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MODIFICATION OF COMBUSTION AND FLY ASH CHARACTERISTICS BY COAL BLENDING

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MODIFICATION OF COMBUSTION AND FLY ASH CHARACTERISTICS BY COAL BLENDING

by

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ABSTRACT

Pilot-scale boiler trials were conducted to study the combustion and fly ash precipitation characteristics of a series of two- and three-component bituminous coal blends. The blends consisted of a partially oxidized eastern US coal with selected additions of either a western Canadian oxidized coal and/or a western Canadian unoxidized coal.

It was found that the degree of carbon burn-out was highly dependent on the concentration of unreactive coal macerals in each blend, and that additions of the Canadian unoxidized coal improved the burn-out of both the US and Canadian oxidized coals. For blends with about 50% US coal the fly ash resistivity decreased dramatically as the combustible in fly ash exceeded 12%.

The base to acid ratio and the potential slagging temperature of the coal input ash provided reliable indicators of the structure of the furnace ash deposits. In all trials the moderate slagging and fouling tendency of the US coal was reduced by blending with one or both of the high-ash fusion Canadian coals.

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INTRODUCTION

Over the past few years many coal-fired power plants around the world, particularly those which depend on non-captive sources, have turned to blending their design coal with one or more off-specification coals to obtain: (a) wider availability (b) better security of supply (c) less expensive fuel or (d) lower sulphur content. This practice can, however, result in serious operating problems if the design coal and the substitute coals in a blend are not compatible. For example, inert coal macerals may reduce combustion efficiency, some combinations of coal ash produce low-melting eutectics and low-sulphur coals may decrease precipitator efficiency.

This paper gives a detailed analysis of three bituminous coals and identifies the physico-chemical properties which significantly impacted on combustion efficiency, fireside ash deposition and precipitator performance in a pilot-scale research boiler. It also describes a complementary series of combustion trials in which the same three coals were burned as two- and three-component blends under typical utility boiler conditions.

RESEARCH OBJECTIVES

The objectives of this research study were:

1. To evaluate the relative combustion reactivity of the three bituminous coals - one eastern US and two western Canadian - prior to burning.
2. To determine the proportions of one or both of the Canadian coals that could be blended with the US coal without significantly affecting combustion performance.
3. To establish the influence of the selected coal blends on fly ash resistivity and ash precipitability.
4. To compare the fouling and slagging tendency of fireside deposits produced from each blend with predictive relationships.

COAL PROPERTIES

ASTM Analyses

The analyses of the three commercially available coals are given in Table 1 and their coal ash characteristics are given in Table 2.

As shown in Table 1, the US coal and one of the Canadian coals were ranked as high-volatile bituminous whereas the other Canadian coal was ranked as medium-volatile bituminous by ASTM classification procedures. For convenience, these coals have been designated as US Hi-Vol, Can Hi-Vol and Can Med-Vol throughout this paper. Relative to the two Canadian coals, the US coal had a higher sulphur content, a higher calorific value, lower ash fusion temperatures and a lower grindability.

Coal Reactivity

The reactivity or ease of combustibility of the three base coals was evaluated by both petrographic examinations and thermogravimetric analyses.

The petrographic data, given in Table 3, indicate that the coals in descending order of reactivity would be Can Hi-Vol, US Hi-Vol and Can Med-Vol. This ranking, based on the proportions of reactive and inert or oxidized macerals present, is further supported by the reflectance values which generally decrease as coal rank decreases and combustion reactivity increases. Four particle size ranges each coal, -200, -100, -50 and -20 mesh, were also examined for variations in maceral compositions, but no major differences were detected. Thus, depletion and enrichment of different maceral types into specific size ranges during milling did not occur with these coals. Figure 1 shows the influence of the various coal macerals on reactivity.

Thermograms for each coal, Figure 2, show no oxidation of the Can Hi-Vol, moderate oxidation of the US Hi-Vol and high oxidation of the Can Med-Vol coal. In Figure 2, the spike to the left of the main curve was found to be a unique characteristic of oxidized coals. Preliminary observations suggest that this spike is due to carboxyl and other oxidized functional groups being evolved from sites on the coal surface prior to evolution of the volatile matter. The Can Hi-Vol coal, which had no spike, showed an almost instantaneous evolution of volatile matter followed by a very rapid burn-out of the char. The other two coals had longer char or coke burn-out times indicating a much lower degree of reactivity.

Although the petrographic and thermographic data, together with the proximate analyses, provide good indicators of relative reactivity, they require considerable refinement and correlation with other physico-chemical factors before a precise measure of reactivity is possible. Some of the factors that are considered to influence combustion reativity are (a) specific surface (b) the Q-factor for volatile matter (c) the amount and distribution of inertinite in reactive macerals (d) the amount and composition of the functional groups evolved during the thermogravimetric anlaysis (e) porosity and (f) coking propensity.

RESEARCH FACILITY AND OPERATING PROCEDURES

The pilot-scale research boiler used for this series of combustion experiments, Figure 3, is designed to burn pulverized bituminous coal at 60-70 kg/h with independent control over excess combustion air, coal fineness and firing rate. Details of this experimental combustion facility are described elsewhere (1).

The experimental matrix included 11 combustion trials using the coals and coal blends shown in Table 4. During each trial, which lasted 6 h to 8 h, the coal fineness, heat input and oxygen in flue gas were nominally held at 85% less than 75 µm, 1.85 GJ/h (0.52 MWt) and 3.2% respectively. Moisture levels of the as fired coal varied from 1.2% to 8.1% and reflected the air-dried condition of the three base coals.

During each trial the following analyses and measurements were taken at the locations designated in Figure 3.

(a) Proximate, ultimate and ash analysis and ash fusion determinations on a bulk sample of crushed coal composed of hourly grab samples. Pulverizer inlet.

(b) Bottom ash. Station 1.

(c) Moisture and sieve analyses of pulverized coal. Station 2.

(d) Ash fouling tendency. Station 3.

