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PILOT SCALE COMBUSTION TRIALS WITH  
HIGH-ASH SASKATCHEWAN LIGNITES

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by

T. D. Brown\* and G. K. Lee\*

ABSTRACT

As part of a joint federal-provincial (Saskatchewan) lignite evaluation program, two samples of high-ash Saskatchewan lignite from the Estevan and Willow Bunch areas were burned in a pulverized-fired, pilot-scale research boiler to establish criteria for their use as boiler fuels; a normal-ash Saskatchewan lignite, known as Utility, was used as a reference fuel.

It was found that the Willow Bunch lignite, with over 35% ash, could be burned safely and efficiently, but the Estevan lignite with over 50% ash produced an unstable flame and an unacceptable amount of combustibles in the fly ash. For all three fuels it was possible to collect the fly ash at high efficiency by electrostatic precipitation; furthermore, the ash residues neutralized over 60% of the sulphur in the fuel.

Studies of fusion temperatures of ash deposits revealed, for all three fuels, the existence of a eutectic due to alkali enrichment in the vicinity of the boiler screen tubes and the simulated superheater region. However, the ash deposits of both low-alkali, high-ash lignites were dry and powdery, whereas those of the high alkali Utility lignite were sintered and cohesive.

Reduction of ash in the Estevan lignite by either selective mining or coal beneficiation to less than 40% is desirable for good combustion performance.

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## INTRODUCTION

Under an agreement, dated 19 September 1974, the Department of Energy, Mines and Resources and the Saskatchewan Department of Mineral Resources co-operated in a joint two-phase program for the bulk sampling and testing of high-ash lignite from the Ravenscrag formation of Saskatchewan. Phase I involved the bulk sampling of lignite at selected sites by reverse-circulation drilling under the supervision of the Saskatchewan Department of Mineral Resources, whereas Phase II involved fuel upgrading and combustion evaluations of the bulk lignite samples by the Department of Energy, Mines and Resources.

This report describes the combustion trials conducted under Phase II and gives an assessment of the combustion and ash-fouling characteristics of two bulk lignite samples recovered from the Estevan and Willow Bunch areas respectively. Utility lignite, which is normally burned at the Boundary Dam Power Station by the Saskatchewan Power Corporation, was also included in the combustion trials to establish a baseline for comparing the performance of the bulk samples under realistic boiler firing conditions.

## RESEARCH OBJECTIVE

The objective of the combustion trials and the related analytical studies was to elucidate the major technical and operational parameters that must be resolved in order to successfully burn high-ash lignites in thermal power boilers. The parameters selected for evaluation were as follows:

1. Coal comminution and handling characteristics;
2. Combustion performance of each fuel at excess air levels corresponding to 3% and 5% O<sub>2</sub> in the flue gas;
3. Generation of particulate and gaseous pollutants during combustion;
4. Corrosion potential of condensed sulphuric acid on "cold end" boiler surfaces;
5. Fouling potential of low-melting ash constituents on both high-temperature (superheater) and low-temperature (furnace wall, screen and air preheater tubes) heat transfer surfaces;
6. Collection efficiency of fly ash by electrostatic precipitation.

## PILOT-SCALE RESEARCH BOILER

The research boiler, illustrated in Figure 1, was used for the three series of combustion trials described herein. All components and ancillaries were essentially the same as those described elsewhere<sup>1/</sup>, except for the two following design modifications. First, the two opposed burners were supplied with individually metered amounts of pulverized coal from a bin feed system rather than directly from the pulverizer. This arrangement permitted separation of moisture-laden air from the pulverizer coal stream prior to burning in order to improve ignition of the high ash fuels. Second, a simulated superheater was installed immediately downstream of the screen tubes to accommodate studies of fly ash build-up on high-temperature metal tube surfaces. This device, shown in Figure 2, was designed with detachable headers to facilitate the removal of ash deposits and the replacement of tubes.

