	0.7	1.00
K_2O (% Ash)[1]	0.06	0.10
GRAVITY FRACTIONATION		
% Iron in 2.9 Sink	87.7	89.8

(1) Calculated number based on active alkali in coal.

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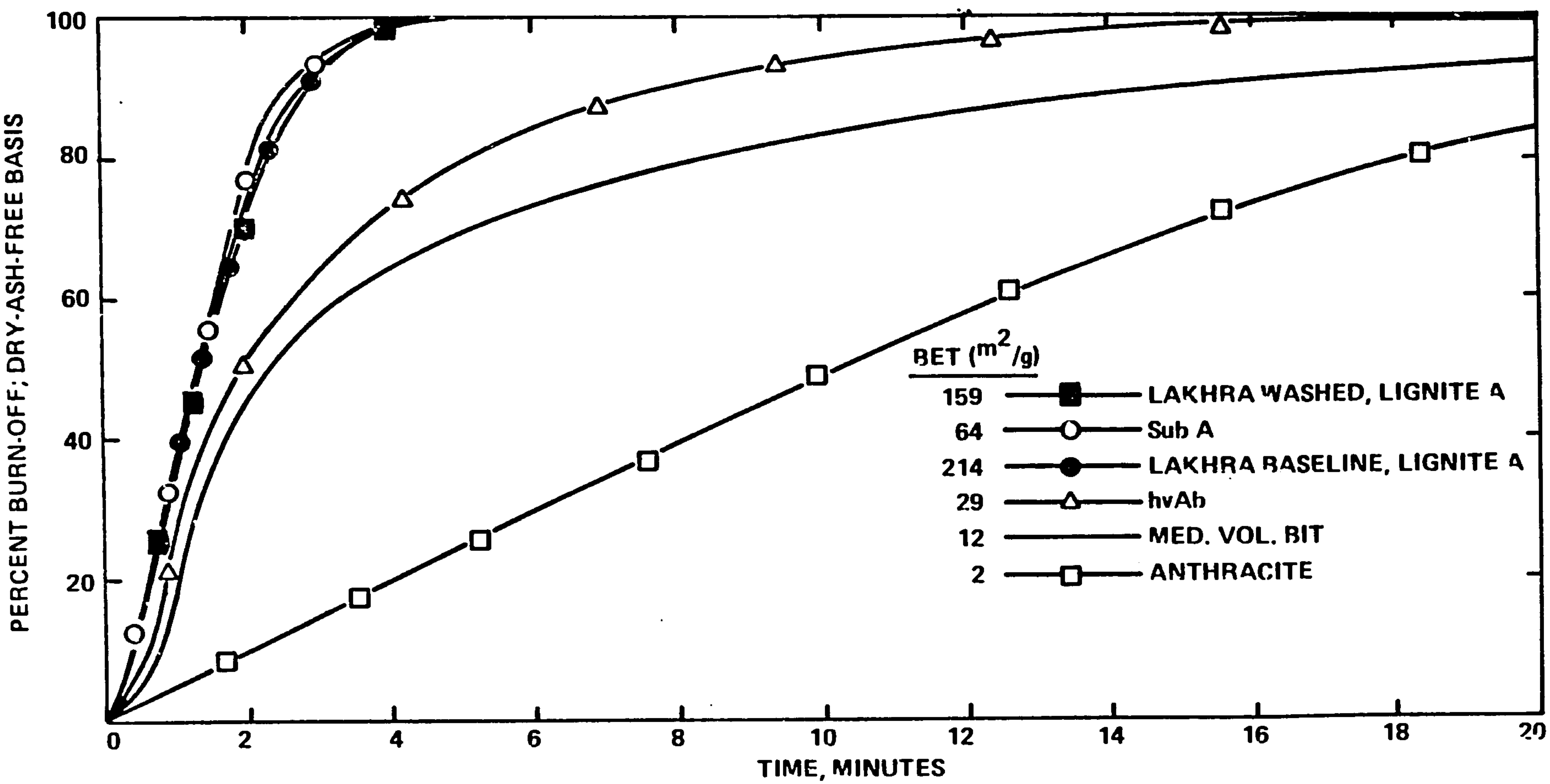


FIGURE 4-1 THERMOGRAVIMETRIC BURN-OFF OF LAKHRA WASHED 200 x 400 MESH DTFS CHARS AT 700°C

Results of the BET specific pore surface area are between Sub A (64 m^2/g) and lig A (250 m^2/g) coals indicating good reactivity. The BET pore surface areas are presented in Figure 4-1 with reference chars. Pore surface area decreases (214 to 159 m^2/g) as the coal is cleaned in agreement with TGA results. The changes in combustion characteristics due to cleaning are relatively small.

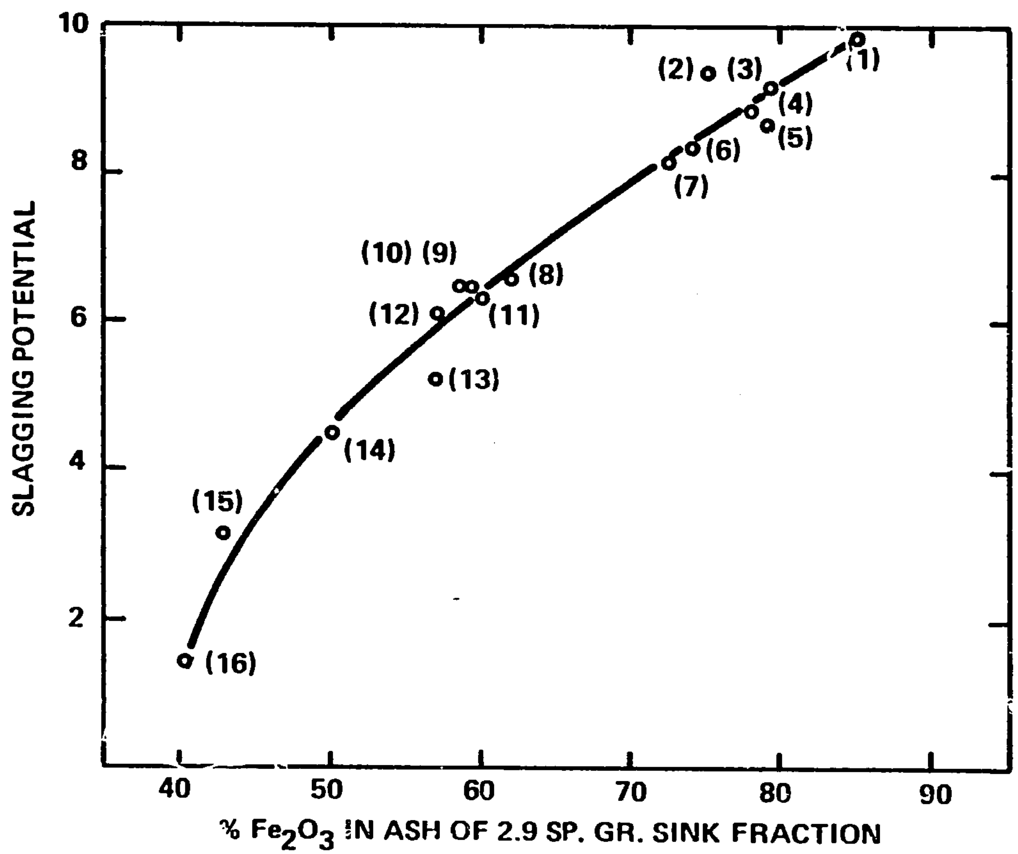
C-E has performed Gravity Fractionation Analyses (GFA) on the Lakhra washed coal and results indicate that the coal has severe fouling potential. A summary of analyses are provided in Appendix J for Lakhra washed as well as baseline coals. The key information derived from GFA is the concentration of liberated pyrite particles contained in the fuel. This information is reflected by the percentage of iron in the ash of the 2.9 sink fraction of the coal. The percentage of iron in the 2.9 sink fraction has shown excellent correlation with observed slagging performance in field units (Figure 4-2). In general, coals having greater than 75% Fe_2O_3 in the ash of the 2.9 sink fraction exhibit high slagging potential. Results of the GFA show extremely high (>85%) percentages of Fe_2O_3 in the 2.9 sink fraction of the washed coal as well as the baseline indicating severe slagging potentials.

Results of the weak acid leaching tests indicate low to moderate fouling potential for the washed coal. Total active alkali contents in the ash are low, but this is somewhat offset by the relatively high ash loading. The percentage of active sodium in the washed coal appears to be 100% of the total sodium content (.25% on a coal basis). The percentage of active potassium was less than 10% of the total potassium in the coal. Low concentrations of active potassium are typical for most U.S. coals. The Lakhra baseline coal yielded similar results. Overall the concentrations of active sodium and potassium are low to moderate coupled with the high ash loading and moderate susibility temperatures indicating a moderate fouling potential for both washed and baseline coals.

In summary, the special bench tests conducted by themselves indicate the Lakhra washed coal has severe slagging potential and low to moderate fouling potential (similar to the baseline coal). In combination with the ASTM

FIGURE 4-2

EFFECT OF SEGREGATED IRON ON COAL ASH SLAGGING
SLAGGING POTENTIAL vs
PERCENT IRON IN 2.9 GRAVITY FRACTION



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analyses, the slagging potential of the washed coal would be considered severe. Ash fouling potential would be considered moderate based upon the compilation of special and ASTM tests. Baseline and washed coal results are very similar for slagging and fouling. The abrasiveness of the coal would be considered low in comparison to that for the baseline coal. Ignition stability and turndown characteristics would be considered good. TGA and BET tests generally show good reactivity and low carbon loss potential.

PULVERIZATION CHARACTERISTICS

The pulverization characteristics of the Lakhra baseline and washed coals were evaluated in C-E's model 271 bowl mill prior to combustion testing. Both coals were easy to pulverize to the specified distribution of 70% through 200 mesh. Overall, the pulverization characteristics of the washed coal were similar to those for the baseline coal.

Pulverizer power consumption in the 271 bowl mill at a 613 kg/hr (1350 lb/hr) feed rate was 7.8 kW-hr/tonne (7.1 kw-hr/ton) for the washed coal compared to 8.4 kW-hr/tonne (7.6 kw-hr/ton) for the baseline coal. The requirement to operate the mill empty is approx. 2.2 W/kg (2 kw/ton). Energy requirements to grind each fuel were similar on a per ton basis, however they differed on a fuel heat input (Btu) basis. Power consumption decreased with the washed coal, 0.31 vs 0.49 kw-hr/GJ (0.33 vs 0.52 kw-hr/10^6 Btu) (dry) due to its increased higher heating value. See Table 4-3.

Both of the coals could be pulverized at the rated mill capacity of 613 kg/hr (1350 lb/hr) without excessive spillage. The mill reject rate for the washed coal was 0.8% versus 2.1% for the baseline. Analysis of the composite mill reject samples is shown in Table 4-4. The ratio of the reject flow and reject composition to the coal flow and coal composition indicate rejection of 4.8% sulfur and 2.3% ash from the baseline and 1.5% sulfur and 1.7% ash from the washed coal. The decrease in the amount reject for the washed coal can be attributed to the reduction in ash loading and decreased presence of pyrite particles.

TABLE 4-3

PULVERIZATION CHARACTERISTICS FOR LAKHRA BASELINE AND WASHED COALS

	WASHED	BASELINE
POWER REQUIREMENT		
kw-hr/ton	7.1	7.6
kw-hr/10^6Btu	0.33	0.52
MILL REJECT (% of feed)	0.8	2.1
HARDGROVE GRINDABILITY INDEX	67	71

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TABLE 4-4

MILL REJECT SAMPLE ANALYSIS OF LAKHRA WASHED AND BASELINE COALS

	WASHED		BASELINE	
	As-Received	Moisture Free	As-Received	Moisture Free
MOISTURE (TOTAL)	3.3		9.9	--
ASH	21.5		36.4	40.4
SULFUR	5.5	5.7	12.5	13.9
FORMS OF SULFUR				
Pyritic	3.9	4.0	10.1	11.2
Sulfate	0.2	0.2	0.7	0.8
Organic	1.4	1.5	1.7	1.9
ASH COMPOSITION				
SiO_2	34.8		33.8	
Al_2O_3	21.8		17.5	
Fe_2O_3	26.1		37.4	
CaO	5.7		3.3	
MgO	1.7		1.0	
Na_2O	1.8		0.5	
K_2O	0.6		0.6	
TiO_2	1.9		1.4	
SO_3	5.3		4.2	
Total	99.7		99.7	

The pulverization characteristics are in general agreement with the ASTM grindability data. The grindability for the washed and baseline coals were similar 67 and 71, respectively. This data indicates that both coals should be easy to grind.

In summary, both coals exhibited similar pulverization characteristics. Grinding energy on a per ton basis was similar for both coals and therefore pulverizer energy consumption for a given unit size would decrease due to the lower feed rates associated with the higher fuel calorific values resulting from the washed coal.

FIRESIDE PERFORMANCE TEST RESULTS

Combustion Properties for Lakhra Washed Coal

The combustion characteristics during each of the Lakhra washed coal tests were good. A good intense stable flame was obtained indicating there should be no potential turndown/stability problems firing this coal. Lakhra baseline and washed coals exhibited similar combustion characteristics.

Isokinetic fly ash samples were collected throughout test firing. Fly ash samples were examined for carbon burnout, chemical composition, mass mean particle size and SEM characteristics. The fly ash analyzed for composition, particle size and SEM represents a composite of several samples (Table 4-5).

Carbon contents of the fly ash isokinetically collected down stream of the convection section were similar throughout the Lakhra washed testing. Values for the washed coal were 0.6% while those for the baseline were 0.1%.

Carbon conversions for the washed coal were 99.8% based on the ash tracer method. Conversion for the baseline was 99.9%. Carbon conversion is the percentage of carbon burned in the furnace based on the initial amount of carbon entering the furnace. The ash tracer method was selected to calculate conversion since it provides the most conservative values assuming that all of the ash in the coal is present as fly ash.

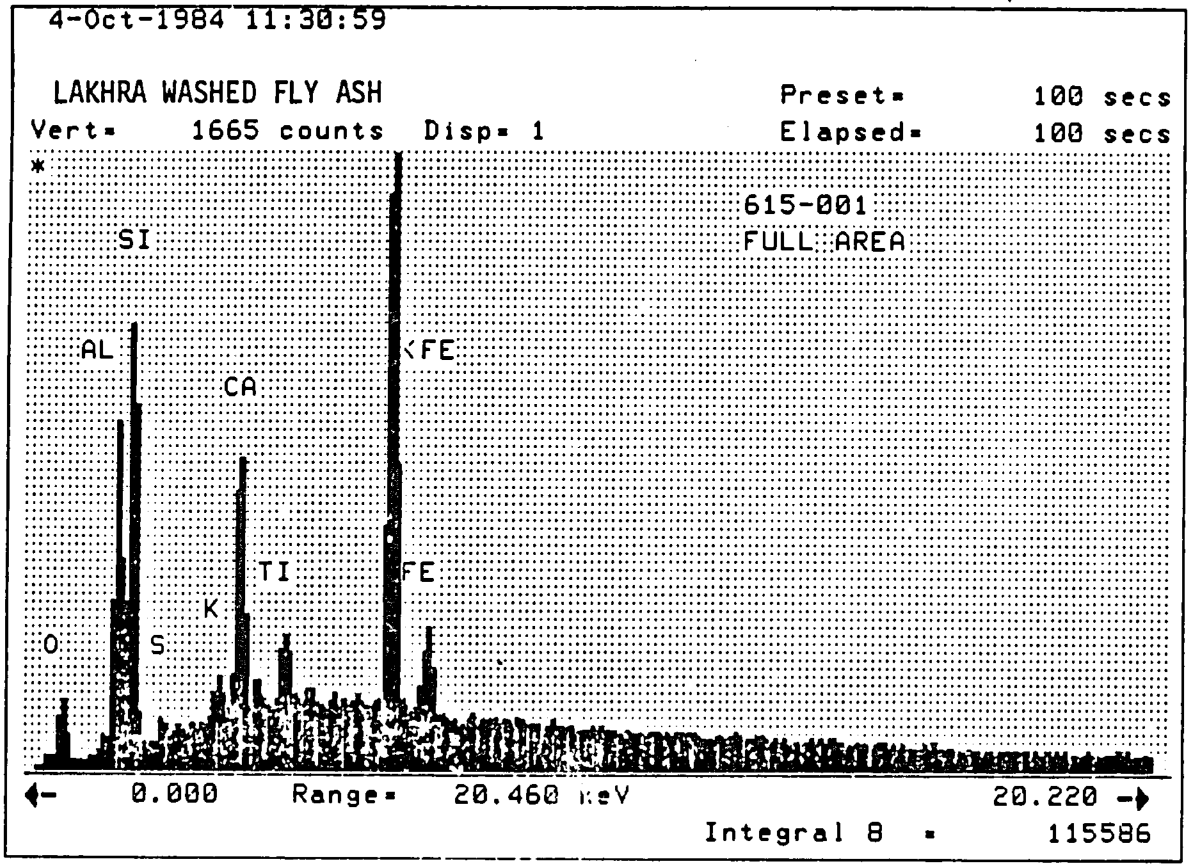
TABLE 4-5
COMBUSTION EFFICIENCY DATA FOR LAKHRA WASHED AND BASELINE COALS

	FIRING RATE (10^6 BTU/HR)	AVE. PEAK FLAME TEMP. (°F)	MASS MEDIAN DIAMETER (μ)	FLYASH CARBON CONTENT (%)	CARBON CONVERSION (%)
LAKHRA WASHED	2.92	2650	7.3	0.6	99.8
LAKHRA BASELINE	2.82	2600	5.0	0.1	99.9

Fly ash compositions generally reflected the composition of the as-fired coal for both washed and baseline coals. Analytical spectrum from the scanning election microscope (SEM) indicated that iron, silica and alumina are the major constituents of both fly ashes (Figure 4-3). The higher calcium content in the washed coals fly ash, 5.2 vs 3.8 for the baseline is readily seen in the spectrum given the similar ratios of other constituents. Overall the SEM analysis is in agreement with the standard ash compositions for the fly ash. Fly ash fusibilities similarly reflected their coals fusibilities (Table 4-6). There was no desirable difference in fly ash contents between samples from the same coal.

Mass mean particle diameter (MMD) was determined by laser diffraction analyses (Table 4-5). The washed coal yielded a MMD of 7u while the baseline yielded 5u MMD for combustion temperature of 1427°C (2600°F). The larger MMD for the washed coal are partially attributed to higher carbon content found with coal cleaning.

In summary, combustion of the coals was good for all test firing rates. Ignition and flame stability was good. Carbon conversions were 99.8 for the Lakhra washed coal and 99.9% for the baseline coal, based on the ash tracer method. Mass median diameter increased somewhat with coal cleaning.



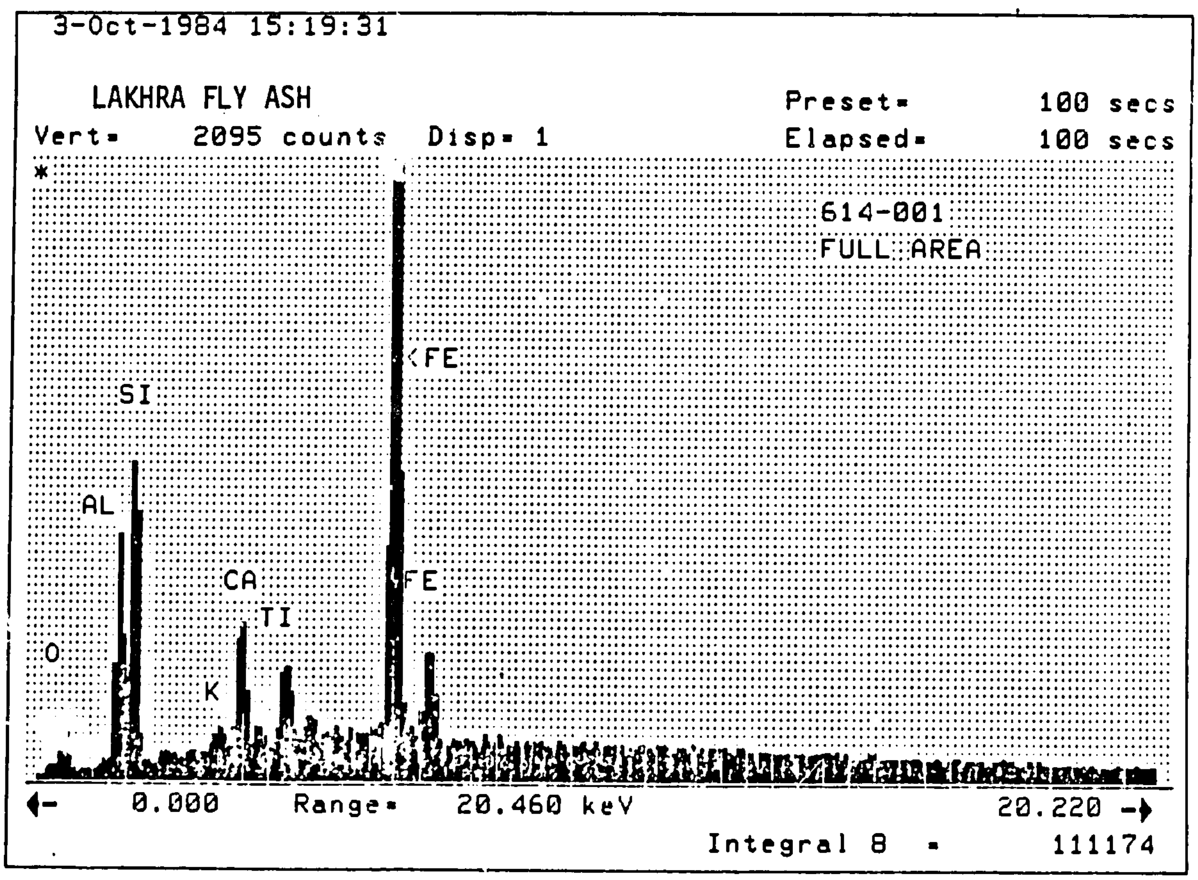


FIGURE 4-3 SCANNING ELECTRON MICROSCOPY ANALYTICAL SPECTRUM

TABLE 4-6
LAKHRA WASHED COAL FLY ASH ANALYSIS

	WASHED	BASELINE
Ash Content, (WT. %)	98.8	99.4
Carbon, (WT. %)	0.6	0.1
Ash Fusibility, (°F)		
IT	2110	2020
ST	2230	2340
HT	2280	2530
FT	2460	2640
Ash Composition, (WT. %)		
SiO_2	41.9	45.7
Al_2O_3	28.0	30.2
Fe_2O_3	16.8	15.8
CaO	5.2	3.3
MgO	2.4	1.5
Na_2O	1.4	0.9
K_2O	0.6	0.6
TiO_2	1.1	1.7
SO_3	1.0	1.1
TOTAL	98.4	101.0
MMD (microns)	7.3	5.0
Carbon Conversion	99.8	99.9

Ash Slagging Characteristics for Lakhra Washed Coal

Test results indicate that the Lakhra Washed coal has a severe ash slagging potential. The classification of slagging potential was based upon the following criteria for the Fireside Performance Test Facility as follows:

Critical Firing Rate KW (10^6BTU/hr)	Critical Flame Temperature °C (°F)	Potential
1170 (4.0)	>1680(>3050)	Low
1050 - 1170 (3.6-4.0)	1590 - 1680 (2900-3050)	Moderate
940 - 1050 (3.2-3.6)	1510 - 1590 (2750-2900)	High
<940 (<3.2)	<1510 (<2750)	Severe

Slagging characteristics of the washed Lakhra coal were similar to the baseline fuel, having lower bottom ash buildup rate due to the lower ash content.

The waterwall deposit characteristics of the washed fuel was highly dependent on furnace conditions. The maximum conditions which yield cleanable waterwall deposits were determined by varying the furnace flame temperature between test runs at a constant thermal loading equal to 856 KW (2.92×10^6Btu/hr). The maximum or "critical" conditions for deposits to be effectively cleaned by sootblowing were at flame temperature of 1427 - 1444°C (2600 - 2630°F). Critical conditions for the washed and baseline coals are within 30°F reflecting similar performance. Furnace deposits for the baseline coal were cleanable at flame temperatures up to 1427°C (2600°F) above this temperature deposits were uncontrollable. The similarity in critical temperatures indicates a potential for similarity in firing unit design. A detailed comparison of waterwall deposit characteristics for Lakhra washed coal are provided in Table 4-7 and illustrated by on-line waterwall deposit photographs shown in Figure 4-4 to 4-7.

TABLE 4-7
LAKHRA WASHED COAL/FPTF
WATERWALL ASH SLAGGING CHARACTERISTICS

TEST NO.	Q ($x10^6$ Btu/hr)	PANEL ELEVATION	AVE. PEAK TEMP. (°F)	W W PANEL COVERAGE %	DEPOSIT THICKNESS (INCH)	DEPOSIT STATE	CLEANABILITY
1	2.92	B	2550	100	1/8 - 1/4	Highly Sintered	Excellent
		C	2630	100	1/4 - 1/2	Highly Sintered, Molten Droplets	Good
2	2.92	B	2630	100	1/4 - 1/2	Highly Sintered, Molten Overlay	Good
		C	2710	100	1/2	Molten	Poor
3	2.92	B	2610	100	1/8 - 1/4	Highly Sintered, Molten Droplets	Good
		C	2670	100	1/8 - 1/4	Highly Sintered, Molten Overlay	Good
4	2.92	B	2560	100	1/4 - 1/2	Highly Sintered, Molten Overlay	Good
		C	2670	100	1/8 - 1/4	Molten	Poor
5	2.92	B	2570	100	1/2	Highly Sintered	Excellent
		C	2650	100	1/2 - 3/4	Highly Sintered, Molten Overlay	Marginal
6	2.92	B	2520	100	1/4 - 1/2	Highly Sintered	--
		C	2610	100	1/4 - 1/2	Highly Sintered	--

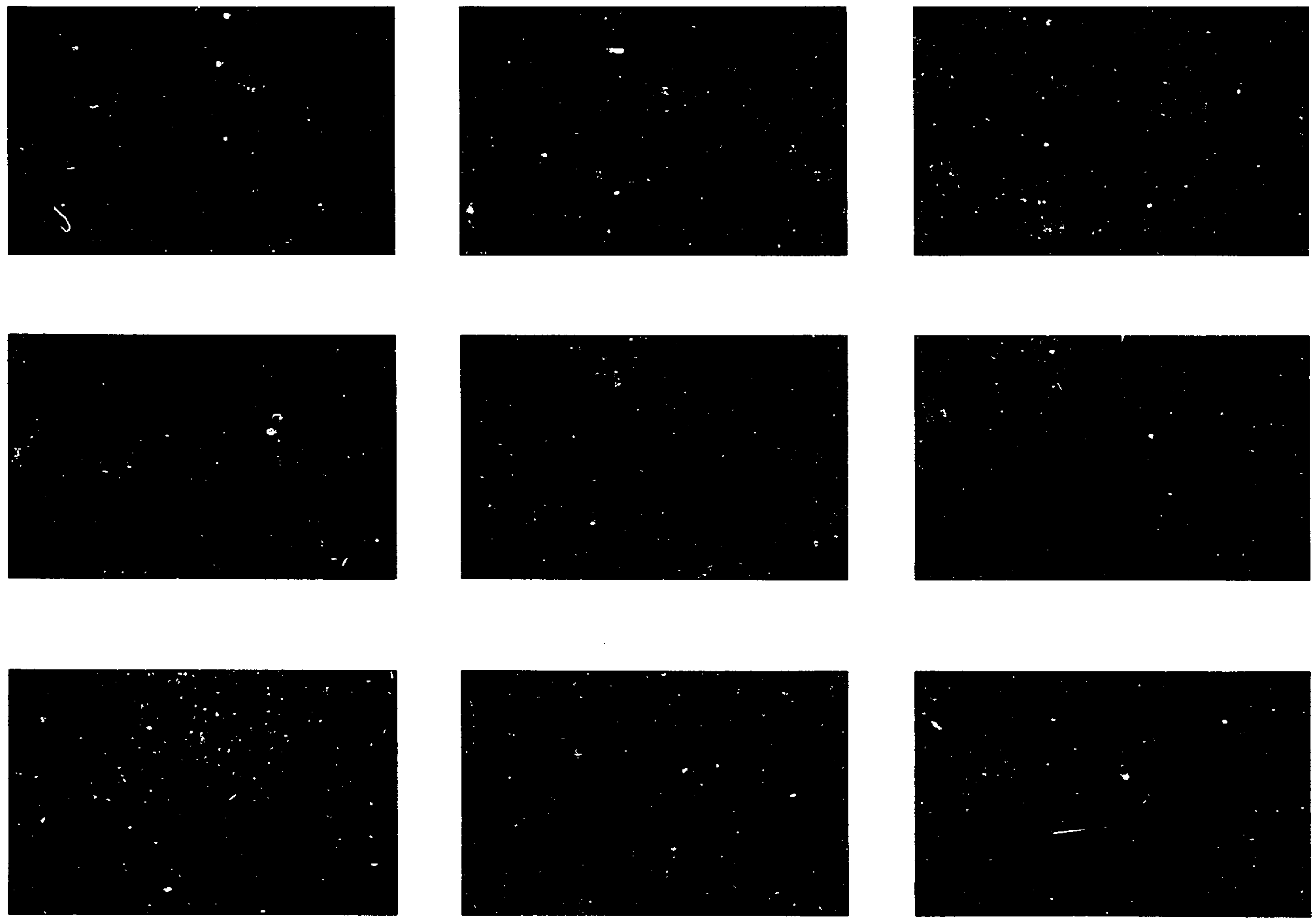
LAKHRA WASHED COAL TESTING
IN SITU WATERWALL PANEL B DEPOSITS

AFTER 4 HOURS | AFTER 12 HOURS | AFTER SOOTBLOWING

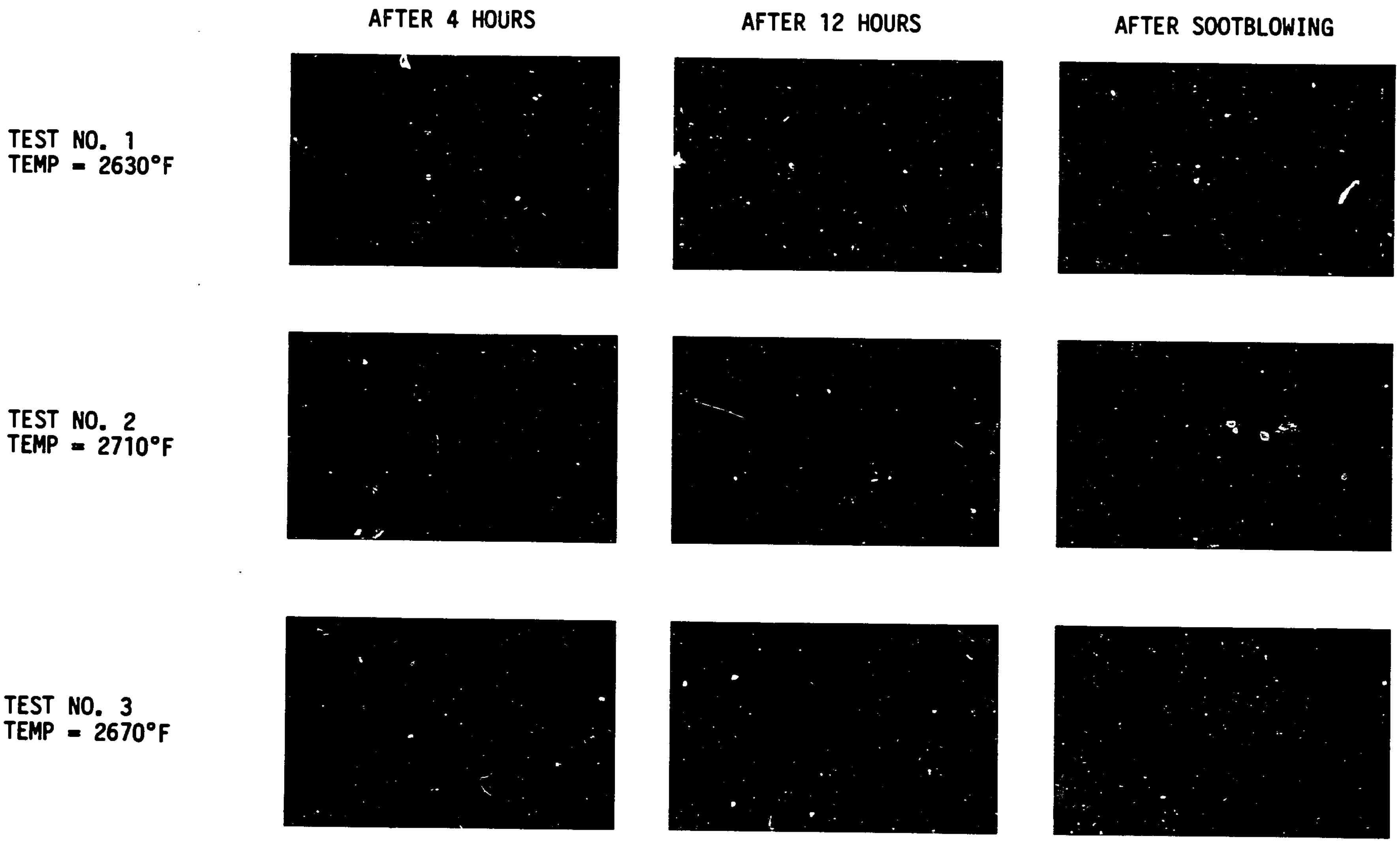
TEST NO. 1
TEMP = 2550°F

TEST NO. 2
TEMP = 2630°F

TEST NO. 3
TEMP = 2610°F



LAKHRA WASHED COAL TESTING
IN SITU WATERWALL PANEL C DEPOSITS



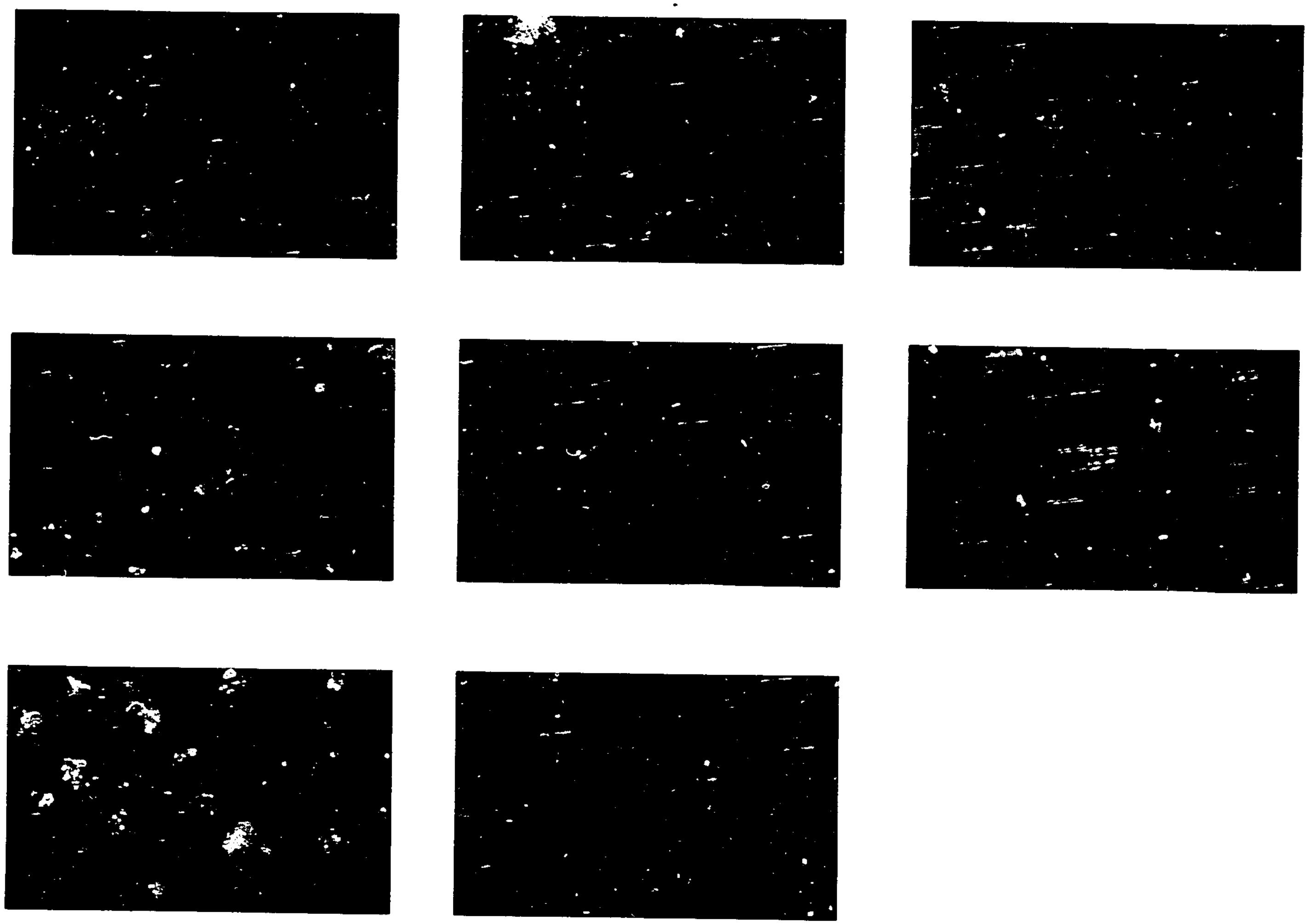
LAKHRA WASHED COAL TESTING
IN SITU WATERWALL PANEL B DEPOSITS

AFTER 4 HOURS | AFTER 12 HOURS | AFTER SOOTBLOWING

TEST NO. 4
TEMP = 2560°F

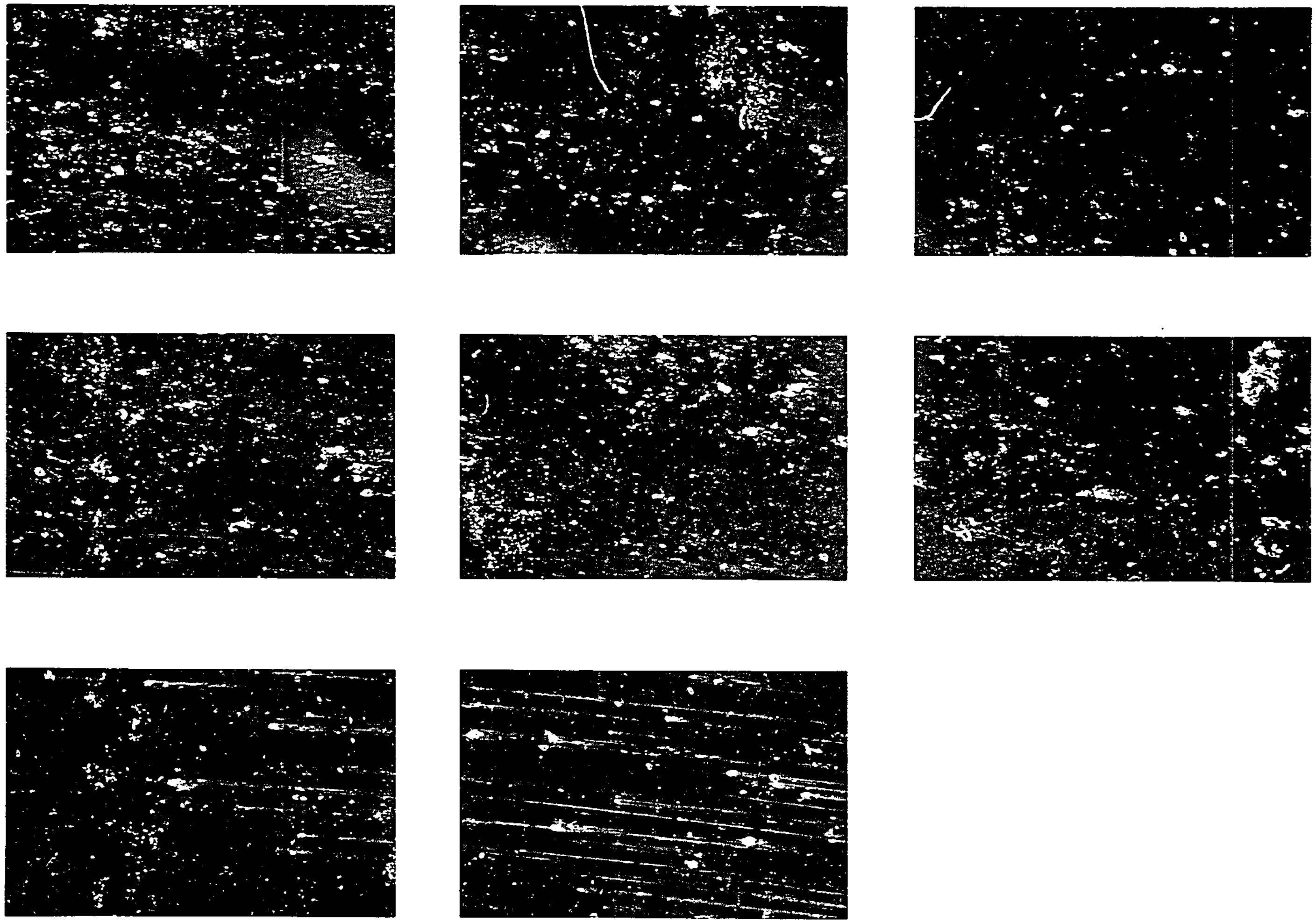
TEST NO. 5
TEMP = 2570°F

TEST NO. 6
TEMP = 2520°F



LAKHRA WASHED COAL TESTING
IN SITU WATERWALL PANEL C DEPOSITS

AFTER 4 HOURS | AFTER 12 HOURS | AFTER SOOTBLOWING



TEST NO. 4
TEMP = 2670°F

TEST NO. 5
TEMP = 2650°F

TEST NO. 6
TEMP = 2610°F

Cleanability and Physical Properties of Waterwall Deposits. Physical properties of waterwall deposits were highly dependent on flame temperature. During the washed coal tests the "critical" temperature for controlling lower furnace ash deposits was 1427 to 1444°C (2600 to 2630°F). At this temperature range, deposits were highly sintered with molten droplets, .3 to 1.3 cm (1/8 to 1/2 inches) thick with 100% coverage and exhibited good cleanability. Deposits at 1427°C (2600°F) were entirely removable while at 1444°C (2630°F) 10% of the panel was not removable. Above 1466°C (2670°F), waterwall panel deposits were molten 0.6 to 1.3 cm (1/4 to 1/2) inches thick covering 100% of the panel. These deposits were not entirely removable, 50% remained on the panel. Hence, it had poor cleanability. Deposits below 1410°C (2570°F) were highly sintered, 0.3 to 1.3 cm (1/8 to 1/2 inches) thick with 100% panel coverage. These deposits were easily removable and exhibited excellent cleanability. The critical flame temperature waterwall photos are in Figure 4-4 Test No. 3 (1432°C, 2610°F) and Figure 4-5 Test No. 1 (1444°C, 2630°F).

Deposits were assessed during each test at two furnace elevations (Panels B and C). Panel C was located in the higher temperature zone approximately 0.9 m (3 ft.) above the burner, and Panel B was approximately 1.4 m, (4.5 ft.) above the burner. Photos of both panels at each test point before and after sootblowing are shown in Figures 4-4 through 4-7.

Similar deposit physical characteristics were found for the baseline coal at comparable temperatures. Furnace deposits for the baseline coal were cleanable at flame temperatures up to 1427°C (2600°F). Above this temperature, deposits were not removable. At 1427°C (2600°F), deposits were highly sintered with a molten outer layer, 1.3 cm (1/2 inch) thick and exhibited good cleanability. Above this temperature, deposits were molten and exhibited poor cleanability.

The maximum or "critical" conditions for the Lakhra washed waterwall deposits to be effectively cleaned by sootblowing were at flame

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temperatures of 1427-1444°C (2600 - 2630°F) for the washed coal. The baseline coal similarly exhibited 1427°C (2600°F) as the limiting temperature for removable deposits. The washed coal exhibited similar physical characteristics at comparable baseline flame temperatures.

Waterwall Heat Flux Data. Heat flux results, consistent with visual observations, indicate greater heat flux recovery/cleanability with sintered outer and/or inner deposits than with molten deposits. Low temperature tests generally exhibited a lower heat flux due to the insulating nature of sintered deposits and lower flame temperatures. High temperature tests which produced a more fluid deposit resulted in higher final heat fluxes. The differences in deposit physical properties is illustrated by the rate of decline and final heat flux measurement. Final heat fluxes for the washed coal at 1410, 1444 and 1488°C are 31.5, 48.9 and 62.1 kW/m^2 (2570, 2630 and 2710°F are 10.0, 15.5, and $19.7x10^3$ Btu/hr $ft.^2$) with increasing percentage of molten deposit. See Figure 4-8.

Waterwall heat flux data provides information on the thermal resistance of deposit accumulation. This reflects the influence of physical state, deposit thickness and composition, panel coverage, temperature and heat input has on the waterwall panel heat flux. Waterwall panel heat absorption data from each test are presented in Table 4-8 and Appendix K.

