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THE DIRECT COMBUSTION OF LOW GRADE COAL FOR THERMAL ELECTRIC GENERATION

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April 1982

For presentation to the American Power Conference, Chicago, Illinois, April 26-29, 1982

ENERGY RESEARCH PROGRAM
ENERGY RESEARCH LABORATORIES
DIVISION REPORT 82-18 (OP)

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by

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ABSTRACT

This paper describes a series of pilot-scale combustion trials with three coals, both before and after washing, from a large, low-grade coal deposit in British Columbia.

It was established that raw coals with higher heating values over 10.5 MJ/kg on an equlibrium moisture basis (24%) could be successfully burned using conventional pulverized-fired technology; however, provision must be made to handle the large volume of bulky ash deposits and abrasive fly ash produced. Removal of extraneous clay by washing improved handling and combustion performance with no effect on ash composition or resistivity, although ash stickiness and NO_x emissions both increased.

High- and low-temperature corrosion of heat transfer surfaces should not be significant with either raw or washed coals.

The operational benefits of using washed instead of raw coal in a pulverized-fired utility boiler, must be carefully evaluated against the cost, availability and environmental impact of a beneficiation plant at the site of the deposit.

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INTRODUCTION

The Canadian Combustion Research Laboratory (CCRL) carried out a series of pilot-scale combustion trials on low-grade coal from a large, undeveloped deposit in British Columbia to determine the feasibility of using the coal in pulverized-fired utility boilers. This coal is ranked as sub-bituminous C by ASTM classification procedures, and in addition to the high moisture content typical of low rank coals, it has a high and variable ash content. The combustion properties of the coal were, however, largely unknown. Thus, the research program was designed to incorporate combustion trials with seven different coals, six of which were from the undeveloped deposit. The seventh coal a commercially available Alberta sub-bituminous coal provided a reference against which the performance of the experimental coals could be compared.

This report describes the objectives of the program, the test coals, and the experimental facilities and procedures employed. It also gives an evaluation of the combustion trials and identifies potential areas of concern in the design of full-scale boilers for burning this undeveloped coal resource.

OBJECTIVES OF THE RESEARCH PROJECT

Combustion research on a pilot-scale offers several advantages over full-scale burns such as low cost, rapid generation of results, convenient modification of conditions, and flexibility of approach. Moreover, reliable trends can be established by comparing the performance of unknown fuels with that of a reference fuel for which full-scale operational data are known. These trends can then be validated in carefully designed, full-scale combustion trials with minimal risk to system availability.

This approach was used in formulating an experimental work plan having the following objectives:

1. To establish whether three raw coals with different calorific values from this low-grade deposit could be successfully burned using conventional pulverized-firing technology without supplementary fuel.
2. To establish whether combustion performance was likely to be improved through upgrading the same three raw coals by water washing.
3. To determine, insofar as possible, major design features required in a utility-type steam generator for burning this coal.

COAL PROPERTIES

All three of the raw experimental coals, designated as A-raw, B-raw and C-raw, contained moisture well in excess of their equilibrium level of about 24% and exhibited poor handling properties because clay inclusions absorbed most of the free water and converted these coals into a cohesive, intractable mass. When air or kiln dried to sub-equilibrium moisture levels all three raw coals flowed freely but tended to be friable and dusty. On the other hand, the same three coals after beneficiation by water washing, designated as A-washed, B-washed and C-washed, flowed readily even with large amounts of free water.

Analytical Data

Analytical data for each coal are given in Table 1. All of the experimental coals, except the A-raw coal, had volatile matter contents comparable to the reference coal on a dry basis. Figure 1 shows the calorific values and the ash contents of the seven coals at various moisture levels; the points show each coal on an equilibrium moisture and an "as fired" basis. The experimental dry coals, which were characterized by calorific values ranging from 12.1 to 22.7 MJ/kg with corresponding ash contents ranging from 50.2 to 28.1%, were all of lower quality than the dry reference coal which had a calorific value of 24.1 MJ/kg at 14.9% ash.

The ash analyses and ash fusion data, Table 2, indicate that fouling and slagging potential of all six experimental coals should be low. Washing had little or no effect on either the total sodium as oxide in ash, the sulphur in coal or the ash fusion temperatures.

Petrographic Data

The maceral constituents in coal, listed on Table 3, provide a preliminary indication of coal reactivity or the ability of a coal to burn readily.

Petrographic examinations showed that each of the three raw experimental coals, on a moisture, mineral matter free basis, contained over 80% vitrinite, a high reactivity maceral. Therefore ignition, flame stability and carbon burn-out were predicted to be good to excellent, and its potential for spontaneous combusiton in storage, particularly if the total moisture content falls 15% was rated as high. The petrographic data also suggest that the experimental coals need not be as finely ground as higher rank coals in conventional pulverized-fired boilers.

The mineral matter in the raw experimental coals was a mix of kaolinitic and montmorillonitic clays and silica, most of which was finely dispersed throughout the coal. The remaining mineral matter appeared as large clay lenses or occulsions, a feature that was not present in the washed coals.

Large lumps of extraneous clay in raw coal can usually be rejected during primary crushing with Bradford-type breakers but the residual montmorillinite would adversely effect recovery of magnetite in a heavy media wash plant. Therefore, jigs or cyclones would seem to be more appropriate for water washing the experimental coals.

RESEARCH BOILER AND OPERATING PROCEDURE

The pilot-scale research boiler used for these trials is illustrated in Figure 2. It is nominally rated at 0.7 MWt but was derated to 0.6 MWt due to limitations in pulverizer capacity when high ash, high moisture coals are burnt.

The experimental program consisted of a series of 18 combustion trials which incorporated the following independent and dependent parameters.

Independent Parameters

1. Seven coal samples; three grades of experimental raw coal, the same three coals after beneficiation, and the Alberta reference coal.
2. Each coal at a moisture level corresponding to about 50% of equilibrium and when possible at 95% of equilibrium.
3. Each coal at excess air levels corresponding to 3% and 5% oxygen in the flue gas respectively.

Dependent Parameters

The following measurements were taken at the locations shown in Figure 1.