(e) CO_2, O_2, CO, SO_2 and NO_x continuously. Station 4,

(f) Isokinetic fly ash loading. Station 5.

(g) In-situ fly ash resistivity at 120°C. Station 6.

(h) Electrostatic precipitator efficiency. Station 7.

EXPERIMENTAL OBSERVATIONS AND RESULTS

All coals and coal blends ignited readily and produced stable flames without support firing. CO levels were consistently less than 0.1% and smoke opacity was less than 10% at 3% to 4% O_2.

The colour of fly ash samples which became darker as the fraction of the Can Med-Vol coal increased and lighter as the fraction of Can Hi-Vol coal increased, appeared to confirm the higher carbon carry-over predicted from the combustion reactivities.

Carbon Carry-over

The combustible content of the fly ash decreased progressively as the reactivity of each coal or coal blend increased. As shown in Figure 4, the burn-out of each blend increased with additions of Can Hi-Vol coal and decreased with additions of Can Med-Vol coal. Moreover, the burn-out of the US Hi-Vol coal improved when blended with the Can Hi-Voal coal. It is interesting to note that the measured combustible in fly ash from the coal blends was, in every case, lower than those calculated by pro-rating the combustible in fly ash obtained from each of the base coals. Therefore, the carbon carry-over from these particular blends resulted both from enhanced carbon burn-out of the lower reactivity coals, and from the dilution effect of the lower combustible fly ash from the higher reactivity coal. Combustible contents in the fly ash of the Can Hi-Vol, US Hi-Vol and Can Hi-Vol coals were 1.6%, 12.3% and 40.3% respectively, corresponding to combustion efficiencies of 99.7%, 98.4% and 82.0%.

In another series of trials with the same coal blends, the carbon carry-over as expected, decreased with finer grinds and increased with coarser grinds.

Electrical Resistivity of Fly Ash

In-situ fly ash resistivities are primarily influenced by the flue gas temperature, the combustible content of the fly ash, the sulphur content of the fuel and the fly ash morphology. Figure 5 shows that optimum fly ash resistivities for cold precipitators fall in a region favouring blends with a maximum of about 25% by weight of Can Med-Vol coal with the balance being either US Hi-Vol and/or Can Hi-Vol coal. Bulk resistivity values for combustible-free fly ash from the low-sulphur Canadian coals approached 10^{12} ohm-cm whereas the medium-sulphur US coal yielded combustible-free fly ash values of 10^9 ohm-cm.

Figure 6 shows the typical step curve which is obtained when the log resistivity of the fly ash is plotted against percent combustible in the fly ash. This graph shows that the critical carbon content of the fly ash occurred at 12% weight for blends containing 50% US coal; the proportion of each Canadian coal in the remaining 50% of the blend did not appear to have a pronounced effect on resistivity.

Precipitator Efficiency

As shown in Figure 7, ash precipitation efficiencies tended to be high for roughly equal proportions of each coal in the three component blends and low for each of the unblended coals. Moderately high efficiencies were obtained with two component blends containing 50% US Hi-Vol and 50% Can Med-Vol coal. Blending appeared to improve precipitator efficiencies significantly relative to the base coals alone.

Fouling and Slagging Potential

The fouling and slagging potential of each coal or coal blend was predicted from established empirical relationships. These values were then compared with the observed structure of the fireside deposits.

The tendency of the coals and coal blends to cause fouling of convection surfaces was estimated from the sodium oxide content of the input fuel ash. Using the classification given in Table 5, all three base coals and consequently all coal blends should have a low fouling potential. This prediction was verified by an inspection of the superheater deposits which were all loosely adherent and powdery.

The base to acid ratios, Figure 8, and the potential slagging temperatures, Figure 9, both suggest that the US coal and all blends containing over 50% US coal will produce ash deposits having a moderate slagging tendency (2). On the other hand, the two Canadian coals either alone or in blends containing less than 50% US coal should have a low slagging tendency.

A visual inspection of the furnace bottom deposits after each trial confirmed the trends indicated by the two empirical indicators of slagging.

CONCLUSIONS

1. Potential operational problems associated with the use of substitute coals and coal blends in pulverized-fired boilers can be minimized or avoided by carefully evaluating the coal and coal ash properties prior to utilization.
2. Petrographic and thermogravimetric analyses, in conjunction with ASTM analyses, can be used to identify possible problems with carbon burn-out. Combustible levels exceeding 10% by weight of the fly ash generally result in poor precipitator efficiencies.
3. The combustible content of the fly ash from the oxidized coals was reduced by blending with the higher reactivity coals. However, in other studies involving blends of a highly-oxidized and an unoxidized coal, the high carbon carry-over from a highly oxidized coal was only diluted by the very low carbon carry-over from a highly reactive coal.
4. Empirical and ASTM indicators for ash slagging and fouling should not be applied to blended coals without experimental verification. The physico-chemical behaviour of multiple mineral constituents is best studied in bench- or pilot-scale facilities where temperature, chemical and ash deposition conditions are to some representative of those in operating units.

RESEARCH NEEDS

Four areas of priority research suggested by the severity of the operational problems encountered during the combustion of off-specificaiton coals are:

a) Basic coal research to elucidate the role of maceral types, volatile species and char structure on the combustion rate of pulverized coal.

b) A combustion test procedure for rapidly determining the relative combustion reactivity of pulverized coals and coal blends.

c) Studies correlating coal mineral type and distribution with both short-term, experimental ash deposition properties and long-term, slagging and fouling characteristics of deposits from operational boilers.

d) An inexpensive, empirical, high-temperature test for predicting slagging and fouling potential of ash from single or multi-component coals.

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1. Friedrich, F. D., Lee, G. K. and Mitchell, E. R. "Combustion and fouling characteristics of two Canadian lignites"; Trans ASME J Eng Power, New York, Vol 4; 127-132; 1972.

2. Bryers, R. W. "On-line measurements of fouling and slagging and correlation with predictive indices in conventionally fired steam generators"; Proc. Low Rank Coal Technology Workshop; San Antonio, Texas; 2-49 to 2-101; June 1981.