A comparison of waterwall heat flux, immediately before and after sootblowing provides a quantitative indication of sootblower effectiveness (i.e., cleanability). The heat flux for the Lakhra washed coal at the "critical" flame temperature range recovered from 46 kW/m^2 (14.5 x 10^3 Btu/hr - $ft.^2$) before sootblowing to 217 kW/m^2 ($68.8x10^3$ Btu/hr - $ft.^2$) after sootblowing at 1432°C (2610°F) indicating complete deposit removal. At 1444°C (2630°F), the heat flux recovered from 49 kW/m^2 ($15.5x10^3$ Btu/hr-$ft.^3$) to 192 kW/m^2 ($60.7x10^3$ Btu/hr-$ft.^3$) indicating almost complete deposit removal, approximately 10% remained on the panel. The heat flux

FIGURE 4-8 LAKHRA WASHED COAL EVALUATION : AVERAGE P.F.T 2570-2710 DEG.F
HEAT FLUX THROUGH WW PANELS C AND B

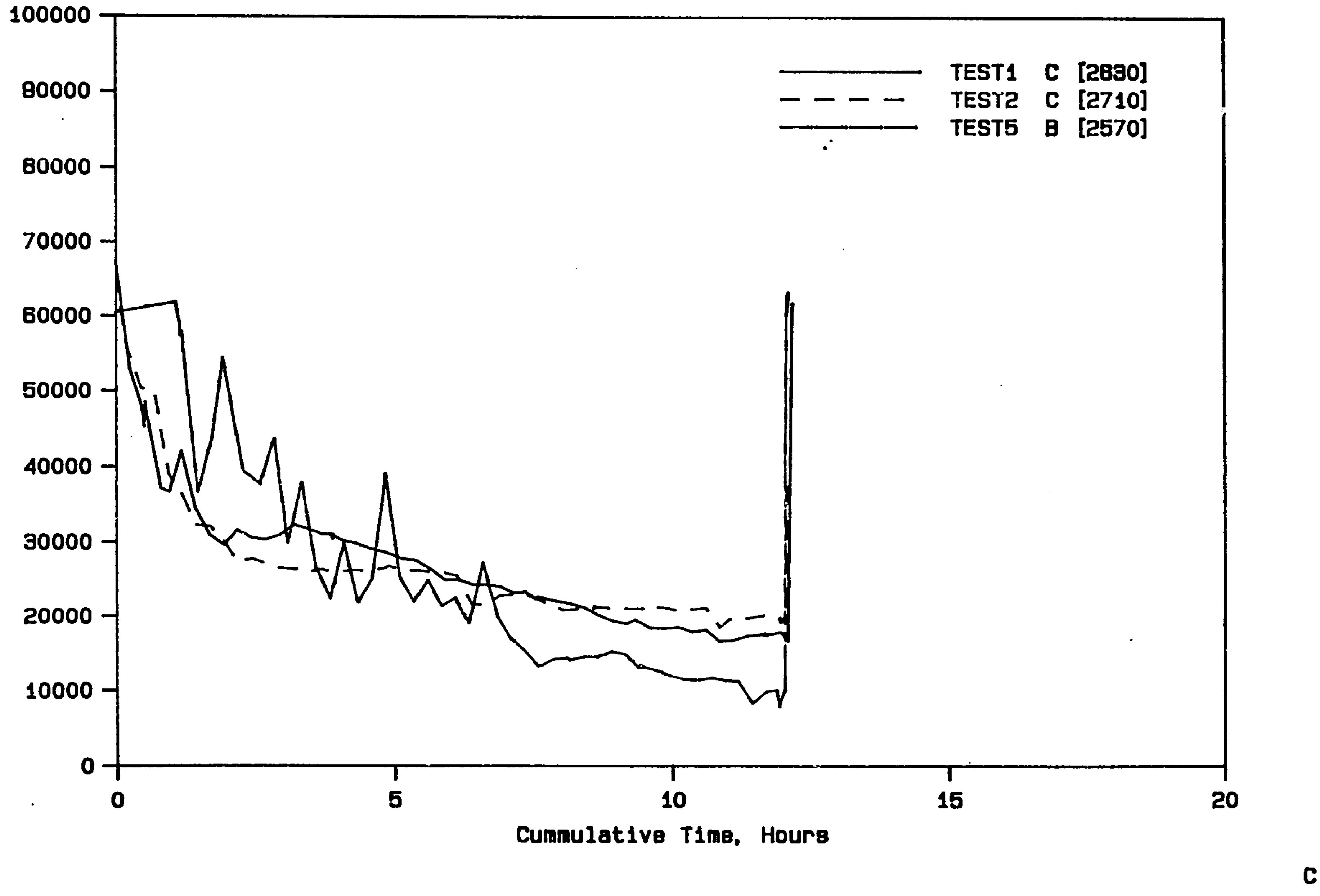


TABLE 4-8

LAKHRA WASHED COAL CHARACTERIZATION

FPTF SLAGGING RESULTS

TEST NO.	Q 10^6 BTU/HR	FLAME TEMPERATURE (°F)		CLEAN PANEL HEAT FLUX NO^3 (BTY/HR FT^2)		HEAT FLUX BEFORE SOOTBLOWING (10^3 BTU/HR-FT^2)		HEAT FLUX AFTER SOOTBLOWING (10^3 BTU/HR-FT^2)		% RECOVERY	
		B	C	B	C	B	C	B	C	B	C
1	2.92	2550	2630	59.3	67.2	12.7	17.5	69.8	60.7	1.00	0.90
2	2.92	2630	2710	68.3	65.6	15.5	19.7	60.9	36.9	0.89	0.56
3	2.92	2610	2670	56.9	69.5	14.5	23.7	68.8	71.6	1.00	1.00
4	2.92	2560	2670	58.1	69.5	19.8	20.6	55.7	18.1	0.96	0.26
5	2.92	2570	2650	60.4	69.8	10.0	11.1	63.2	41.5	1.00	0.59
6	2.92	2520	2610	61.8	47.1	11.7	18.8	--	--	--	--

recoveries, (Q/A after sootblowing/Q/A clean) were 1.0 and 0.90 respectively. These data are consistent with the visual observations showing complete cleanability of the panel at 1422°C (2610°F) and substantial cleanability at 1444°C (2630°F). See Figure 4-9.

The washed coal exhibited similar heat flux properties to those of the baseline coal at similar temperatures. At 1432°C (2610°F), the baseline heat flux recovered from 59 kW/m^2 ($18.7x10^3$ $Btu/hr\text{-}ft^2$) before sootblowing to 181 kW/m^2 ($57.3x10^3$ $Btu/hr\text{-}ft^2$) after sootblowing. The heat flux recovery at this temperature was 88%. This is comparable to the recovery for the washed coal at 1444°C (2630°F), note that at 1432°C (2610°F) the washed coal exhibits 100% recovery. See Figure 4-10.

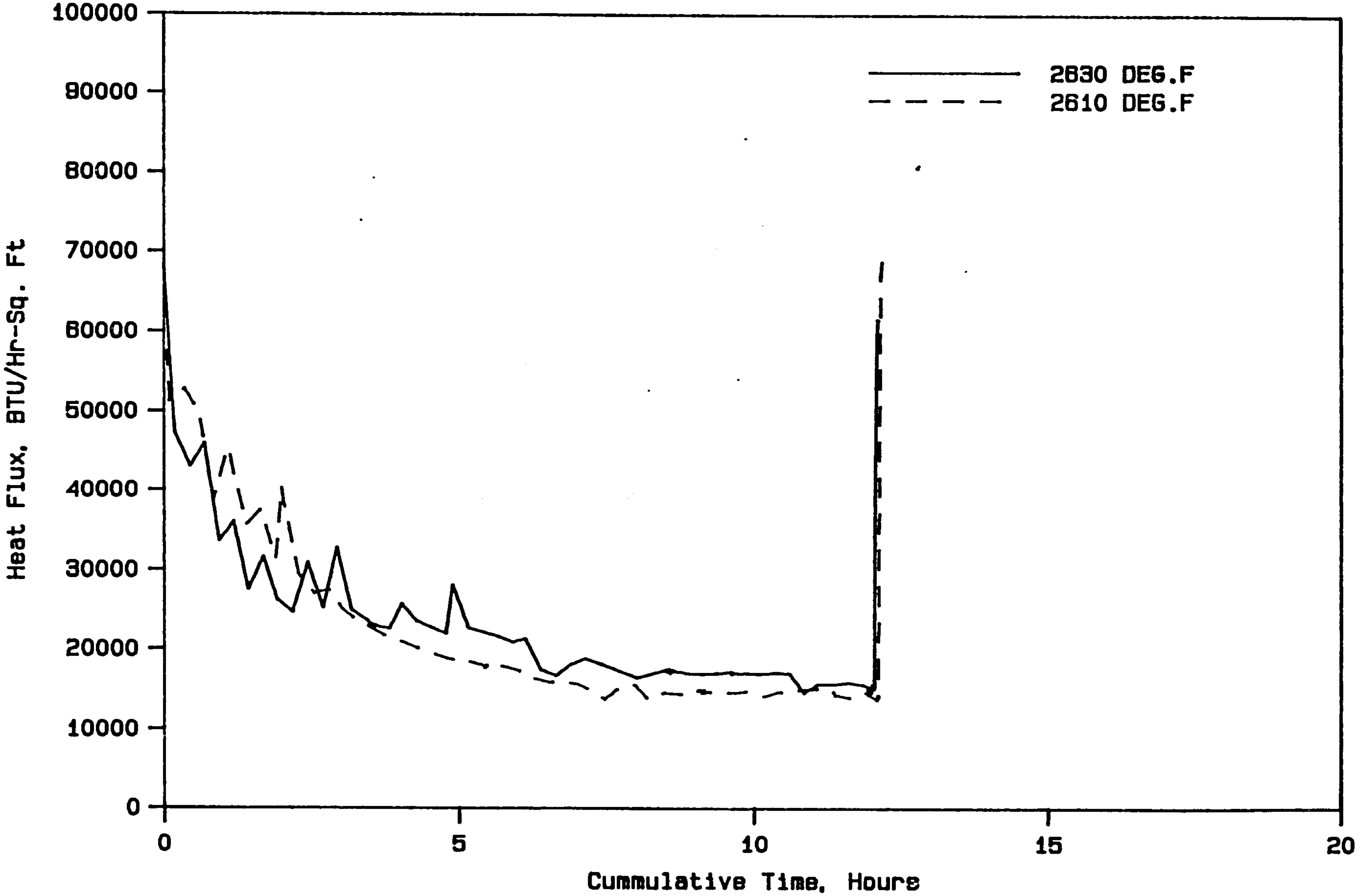
Complete (100%) panel coverage during the washed coal test firing occured within 5 to 6 hours. This accumulation rate was exhibited over the flame temperature range tested 1382 to 1488°C (2520 to 2710°F). The baseline coal exhibited even more rapid deposit buildup varying from 5 to 6 hours. The difference in buildup rates is most likely due to the higher ash content in the baseline coal.

The chemical characteristics of all in-situ waterwall deposits were very similar to the washed pulverized coal. All deposits showed an increase in iron and alumina content and decrease in calcium content. Iron enrichment is typical of high slagging coals. The initial deposit samples from Test No. 6 show an added enrichment of iron and sulfur content with a decrease in silica content. Ash fusibility temperatures were fairly uniform throughout testing. See Tables 4-9 and 4-10 for ash fusion and composition data.

In summary, the physical waterwall deposits were highly dependent on flame temperature. Critical conditions for the washed coal were flame temperatures of 1427 - 1444°C (2600 - 2630°F) and for the baseline were 1427°C, (2600°F). The critical conditions for the two Lakhra coals are close and showed similar performance characteristics indicating severe

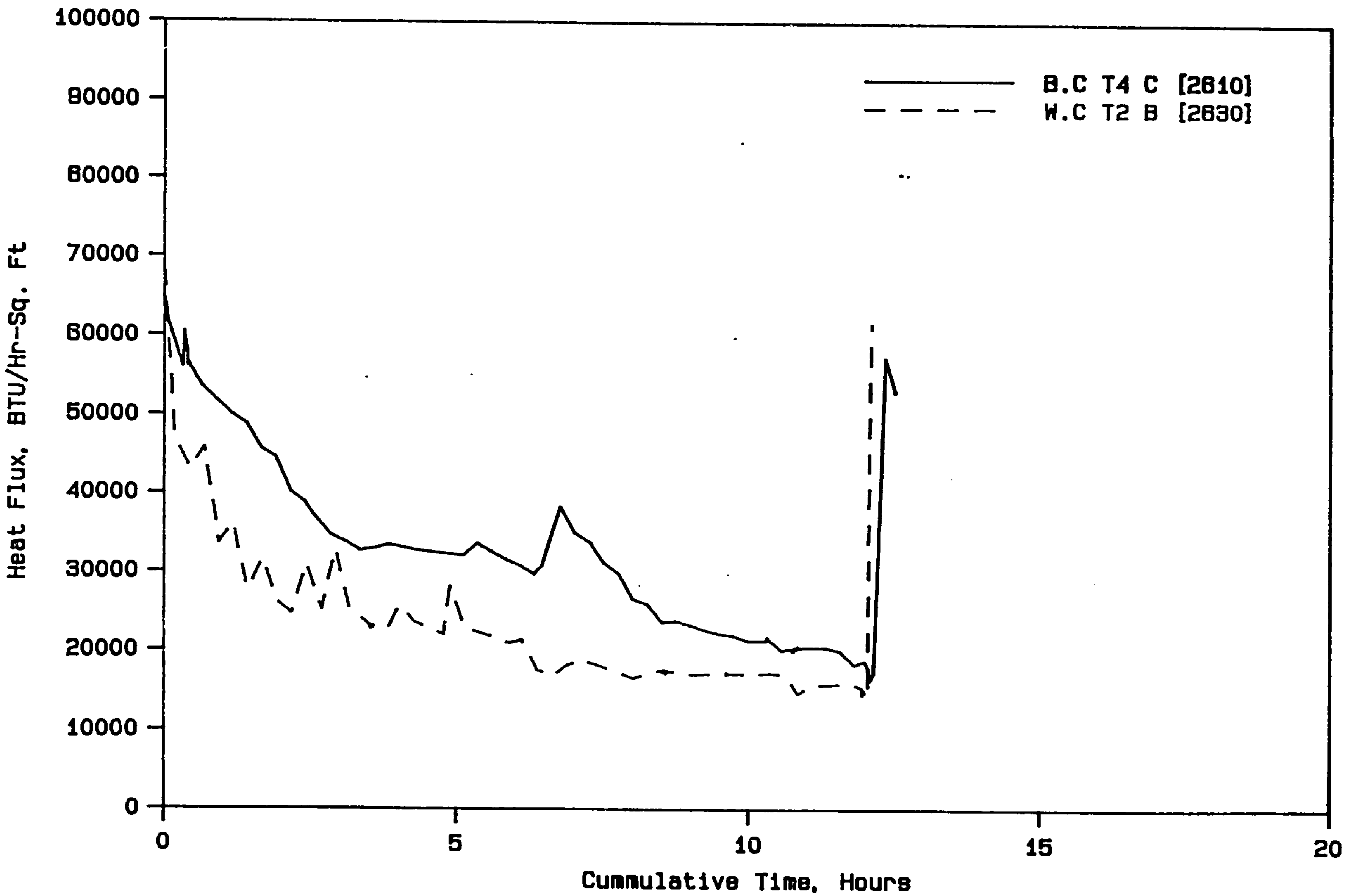
FIGURE 4-9 LAKHRA WASHED COAL EVALUATION : AVERAGE P.F.T 2810-2830 DEG.F FIG.7-10

HEAT FLUX THROUGH W W PANEL B



B

FIGURE 4-10 LAKHRA COAL EVALUATION : BASELINE COAL [B.C]-WASHED COAL [W.C]
HEATFLUX THROUGH WW PANELS C & B : AVERAGE P.F.T 2810-2830 DEG.F



C

TABLE 4-9
WATERWALL DEPOSIT ANALYSIS FOR PANEL B IN-SITU
LAKHRA WASHED COAL FPTF TESTING

	TEST NO. 1 T_f = 2550	TEST NO. 2 T_f = 2630	TEST NO. 3 T_f = 2610	TEST NO. 4 T_f = 2560	TEST NO. 5 T_f = 2570
ASH FUSIBILITY, (°F)					
I.T.	2130	2120	2100	2120	2020
S.T.	2210	2200	2220	2190	2140
H.T.	2270	2260	2280	2260	2250
F.T.	2480	2410	2460	2340	2400
ASH COMPOSITION, (WT %)					
SiO_2	41.7	39.9	42.2	42.2	40.6
Al_2O_3	26.9	25.1	27.5	26.6	24.5
Fe_2O_3	21.8	25.0	24.0	23.1	25.3
CaO	4.4	3.8	4.1	4.3	3.9
MgO	1.7	1.5	1.5	1.5	1.6
Na_2O	1.1	1.1	1.0	1.0	0.9
K_2O	0.5	0.6	0.6	0.5	0.5
TiO_2	1.5	1.4	1.5	1.5	2.4
SO_3	0.1	<0.1	<0.1	<0.1	0.1
TOTAL	99.7	98.4	102.4	100.7	99.8

TABLE 4-10
WATERWALL DEPOSIT ANALYSIS AFTER SHUTDOWN
FOR LAKHRA WASHED COAL
TEST NO. 6

	PANEL B T_f = 2520		PANEL C T_f = 2610	
	INITIAL	OUTER	INITIAL	OUTER
ASH FUSIBILITY, (°F)				
I.T.	2030	2030	2010	2030
S.T.	2120	2080	2080	2110
H.T.	2200	2350	2310	2320
F.T.	2410	2420	2410	2400
ASH COMPOSITION, (WT %)				
SiO_2	35.8	41.3	33.9	39.9
Al_2O_3	23.3	24.5	24.9	23.7
Fe_2O_3	26.2	25.3	27.1	25.4
CaO	4.1	4.3	3.6	4.0
MgO	1.7	1.6	1.6	1.5
Na_2O	1.4	1.1	1.2	1.1
K_2O	0.6	0.6	0.6	0.6
TiO_2	1.3	1.4	1.4	1.5
SO_3	4.3	0.4	4.8	1.6
TOTAL	98.7	100.5	99.1	99.3

slagging potential. Deposit accumulation rates were slightly less with the washed coal. In the FPTF slagging can be controlled by reducing temperature below critical conditions, for a commercial scale unit it will correspond to a large unit design. Wall burners should be avoided because of their high turbulence and subsequent high local flame temperatures. A tangential firing system should provide lower flame temperatures do to its ability to spread out the flame and, hence, result in less slagging. The high rate of bottom ash buildup will require a large ash handling system.

Convection Pass Deposit Characteristics

The fouling potential of the Lakhra washed coal was moderate. Convection tube bonding strengths were less than 4 which is considered to be weakly bonded and cleanable. The physical state of deposits was lightly to moderately sintered over the range of gas temperatures tested, 1155 to 1238°C (2110 to 2260°F). Convection tube deposition was moderate to high throughout testing with an average sootblowing frequency of 5 to 6 hours. Convection pass deposition characteristics are listed in Table 4-11 and shown in Figure 4-11.

Cleanability and Deposit Bonding Strengths. Cleanability was evaluated by techniques such as bonding strength measurements and visual assessment after air lancing. The maximum bonding strength measurement (BSM) for the Lakhra washed coal tests was 3.2. Since a value of 15 is considered marginal for sootblowing the bonding strengths for the coal tested are low. Bonding strength measurements were performed on 2 to 3 inch deposits in each test. This result is similar to that for the baseline coal where deposit to tube bonding strengths were also low (less than 2).

Convection Tube Deposit Accumulation. The Lakhra washed coal yielded deposits 2 to 3 inches in length over the temperature range tested (See Figure 4-11). Convection deposit accumulation was moderate to high but bonding strengths were low. Deposits were, therefore, cleanable. During each test run a high deposition rate in the

TABLE 4-11
LAKHRA WASHED COAL CHARACTERIZATION
FPTF FOULING RESULTS

TEST COAL	AVE. PEAK FLAME TEMP. (°F)	AVG. GAS TEMP. DUCT I (°F)	DEPOSIT THICKNESS (INCH)	DEPOSIT PHYSICAL STATE	DEPOSIT BONDING STRENGTH(1)	SOOTBLOWING FREQUENCY (HR)	CLEANABILITY
ROM 1	2630	2190	2-3	Lightly to Mod Sintered	1.9	6	Excellent
2	2710	2260	2-3	Lightly to Mod Sintered	2.0	6	Excellent
3	2670	2220	2-3	Lightly to Mod Sintered	2.4	6	Excellent
4	2670	2240	2-3	Lightly to Mod Sintered	1.2	6	Excellent
5	2650	2210	2-3	Lightly to Mod Sintered	3.2	6	Excellent
6	2610	2110	2-3	Lightly to Mod Sintered	2.4	6	Excellent

(1) Deposits would build-up and slough-off providing inadequate thickness for bonding strength measurement on most tests.

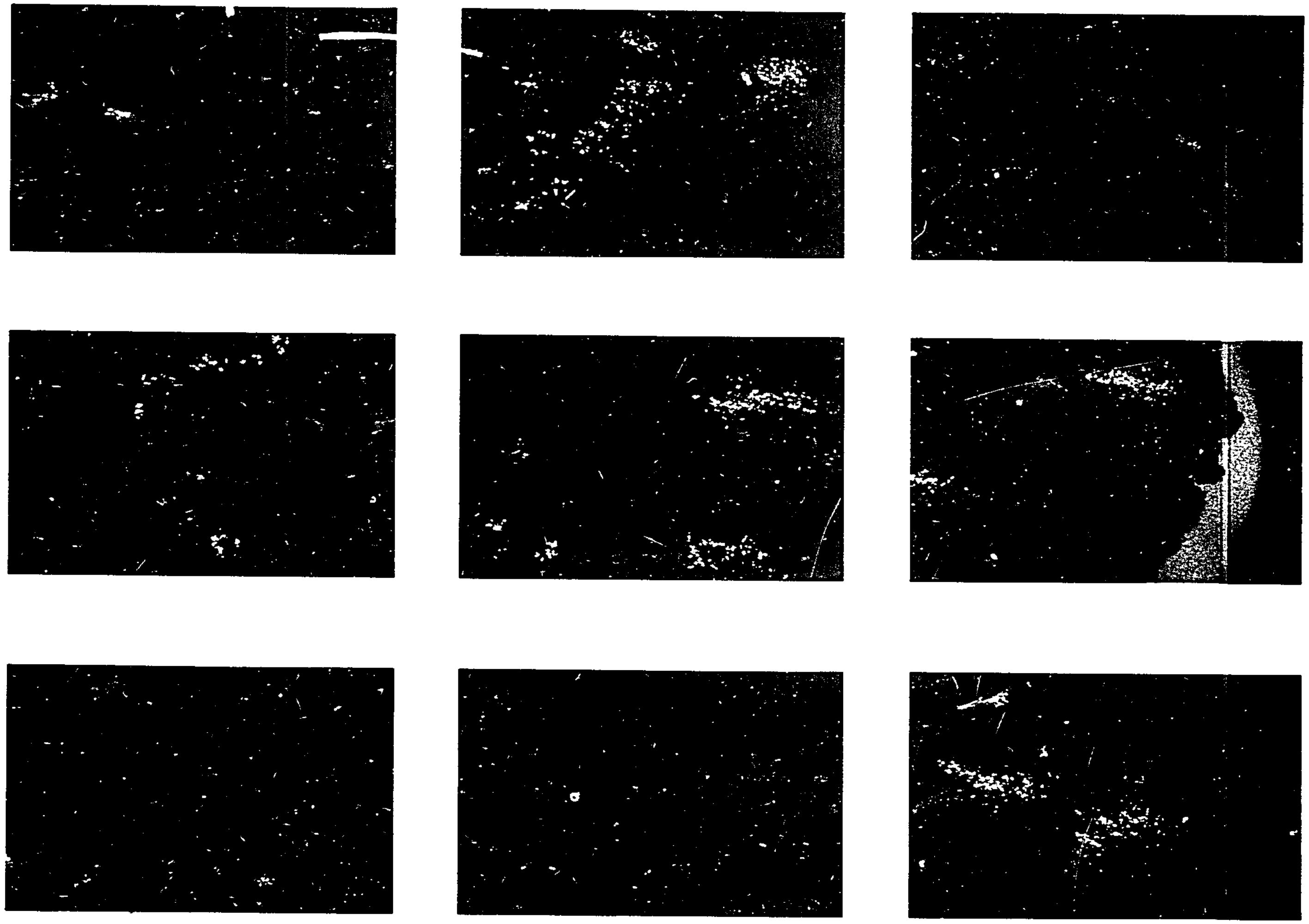
LAKHRA WASHED COAL TESTING
IN SITU SUPERHEATER DEPOSITS PROBE BANK I

AFTER 2 HOURS | AFTER 4 HOURS | AFTER 6 HOURS

T_g = 2260°F

T_g = 2190°F

T_g = 2110°F



transition section of the furnace was observed. The high rate is most likely due to the carryover from furnace slagging. The baseline coals deposit accumulation varied with gas temperature but was generally higher in comparison to the washed coal.

Sootblowing Frequency. Sootblowing requirements for the washed coal were moderate to high as convection tube banks required cleaning every 5 to 6 hours. Convection tube deposit cleanability was excellent. The ease of cleanability is consistent with the low bonding strength and lightly to moderately sintered deposits. The baseline coals sootblowing frequency and accumulation rate varied with gas temperature. Sootblowing was required 3 to 4 hours at 1282°C (2340°F), 5 to 6 hours at 1171°C (2140°F) and 6 to 8 hours at 1121°C (2050°F). Both washed and baseline coals exhibited moderate fouling potential based on deposit buildup, strength and cleanability.

Chemical Properties of Convection Pass Deposits. The ash fusibility and composition of the outer superheater tube deposits were very similar to those for the washed Lakhra coal. The ash composition of the leading probe banks inner deposits had greatly increased iron, sulfur, and calcium content with a significant decrease in silica and alumina. Values for probe banks A and C showed increases to 50.1% and 46.5% for iron content, 12.8% and 14.9% for calcium content, and 12.3% and 14.1% sulfur content. The effects of these values were seen in a significant reduction in ash fusion temperatures. Values ranged from 1160°C IDT. to 1227 °C FT. (2120°F IDT. to 2240°F FT.) in contrast to the 1188°C to 1227 °C (2170°F to 2490°F) range for the outer deposits. The effects of iron fluxing with the increased calcium content to lower fusion temperatures leads to the moderate to high deposit accumulation and the high buildup rate in the transition section. Tables 4-12 and 4-13 exhibit inner and outer convection section deposit analysis.

In summary, the Lakhra washed coal exhibited moderate fouling potential. Convection tube deposits were weakly bonded and readily cleanable with sootblowers. Deposit buildup rates were moderate to high in the 1155 to 1238°C (2110 to 2260°F) range.

TABLE 4-12
SUPERHEATER ASH DEPOSIT ANALYSIS FOR
LAKHRA WASHED COAL TESTING
TEST NO. 6

	BANK A				BANK II	
	PROBE A		PROBE B		PROBE C	
	INITIAL	OUTER	INITIAL	OUTER	INITIAL	OUTER
ASH FUSIBILITY, (°F)						
I.T.	2090	2130	2060	2140	2060	2120
S.T.	2120	2320	2170	2190	2130	2170
H.T.	2130	2390	2230	2220	2150	2190
F.T.	2140	2490	2420	2460	2240	2460
ASH COMPOSITION, (WT. %)						
SiO_2	13.2	42.9	37.0	41.3	12.7	43.4
Al_2O_3	8.8	27.1	24.1	27.5	8.2	27.1
Fe_2O_3	50.1	18.1	19.7	15.6	46.5	17.2
CaO	12.8	5.4	6.0	6.9	14.9	6.4
MgO	1.4	2.2	2.3	2.8	1.3	2.4
Na_2O	0.5	1.6	1.6	1.9	0.4	1.6
K_2O	0.2	0.7	0.6		0.2	0.5
TiO_2	0.6	1.4	1.3	1.4	0.6	1.4
SO_2	12.3	0.3	6.3	0.3	14.1	0.4
TOTAL	99.9	99.7	98.9	98.4	98.9	100.4

TABLE 4-13
SUPERHEATER ASH DEPOSIT ANALYSIS FOR
LAKHRA WASHED COAL TESTING
TEST NO. 6

	BANK II PROBE D OUTER	BANK III PROBE E INITIAL	BANK III PROBE E OUTER	BANK III PROBE F INITIAL	BANK IV PROBE G INITIAL	BANK IV PROBE H INITIAL
ASH FUSIBILITY, (°F)						
I.T.		2130	2050			2070
S.T.	I.S.	2470	2160	I.S.	I.S.	2150
H.T.		2700+	2240			2240
F.T.		2700+	2440			2420
ASH COMPOSITION, (WT. %)						
SiO_2		14.2	43.8	28.5	15.9	42.4
Al_2O_3		6.6	26.5	22.0	8.8	24.9
Fe_2O_3		67.0	18.2	22.9	71.8	19.2
CaO		5.5	7.3	7.0	2.5	6.0
MgO		0.7	2.4	2.0	0.8	2.2
Na_2O		0.7	1.9	1.6	0.6	1.7
K_2O		0.1	1.9	1.6	0.1	0.5
TiO_2		0.4	1.5	1.2	0.5	1.5
SO_2		6.5	0.9	7.0	I.S	4.5
TOTAL		101.7	102.9	102.5	101.0	102.9

I.S. = Insufficient Sample

Commercial design should include low furnace outlet temperatures to reduce convection pass deposit accumulation. The higher temperature convective passes should have wide tube spacing to deal with the relatively high accumulation rates in these regions. These rates for the washed coal will be somewhat less than those for the baseline.

Fly Ash Erosion

The percentage of ash in the coal had a significant influence on fly ash erosion. Coal beneficiation had little influence on the composition of the fly ash, erosion values increased somewhat linearly with increasing ash content. The corresponding ash contents for the washed and baseline coals were 19.1 and 36.4%.

To provide comparative wear values from each test, erosion results were normalized for ash loading, time and velocity. Comparison of normalized wear values for firing rate, time and velocity are summarized Table 4-14. Typical operating values used for normalization were 18.3 m/sec (60 ft/sec) velocity in the superheater section, 10,000 unit operating hrs, and a 856 kW (3.5×10^6 Btu/hr) FPTF firing rate.

To evaluate the difference in ash loading, the fuels were compared using an erosion value normalized for firing rate. The erosion rates were found to be proportional to ash loading. Erosion values for the washed and baseline coals increased from 0.55 to 0.91 mm (21.6 to 35.8 mils) per 10,000 hrs. with increasing ash loading 6.9 to 10.1 g/s (55 to 80 lb/hr). These values, particularly the baseline, are relatively high and will dictate relatively low, yet commercially acceptable convection pass velocities.

Erosion values normalized for lb. ash input show that the coals have similar ash erosiveness. This effect is attributed to the similar coal ash compositions and resulting similarity in fly ash composition. Results indicate that .454 kg (one lb) of ash for the washed coal and baseline coal erodes 1.6×10^{-3} μ and 1.4×10^{-3} μ of tube surface respectively.

TABLE 4-14
LAKHRA WASHED AND BASELINE COAL/FPTF
FLY ASH EROSION CHARACTERISTICS

	Washed	Baseline
Firing Rate	2.92 MBtu/hr.	1.99 to 2.32 MBtu/hr.
Feed Rate	319.4 lb/hr.	258 to 300 lb/hr.
Test Duration	36 hr.	30.75 hr.
Ash Loading	56 lb/hr.	73 to 85 lb/hr.
Gas Velocity	168 ft/s	117 to 134 ft/s
Mass Median Particle Diameter	7μ	5μ
Quartz in Ash	2.5%	2.4%
Maximum Penetration	19.6μ	10.2μ
Normalized Penetrations:		
μ Per Lb. Ash(1)	1.6×10^{-3}	1.4×10^{-3}
Mils Per 10,000 Hr.(2)	21.6	35.8

(1) Erosion normalized per unit mass of ash at 60 ft/sec - assuming 50/50 fly ash/bottom ash split.

(2) Erosion normalized for firing rate at 60 ft/sec and typical unit operating time 10,000 hrs.

To summarize, a significant reduction in fly ash erosiveness was observed with reduced ash loading. Erosion was found to increase lineary with ash loading. Ash content, quartz content and MMD effects being similar showed little influence on tube wear and were overshadowed by the large difference in ash loading between the fuels.

Commercial units firing the baseline coal will require relatively low convection pass velocities. Units firing the washed coal can accommodate somewhat higher velocities than the baseline coal or will have longer tube life than the baseline if fired at similar velocities.

Flue Gas and Particulate Emissions

The effect of coal beneficiation on sulfur emissions was significant due to the reduction of sulfur in the coal. NO_x emissions were not affected by fuel changes but the firing conditions did affect NO_x values. The flue gas emissions measured during each test are summarized in Table 4-15. Fly ash resistivity of this coal is higher than the baseline and can result in lower electrostatic precipitator collection efficiency. It should be noted that these results can only provide information on a relative basis and should not be used as direct comparison between the test fuels or extrapolated to field behavior.

Reduction in the SO_x emissions for the Lakhra washed coal is a direct result of coal cleaning. Sulfur emissions for the washed coal were reduced by 30% with coal beneficiation. The theoretical SO_x for washed and baseline fuels are 4730 and 6960 ppm on a 3% O_2 dry basis, respectively. Measured SO_2 concentrations were very similar (within 13%) of the theoretical sulfur measurements and average values (3% O_2 dry basis) for washed and baseline tests were 4283 and 6000 ppm respectively. See Figure 4-12.

Commercially, the higher sulfur of the Lakhra coals makes SO_x emissions a significant consideration. The U.S. federal limit on SO_x emissions is 0.52 kg SO_2/GJ (1.2 lb $SO_2/10^6$Btu) fired or 90% removal. The theoretical values for these coals are 12 and 26 kg SO_2/GJ 29 and 60 lbs. $SO_2/10^6$Btu washed and baseline, respectively. Beneficiation may offer an alternative way to obtain a modest amount of sulfur reduction.

The fly ash resistivity measured in the FPTF in-situ was 7.6×10^{11} ohm-cm at 153°C (308°F) flue gas temperature with 3 ppm SO_3. This value is higher than the optimum 5×10^9 to 5×10^{10} ohm-cm for electrostatic precipitators operating under normal gas temperature of 149 to 177°C (300 to 350°F). Bench-scale resistivity testing on fly ash isokinetically collected measured 3.0×10^9 ohm-cm at 6% H_2O and 3 ppm SO_3 at 153°C (308°F). See Figures 4-13, 4-14, and 4-15. This laboratory resistivity measurement is slightly lower

TABLE 4-15

LAKHRA WASHED COAL

FLUE GAS EMISSION DURING TEST FIRING IN THE FPTF

HEAT INPUT = 2.92 MBtu/Hr.

TEST NO.	AVERAGE PEAK TEMP. (°F)	CO[1] (PPM)	NO_x[1] (PPM)	SO_2[1][2] (PPM)
1	2630	<1	1374	4337
2	2710	<1	1365	4113
3	2670	<1	1361	4222
4	2670	<1	1180	4342
5	2650	<1	1025	4203
6	2610	<1	1062	4482

(1) 3% O_2 dry basis

Based on SO_2 thermoelectron analyzer (see Appe[illegible] C)

FIGURE 4-12

SO_2 EMISSIONS DURING LAKHRA WASHED TESTING

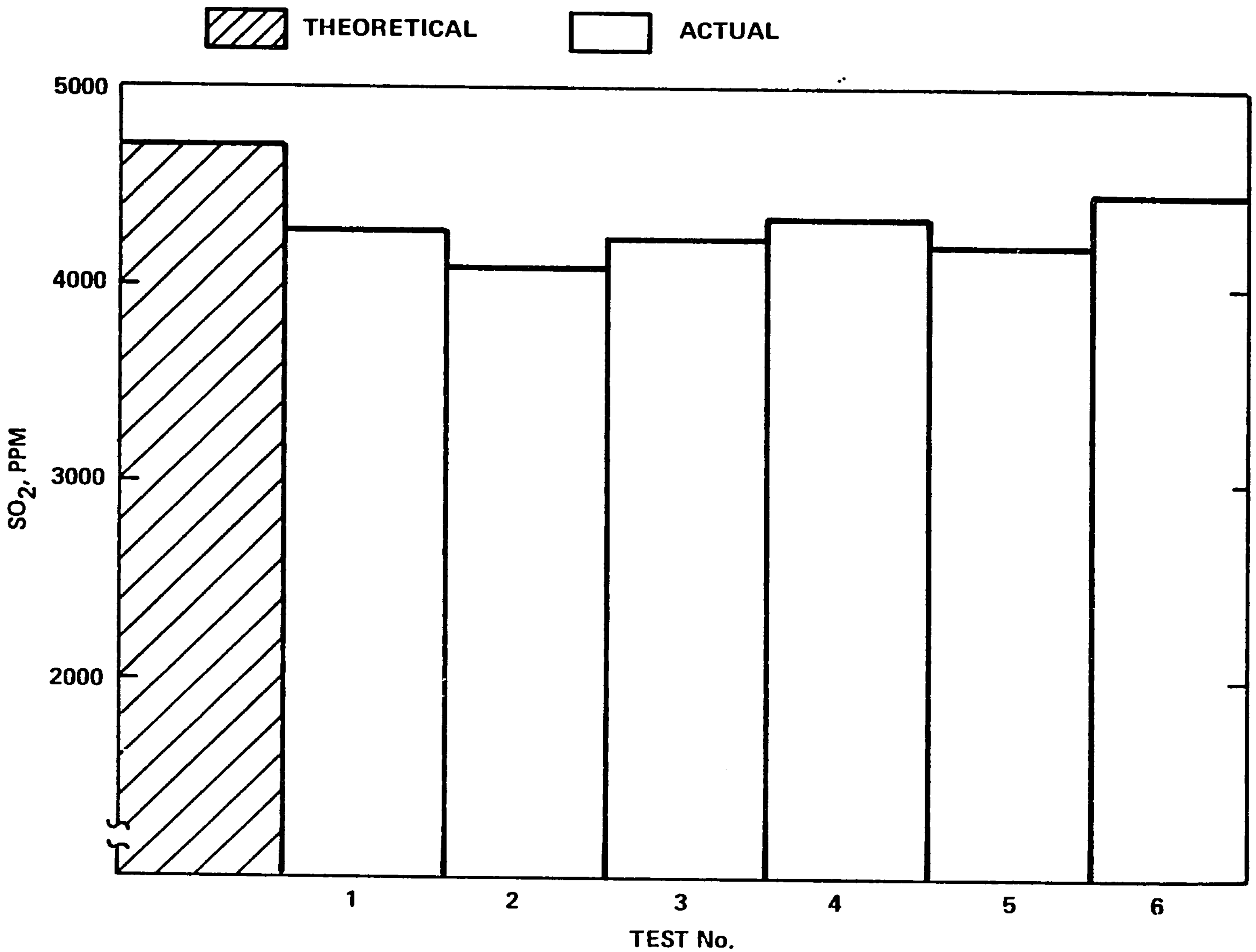


FIGURE 4-13 IN-SITU FLYASH RESISTIVITY

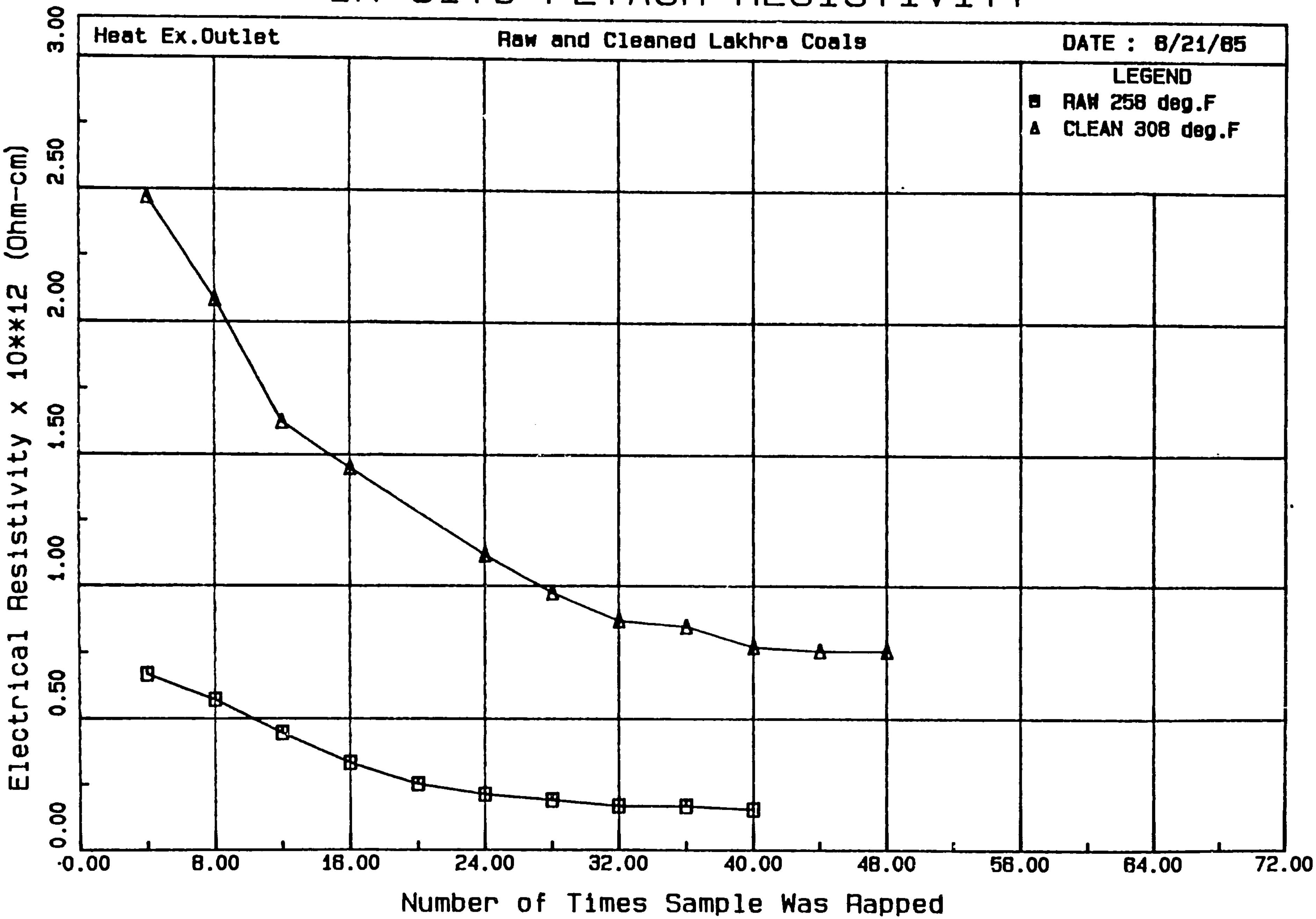


FIGURE 4-14 LABORATORY ASH RESISTIVITY AT 6% H_2O

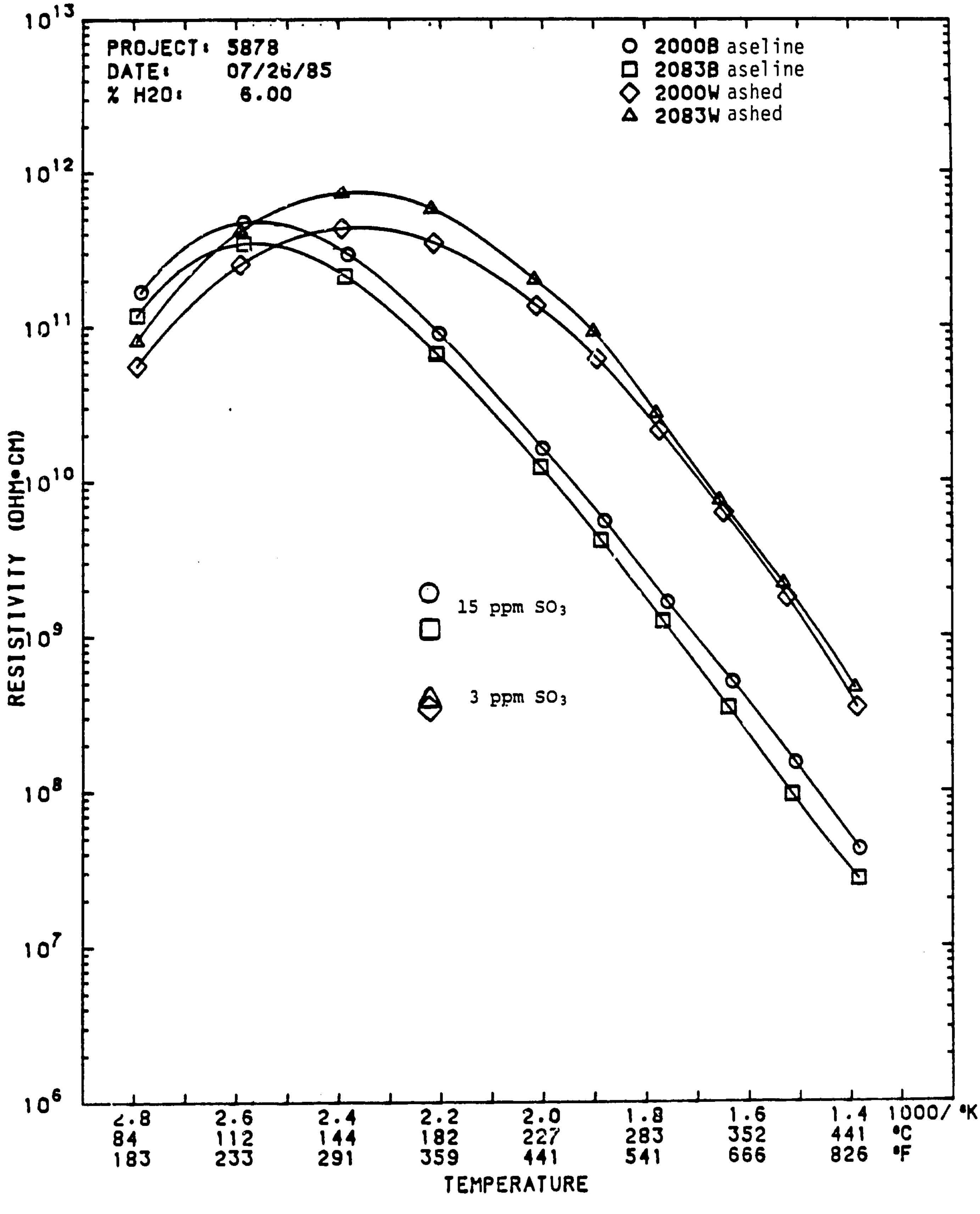
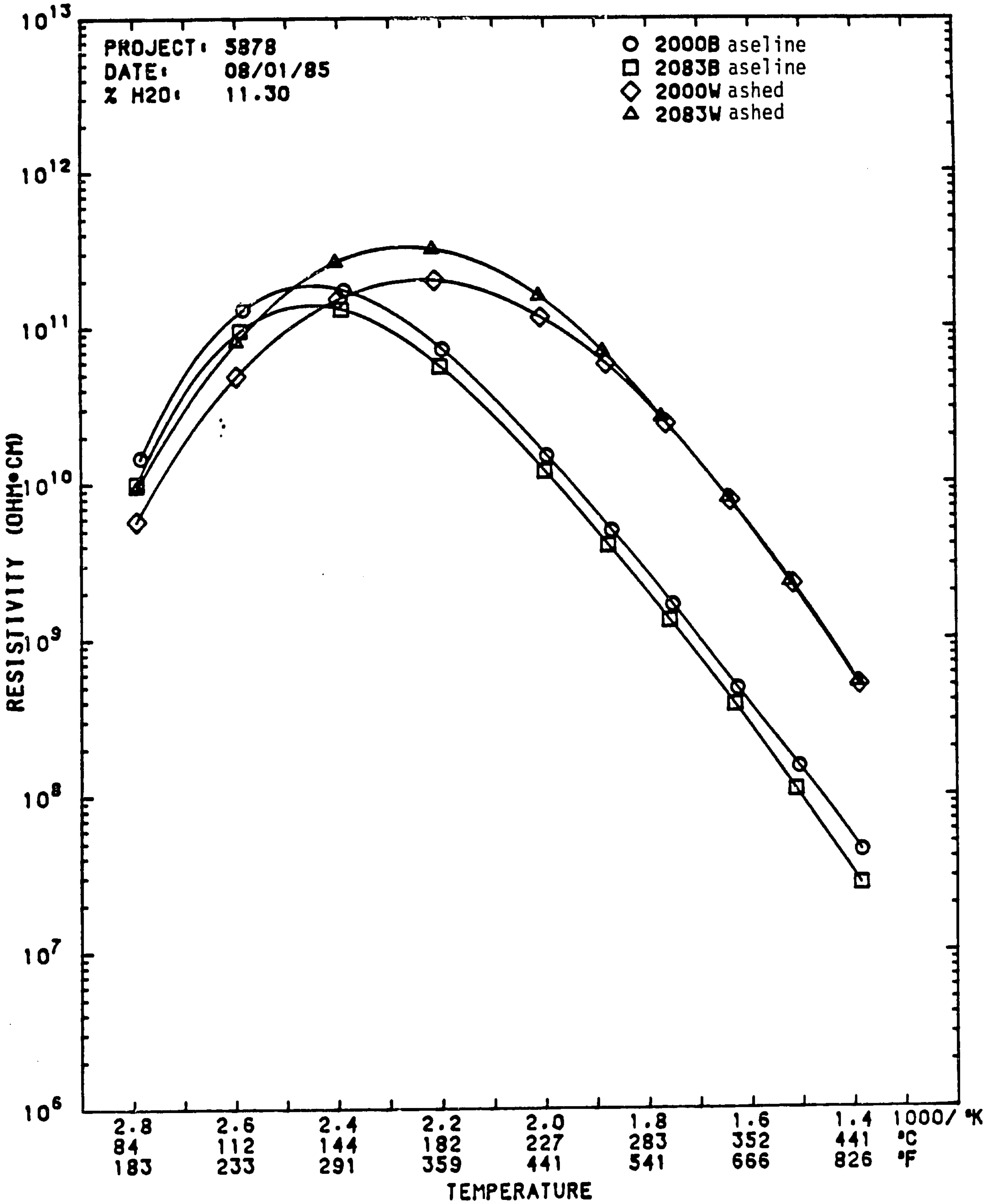


FIGURE 4-15 LABORATORY ASH RESISTIVITY AT 11.3% H_2O



than the theoretical value of 6.9 x 10^{10} ohm-cm at 153°C (308°F), 5% H_2O and 3ppm SO_3 concentrations. Values at comparable moisture levels were generally lower for the baseline coal. The washed coal produced a higher resistance fly ash than the baseline. This indicates that fly ash collection efficiency would be slightly lower with the washed coal. However, the washed coal due to lower ash content may be able to achieve similar particulate emissions at a lower collection efficiency.