1. Proximate, ultimate and ash analysis as well as ash fusion determinations on a bulk sample composed of hourly grab samples. Station 1.
2. Moisture and sieve analysis of pulverized coal. Station 2.
3. Furnace temperature profiles. Stations 3, 4 and 5.
4. CO_2, CO, O_2 and NO_x continuously. Station 6.
5. Ash fouling of cooled and uncooled probes. Stations 7 and 8.
6. SO_2 and SO_3 intermittently. Station 9.
7. Low-temperature corrosion potential. Station 10.
8. Acid dewpoint. Station 11.
9. Isokinetic dust loading. Station 12.
10. In-situ fly ash resistivity at 315°C and 120°C. Stations 11 and 13.
11. Electrostatic precipitator efficiency. Station 14.

Comminution

The classifier setting on the pulverizer was adjusted during each trial to provide about 70% minus 200 mesh (74 μm) particles. As shown in Figure 3, the loss on ignition of both the minus 44 μm and the plus 105 μm coal fractions tended to increase with decreases in ash content but were unaffected by moisture. This indicates that char burn-out times particularly for large particles will increase with increases in ash content. The high ash experimental coals must therefore be pulverized more finely or burned in larger furnaces than the lower ash experimental coals.

In practice both options may be feasible alternatives to beneficiation, the cost of which would be a trade off against a smaller steam generator.

COMBUSTION PERFORMANCE

Steam Rate

The reference coal for the combustion trials had almost the same dry, mineral matter free heat content as the experimental coals. Thus, the steaming rates, normalized with respect to the reference coal shown in Figure 4 were directly proportional to the ash and moisture contents of the coal.

A steam generator designed to tolerate no more than 10% deviation from the reference coal firing rate will be restricted to burning a B-washed quality experimental coal or better. However, a steam generator designed to burn the B-raw, medium quality coal, which requires a firing rate of 25% higher than the reference coal, will, if it has the same 10% tolerance, be capable of burning all coals except the A-raw coal.

Flame Observation

Both flame and burn-out patterns for each trial were recorded. The flame pattern was defined by the region where the carbon monoxide concentration was more than 0.1% and the burn-out pattern was estimated by observing the limits of the visible flame.

As expected the flame and burn-out patterns were both extended when the excess combuston air decreased or when either the ash, residual moisture or the coarse coal particle content increased. This indicated than an excess air level corresponding to 5% O_2 in the flue gas would be desireable and that beneficiation either alone or in combination with drying would permit a reduction in furnace size. The long burn-out pattern for experimental A-raw coal was due to the extremely high ash content of both the fine and coarse particles which contained 56% and 34% ash respectively.

Carbon Carry-over

The thermal loss due to carbon in fly ash, which increased with increases in ash content and particle size distribution of the coal, ranged from less than 1% to about 3% and was generally unaffected by changes in excess combustion air and fuel moisture.

FIRESIDE DEPOSITS

The reference coal produced weakly sintered deposits of moderate thickness whereas the experimental coals produced massive deposits that decreased in thickness and increased in sinter strength as their ash contents decreased; increasing moisture levels of a specific coal resulted in a decrease in sinter strength of the ash deposits.

There was no evidence of slagging with any of the experimental coals, but sintered deposits built-up rapidly on refractory surfaces near the flame zone. These bulky deposits had to be removed periodically, particularly with coals having more than 19 MJ/kg on a dry basis, to prevent a deterioration in boiler performance.

Deposition Probes

Stainless steel deposition probes, air-cooled at 560°C, were located in three different temperature zones of the boiler to obtain an indication of ash fouling propensity. In addition, uncooled refractory probes, which were located adjacent to the air-cooled probes and allowed to equilibrate close to the local combustion gas temperature, were used to simulate conditions at the outer layer of a thick deposit on a cooled tube where initial melting of ash may occur. The air-cooled and uncooled deposition probes located downstream of the burners all accumulated an observable layer of powdery ash during each of the burns with the experimental coals. However, the cooled and the uncooled probes, located under the flame zone, accumulated fairly thick sintered deposits which generally fell off before surface melting occured.

X-ray diffraction analyses showed the same components in all of the ash deposits from the experimental coals irrespective of the type of probe, its furnace location or the coal burned. The major and minor components shown below are listed in order of relative abundance.

Major: Mullite, Quartz, Cristobalite

Minor: Magnetite or an analogous spinel,
Feldspar and Hematite

The mullite and cristobalite represent thermal transfeormation products of kaolinite and montmorillinite whic'` originally existed in the parent coal ash. The quartz was also present in the parent coal ash, but appeared to have passed through the flame without change. The major fly ash compounds, being highly abrasive, caused severe corrosion of convection tubes.

Furnace Bottom Ash

After each trial with the experimental coals, the furnace bottom ash was characterized by large pieces of friable, porous sinter as well as large amounts of dust. Microscopic examinations showed that the sinered material was essentially an agglomeration of fused spheres ranging from 1 μm to 100 μm.

Chemical analysis and ash fusion data for the bottom ash, were only slightly different from the parent coal ash, indicating that few low-melting mineral phases formed during combustion. This was confirmed by differential thermal analysis and hot stage microscopy on a number of bottom ash samples which established that only limited fusion of ash components occurred over a very broad temperature range. The ash from the experimental coals was therefore considered to have a low to medium slagging potential.

BOILER EMISSIONS

Sulphur and Nitrogen Oxides

Sulphur dioxide emissions from the experimental coals, shown in Figure 5, decreased with increases in calorific value, but exceeded the EPA New Source Performance Standards of 0.58 g/MJ with all coals except the C-washed. These emissions accounted for about 90% of the input sulphur because the parent coal ash contained cations with some potential for sulphur neutralization. No acid dewpoints were detected and SO_3 leels were consistently less than 4 ppm for all experimental coals.

The reference coal ash, because of its high alkali or alkali-earth content, neutralized about 50% of the fuel sulphur and produced neither an acide dewpoint nor detectable SO_3 levels.

Nitrogen oxide emissions from the experimental coals, shown in Figure 5, were generally found to decrease with increases in fuel moisture and ash content; washing, by increasing flame temperature, increased nitrogen oxide emissions.

Fly Ash

Figure 6 shows that the dust burden of the flue gas at the precipitator inlet increased progressively with ash content of the experimental coals with the increase being exponential above 40% ash. It also shows that washing of the raw coals was effective in significantly reducing the fly ash loadings at the precipitator inlet.