Table 1 - Coal Analysis

Coal / Analysis	US Hi-Vol	Can Med-Vol	Can Hi-Vol
Proximate, wt % (air dried)			
Moisture	1.25	3.56	8.97
Ash	7.89	15.66	9.24
Volatile Matter	36.15	22.80	34.31
Fixed Carbon	55.86	57.98	48.38
Ultimate, wt % (air dried)			
Carbon	75.97	71.13	69.12
Hydrogen	5.29	4.05	4.07
Sulphur	2.67	0.57	0.27
Nitrogen	1.57	1.01	1.03
Ash	7.99	16.24	10.05
Oxygen (by diff)	6.51	6.98	15.46
Calorific Value, MJ/kg (dry basis)	31.98	28.81	28.02
Hardgrove Grindability	54	77	42
Free Swelling Index	6	n/a	n/a
Age	Carboniferous	Cretaceous	Cretaceous

Table 2 - Coal Ash Characteristics

Coal / Property	US Hi-Vol	Can Med-Vol	Can Hi-Vol
Ash Analysis, wt %			
SiO_2	41.58	46.85	55.44
Al_2O_3	22.61	29.26	17.29
Fe_2O_3	23.85	6.18	5.89
TiO_2	1.06	1.60	0.84
P_2O_5	0.28	0.50	0.26
CaO	3.61	4.23	11.59
MgO	1.38	1.49	1.36
SO_3	3.22	4.72	6.16
Na_2O	0.92	0.69	0.26
K_2O	1.46	0.61	0.90
Cr_2O_3	0.01	1.56	0.01
Ash Fusion Temp, °C Reducing Atm.			
Initial Deformation	1127	1371	1188
Spherical Softening	1193	1482+	1299
Hemispherical Softening	1243	1482+	1338
Fluid	1354	1482+	1377
Oxidizing Atm, °C			
Initial Deformation	1371	1404	1249
Spherical Softening	1410	1482+	1304
Hemispherical Softening	1427	1482+	1349
Fluid	1443	1482+	1377

Table 3 - Coal Maceral Composition

Coal Maceral Type	US Hi-Vol	Can Hi-Vol	Can Med-Hi
Reactives, Vol % mmf			
Vitrinite	58	69.0	22.4
Exinite Resinite	6.0	3.6	1.6
Low Reflectance Semi-Fusinite	3.3	6.1	-
Sub Total	67.3	78.7	24.0
Non-reactives, Vol % mmf			
High Reflectance Vitrinite	0.6	1.3	6.6
Oxidized Vitrinite	17(est)	-	15.0
Semi-fusinite	6.5	6.1	42.2
Fusinite	3.6	11.0	8.4
Micrinite	5.0	2.4	1.8
Sub Total	32.7	21.3	76.0
Total	100	100	100
Reflectance, Mean Max	0.82	0.58	1.08

Table 4 - Coals and Coal Blends Burned

Trial No.	US Hi-Vol	Can Med-Vol	Can Hi-Vol
1*	100	-	-
2*	-	-	100
3*	-	100	-
4*	60	40	-
5*	50	50	-
6**	40	-	60
7*	70	15	15
8*	50	25	25
9	50	15	35
10	43	43	14
11*	30	35	35

*duplicate trials

**triplicate trials

Table 5 - Fouling Potential of Coal Ash

Fouling Category	% Na_2O in Ash	
	$\frac{CaO + MgO}{Fe_2O_3} < 1$	$\frac{CaO + MgO}{Fe_2O_3} > 1$
Low	<0.5	<2
Medium	0.5 - 1.0	2.0 - 6.0
High	1.0 - 2.5	6.0 - 8.0
Severe	>2.5	>8.0