The NO_x measurement is highly sensitive to the firing system. During these pulverized coal tests, a single swirl-type burner was used in conjunction with tangentially injected combustion air. All of the tests were conducted with 70% of the combustion air through the burner and 30% through tangentially placed rings 3 feet above the burner. Typically this firing arrangement generates considerably higher NO_x concentrations than commercial systems.

The NO_x results at 3% O_2 dry basis from the Lakhra washed coal tests ranged from 1025 to 1375 ppm. The variation in NO_x values is attributed to the high rate of burner deposition and slagging potential of the coal. Commercially, the NO_x should not be a limiting factor given fuel nitrogen contents and the range of values measured during this test.

In summary, coal cleaning caused 30% reduction in SO_2 emissions. Fly ash resistivity of this coal was higher than that of the baseline and will result in lower electrostatic precipitator collection efficiency. NO_x emissions were influenced by firing conditions. From a commercial standpoint, the cost effectiveness of coal cleaning for sulfur removal should be investigated.

APPENDIX F

FPTF OPERATING CONDITIONS DURING THE LAKHRA WASHED COAL TESTS

TABLE F-1

FURNACE OPERATING CONDITIONS DURING THE LAKHRA WASHED COAL TESTS

COMBUSTION DATA	TEST NO. 1	TEST NO. 2	TEST NO. 3
FUEL FEED RATE LB/HR	.319E+03	.319E+03	.319E+03
FUEL HHV BTU/HR	.925E+04	.925E+04	.925E+04
TOTAL HEAT INPUT BTU/HR	.329E+07	.329E+07	.307E+07
PRIMARY AIR FLOW LB/HR	.282E+03	.275E+03	.269E+03
PRIMARY AIR TEMP. F	.818E+02	.843E+02	.826E+02
SECONDARY AIR FLOW LB/HR	.252E+04	.249E+04	.253E+04
SECONDARY AIR TEMP. F	.600E+03	.600E+03	.271E+03
OXYGEN (IN FLUE GAS)	.502E-01	.494E-01	.558E-01
FURNACE PRESSURE (INCHES H_2O)	-.350E+00	-.350E+00	-.350E+00
LOWER FURNACE TEMP. F	.263E+04	.271E+04	.267E+04
LOWER FURNACE RESIDENCE TIME SEC.	.147E+01	.146E+01	.145E+01
NHI/PA BTU/HR-FT**2	.396E+06	.396E+06	.396E+06
VOL. HEAT RELEASE RATE BTU/HR-FT**3	.289E+05	.289E+05	.289E+05
WATERWALL TEST PANELS			
PANEL A SURFACE TEMP. F	.549E+03	.577E+03	.538E+03
PANEL B SURFACE TEMP. F	.703E+03	.729E+03	.693E+03
PANEL C SURFACE TEMP. F	.608E+03	.584E+03	.636E+03
PANEL E SURFACE TEMP. F	.708E+03	.477E+03	.467E+03
SUPERHEATER PROBES			
DUCT 1 GAS TEMPERATURE F	.219E+04	.226E+04	.222E+04
DUCT 2 GAS TEMPERATURE F	.200E+04	.217E+04	.203E+04
DUCT 3 GAS TEMPERATURE F	.194E+04	.196E+04	.192E+04
DUCT 4 GAS TEMPERATURE F	.164E+04	.180E+04	.172E+04
DUCT 1 GAS VELOCITY FT/SEC	.577E+02	.585E+02	.582E+02
DUCT 2 GAS VELOCITY FT/SEC	.535E+02	.565E+02	.540E+02
DUCT 3 GAS VELOCITY FT/SEC	.522E+02	.521E+02	.516E+02
DUCT 4 GAS VELOCITY FT/SEC	.458E+02	.485E+02	.472E+02
ASH			
INPUT LB/HR	.558E+02	.558E+02	.558E+02
DUST LOADING LB/HR	.341E+02	.341E+02	.341E+02

TABLE F-2

FURNACE OPERATING CONDITIONS DURING THE LAKHRA WASHED COAL TESTS

COMBUSTION DATA	TEST NO. 4	TEST NO. 5	TEST NO. 6
FUEL FEED RATE LB/HR	.319E+03	.319E+03	.319E+03
FUEL HHV BTU/HR	.925E+04	.925E+04	.925E+04
TOTAL HEAT INPUT BTU/HR	.328E+07	.316E+07	.313E+07
PRIMARY AIR FLOW LB/HR	.266E+03	.265E+03	.265E+03
PRIMARY AIR TEMP. F	.763E+02	.748E+02	.708E+02
SECONDARY AIR FLOW LB/HR	.255E+04	.252E+04	.252E+04
SECONDARY AIR TEMP. F	.580E+03	.387E+03	.340E+03
OXYGEN (IN FLUE GAS)	.434E-01	.490E-01	.490E-01
FURNACE PRESSURE (INCHES H_2O)	-.350E+00	-.350E+00	-.350E+00
LOWER FURNACE TEMP. F	.267E+04	.265E+04	.261E+04
LOWER FURNACE RESIDENCE TIME SEC.	.146E+01	.148E+01	.147E+01
NHI/PA BTU/HR-FT**2	.396E+06	.396E+06	.396E+06
VOL. HEAT RELEASE RATE BTU/HR-FT**3	.289E+05	.289E+05	.289E+05
WATERWALL TEST PANELS			
PANEL A SURFACE TEMP. F	.433E+03	.606E+03	.628E+03
PANEL B SURFACE TEMP. F	.656E+03	.684E+03	.698E+03
PANEL C SURFACE TEMP. F	.646E+03	.528E+03	.484E+03
PANEL E SURFACE TEMP. F	.583E+03	.516E+03	.496E+03
SUPERHEATER PROBES			
DUCT 1 GAS TEMPERATURE F	.224E+04	.221E+04	.211E+04
DUCT 2 GAS TEMPERATURE F	.217E+04	.215E+04	.203E+04
DUCT 3 GAS TEMPERATURE F	.200E+04	.203E+04	.192E+04
DUCT 4 GAS TEMPERATURE F	.177E+04	.179E+04	.172E+04
DUCT 1 GAS VELOCITY FT/SEC	.589E+02	.578E+02	.555E+02
DUCT 2 GAS VELOCITY FT/SEC	.575E+02	.565E+02	.537E+02
DUCT 3 GAS VELOCITY FT/SEC	.537E+02	.539E+02	.513E+02
DUCT 4 GAS VELOCITY FT/SEC	.487E+02	.486E+02	.470E+02
ASH			
INPUT LB/HR	.558E+02	.558E+02	.558E+02
DUST LOADING LB/HR	.341E+02	.341E+02	.341E+02

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APPENDIX G

FPTF FURNACE TEMPERATURE PROFILES DURING THE LAKHRA WASHED COAL TESTS

225

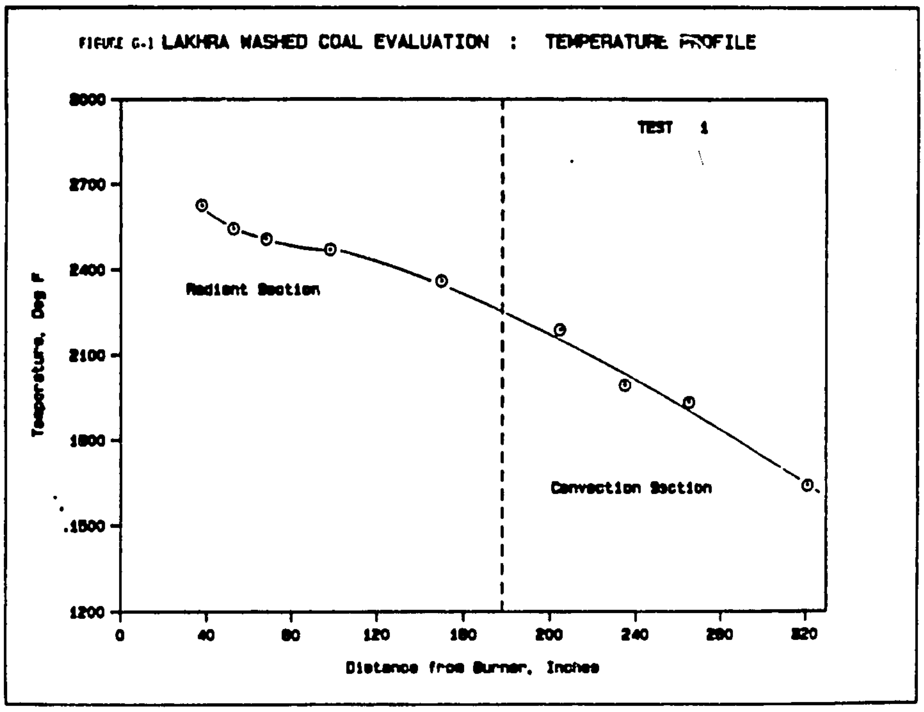


FIGURE G-1 LAKHRA WASHED COAL EVALUATION : TEMPERATURE PROFILE
TEST 1
Radiant Section
Convection Section
Temperature, Deg F
Distance from Burner, Inches
3000
2700
2400
2100
1800
1500
1200
0
40
80
120
160
200
240
280
320

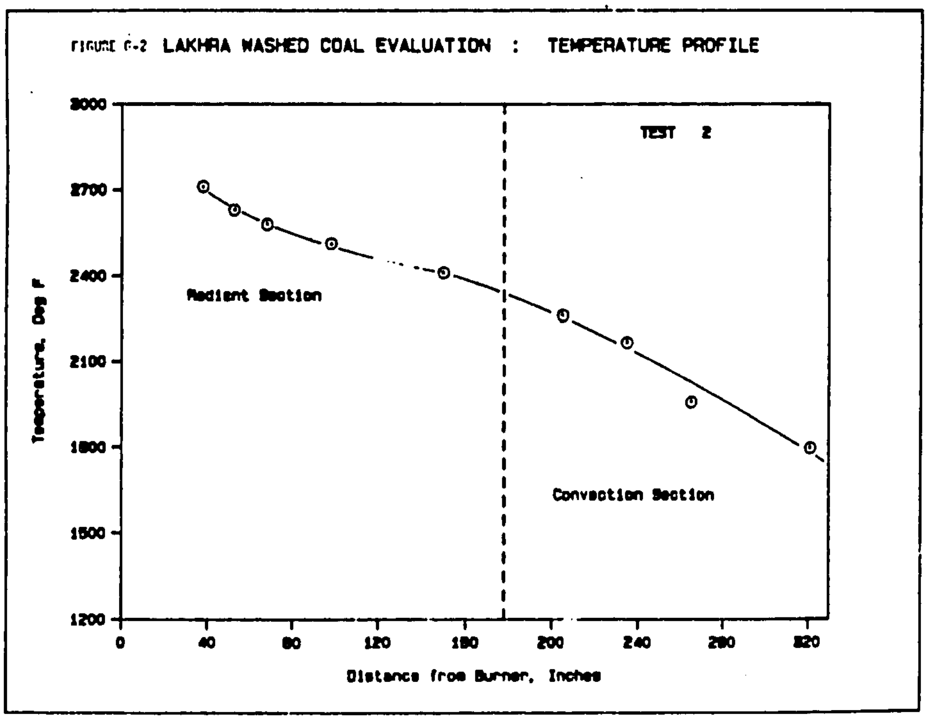


FIGURE G-2 LAKHRA WASHED COAL EVALUATION : TEMPERATURE PROFILE
TEST 2
Radiant Section
Convection Section
Temperature, Deg F
Distance from Burner, Inches
3000
2700
2400
2100
1800
1500
1200
0
40
80
120
160
200
240
280
320

FIGURE G-3 LAKHRA WASHED COAL EVALUATION : TEMPERATURE PROFILE

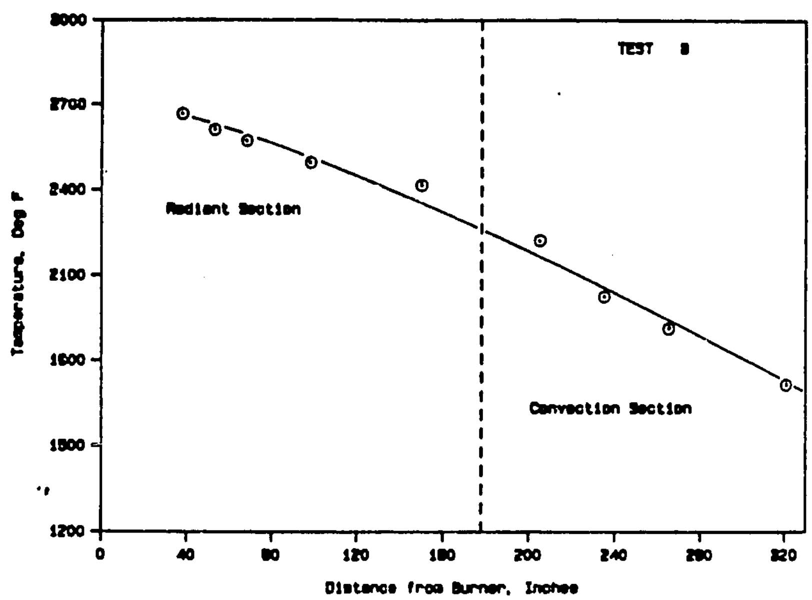


FIGURE G-4 LAKHRA WASHED COAL EVALUATION : TEMPERATURE PROFILE

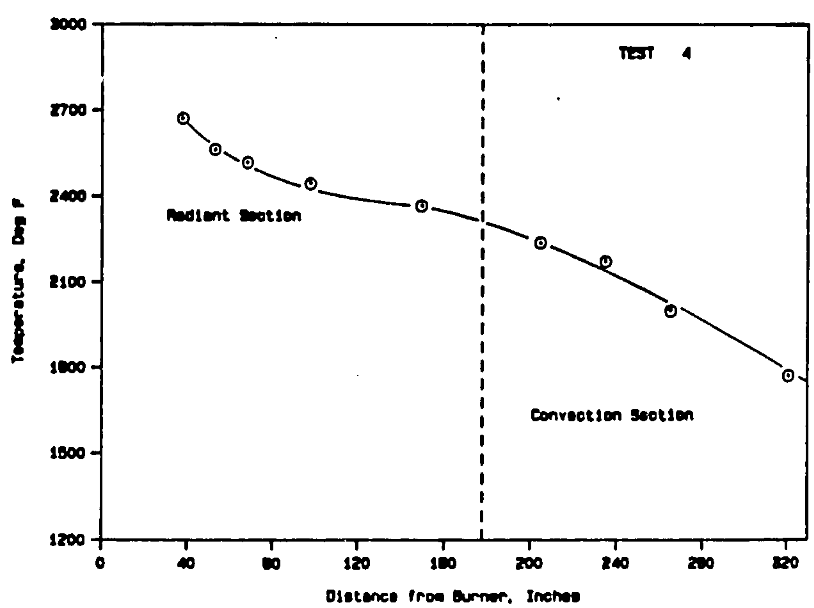


FIGURE G-5 LAKHRA WASHED COAL EVALUATION : TEMPERATURE PROFILE

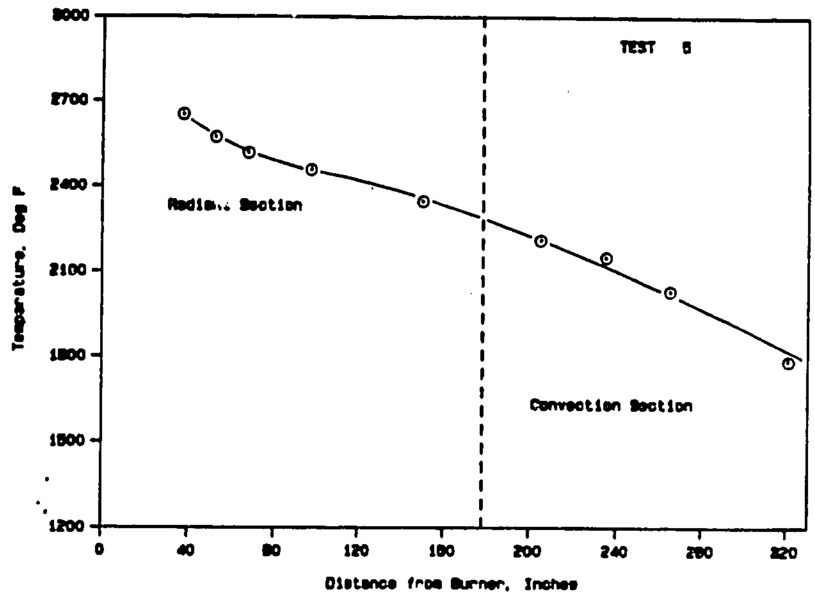
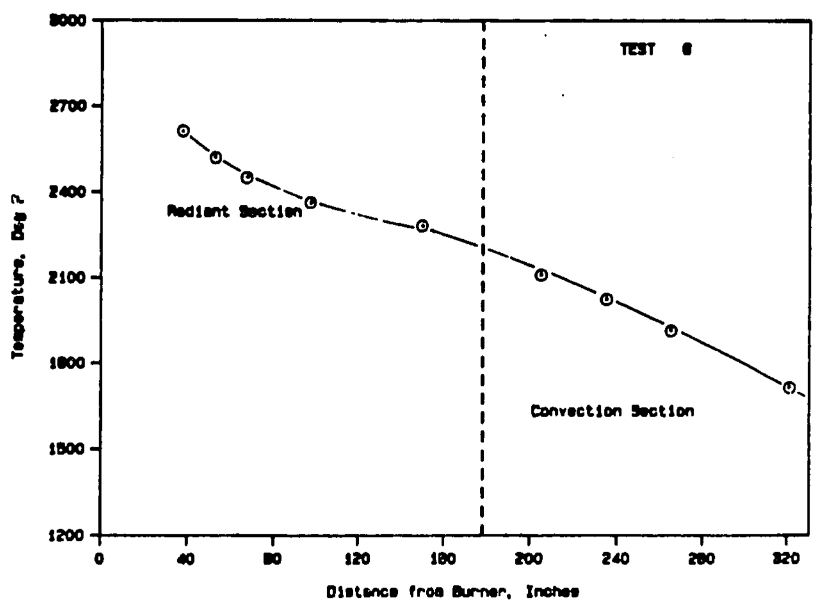


FIGURE G-6 LAKHRA WASHED COAL EVALUATION : TEMPERATURE PROFILE



APPENDIX H

FPTF FURNACE RESIDENCE TIMES FOR THE LAKHRA WASHED COAL TESTING

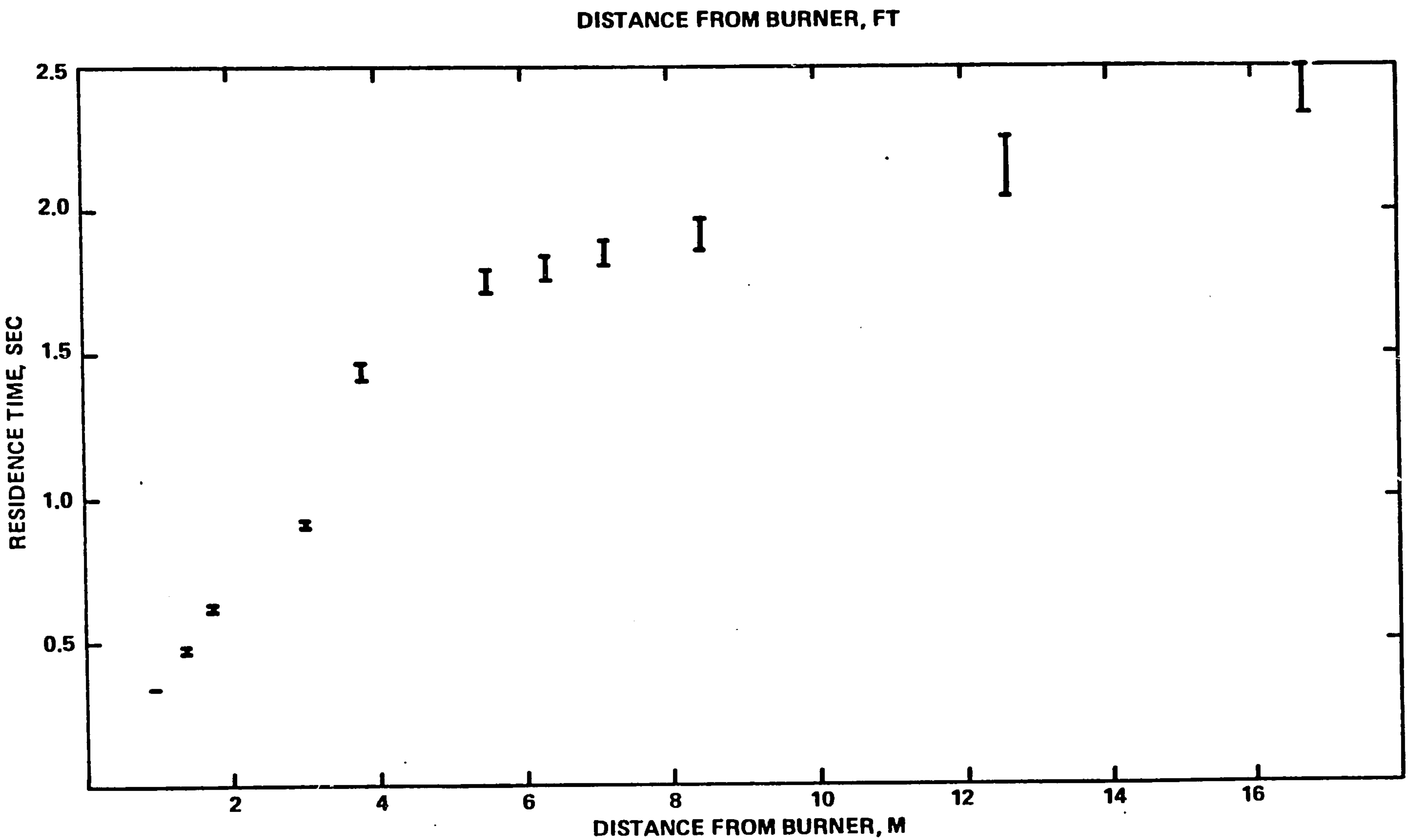


FIGURE II-1 RESIDENCE TIME vs DISTANCE FOR LAKHRA WASHED COAL EVALUATION

TABLE II-1

FPTF FURNACE RESIDENCE TIMES DURING THE LAKHRA WASHED COAL EVALUATION

DISTANCT ABOVE BURNER ft	m	port	RESIDENCE TIME (SEC) TEST NO. 1	TEST NO. 2	TEST NO. 3	TEST NO. 4	TEST NO. 5	TEST NO. 6
3.17	0.96	L1	.34	.34	.34	.34	.34	.34
4.42	1.35	L2	.48	.47	.48	.47	.48	.49
5.67	1.73	L3	.62	.61	.61	.61	.62	.63
8.17	2.49	L3.5	.90	.89	.89	.89	.90	.92
12.5	3.81	L4	1.42	1.41	1.41	1.42	1.43	1.47
18.0	5.49	D1	1.73	1.71	1.71	1.72	1.74	1.79
20.75	6.32	D2	1.78	1.76	1.76	1.77	1.79	1.84
23.25	7.09	D3	1.83	1.81	1.81	1.82	1.83	1.89
27.67	8.43	D4	1.92	1.90	1.86	1.92	1.87	1.97
41.33	12.60	DL	2.20	2.17	2.12	2.20	2.04	2.24
54.75	16.69	O_2 meter	2.48	2.46	2.41	2.43	2.33	2.52

APPENDIX I

FPTF FURNACE MASS AND ENERGY BALANCES DURING THE LAKHRA WASHED COAL TESTS

TABLE I-1

MASS AND ENERGY BALANCES DURING THE LAKHRA WASHED COAL TESTING

	TEST NO. 1		TEST NO. 2		TEST NO. 3	
METHOD 1-------						
FLUE GAS FLOW RATE LB/HR	.307E+04	.	.303E+04		.306E+04	
COMPOSITION IN MOLES/HR						
OXYGEN	.419E+01	4.01	.392E+01	3.80	.412E+01	3.96
CARBON DIOXIDE	.137E+02	13.08	.137E+02	13.24	.137E+02	13.12
WATER	.104E+02	9.91	.103E+02	10.01	.103E+02	9.94
SULFUR DIOXIDE	.379E+00	.36	.379E+00	.37	.379E+00	.36
NITROGEN	.760E+02	72.64	.749E+02	72.58	.756E+02	72.62
METHOD 1-------						
HEAT LOSS FROM REFRACTORY BTU/HR	.193E+06	5.86	.208E+06	6.28	.124E+06	4.02
HEAT LOSS FROM PANEL	.150E+06	4.56	.123E+06	3.76	.136E+06	4.42
HEAT LOSS FROM WATER COOLED FRAME	.306E+05	.93	.445E+05	1.35	.630E+05	2.05
HEAT LOSS FROM FLY ASH	.171E+05	.52	.176E+05	.53	.172E+05	.56
HEAT LOSS FROM FLUE GAS	.183E+07	55.66	.187E+07	56.96	.184E+07	59.90
HEAT LOSS FROM ROOF	.386E+05	1.17	.349E+05	1.06	.277E+05	.90
HEAT LOSS FROM PROCESS HEATER	.586E+05	1.78	.481E+05	1.46	.457E+05	1.49
HEAT LOSS FROM S.H. TRANSITION	.105E+06	3.19	.115E+06	3.49	.120E+06	3.92
HEAT LOSS FROM S.H. FRAME	.506E+06	1.64	.519E+05	1.58	.415E+05	1.35
HEAT LOSS FROM S.H. DUCT	.236E+06	7.17	.241E+06	7.33	.247E+06	8.04
HEAT LOSS FROM OBS. PORT	.449E+05	1.36	.517E+05	1.58	.448E+05	1.46
HEAT LOSS FROM BURNER	.104E+06	3.17	.924E+05	2.81	.535E+05	1.74
HEAT LOSS FROM FURNACE BOTTOM LEFT	.813E+05	2.47	.659E+05	2.01	.423E+05	1.37
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.616E+06	1.87	.553E+05	1.68	.394E+05	1.28
METHOD 2-------						
FLUE GAS FLOW RATE LB/HR	.328E+04	.	.325E+04		.338E+04	
COMPOSITION IN MOLES/HR						
OXYGEN	.557E+01	5.02	.548E+01	4.94	.643E+01	5.58
CARBON DIOXIDE	.137E+02	12.30	.137E+02	12.36	.137E+02	11.86
WATER	.108E+02	9.43	.106E+02	9.47	.106E+02	9.16
SULFUR DIOXIDE	.379E+00	.34	.379E+00	.34	.379E+00	.33
NITROGEN	.810E+02	72.92	.806E+02	72.89	.842E+02	73.07
METHOD 2-------						
HEAT LOSS FROM REFRACTORY BTU/HR	.193E+06	5.86	.208E+06	6.28	.124E+06	4.02
HEAT LOSS FROM PANEL	.150E+06	4.56	.123E+06	3.76	.136E+06	4.42
HEAT LOSS FROM WATER COOLED FRAME	.305E+05	.93	.445E+06	1.35	.630E+05	2.05
HEAT LOSS FROM FLY ASH	.171E+05	.52	.176E+05	.53	.172E+05	.56
HEAT LOSS FROM FLUE GAS	.195E+07	59.12	.200E+07	60.96	.203E+07	66.15
HEAT LOSS FROM ROOF	.385E+05	1.17	.349E+05	1.06	.277E+05	.90
HEAT LOSS FROM PROCESS HEATER	.585E+05	1.78	.481E+05	1.46	.457E+05	1.49
HEAT LOSS FROM S.H. TRANSITION	.105E+06	3.19	.115E+06	3.49	.120E+06	3.92
HEAT LOSS FROM S.H. FRAME	.505E+06	1.54	.519E+05	1.58	.415E+05	1.35
HEAT LOSS FROM S.H. DUCT	.236E+06	7.17	.241E+06	7.33	.247E+06	8.04
HEAT LOSS FROM OBS. PORT	.449E+05	1.36	.517E+05	1.58	.448E+05	1.46
HEAT LOSS FROM BURNER	.104E+06	3.17	.924E+05	2.81	.535E+05	1.74
HEAT LOSS FROM FURNACE BOTTOM LEFT	.813E+06	2.47	.659E+05	2.01	.423E+05	1.37
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.616E+05	1.87	.553E+05	1.68	.394E+05	1.28
METHOD 1-------TOTAL HEAT INPUT BTU/HR	.329E+07	.	.329E+07		.307E+07	
TOTAL HEAT OUTPUT BTU/HR	.315E+07		.317E+07		.299E+07	
HEAT UNACCOUNTED FOR	4.24		3.58		2.66	
METHOD 2-------TOTAL HEAT INPUT, BTU/HR	.329E+07		.329E+07		.307E+07	
TOTAL HEAT OUTPUT, BTU/HR	.327E+07		.330E+07		.318E+07	
HEAT UNACCOUNTED FOR	.77		- .41		-3.59	
METHOD 1-------TOTAL MATERIAL INPUT LB/HR	.313E+04		.309E+04		.312E+04	
TOTAL MATERIAL OUTPUT LB/HR	.313E+04		.309E+04		.312E+04	
MATERIAL UNACCOUNTED FOR	- .02		- .02		- .02	
METHOD 2-------TOTAL MATERIAL INPUT LB/HR	.332E+04		.330E+04		.344E+04	
TOTAL MATERIAL OUTPUT LB/HR	.332E+04		.330E+04		.344E+04	
MATERIAL UNACCOUNTED FOR	.00		- .00		- .00	

TABLE I-2

MASS AND ENERGY BALANCES DURING THE LAKHRA WASHED COAL TESTING

	TEST NO. 4		TEST NO. 5		TEST NO. 6	
METHOD 1-------						
FLUE GAS FLOW RATE LB/HR	.308E+04		.305E+04		.305E+04	
COMPOSITION IN MOLES/HR						
OXYGEN	.424E+01	4.05	.405E+01	3.90	.401E+01	3.87
CARBON DIOXIDE	.137E+02	13.09	.137E+02	13.16	.137E+02	13.19
WATER	.104E+02	9.89	.103E+02	9.96	.103E+02	9.98
SULFUR DIOXIDE	.379E+00	.36	.379E+00	.36	.379E+00	.37
NITROGEN	.761E+02	72.65	.754E+02	72.61	.752E+02	72.60
METHOD 1-------						
HEAT LOSS FROM REFRACTORY BTU/HR	.179E+06	5.45	.184E+06	5.84	.162E+06	5.19
HEAT LOSS FROM PANEL	.182E+06	5.54	.160E+06	5.07	.118E+06	3.79
HEAT LOSS FROM WATER COOLED FRAME	.745E+05	2.27	.570E+05	1.81	.435E+05	1.39
HEAT LOSS FROM FLY ASH	.171E+05	.52	.177E+05	.56	.170E+05	.55
HEAT LOSS FROM FLUE GAS	.183E+07	55.86	.189E+07	60.05	.181E+07	57.84
HEAT LOSS FROM ROOF	.321E+05	.98	.303E+05	.96	.289E+05	.93
HEAT LOSS FROM PROCESS HEATER	.593E+05	1.80	.444E+05	1.41	.340E+05	1.09
HEAT LOSS FROM S.H. TRANSITION	.132E+06	4.02	.140E+06	4.44	.115E+06	3.67
HEAT LOSS FROM S.H. FRAME	.539E+05	1.64	.515E+05	1.63	.474E+05	1.52
HEAT LOSS FROM S.H. DUCT	.277E+06	8.43	.294E+06	9.32	.245E+06	7.82
HEAT LOSS FROM OBS. PORT	.413E+05	1.26	.369E+05	1.17	.331E+05	1.06
HEAT LOSS FROM BURNER	.101E+06	3.07	.603E+05	1.91	.535E+05	1.71
HEAT LOSS FROM FURNACE BOTTOM LEFT	.648E+05	1.97	.448E+05	1.42	.456E+05	1.46
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.623E+05	1.90	.419E+05	1.33	.428E+05	1.37
METHOD 2-------						
FLUE GAS FLOW RATE LB/HR	.313E+04		.324E+04		.324E+04	
COMPOSITION IN MOLES/HR						
OXYGEN	.462E+01	4.34	.541E+01	4.90	.541E+01	4.90
CARBON DIOXIDE	.137E+02	12.82	.137E+02	12.39	.137E+02	12.39
WATER	.104E+02	9.75	.105E+02	9.49	.105E+02	9.49
SULFUR DIOXIDE	.379E+00	.36	.379E+00	.34	.379E+00	.34
NITROGEN	.775E+02	72.73	.804E+02	72.88	.804E+02	72.88
METHOD 2-------						
HEAT LOSS FROM REFRACTORY BTU/HR	.179E+06	5.45	.184E+06	5.84	.162E+06	5.19
HEAT LOSS FROM PANEL	.182E+06	5.54	.160E+06	5.07	.118E+06	3.79
HEAT LOSS FROM WATER COOLED FRAME	.745E+05	2.27	.570E+05	1.81	.435E+05	1.39
HEAT LOSS FROM FLY ASH	.171E+05	.52	.177E+05	.56	.170E+05	.55
HEAT LOSS FROM FLUE GAS	.187E+07	56.82	.201E+07	63.73	.192E+07	61.50
HEAT LOSS FROM ROOF	.321E+05	.98	.303E+05	.96	.289E+05	.93
HEAT LOSS FROM PROCESS HEATER	.593E+05	1.80	.444E+05	1.41	.340E+05	1.09
HEAT LOSS FROM S.H. TRANSITION	.132E+06	4.02	.140E+06	4.44	.115E+06	3.67
HEAT LOSS FROM S.H. FRAME	.539E+05	1.64	.515E+05	1.63	.474E+05	1.52
HEAT LOSS FROM S.H. DUCT	.277E+06	8.43	.294E+06	9.32	.245E+06	7.82
HEAT LOSS FROM OBS. PORT	.413E+05	1.26	.369E+05	1.17	.331E+05	1.06
HEAT LOSS FROM BURNER	.101E+06	3.07	.603E+05	1.91	.535E+05	1.71
HEAT LOSS FROM FURNACE BOTTOM LEFT	.648E+05	1.97	.448E+05	1.42	.456E+05	1.46
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.623E+05	1.90	.419E+05	1.33	.428E+05	1.37
METHOD 1-------TOTAL HEAT INPUT BTU/HR	.328E+07		.316E+07		.313E+07	
TOTAL HEAT OUTPUT BTU/HR	.326E+07		.321E+07		.294E+07	
HEAT UNACCOUNTED FOR	.78		-1.62		5.89	
METHOD 2-------TOTAL HEAT INPUT, BTU/HR	.328E+07		.316E+07		.313E+07	
TOTAL HEAT OUTPUT, BTU/HR	.329E+07		.332E+07		.306E+07	
HEAT UNACCOUNTED FOR	- .18		-5.31		2.23	
METHOD 1-------TOTAL MATERIAL INPUT LB/HR	.313E+04		.311E+04		.310E+04	
TOTAL MATERIAL OUTPUT LB/HR	.313E+04		.311E+04		.310E+04	
MATERIAL UNACCOUNTED FOR	- .02		- .02		- .02	
METHOD 2-------TOTAL MATERIAL INPUT LB/HR	.319E+04		.329E+04		.329E+04	
TOTAL MATERIAL OUTPUT LB/HR	.319E+04		.329E+04		.329E+04	
MATERIAL UNACCOUNTED FOR	.00		.00		.00	

APPENDIX J

GRAVITY FRACTIONATION DATA FOR LAKHRA COALS

TABLE J-1

ASH COMPOSITION OF LAKHRA WASHED COAL GRAVITY FRACTIONATION

GRAVITY FRACTIONATION CUT	1.5F	1.5 x 1.9	1.9 x 2.9	2.9S
ASH CONTENT, WT% (DRY BASIS)	11.4	23.5	61.4	63.4
ASH COMPOSITION, WT%				
SiO_2	34.7	44.8	41.8	6.3
Al_2O_3	23.8	29.4	26.2	2.4
Fe_2O_3	14.0	14.3	19.7	89.8
CaO	7.0	4.0	5.2	0.8
MgO	3.9	2.0	0.7	0.1
Na_2O	2.0	1.1	0.4	0.2
K_2O	0.5	0.6	0.5	0.1
TiO_2	2.2	2.2	1.6	0.4
SO_3	10.3	1.6	4.1	0.5
TOTAL	98.4	100.0	100.2	100.6

TABLE J-2

ASH COMPOSITION OF LAKHRA BASELINE COAL GRAVITY TRACTIONS

Gravity Fraction	1.5F	1.5 x 1.9	1.9 x 2.5	2.5 x 2.9	2.95
SiO_2	31.6	43.7	47.9	54.7	4.2
Al_2O_3	20.8	28.4	29.1	29.3	2.4
Fe_2O_3	11.9	14.5	12.9	8.3	87.7
CaO	10.0	3.4	2.6	1.9	0.3
MgO	5.4	1.9	0.8	0.6	0.1
Na_2O	2.5	1.2	0.3	0.4	0.1
K_2O	0.4	0.5	0.5	0.6	0.2
TiO_2	2.3	2.5	2.1	2.4	0.3
SO_3	13.3	3.0	2.6	1.3	3.2
TOTAL	98.2	99.1	98.8	99.5	98.4

APPENDIX K

FPTF WATERWALL HEAT FLUX PLOTS DURING LAKHRA WASHED COAL EVALUATION

FIGURE K-1 LAKHRA WASHED COAL EVALUATION
HEAT FLUX THROUGH W W PANELS : TEST 1

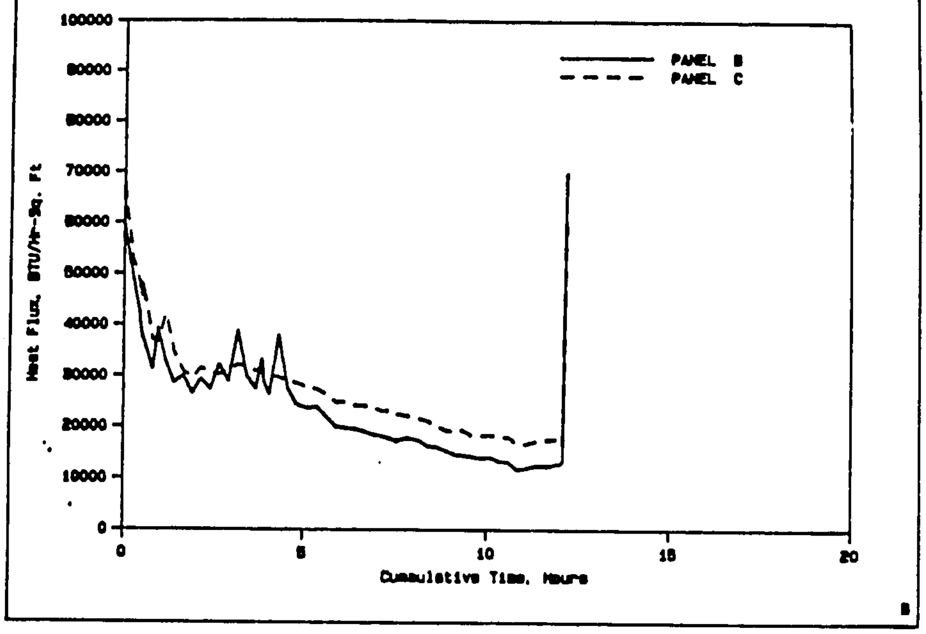


FIGURE K-2 LAKHRA WASHED COAL EVALUATION
HEAT FLUX THROUGH W W PANELS : TEST 2

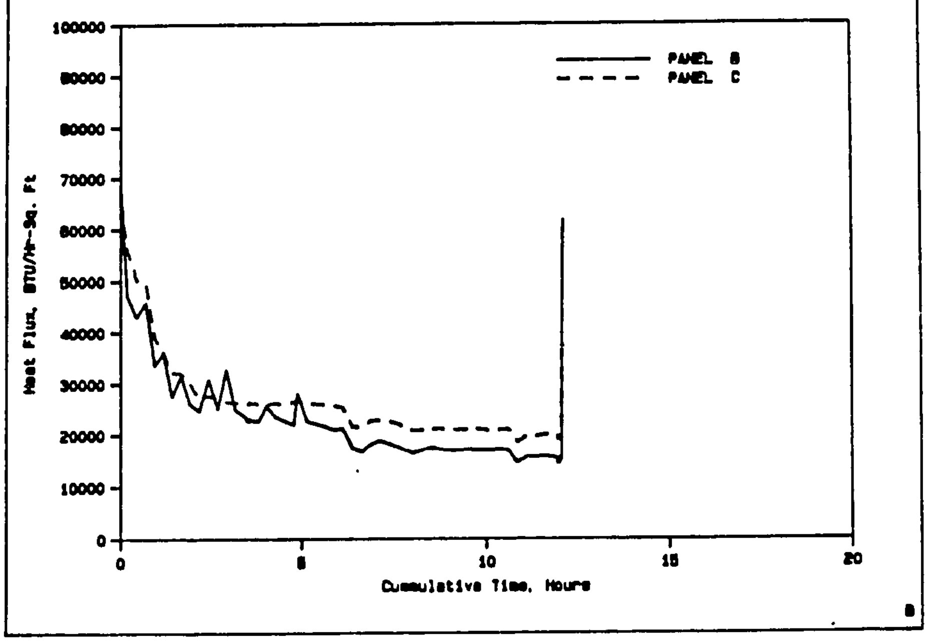


FIGURE K-3 LAKHRA WASHED COAL EVALUATION
HEAT FLUX THROUGH W W PANELS : TEST 3

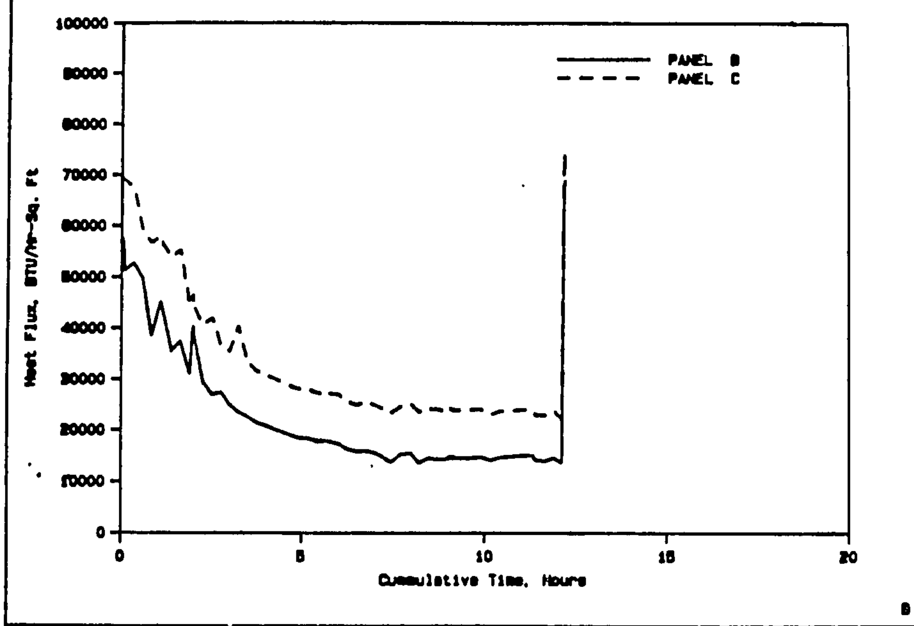


FIGURE K-4 LAKHRA WASHED COAL EVALUATION
HEAT FLUX THROUGH W W PANELS : TEST 4

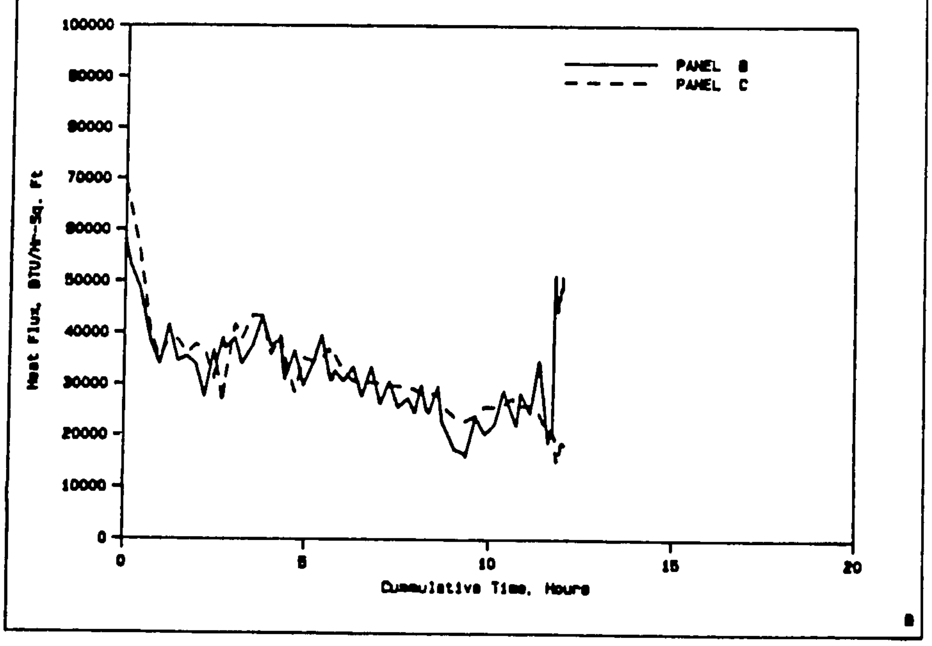


FIGURE K-5 LAKHRA WASHED COAL EVALUATION
HEAT FLUX THROUGH W W PANELS : TEST 5

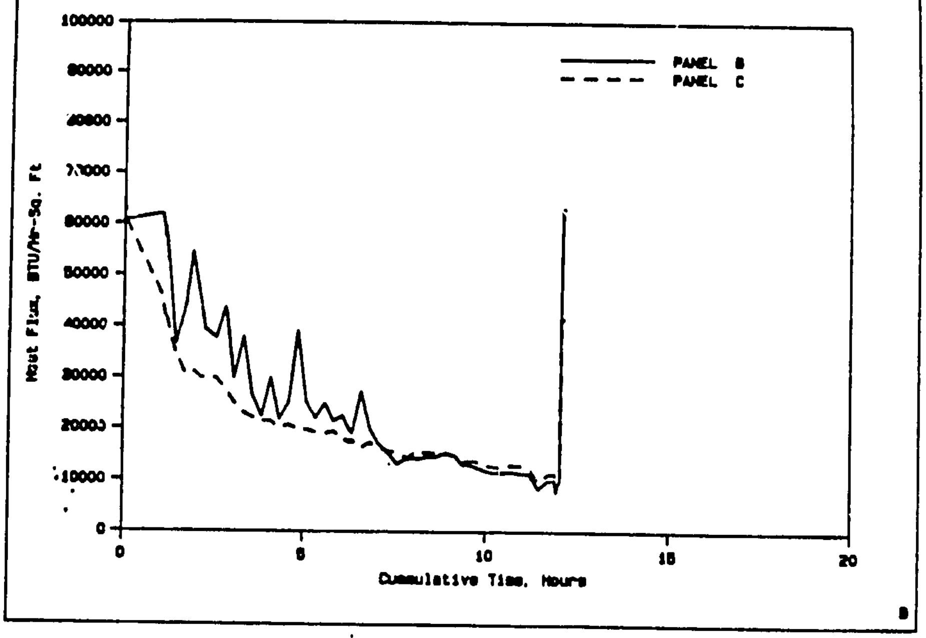
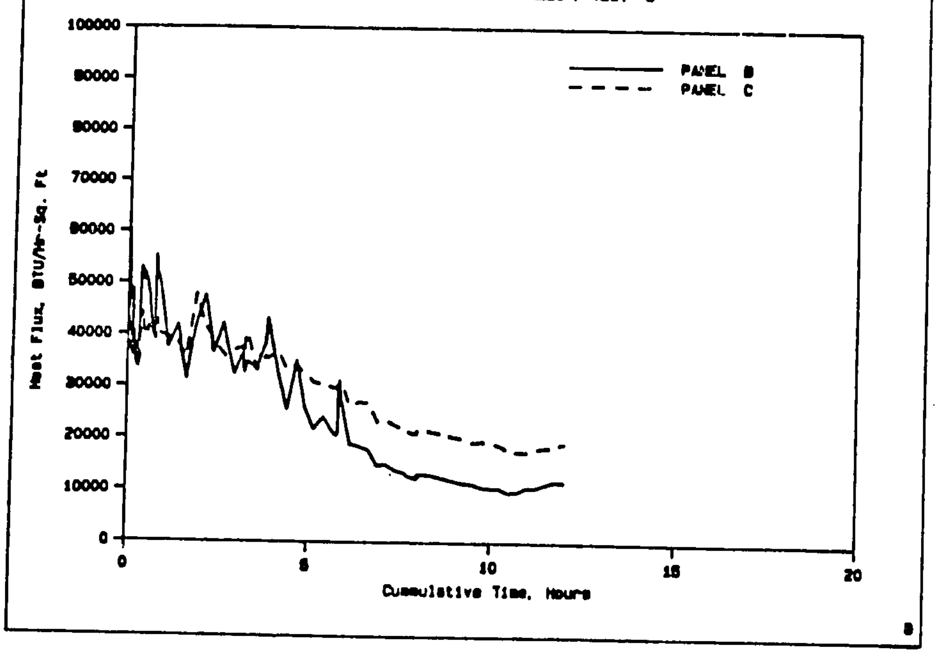


FIGURE K-6 LAKHRA WASHED COAL EVALUATION
HEAT FLUX THROUGH W W PANELS : TEST 6



APPENDIX L

TEXT TABLES IN S. I. UNITS

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TABLE 3-1 (Continued)

LAKHRA WASHED TEST MATRIX

TEST NO.	FUEL FEED RATE: KG/HR	FIRING RATE KW	EXCESS AIR (%)	AVERAGE PEAK FLAME (°C)
1	145	856	25	1444
2	145	856	25	1488
3	145	856	25	1466
4	145	856	25	1466
5	145	856	25	1455
6	145	856	25	1432

TABLE 3-2 (Continued)
FURNACE TEMPERATURE PROFILE DURING
LAKHRA WASHED COAL EVALUATION

TEST NO.	AVE. PEAK TEMP. (°C)	FURNACE TEMPERATURE L_1(0.9M)	L_2(1.2M)	L_3(2.1M)	$L_{3.5}$(2.4M)	L_4(3.6M)	ENTERING S.H. TEMPERATURES I	II	III	IV
1	1444	1444	1400	1377	1355	1294	1200	1094	1060	894
2	1488	1488	1444	1416	1377	1321	1238	1188	1071	982
3	1466	1466	1427	1410	1371	1327	1216	1110	1050	938
4	1466	1466	1405	1382	1344	1300	1227	1188	1093	966
5	1455	1455	1410	1382	1350	1344	1210	1177	1110	977
6	1432	1432	1382	1344	1294	1250	1154	1110	1050	938

TABLE 3-3 (Continued)

LAKHRA WASHED COALS
FURNACE RADIANT SECTION RESIDENCE TIME

TEST NO.	AVE. PEAK FLAME TEMP. °C	LOWER FURNACE RESIDENCE TIME (SEC)
1	1444	1.42
2	1488	1.41
3	1466	1.41
4	1466	1.42
5	1455	1.43
6	1432	1.47

TABLE 4-1 (Continued)

FUEL ANALYSIS FOR LAKHRA WASHED AND BASELINE COALS AS-RECEIVED

	LAKHRA BASELINE		LAKHRA WASHED	
	AS RECEIVED	MOISTURE FREE	AS RECEIVED	MOISTURE FREE
PROXIMATE, WT. PERCENT				
MOISTURE (TOTAL)	26.3		36.6	
VOLATILE MATTER	25.8	35.0	26.6	41.6
FIXED CARBON (DIFF)	21.1	28.6	24.9	39.3
ASH	26.8	36.4	12.1	19.1
TOTAL	100.0	100.0	100.0	100.0
HHV, (KJ/KG)	12,580	17,070	15,240	24,030
ULTIMATE, WT. PERCENT				
MOISTURE (TOTAL)	26.3		36.6	
HYDROGEN	2.7	3.6	3.0	4.7
CARBON	29.9	40.6	36.3	57.2
SULFUR	4.5	6.1	3.0	4.7
NITROGEN	0.5	0.7	0.8	1.2
OXYGEN (DIFF)	9.3	12.6	8.2	13.1
ASH	26.8	36.4	12.1	19.1
TOTAL	100.0	100.0	100.0	100.0
ASH FUSIBILITY RED ATM				
I.T. DEG C	1082		1155	
S.T. DEG C	1332		1282	
H.T. DEG C	1355		1327	
F.T. DEG C	1382		1350	
TEMP DIFF (FT-IT)	300		200	
ASH COMPOSITION, WT. PERCENT				
SiO2	43.6		39.0	
AL2O3	27.2		22.9	
FE2O3	17.2		19.3	
CAO	3.3		5.3	
MGO	1.3		2.2	
NA2O	0.7		1.2	
K2O	0.7		0.6	
TiO2	1.9		1.5	
P2O5	N/A		N/A	
SO3	3.9		6.4	
TOTAL	99.8		98.4	
BASE/ACID	0.32		0.45	
FE2O3/CAO	5.21		3.64	
FUEL RATIO (FC/VM)	0.82		0.95	
FORMS OF SULFUR				
SULFATE AS S	0.1		< 0.1	
PYRITE AS S	4.2		1.5	
ORGANIC AS S	0.3		1.4	

TABLE 4-2 (Continued)

BENCH-SCALE AND SPECIAL BENCH-SCALE TEST RESULTS FOR LAKHRA BASELINE AND LAKHRA WASHED COALS

	BASELINE	WASHED
ABRASION INDEX (g Metal Loss/tonne)	25	6.25
QUARTZ CONTENT (%)	1.7	0.4
WEAK ACID LEACHING:		
Na_2O (ppm Coal)	1870	1720
K_2O (ppm Coal)	160	120
Na_2O (% Ash)[1]	0.7	1.00
K_2O (% Ash)[1]	0.06	0.10
GRAVITY FRACTIONATION		
% Iron in 2.9 Sink	87.7	89.8

(1) Calculated number based on active alkali in coal.