The bulk density of the fly ash from the experimental coals at about 0.76 kg/m^3 was about one-half of the 1.42 kg/m^3 obtained for the fly ash from the reference coal. Although this implies that structural requirements for fly ash hoppers and ducts for a boiler designed to burn the experimental coals could be less severe than those for the reference coal, it should be noted that the capacity of the hoppers for the experimental coal fly ash must be much larger to compensate for the combined effect of the lower bulk density and a higher dust loading in the flue gas.

Electrical Resistivity

At flue gas temperatures of 150°C the in-situ resistivity values of reference fly ash ranged from 10^9 and 10^{11} ohm-cm whereas those from the experimental coals generally fell between 10^{11} and 10^{12} ohm-cm. The values for both the reference and the experimental coals decreased by about one order of magnitude when resistivity mesurements were taken at a flue gas temperature of 270°C. Thus, a slight improvement in resistivity can be obtained by precipitating the fly ash from the experimental coal at 270"C rather than at 150°C.

The bulk electrical resistivity of fly ash collected at the inlet of the precipitator were also measured using the procedure given in Section 4.05 of the ASME Power Test Code No. 28-1965. These resistivities, which were measured over a temperature range of 93°C to 371°C and at 150°C and 270°C, were about one order of magnitude higher than those measured in-situ at CCRL.

The variation in values between the bulk and in-situ measurements are not considered to be significant because of procedural differences in the two methods.

Correlation Between Precipitator Efficiency and Fly Ash Resistivity

The electrostatic precipitator was a research model which was modified to provide an efficiency of 90% with the reference coal. In its original state, it collected essentially all of the particulate matter in the flue gas and did not permit an assessment of ash precipitability for the different coals.

The precipitator efficiencies with fly ash from the experimental coals which averaged about 95% were superior to that obtained with fly ash from the reference coal. These results appear to be anomalous because the fly ash resistivity values for the reference coal, which bracketed 10^9 ohm-cm, are generally associated with the highest precipitator efficiencies, whereas those for the experimental coals, being all above 10^{11} ohm-cm, suggest that precipitator efficiencies will be low. The apparent discrepancy can, however, be explained by the differences in particle size distribution of the fly ash shown in Figure 7.

Most of the particles of the fly ash from the experimental coals were not only larger than those of the fly ash from the reference coal but a smaller fraction of the fly ash from the experimental coal was between 0.1 µm, and 3 µm, the "difficult-to-collect" size range. Thus, the fly ash from the experimental coals appears to be more susceptible to precipitation than the fly ash from the reference coal.

This explanation agrees with empirical studies which indicate that precipitator efficiency decreases inversely with the square root of the particle size. In addition, since gravitational settling mechanisms generally improve the overall performance of a precipitator, the fly ash from the experimental coals should be more easily collected than those from the reference coal. Thus, any reduction in the clay or fine mineral content of the experimental coals by beneficiation would favour both an increase in precipitator efficiency and a significant reducion in precipitator size.

BOILER DESIGN CONSIDERATIONS FOR BURNING THE EXPERIMENTAL COALS

A number of factors, which could impact significantly on the successful use of this low-grade resource in utility boilers, have been identified. These are summarized below:

a) Removal of extraneous clay from the raw coal during primary crushing will minimize in-plant conveying problems.

b) Spontaneous ignition is a potential problem during coal storage. Therefore, suitable fire precautions such as compacted stockpiles and provision for flooding the bunkers may be necessary.

c) It appears that experience with the reference coal can be applied directly to size pulverizers for the experimental coals. At the same throughput the same size distribution can be expected, but allowance must be made for higher quantities of the experimental coal required for the same energy input. Allowance must also be made for the fact that carbon carryover tends to increase with increasing ash content; therefore, the higher the ash content of the experimental coal burned, the finer the grind should be. Alternatively, residence time can be increased by providing a larger furnace.

d) If the steam generators are designed for a coal having 14.0 MJ/kg on a equilibrium moisture basis, it should be possible to supply a coal of uniform quality with optimum resource recovery. For example, all raw coal between 8 MJ/kg and 16 MJ/kg on an equilibrium moisture basis could be blended with higher quality raw or washed coals to obtain a 14.0 MJ/kg product.

e) All of the experimental coals, particularly the raw coals, produced large porous sinters on the furnace walls that subsequently fell off, filling the furnace bottom. To avoid slag formation, a full-scale furnace must be designed to eliminate flame impingement and zones of high temperature. Also, to cope with the large volumes of sinter and low-bulk-density fly ash, the furnace must have a generously-proportioned bottom hopper designed to prevent ash bridging, and it must have a high-capacity ash removal system, incorporating a sinter crusher.

f) Dust loadings at the precipitator inlet will be very high with the experimental coal unless gravitational settling of fly ash in the steam generator is optimized. If 40% or more of the ash can be trapped in the steam generator, the size of the precipitator can be significantly reduced.

g) To achieve the same ash collection efficiency as for the reference coal, the specific collection area of a cold precipitator for an experimental coal containing 25% to 30% ash would have to be at least 30% greater than for the reference coal.

h) Problems with acid mist emissions or low temperature corrosion are unlikely. Nitric oxide emissions can probably be kept within acceptable limits by operating at 3% O_2 in the flue gas, and by controlling flame properties through appropriate burner and furnace design.

CONCLUSIONS

The research project established that the experimental coals which exceeded 13 MJ/kg on a dry basis:

a) handled satisfactorily at moisture levels below their equilibrium value.

b) ignited readily and produced bright, stable flames without support fuel. All coals were considered to be more reactive, notwithstanding their higher ash content, than the reference coal.

c) may cause excessive erosion of boiler tube surfaces because of the large quantities of quartz and highly abrasive mullite in the fly ash.

d) produced bulky, sintered deposits that adhered weakly to the refractory furnace walls.

e) were unlikely to cause superheater corrosion because well-defined liquid phases were not present in ash deposits collected at temperatures above 500°C.

f) had a very low potential for low-temperature corrosion because no acid dewpoint was detected.

g) produced a fly ash having better precipitation characteristics than the fly ash from the reference fuel despite in-situ electrical resistivity values indicating that precipitator performance could be poor.

h) resulted in about 10% of the fuel sulphur being neutralized by cations in the coal ash and in NO emissions which decreased with increases in ash and moisture content. Excess combustion air had little effect on NO emissions.