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

Reactivity Decreases →

← Ignition, Flame Stability, Burn-out Improves

Fig. 1 - Combustion reactivity of coal macerals

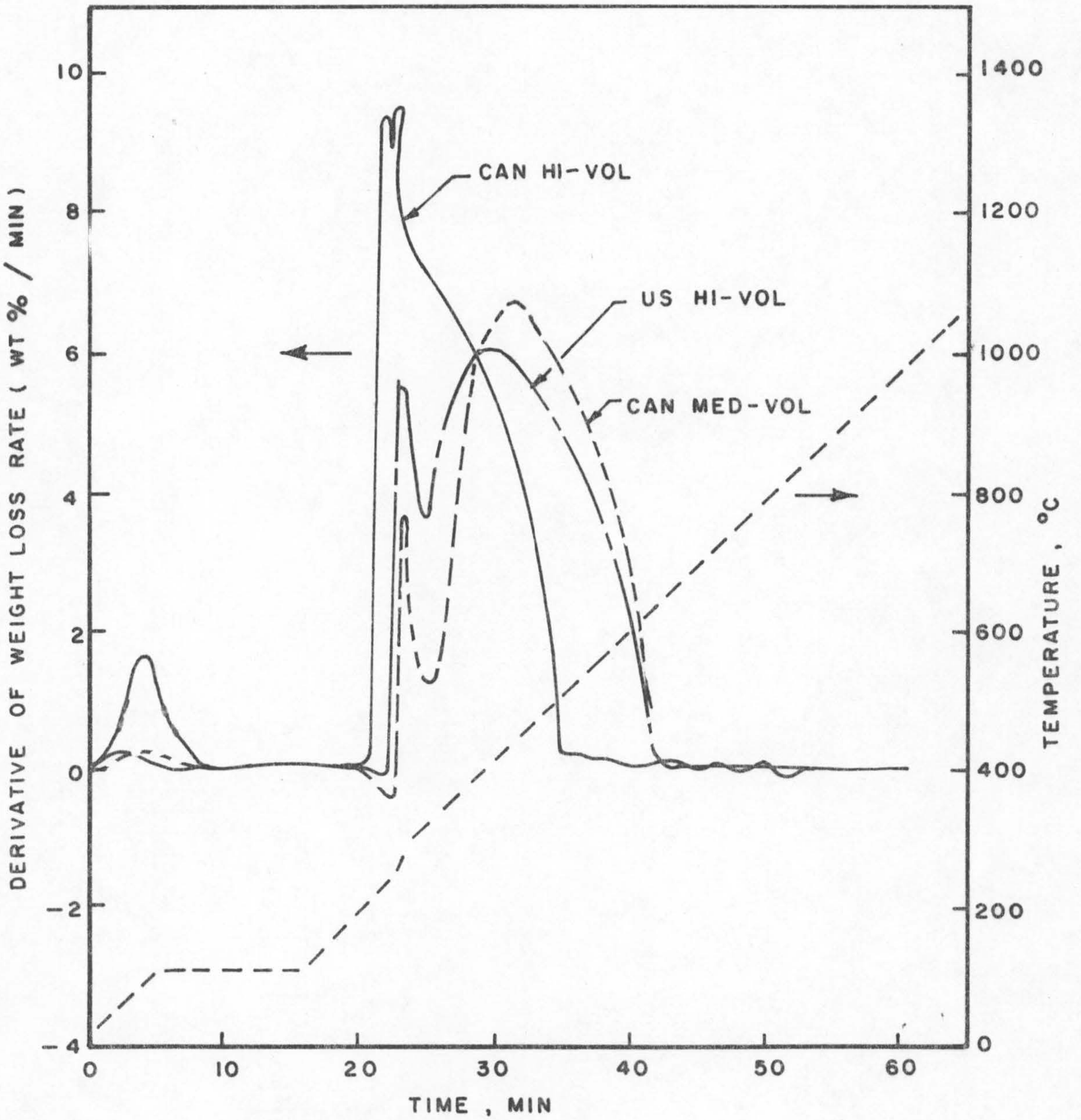