TABLE 4-3 (Continued)

PULVERIZATION CHARACTERISTICS FOR LAKHRA BASELINE AND WASHED COALS

	WASHED	BASELINE
POWER REQUIREMENT		
kw-hr/tonne	7.8	8.1
kw-hr/GJ	0.31	0.49
MILL REJECT (% of feed)	0.8	2.1
HARDGROVE GRINDABILITY INDEX	67	71

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TABLE 4-5 (Continued)

COMBUSTION EFFICIENCY DATA FOR LAKHRA WASHED AND BASELINE COALS

	FIRING RATE (KW)	AVE. PEAK FLAME TEMP. (°C)	MASS MEDIAN DIAMETER (μ)	FLYASH CARBON CONTENT (%)	CARBON CONVERSION (%)
LAKHRA WASHED	856	1455	7.3	0.6	99.8
LAKHRA BASELINE	826	1432	5.0	0.1	99.9

TABLE 4-6 (Continued)
LAKHRA WASHED COAL FLY ASH ANALYSIS

	WASHED	BASELINE
Ash Content, (WT. %)	98.8	99.4
Carbon, (WT. %)	0.6	0.1
Ash Fusibility, (°C)		
IT	1155	1105
ST	1221	1282
HT	1250	1388
FT	1350	1450
Ash Composition, (WT. %)		
SiO_2	41.9	45.7
Al_2O_3	28.0	30.2
Fe_2O_3	16.8	15.8
CaO	5.2	3.3
MgO	2.4	1.5
Na_2O	1.4	0.9
K_2O	0.6	0.6
TiO_2	1.1	1.7
SO_3	1.0	1.1
TOTAL	98.4	101.0
MMD (microns)	7.3	5.0
Carbon Conversion	99.8	99.9

TABLE 4-7 (Continued)
LAKHRA WASHED COAL/FPTF
WATERWALL ASH SLAGGING CHARACTERISTICS

TEST NO.	Q (KW)	PANEL ELEVATION	AVE. PEAK TEMP. (°C)	W W PANEL COVERAGE %	DEPOSIT THICKNESS (CM)	DEPOSIT STATE	CLEANABILITY
1	856	B	1400	100	.3 - .6	Highly Sintered	Excellent
		C	1444	100	.6 - 1.3	Highly Sintered, Molten Droplets	Good
2	856	B	1444	100	.6 - 1.3	Highly Sintered, Molten Overlay	Good
		C	1488	100	1.3	Molten	Poor
3	856	B	1432	100	.3 - .6	Highly Sintered, Molten Droplets	Good
		C	1466	100	.3 - .6	Highly Sintered, Molten Overlay	Good
4	856	B	1405	100	.6 - 1.3	Highly Sintered, Molten Overlay	Good
		C	1466	100	.3 - .6	Molten	Poor
5	856	B	1410	100	1.3	Highly Sintered	Excellent
		C	1455	100	1.3 - 1.9	Highly Sintered, Molten Overlay	Marginal
6	856	B	1382	100	.6 - 1.3	Highly Sintered	--
		C	1432	100	.6 - 1.3	Highly Sintered	--

TABLE 4-8 (Continued)

LAKHRA WASHED COAL CHARACTERIZATION

FPTF SLAGGING RESULTS

TEST NO.	Q (kW)	FLAME TEMPERATURE (°C)		CLEAN PANEL HEAT FLUX (kW/m^2)		HEAT FLUX BEFORE SOOTBLOWING (kW/m^2)		HEAT FLUX AFTER SOOTBLOWING (kW/m^2)		% RECOVERY	
		B	C	B	C	B	C	B	C	B	C
1	856	1400	1444	187	212	40	55	220	191	1.00	0.90
2	856	1444	1488	215	207	49	62	192	116	0.89	0.56
3	856	1432	1466	179	219	46	75	217	225	1.00	1.00
4	856	1405	1466	183	219	62	65	176	57	0.96	0.26
5	856	1410	1455	190	220	32	35	199	131	1.00	0.59
6	856	1382	1432	195	148	37	59	--	--	--	--

TABLE 4-9 (Continued)
WATERWALL DEPOSIT ANALYSIS FOR PANEL B IN-SITU
LAKHRA WASHED COAL FPTF TESTING

	TEST NO. 1 T_f = 1400	TEST NO. 2 T_f = 1440	TEST NO. 3 T_f = 1430	TEST NO. 4 T_f = 1400	TEST NO. 5 T_f = 1410
ASH FUSIBILITY, (°C)					
I.T.	1166	1160	1150	1160	1105
S.T.	1210	1205	1216	1200	1171
H.T.	1244	1238	1250	1238	1232
F.T.	1360	1321	1350	1282	1316
ASH COMPOSITION, (WT %)					
SiO_2	41.7	39.9	42.2	42.2	40.6
Al_2O_3	26.9	25.1	27.5	26.6	24.5
Fe_2O_3	21.8	25.0	24.0	23.1	25.3
CaO	4.4	3.8	4.1	4.3	3.9
MgO	1.7	1.5	1.5	1.5	1.6
Na_2O	1.1	1.1	1.0	1.0	0.9
K_2O	0.5	0.6	0.6	0.5	0.5
TiO_2	1.5	1.4	1.5	1.5	2.4
SO_3	0.1	<0.1	<0.1	<0.1	0.1
TOTAL	99.7	98.4	102.4	100.7	99.8

TABLE 4-10 (Continued)
WATERWALL DEPOSIT ANALYSIS AFTER SHUTDOWN
FOR LAKHRA WASHED COAL
TEST NO. 6

	PANEL B T_f = 1380		PANEL C T_f = 1430	
	INITIAL	OUTER	INITIAL	OUTER
ASH FUSIBILITY, (°F)				
I.T.	1110	1110	1100	1110
S.T.	1160	1138	1138	1154
H.T.	1200	1288	1266	1271
F.T.	1321	1327	1321	1316
ASH COMPOSITION, (WT %)				
SiO_2	35.8	41.3	33.9	39.9
Al_2O_3	23.3	24.5	24.9	23.7
Fe_2O_3	26.2	25.3	27.1	25.4
CaO	4.1	4.3	3.6	4.0
MgO	1.7	1.6	1.6	1.5
Na_2O	1.4	1.1	1.2	1.1
K_2O	0.6	0.6	0.6	0.6
TiO_2	1.3	1.4	1.4	1.5
SO_3	4.3	0.4	4.8	1.6
TOTAL	98.7	100.5	99.1	99.3

TABLE 4-11
LAKHRA WASHED COAL CHARACTERIZATION
FPTF FOULING RESULTS

TEST COAL		AVE. PEAK FLAME TEMP. (°C)	AVG. GAS TEMP. DUCT I (°C)	DEPOSIT THICKNESS (CM)	DEPOSIT PHYSICAL STATE	DEPOSIT BONDING STRENGTH(1)	SOOTBLOWING FREQUENCY (HR)	CLEANABILITY
ROM	1	1444	1200	5-7.5	Lightly to Mod Sintered	1.9	6	Excellent
	2	1488	1238	5-7.5	Lightly to Mod Sintered	2.0	6	Excellent
	3	1466	1216	5-7.5	Lightly to Mod Sintered	2.4	6	Excellent
	4	1466	1227	5-7.5	Lightly to Mod Sintered	1.2	6	Excellent
	5	1455	1210	5-7.5	Lightly to Mod Sintered	3.2	6	Excellent
	6	1432	1155	5-7.5	Lightly to Mod Sintered	2.4	6	Excellent

(1) Deposits would build-up and slough-off providing inadequate thickness for bonding strength measurement on most tests.

TABLE 4-12 (Continued)
SUPERHEATER ASH DEPOSIT ANALYSIS FOR
LAKHRA WASHED COAL TESTING
TEST NO. 6

	BANK A				BANK II	
	PROBE A		PROBE B		PROBE C	
	INITIAL	OUTER	INITIAL	OUTER	INITIAL	OUTER
ASH FUSIBILITY, (°C)						
I.T.	1144	1166	1127	1171	1127	1160
S.T.	1160	1271	1188	1200	1166	1188
H.T.	1166	1310	1221	1216	1177	1200
F.T.	1171	1366	1327	1350	1227	1350
ASH COMPOSITION, (WT. %)						
SiO_2	13.2	42.9	37.0	41.3	12.7	43.4
Al_2O_3	8.8	27.1	24.1	27.5	8.2	27.1
Fe_2O_3	50.1	18.1	19.7	15.6	46.5	17.2
CaO	12.8	5.4	6.0	6.9	14.9	6.4
MgO	1.4	2.2	2.3	2.8	1.3	2.4
Na_2O	0.5	1.6	1.6	1.9	0.4	1.6
K_2O	0.2	0.7	0.6	0.7	0.2	0.5
TiO_2	0.6	1.4	1.3	1.4	0.6	1.4
SO_2	12.3	0.3	6.3	0.3	14.1	0.4
TOTAL	99.9	99.7	98.9	98.4	98.9	100.4

TABLE 4-13 (Continued)
SUPERHEATER ASH DEPOSIT ANALYSIS FOR
LAKHRA WASHED COAL TESTING
TEST NO. 6

	BANK II	BANK III			BANK IV	
	PROBE D	PROBE E		PROBE I	PROBE G	PROBE H
	OUTER	INITIAL	OUTER	INITIAL	INITIAL	INITIAL
ASH FUSIBILITY, (°C)						
I.T.		1166	1121			1132
S.T.	I.S.	1355+	1182	I.S.	I.S.	1177
H.T.		1482+	1227			1227
F.T.		1482+	1338			1327
ASH COMPOSITION, (WT. %)						
SiO_2		14.2	43.8	28.5	15.9	42.4
Al_2O_3		6.6	26.5	22.0	8.8	24.9
Fe_2O_3		67.0	18.2	22.9	71.8	19.2
CaO		5.5	7.3	7.0	2.5	6.0
MgO		0.7	2.4	2.0	0.8	2.2
Na_2O		0.7	1.9	1.6	0.6	1.7
K_2O		0.1	1.9	1.6	0.1	0.5
TiO_2		0.4	1.5	1.2	0.5	1.5
SO_2		6.5	0.9	7.0	I.S	4.5
TOTAL		101.7	102.9	102.5	101.0	102.9

I.S. = Insufficient Sample

TABLE 4-14 (Continued)
LAKHRA WASHED AND BASELINE COAL/FPTF
FLY ASH EROSION CHARACTERISTICS

	Washed	Baseline
Firing Rate	856 kW	583 to 680 kW
Feed Rate	40.3 g/s	32.5 to 37.8 g/s
Test Duration	36 hr.	30.75 hr.
Ash Loading	7.06 g/s	9.2 to 10.7 g/s
Gas Velocity	51.2 m/s	35.7 to 40.8 m/s
Mass Median Particle Diameter	7_u	5_u
Quartz in Ash	2.5%	2.4%
Maximum Penetration	19.6_u	10.2_u
Normalized Penetrations:		
μ Per kg. Ash(1)	3.5×10^{-3}	3.1×10^{-3}
MM Per 10,000 Hr.(2)	0.55	0.91

(1) Erosion normalized per unit mass of ash at 18.3 m/sec - assuming 50/50 fly ash/bottom ash split.

(2) Erosion normalized for firing rate at 18.3 m/sec and typical unit operating time 10,000 hrs.

TABLE 4-15 (Continued)
LAKHRA WASHED COAL
FLUE GAS EMISSION DURING TEST FIRING IN THE FPTF
HEAT INPUT = 856 kW

TEST NO.	AVERAGE PEAK TEMP. (°C)	$CO^{(1)}$ (PPM)	$NO_x^{(1)}$ (PPM)	$SO_2^{(1)(2)}$ (PPM)
1	1444	<1	1374	4337
2	1488	<1	1365	4113
3	1466	<1	1361	4222
4	1466	<1	1180	4342
5	1455	<1	1025	4203
6	1432	<1	1062	4482

(1) 3% O_2 dry basis

Based on SO_2 thermoelectron analyzer (see Appen C)

COMBUSTION PERFORMANCE CHARACTERIZATION OF LAKHRA BT-11 COALS

PROJECT 900029

KDL-85-F-21

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SUMMARY

INTRODUCTION

The final phase of the Lakhra combustion testing consisted of evaluating BT-11 seams 1 and 2 coals in the Fireside Performance Test Facility (FPTF). The key objectives were to assess the combustion/performance characteristics for coals from different areas of the Lakhra field, and to incorporate the findings for a successful boiler design study.

Testing of the BT-11 coals entailed both bench and pilot scale evaluations. Specific areas addressed included:

- Pulverization and Abrasion Characteristics
- Relative Combustion Characteristics
- Furnace Slagging
- Convective Pass Fouling
- Relative Gaseous and Particulate Emissions
- Fly Ash Erosion

Results obtained from the BT-11, baseline and washed coals were compared to provide feedbacks for the 300 MWe Lakhra coal-fired unit design study.

BENCH SCALE CHARACTERISTICS

The ASTM volatile matter contents for the BT-11 seams 1 and 2 coals are 38.7 and 33.6%, and the ash contents are 32.4 and 38.7% on a moisture free basis. The higher heating values are 17.1 MJ/Kg (7,360 Btu/lb) and 16.1 MJ/Kg (6,925 Btu/lb) respectively on the same basis. Char samples prepared from these two coals have similar characteristics as baseline and washed. They have high BET surface areas of 310 and 231 m^2/g and rapid char burn-off rates. Hence, from reactivity standpoint, these Lakhra coals should not present carbon heat loss problems under normal circumstances.

The sulfur content in the BT-11 coals are higher, 8.1 and 9.1% for seams 1 and 2 compared to 6.1 and 4.7% for baseline and washed on a moisture free basis. The sulfur in pyritic form is 75% for seam 1 and 78% for seam 2, compared to 93% for baseline and 50% for washed. With exception for the higher initial deformation temperatures, other ash fusibility temperatures of the BT-11 coals are generally lower. Values range from 1149 to 1332°C (2100 to 2430°F) for seam 1 and 1160 to 1304°C (2120 to 2380°F) for seam 2, compared to 1082 to 1382°C (1980 to 2520°F) for the baseline and 1116 to 1330°C (2040 to 2440°F) for the washed, I.T. to F.T. respectively.

Ash analysis shows the BT-11 coals have higher iron content than the baseline and washed; 27.0 and 22.6% compared to 17.2 and 19.2%. Gravity fractionation analysis shows the coal ash in the 2.9 sink contains 83.5% Fe_2O_3 for seam 1, and 88.8% Fe_2O_3 for seam 2, compared to 87.7% Fe_2O_3 for baseline and 89.9% Fe_2O_3 for washed. The high Fe_2O_3 content in the 2.9 sink fraction and the low to moderate ash fusibility temperatures indicate all these Lakhra coals would exhibit severe slagging potential. The BT-11 coals would be slightly worse than the baseline and washed due to their higher iron content and generally lower ash fusibility temperatures.

The sodium content in the ash is 0.7 and 0.8% for BT-11 seams 1 and 2. These values are the same as in the baseline ash, and are slightly less than the washed 1.2%. The low to moderate ash fusibility temperatures coupled with high ash loading would indicate a moderate fouling potential for the BT-11 seams 1 and 2, baseline and washed coals.

PULVERIZATION CHARACTERISTICS

Pulverization characteristics of the BT-11 seams 1 and 2, baseline and washed coals are in general similar. All four coals are easy to grind. The energy required per tonne to pulverize in the FPTF bowl mill is lowest with the BT-11 seam 2, 7.6 Kw-hr/tonne (6.9 Kw-hr/ton); followed by the washed coal, 7.8 Kw-hr/tonne (7.1 Kw-hr/ton); the BT-11 seam 1, 8.2 Kw-hr/tonne (7.4 Kw-hr/ton); and the baseline 8.4 Kw-hr/tonne (7.6 Kw-hr/ton). However, on a per fuel heat input basis, the grinding energy required is similar for the BT-11 seams 1 and 2 and the baseline, 0.46, 0.47, and 0.49 Kw-hr/GJ (0.48, 0.50, and 0.52 Kw-hr/10^6 Btu), but it is significantly lower for the washed, 0.32 Kw-hr/GJ (0.34 Kw-hr/10^6 Btu). This is attributed to the reduction in fuel throughput associated with increased higher heating value of the washed coal. At a mill capacity of 612 Kg/hr (1350 lbs/hr), the mill rejection rates are 0.7 and 0.2% for BT-11 seams 1 and 2 compared to the 2.1% for the baseline and 0.8% for the washed coal.

Bench scale abrasion results show the relative mill wear potential is moderate for both BT-11, high for the baseline, and low for the washed coal. The respective abrasion indices are 28, 30, 50 and 12 for these coals.

COMBUSTION PERFORMANCE CHARACTERISTICS

Relative Combustion Characterization

The two BT-11 coals ignited easily and produced a good stable flame during pilot-scale testing. Analysis of the fly ash samples collected during the critical flame temperature tests show the carbon content is very low, 0.3 and 0.2% for seams 1 and 2 respectively, indicating a better than 99.9% carbon conversion for each coal. These, along with the previous results obtained from the baseline and washed, indicate all four Lakhra coals have very good combustion characteristics.

Furnace Slagging

Both BT-11 seams 1 and 2 coals have similar severe slagging characteristics and are generally slightly worse than the baseline and washed coals. Cleanability of the waterwall deposits is highly dependent on furnace temperature. The critical flame temperature established for cleanable waterwall deposits is 1410°C (2570°F) for the two BT-11 coals, 1427°C (2600°F) for the baseline, and 1443°C (2630°F) for the washed.

The physical state of the waterwall deposits is similar between all four Lakhra coals. Highly sintered with molten outer layer deposits developed during the respective critical flame temperature test. Deposits from the two BT-11 seams and baseline coal have similar thickness of 12.7 to 20 mm (1/2 to 3/4 inch), but are generally thinner with washed coal, 9.5 tc 12.7 mm (3/8 to 1/2 inch).

Waterwall heat flux data obtained during the critical test conditions showed the heat transfer reduction is similar between BT-11 seams 1 and 2 and baseline coal, 66.5%, 68.2%, and 71.1% respectively. Heat flux reduction for washed coal was slightly lower; 60.1%, reflecting the slightly thinner deposits formed on the waterwall panels with this coal.

During each test firing, bottom ash accumulation rate for both BT-11 coals was very high, requiring frequent handling. These results are similar to the baseline and slightly worse than the washed. The ash split for all four coals was similar, approximately 40% bottom ash to 60% fly ash in the FPTF.

Convective Pass Fouling

The BT-11 seams 1 and 2 showed similar moderate fouling potential as the baseline and washed. Convective pass deposit accumulation is rapid, but deposit to tube bonding strengths are low (less than 2), thus deposits are easily cleanable by sootblowing. Deposit buildup is most rapid with the BT-11 seam 2, slightly less with BT-11 seam 1, and less with baseline and washed. Sootblowing requirements were every 3 to 4 hours for BT-11 seam 2; 4 to 5 hours for BT-11 seam 1; 5 to 6 hours for baseline; and 6 hours for washed at gas temperature range of 1138 to 1165°C (2080 to 2130°F).

Similar to the baseline and washed, a high deposition rate in the transition section of the FPTF furnace occurred during the BT-11 seams 1 and 2 tests. The high rate was due to the carry-over effect from furnace slagging.

Particulate and Gaseous Emissions

The average mass median particle size of the fly ash samples collected from the BT-11 seam 1 and 2 coals are 8.6 and 7.7 microns, respectively. The fly ash resistivity measured on-line in the FPTF is 5.48 x 10^{10} ohm-cm at 116°C (240°F) flue gas temperature wit.. 17pmm SO_3 and 8% moisture during the BT-11 seam 1 test. This resistivity value falls within the optimum 5 x 10^9 to 5 x 10^{10} ohm-cm range for electrostatic precipitators operating under normal gas temperatures of 149 to 177°C (300 to 350°F). It is also lower compared to the baseline 1.76 x 10^{11} ohm-cm and washed 7.6 x 10^{11} ohm-cm. Fly ash collection efficiency would therefore be higher with the BT-11 coals.

Higher sulfur content in the BT-11 coals resulted higher SO_2 emissions than the baseline and washed coals. The measured SO_2 emissions from the FPTF are 8570 and 9182 ppm (3% O_2 dry) for FT-11 seams 1 and 2 compared to 6340 and 4283 ppm (3% O_2 dry), for baseline and washed respectively. Sulfur retentions by the respective ash are 13.6 and 15.1%, and 9 and 13%. The NO_x emissions measured from the FPTF are 920 and 960 ppm for BT-11 seams 1 and 2, 860 and 1374 ppm for baseline and washed.

Fly Ash Erosion

The BT-11 seam 1 coal has a relatively high fly ash erosion potential. The normalized wastage rate is slightly higher, 0.95 mm (37.5 mils) compared to baseline 0.91mm (35.9 mils) on a 10000 operating hours at 18.3 m/sec (60 ft/sec) basis. Fly ash erosion for washed is 0.55mm (21.6 mils) on the same basis. The slightly higher erosion of the BT-11 seam 1 and baseline coals are attributed to their higher ash loading.

CONCLUSIONS AND RECOMMENDATIONS

FPTF results indicate the Lakhra baseline, washed and BT-11 coals can be commercially fired in a properly designed furnace. Specific conclusions include:

- All four coals have very good combustion characteristics. Both bench and pilot scale results indicate these coals should not present any carbon heat loss under normal circumstances.

- Pulverization of these coals is easily accomplished requiring relatively low energy for grinding. There is no apparent compaction/pasting potential in the bowl mill. The relatively low abrasiveness of the washed coal should pose a low mill wear potential. The high abrasion characteristics of the baseline and the BT-11 coals can be addressed with proper mill lining materials.

- Furnace slagging is the controlling factor utilizing these coals. However, the severe slagging in the FPTF can be effectively controlled by reducing furnace flame temperature; below 1427°C (2600°F) for the baseline, 1440°C (2630°F) for the washed, and 1410°C (2570°F) for the BT-11. These will correspond to a very large furnace design.

Design options such as extended windbox and concentric firing should also be considered. The high bottom ash buildup will require a large ash handling system.

- o Ash fouling potentials of these coals are moderate. Convection deposit accumulation rates are rapid due to their high ash loadings and furnace slag carry-overs in the high gas temperature section. Deposit buildup is most rapid with the BT-11 seam 2, slightly less with the BT-11 seam 2, and less with the baseline and the washed. Deposit to tube bonding strengths are low for each of these coals, indicating deposits can be readily cleanable by sootblowing. Convective pass deposition rate can be minimized by reducing gas temperature to below 1149°C (2100°F). Proper sootblower coverage should be provided for effective deposit removal.

- o Fly ash resistivities of the baseline and BT-11 fall within the typical range for most commercial coals and should not present problems for electrostatic precipitator collection efficiency. The washed coal has slightly higher fly ash resistivity and would not be as efficient. However, lower collection efficiency is possible for the washed coal and still achieve the same particulate emission limits due to its lower ash loading.

- o The baseline and BT-11 coals have a high fly ash erosion rate attributed to their high ash loadings, but can be reduced by designing commercially acceptable low gas velocities in the convective pass. The washed coal fly ash erosion rate is moderate due to its reduced ash loading.

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TABLES

ILLUSTRATIONS

Section 1

INTRODUCTION

The Water and Power Development Authority (WAPDA) of Pakistan is interested in constructing a series of 300 MWe power generation stations firing the indigenous Lakhra coals as boiler fuel to meet future energy requirements. Comprehensive Lakhra Coal Mine and Power Plant Facility studies are underway with sponsorship from the United States Agency for International Development (USAID). Gilbert/Commonwealth, Inc. has been contracted to conduct the Lakhra Power Generation Project feasibility study.

The typical Lakhra coal has high sulfur, high ash with high iron content, and relatively low ash fusibility temperatures. Its quality can vary significantly from seam to seam within the coal field. These factors and others represent areas of concern in boiler design and operation. Combustion Engineering (C-E) was subcontracted to conduct a comprehensive test program/design study to address these concerns. Four Lakhra coals were evaluated; the baseline PMDC-2, the washed PMDC-2, and the BT-11 seams 1 and 2 coals. Testing consisted of both bench and pilot scale evaluations which included:

- Pulverization and Abrasion Characteristics
- Relative Combustion Characteristics
- Furnace Slagging
- Convective Pass Fouling
- Relative Gaseous and Particulate Emissions
- Fly Ash Erosion

The subject report provides detailed assessments of the Lakhra BT-11 seams 1 and 2 coals and their combustion/performance characteristics in comparison to the baseline and washed coals.

Section 2

TEST PROCEDURES

BENCH SCALE CHARACTERIZATION

Standard ASTM (American Society for Testing Materials) and special in-house methods were used to assess the bench scale fuel characteristics and the relative combustion behaviors of the BT-11 seams 1 and 2 coals. Details of these techniques and their usefulness are described in Section 2 of the Lakhra baseline report.

PILOT SCALE PULVERIZATION

Pulverization characteristics of the BT-11 seams 1 and 2 coals were evaluated in a CE Model No. 271 bowl mill at conditions same as for the baseline and washed to allow direct comparisons between the different Lakhra coals. They were pulverized at feed rate of 612 Kgs/hr (1350 lbs/hr), mill outlet temperature of 60°C (140°F) and fuel fineness of 70 ± 3% through 75 microns (200 mesh). Mill power consumption, mill rejection rate and general grinding characteristics from each coal were evaluated and compared to assess the overall Lakhra coal pulverization behaviors.

PILOT SCALE COMBUSTION PERFORMANCE EVALUATTION

The combustion performance of the Lakhra BT-11 coals was evaluated in the Fireside Performance Test Facility (FPTF). Description of the facility is in Appendix C of the Lakhra baseline report. Test firing in the FPTF allows direct comparison of the performance characteristics between Lakhra baseline, washed and BT-11 seams 1 and 2, and provides feedback for an effective utility boiler design study.

TEST PROGRAM

Table 2-1 lists the five tests conducted for the Lakhra BT-11 coals; three for seam 1 and two for seam 2. All tests were conducted with 70 ± 3% through 75 microns (200 mesh) fuel fineness and 25% excess air level to simulate typical field units operating with high slagging coals. Each test was performed at 2.95 GJ/hr (2.80 x 10^6 Btu/hr) with varying flame temperatures. The key objective was to establish the critical flame temperature at which furnace deposits are still cleanable by sootblowing in the FPTF. The furnace conditions at which wall-blowers are no longer effective in removing deposits are very important from a design standpoint as they dictate the maximum thermal loadings at which a slagging limited boiler can continuously operate.

Initial test conditions for the BT-11 coals were selected based upon the critical conditions established for the baseline coal. At the conclusion of this test furnace slagging and convective pass fouling characteristics were assessed. Furnace temperature was subsequently adjusted and controlled by changing the combustion air temperature in order to bracket for the critical conditions at which waterwall deposits can still be cleanable.

Assessment of the furnace slagging was accomplished by determining deposit coverage and its effects on waterwall panel heat flux, deposit cleanability, deposit physical and chemical characteristics. Convective pass fouling was assessed by the deposit buildup rate, deposit cleanability and deposit physical and chemical properties. The technique and criteria employed to classify the slagging and fouling potentials of a fuel in the FPTF are described in Section 2 of the Lakhra baseline report.

Fly ash samples were collected isokinetically downstream of the convective pass of the FPTF. These samples were analyzed for carbon and chemical composition by ASTM methods, particle size distribution by laser diffraction technique, free quartz content by X-ray diffraction, fly ash resistivity by

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in-situ and by bench-scale measurements. These results were related to the relative combustion behavior, fly ash collectivity and fly ash erosion results for each test coal.

Flue gas samples were analyzed periodically during each test run. A gas analysis system was used to measure the flue gas concentrations of No_x, SO_2, SO_3, CO and O_2 on a dry basis.

Fly ash erosion characteristics of the BT-11 seam 1 coal were evaluated on-line in the FPTF in a special high velocity convection section using a special test probe. The same surface activation technique described in Section 2 of the Lakhra baseline report was used to determine metal loss after exposure. The BT-11 seam 2 was not evaluated for fly ash erosion due to its short test periods (total of 24 hours) limited by the availability of coal supply.

Results obtained from the BT-11 coals were analyzed and compared to the baseline and washed. The overall combustion/performance characteristics of these coals were assessed to provide input parameters for an effective power boiler furnace design firing the Lakhra coals.

TABLE 2-1

LAKHRA BT-11 COAL EVALUATION TEST MATRIX

COAL TYPE	TEST NO.	FIRING RATE GJ/HR ($x10^6$ Btu/Hr)	EXCESS AIR %	TARGET FLAME TEMPERATURE °C (°F)	ACTUAL FLAME TEMPERATURE °C (°F)
Seam 1	1	2.95 (2.80)	25	1427 (2600)	1443 (2630)
	2	2.94 (2.79)	25	1400 (2550)	1410 (2570)
	3	2.95 (2.80)	25	1410 (2570)	1410 (2570)
Seam 2	1	2.95 (2.80)	25	1454 (2650)	1465 (2670)
	2	2.95 (2.80)	25	1427 (2600)	1410 (2570)

Section 3

TEST RESULTS

BENCH SCALE CHARACTERIZATION

Representative samples from the Lakhra BT-11 seams 1 and 2 coals were subjected to a series of bench scale analyses. Testing included standard ASTM analyses typically used for characterization of solid fuels, and special analyses which provide information on the relative fuel reactivity and char burn-off rate, as well as more indepth information on the mineral matter in the ash for each coal.

Standard ASTM Tests

Analytical data on the Lakhra BT-11 coals are summarized in Table 3-1. Comparison between these coals and the baseline and washed are shown in Table 3-2. The volatile matters (VM) are 57.1 and 54.8%, and the higher heating values (HHV) are 26.22 and 26.20 MJ/kg (11,285 and 11,276 Btu/lb) for seams 1 and 2 respectively on a moisture and ash free basis. These values are comparable to the Baseline 55% and 26.8 MJ/kg. The washed coal has similar VM 51.9% but higher HHV 29.7 MJ/kg (12,768 Btu/lb) due to its reduced ash content from cleaning. The VM and HHV values for each of these four coals, coupled with the fact that they are non-swelling and hence do not soften upon rapid heating, are indicative of good burning qualities.

Results of the ultimate analysis show both BT-11 coals have higher sulfur content than the baseline and washed, 8.1 and 7.8% versus 6.1 and 4.7% respectively from the BT-11 seams 1 and 2 coals on a moisture free basis. Sulfur form analysis indicate 75.3 and 78.1% of the total sulfur are pyritic, 0.8 and 0.7% are sulfate and 1.2 and 1.3% organic. Firing these coals under complete combustion and without any sulfur removal would yield higher sulfur oxide emissions, 9.1 and 11.3 g SO_2/MJ (21.2 and 26.2 lbs/10^6 Btu) versus 7.2 and 3.9 g SO_2/MJ (16.6 and 9.1 lbs/10^6 Btu) for the baseline and washed.

High ash content with high iron and low sodium compounds in the ash are the typical characteristics of the Lakhra coals. The ash contents are 32.4, 38.7, 36.4 and 19.1% for BT-11 seams 1 and 2, baseline and washed, on a dry basis. The corresponding ash loading would be 18.3, 24.0, 21.3 and 18.5 g/MJ (42.5, 55.9, 49.6 and 18.5 lbs/10^6 Btu) for the respective coals. Ash composition analysis show a higher percentage of iron (22.6 and 27.0% versus 17.2 and 19.3%) and similar low sodium (0.8 and 0.7% versus 0.7 and 1.2%) compounds in the BT-11 seams 1 and 2 coal ashes compared to the baseline and washed.

Slagging characteristics of a coal is commonly evaluated by the ash fusibility temperatures, the base to acid ratio, and the iron to calcium ration. The BT-11 seams 1 and 2 coals have relatively low to moderate ash fusibility temperatures. The initial ash deformation temperatures of these coals are higher, but other fusibility temperatures are lower than the baseline and washed; 1149 and 1160°C (2100 and 2120°F) compared to 1082 and 1116°C (1980 and 2040°F) I.T.; and 1332 and 1304°C compared to 1382 and 1338°C (2520 and 2440°F) F.T. These low to moderate ash fusibility temperature results would indicate a good potential for forming fluid deposits in the furnace with each of these coals.

The principle of the base-to-acid ratio is based upon the tendency of ash constituents to combine according to their acidic and basic properties to form low melting salts; values of this ratio between 0.4 and 0.7 have been correlated to low melting ashes. The BT-11 coal ashes have base to acid ratios falling within this problem range, 0.4 and 0.5 seams 1 and 2 respectively. These results are consistent with the baseline and washed ratios of 0.32 and 0.45, and with their respective low to moderate ash fusibility temperatures.

The iron-to-calcium ratio is used as a slagging indicator to account for the fluxing effect of calcium upon iron. This fluxing effect is generally seen with coals having ratios between 10 and 0.2 and is generally most pronounced for ratios between 3 and 0.3. Results for the BT-11 coals fall well above this range, 9.0 and 13.5 for seams 1 and 2 respectively. The high iron content in the ash appears to be the most significant characteristic. Iron compounds in segregated form are known to play a dominant role in slagging behavior. In a reduced state, pyritic iron along with fluxing constituents often result in low melting temperature ash and the potential for troublesome fused/molten furnace deposits. Hence, the high iron content and the low to moderate ash fusibility temperatures of the BT-11 coals would indicate high slagging potential. These results are similar to the baseline and the washed. The BT-11 coals would result slightly worse slagging because of their higher iron in the ash and generally lower ash fusibility temperatures.

The primary considerations when evaluating the fouling potential of a fuel are the ash initial deformation and soften temperatures, and the alkali and alkaline earth concentrations. Sodium, in particular, can play a major role in convective pass fouling. Sodium vaporizes during combustion and subsequently reacts chemically and physically downstream in the boiler, providing a sticky bonding matrix to build convection pass deposit. Similar to the baseline and washed, the sodium content is low in both BT-11 coals, consisting of less than 0.8% of the total ash. Thus from the sodium standpoint, all four Lakhra coals should have a low fouling potential. However, the high ash loading and other factors such as slag carry-over phenomena from the lower furnace can still lead to high fouling. The generally lower ash fusibility temperatures and the potentially higher slag carry-over rate due to the higher iron content of the BT-11 coals would result slightly higher fouling than the baseline and washed.

The Hardgrove Grindability Index (HGI) is used to determine the relative ease of coal pulverization. Normally, the higher the HGI, the less energy is required to grind the coal to a desired fineness. Values obtained from the BT-11 seams 1 and 2 are 78 and 106, from the baseline and washed are 71 and 67. These results indicate all four Lakhra coals are easy to pulverize. The BT-11 seam 2 would be easiest to grind, followed by BT-11 seam 1, baseline and washed.

To summarize, standard ASTM analyses indicate the two BT-11 coals have generally similar good combustion characteristics as the baseline and washed. All four coals would be easy to pulverize. Slagging potentials of the two BT-11 coals is similarly high, and fouling potential is similarly moderate. They would be slightly worse compared to the baseline and washed due to their higher iron content in the ash and their generally lower ash fusibility temperatures.

TABLE 3-1

ANALYSIS OF RAW LAKHRA BT-11 COAL SAMPLES

	SEAM 1		SEAM 2	
	As Received	Moisture Free	As Received	Moisture Free
Proximate, Wt. Percent				
Moisture (Total)	25.2	—	29.8	—
Volatile Matter	28.9	38.7	23.6	33.6
Fixed Carbon (Diff.)	21.7	28.9	19.5	27.7
Ash	24.2	32.4	27.1	38.7
Total	100.0	100.0	100.0	100.0
HHV, Btu/lb	5710	7630	4860	6925
LB Ash/10^6 Btu	42.5		55.9	
Ultimate, Wt. Percent				
Moisture (Total)	25.2	—	29.8	—
Hydrogen	2.8	3.7	2.1	3.0
Carbon	31.0	41.4	26.7	38.1
Sulfur	6.1	8.1	6.4	9.1
Nitrogen	0.6	0.8	0.5	0.8
Oxygen (Diff.)	10.1	13.6	7.4	10.3
Ash	24.2	32.4	27.1	38.7
Total	100.0	100.0	100.0	100.0
Sulfur Form				
Pyritic	4.6	6.1	5.0	7.1
Sulfate	0.6	0.8	0.5	0.7
Organic	0.9	1.2	0.9	1.3
Ash Fusibility				
I.T. Deg. F	2100		2120	
S.T. Deg. F	2310		2250	
H.T. Deg. F	2370		2330	
F.T. Deg. F	2430		2380	
Temp. Diff. (FT-IT)	330		260	
Ash Composition, Wt. Percent				
SiO_2	40.9		42.4	
Al_2O_3	24.6		20.4	
Fe_2O_3	22.6		27.0	
CaO	2.5		2.0	
MgO	1.3		1.2	
Na_2O	0.8		0.7	
K_2O	0.2		0.5	
TiO_2	1.6		1.8	
SO_3	3.2		1.7	
Total	97.7		97.7	
Ratios				
Base/Acid	0.4		0.5	
Fe_2O_3/CaO	9.0		13.5	
SiO_2/Al_2O_3	1.7		2.1	
Acetic Acid Reachable, %				
Na_2O	0.78		0.70	
K_2O	0.05		0.06	
Grindability	78		106	
Abrasiveness	28		30	
Free Quartz, %	0.9		3.0	

TABLE 3-2

COMPARISON OF BENCH-SCALE ANALYSES BETWEEN LAKHRA COALS

	PMDC BASELINE	PMDC WASHED	BT-11 SEAM 1	BT-11 SEAM 2
PROXIMATE, WT % (DRY)				
VOLATILE MATTER	35.0	41.6	38.7	33.6
FIXED CARBON	28.6	39.3	28.9	27.7
ASH	36.4	19.1	32.4	38.7
TOTAL	100.0	100.0	100.0	100.0
HHV, BTU/LB (DRY)	7,340.0	10,330.0	7,630.0	6,925.0
ULTIMATE, WT% (DRY)				
HYDROGEN	3.6	4.7	3.7	3.0
CARBON	40.6	57.2	41.4	38.1
SULFUR	6.1	4.7	8.1	9.1
NITROGEN	0.7	1.2	0.8	0.8
OXYGEN	12.6	13.1	13.6	10.3
ASH	36.4	19.1	32.4	38.7
TOTAL	100.0	100.0	100.0	100.0
ASH FUSIBILITY, °F				
I.T.	1980	2040	2100	2120
S.T.	2430	2350	2310	2250
H.T.	2470	2410	2370	2330
F.T.	2520	2440	2430	2380
ASH COMPOSITION, WT %				
SiO_2	43.6	39.0	40.9	42.4
Al_2O_3	27.2	22.9	22.6	27.0
Fe_2O_3	17.2	19.3	22.6	27.0
CaO	3.3	5.3	2.5	2.0
MgO	1.3	2.2	1.3	1.2
Na_2O	0.7	1.2	0.8	0.7
K_2O	0.7	0.6	0.2	0.5
TiO_2	1.9	1.5	1.6	1.8
SO_3	3.9	6.4	3.2	2.7
TOTAL	99.8	98.4	97.7	98.7
Fe_2O_3 in 2.9 sink, WT%	87.7	89.8	83.5	88.8
GRINDABILITY	71	67	78	106
ABRASIVENESS	50	12	28	30

Special Bench-Scale Tests

Five special bench-scale tests were conducted for all four Lakhra coals. Testing included Thermo-Gravimetric analysis, specific surface area, abrasion index, weak acid leaching, and gravity fractionation analysis.

Results of the Thermo-Gravimetric Analysis are shown in Figure 3-1. Char burn-off curves obtained from various U.S. coals with known commercial experience are shown for comparison basis. The curves for all the Lakhra coal chars show a rapid burn-off rate. The reactivity of each of these chars is comparable to the reference U.S. Montana subbituminous coal which has good field combustion characteristics. These results are consistent with the standard ASTM tests indicating good burning qualities of these coals.

Table 3-3 shows the specific surface areas of the Lakhra and the reference coal chars. On a dry, ash free basis, the BT-11 seams 1 and 2, baseline and washed coal chars have BET surface areas of 310, 231, 214.4 and 159 m^2/g respectively. Overall, the from reactivity stand point, rapid char burn-off rate and the high surface area of these coals indicate they should not present carbon heat loss problems.

The abrasion index is a measure of relative mill wear potential. Values obtained from the BT-11 seams 1 and 2, baseline and washed are 14 and 15, 25 and 6 Kgs/1000 tonne (29 and 30, 50 and 12 lbs/1000 tons) respectively. These results would indicate a relatively moderate mill wear potential for the BT-11 coals, high for the baseline and low for the washed.

The weak acid leaching analysis provides more definitive information on the nature of the alkalis in the ash. The technique detects "active" alkalis which are loosely bound, and are likely to volatilize during combustion and be instrumental in ash fouling. The BT-11 coals were leached at pH value of 3 and the leachates were subsequently analyzed for sodium, calcium and magnesium contents. Results show the total sodium in these coal ashes are low, 0.8 and 0.7%, of which 98 and 99% are in the "active form". These results are similar to the baseline and washed. Low to moderate ash fusibility temperature and high ash loading would indicate a moderate fouling for all these coals. The BT-11s would be slightly worse due to their generally lower ash fusibility temperatures and their higher iron content in the ash.