Washing the experimental coals resulted in easier handling, higher flame tempertures, slightly lower sulphur emissions, reduced ash deposition and erosion and reduced fly ash loadings relative to the corresponding raw coal. These benefits were off-set, however, by higher nitric oxide emissions and the formation of more strongly sintered fireside deposits. Washing produced no changes in ash composition or ash melting properties.

TABLE 1

Coal Analysis

Coal - Source Identification Type	Alta Reference Raw	Undeveloped BC Deposit					
		A Raw	A Washed	B Raw	B Washed	C Raw	C Washed
Analysis							
Calorific Value, MJ/kg	24.1	12.1	18.8	17.2	20.6	19.6	22.7
Proximate, wt % dry							
Ash	14.9	50.2	30.2	32.4	20.9	28.1	18.9
Volatile Matter	34.5	25.0	32.8	34.8	39.2	35.3	38.1
Fixed Carbon	50.6	24.3	37.1	32.8	40.0	36.5	43.1
	85.1	49.3	69.9	67.6	79.2	71.8	81.2
Ultimate, wt % dry	16.2	12.0	14.1	13.3	14.1	13.8	14.4
Carbon	63.0	32.4	48.0	46.4	54.8	49.5	57.7
Hydrogen	3.9	2.7	3.4	3.5	3.9	3.6	4.0
Sulphur	0.2	1.1	1.2	1.0	0.8	0.8	0.7
Nitrogen	0.8	0.7	1.0	1.0	1.0	1.0	1.2
Oxygen	17.2	13.4	14.8	15.8	17.7	17.1	17.6
Ash	14.9	49.8	30.0	32.3	22.1	28.1	18.1
Sulphur Forms, wt %							
Pyrite		0.5	0.6	0.5	0.6	0.5	
Organic		0.4	0.3	0.3	0.1	0.1	
Sulphate		0.2	0.3	0.2	0.1	0.2	
Equilibrium Moisture, wt %	17	22	25	22	23	24	24
Hardgrove Grindability Index	43	60	44	46	43	44	38

TABLE 2

Ash Analysis and Ash Fusion Data

Coal Identification	Reference	A-Raw	A-Washed	B-Raw	B-Washed	C-Raw	C-Washed
Ash Analysis, wt %							
SiO_2	49.0	56.5	54.6	50.0	48.7	50.8	50.7
Al_2O_3	23.8	29.8	29.5	29.8	31.4	30.1	29.5
Fe_2O_3	4.5	7.1	8.3	9.6	6.7	7.2	5.8
Mn_3O_4	1.0	0.3	0.1	0.1	0.1	0.1	0.1
TiO_2	0.5	1.1	1.7	1.3	1.5	1.1	1.3
P_2O_5	0.2	0.1	0.2	0.4	0.4	0.2	0.4
CaO	13.1	1.4	2.5	4.0	4.6	2.6	3.6
MgO	0.9	1.3	1.2	1.2	1.5	1.3	1.6
SO_3	2.5	1.0	2.0	3.3	2.9	2.8	3.2
Na_2O	2.4	0.5	0.5	0.3	0.3	0.5	0.6
K_2O	0.3	0.8	0.7	0.4	0.4	0.6	0.6
Cl	0	0.01	0.01	0.01	0	0	0.02
Ash Fusion Data							
Reducing Atm, °C							
- Initial	1274	1371	1352	1381	1378	1391	1327
- Spherical	1313	+1500	1471	1458	+1500	+1500	1487
- Hemispherical	1374	+1500	+1500	1490	+1500	+1500	+1500
- Fluid	1440	+1500	+1500	+1500	+1500	+1500	+1500
Oxidizing Atm, °C							
- Initial	1324	+1500	1449	1465	1445	1477	1445
- Spherical	1363	+1500	+1500	+1500	+1500	+1500	+1500
- Hemispherical	1398	+1500	+1500	+1500	+1500	+1500	+1500
- Fluid	1438	+1500	+1500	+1500	+1500	+1500	+1500

TABLE 3

Combustion Reactivity of Coal Macerals

Resinite	Vitrinite	Semi-fusinite
Exinite	Tellinite	Massive Micrinite
Finely Divided Micrinite	Low-reflectance Semi-fusinite	Oxidized Vitrinite
		Fusinite