Fig. 2 - Thermogravimetric curves for the three base coals

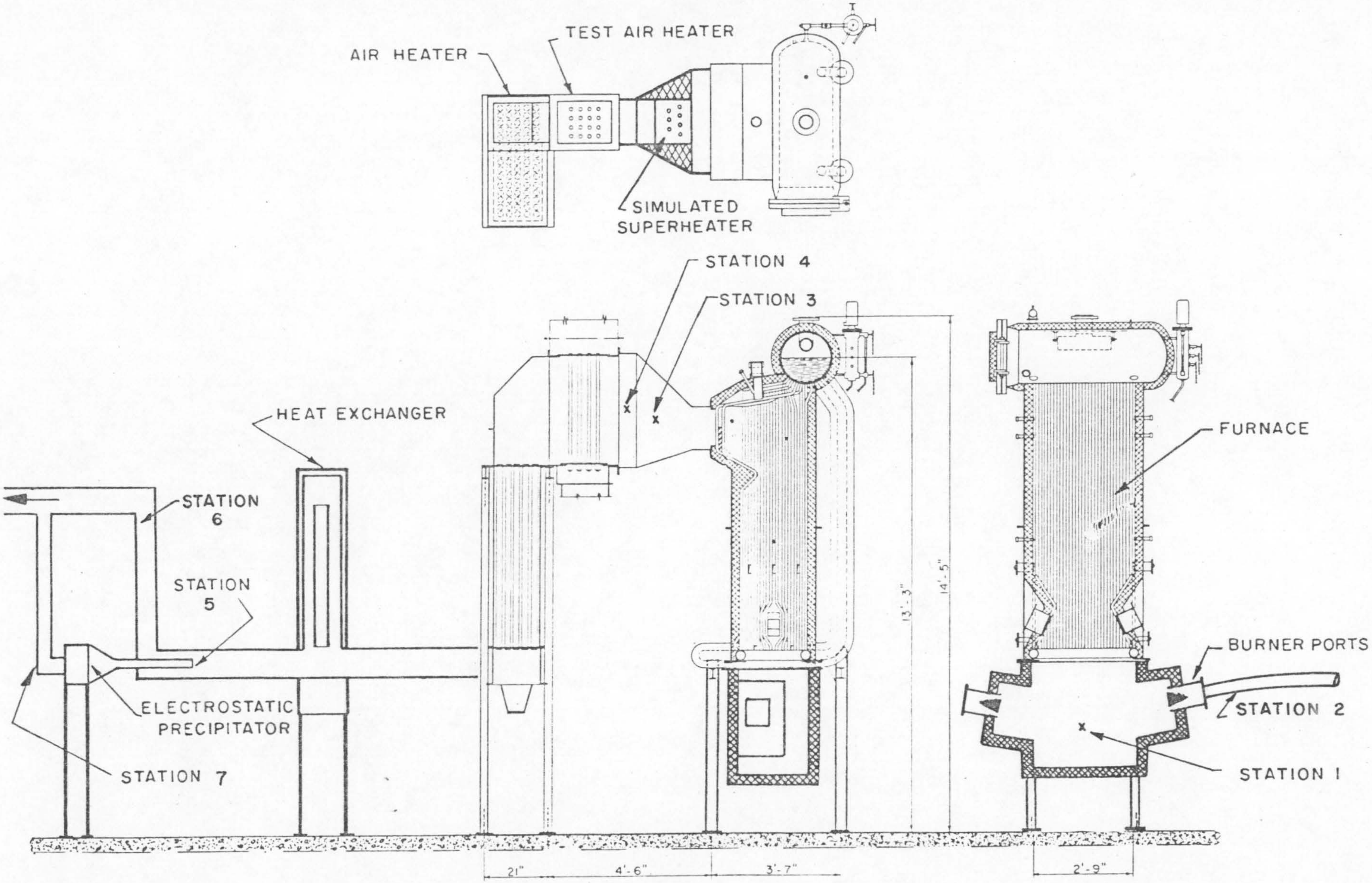

Fig. 3 - CCRL pilot-scale research boiler used for coal blending trials