The gravity fractionation analysis was conducted on composite pulverized coal samples obtained during the FPTF combustion performance evaluation. This analysis quantifies the amount of segregated irons presented in the coal ash. Figure 3-2 shows a good correlation between the percentage of iron in the 2.9 sink fraction and the observed slagging performance in the field units designated by numbers 1 through 16. In general, coals having greater than 70% Fe_2O_3 in the ash of 2.9 sink fractions would exhibit high slagging potential.

Four gravity fractions using organic liquids having specific gravities of 1.5, 1.9, 2.5 and 2.9 were used. Each of these cuts were subjected for ASTM ash analyses. Results are shown in Table 3-4. The Fe_2O_3 in the 2.9 sink fraction is 83.5% for BT-11 seam 1 and 88.8% for seam 2. The baseline and washed yielded similar results, 87.7 and 89.8%, respectively. The extremely high Fe_2O_3 concentration coupled with the high ash content and low to moderate ash fusibility temperatures would indicate a severe slagging potential for these coals.

Overall, the special bench-scale tests are consistent with the standard ASTM tests and provide additional information indicating the BT-11 coals have similar good combustion reactivity as the baseline and washed. The mill wear potential of the these coals would be moderate compared to high for the baseline and low for the washed. The gravity fractionation results show a high concentration of segregated iron compounds in each of the BT-11, baseline and washed coal ashes. The weak acid leaching results show although the total sodium is similarly low in each coal ash, most of it is in "active" form. All these Lakhra coals would have a severe slagging and moderate fouling potential. The BT-11 coals would be slightly worse than the baseline and washed due to their higher iron content in the ash and generally lower ash fusibility temperatures.

FIGURE 3-1
THERMOGRAVIMETRIC BURN-OFF OF 200 x 400 MESH DTFS CHARS AT 700°C

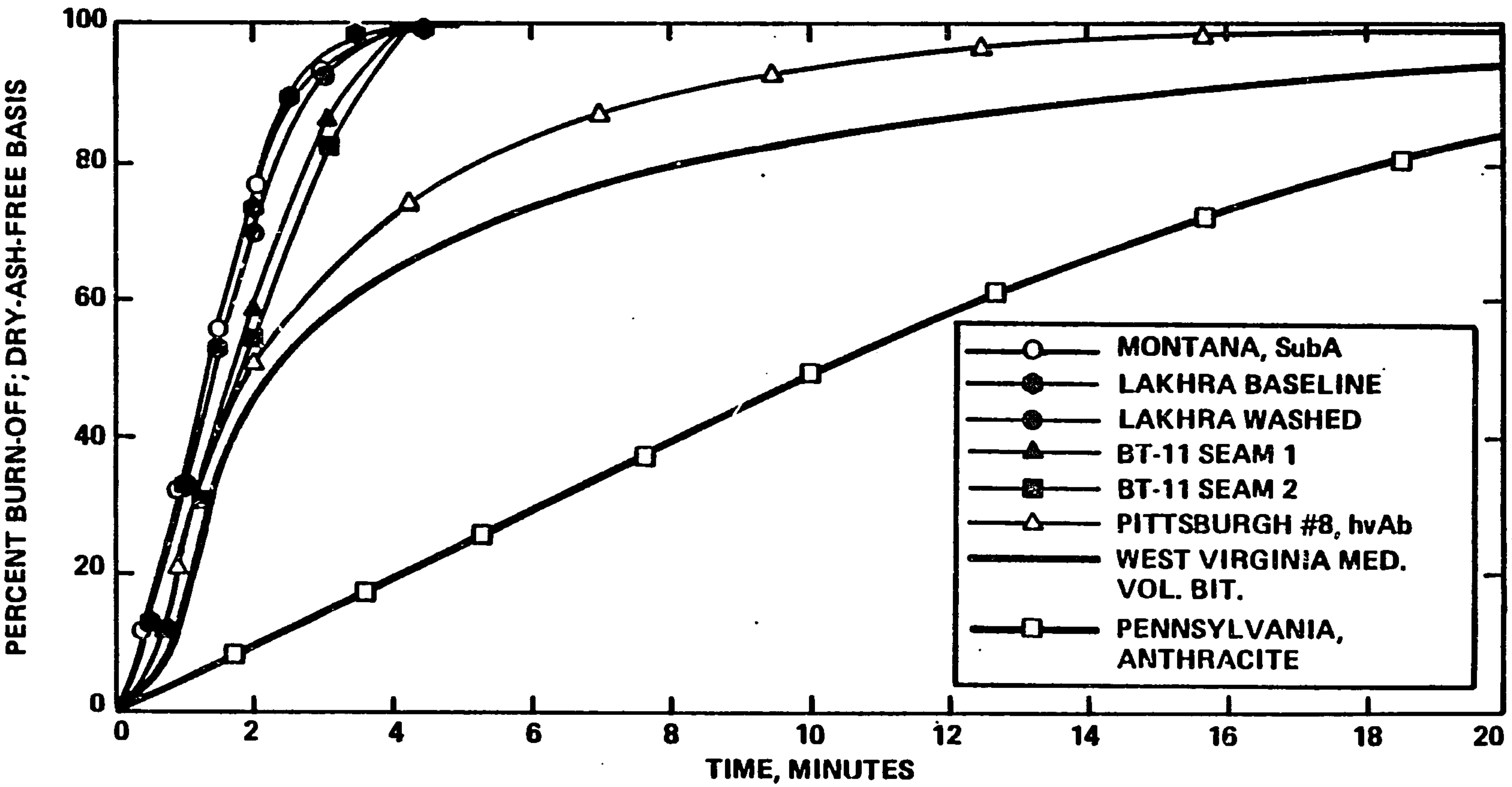


TABLE 3-3

BET SURFACE AREA OF THE 200 X 400 MESH ANALYTICAL CHAR SAMPLES

Char Origin	CHAR PROXIMATE ANALYSES, WT.%				BET Surface Area, M^2/g, dry-ash-free
	Moisture	Volatile Matter	Fixed Carbon	Ash	
Montana, SubA	1.7	3.1	79.8	15.4	64.3
Pittsburge #8 hvAb	0.1	1.5	86.5	11.9	29.2
West Virginia Med. Vol. Bit.	0.0	0.1	70.3	29.6	12.3
Pennsylvania Anthracite	0.0	0.6	92.6	6.8	2.6
Lakhra Baseline	2.5	2.0	45.3	50.2	214.4
Lakhra Washed	3.2	2.7	60.6	33.5	159.0
Lakhra BT-11 Seam 1	2.4	1.4	31.2	65.0	310.0
Lakhra BT-11 Seam 2	2.8	2.0	46.3	48.9	231.0

FIGURE 3-2

EFFECT OF SEGREGATED IRON ON COAL ASH SLAGGING
SLAGGING POTENTIAL
VERSUS
PERCENT IRON IN 2.9 GRAVITY FRACTION

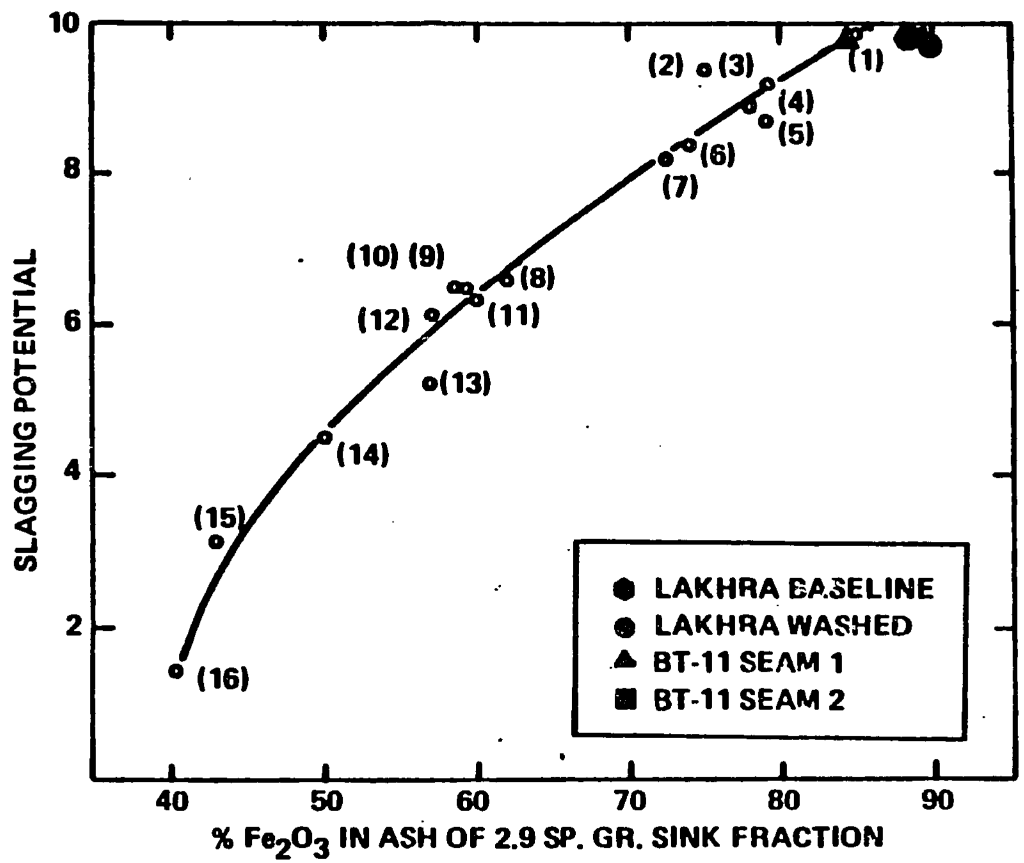


TABLE 3-4

ASH COMPOSITION OF LAKHRA BT-11 GRAVITY FRACTIONS

	1.5	1.5 - 1.9	1.9 - 2.5	2.5 - 2.9	2.9 Sink
SEAM 1					
Ash Composition %					
SiO_2	27.1	39.5	46.7	58.5	6.6
Al_2O_3	12.8	24.6	29.0	31.3	2.4
Fe_2O_3	22.5	24.7	13.3	6.6	83.5
CaO	3.8	1.5	3.1	0.5	0.3
MgO	4.8	1.7	0.7	0.6	0.1
Na_2O	2.3	0.9	0.4	0.2	0.1
K_2O	0.5	0.5	0.6	0.7	0.1
TiO_2	1.3	1.4	1.6	1.8	0.4
SO_3	25.2	2.2	2.9	0.4	5.3
Total	100.3	97.0	98.3	100.6	98.8
SEAM 2					
SiO_2	27.3	42.7	49.0	57.9	7.2
Al_2O_3	15.4	25.6	29.3	28.0	2.4
Fe_2O_3	25.3	20.8	12.3	8.7	88.8
CaO	4.2	2.2	3.4	0.7	0.3
MgO	4.7	1.8	0.8	0.7	0.1
Na_2O	2.4	1.0	0.3	0.4	0.1
K_2O	0.3	0.7	0.9	1.0	0.2
TiO_2	0.9	2.3	1.9	2.5	0.3
SO_3	19.6	1.5	2.6	0.5	1.1
Total	100.1	98.6	100.5	100.4	100.6

PULVERIZATION

The BT-11 seams 1 and 2, baseline and washed coals were pulverized in the FPTF bowl mill. Results are summarized in Table 3-5. Overall, pulverization characteristics of these coals were generally similar. All four coals were easy to grind. The energy required per ton to pulverize to 70± 3% through 75 microns (200 mesh) fineness was lowest with the BT-11 seam 2, followed by the washed, the BT-11 seam 1, and the baseline. The respective values were 7.6, 7.8, 8.2 and 8.4 Kw-hr/tonne (6.9, 7.1, 7.4 and 7.6 Kw-hr/ton). However, on a per GJ (10^6 Btu) basis, the grinding energy required was similar for the BT-11 seams 1 and 2 and the baseline, 0.46, 0.47, and 0.49 Kw-hr/GJ (0.48, 0.50, and 0.52 Kw-hr/10^6 Btu) respectively; but it was significantly lower with the washed, 0.32 Kw-hr/GJ (0.34 Kw-hr/10^6 Btu), due to the reduction in fuel throughput associated with increased higher heating value of the washed coal.

All these coals could be pulverized at a mill capacity of 613 Kg/hr (1350 lb/hr) without excessive spillage. The mill rejection rate was 0.7, 0.2, 2.1, and 0.8% for BT-11 seams 1 and 2, baseline and washed, respectively. Analysis of the composite mill reject samples from BT-11 seams 1 and 2 coals are shown in Table 3-6. The ratio of the reject flow and reject composition to the coal flow and coal composition indicate rejection of 1.8 and 0.5% sulfur, and 1.2 and 0.3% ash from the raw BT-11 seams 1 and 2 coals. The corresponding values for the baseline and washed coals are 4.8 and 1.5% sulfur, and 2.3 and 1.7% ash, respectively.

In summary, all four coals exhibited good pulverization characteristics requiring relatively low mill power consumption for grinding. Bench scale abrasion index indicates a moderate potential to cause mill wear for the BT-11 coals, high for the baseline and low for the washed.

TABLE 3-5

COMPARISON OF PULVERIZATION CHARACTERISTICS BETWEEN LAKHRA COALS

	BASELINE	WASHED	BT-11-1	BT-11-2
Hardgrove Grindability	71	67	78	106
Mill Power Requirement				
Kw-hr/Tonne (Kw-hr/ton)	8.4 (7.6)	7.8 (7.1)	8.2 (7.4)	7.6 (6.9)
Kw-hr/GJ (Kw-hr/10^6 Btu)	0.49 (0.52)	0.32 (0.34)	0.46 (0.48)	0.47 (0.50)
Mill Rejection Rate (Wt.% of Coal Feed)	2.1	0.8	0.7	0.2
Abrasion Index	50	12	28	30
Quartz Content %	1.7	0.4	0.9	3.0

TABLE 3-6

ANALYSIS OF LAKHRA BT-11 COAL MILL REJECT SAMPLES

	SEAM 1 As Received	SEAM 1 Moisture Free	SEAM 2 As Received	SEAM 2 Moisture Free
Proximate, Wt. Percent				
Moisture (Total)	4.6	---	7.1	---
Volatile Matter	28.6	30.0	25.9	27.8
Fixed Carbon (Diff)	14.0	14.7	17.2	18.6
Ash	52.8	55.3	49.8	53.6
Total	100.0	100.0	100.0	100.0
HHV, Btu/lb	4051	4246	4165	4485
Ultimate, Wt. Percent				
Moisture (Total)	4.6	---	7.1	---
Hydrogen	1.7	1.8	1.4	1.5
Carbon	18.3	19.2	17.8	19.1
Sulfur	19.8	20.8	21.8	23.5
Nitrogen	0.4	0.4	0.3	0.4
Oxygen (Diff)	2.4	2.5	1.8	1.9
Ash	52.8	55.3	49.8	53.6
Total	100.0	100.0	100.0	100.0
Sulfur Form				
Pyritic	16.4		17.9	
Sulfate	2.1		1.4	
Organic	1.3		2.5	
Ash Fusibility (Red.)				
I.T. Deg F	2040		1950	
S.T. Deg F	2130		2010	
H.T. Deg F	2190		2030	
F.T. Deg F	2410		2190	
Temp Diff (FT-IT)	370		240	
Ash Composition, Wt. Percent				
SiO_2	22.5		23.5	
Al_2O_3	13.7		11.7	
Fe_2O_3	55.4		59.5	
CaO	0.7		0.6	
MgO	0.4		0.5	
Na_2O	0.1		0.2	
K_2O	0.3		0.3	
TiO_2	0.9		1.4	
SO_3	5.8		2.2	
Total	99.2		99.9	
Ratios				
Base/Acid	1.5		1.7	
Fe_2O_3/CaO	79.1		99.2	
SiO_2/Al_2O_3	1.6		2.0	

PILOT-SCALE COMBUSTION PERFORMANCE EVALUATION

As-Fired Fuel Analysis

Composite samples were collected during the BT-11 seams 1 and 2 FPTF test firings for analysis. Overall, the as-fired fuel samples are consistent with their respective raw coal. Proximate and ultimate analysis results presented in Table 3-7 show 28.9 and 30.1% ash, and 7.8 and 8.4% sulfur for seams 1 and 2 respectively on a moisture free basis. These values are lower compared to the raw coal results of 32.4 and 38.7% ash, and 8.1 and 9.1% sulfur. The differences are mostly accounted for by the amount of mill rejects.

Ash fusibility and ash composition of the as-fired fuels show a slightly higher ash fluid temperature, 1377 and 1310^{o}C (2510 and 2390^{o}F) versus 1332 and 1304^{o}C (2430 and 2380^{o}F), and slightly lower iron content, 21.3 and 19.6% versus 22.6 and 27.0%, than the raw coal seams 1 and 2 respectively.

Particle size analysis of the as-fired fuel samples is shown in Figure 3-3. Samples were determined by sieve analysis for all materials greater than 75 microns (200 mesh) and by laser diffraction technique for all materials less than 75 microns (200 mesh). Results show 70.6 and 71.0% through 75 microns (200 mesh) with the mass median particle diameters (MMD) of 48 and 46 microns for the seams 1 and 2 composite samples respectively.

Furnace Operating Conditions

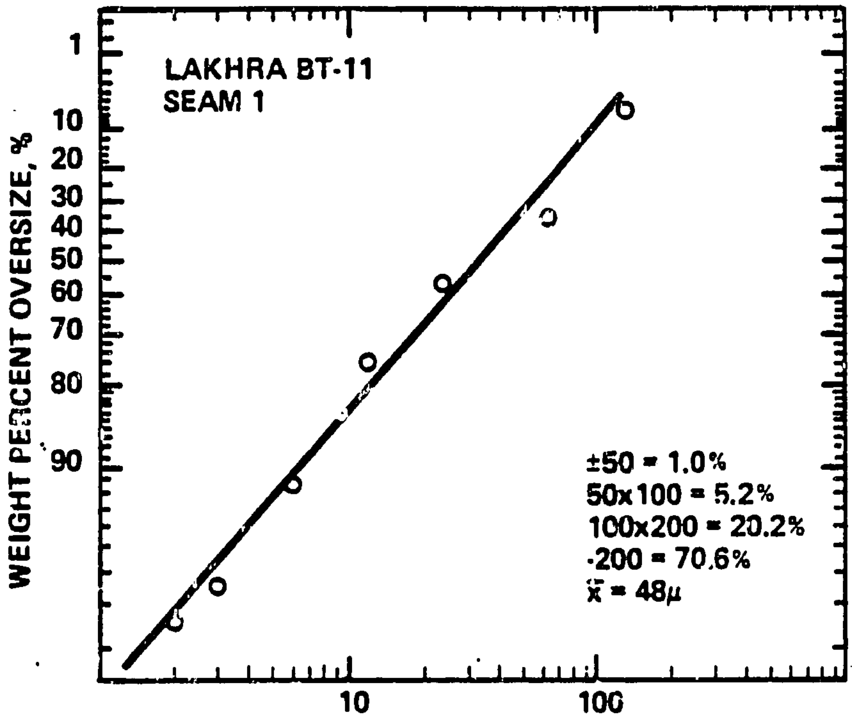
Furnace operating conditions during each of the test runs are summarized in Tables 3-8. Each test was conducted at 25% excess air level to simulate a typical field unit operating with high slagging coal. With exception for seam 2 Test 2 when the furnace was shutdown for deslagging, the duration for all other tests were conducted for approximately 12 hours. The fuel loading was kept at 2.95 GJ/hr (2.80 x 10^{6} Btu/hr) to allow direct comparison between the baseline and washed coals.

TABLE 3-7

ANALYSIS OF AS-FIRED PULVERIZED LAKHRA BT-11 COAL SAMPLES

	SEAM 1 As Fired	SEAM 1 Moisture Free	SEAM 2 As Fired	SEAM 2 Moisture Free
Proximate, Wt. Percent				
Moisture (Total)	7.9	—	8.4	—
Volatile Matter	36.1	39.2	33.8	36.9
Fixed Carbon (Diff)	29.4	31.9	30.2	33.0
Ash	26.6	28.9	27.6	30.1
Total	100.0	100.0	100.0	100.0
HHV, Btu/lb	7340	7975	7300	7970
Lb/Ash/mm Btu	36.2		37.8	
Ultimate, Wt. Percent				
Moisture (Total)	7.9	—	8.4	—
Hydrogen	3.4	3.6	3.5	3.8
Carbon	41.4	44.9	39.8	43.4
Sulfur	7.2	7.8	7.7	8.4
Nitrogen	0.7	0.8	0.8	0.8
Oxygen (Diff)	12.8	13.9	12.2	13.5
Ash	26.6	28.9	27.6	30.1
Total	100.0	100.0	100.0	100.0
Sulfur Form				
Pyritic	2.6		2.8	
Sulfate	1.4		0.9	
Organic	3.1		2.1	
Ash Fusibility (Red.)				
I.T. Deg F	2070		1930	
S.T. Deg F	2250		2200	
H.T. Deg F	2460		2340	
F.T. Deg F	2510		2390	
Temp Diff (FT-IT)	440		460	
Ash Composition, Wt. Percent				
SiO_2	38.8		44.3	
Al_2O_3	26.1		24.4	
Fe_2O_3	21.3		19.6	
CaO	3.1		0.8	
MgO	1.4		0.4	
Na_2O	0.7		0.8	
K_2O	0.5		0.7	
TiO_2	2.5		2.8	
SO_3	3.7		4.0	
Total	98.1		97.8	
Ratios				
Base/Acid	0.4		0.3	
Fe_2O_3/CaO	6.9		23.3	
SiO_2/Al_2O_3	1.5		1.8	
Screen Analysis				
±50	1.0		1.1	
50 x 100	5.2		5.5	
100 x 200	20.2		22.4	
-200	73.6		71.0	
MMD, Microns	48.0		46.0	

FIGURE 3-3
ROSIN-RAMMLER PLOT OF AS-FIRED LAKHRA BT-11 COAL SAMPLES



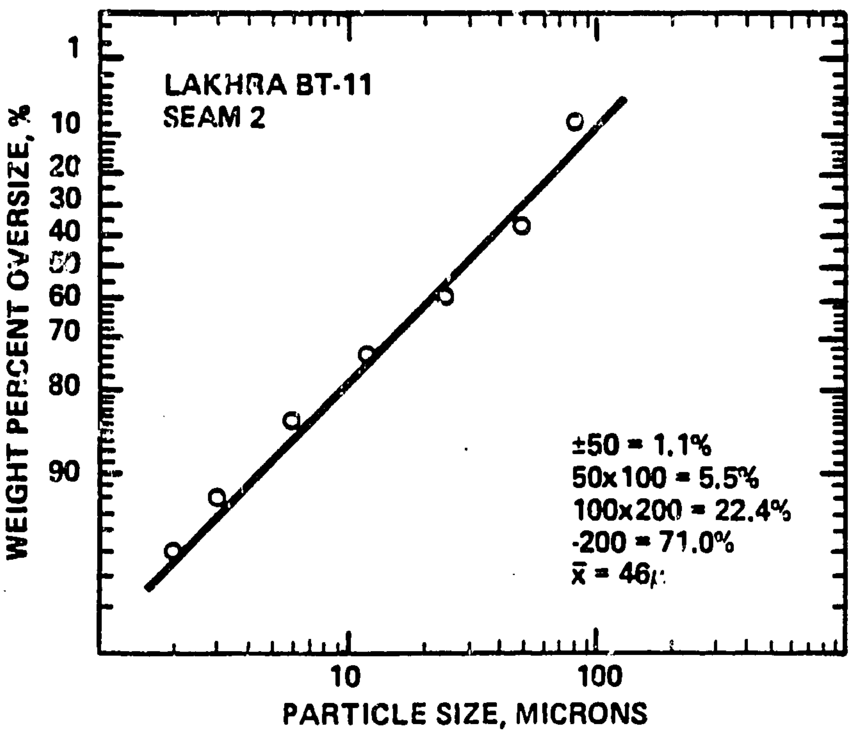


TABLE 3-8

FPTF FURNACE OPERATING CONDITIONS DURING THE LAKHRA BT-11 COAL EVALUATION

	SEAM 1			SEAM 2	
	TEST 1	TEST 2	TEST 3	TEST 1	TEST 2
COMBUSTION DATA					
FUEL FEET RATE LB/HR	.381E+03	.380E+03	.382E+03	.382E+03	.383E+03
FUEL HHV BTU/HR	.734E+04	.734E+04	.734E+04	.730E+04	.730E+04
TOTAL HEAT INPUT BTU/HR (FROM FUEL AND PREHEATED SECONDARY AIR)	.301E+07	.290E+07	.292E+07	.305E+07	.315E+07
PRIMARY AIR FLOW LB/HR	.263E+03	263E+03	.259E+03	.257E+03	.257E+03
PRIMARY AIR TEMP. F	.860E+02	.860E+02	.890E+02	.700E+02	.750E+02
SECONDARY AIR FLOW LB/HR	.242E+04	.244E+04	.242E+04	.242E+04	.241E+04
SECONDARY AIR TEMP. F	.430E+03	.260E+03	.266E+04	.485e+03	.650e+03
OXYGEN (IN FLUE GAS)	.454E-01	.461E-01	.470E-01	.415E-01	.471E-01
FURNACE PRESSURE (INCHES H2O)	.332E+02	.327E+02	.350E+02	.406E+02	.300E-02
LOWER FURNACE TEMP. F	.263E+04	.257E+04	.257E+04	.257E+04	.267E+04
LOWER FURNACE RESIDENCE TIME SEC.	.155E+01	.155W+01	.154E+01	.156E+01	.154E+01
WATERWALL TEST PANELS					
PANEL B SURFACE TEMP. F	.610E+03	.599E+03	.623E+03	.601E+03	.653E+03
PANEL C SURFACE TEMP. F	.543E+03	.635E+03	.659E+03	.601E+03	.628E+03
SUPERHEATER PROBES					
DUCT 1 GAS TEMPERATURE F	.214E+04	.210E+04	.212E+04	.214E+04	.208E+04
DUCT 2 GAS TEMPERATURE F	.201E+04	.198E+04	.200E+04	.201E+04	.194E+04
DUCT 3 GAS TEMPERATURE F	.185E+04	.183E+04	.182E+04	.184E+04	.181E+04
DUCT 4 GAS TEMPERATURE F	.164E+04	.162E+04	.161E+04	.166E+04	.163E+04
DUCT 1 GAS VELOCITY FT/SEC	.542E+02	.538E+02	.548E+02	.548E+02	.545E+02
DUCT 2 GAS VELOCITY FT/SEC	.514E+02	.513E+02	.514E+02	.517E+02	.514E+02
DUCT 3 GAS VELOCITY FT/SEC	.471E+02	.492E+02	.500E+02	.510E+02	.478E+02
DUCT 4 GAS VELOCITY FT/SEC	.432E+02	.443E+02	.438E+02	.443E+02	.442E+02
ASH					
INPUT LB/HR	.101E+03	.101E+03	.102E+03	.105E+03	.106E+03
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Furnace Temperature Profile

Furnace temperature profile was carefully monitored and recorded throughout each test. Results of the flame and gas temperatures are summarized in Table 3-9. Individual temperature profiles with respect to burner distance and to residence time for each of the test runs are plotted in Figures 3-4 through 3-7. Furnace temperatures were measured by using a single shielded, high velocity suction pyrometer. Four traverse measurements were taken at five furnace ports located approximately 0.9m (3 ft.), 1.2m (4 ft.), 2.1m (7 ft.), 2.4m (8 ft.), and 3.7m (12 ft) above the burner during each test. Two traverse measurements were taken at each of the eight convection section ports. Adjustments were made during each test to maintain the variation of traverse temperatures within 100°F for a given radial location. The average peak flame temperature occurred in L1 and L2 throughout each of these test runs. Peak flame temperatures ranged from 1463 to 1410°C (2630 to 2570°F) for seam 1 and 1465 to 1410°C (2670 to 2570°F) for seam 2.

The gas temperature entering the convective pass section ranged from 1171 to 877°C (2140 to 1610°F) for seam 1, and 1171 to 888°C (2140 to 1630°F) for seam 2. The reduction of gas temperature from superheater banks I to IV was roughly 500°F throughout all test firings. Variation between the traverse temperatures for a given superheater section port was less than 25°F. The corresponding gas velocity entering the superheater ranged from 16.7 to 13.2m/sec (54.8 to 43.2 ft/sec) for seam 1, and 16.7 to 13.5m/sec (54.8 to 44.2 ft/sec) for seam 2.

Furnace Residence Time

The furnace radiant section residence time during these tests ranged from 1.54 to 1.55 second for seam 1, and 1.54 to 1.56 seconds for seam 2. These values are similar to the typical commercial pulverized coal fired units of 1.5 to 2.0 seconds.

TABLE 3-9

TEMPERATURE PROFILES DURING THE LAKHRA BT-11 COAL EVALUATION

COAL TYPE	TEST NO.	FIRING RATE GJ/HR ($x10^6$ Btu/Hr)	RADIANT SECTION °C (°F) L1	L2	L3	L3A	L4	CONVECTIVE SECTION °C (°F) I	II	III	IV
Seam 1	1	2.95 (2.80)	1443 (2630)	1377 (2510)	1354 (2470)	1343 (2450)	1300 (2370)	1171 (2140)	1100 (2010)	1010 (1850)	893 (1640)
	2	2.94 (2.79)	1410 (2570)	1371 (2500)	1354 (2470)	1338 (2440)	1277 (2330)	1149 (2100)	1082 (1980)	1000 (1830)	882 (1620)
	3	2.95 (2.80)	1410 (2570)	1366 (2490)	1332 (2430)	1327 (2420)	1293 (2360)	1160 (2120)	1093 (2000)	993 (1820)	877 (1610)
Seam 2	1	2.95 (2.80)	1465 (2670)	1400 (2550)	1388 (2530)	1349 (2460)	1265 (2310)	1171 (2140)	1100 (2010)	1004 (1840)	904 (1660)
	2	2.95 (2.80)	1410 (2570)	1388 (2510)	1354 (2470)	1338 (2440)	1260 (2300)	1138 (2080)	1060 (1940)	988 (1810)	888 (1630)

FIGURE 3-4
FPTF TEMPERATURE PROFILES DURING THE LAKHRA BT-11 SEAM 1 COAL EVALUATION

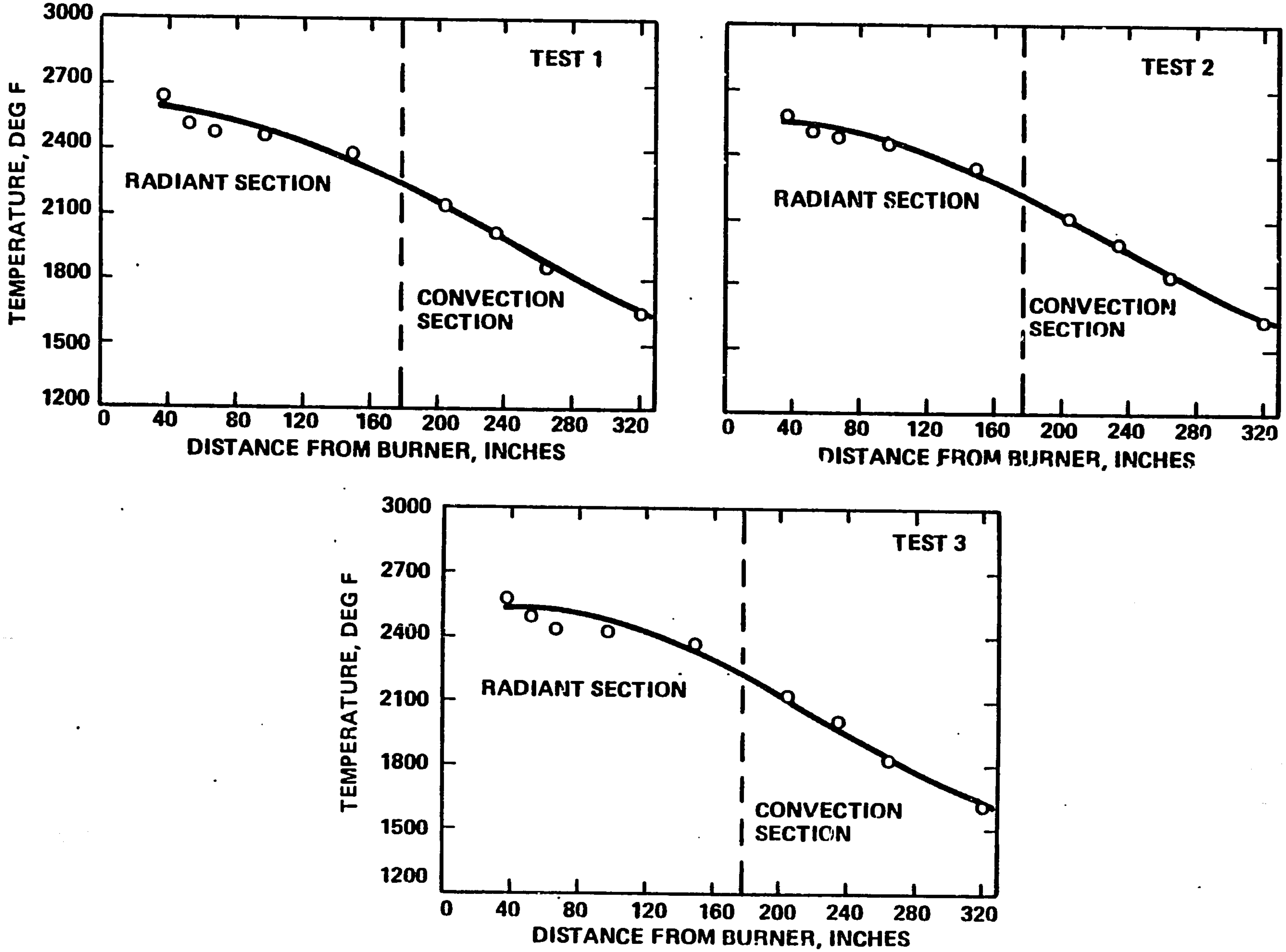


FIGURE 3-5
FPTF TEMPERATURE PROFILES DURING THE LAKHRA BT-11 SEAM 2 COAL EVALUATION

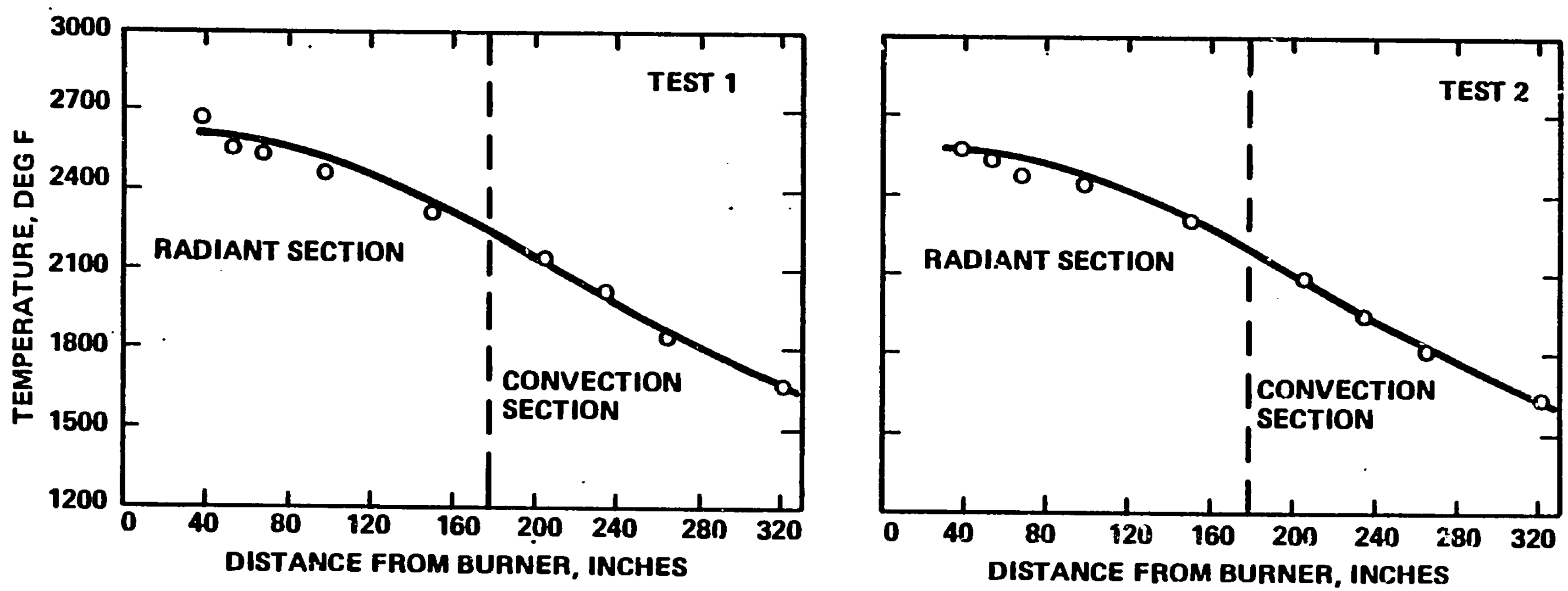


FIGURE 3-6
RESIDENCE TIME IN THE FPTF DURING THE LAKHRA BT-11 COAL EVALUATION
SEAM 1

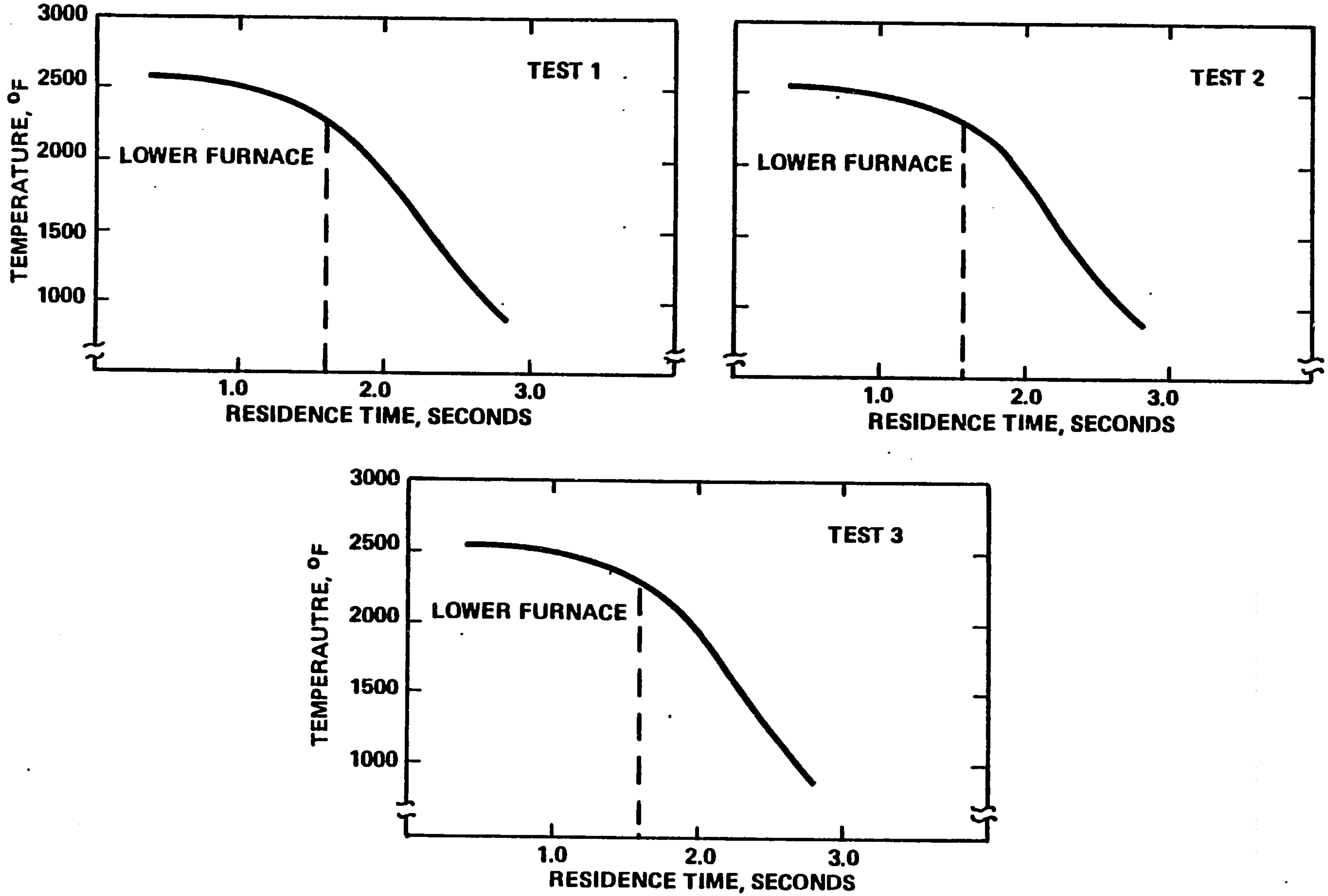


FIGURE 3-7
RESIDENCE TIME IN THE FPTF DURING THE LAKHRA BT-11 COAL EVALUATION
SEAM 2

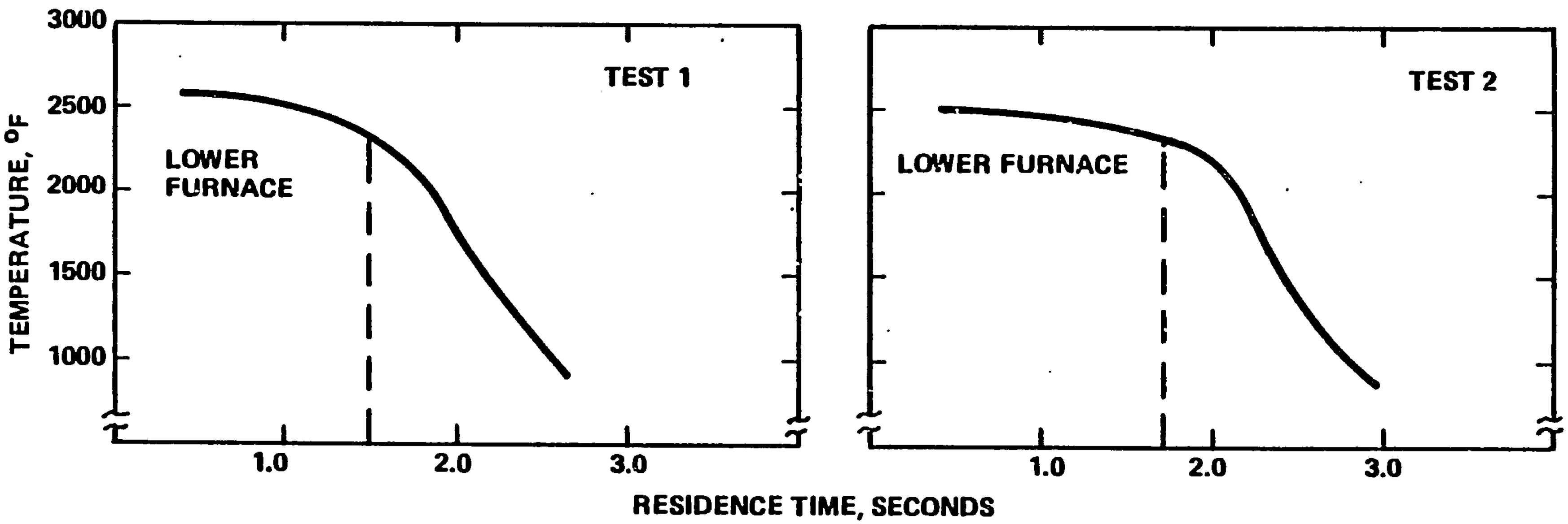


TABLE 3-10

MASS AND ENERGY BALANCES DURING THE LAKHRA BT-11 COAL EVALUATION

	SEAM 1						SEAM 2			
	TEST 1		TEST 2		TEST 3		TEST 1		TEST 2	
METHOD 1--------- FLUE GAS FLOW RATE LB/HR	.296E+04		.298E+04		.296E+04		.295E+04		.295E+04	
COMPOSITION IN MOLES/HR										
OXYGEN	.382E+01	3.82	.399E+01	3.97	.373E+01	3.74	.370E+01	3.69	.360E+01	3.60
CARBON DIOXIDE	.131E+02	13.12	.131E+02	13.01	.132E+02	13.19	.132E+02	13.21	.133E+02	13.28
WATER	.984E+01	9.84	.984E+01	9.77	.987E+01	9.88	.101E+02	10.13	.102E-02	10.18
SULFUR DIOXIDE	.854E+00	.85	.852E+00	.85	.857E+00	.86	.703E+00	.70	.705E+00	.71
NITROGEN	.724E+02	72.37	.729E+02	72.41	.723E+02	72.34	.724E+02	72.26	.722E+02	72.24
METHOD 1--------										
HEAT LOSS FROM REFRACTORY BTU/HR	.155E+06	5.13	.143E+06	4.94	.146E+06	4.99	.170E+06	5.57	.170E+06	6.52
HEAT LOSS FROM PANEL	.113E+06	3.75	.105E+06	3.63	.117E+06	4.02	.154E+06	5.07	.161E+06	5.10
HEAT LOSS FROM WATER COOLED FRAME	.630E+05	2.09	.668E+05	2.30	.635E+05	2.17	.662E+05	2.17	.955E+05	3.03
HEAT LOSS FROM FLY ASH	.323E+05	1.07	.317E+05	1.09	.323E+05	1.11	.338E+05	1.11	.326E+05	1.03
HEAT LOSS FROM FLUE GAS	.167E+07	55.31	.165E+07	56.75	.166E+07	56.97	.176E+07	57.89	.168E+07	53.10
HEAT LOSS FROM ROOF	.387E+05	1.28	.398E+05	1.37	.429E+05	1.47	.451E+05	1.48	.429E+05	1.36
HEAT LOSS FROM PROCESS HEATER	.770E+05	2.56	.767E+05	2.64	.807E+05	2.77	.946E+05	3.10	.695E+05	2.20
HEAT LOSS FROM S.H. TRANSITION	.111E+06	3.67	.136E+06	4.68	.126E+06	4.32	.142E+06	4.68	.111E+06	3.53
HEAT LOSS FROM S.H. FRAME	.503E+05	1.67	.444E+05	1.53	.477E+05	1.63	.891E+05	2.92	.598E+05	1.90
HEAT LOSS FROM S.H. DUCT	.196E+06	6.50	.333E+06	11.49	.322E+06	11.03	.340E+06	11.16	.281E+06	8.92
HEAT LOSS FROM OBS. PORT	.361E+05	1.20	.335E+05	1.15	.357E+05	1.22	.379E+05	1.24	.555E+05	1.76
HEAT LOSS FROM BURNER	.383E+05	1.27	.199E+05	.68	.204E+05	.70	.387E+05	1.27	.767E+05	2.43
HEAT LOSS FROM FURNACE BOTTOM LEFT	.550E+05	1.82	.308E+05	1.06	.195E+05	.67	.403E+05	1.32	.659E+05	2.09
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.318+05	1.06	.186E+05	.64	.122E+05	.42	.242E+05	.80	.409E+05	1.30
METHOD 2-------- FLUE GAS FLOW RATE LB/HR	.309E+04		.309E+04		.313E+04		.303E+04		.314E+04	
COMPOSITION IN MOLES/HR										
OXYGEN	.474E+01	4.54	.483E+01	4.61	.498E+01	4.70	.427E+01	4.15	.502E+01	4.71
CARBON DIOXIDE	.131E+02	12.57	.131E+02	12.51	.132E+02	12.44	.132E+02	12.86	.133E+02	12.43
WATER	.993E-01	9.50	.992E+01	9.47	.998E+01	9.43	.102E+02	9.91	.103E+02	9.64
SULFUR DIOXIDE	.854E+00	.82	.852E+00	.81	.857E+00	.81	.703E+00	.68	.705E+00	.66
NITROGEN	.758E+02	72.58	.760E+02	72.60	.769E+02	72.62	.745E+02	72.40	.775E+02	72.56
METHOD 2--------										
HEAT LOSS FROM REFRACTORY BTU/HR	.155E+06	5.13	.143E+06	4.94	.146E+06	4.99	.170E+06	5.57	.206E+06	6.52
HEAT LOSS FROM PANEL	.113E+06	3.75	.105E+06	3.63	.117E+06	4.02	.154E+06	5.07	.161E+06	5.10
HEAT LOSS FROM WATER COOLED FRAME	.630E+05	2.09	.668E+05	2.30	.635E+05	2.17	.662E+05	2.17	.955E05	3.03
HEAT LOSS FROM FLY ASH	.323E+05	1.07	.317E+05	1.09	.323E+05	1.11	.338E+05	1.11	.826E+05	1.03
HEAT LOSS FROM FLUE GAS	.174E+07	57.71	.171E+07	58.95	.176E+07	60.30	.181E+07	59.44	.179E07	56.65
HEAT LOSS FROM ROOF	.387E+05	1.28	.398E+05	1.37	.429E+05	1.47	.451E+05	1.48	.429E+05	1.36
HEAT LOSS FROM PROCESS HEATER	.770E+05	2.56	.767E+05	2.64	.807E+05	2.77	.946E+05	3.10	.695E+05	2.20
HEAT LOSS FROM S.H. TRANSITION	.111E+06	3.67	.136E+06	4.68	.126E+06	4.32	.142E+06	4.68	.111E+06	3.53
HEAT LOSS FROM S.H. FRAME	.503E+05	1.67	.444E+05	1.53	.477E+05	1.63	.891E+05	2.92	.598E+05	1.90
HEAT LOSS FROM S.H. DUCT	.196E+06	6.50	.333E+06	11.49	.322E+06	11.03	.340E+06	11.16	.281E+06	6.92
HEAT LOSS FROM OBS. PORT	.361E+05	1.20	.335E+05	1.15	.357e+05	1.22	.379E+05	1.24	.555E+05	1.76
HEAT LOSS FROM BURNER	.383E+05	1.27	.199E+05	.68	.204E+05	.70	.387E+05	1.27	.767E+05	2.43
HEAT LOSS FROM FURNACE BOTTOM LEFT	.550E+05	1.82	.308E+05	1.06	.195E+05	.67	.403E+05	1.32	.659E+05	2.09
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.318E+05	1.06	.186E+05	.64	.122E+05	.42	.242E+05	.80	.409E+05	1.30
METHOD 1--------TOTAL HEAT INPUT BTU/HR	.301E+07		.290E+07		.292E+07		.305E+07		.315E+07	
TOTAL HEAT OUTPUT BTU/HR	.280E+07		.287E+07		.287E+07		.319E+07		.312E+07	
HEAT UNACCOUNTED FOR	6.93		1.17		1.66		4.59		1.07	
METHOD 2--------TOTAL HEAT INPUT BTU/HR	.301E+07		.290E+07		.292E+07		.305E+07		.315E+07	
TOTAL HEAT OUTPUT BTU/HR	.288E+07		.293E+07		.297E+07		.323E+07		.323E+07	
HEAT UNACCOUNTED FOR	4.53		1.03		1.68		6.14		2.48	
METHOD 1--------TOTAL MATERIAL INPUT LB/HR	.306E+04		.308E+04		.306E+04		.306E+04		.305E+04	
TOTAL MATERIAL OUTPUT LB/HR	.306E+04		.308E+04		.306E+04		.306E+04		.305E+04	
MATERIAL UNACCOUNTED FOR	.0		.0		.0		.0		.0	
METHOD 2--------TOTAL MATERIAL INPUT LB/HR	.319E+04		.319E+04		.323E+04		.314E+04		.325E+04	
TOTAL MATERIAL OUTPUT LB/HR	.319E+04		.319E+04		.323E+04		.314E+04		.325E+04	
MATERIAL UNACCOUNTED FOR	.0		.0		.0		.0		.0	

Mass and Energy Balances

Table 3-10 shows the mass and energy balances which include all mass and heat flows from the burner to the first probe bank of the superheater duct during each test. Values presented were obtained by two calculation methods. Method 1 is based on the measured primary and secondary air inputs. Method 2 is based on the measured oxygen concentration in the flue gas. Both of these methods assumed a 100% carbon conversion, as the CO measured in the flue gas was negligible. The overall heat unaccounted for ranged from 1.03 to 6.93% for seam 1, and 1.07 to 6.14% for seam 2. Since the unburned carbon contents in the fly ash are 0.3 and 0.2% for each of the seams 1 and 2 tests, the associated heat loss was less than 0.3 and 0.2% respectively. The discrepancies were most likely due to the radiation losses from the furnace exterior. The ash split during each test was approximately 60% fly ash and 40% bottom ash in the FPTF. The rapid bottom ash buildup required frequent handling throughout each test period.