Reactivity Decreases →

← Ignition, Flame Stability, Burnout Impoves

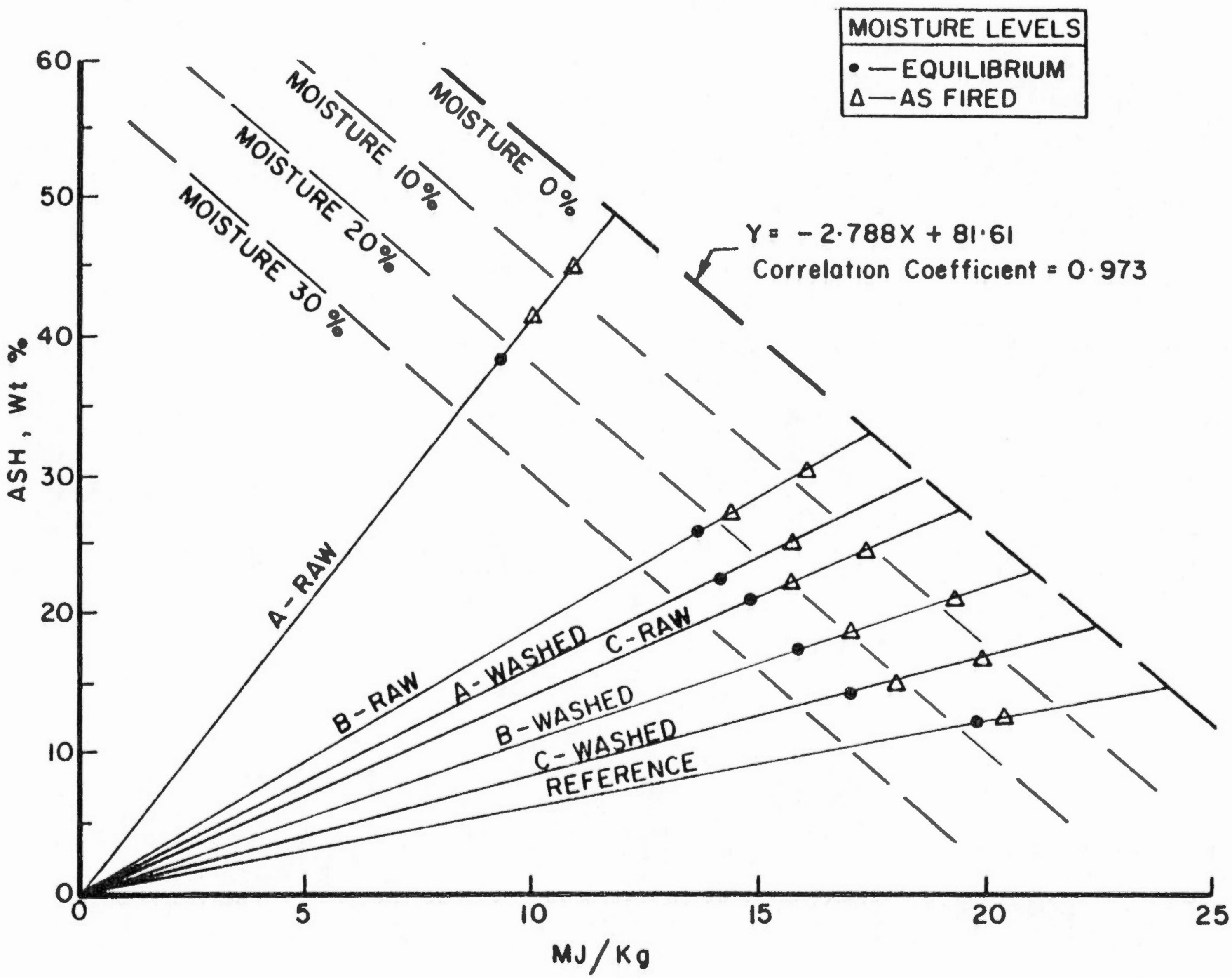

Fig. 1 - Ash-calorific value graph for test coals. The lines extending from the origin show the effect of moisture on the calorific value of each coal. Equation is the linear regression for the 18 data points.

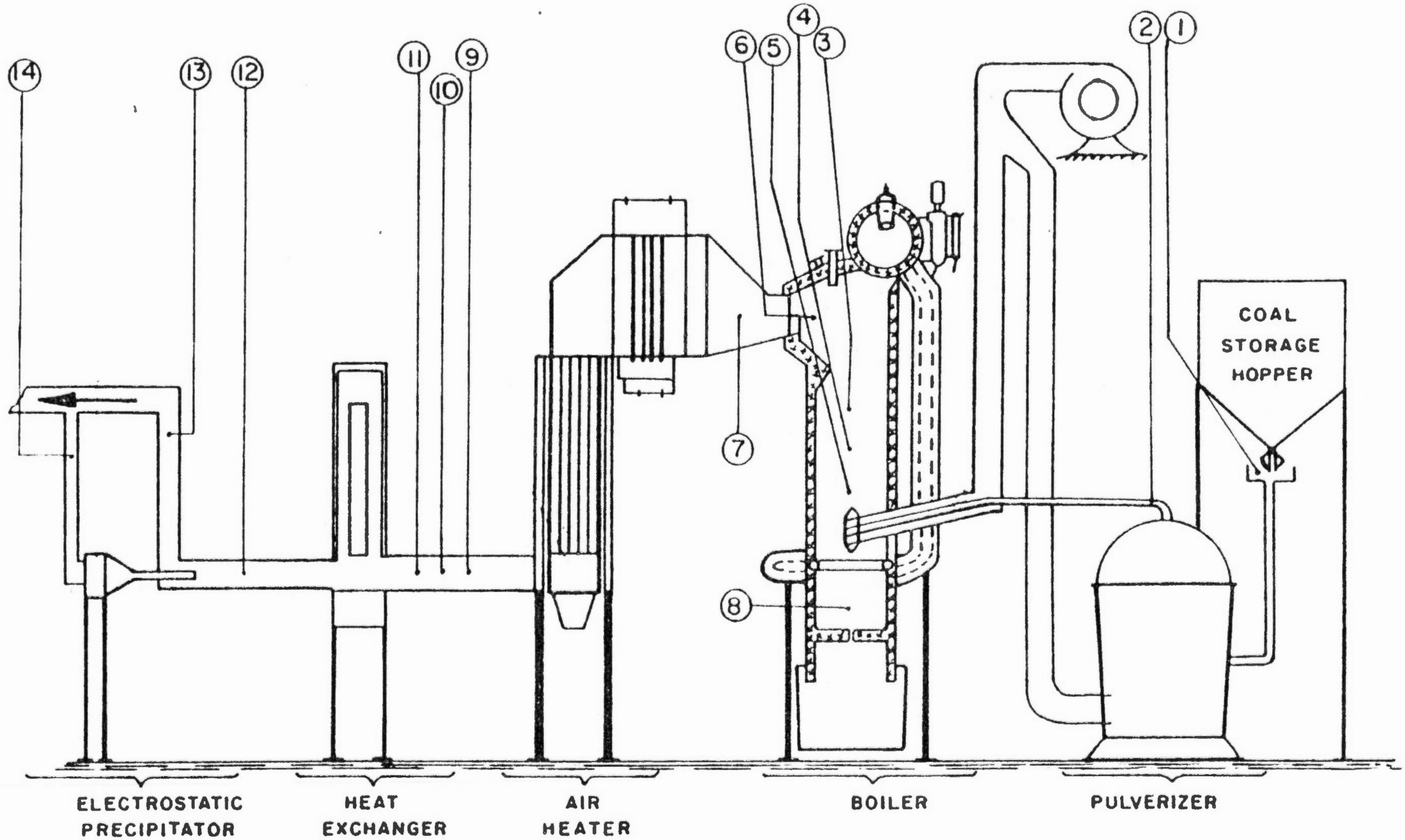

Fig. 2 - Schematic illustration of the pilot-scale boiler showing the sampling stations