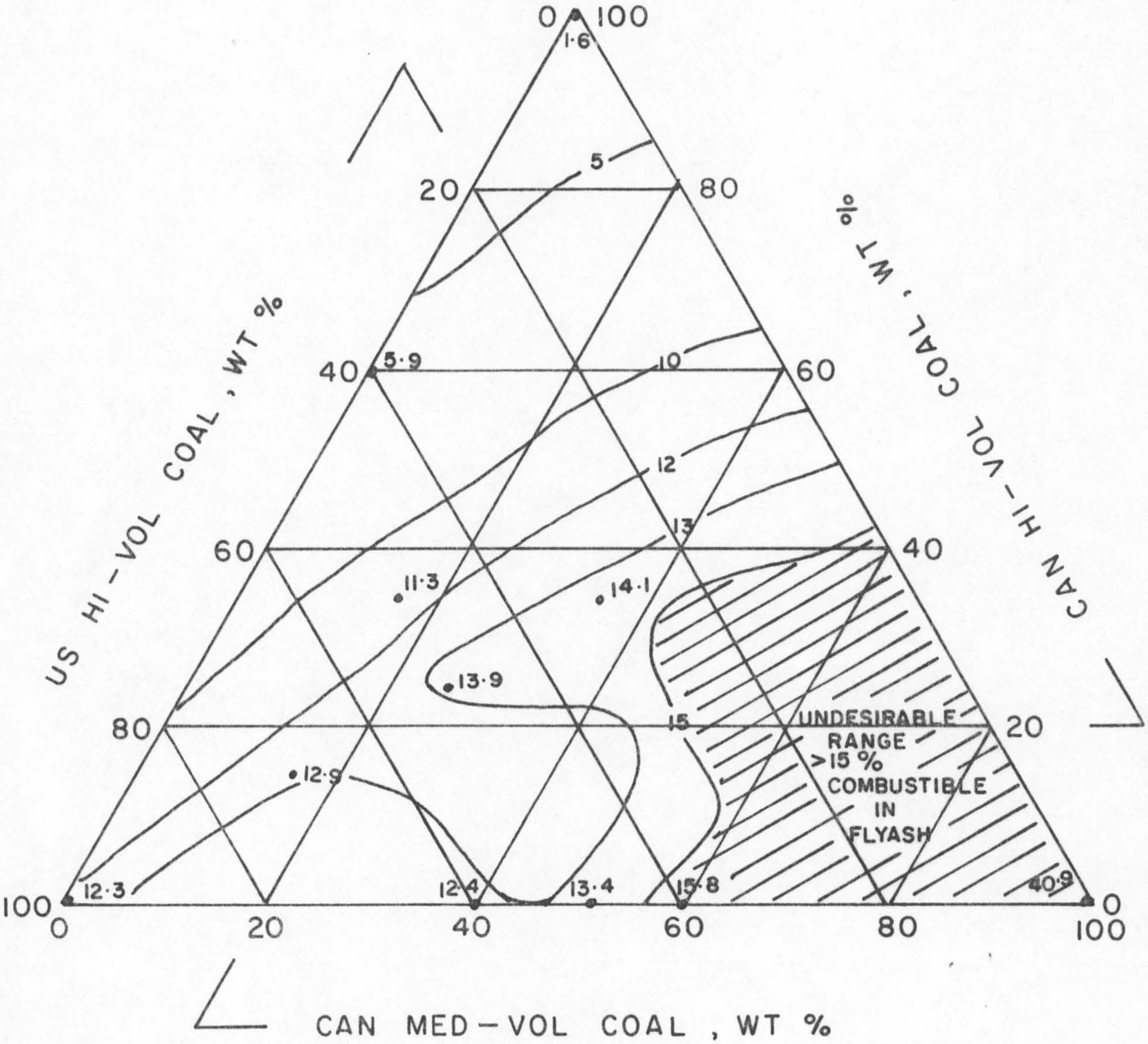

Fig. 4 - Combustible content of fly ash from coal blends

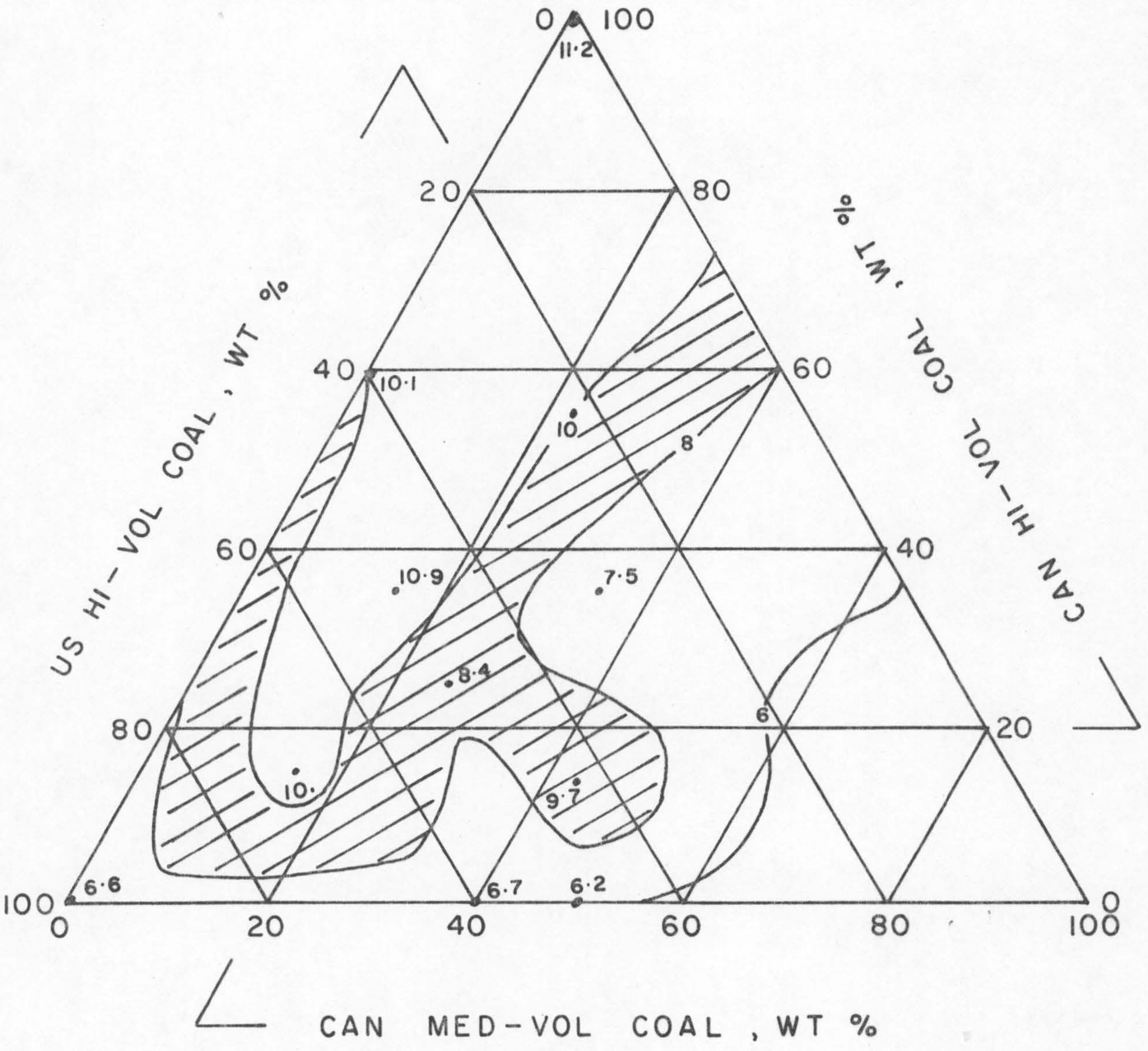

Fig. 5 - In-situ electrical resistivity of fly ash from coal blends