Relative Combustion Characteristics

Combustion characteristics of the BT-11 coals are similarly good as the baseline and washed. They burnt easily with good stable flame throughout each test condition. Fly ash analysis show the carbon content was low, 0.3 and 0.2% for seams 1 and 2 respectively. The carbon conversion was better than 99.9% for each of these coals.

Furnace Slagging Characteristics

Furnace slagging was characterized by assessing the deposit buildup, deposit cleanability, deposit interference on heat transfer through waterwall, and deposit physical and chemical characteristics. Overall, results indicate the furnace temperature was the most critical parameter controlling slagging of the Lakhra coals. Both BT-11 seams 1 and 2 exhibited severe slagging and were generally slightly worse than the the baseline and the washed. The critical flame temperature established for cleanable waterwall deposits in the FPTF was 1410°C (2570°F) for the BT-11 coals, 1427°C (2600°F) for the baseline, and 1440°C (2630°F) for the washed.

TABLE 3-11

WATERWALL HEAT FLUX RECOVERY DURING THE LAKHRA BT-11 COAL EVALUATION

COAL TYPE	TEST NO.	FIRING RATE GJ/HR ($\times 10^6$ Btu/Hr)	FLAME TEMP AT PANELS °C (°F) B	C	INITIAL HEAT FLUX $\times 10^2$ MJ/HR-M^2 ($\times 10^3$ BTU/HR-FT^2) B	C	FINAL HEAT FLUX $\times 10^2$ MJ/HR-M^2 (10^3 BTU/HR-FT^2) B	C	HEAT FLUX RECOVERY (%) B	C
SEAM 1	1	2.95 (2.80)	1400 (2550)	1438 (2620)	7.22 (63.6)	7.20 (63.4)	1.27 (11.2)	1.22 (10.7)	100	33
	2	2.94 (2.79)	1390 (2530)	1410 (2570)	6.66 (58.6)	7.82 (68.9)	1.84 (16.2)	2.62 (23.1)	100	100
SEAM 2	1	2.95 (2.80)	1377 (2510)	1465 (2670)	7.00 (61.6)	7.38 (65.0)	2.83 (24.9)	2.36 (20.3)	80	22
	2	2.95 (2.80)	1371 (2500)	1410 (2570)	6.59 (58.0)	6.11 (53.8)	3.09 (27.2)	2.19 (19.3)	99	94

The Waterwall Heat Flux Data obtained from each test provides information on the overall effect of waterwall deposits on heat transfer and the relative deposit buildup rate. Comparison between the initial heat flux with clean panel and heat flux after sootblowing provides a quantitative indication of the ease of deposit removal and sootblower effectiveness.

The furnace conditions and slagging results from the BT-11 tests are summarized in Table 3-11. Furnace deposits at two furnace elevations (panels C and B) were assessed. Panel C is located approximately 0.9M (3 ft) above the burner and panel B is approximately 1.4M (4.5 ft) above the burner.

Overall, results show both BT-11 coals exhibit a relatively rapid deposit accumulation rate. Heat transfer through panel C at the conclusion of the critical flame temperature tests was reduced by 66.5 and 68.2% for seams 1 and 2 respectively. These reduction values are comparable to the baseline 71.1% and are greater than the washed 60.1%. The lower heat flux reduction for the washed coal was due to the slightly thinner deposits developed from this fuel.

The cleanability of waterwall Deposits are illustrated by the heat flux recovery after sootblowing. Results are summarized in Table 3-11 and depicted by the heat flux plots shown in Figures 3-8 to 3-9 for each of the BT-11 coals. Results from panels B and C indicate the waterwall deposits were cleanable at critical flame temperature of 1410°C (2570°F) for both seams 1 and 2. Heat flux recovery was better than 94% under this condition. Above this flame temperature, heat flux was only partially recovered as deposits were uncontrollable and would not be completely cleaned by sootblower.

Figures 3-10 and 3-11 show photographs depicting the BT-11 seams 1 and 2 on-line deposit accumulation on the waterwall panels B and C, and the effect of sootblowing at the end of each test. Results are in agreement with the heat flux recovery data. Waterwall panels were cleaned to bare surface as deposits were effectively removed at 1410°C (2570°F) flame temperature. Deposits were only partially cleaned above this temperature for both BT-11 coals.

Waterwall deposits developed from the baseline, the washed and the BT-11 seam 1 coals at their respective control flame temperature are shown in Figure 3-12 for comparison. Overall, these coals show similar characteristics. Deposits from the baseline and seam 1 show almost identical thickness and coverage. Deposits from the washed was generally thinner with slightly less coverage. The difference is attributed to the reduced ash loading of the washed coal.

The Physical Properties of the Waterwall Deposits from the BT-11 coals are summarized in Table 3-12. Comparison between the deposits from these coals and the baseline and washed are shown in Figure 3-12 and Table 3-13. Overall, the physical state of these deposits are similar. Highly sintered deposits with molton outer layers were developed during the critical conditions for each coal. Deposits from the baseline and seam 1 had almost identical thickness of 12.7 to 20 (1/2 to 3/4 in) mm (1/2) with 100% panel coverage. Deposits from the washed had similar coverage but were generally thinner, 0.6 to 12.7mm (1/4 to 1/2 in.), due to its reduced ash loading.

Chemical Analysis of the Waterwall Deposits from BT-11 seam 1 indicate deposits from both panels B and C were in general similar to the as-fired coal ash. Both the initial and outer deposits showed slight enrichment in Fe_2O_2 content, with other constituents remained relatively the same. Ash fusibility temperatures of the waterwall deposits were generally lower. it ranged from 1060°C (1940°F) initial deformation temperature to 1371°C (2500°F) fluid temperature compared to 1132°C (2070°F) and 1377°C (2510°F) for the as-fired coal ash. The lower ash fusibility temperature are attributed to the slight increased in iron content. Waterwall deposits from the BT-11 seam 2 were not collected as they were cleaned on line during the sootblowing evaluation.

In summary, the Lakhra BT-11 seams 1 and 2, baseline and washed coals exhibit severe slagging potential. The BT-11 coals were slightly worse, while the washed was slightly better than the baseline. Waterwall deposits were cleanable at flame temperature of 1410°C (2570°F) for the BT-11 coals, 1427°C (2600°F) for the baseline, and 1440°C (2630°F) for the washed.

FIGURE 3-8
HEAT FLUX THROUGH WATERWALL PANELS
DURING THE LAKHRA BT-11 SEAM 1 COAL EVALUATION

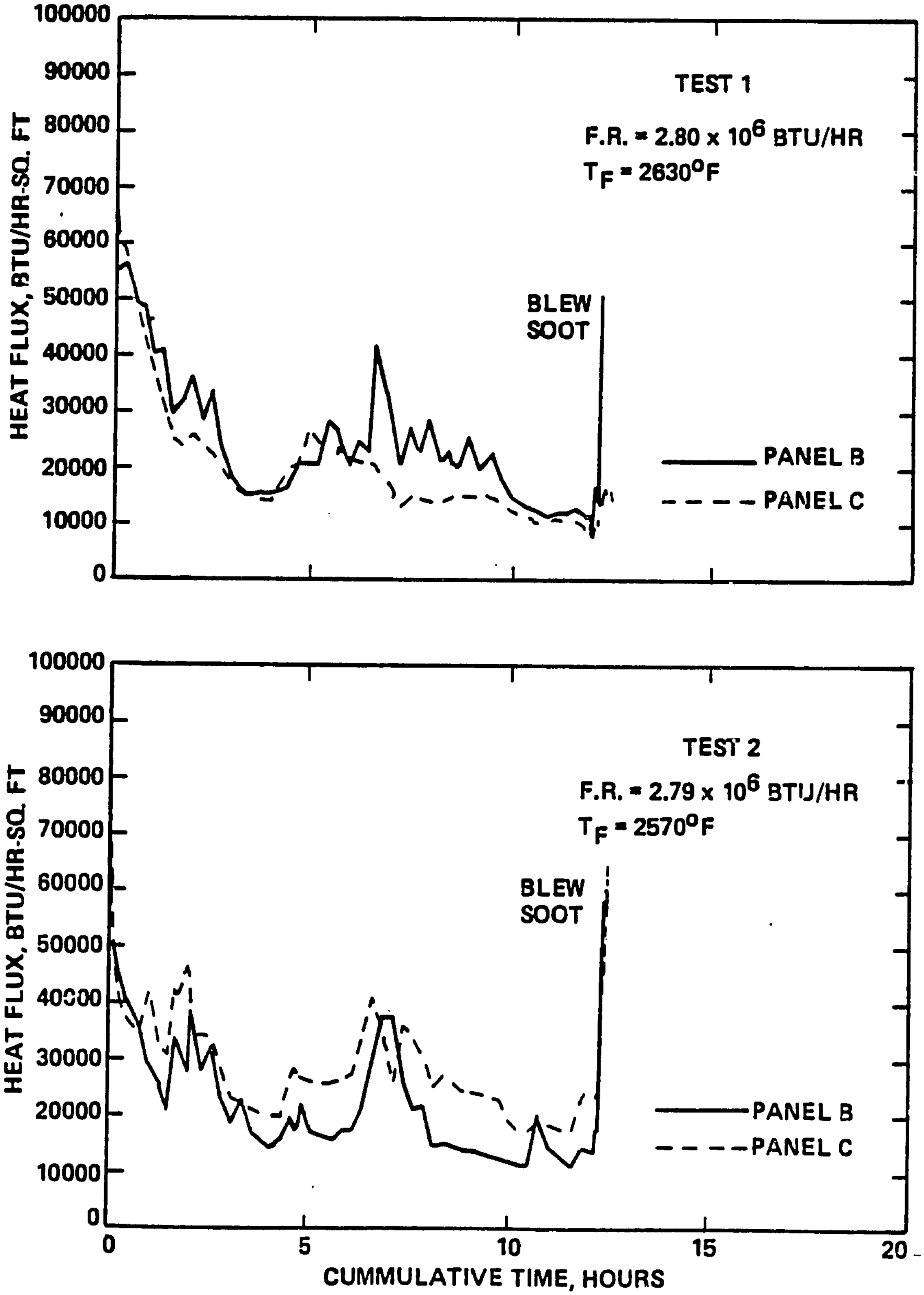
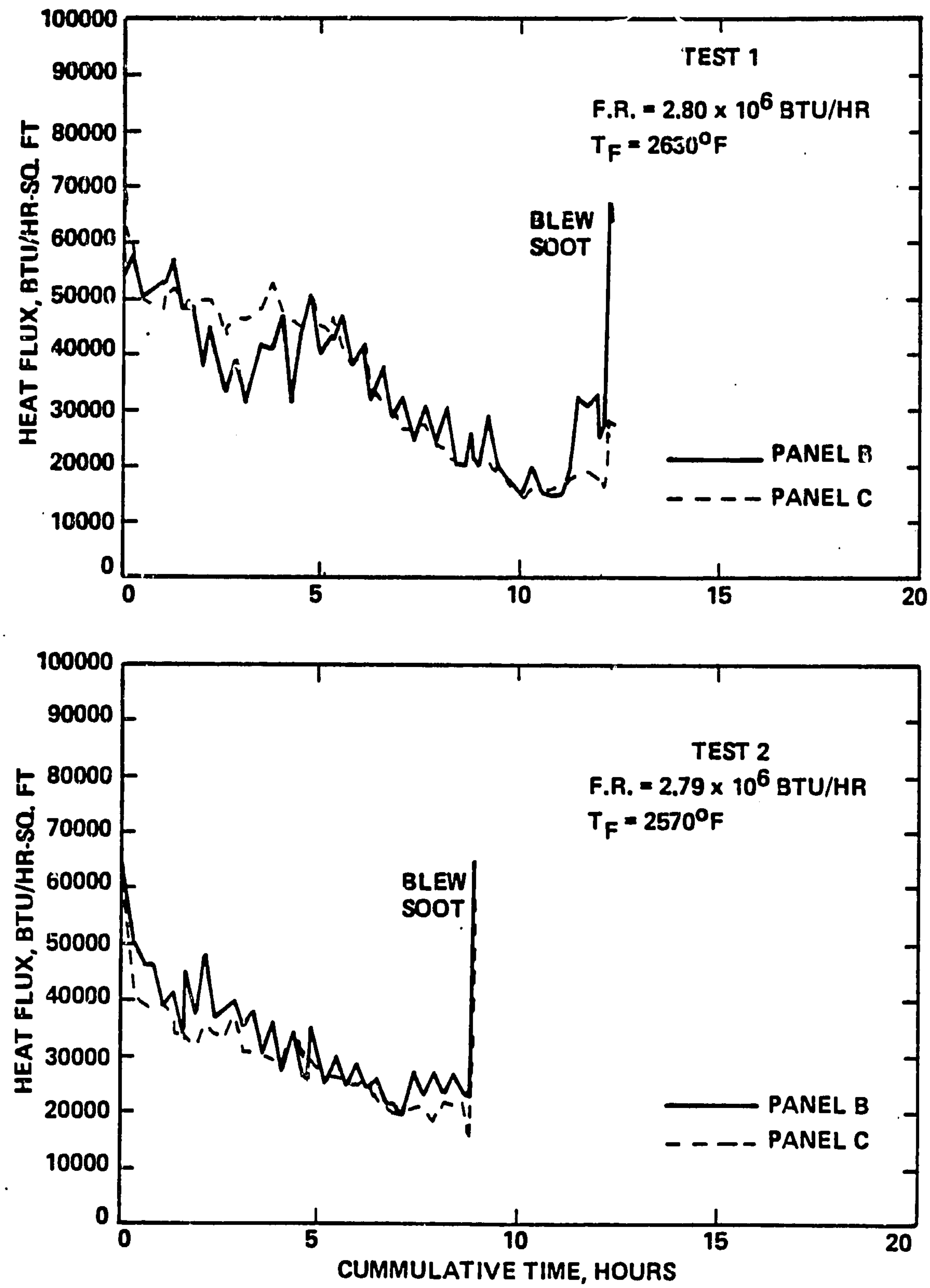


FIGURE 3-9
HEAT FLUX THROUGH WATERWALL PANELS
DURING THE LAKHRA BT-11 SEAM 2 COAL EVALUATION

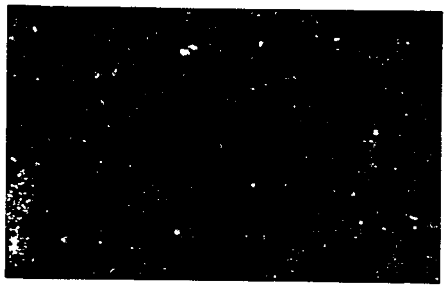


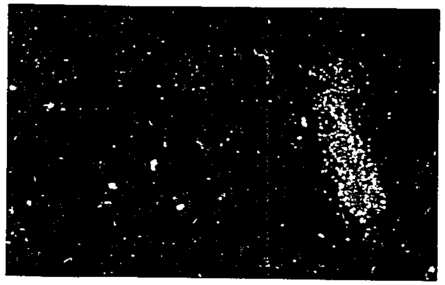
ASH DEPOSITION ON WATERWALL PANELS DURING THE LAKHRA BT-11 SEAM 1 COAL EVALUATION

TEST 1

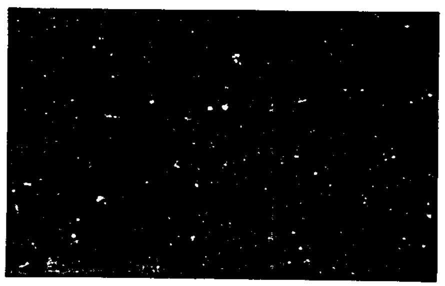
T_B = 2510°F

T_C = 2630°F





End of Test

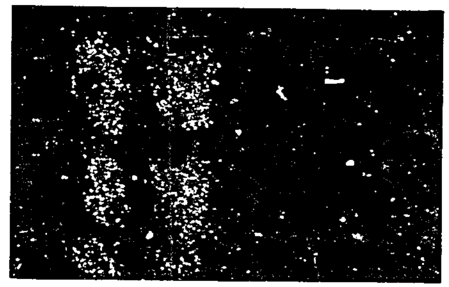


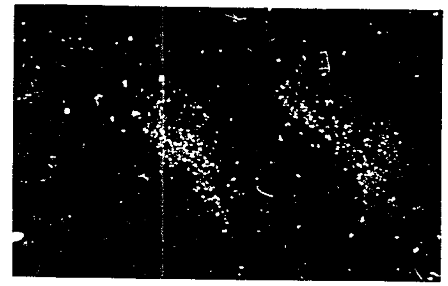
After Sootblowing

TEST 2

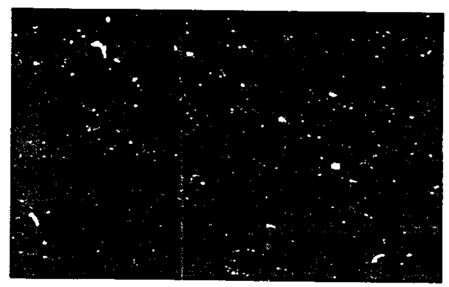
T_B = 2490°F

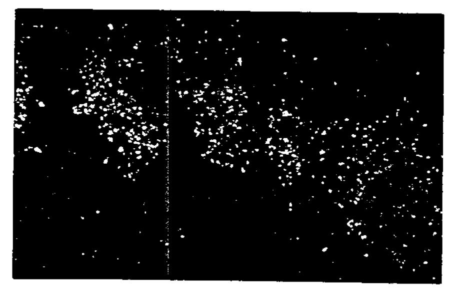
T_C = 2570°F





End of Test



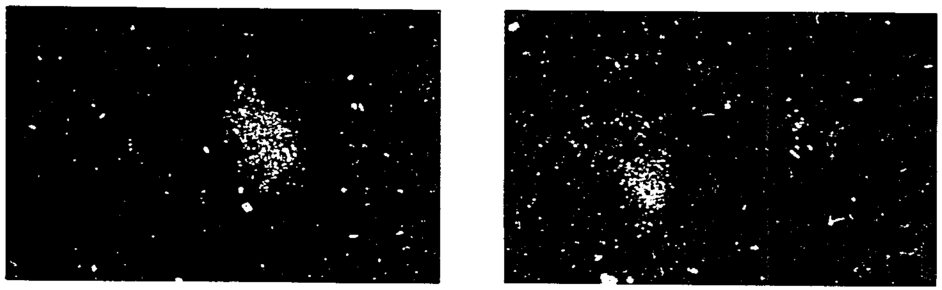


After Sootblowing

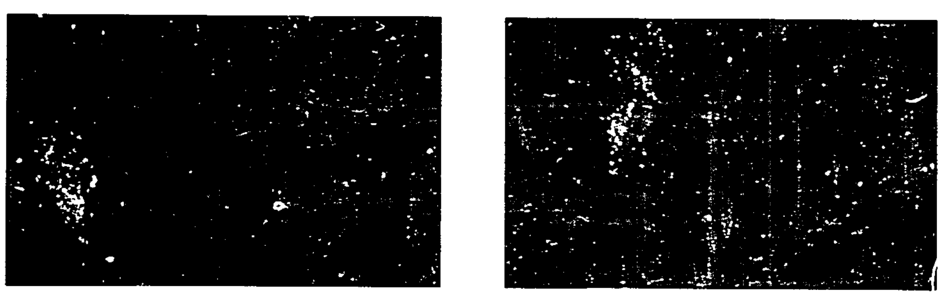
ASH DEPOSITION ON WATERWALL PANELS DURING THE LAKHRA BT-11 SEAM 2 COAL EVALUATION

TEST 1

T_B = 2550 °F T_C = 2670 °F



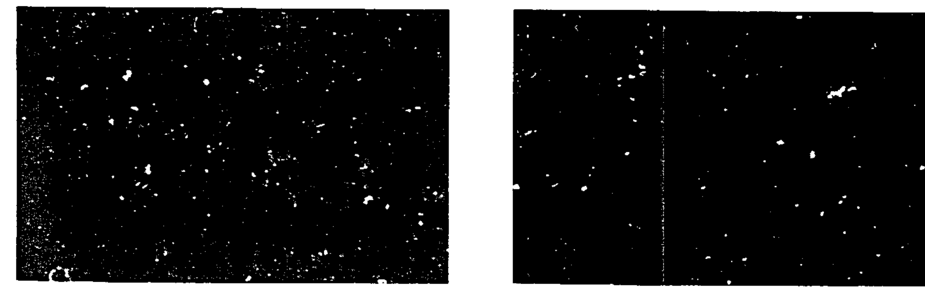
End of Test



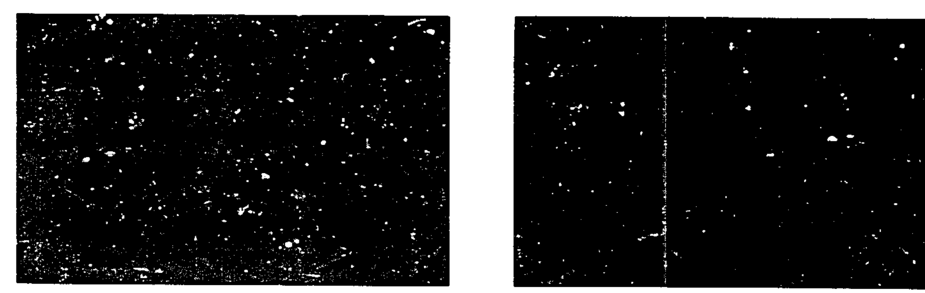
After Sootblowing

TEST 2

T_B = 2510 °F T_C = 2570 °F



End of Test



After Sootblowing

TABLE 3-12

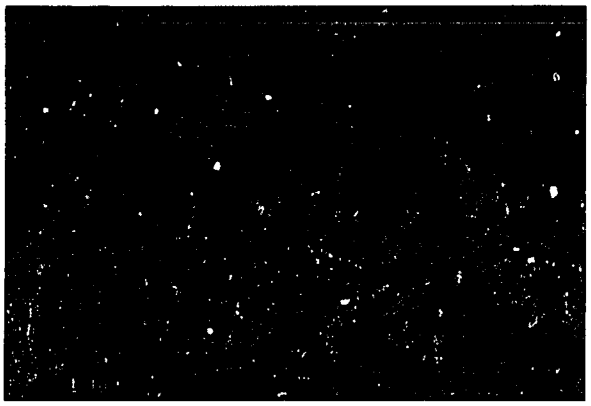
WATERWALL DEPOSIT PHYSICAL CHARACTERISTICS OF THE LAKHRA BT-11 COALS

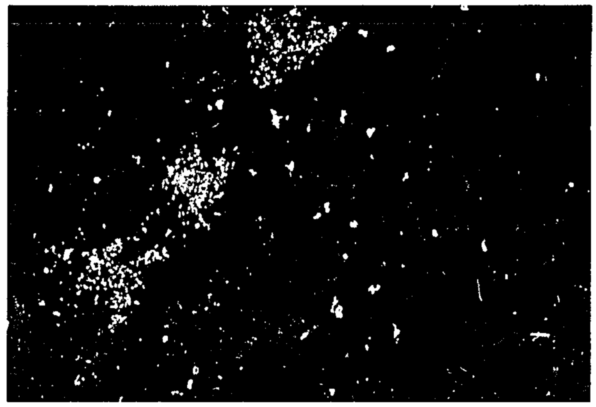
COAL TYPE	TEST NO.	FIRING RATE GJ/HR ($X10^6$ BTU/HR)	AVG. FLAME TEMPERATURE °C (°F)	DEPOSIT COVERAGE %	DEPOSIT THICKNESS mm (in)	DEPOSIT PHYSICAL STATE	DEPOSIT CLEANABILITY
SEAM 1	1	2.95 (2.80)	1443 (2630)	100	12.7 (0.5)	MOLTEN	POOR
	2	2.94 (2.79)	1410 (2570)	100	12.7 (0.5)	HIGHLY SINTERED MOLTEN OUTER	GOOD
SEAM 2	1	2.95 (2.80)	1465 (2670)	100	12.7-19.1 (0.5-0.75)	HIGHLY SINTERED MOLTEN OUTER	POOR
	2	2.95 (2.80)	1410 (2570)	100	12.7 (0.5)	HIGHLY SINTERED MOLTEN OUTER	GOOD

WATERWALL ASH DEPOSITION FROM THE LAKHRA COALS

BASELINE COAL

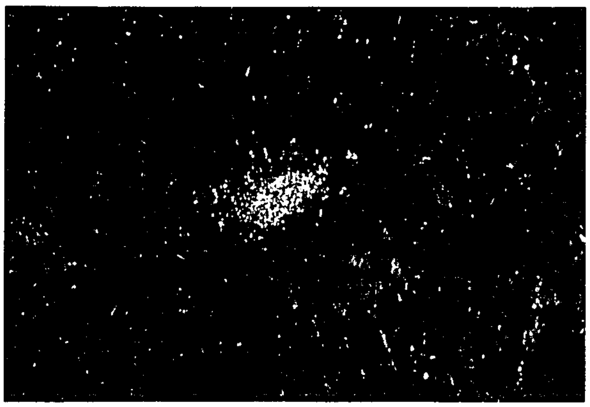
T_B = 2500°F T_C = 2610°F

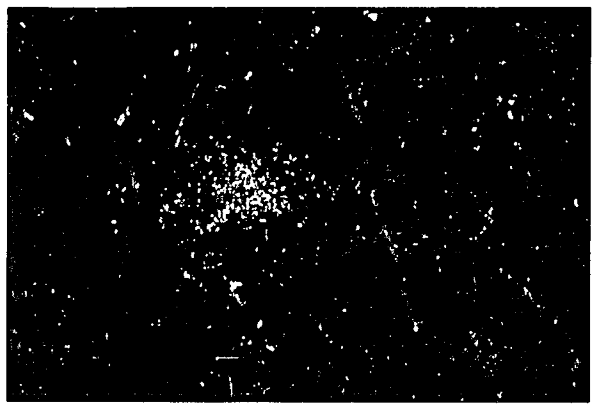




WASHED COAL

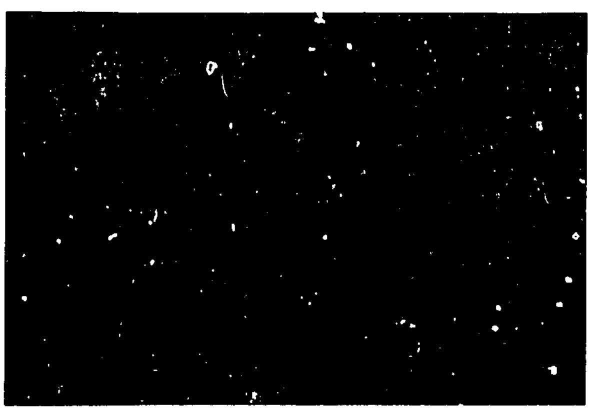
T_B = 2520°F T_C = 2610°F





BT-11 SEAM 1

T_B = 2490°F T_C = 2570°F



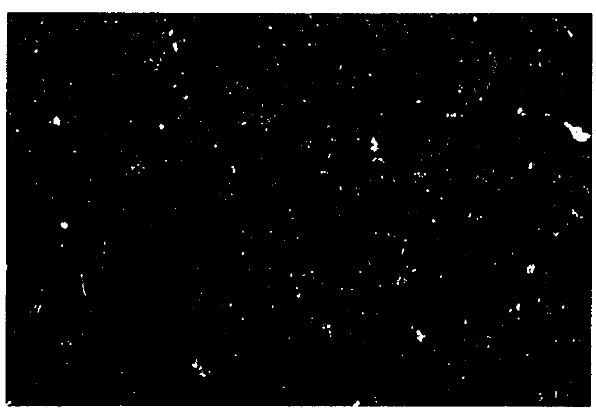


TABLE 3-13

COMPARISON OF WATERWALL DEPOSIT PHYSICAL CHARACTERISTICS BETWEEN LAKHRA COALS

COAL TYPE	FIRING RATE GJ/HR ($X10^6$ BTU/HR)	AVG. FLAME TEMPERATURE °C (°F)	DEPOSIT COVERAGE %	DEPOSIT THICKNESS mm (in)	DEPOSIT PHYSICAL STATE	DEPOSIT CLEANABILITY
BASELINE	2.97 (2.82)	1427 (2600)	100	12.7 (0.5)	HIGHLY SINTERED MOLTEN OUTER	GOOD
WASHED	3.08 (2.92)	1432 (2610)	100	0.6–12.7 (0.5)	HIGHLY SINTERED MOLTEN OUTER	GOOD
BT-11-1	2.94 (2.79)	1410 (2570)	100	12.7 (0.5)	HIGHLY SINTERED MOLTEN OUTER	GOOD
BT-11-2	2.95 (2.80)	1410 (2570)	100	12.7 (0.5)	HIGHLY SINTERED MOLTEN OUTER	GOOD

TABLE 3-14

ANALYSIS OF WATERWALL DEPOSITS COLLECTED FROM LAKHRA BT-11 SEAM 1 COAL TESTING

	Panel C		Panel B	
	Initial	Outer	Initial	Outer
Ash Fusibility				
I. T. °F	1940	1990	1950	1940
S. T.	2080	2090	2210	2220
H. T.	2370	2270	2360	2480
F. T.	2450	2420	2440	2500
Ash Composition				
SiO_2	40.4	43.8	38.9	43.8
Al_2O_3	25.3	26.5	23.8	26.2
Fe_2O_3	25.1	23.2	25.7	23.3
CaO	3.1	3.2	2.1	2.9
MgO	1.2	1.1	1.2	1.2
Ma_2O	0.5	0.5	0.6	0.5
K_2O	0.5	0.5	0.5	0.5
TiO_2	2.0	2.0	1.9	1.9
SO_3	0.9	0.1	3.5	0.2
TOTAL	99.1	100.9	98.2	100.5

Convective Pass Fouling Characteristics

The convective pass deposit characteristics were assessed by the relative deposit buildup, deposit bonding strength, and deposit physical and chemical properties. Results indicate the BT-11 seams 1 and 2, baseline and washed coals have moderate fouling potential. The rate of deposit buildup was higher than the baseline and washed, but deposit to tube bonding strengths remained low, thus deposits were easily cleaned by sootblowing for each coal.

Convective Pass Deposit Buildup Rates are depicted by the deposit growth time sequence photographs shown in Figure 3-13. The effects of gas temperature, gas velocity and firing rate upon deposition rate were assessed. Results show both BT-11 coals had higher deposit buildup rates than the baseline and washed. Sootblowing was required every 3 to 4 hours for seam 2, 4 to 5 hours for seam 1, 5 to 6 hours for baseline, and 6 hours for washed at similar gas temperatures of 1138 to 1165°C (2080° to 2130°F).

Observations made during each of the BT-11 test runs indicate there was a higher amount of deposit carryover from the furnace compared to the baseline and washed. This is most likely attributed to the higher Fe_2O_3 content in the ash and the generally lower ash fusibility temperature of the BT-11 coals. Deposits built up rapidly in the higher gas temperature transition, 1260 to 1230°C (2300° to 2370°F), between the furnace and the convection duct. This behavior has often been observed with high slagging fuels tested in the FPTF and in field units. Ample sootblower coverage will be required for deposit removals in the high temperature convective passes.

Deposit Bonding Strength was measured to assess the relative ease of deposit removal from the superheater tube surfaces. Measurements were taken on-line when the deposit accumulated on the convection probe surface reached approximately 76mm (3 inch) thick. Results show BT-11 coals have low deposits to tube bonding strength (up to 2.1) at flame temperatures up to 1465°C (2670°F) and gas temperature up to 1171°C (2140°F). The low bonding strength was similar to the baseline and washed coal results. Overall, because of the low bonding strength and the lightly sintered deposit, deposit removal for all four Lakhra coals was easily accomplished by sootblowing.

Convective pass Deposit Physical Characteristics of the BT-11 coals are summarized in Table 3-15. Results are similar characteristics to the baseline and washed presented in Table 3-16. Deposits consisted of a thin sintered scale initial layer of 3.2 mm (1/8 in.), and a 76 to 102 mm (3 to 4 in) outer layer. The physical state of the outer layer was lightly sintered indicating the low bonding strength characteristics of these coals throughout each test firing conditions.

Chemical Analyses of The Convective Pass Deposit Samples are presented in Table 3-17. Both the initial and outer deposits from each probe bank showed lower ash fusibility temperatures than the as-fired coal ash. The difference was most significant with the deposits from banks I and II, ranging from 1049 to 1177°C (1920 to 2150°F) compared to 1132 to 1377°C (2070 to 2510°F), I.T. to F.T. of the as-fired coal ash. Ash composition shows the outer deposits were similar, but the initial deposits had significant enrichments in iron content compared to the as-fired coal ash. This phenomena is attributed to the carryover effect of the furnace slagging.

Overall, the BT-11 seams 1 and 2 coals have similar moderate fouling potential. Convective deposit accumulation was higher than the baseline and washed, but deposit to tube bonding strengths were similarly low, thus deposits were easily cleanable. Deposit buildup was most rapid with BT-11 seam 2, slightly less with seam 1, followed by the baseline and washed. Sootblowing requirements were 3 to 4 hours for seam 2, 4 to 5 hours for seam 1, 5 to 6 hours for baseline and 6 hours for washed at similar gas temperatures of 1138 to 1165°C (2080 to 2130°F). A higher deposition rate in the transition section of the furnace due to carryover from slagging was also observed with the BT-11 coals.

TABLE 3-15

CONVECTIVE PASS FOULING CHARACTERISTICS OF LAKHRA BT-11 COALS

COAL TYPE	GAS TEMPERATURE °C (°F)	ASH LOADING Kg/Hr (LB/HR)	GAS VELOCITY M/Sec (FT/SEC)	PHYSICAL STATE INITIAL	PHYSICAL STATE OUTER	BONDING STRENGTH BSM	SOOTBLOWING FREQUENCY (HR)
SEAM 1	1171 (2140)	30.4 (67.1)	16.5 (54.2)	SINTERED SCALE	SIGHTLY SINTERED	2.1	4-5
	1149 (2100)	30.5 (67.2)	16.4 (53.8)	SINTERED SCALE	SIGHTLY SINTERED	2.0	4-5
SEAM 2	1171 (2140)	30.4 (67.0)	16.7 (54.8)	SINTERED SCALE	SIGHTLY SINTERED	2.1	3-4
	1138 (2080)	30.5 (67.3)	16.6 (54.5)	SINTERED SCALE	SIGHTLY SINTERED	2.3	3-4

TABLE 3-16

COMPARISON OF FOULING CHARACTERISTICS BETWEEN LAKHRA COALS

COAL TYPE	GAS TEMPERATURE °C (°F)	ASH LOADING Kg/Hr (LB/HR)	GAS VELOCITY M/Sec (FT/SEC)	PHYSICAL STATE INITIAL	OUTER	BONDING STRENGTH BSM	SOOTBLOWING FREQUENCY (HR)
BASELINE	1165 (2130)	34.0 (75.0)	17.2 (56.5)	SINTERED SCALE	SIGHTLY SINTERED	4.0	5-6
WASHED	1154 (2110)	25.3 (55.8)	16.9 (55.5)	SINTERED SCALE	SIGHTLY SINTERED	2.4	6
BT-11-1	1171 (2100)	30.5 (67.2)	16.4 (53.8)	SINTERED SCALE	SIGHTLY SINTERED	2	4-5
BT-11-2	1138 (2080)	30.5 (67.3)	16.6 (54.5)	SINTERED SCALE	SIGHTLY SINTERED	2	3-4

TABLE 3-17

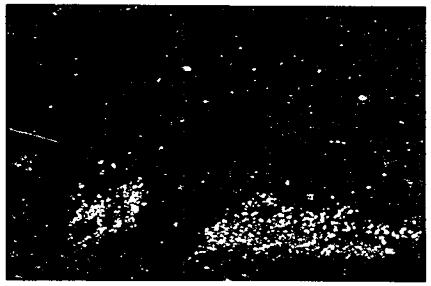
ANALYSIS OF CONVECTIVE PASS DEPOSITS COLLECTED FROM LAKHRA BT-11 SEAM 1 COAL TESTING

	Bank I		Bank II		Bank III		Bank IV	
	Initial	Outer	Initial	Outer	Initial	Outer	Initial	Outer
Ash Fusibility								
I. T. °F	1970	1920	2020	1970	2020	1950	1910	1950
S. T.	2050	2160	2130	2110	2140	2110	2100	2220
H. T.	2090	2350	2150	2390	2390	2340	2290	2240
F. T.	2150	2400	2180	2440	2410	2450	2340	2460
Ash Composition								
SiO_2	17.2	45.5	10.8	47.3	10.3	43.8	12.2	40.4
Al_2O_3	9.9	25.4	7.1	24.1	6.5	26.7	7.9	26.4
Fe_2O_3	49.2	20.1	59.9	18.1	64.8	22.9	48.2	22.7
CaO	11.0	4.9	10.4	2.7	9.3	3.0	14.5	3.1
MgO	1.1	1.8	0.7	1.6	0.5	1.1	0.7	1.3
Na_2O	0.2	0.9	0.2	0.9	0.2	0.5	0.3	0.5
K_2O	0.2	0.8	0.1	0.7	0.2	0.6	0.2	0.6
TiO_2	1.1	2.2	0.6	2.2	0.4	1.9	0.8	2.1
SO_3	10.4	0.1	9.5	0.7	8.3	0.6	13.4	1.4
TOTAL	100.3	101.6	99.3	98.3	100.5	101.1	98.2	98.5

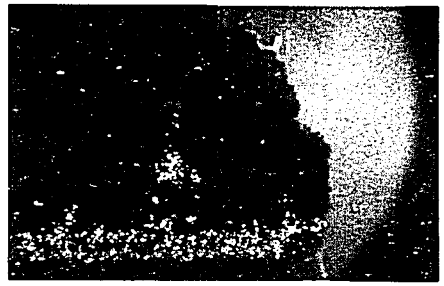
ASH DEPOSITION ON SUPERHEATER PROBE DURING THE LAKHRA BT-11 COAL EVALUATION

SEAM 1 AVERAGE GAS TEMPERATURE 2100°F

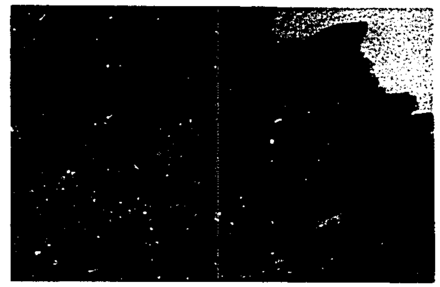
0 HR



2 HRS

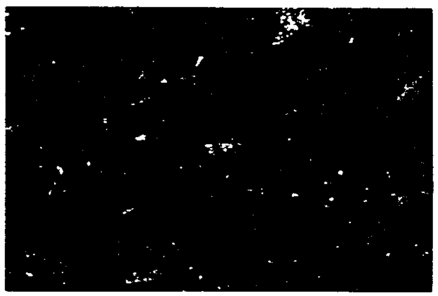


4 HRS

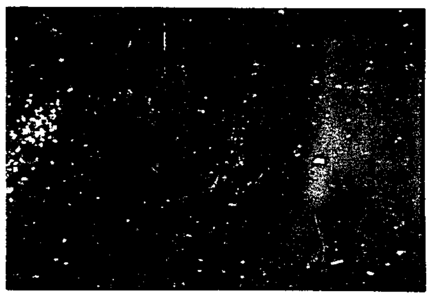


6 HRS

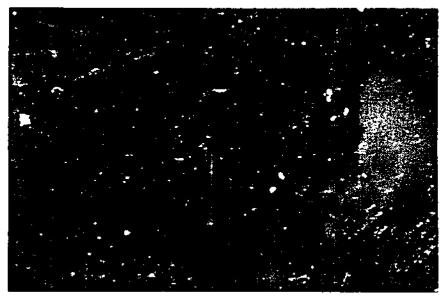
SEAM 2 AVERAGE GAS TEMPERATURE 2080°F



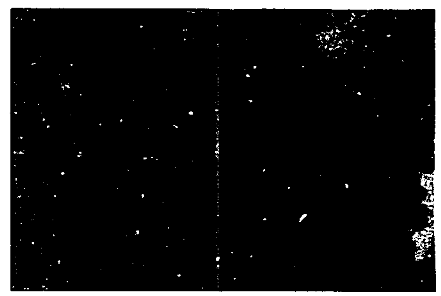
0 HR



2 HRS



4 HRS



6 HRS

EMISSIONS

Particulate Emission

Fly ash samples were collected isokinetically during the respective critical flame temperature test for BT-11 seams 1 and 2 coals. These samples were submitted for particle size distribution, chemical composition, free quartz content and bench-scale fly ash resistivity analyses. In-situ fly ash resistivity was additionally measured during the seam 1 test. This measurement was not taken for seam 2 due to its relatively short test period (24 hours). Overall, results show the fly ash generated from seams 1 and 2 coals have similar mass median particle diameters of 8.6 and 7.7 microns respectively. The carbon contents were very low at 0.3 and 0.2%, indicating the carbon conversion was better than 99.9% for these two coals. Isokinetic dust loading show approximately 60% of the total fuel ash input was emitted from the flue gas. In-situ fly ash resistivity was 5.5×10^{10} ohm-cm for BT-11 seam 1, indicating fly ash generated from this coal should be easier to collect by electrostatic precipitation than the baseline and the washed.

Chemical Analysis of The Fly Ash Samples are summarized in Table 3-18. In general, ash fusibility temperatures were lower than the as-fired coal ash, ranging from 1077 to 1354°C (1970 to 2470°F) and 1049 to 1349°C (1920 to 2460°F) compared to 1132 to 1377°C (2070 to 2510°F) and 1054 to 1310°C (1930 to 2390°F) I.T. to F.T. for seams 1 and 2 respectively. Ash composition of these samples shows little variation from the respective as-fired coal ash. The carbon contents were 0.3 and 0.2% for both samples, indicating very good combustion efficiency firing this coal in the FPTF. The resulting carbon conversion was better than 99.9% for each coal. The good combustion characteristics of these coals are consistent with the bench scale results and are similar to the baseline and washed.

TABLE 3 - 18

ANALYSIS OF FLY ASH SAMPLES FROM LAKHRA BT-11 COALS

	SEAM 1	SEAM 2
CARBON %	0.3	0.2
ASH FUSIBILITY, °F		
I.T.	1970	1920
S.H.	2260	2160
H.T.	2440	2380
F.T.	2470	2460
ASH COMPOSITION, %		
SiO_2	42.1	43.4
Al_2O_3	27.2	26.4
Fe_2O_3	19.9	20.9
CaO	4.6	3.4
MgO	1.5	1.5
Na_2O	0.8	0.8
K_2O	0.5	0.6
TiO_2	2.2	2.0
SO_3	1.2	0.9
Total	100.0	99.9
Mass Median Diameter,	8.6	7.7
Free Quartz, %	2.3	2.7

Fly Ash Resistivity of a fuel is affected by the ash chemical composition, flue gas temperature, SO_3 concentration, moisture content and fly ash particle size. Generally fly ash resistivities appear to be desirable in the 10^9 to 10^{11} ohm-cm range. Values of 5×10^9 to 5×10^{10} ohm-cm are considered to be optimum for electrostatic precipitator operating at a gas temperature range of 149 to 177°C (300 to 350°F).