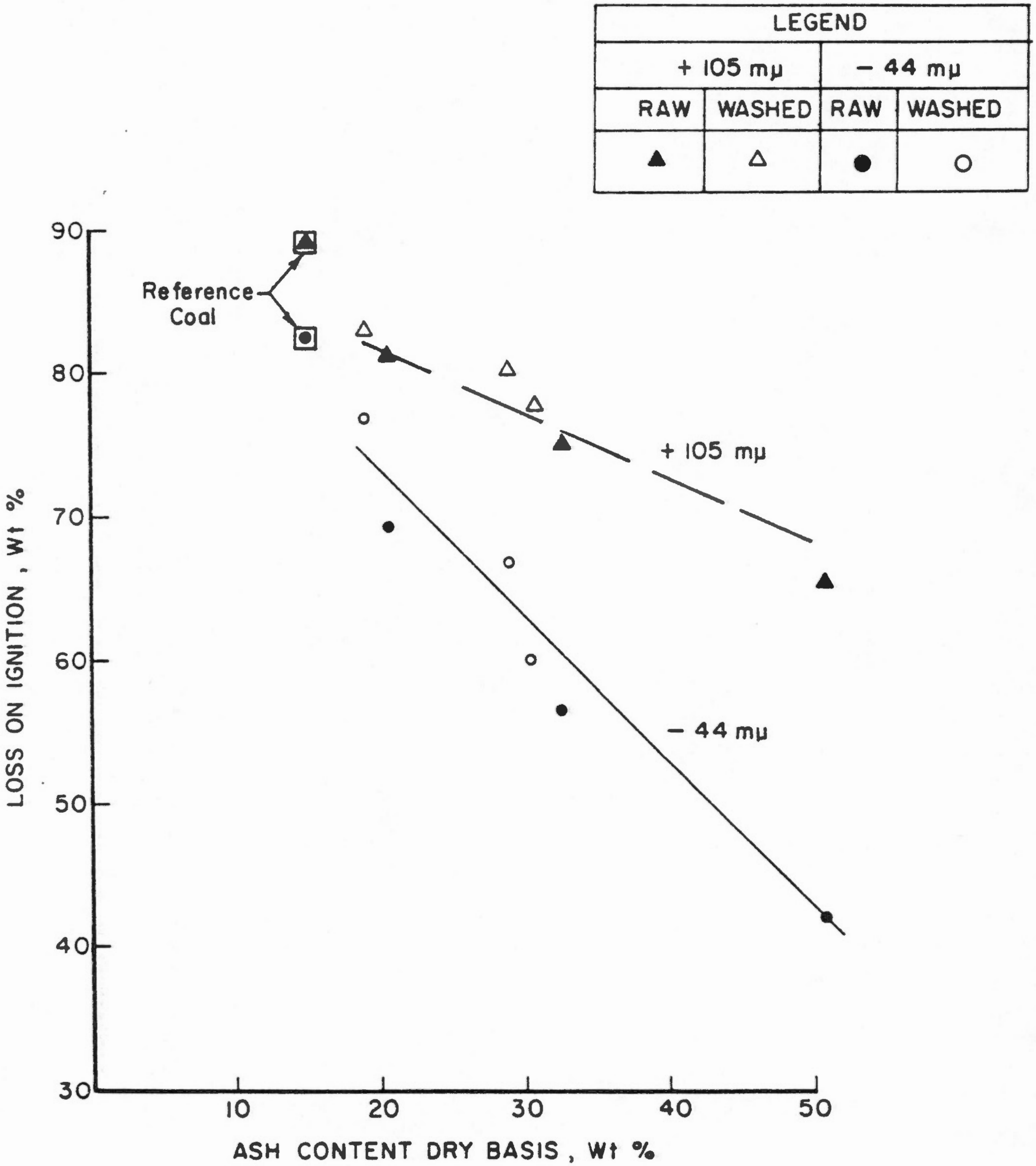

Fig. 3 - Loss on ignition of coarse and fine size fractions of pulverized coal.