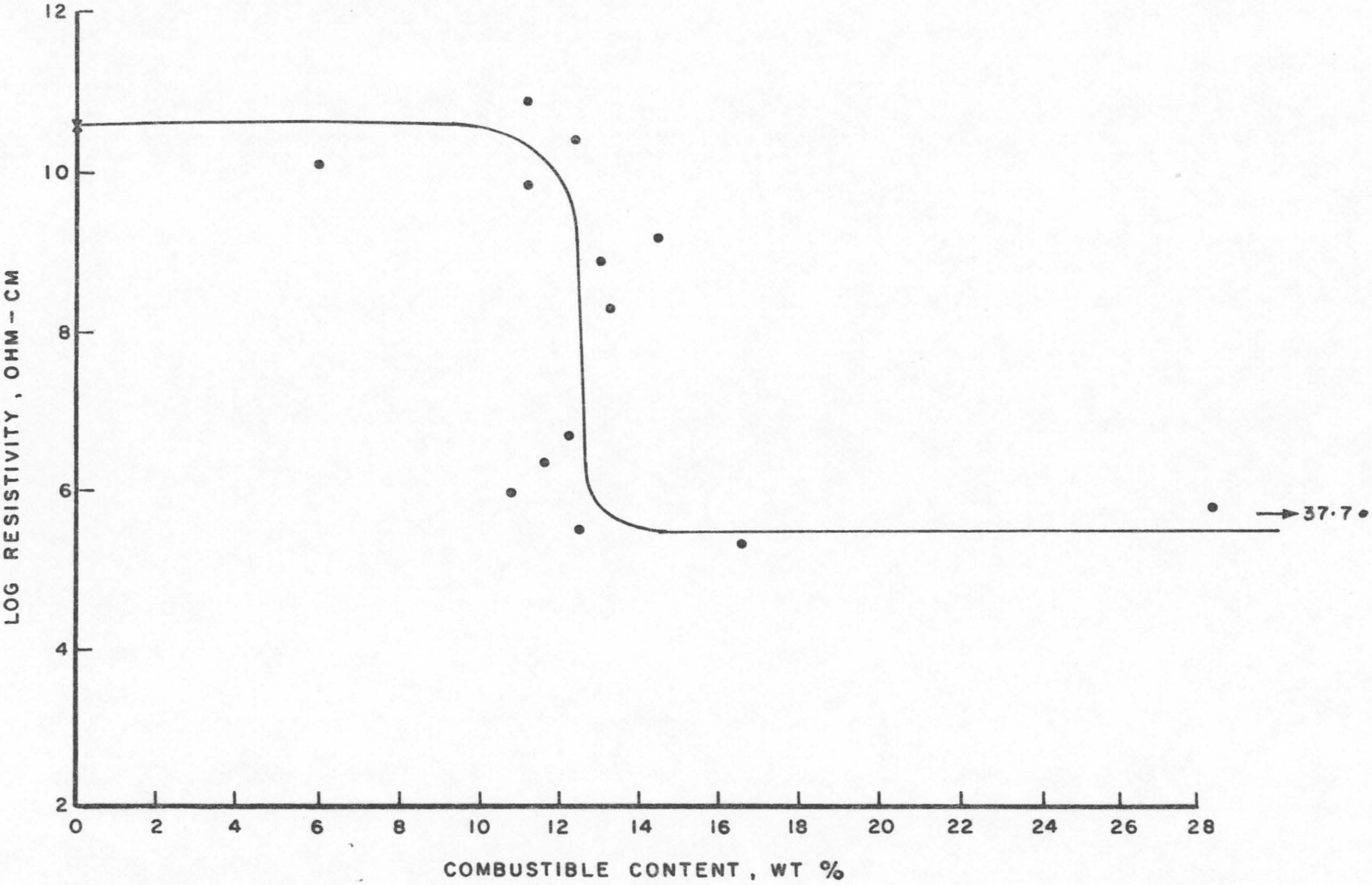

Fig. 6 - Resistivity curves for fly ash from 50% nominal blends of US coal

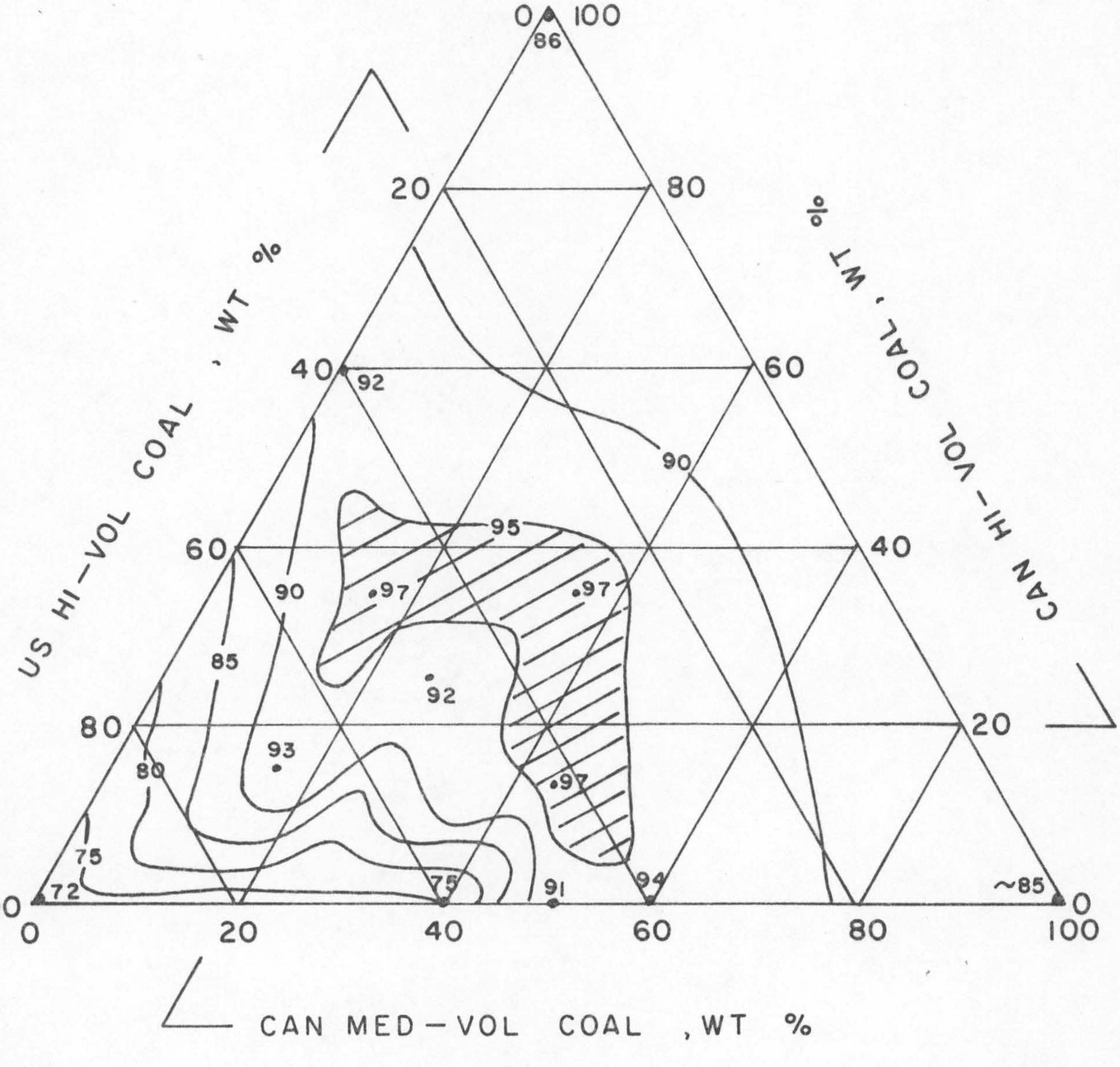

Fig. 7 - Precipitator efficiencies for fly ash from coal blends