Fly ash resistivity of the BT-11 seam 1 coal was measured by an in-situ resistivity probe system described in Appendix E of the baseline report and by a bench scale method. It should be noted that these measurements only provide a relative number and should not be used as an absolute value. Fly ash resistivity is highly dependent on fuel properties, flue gas composition, deposition packing density on collecting surfaces, field unit design and operating conditions. Overall, results presented in Table 3-19 show the average in-situ fly ash resistivity measured from this coal is 5.50×10^{10} ohm-cm at gas temperature of 115°C (240°F) with 8% moisture and 17 ppm SO_3. This value is lower compared to the baseline 1.00×10^{11} ohm-cm at 124°C (255°F) with 8% moisture and 15 PPM SO_3, and to the washed 7.6×10^{11} ohm-cm at 158°C (308°F) with 11% moisture and 3 ppm SO_3. Thus fly ash generated from the BT-11 seam 1 would be easier to collect by electrostatic precipitator than the baseline and the washed.

Measurements conducted by bench scale method using fly ash samples collected from Isokinetic dust loading under simulated gas environment are shown in Table 3-19. Bench results indicate at 116°C (240°F) gas temperature, fly ash resistivity is 7.5×10^{11} ohm-cm without SO_3, and 4.2×10^8 ohm-cm with 17 ppm SO_3 for BT-11 seam 1 coal. These values are comparable to the theoretical calculations of 1.3×10^{11} ohm-cm without SO_3 and 9.5×10^8 with 17 ppm SO_3, but are lower compared to the in-situ results.

Overall, although there are discrepancies in the fly ash resistivity results by different measurement techniques, values obtained for the BT-11 coals fall within the typical range for most commercial coals and should not present any problem for electrostatic precipitator collection efficiency.

TABLE 3 - 19

COMPARISON OF FLY ASH RESITIVITY RESULTS FROM LAKHRA COALS

COAL TYPE	FLUE GAS TEMPERATURE °C (°F)	MOISTURE CONTENT %	SO_3 CONC. PPM	IN-SITU RESISTIVITY OHM-CM	BENCH RESISTIVITY OHM-CM	THEORETICAL RESISTIVITY OHM-CM
BASELINE	124 (255)	8.0	0	---	0.5×10^{11}	2.9×10^{11}
		8.0	15	1.8×10^{11}	2.5×10^{9}	1.7×10^{9}
WASHED	153 (308)	11.0	0	---	2.0×10^{11}	1.2×10^{11}
		11.0	3	7.6×10^{11}	3.0×10^{9}	6.9×10^{10}
BT-11-1	116 (240)	8.0	0	---	7.5×10^{11}	1.3×10^{11}
		8.0	17	5.5×10^{10}	4.2×10^{8}	9.5×10^{8}

Flue Gas Emissions

Flue gas emissions measured during each of the BT-11 seams 1 and 2 tests are summarized in Table 3-20. Overall, the SO_2 emission from these coals is higher compared to the baseline and washed. It ranges from 8451 to 8570 ppm for seam 1 and 9106 to 9182 ppm for seam 2 compared to their theoretical sulfur emissions of 9933 and 10820 ppm on a dry, 3% O_2 basis. These results indicate only a small amount of sulfur was retained by the coal ash alkali and alkaline earths constituents, ranging from 13.6 to 13.9% for seam 1 and 15.1 to 15.8% for seam 2. The SO_2 emission was 5910 to 6340 ppm for the baseline, and 4113 to 4482 ppm for the washed. Their respective theoretical emissions were 6960 and 4730 ppm. The corresponding sulfur retentions by the coal ash were 8.4 to 9.6% and 5.2 to 13.0%, respectively.

The NO_x emissions is highly sensitive to the firing system. Values presented in Table 3-18 can only provide information on a relative basis, as the FPTF consists of a single burner which provides rapid mixing between fuel and combustion air, resulting rapid, intense combustion that tends to promote NO_x formation. The NO_x results were similar between the BT-11, baseline and washed coals. It ranged from 920 to 1020 ppm for seam 1, 960 to 1035 ppm for seam 2, 800 to 1260 ppm for baseline, and 1025 to 1374 ppm for washed on a 3% O_2 dry basis. The higher values correspond to tests at higher flame temperatures. Overall, based on these data and the relatively low nitrogen content of 0.8% to 1.2% dry basis, NO_x emission should not be a limiting factor utilizing these coals.

In summary, the BT-11 seams produce higher SO_2 emissions than the baseline and washed due to their higher sulfur content in the coal. Results show only a small amount (5.2 to 13.0%) is being retained by the coal ash. NO_x emission should not be a problem firing these coals.

TABLE 3-20

LAKHRA BT-11 COAL FLUE GAS EMISSIONS

COAL TYPE	TEST NO.	FIRING RATE GJ/HR ($\times 10^6$ Btu/Hr)	AVERAGE FLAME TEMPERATURE °C (°F)	CO PPM AT 3% O_2, DRY	NO_x PPM AT 3% O_2, DRY	SO_2 PPM AT 3% O_2, DRY	SULFUR RETAINED %
SEAM 1	1	2.95 (2.80)	1465 (2670)	50	1020	8541	13.9
	2	2.94 (2.79)	1410 (2570)	60	920	8570	13.6
SEAM 2	1	2.95 (2.80)	1443 (2630)	64	1035	9106	15.8
	2	2.95 (2.80)	1410 (2570)	57	960	9182	15.1

FLY ASH EROSION

Fly ash erosion for the BT-11 seam 1 coal was measured during the critical flame temperature test. Results are summarized in Table 3-21. This coal exhibits the highest fly ash erosion rate compared to the baseline and washed. The average maximum wear was 34.9 microns/hr at 54.1 m/sec (177.4 ft/sec) gas velocity and 2.95 GJ (2.80 x 10^6 Btu/hr) firing rate with 46.1 Kg/hr (101.7 lbs/hr) ash loading exposed for 34.2 hours.

To provide a comparative wear value between this coal and the baseline and washed, each erosion rate was normalized per unit mass of ash, and per heat input at typical field gas velocity of 18.3 m/sec (60 ft/sec.) Results are 3.3 x 10^3, 3.5 x 10^3 and 3.3 x 10^3 microns/Kg ash, and 0.95, 0.91, and 0.55 mm/10,000 hrs for BT-11 seam 1, baseline and washed coal respectively. These data indicate while the erosion rate per unit weight of ash was comparable between the three coals, the higher ash loading of the BT-11 seam 1 resulted higher erosion compared to the baseline and washed. The x-ray diffraction analysis show the fly ash samples from these coals had similar free quartz content, 2.7, 2.4, and 2.5% respectively for Bt-11 seam 1, baseline and washed coal respectively.

In summary, results show the BT-11 and the baseline exhibited relatively high erosion rate. The BT-11 was most erosive due to its higher ash loading. The washed had moderate erosion due to its reduced ash loading for similar fuel heat input. All three coal fly ash samples had similar free quartz content. The high erosiveness of the BT-11 and baseline will require a lower gas velocity in the convective pass to reduce metal wastage.

TABLE 3 - 21

IN-SITU FLY ASH EROSION RESULTS FROM LAKHRA COAL TESTING

	BASELINE	WASHED	BT-11-1
FIRING RATE			
$\times 10^3$ MJ/Hr	2.97	3.08	2.95
($\times 10^6$ Btu/Hr)	(2.82)	(2.92)	(2.80)
ASH LOADING			
Kg/Hr	38.8	25.4	46.1
(Lbs/Hr)	(85.5)	(56.0)	(101.7)
GAS VELOCITY			
M/Sec	40.8	51.2	54.1
(Ft/Sec)	(134)	(168)	(177.4)
ALPHA QUARTZ			
%	2.4	2.5	2.7
MAX. WEAR			
microns	10.2	19.6	34.9
EROSION RATE			
microns/Hr	0.32	0.54	1.02
NORMALIZED WEAR			
$\times 10^{-3}$ microns/Kg Ash	3.1	3.5	3.3
NORMALIZED WEAR			
mm/10^4 Hr	0.91	0.55	0.95
(mil/10^4 Hr)	(35.9)	(21.6)	(37.5)

STEAM GENERATOR DESIGN

AND

PERFORMANCE EVALUATION REPORT

LAKHRA POWER PROJECT

Prepared by
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1000 Prospect Hill Road
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Steam Generator Design and Performance Evaluation

For a 300 Mw Unit

Introduction

The proper design, operation and reliability of a steam generator unit requires the ability to maintain load over extended time intervals with a minimum of carbon loss and with control of slag and deposit build-up. Properties of coal that influence the design, which in turn will permit continuing efficient combustion and minimize operating problems are the heat content of the fuel, ash content, fuel moisture, sulfur content, volatile matter, agglomerating characteristics, ash composition and fusibility temperatures. The laboratory testing of the Lakhra coal has indicated that particular attention be paid to the design of the unit with respect to the severe slagging potential, corrosion potential, and high erosion/abrasion potential of the fuel on the steam generator. Conservatively addressing each combustion characteristic in the furnace design will result in a highly reliable, available and maintainable steam generator.

Recommended Furnace Design Parameters

The combustion test results for the Lakhra coal indicate that this fuel can be successfully fired as long as the furnace is properly designed for the severe slagging and medium fouling characteristics of the coal. With this in mind and Combustion Engineering's extensive experience in firing and designing steam generators for all types of coals, we recommend the following conservative design parameters:

a. The net heat per plan area release rate should be designed for approximately 1.3 - 1.4 x 10^6 BTU/Hr-Ft^2 (3.5 - 3.8 x 10^6 Kcal/Hr-m^2).

330

b. The net heat release rate (NHI/EPRS) at the furnace outlet plane should be limited to a range of 60000 to 65000 BTU/Hr-Ft^2(162800 to 176400 $\frac{Kcal}{Hr\text{-}m^2}$).

The net release rate at the furnace outlet plane is an important parameter in conservatively designing a furnace. The furnace outlet plane is defined as a plane which passes perpendicular to the gas flow where the furnace gases reach the first convection superheater or reheater surface. These design values establish the necessary furnace retention time to properly burn the fuel as well as to reduce the temperature of the gaseous products of combustion. This insures that the gas temperature at the entrance to the closely spaced convection surface (furnace outlet plane) is low enough to prevent fouling in the convection pass. The recommended heat release rate for this unit was based on no platenized heating surface in the upper furnace area. This will provide additional protection against slag falls which could result in damage to the lower furnace hopper area. See attached sketch no. UA-850-324-0 for the recommended furnace arrangement utilizing a typical 300 Mw rating.

c. The distance from the upper fuel nozzle to the furnace arch is a function of the furnace width and depth as well as the fuel slagging characteristics. The recommended distance from the top nozzle to the upper furnace arch for this unit is approximately 65 to 70 feet. This distance will insure low flue gas temperatures entering the closely spaced convection sections. Subsequently, ash build-up on convective sections will be minimized.

d. In addressing the high corrosion potential of the Lakhra coal, a minimum of 25% excess air at MCR is recommended. This level of excess air firing will insure an oxidizing atmosphere in all regions of the furnace.

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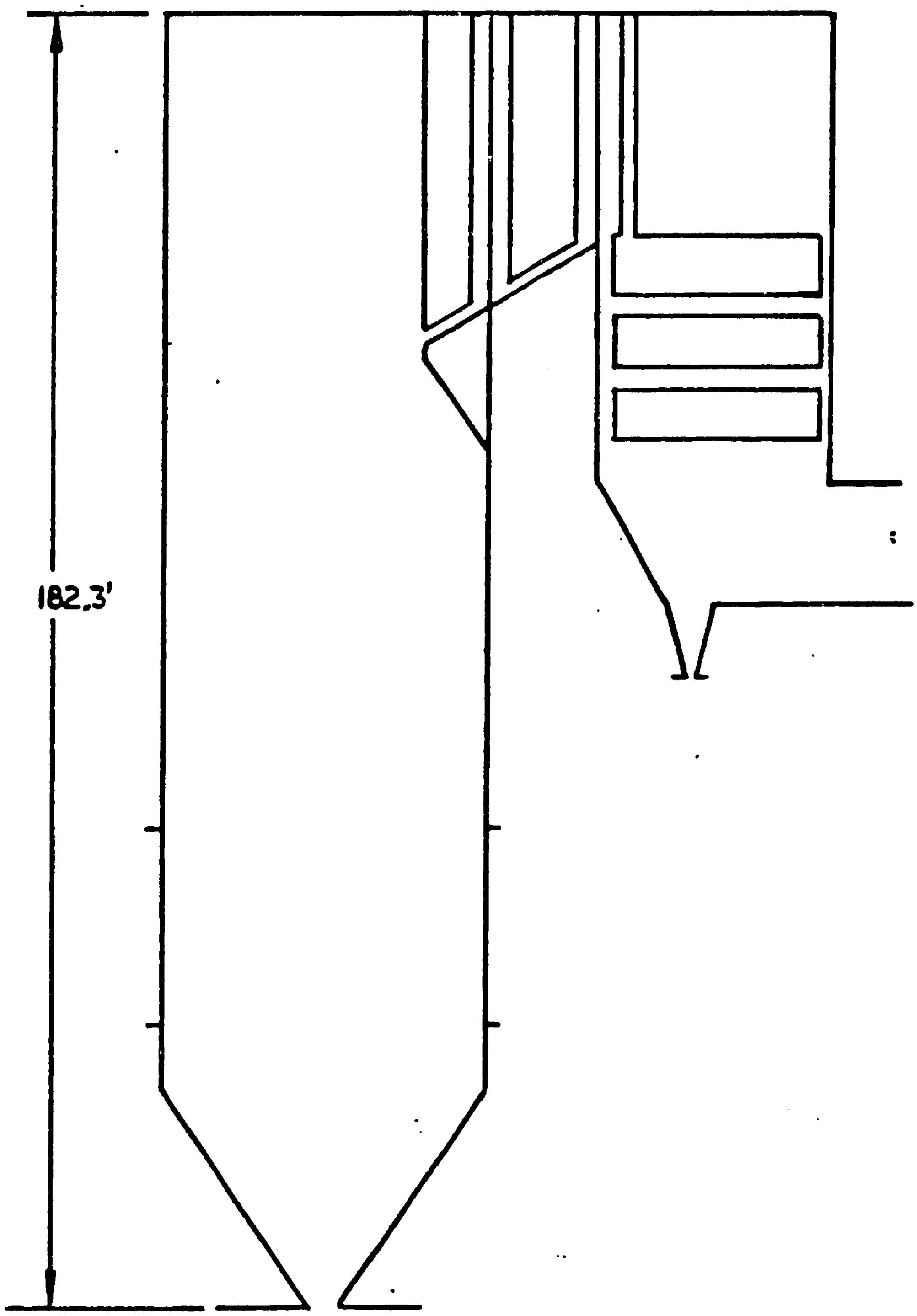

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C-E POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

LAKHRA POWER PROJECT 300 MW

PAKISTAN

SCALE

DWG. NO. UA-850-324-0

The combination of a conservative furnace plan area and increased excess air will minimize the potential for corrosive slag build-up in the furnace. In addition to the recommended levels of excess air, attention should be paid to the design of the firing system to avoid high localized heat release as well as the pulverized coal fineness and the uniform distribution of coal and air in the furnace. Each of these measures will reduce the potential for waterwall corrosion.

Convective Pass Design

a. Operating experience on units firing similar coals to the Lakhra coal indicates the need for wide transverse tube spacings throughout the unit to reduce the fouling rate and potential bridging of ash deposits between adjacent tubes or assemblies. The Lakhra coal has been found to exhibit a moderate fouling potential on convective sections. The following spacing criteria should avoid uncontrollable deposit build-up, minimize erosion potential and allow pieces of accumulated ash loosened by soot blowers to pass through tube banks and avoid bridging the span between adjacent tube rows:

Flue Gas Temperature Range	Minimum Clear Transverse Spacing
2100 - 1850°F (1149 - 1010°C)	13" clear (330mm)
1850 - 1550°F (1010 - 843°C)	6½" clear (165mm)
1550 - 1150°F (843 - 621°C)	4" clear (101mm)
below 1150°F (621°C)	2.5" clear (63.5mm)

b. The Lakhra baseline coal exhibited a relatively high erosion rate potential. It is essential to design units for erosive and abrasive fuels with low flue gas velocities throughout the convective sections. The recommended maximum design velocities for this unit should be 45 feet per second (14 meters per second). Also, it is recommended that the economizer section utilize bare tubes in an inline arrangement. These values will reduce the rate of fly ash erosion throughout the superheater, reheater and economizer sections to acceptable levels.

Material Selection

The Lakhra coal, based on our laboratory testing, was shown to have an extremely high corrosion potential. In order to minimize the impact of superheater/reheater high temperature corrosion the following maximum allowable external tube metal temperatures are recommended:

Tube Material	Recommended Maximum Outside Metal Temperature
Carbon Steel	800°F (426.7°C)
T-11, T-22	950°F (510°C)
T-91	1000°F (537.8°C)
Austenitic Steels	1300°F (704.4°C)

Further protection of superheater and reheater materials will be realized by designing the unit with 1800 psi (126.6 kg/cm^2) at the turbine throttle and steam temperatures of 950°F/950°F (509.9°C/509.9°C) at the superheater and reheater outlet. The recommended lower pressure/temperature cycle, as compared to other possible choices, will result in reduced pressure part material thicknesses and lower metal surface temperatures. Based on results from corrosion tube testing in our lab, it was confirmed that lower outlet steam temperatures will significantly reduce tube metal wastage for superheater and reheater ferritic materials. The combined effect of a lower pressure, lower steam temperature cycle will provide a conservative approach toward reducing the high temperature corrosion potential of the Lakhra coal.

Soot Blower Coverage

The soot blower requirements, both wall blowers in the furnace and retractable blowers in the convective passes, must be properly selected for this project. The Lakhra coal, possessing a large quantity of ash and severe slagging potential will require an extensive quantity of wall blowers in the furnace. Wall blowers should be spaced on approximately 8 foot centers both horizontally and vertically. Retractable blowers in the convective areas should be located on approximately 10 to 12 ft. vertical centers. A recommended preliminary soot blower layout is shown on the attached sketch no. UA-850-325. The recommended wall blower and retractable soot blower coverage will effectively handle the moderately fouling Lakhra coal. As was confirmed through laboratory testing, the bonding strengths of ash deposits from firing the Lakhra coal are relatively weak and should be controllable with the above recommended soot blower coverage.

Steam or air soot blowers can be utilized for this project. If air is chosen as the blowing medium, adequate compressor capacity as well as 100% compressor back-up are recommended.

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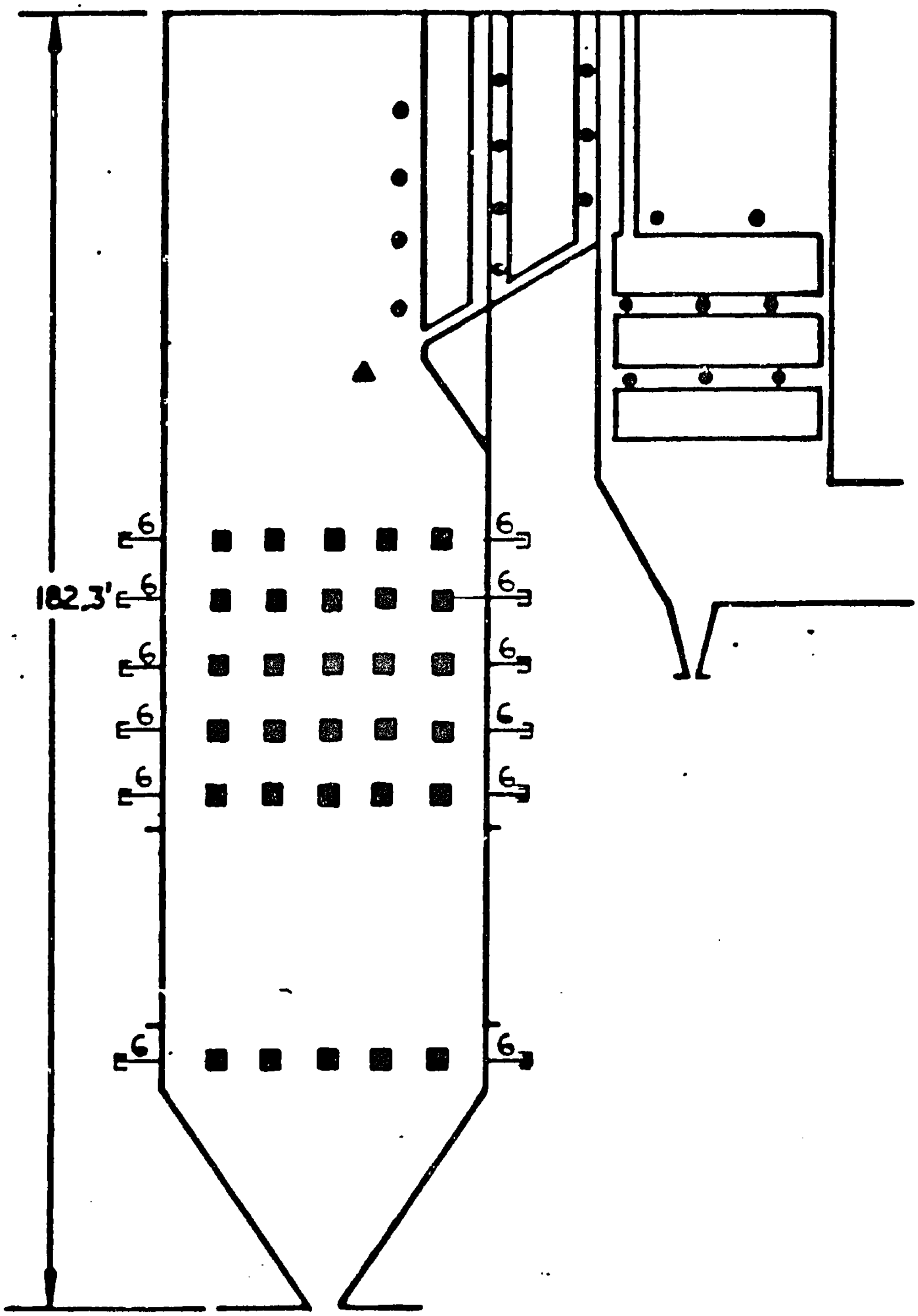

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C-E POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

LAKHRA POWER PROJECT 300 MW

PAKISTAN

SCALE

DWG. NO. UA-850-325-0

Pulverizer Design

In general, the capacity of a given size pulverizer (weight output per unit of time) varies as a function of coal moisture, grindability (ease of pulverization) and coal fineness. The wider the range in coal calorific value, moisture content and grindability, the greater must be the overall pulverizer capacity. The Lakhra coal has a relatively low heat content, high moisture and high grindability. A milling system for burning the Lakhra design coal should be based on providing at least 70% through 200 mesh screen coal fineness as well as maintaining unit capacity at MCR with one mill out of operation. All other mills should be operating at approximately 90% of their rated capacity. This sizing criteria will allow for reduced mill capacity without loss of unit load when pulverizer grinding elements wear. For the 300 Mw project, a six (6) bowl mill arrangement is recommended. Utilizing six (6) mills will provide good milling system turndown as well as sufficient milling capacity to burn the range of lower grade lignitic fuels expected at this plant.

Due to the high abrasiveness of the Lakhra fuels, it is also recommended to provide abrasion resistant materials for the pulverizer components subjected to erosion. These items would normally include the rolls, grinding rings and various liners. Additionally, a coal pipe nominal thickness of ½ inch and ceramic lined elbows are recommended.

Air Heater Design Criteria

Steam generator air heaters are essential in cooling the flue gases before they pass to the atmosphere, thereby enhancing unit efficiency; at the same time they raise the temperature of the incoming air of combustion and provide the hot air for drying the pulverized coal. For the Lakhra Power Project, CE recommends a Ljungstrom type trisector air heater. The minimum recommended hot air requirement for adequately drying the expected moisture coals is 700°F (371.1°C) at MCR. Based on this criteria, CE expects a reasonable uncorrected gas temperature exiting the air heater would be 325°F (162.8°C). The ambient air is assumed to be 80°F (26.7°C).

While overall unit efficiency can be slightly improved by adding additional heating surface to reduce the air heater exit gas temperature, this would lower the cold end metal temperatures to a point approaching the acid dew point of the flue gas. Consequently, cold end materials of the air heater would be more prone to low temperature corrosion resulting in higher maintenance costs and build-up of dust particles on the cold end heating surface. This would increase the air heater draft loss and require more frequent off line cleaning (water washing) of the air heater.

The rate of acid condensation depends on the sulfur content of the fuel, firing procedures, excess air, and the presence of moisture. The acid dew point varies with the concentration of sulfur trioxide in the flue gas. High sulfur coals result in the existence of a dew point at a higher temperature, thus requiring higher temperatures to prevent corrosion and fouling. (see attached CE Air Preheater Co. Cold End Temperature and Material Selection Guide).

For the Lakhra Project, a minimum average cold end temperature of 185°F is recommended. At the MCR load point, based on 80°F inlet air (assuming no fan rise) and an uncorrected exit gas temperature of 325^{o}F, the average cold end temperature is 202.5^{o}F. At reduced loads or lower ambient temperature conditions, the cold end metal temperature is maintained at 185^{o}F through the use of a steam coil air heater located in the cold air duct between the FD fan and the main air preheater. The steam coils increase the temperature of the cold air entering the heater, causing an increase in air heater metal temperature.

As an additional protection for minimizing the rate of low temperature corrosion, replaceable low alloy corrosion resistant material is provided at the cold end sections of the trisector air preheaters.

Based on the above design recommendations, sufficient hot air, optimized unit efficiency and good air heater reliability will be achieved.

Ductwork Design Criteria

The laboratory testing of the Lakhra coals confirmed that the fly ash from burning the fuel is quite erosive. Since gas velocity is the single most important parameter to be selected in minimizing erosion, the following air and gas velocities for the design of the ductwork are recommended:

Cold Air Ductwork:	2500 ft/min (max) (12.7 m/sec)
Hot Air Ductwork:	4000 ft/min (max) (20.3 m/sec)
Flue Gas Ductwork:	3000 ft/min (max) (15.2 m/sec)

It is also recommended that the flue gas ductwork use external bracing wherever possible. With this design, the impact of fly ash erosion on duct internals will be minimized and overall unit availability improved. As an additional benefit, lower duct draft losses will result in reduced power consumption for the induced draft fans.

Fan Design Criteria

a. Primary Air Fan

The recommended design criteria for selection of the primary air fan is as follows:

1. Select the PA fans based on all pulverizers operating. (i.e. 6 of 6 mills for the 300 Mw unit and 7 of 7 for the 350 Mw unit).
2. Include the primary air to gas air heater leakages based on the condition will all mills operating.
3. Add a 25% tolerance to the volumetric rate calculated above.
4. Determine the maximum operating static head condition at MCR with all mills in service.
5. Add a 30% tolerance to the static head.
6. Adjust volumetric flow for specific site conditions. (i.e. ambient air temperature, altitude, humidity).

b. Forced Draft Fan

The design of the forced draft fan is based on the required secondary air flow at MCR with the minimum possible number of mills in service. (i.e. 5 of 6 mills operating for the 300 Mw unit and 6 of 7 mills operating for the 350 Mw unit). The fan design tolerances at the MCR operating condition shall be as follows:

1. Volumetric Flow : 25%
2. Static Pressure : 50%

Appropriate air heater leakages at MCR must be applied to obtain the design volumetric flow rate. Also, appropriate corrections to the volumetric flow rate must be made for specific site conditions (i.e. ambient air temperature, altitude, humidity).

c. Induced Draft Fan

The induced draft fan is designed at MCR operating conditions with appropriate air heater leakages and the following tolerances:

1. Volumetric Flow : 20%
2. Static Pressure : 30%

An additional $20^{o}F$ should be applied to the actual gas temperature entering the induced draft fan.

In summary, the fan design tolerances at MCR operating conditions shall be as follows:

Fan Duty	Tolerance (%)		Notes
	Volume	Static Pressure	
Primary Air	25	30	Based on air flow with all mills in service.
Forced Draft	25	50	Based on air flow with minimum number of mills in service.
Induced Draft	20	30	An additional tolerance of $20^{o}F$ on the corrected gas temperature exiting the air heater.

Performance Data at MCR Operating Conditions

Firing the Lakhra PMDC-2 Coal (see attached design coal analysis)

Evaporation	lbs/hr (kg/hr)	2388304	(1083328)
Temperature at SHO	^oF (^oC)	960	(516)
Pressure at SHO	psig (kg/cm^2)	1995	(140.3)
Superheater Pressure Drop	psi (kg/cm^2)	115	(8.1)
Feedwater Temperature	^oF (^oC)	476	(246.7)
Feedwater Temperature Leaving Economizer	^oF (^oC)	610	(321.1)
Economizer Pressure Drop (Friction Only)	psi (kg/cm^2)	30	(2.1)
Reheater Flow	lbs/hr (kg/hr)	2112694	(958312)
Temperature at Reheater Outlet	^oF (^oC)	960	(515.6)
Temperature at Reheater Inlet	^oF (^oC)	660	(348.9)
Pressure at Reheater Inlet	psi (kg/cm^2)	563	(39.6)
ater Pressure Drop	psi (kg/cm^2)	25	(1.8)
Gas Temperature Leaving Economizer	^oF (^oC)	775	(412.8)
Gas Temperature Leaving Air Heater(uncorr.)	^oF (^oC)	325	(162.8)
Ambient Air Temperature	^oF (^oC)	80	(26.7)
Primary Air Temperature Leaving Air Heater	^oF (^oC)	723	(383.9)
Secondary Air Temperature Leaving Air Heater	^oF (^oC)	707	(375)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	3653034	(1657005)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	3008662	(1364720)
Excess Air	%	25	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.60	(1.08)
Boiler Efficiency at MCR (incl. heat credits)	%	80.90	

Performance Data at MCR Operating Conditions (continued)

Firing the Lakhra PMDC-2 Coal (see attached design coal analyses)

Summary of Heat Losses	
Dry Gas Loss	5.54%
H_2 and H_2O in Fuel	11.80%
H_2O in Air	0.13%
Unburned Carbon	0.15%
Radiation	0.18%
Unaccounted and Mfg.'s Margin	1.50%
Total Heat Losses	19.30%
Heat Credits	0.20%
Total Boiler Efficiency	80.90%

Typical As Received Coal Analysis of The Lakhra Coal (PMDC-2) Raw Coal

Proximate Analysis, Wt. %	
Moisture	30.0
Volatile Matter	24.5
Fixed Carbon	20.0
Ash	25.5
TOTAL	100.0
HHV, BTU/lb	5140
Lb Ash/10^6 BTU	49.6
Ultimate Analysis, Wt. %	
Moisture	30.0
Hydrogen	2.5
Carbon	28.4
Sulfur	4.3
Nitrogen	0.5
Oxygen	8.8
Ash	25.5
TOTAL	100.0
Hardgrove Grindability Index	71

Typical As Received Coal Analysis of The

Lakhra Coal (PMDC-2) Raw Coal

Fusibility Temperatures (Reducing)

I. T.	$^{o}F(^{o}C)$	1980	(1082.2)
S.T.	$^{o}F(^{o}C)$	2430	(1332.2)
H.T.	$^{o}F(^{o}C)$	2470	(1354.4)
F.T.	$^{o}F(^{o}C)$	2520	(1382.2)

Ash Composition Wt. %

SiO_2	43.6
Al_2O_3	27.2
Fe_2O_3	17.2
CaO	3.3
MgO	1.3
Na_2O	0.7
K_2O	0.7
TiO_2	1.9
P_2Os	-
SO_3	3.9
Undetermined	0.2
TOTAL	100.0

Suggested Performance Guarantees

The following are the recommended steam generator performance guarantees firing the design Lakhra coal:

Steam Capacity ____(MCR)____ lbs. of steam/hr.

At a capacity of __(MCR)__ lbs. of steam/hr., the following is also guaranteed:

Overall Efficiency, pct.	
*Temperature of steam leaving superheater (plus or minus 10°F)	°F
**Temperature of steam leaving reheater (plus or minus 10°F)	°F
Pressure drop from steam drum to superheater outlet (plus or minus 10%)	psi
Pressure drop from reheater inlet to reheater outlet (plus or minus 10%)	psi
Economizer pressure drop (friction only) (plus or minus 10%)	psi
Air Resistance (based on scope of supply of boiler manufacturer) (plus or minus 10%)	in.wg.
Draft Loss (based on scope of supply of boiler manufacturer) (plus or minus 10%)	in.wg.
Maximum solids carryover to superheater	ppm
NO_x emission leaving economizer	$lbs/10^6 BTU$

*Controlled from a primary steam flow of ____________ lbs per hour to ____________ lbs per hour.

**Controlled from a reheater steam flow of ____________ lbs per hour to ____________ lbs per hour.

The above guarantees are subjected to the fulfillment of performance conditions specified in the Company's proposal. A guarantee of a 60% to 75% control range for both the superheater and reheater outlet steam temperature is typical.

Affects of Design Coal and Ash Variation

A basic understanding of the role that coal properties play in furnace performance is essential for designing a unit that will provide the highest unit availability and reliability. Major segments for consideration in furnace performance are: combustion efficiency, as indicated by flame stability and complete carbon burnout; the slagging and fouling properties of the ash; the potential for metal corrosion; and erosion characteristics of fly ash in the gas streams.

Laboratory test results of the three Lakhra coals indicated that these fuels ignite easily and produce good stable flames. Analysis of the fly ash samples collected showed that the carbon content was very low, corresponding to better than 99.9% carbon conversion. Thus we anticipate no combustion problems for the full range of Lakhra coals to be fired in this unit.

The amount and specific nature of the mineral matter in coal is significant in assessing the slagging potential of fuels. The high quantity of ash, the high sulfur content, low fusibility temperatures and relatively high iron content of the Lakhra coals all contribute towards a fuel having a severe slagging potential. This was further confirmed by actual laboratory testing of the Lakhra coals in our solid fuel burning testing facility. A properly sized furnace with conservative plan area release rates, higher operating levels of excess air and uniform fineness of pulverized fuel are essential design features for minimizing slagging and corrosive waterwall deposits in furnaces.

The Lakhra coals exhibited moderate fouling potential. Convective deposit accumulation during lab testing was high, however, deposit bonding strengths were low. With the full range of Lakhra coals to be fired in this unit, fouling should be controllable. Conservative transverse tube spacing as well as liberal soot blower coverage will significantly minimize fouling and potential deposit buildup in the convective passes.

The Lakhra coals all indicate a propensity toward forming corrosive compounds. The three major areas where external pressure part corrosion may occur during unit operation are: (1) the waterwalls in the vicinity of the firing zone, (2) the high temperature superheater and reheater surfaces, and (3) the air heaters. Our design recommendations for a low area heat release rate, lower superheater and reheater outlet steam temperatures, 1800 psi thermal cycle and conservative material selection criteria will significantly reduce the corrosion potential of the Lakhra fuels. Recommendations for a minimum average cold end temperature of $185^{o}F$ as well as low alloy corrosion resistant material will minimize low temperature corrosion for the Ljungstrom air preheater.

In general, the higher the percentage of ash in coal, and the higher the percentages of constituents reported as SiO_2 (specifically free quartz), Al_2O_3 and Fe_2O_3 in the ash, the greater the erosion potential. The fly ash erosion of the Lakhra coal has been confirmed to be relatively high. In order to avoid serious problems associated with an erosive ash, low flue gas velocities through the convective pass and backend flue gas ductwork are recommended. With low flue gas velocities, the potential for erosive problems will be minimized.

The high Hardgrove grindability indexes of the Lakhra coals indicate that these fuels are easy to pulverize. However, as was confirmed in the lab, these coals are highly abrasive. Abrasion is defined as the "sandpaper" effect of solid particles moving parallel to, and in contact with, a boundary surface. The rate of abrasive wear on pulverizers depends primarily on the type and quantity of impurities in the coal. The high abrasiveness of the Lakhra coals can be attributed to its high ash content and associated constituents of silicon dioxide as free quartz and iron oxide. As previously discussed, abrasion resistant materials are recommended for the pulverizer high wear components (i.e. rolls, rings, liners, etc.) as well as fuel pipe elbows.

Imported Coals

The use of imported coals from Australia will have significant impact on the boiler performance in a unit designed to fire the Lakhra coals. Typical imported coal properties indicate that these fuels pose none of the slagging or corrosive related problems associated with burning the Lakhra fuels. The Australian coals are essentially clean burning fuels with high heat content, low sulfur and relatively low moisture and ash as compared to the Lakhra coals. In order to achieve comparable boiler performance when burning the cleaner Australian coals, we recommend the following:

a. Increase excess air firing from 25% to 30% -The additional excess air will increase the gas mass flow and thus the sensible heat available to the convective sections when firing the cleaner fuels.

b. Operation of the fuel nozzle tilts in the upward position -Locating the main firing zone at a higher point in the furnace will provide a higher thermal head for the superheater and reheater convective sections.

c. Refractory line localized areas of the waterwalls with Super 3000 material -Lining the furnace walls with refractory material reduces the furnace waterwall heat absorption and increases the available thermal head to the superheater and reheater convective sections.

The above recommendations will achieve reasonably satisfactory performance when firing these coals at the maximum continuous rating of the unit. However, a reduced control range for maintaining full steam temperature can be expected with these fuels.

This unit could also be designed with gas recirculation when firing an imported coal or with an oversurfaced quantity of superheater and reheater material. Both alternatives are expensive and result in much higher maintenance coats. Also, oversurfacing would result in continuous desuperheating spray requirements while firing the Lakhra coal.

It should be noted that the design of the auxiliary equipment must be based on firing the lower grade Lakhra coals. Consequently, the equipment would be significantly oversized for achieving optimum performance when burning the higher quality Australian coals.

300 MW UNIT

Performance Data at MCR Operating Conditions

Firing the Australian Coals (see attached Australian coal analyses)

Evaporation	lbs/hr (kg/hr)	2388304	(1083328)
Temperature at SHO	°F (°C)	960	(516)
Pressure at SHO	psig (kg/cm^2)	1995	(140.3)
Superheater Pressure Drop	psi (kg/cm^2)	115	(8.1)
Feedwater Temperature	°F (°C)	476	(246.7)
Feedwater Temperature Leaving Economizer	°F (°C)	596	(313.3)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	30	(2.1)
Reheater Flow	lbs/hr (kg/hr)	2112694	(958312)
Temperature at Reheater Outlet	°F (°C)	960	(515.6)
Temperature at Reheater Inlet	°F (°C)	660	(348.9)
Pressure at Reheater Inlet	psi (kg/cm^2)	563	(39.6)
Reheater Pressure Drop	psi (kg/cm^2)	25	(1.8)
Gas Temperature Leaving Economizer	°F (°C)	794	(423.3)
Gas Temperature Leaving Air Heater (uncorr.)	°F (°C)	324	(162.2)
Ambient Air Temperature	°F (°C)	80	(26.7)
Primary Air Temperature Leaving Air Heater	°F (°C)	740	(393.3)
Secondary Air Temperature Leaving Air Heater	°F (°C)	726	(385.6)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	3314224	(1503322)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	2912875	(1321271)
Excess Air	%	30	
NO_x Emissions	$lbs/10^6$ BTU ($kg/10^6$ kcal)	0.60	(1.08)
Boiler Efficiency at MCR (incl. heat credits)	%	87.41	

*Performance based on coating furnace walls.

Typical As Received Coal Analyses of The

Australian Coals

Proximate Analysis, Wt. %

	New South Wales	Queensland
Moisture	12.0	12.0
Volatile Matter	26.0	16.6
Fixed Carbon	46.0	55.4
Ash	16.0	16.0
TOTAL	100.0	100.0
HHV, BTU/lb	10,500	11,000
Lb Ash/10^6 BTU	15.2	14.5

Ultimate Analysis, Wt. %

	New South Wales	Queensland
Moisture	12.0	12.0
Hydrogen	3.8	3.2
Carbon	59.3	62.6
Sulfur	0.3	0.6
Nitrogen	1.2	1.2
Oxygen	7.4	4.4
Ash	16.0	16.0
TOTAL	100.0	100.0

Typical As Received Coal Analyses of The

Australian Raw Coals

Ash Composition Wt. %

	New South Wales	Queensland
SiO_2	62.7	53.0
Al_2O_3	18.0	20.0
Fe_2O_3	6.1	5.5
CaO	5.5	7.7
MgO	1.1	5.0
Na_2O	1.0	2.5
K_2O	1.9	1.3
TiO_2	0.7	0.6
P_2O_5	0.1	0.6
SO_3	1.2	2.5
Undetermined	1.7	1.3
TOTAL	100.0	100.0

The Influence of Oil Firing

A unit designed to fire the Lakhra coal must be conservatively sized to minimize the operational impact of potentially high slagging in the furnace. All design considerations must accommodate the coal and ash characteristics of the Lakhra fuel. As with an imported coal, it will be very difficult to achieve comparable boiler performance when firing oil in such a large furnace. Even with gas recirculation, use of an additive and oil burners in the full up tilt position, superheater and reheater outlet steam temperatures of 950^{o}F/950^{o}F cannot be achieved.

The use of fuel oil additives reduces the furnace waterwall heat absorption thereby providing additional thermal head to the superheater and reheater convective sections. Also, additives protect against possible gas side corrosion caused by the effects of impurities (specifically sulfur, vanadium and sodium) in fuel oils. There are a variety of fuel oil additives available, composed of different proprietary formulations of fine magnesium oxide and/or aluminum oxide suspended in light oil. Such additives are introduced into the furnace by means of a metering pumping system that injects the light oil into the main oil stream before the oil guns.

To achieve satisfactory performance when firing oil, additional superheater and reheater surface is required. The increased surface, however, would negatively impact furnace performance when firing the Lakhra coal. Significant amounts of desuperheating spray would be required at MCR to effectively control superheater and reheater outlet steam temperatures. Subsequently, it is not recommended to compromise the design of this unit for oil firing. If oil firing must be seriously considered, then reduced thermal performance should be anticipated.

The following is a partial list of the additional equipment required to support oil firing:

Main fuel oil pump and heater set

Main fuel retractable oil guns

Fuel oil piping

Main oil trip valves, recirculation valves

Fuel oil storage tanks

Steam atomizing piping and control valves

Fuel oil controls and instrumentation

Heat tracing of fuel piping

A typical motor list to support dual fuel firing is as follows:

<u>Typical Motor Service</u>

Forced draft fan

Primary air fan

Induced draft fan

Pulverizers

Air preheaters

Soot blower motors

Mill seal air fans

Ignitor air fans

Scanner air fans

Gas recirculation fan

Fuel oil pumps

The motors indicated above are those required to drive major equipment and they shall be the squirrel cage, constant speed type. The actual quantity, horsepower output, rpm, etc. of the above listed motors will be determined during the actual design of the unit.

300 MW UNIT

*Performance Data at MCR Operating Conditions

Firing No. 6 Oil (see attached typical fuel oil analysis)

Evaporation	lbs/hr (kg/hr)	2388304	(1083328)
Temperature at SHO	°F (°C)	815	(435.0)
Pressure at SHO	psig (kg/cm^2)	1995	(140.3)
Superheater Pressure Drop	psi (kg/cm^2)	115	(8.1)
Feedwater Temperature	°F (°C)	476	(246.7)
Feedwater Temperature Leaving Economizer	°F (°C)	550	(287.8)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	30	(2.1)
Reheater Flow	lbs/hr (kg/hr)	2112694	(958312)
Temperature at Reheater Outlet	°F (°C)	815	(435.0)
Temperature at Reheater Inlet	°F (°C)	615	(323.9)
Pressure at Reheater Inlet	psi (kg/cm^2)	563	(39.6)
heater Pressure Drop	psi (kg/cm^2)	25	(1.8)
Gas Temperature Leaving Economizer	°F (°C)	695	(368.3)
Gas Temperature Leaving Air Heater (uncorr.)	°F (°C)	320	(160.0)
Ambient Air Temperature	°F (°C)	80	(26.7)
Primary Air Temperature Leaving Air Heater	°F (°C)	--	--
Secondary Air Temperature Leaving Air Heater	°F (°C)	620	(326.7)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	(2528524)	(1146931)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	(2266605)	(1028125)
Excess Air		20	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.30	(0.54)
Boiler Efficiency at MCR (incl. heat credits)		88.01	

*Performance based on additive firing.

Typical No. 6 Fuel Oil Analysis

	Percent by Weight %
Carbon	86.5
Hydrogen	11.10
Nitrogen	0.4
Oxygen	0.9
Sulfur	1.0
Ash	0.1
HHV (as fired) BTU/lb	18700

Analysis of Units Firing Similar Coals to the Lakhra Coals

As can be seen by the attached chart, no single coal truly represents all the coal properties and combustion characteristics that would be experienced by firing a Lakhra coal. The Spanish lignite, fired at Alcudia II, represents the closest coal with respect to its low heat content, high ash and high sulfur content. However, the Spanish lignite does not possess the high abrasive characteristics that are apparent with the Lakhra coals.

The Soto de Ribera coal has high ash, low sulfur, low heating content and high silica and alumina. The low fusion temperatures combined with the high ash loading reflect a moderately slagging fuel. Also, this coal is somewhat more abrasive than the Lakhra coal.

The Chinese lignite is relatively high in moisture, high in ash, low in sulfur, low in heat content and high in silica and alumina. This is a very abrasive fuel as well as a moderate slagger. This coal does not have any of the corrosive characteristics that would be expected with firing the Lakhra coal.

All three (3) Indian coals are high in ash, low in sulfur, low in heat content and high in alumina and silica. These fuels are highly abrasive and must be properly designed for low velocities in minimizing erosion.

In summary, the coals depicted above are high in ash loading and low in heat content. The operating experience at Alcudia II indicates that favorable performance and reliable unit operation can be achieved when firing a high ash, high sulfur fuel.

List of Units Firing Similar Coals to the Lakhra Coals

1. Gas Y Electricidad S.A.

   Central Termica de Alcudia II

   Units #1 & #2

   Rating: 125 MW

   SHO Pressure/Temperature 1900 psig/1000^{o}F
   SH/RH Flow 882000 lbs/hr / 772000 lbs/hr

2. Central Termica Soto de Ribera

   Soto de Ribera Unit #3

   Rating: 371 MW

   SHO Pressure/Temperature 2500 psig/1005^{o}F
   SH/RH Flow 2470000 lbs/hr / 2160000 lbs/hr

3. People's Republic of China

   Yuan Bao Shan Power Station

   Rating: 600 MW

   SHO Pressure/Temperature 2653 psig/1005^{o}F
   SH/RH Flow 4427000 lbs/hr / 3602000 lbs/hr

4. National Thermal Power Corporation

   Korba Units

   Ramagundam Units

   Singrauli Units

   Rating: 500 MW

   SHO Pressure/Temperature 2531 psig/1005^{o}F
   SH/RH Flow 3802935 lbs/hr / 3373838 lbs/hr

Significant Coal Properties Comparison of Units Firing Similar Coals

to the Lakhra Coals

Unit Name	Lakhra Project	Gas Y Electricidad S.A. Alcudia II	Central Termica Soto de Ribera	People's Republic of China	NPTC Korba	NPTC Ramagundam	NPTC Singrauli
Moisture, %	30.0	14.0	15.0	25.12	12.00	10.00	16.00
Ash, %	25.5	32.25	31.5	30.09	44.00	32.00	30.00
Sulfur, %	4.29	6.02	0.9	0.43	0.26	0.38	0.27
HHV, BTU/lb	5140	5263	7740	5383	6300	7740	7290
$SiO_2 + Al_2O_3$,%	70.8	29.76	80.0*	81.9	87.59	81.15	84.2
Fe_2O_3, %	17.2	3.23	8.0*	11.8	5.60	8.40	6.4
CaO, %	3.3	47.32	3.0*	2.3	1.43	7.06	1.8
Na_2O, %	0.7	0.10	0.75*	0.3	< 0.6*	< 0.5*	0.4
Initial Def.Temp ^oF	1980	*2700$^+$	2192	2040	2138	2460	2174
Fluid Temp. ^oF	2520	*2700$^+$	2696	2570	2552	2552	2552$^+$
Base/Acid Ratio	0.32	1.77	0.21*	0.21	0.10*	0.22*	0.14
Lbs Ash/10^6 BTU	49.6	61.3	40.7	55.9	69.8	41.3	41.2
Lbs Sulfur/ 10^6 BTU	8.35	11.44	1.16	0.8	0.41	0.41	0.37
Grindability, HGI	71	70	65	55	58	50	50

*Estimated values

Summary of Coal Characteristics of Units Firing Similar Coals

to the Lakhra Coals

Unit Name	Lakhra Project	Gas Y Electricidad S.A. Alcudia II	Central Termica Soto de Ribera	People's Republic of China	NPTC Korba	NPTC Ramagundam	NPTC Singrauli
Slagging	HIGH	HIGH	MODERATE	MODERATE	LOW	LOW	LOW
Corrosive	HIGH	HIGH	LOW	LOW	LOW	LOW	LOW
Fouling	MODERATE	HIGH	LOW	LOW	LOW	LOW	LOW
Erosive/Abrasive	HIGH	LOW	HIGH	HIGH	HIGH	HIGH	HIGH
Grindability	HIGH	HIGH	HIGH	MODERATE	MODERATE	MODERATE	MODERATE

Summary

The furnace design recommendations presented in this report were based on extensive laboratory testing of the Lakhra coal fired in our solid fuel burning testing facility. Having firsthand knowledge of the expected behavior of coal ash is essential towards optimizing the furnace design for high unit availability and reliability.