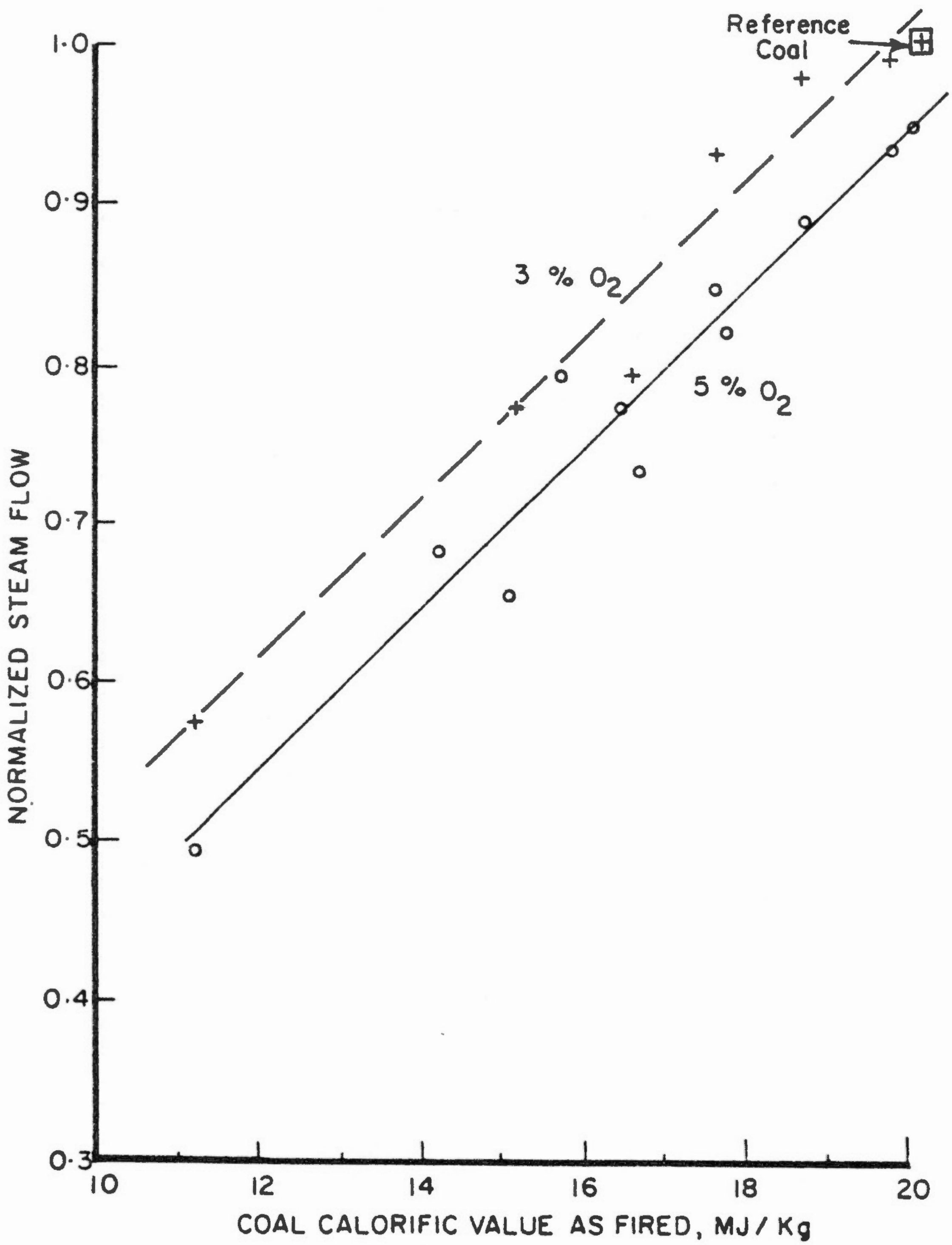

Fig. 4 - Steam flow normalized to the reference coal at 3% O_2.

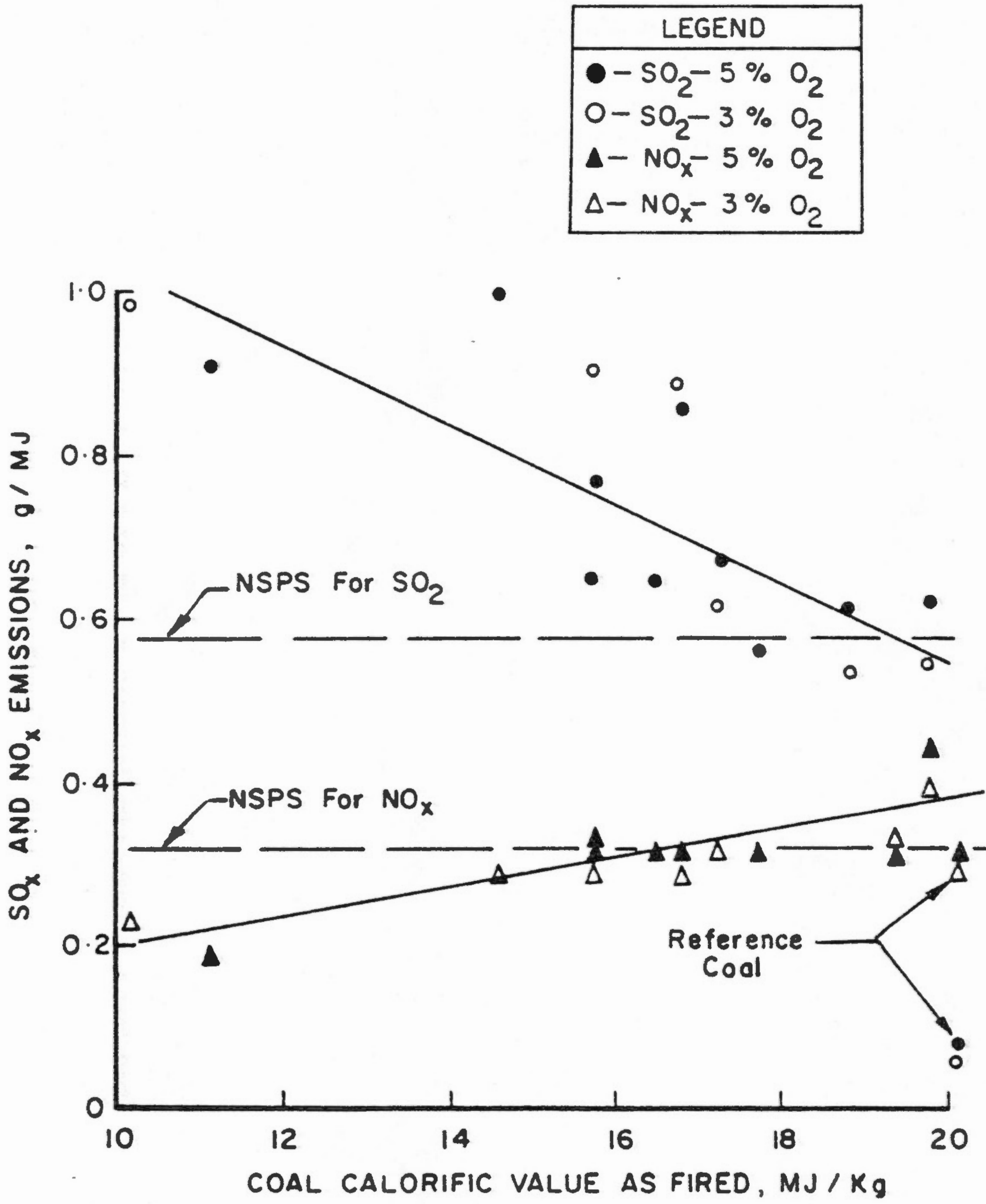

Fig. 5 - SO_x and NO_x emissions for various coal qualities.