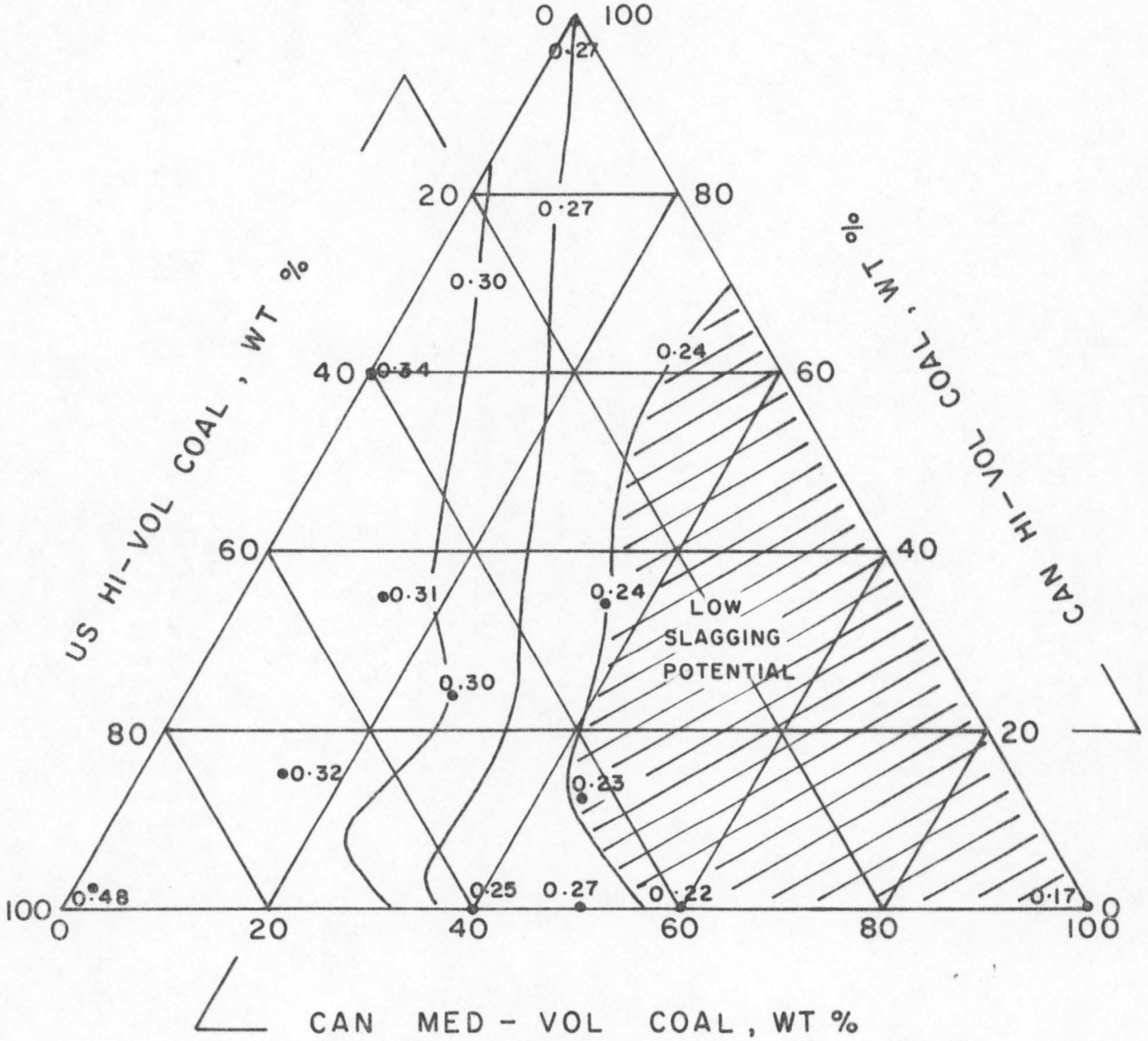

Fig. 8 - Base to acid ratios for ash in coal blends

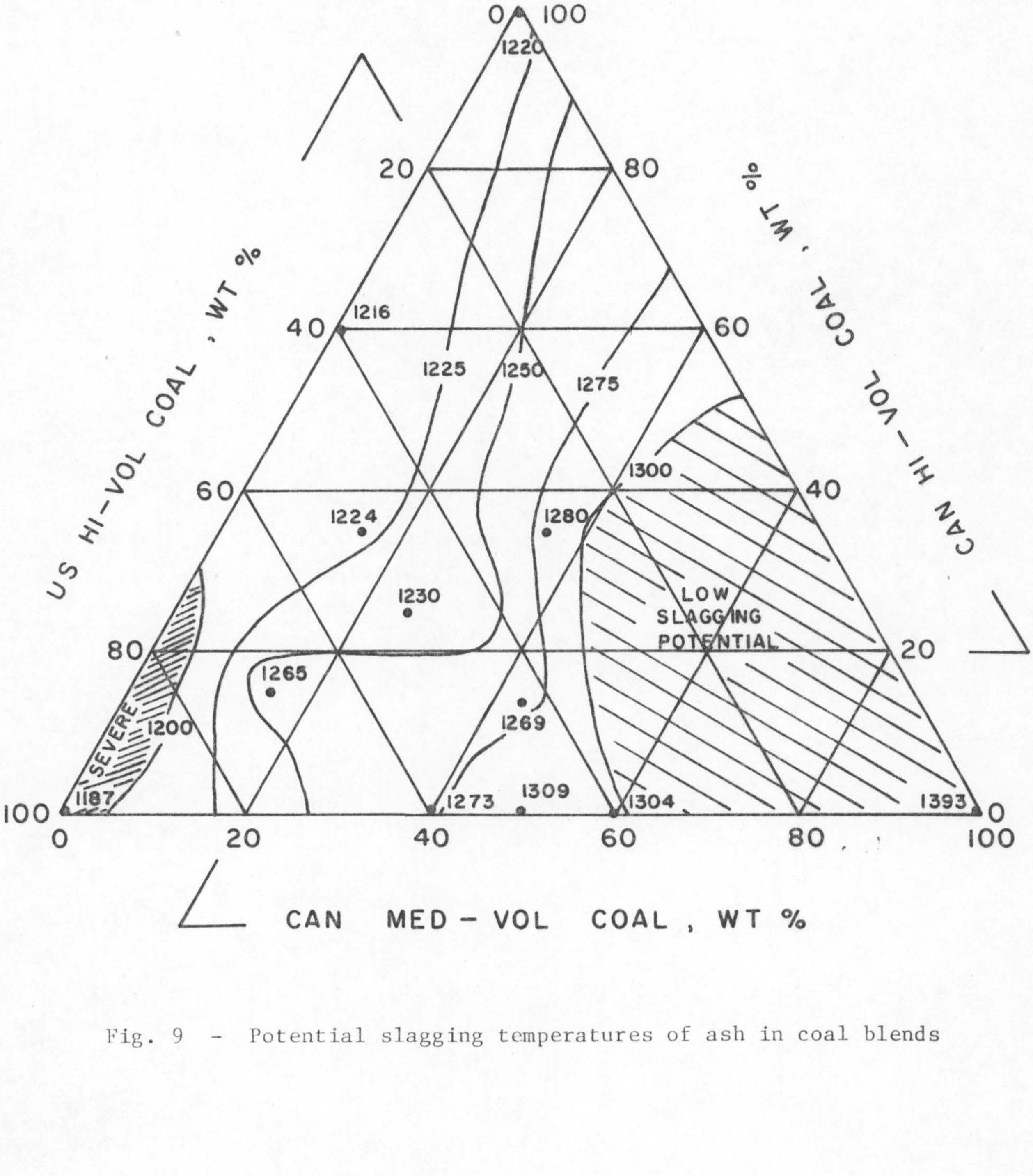

Fig. 9 - Potential slagging temperatures of ash in coal blends