The laboratory testing of the Lakhra fuels indicated that major emphasis be placed on designing a large furnace with low plan area release rates to control the potentially high slagging and corrosive aspects of this fuel. It was also evident that based on the highly abrasive characteristics of the ash major emphasis be placed upon designing a unit with low flue gas velocities in the convective areas. The high corrosive potential of the Lakhra fuel was addressed by our conservative material selection recommendations, the 1800 psi, $950^{o}F/950^{o}F$ thermal cycle, the high average cold end temperature criteria for the air preheater as well as the higher levels of excess air firing. The lower pressure/temperature cycle will have the following advantages over a 2400 psi cycle:

a. Greater fuel flexibility

b. Higher available thermal head

c. Higher unit availability and reliability

d. Easier maintainability

e. Simpler unit operation

f. Lower material cost

The moderate fouling potential of the Lakhra coal has been considered in our design with respect to the recommended transverse convective spacings specified in this report. Also, a conservative number of furnace wall blowers and retractable soot blowers have been recommended for effective furnace cleaning.

A six (6) mill arrangement will provide a complete spare when operating at MCR conditions firing the Lakhra design fuel. The six (6) mills provide good unit turndown and adequate capacity to accommodate the firing of poorer grade coals. The air heaters have been designed to properly dry the expected high moisture levels of these coals.

Laboratory testing also confirmed that coal cleaning does not improve the raw coal slagging and fouling characteristics. Thus the cost of coal washing as well as the reliability of this equipment must be carefully evaluated before such methods can be recommended. Coal washing will reduce the quantity of ash and sulfur thus requiring smaller capacity ash removal systems and precipitators. However, we see little advantage with regard to reducing costs relative to the overall boiler design.

As previously cited, the firing of imported coals and/or oil in a Lakhra designed furnace has several drawbacks. Basically the furnace is too large to achieve satisfactory furnace performance when firing these clean burning fuels. If some modifications were made such as coating furnace walls, operating at higher excess air levels and modulating coal nozzle tilts, comparable furnace performance could be achieved when burning the Australian coals. Oil firing, however, will require more extensive changes for maintaining satisfactory full load performance.

The design recommendations for this project were based on the valuable testing results obtained from burning the three Lakhra sample coals in our fuel burning lab facilities. Based on the conservative design criteria recommended in our report, we are confident that a highly reliable, available and maintainable steam generator can be designed to successfully fire the Lakhra coals.

Steam Generator Design and Performance Evaluation

For a 350 Mw Unit

A review of the attached performance fuel and nine (9) sample coal analyses provided by J. T. Boyd Co. has been made with respect to the design of a 350 Mw unit. In general, these coals are lower in heat content, higher in moisture and higher in ash than those previously indicated in our report. However, upon closer evaluation, it is evident that the combustion characteristics and fuel properties pertinent to the proper design of a steam generator parallel those coals previously tested in our laboratories. Subsequently, the same furnace design guidelines are recommended.

As can be seen from the attached drawing (no. UA-850-377) a 350 Mw unit would be approximately 13'-6" taller than the previously specified 300 Mw unit. The number of wall blowers and retractable soot blowers indicated on the attached drawing (no. UA-850-380) is exactly the same as that shown for the 300 Mw unit.

The significant properties of higher moisture, lower heat content and higher ash will result in higher hot air requirements (725°F to 750°F), additional milling capacity (seven (7) total mills), increased primary air fan capacity and increased loadings for the ash handling systems. Attached are typical performance data at 100% VWO and 95% VWO firing the specified performance fuel.

In summary, the previously recommended design criteria will be suitable for designing a reliable 350 Mw steam generator for the Lakhra Project.

Typical Performance Fuel Analysis

Proximate Analysis, Wt. %		Range (% Dry Basis)
Moisture	32.0	— —
Volatile Matter	23.5	32.15 - 39.58
Fixed Carbon	20.0	23.68 - 35.82
Ash	24.5	26.17 - 41.87
TOTAL	100.0	— —
HHV, BTU/lb	5100	6060 - 8950
Lb Ash/10^6 BTU	48.0	— —

Ultimate Analysis, (Wt. % As Fired)		Range (% Dry Basis)
Moisture	32.0	— —
Hydrogen	2.1	2.76 - 3.66
Carbon	29.1	35.61 - 50.75
Sulfur	4.9	6.02 - 9.85
Nitrogen	0.6	0.66 - 1.08
Oxygen	6.8	9.69 - 12.84
Ash	24.5	26.17 - 41.87
TOTAL	100.0	— —

Typical Performance Fuel Analysis

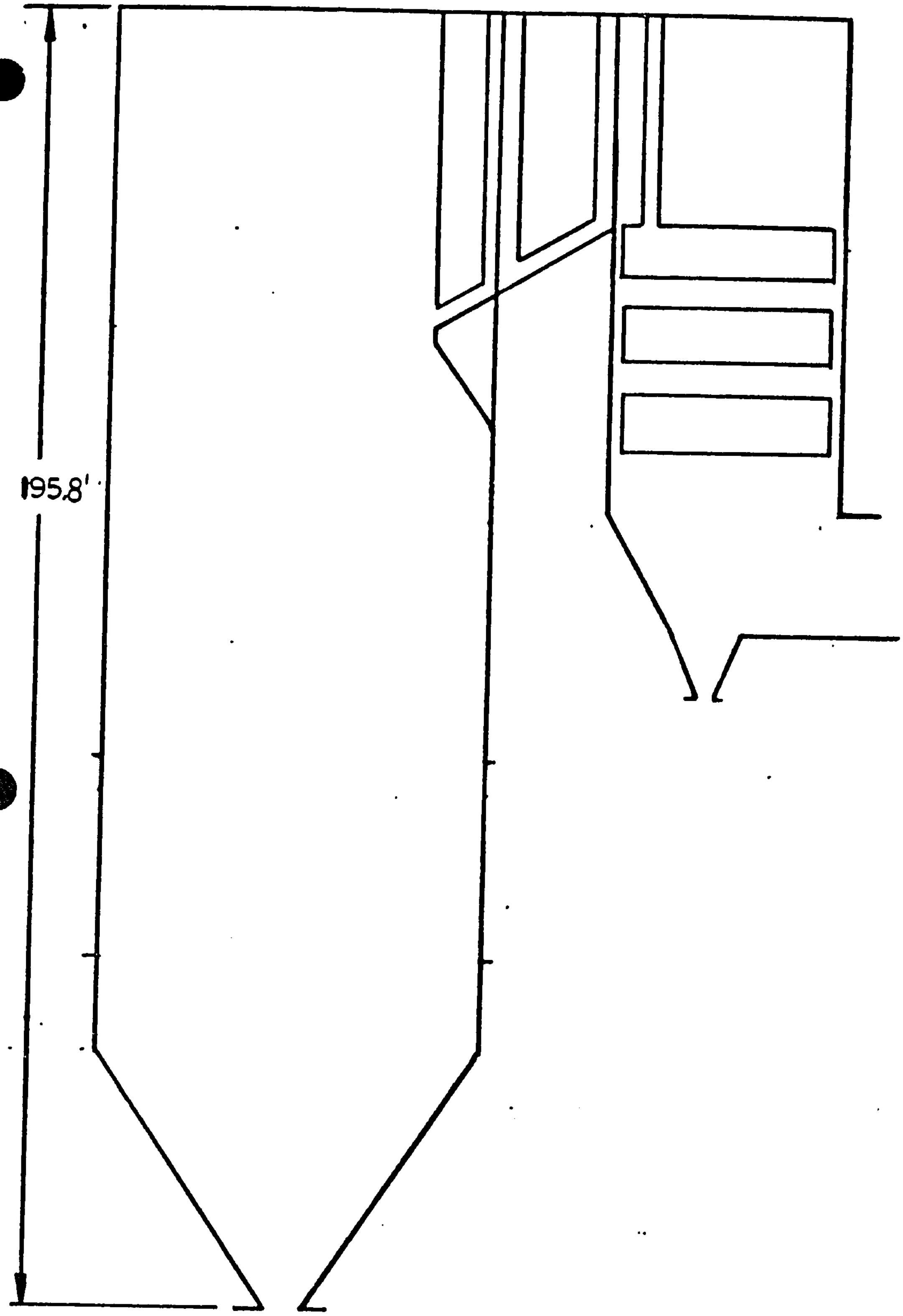
Fusibility Temperatures (Reducing)				Range
I. T.	$^oF(^oC)$	2094	(1145.6)	2001(1093.8) - 2443(1339.3)
S. T.	$^oF(^oC)$	2124	(1162.2)	2005(1096.1) - 2453(1345.0)
H. T.	$^oF(^oC)$	2157	(1180.5)	2012(1100.0) - 2463(1350.6)
F. T.	$^oF(^oC)$	2263	(1239.4)	2046(1118.9) - 2508(1375.6)

Ash Composition Wt. %		Range
S_iO_2	39.6	32.34 - 47.68
Al_2O_3	20.2	12.12 - 26.30
Fe_2O_3	24.5	17.02 - 33.60
CaO	3.7	2.11 - 8.39
MgO	1.6	0.79 - 2.54
Na_2O	0.7	0.32 - 1.02
K_2O	0.6	0.45 - 0.76
TiO_2	2.0	1.33 - 3.16
P_2O_5	0.8	0.56 - 0.93
SO_3	5.6	2.20 - 10.55
Undetermined	0.7	
TOTAL	100.0	

ignificant Coal Properties of Proposed Fuels for Lakhra Project (J. T. Boyd Co. Sample Analyses)

Coal Sample Designation:	Performance	W-C2	W-C1	E-C2	E-B1	C-A2	W-A2	W-A1	E-A1	C-A3
Moisture, %	32.00	25.00	32.00	35.00	45.00	45.00	45.00	38.00	42.00	38.00
Ash, % (as rec'd)	24.48	31.46	27.88	25.93	15.31	15.22	15.27	18.24	15.81	19.76
Sulfur, % (as rec'd)	4.94	6.35	5.20	4.21	4.05	4.65	4.54	5.49	4.32	4.98
HHV, BTU/Lb (as rec'd)	5100	4545	4483	4453	4851	4854	4694	5141	5152	5106
$S_iO_2 + Al_2O_3$, %	59.77	66.04	67.30	69.48	51.56	54.05	57.37	58.85	59.84	57.89
Fe_2O_3, %	24.54	19.11	17.79	19.92	31.02	31.88	25.53	26.11	25.16	27.55
CaO, %	3.70	3.88	3.06	2.13	4.28	3.92	3.52	2.89	3.63	3.07
Na_2O, %	0.72	0.48	0.32	0.70	0.94	0.81	0.74	0.58	0.69	0.78
Initial Def. Temp(^oF) (Reducing)	2094	2140	2108	2104	2047	2001	2065	2017	2046	2012
Fluid Temp.(^oF)(Red.)	2263	2492	2312	2490	2195	2046	2133	2132	2230	2189
Base/Acid Ratio	0.51	0.37	0.35	0.34	0.73	0.69	0.54	0.52	0.51	0.55
Lbs Ash/10^6BTU	48.0	69.2	62.2	58.2	31.6	31.4	32.5	35.5	30.7	38.7
Lbs Sulfur/10^6 BTU	9.69	13.97	11.60	9.45	8.35	9.58	9.67	10.68	8.39	9.75

REVISIONS



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C-E POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

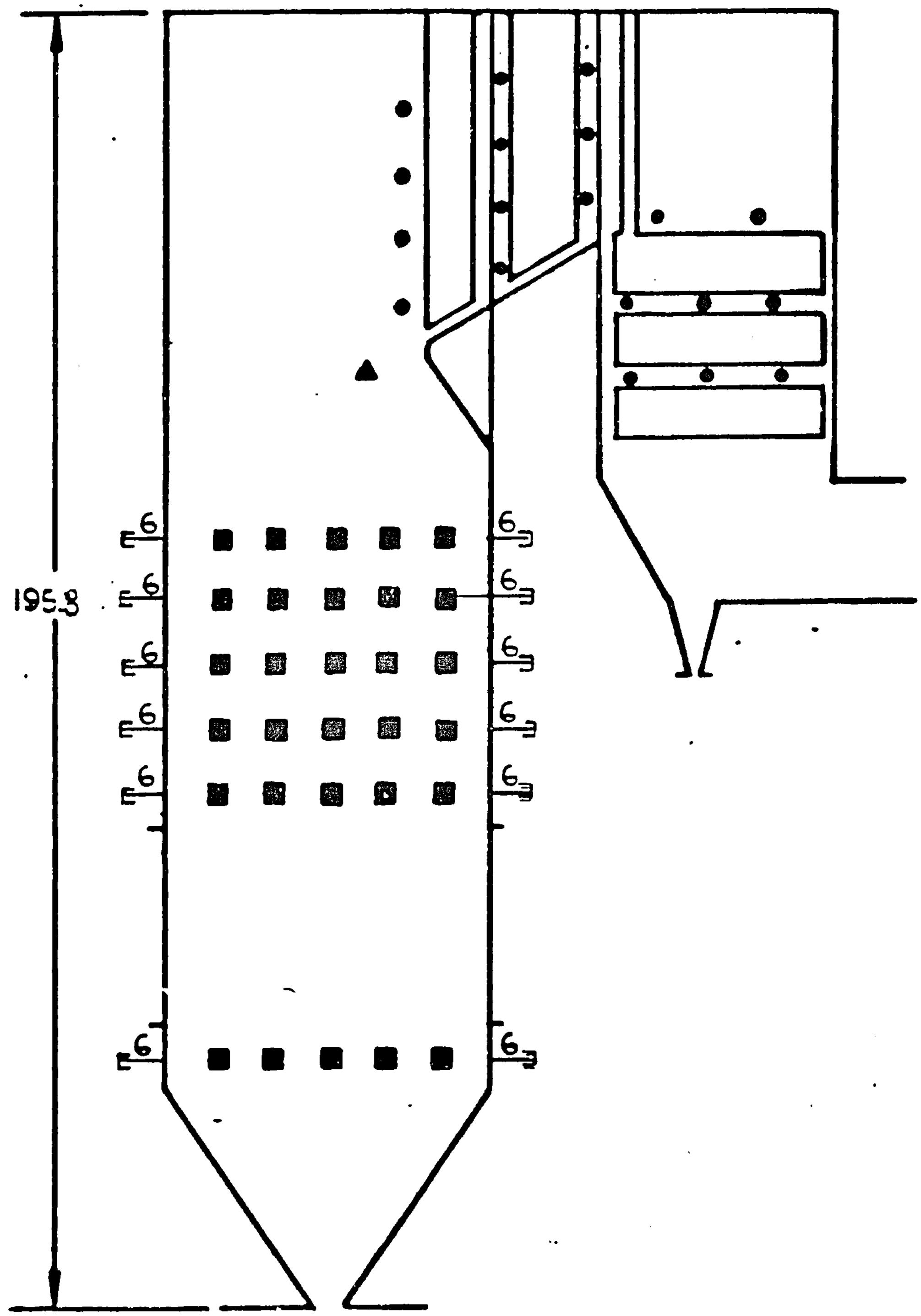
LAKHRA POWER
PROJECT 350 MW

PAKISTAN

SCALE

DWG. NO. UA 850-377

REVISIONS



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DATE 10.3.85 APPROVED

C-E POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

LAKHRA POWER PROJECT 350 MW

PAKISTAN

SCALE

DWG. NO. UA-850-380-0

Performance Data at 100% Operating Conditions

Firing the Lakhra Typical Performance Fuel Analysis Coal (see attached design coal analysis) pg. 33-34

Evaporation	lbs/hr (kg/hr)	2893000	(1312256)
Temperature at SHO	^oF (^oC)	955	(512.8)
Pressure at SHO	psig (kg/cm^2)	1900	(133.6)
Superheater Pressure Drop	psi (kg/cm^2)	115	(8.1)
Feedwater Temperature	^oF (^oC)	466	(241.1)
Feedwater Temperature Leaving Economizer	^oF (^oC)	604	(317.8)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	30	(2.1)
Reheater Flow	lbs/hr (kg/hr)	2612235	(1184870)
Temperature at Reheater Outlet	^oF (^oC)	955	(512.8)
Temperature at Reheater Inlet	^oF (^oC)	629	(331.7)
Pressure at Reheater Inlet	psi (kg/cm^2)	482	(33.8)
Reheater Pressure Drop	psi (kg/cm^2)	26	(1.9)
Gas Temperature Leaving Economizer	^oF (^oC)	800	(426.7)
Gas Temperature Leaving Air Heater (uncorr.)	^oF (^oC)	335	(168.3)
Ambient Air Temperature	^oF (^oC)	80	(26.7)
Primary Air Temperature Leaving Air Heater	^oF (^oC)	733	(389.4)
Secondary Air Temperature Leaving Air Heater	^oF (^oC)	708	(375.6)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	4541494	(2060008)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	3664655	(1662277)
Excess Air	%	25	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.60	(1.08)
Boiler Efficiency at MCR (incl. heat credits)	%	80.83	

Performance Data at 100% Operating Conditions

Firing the Lakhra Typical Performance Fuel Analysis Coal

(see attached design coal analysis pg. 33-34)

Summary of Heat Losses	
Dry Gas Loss	5.81%
H_2 and H_2O in Fuel	11.59%
H_2O in Air	0.14%
Unburned Carbon	0.15%
Radiation	0.18%
Unaccounted and Mfg.'s Margin	1.50%
Total Heat Losses	19.37%
Heat Credits	0.2%
Total Boiler Efficiency	80.83%

Performance Data at 95% VWO Operating Conditions

Firing The Lakhra Typical Performance Fuel Analysis Coal (see attached design coal analysis) pg. 33-34

Evaporation	lbs/hr (kg/hr)	2750000	(1247392)
Temperature at SHO	^oF (^oC)	955	(512.8)
Pressure at SHO	psig (kg/cm^2)	1890	(132.9)
Superheater Pressure Drop	psi (kg.cm^2)	105	(7.4)
Feedwater Temperature	^oF (^oC)	461	(238.3)
Feedwater Temperature Leaving Economizer	^oF (^oC)	601	(316.1)
Economizer Pressure Drop (Friction Only)	psi (kg/cm^2)	27	(1.9)
Reheater Flow	lbs/hr (kg/hr)	2491060	(1129937)
Temperature at Reheater Outlet	^oF (^oC)	955	(512.8)
Temperature at Reheater Inlet	^oF (^oC)	626	(330.0)
Pressure at Reheater Inlet	psi (kg/cm^2)	458	(32.2)
Reheater Pressure Drop	psi (kg/cm^2)	23	(1.7)
Gas Temperature Leaving Economizer	^oF (^oC)	787	(419.4)
Gas Temperature Leaving Air Heater (uncorr.)	^oF (^oC)	330	(165.6)
Ambient Air Temperature	^oF (^oC)	80	(26.7)
Primary Air Temperature Leaving Air Heater	^oF (^oC)	721	(382.8)
Secondary Air Temperature Leaving Air Heater	^oF (^oC)	697	(369.4)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	4334369	(19[illegible]6057)
Total Air Leaving Economizer	lbs/hr (kg/hr)	3559785	(1614708)
Excess Air		25	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.60	(1.08)
Boiler Efficiency at MCR (incl. heat credits)		80.99	

Performance Data at 95% VWO Operating Conditions

Firing the Lakhra Typical Performance Fuel Analysis Coal

(see attached design coal analysis pg. 33-34)

Summary of Heat Losses	
Dry Gas Loss	5.69%
H_2 and H_2O in Fuel	11.56%
H_2O in Air	0.13%
Unburned Carbon	0.15%
Radiation	0.18%
Unaccounted and Mfg.'s Margin	1.50%
Total Heat Losses	19.21%
Heat Credits	0.20%
Total Boiler Efficiency	80.99%

<u>350 MW UNIT</u>

*Performance Data at 100% Operating Conditions

Firing the Australian Coals (see attached Australian coal analyses)

Evaporation	lbs/hr (kg/hr)	2893000	(1312256)
Temperature at SHO	°F (°C)	955	(512.8)
Pressure at SHO	psig (kg/cm^2)	1900	(133.6)
Superheater Pressure Drop	psi (kg/cm^2)	115	(8.1)
Feedwater Temperature	°F (°C)	466	(241.1)
Feedwater Temperature Leaving Economizer	°F (°C)	596	(313.3)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	30	(2.1)
Reheater Flow	lbs/hr (kg/hr)	2612235	(1184870)
Temperature at Reheater Outlet	°F (°C)	955	(512.8)
Temperature at Reheater Inlet	°F (°C)	629	(331.7)
Pressure at Reheater Inlet	psi (kg/cm^2)	482	(33.8)
Reheater Pressure Drop	psi (kg/cm^2)	26	(1.9)
Gas Temperature Leaving Economizer	°F (°C)	785	(418.3)
Gas Temperature Leaving Air Heater (uncorr.)	°F (°C)	316	(157.8)
Ambient Air Temperature	°F (°C)	80	(26.7)
Primary Air Temperature Leaving Air Heater	°F (°C)	723	(383.9)
Secondary Air Temperature Leaving Air Heater	°F (°C)	704	(373.3)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	3960496	(1796469)
Total Air Leaving Air I	lbs/hr (kg/hr)	3470521	(1574218)
Excess Air	%	25	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.60	(1.08)
Boiler Efficiency at MCR (incl. heat credits)	%	87.47	

*Performance based on coating furnace walls.

350 MW Unit

*Performance Data at 95% VWO Operating Conditions

Firing the Australian Coals (see attached Australian coal analyses)

Evaporation	lbs/hr (kg/hr)	2750000	(1247392)
Temperature at SHO	^oF (^oC)	955	(512.8)
Pressure at SHO	psig (kg/cm^2)	1890	(132.9)
Superheater Pressure Drop	psi (kg/cm^2)	105	(7.4)
Feedwater Temperature	^oF (^oC)	461	(238.3)
Feedwater Temperature Leaving Economizer	^oF (^oC)	589	(309.4)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	27	(1.9)
Reheater Flow	lbs/hr (kg/hr)	2491060	(1129937)
Temperature at Reheater Outlet	^oF (^oC)	955	(512.8)
Temperature at Reheat	^oF (^oC)	626	(330.0)
Pressure at Reheater Inle	psi (kg/cm^2)	458	(32.2)
Reheater Pressure Drop	psi (kg/cm^2)	23	(1.7)
Gas Temperature Leaving Economizer	^oF (^oC)	770	(410.0)
Gas Temperature Leaving Air Heater (uncorr.)	^oF (^oC)	310	(154.4)
Ambient Air Temperature	^oF (^oC)	80	(26.7)
Primary Air Temperature Leaving Air Heater	^oF (^oC)	711	(377.2)
Secondary Air Temperature Leaving Air Heater	^oF (^oC)	693	(367.2)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	3760992	(1705975)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	3295698	(1494919)
Excess Air	%	25	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.60	(1.08)
Boiler Efficiency at MCR (incl. heat credits)	%	87.98	

*Performance based on coating furnace walls.

Typical As Received Coal Analyses of The

Australian Coals

Proximate Analysis, Wt. %

	New South Wales	Queensland
Moisture	12.0	12.0
Volatile Matter	26.0	16.6
Fixed Carbon	46.0	55.4
Ash	16.0	16.0
TOTAL	100.0	100.0
HHV, BTU/lb	10,500	11,000
Lb Ash/10^6 BTU	15.2	14.5
Ultimate Analysis, Wt. %		
Moisture	12.0	12.0
Hydrogen	3.8	3.2
Carbon	59.3	62.6
Sulfur	0.3	0.6
Nitrogen	1.2	1.2
Oxygen	7.4	4.4
Ash	16.0	16.0
TOTAL	100.0	100.0

Typical As Received Coal Analyses of The

Australian Raw Coals

Ash Composition Wt. %

	New South Wales	Queensland
SiO_2	62.7	53.0
Al_2O_3	18.0	20.0
Fe_2O_3	6.1	5.5
CaO	5.5	7.7
MgO	1.1	5.0
Na_2O	1.0	2.5
K_2O	1.9	1.3
TiO_2	0.7	0.6
P_2O_5	0.1	0.6
SO_3	1.2	2.5
Undetermined	1.7	1.3
TOTAL	100.0	100.0

350 MW UNIT

*Performance Data at 100% Operating Conditions

Firing No. 6 Oil (see attached typical fuel oil analysis)

Evaporation	lbs/hr (kg/hr)	2893000	(1312256)
Temperature at SHO	°F (°C)	815	(435.0)
Pressure at SHO	psig (kg/cm^2)	1900	(133.6)
Superheater Pressure Drop	psi (kg/cm^2)	115	(8.1)
Feedwater Temperature	°F (°C)	466	(241.1)
Feedwater Temperature Leaving Economizer	°F (°C)	550	(287.8)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	30	(2.1)
Reheater Flow	lbs/hr (kg/hr)	2612235	(1184870)
Temperature at Reheater Outlet	°F (°C)	815	(435.0)
Temperature at Reheater Inlet	°F (°C)	615	(323.9)
Pressure at Reheater Inlet	psi (kg/cm^2)	482	(33.8)
Reheater Pressure Drop	psi (kg/cm^2)	26	(1.9)
Gas Temperature Leaving Economizer	°F (°C)	695	(368.3)
Gas Temperature Leaving Air Heater (uncorr.)	°F (°C)	320	(160.0)
Ambient Air Temperature	°F (°C)	80	(26.7)
Primary Air Temperature Leaving Air Heater	°F (°C)	—	--
Secondary Air Temperature Leaving Air Heater	°F (°C)	620	(326.7)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	(3156124)	(1431608)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	(2829195)	(1283314)

Excess Air		20	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.30	0.54
Boiler Efficiency at MCR (incl. heat credits)		88.01	

*Performance based on additive firing.

350 MW UNIT

*Performance Data at 95% VWO Operating Conditions

Firing No. 6 Oil (see attached typical fuel oil analysis)

Evaporation	lbs/hr (kg/hr)	2750000	(1247392)
Temperature at SHO	^oF (^oC)	800	(426.7)
Pressure at SHO	psig (kg/cm^2)	1890	(132.7)
Superheater Pressure Drop	psi (kg/cm^2)	105	(7.4)
Feedwater Temperature	^oF (^oC)	461	(238.3)
Feedwater Temperature Leaving Economizer	^oF (^oC)	550	(287.8)
Economizer Pressure Drop (Friction only)	psi (Kg/cm^2)	27	(1.9)
Reheater Flow	lbs/hr (kg/hr)	2491060	1129937
Temperature at Reheater Outlet	^oF (^oC)	800	(425.7)
Temperature at Reheater Inlet	^oF (^oC)	610	(331.1)
Pressure at Reheater Inlet	psi (kg/cm^2)	458	(32.2)
Reheater Pressure Drop	psi (kg/cm^2)	23	(1.7)
Gas Temperature Leaving Economizer	^oF (^oC)	685	(362.8)
Gas Temperature Leaving Air Heater (uncorr.)	^oF (^oC)	315	(157.2)
Ambient Air Temperature	^oF (^oC)	80	(26.7)
Primary Air Temperature Leaving Air Heater	^oF (^oC)	-	-
Secondary Air Temperature Leaving Air Heater	^oF (^oC)	600	(315.6)
Gas Flow Leaving Economizer	lbs/hr (kg/hr)	2952011	(1339023)
Total Air Leaving Air Heater	lbs/hr (kg/hr)	2636595	(1195952)
Excess Air		20	
NO_x Emissions	lbs/10^6 BTU (kg/10^6 kcal)	0.30	0.54
Boiler Efficiency at MCR (incl. heat credits)		88.41	

*Performance based on additive firing.

Typical No. 6 Fuel Oil Analysis

	Percent by Weight %
Carbon	86.5
Hydrogen	11.10
Nitrogen	0.4
Oxygen	0.9
Sulfur	1.0
Ash	0.1
HHV (as fired) BTU/lb	18700

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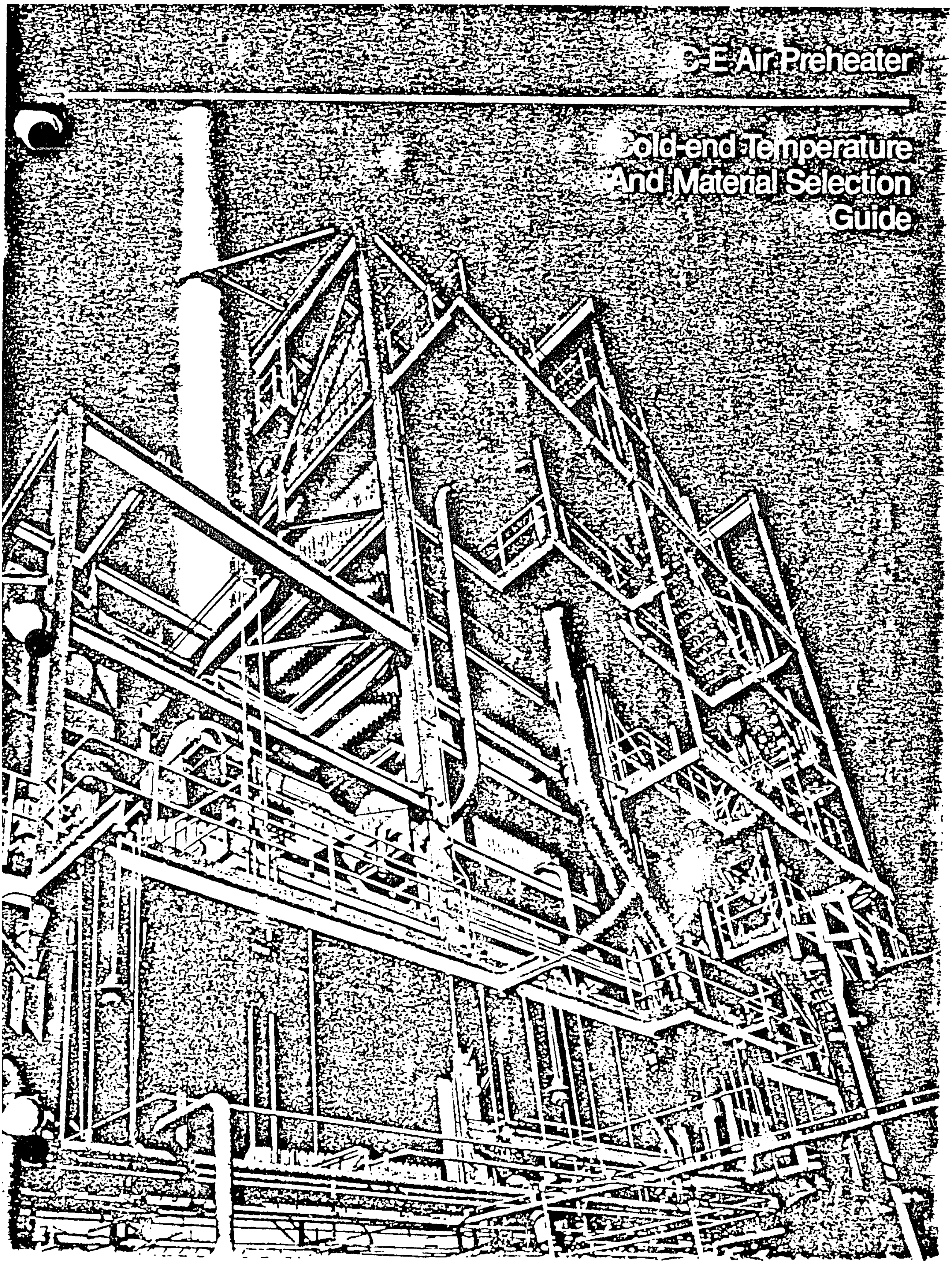
C-E Air Preheater

Cold-end Temperature And Material Selection Guide



Ljungstrom® Air Preheater
Cold-end Temperature
And Material Selection Guide

Cold-end Protection

This temperature guide is intended to aid the power plant designer and the operator. The designer will be concerned with the selection and sizing of cold-end protection equipment. For oil firing, the designer will also have to evaluate the given combinations of corrosion-resistant materials and average cold-end temperatures. The guide will aid the boiler operator in maintaining an economic balance between high boiler efficiency and maintenance costs.

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Coal Firing

Corrosion potential of cold-end heat transfer surface is not as great in coal-fired plants as in oil-fired installations. For coal-fired applications, the use of low-alloy steel for cold-end heat transfer surface should provide satisfactory operating life.

When firing coal, deposits may form in the cold-end heat transfer surface; this can be controlled by soot blowing and occasional water washing.

The guide shown on this page indicates the recommended operating temperatures for bituminous coals. Operation at these temperature levels will result in limiting deposit formation and corrosion due to flue gas reactions at the extreme cold end of the air preheater. The guide can also be used when firing low-rank coals (subbituminous and lignites).

The low-rank coals are defined as those where the me (CaO) + magnesia (MgO) is greater than the ferric oxide (Fe_2O_3) in the ash.

Before using the guide, an adjustment to the sulfur content is required.

If the sulfur content is known as a percentage, an adjustment to the sulfur content for low-rank coal is made by determining the equivalent sulfur (ES). The calculation, with an example, is as follows:

$$ES = \frac{14{,}000 \times S}{HHV}$$

Where: ES = % equivalent sulfur
S = % sulfur in low-rank coal, as fired

HHV = Higher heating value (as fired) of low-rank coal in Btu/lb

Example:

S = 1.6%

HHV = 10,400 Btu/lb

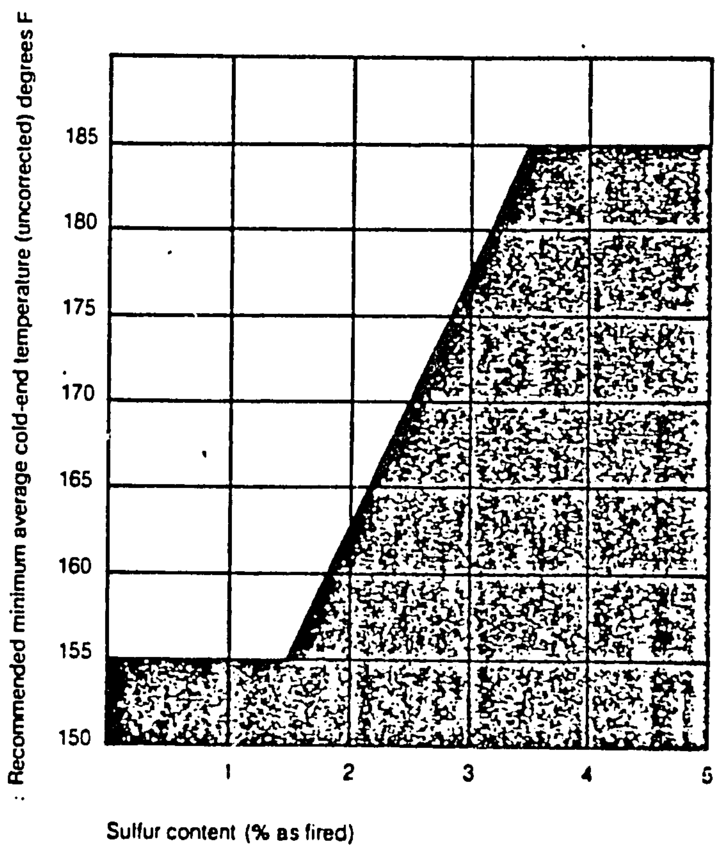
$$ES = \frac{14{,}000 \times 1.6}{10{,}400}$$

ES = 2.15%

The recommended ACET from the guide is 165°F.

Guide for Bituminous Coal Firing

This guide can also be used for subbituminous and lignite coals by adjusting for the sulfur content. Refer to the text on this page for details.



Recommended minimum average cold-end tem; rature
Pulverized anthracite: 150°F
Natural Gas (sulfur-free): 150°F
Gases other than sulfur-free natural gas must be considered individually.

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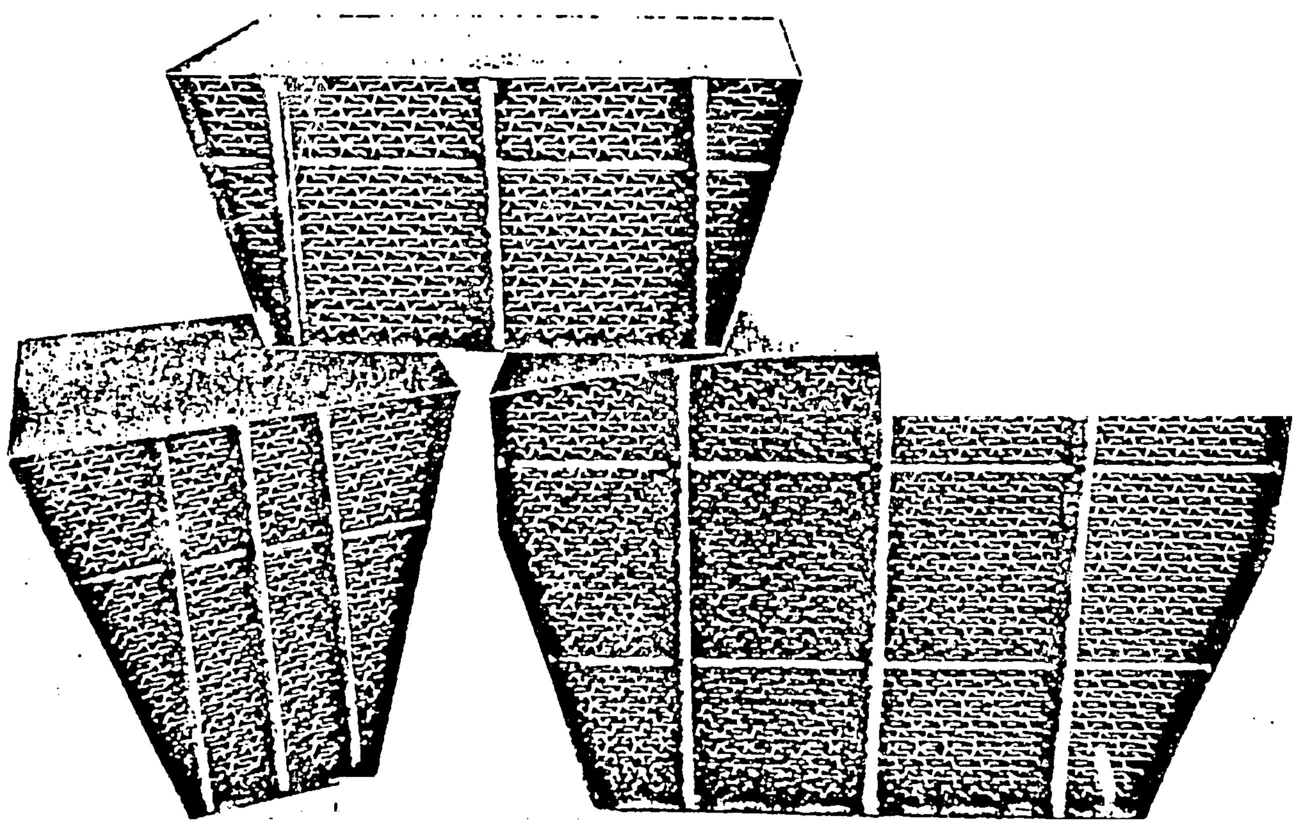
Oil Firing

Low-temperature corrosion potential in oil-fired installations is greater than in coal-fired units. However, oil fired deposits can be more soluble and their formation controlled by the soot blowers and washing equipment.

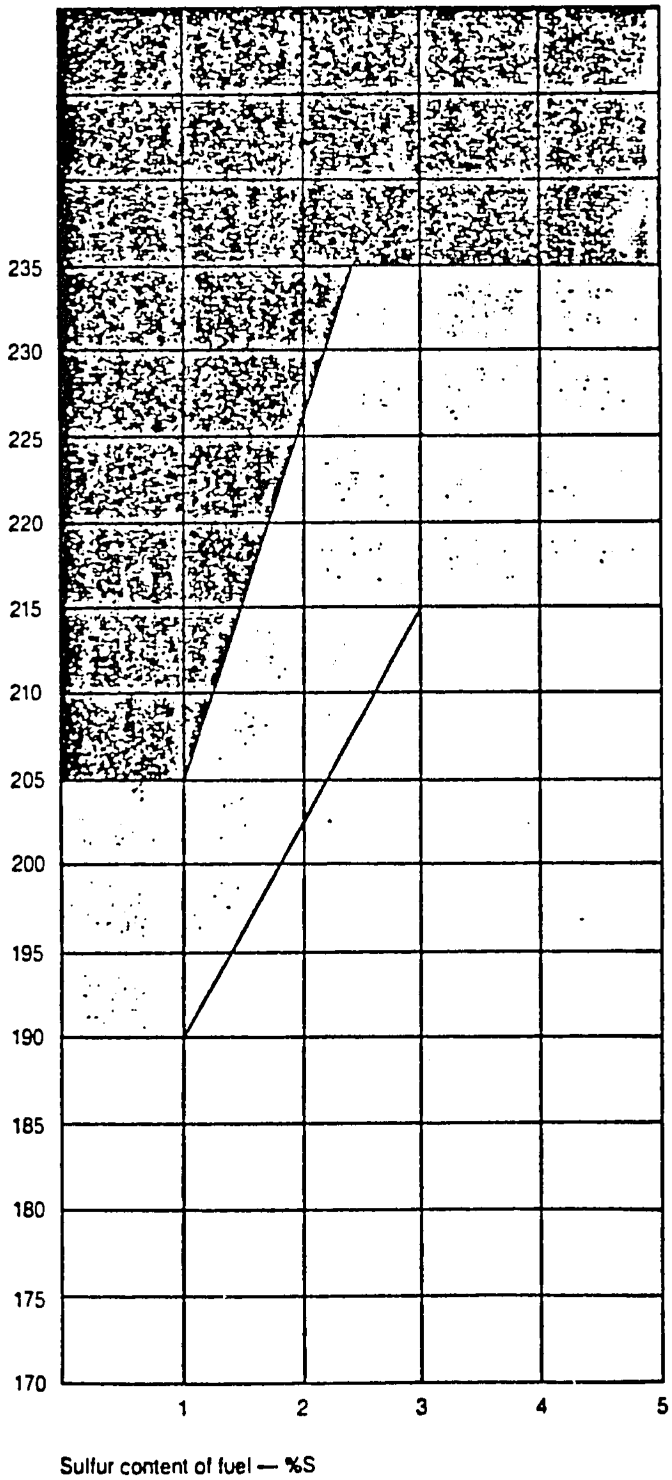
Porcelain enameled heat transfer surface has been effective in reducing corrosion of the low-temperature surface of oil-fired units. Enameled heat transfer surface permits operation at temperatures below those safe for conventional materials.

Exposure of heat transfer surfaces to acids varies with fuel composition and cold-end temperatures. The chart on page 5 plots sulfur content and cold-end temperature for oil firing with five percent or more excess air.



Guide for Oil Firing

Recommended materials specification for oil-fired applications.



■ In this range, the corrosion potential is limited to the extreme cold end of the cold-end layer of heat transfer surface.

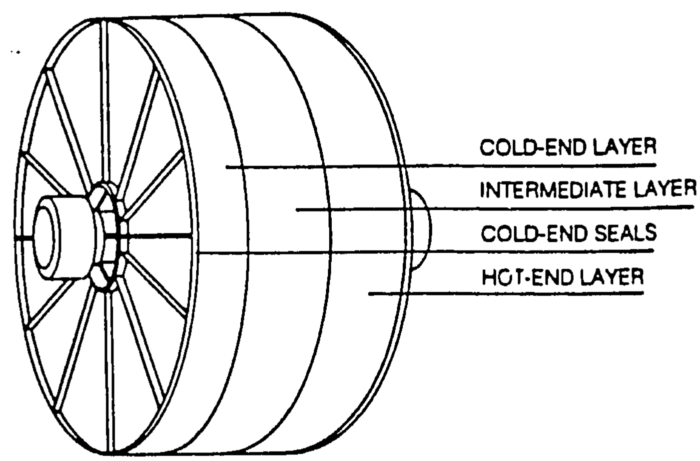
Materials recommended: Corrosion resistant low-alloy cold-end surface; mild steel hot-end and intermediate layers of surface; mild steel rotor.

□ In this range, the corrosion potential extends into the center of the cold-end layer of heat transfer surface.

Materials recommended: Enameled cold-end surface; enameled cold-end seals; corrosion resistant low-alloy intermediate surface; mild steel hot-end surface. It is also recommended that the cold end of the rotor be fabricated of corrosion resistant low-alloy steel to the same depth as the cold-end layer of enameled surface.

□ In this range, the corrosion potential extends into the intermediate layer of heat transfer surface.

Materials recommended: Enameled cold-end and intermediate layers of heat transfer surface; enameled cold-end seals; mild steel or corrosion resistant low-alloy hot-end surface. It is also recommended that the cold end of the rotor be fabricated of corrosion resistant low-alloy steel to at least the same depth as both the cold-end and intermediate layers of heat transfer surface.



Various Fuels

Operating experience has shown that an average cold-end temperature of 150°F yields satisfactory control of fouling and corrosion of cold-end surfaces for both pulverized anthracite and sulfur-free natural gas fuels.

The continued demand for energy conservation has resulted in the firing of a wide variety of process fuels, refuse and waste process gases. The firing of fuels in combination has also become common. Because of this, it is necessary to examine these fuels individually to determine a recommended minimum average cold-end temperature. C-E Air Preheater will be glad to assist you in this evaluation.

A Summary

Air preheater cold-end fouling and corrosion can normally be attributed to one or both of two factors.

The first factor involves chemical or physical reactions resulting from the corrosion and fouling potential of the flue gas. The corrosion and fouling location can be controlled by the average cold-end temperature level.

The second factor causing fouling and corrosion is the addition of moisture from boiler or economizer tube leaks, wet soot blowing media, steam coil leaks, incomplete water washing and unprotected forced draft fan inlets. Fouling and corrosion from this factor cannot be avoided by controlling cold-end temperature and are beyond the scope of this guide. Therefore, the operator should take every precaution to minimize the introduction of external moisture.

Because of the complexity of variables affecting the fouling and corrosion potential of combustion flue gases, no single set of rules can be applied to all installations. An operator may find from experience with his particular installation that it is desirable to raise or lower the average cold-end temperature from that indicated by the guide.

In such cases, field experience should be followed.