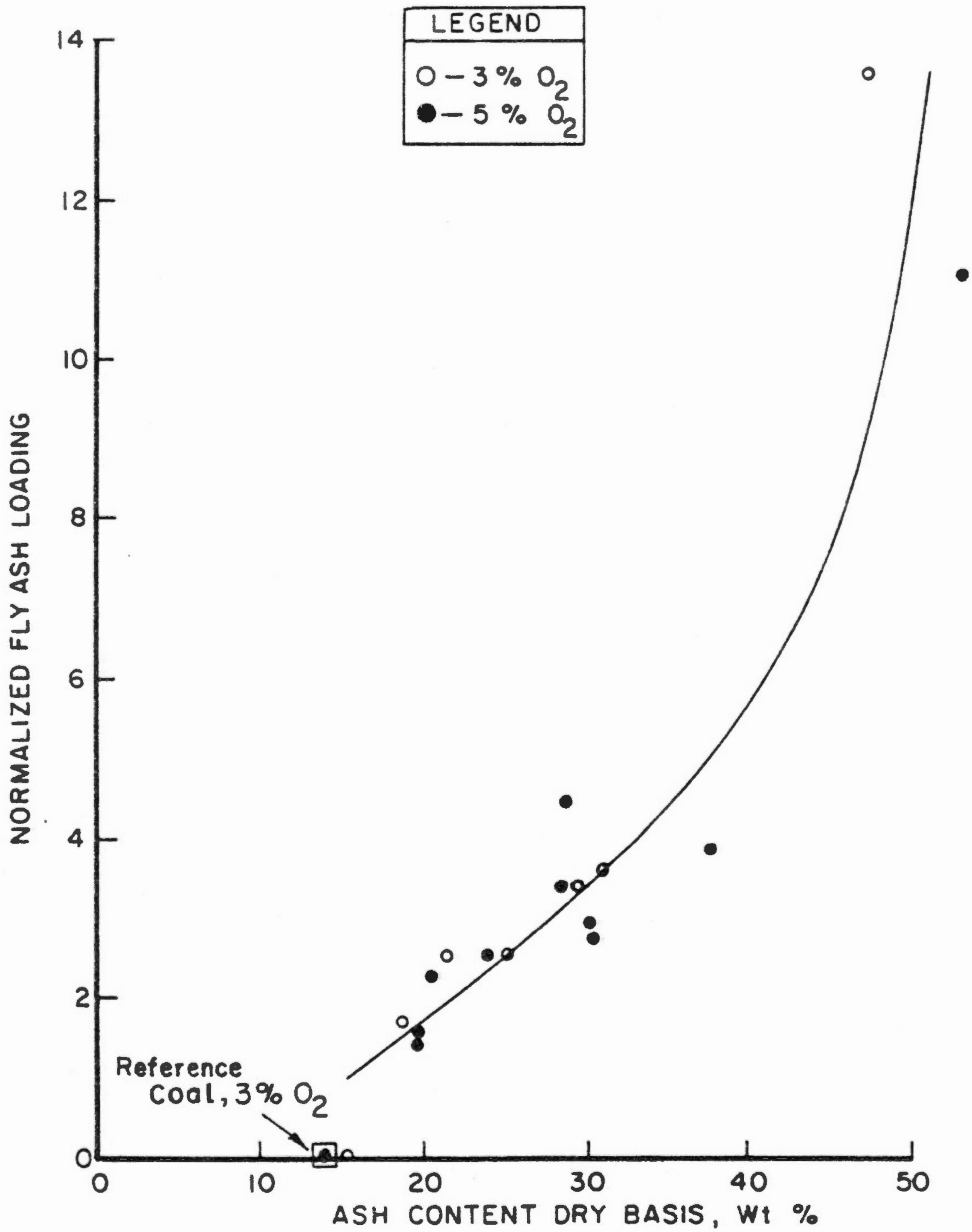

Fig. 6 - Fly ash loading at precipitator inlet normalized to the reference coal at 3% O_2.

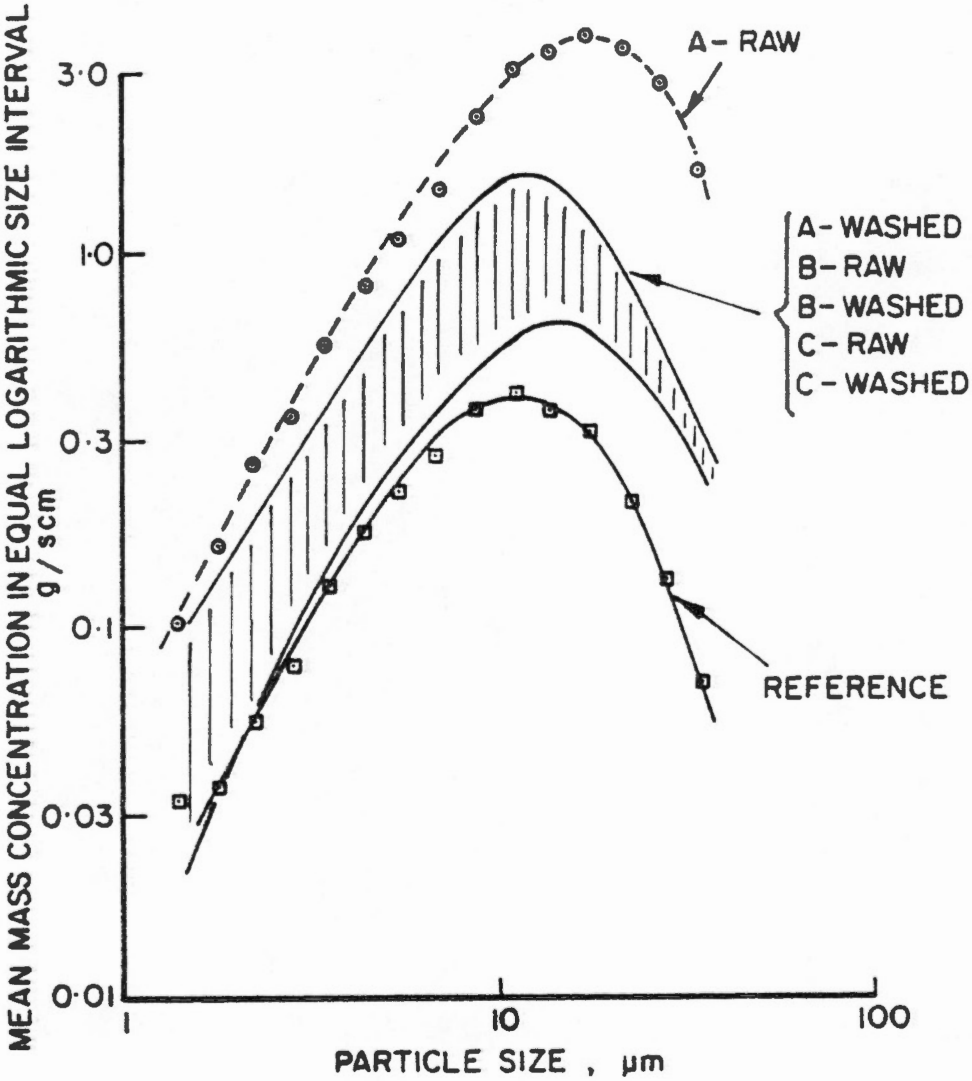

Fig. 7 - Variation in fine particle sizes of the fly ash entering the electrostatic precipitator.