## LIGNITE CHARACTERISTICS

Both bulk samples of high-ash lignite were shipped to Ottawa in sealed drums that were labelled either "Estevan-Site 134R" or "Willow Bunch-Site 182R". Correspondence received from the Saskatchewan Department of Mineral Resources indicated that the total weight of each bulk sample, including 15% free water, was about 2500 lb. However, a visual inspection of each sample showed wide variations in both extraneous ash and free water content from drum to drum, depending on the drill core location. For this reason, it was decided to air dry and then mechanically blend the entire contents of each bulk sample prior to crushing, grinding and burning. The Estevan sample was particularly difficult to dry and blend because it contained a number of large lumps of wet clay, while the Willow Bunch sample, although saturated with water, had noticeably less free clay and presented no problems during drying and blending.

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<sup>1/</sup>F. D. Friedrich, G. K. Lee and E. R. Mitchell, "Combustion and Fouling Characteristics of Two Canadian Lignites", Journal of Engineering for Power, April 1972, pp 127-132.

The Utility lignite, which was used as a reference fuel, was obtained from the storage pile at Boundary Dam Power Station. It was relatively low in both free moisture and occluded clay and was fairly uniformly mixed; thus, neither drying nor blending was required.

Table 1 gives the physical and chemical properties of the three lignites evaluated.

## EXPERIMENTAL PROCEDURE

### Operation of the Research Boiler

A combustion trial was carried out with each lignite. Each trial consisted of one or more tests at excess combustion air levels of ca. 25%, 15% and, when possible, 5%, (corresponding to 5%, 3% and 1% O<sub>2</sub> in the flue gases). Fuel input in all cases was about 340 lb/hr. An oil support burner was kept on standby at all times, but was only required to maintain flame stability during the trial with Estevan lignite.

During each trial the superheater metal temperature was controlled at 566°C maximum, smoke opacity was kept below No. 1 Ringlemann, and CO concentrations were controlled at 0.1% or less.

To ensure uniformity in the combustion evaluation of each coal, the furnace was allowed to reach thermal equilibrium at the desired excess air level before any test measurements were taken. After completion of these measurements, which required about 2 hours, all convection surfaces were cleaned by soot-blowing. This procedure was repeated for each of the combustion tests.

At the end of the combustion performance trials with each coal (a) the experimental superheater was removed with ash deposits intact, (b) samples of fireside deposits were removed from selected locations throughout the boiler, (c) all fireside boiler surfaces were thoroughly water washed, and (d) any residual lignite was cleaned from the coal handling system.

### Performance Parameters

The parameters measured during each series of combustion trials and the locations of the sampling stations (see Figure 1) are summarized below:

1. Fuel and ash analyses of crushed coal by hourly grab samples, pulverizer inlet.
2. Fineness of coal grind, coal metering bin.
3. CO<sub>2</sub> and CO by continuous infra-red monitors, Station 5.
4. O<sub>2</sub> by continuous paramagnetic monitor, Station 5.
5. NO and NO<sub>2</sub> by continuous chemiluminescent monitor, Station 8.
6. SO<sub>2</sub> continuously by automated West-Gaeke Method, Station 8.
7. Smoke opacity by continuous light absorption monitor, Station 14.
8. Dewpoint and rate of acid build-up intermittently by BCURA dewpoint meter, Station 9.
9. SO<sub>3</sub> intermittently by hot water condensation method, Station 11.
10. Low-temperature corrosion potential, measured by three mild-steel probes inserted simultaneously into the breeching and maintained at three different temperatures for about 4 hr while each coal was being burned. Oxygen in flue gas during these measurements was 3% or more, Station 10.
11. Fly ash loading, by a combined cyclone-filter system. These samples were also analyzed chemically and examined for size distribution, Station 7.
12. Ash fouling of heat transfer surfaces, evaluated by examination of the thickness, physical structure, chemical composition and melting characteristics of selected ash deposits, Stations 1, 2, 3, 4, and 6.
13. Dust collection efficiency, determined by passing part of the flue gas through a small electrostatic precipitator for 1 hr during operation at the 3% O<sub>2</sub> condition with each fuel. Inlet and outlet dust loadings were measured to establish the efficiency of precipitation, Station 7 and 13. The dust collected by the precipitator was analyzed to determine its chemical properties, Station 12.



## EXPERIMENTAL DATA AND DISCUSSION

### Coal Comminution

After air drying and blending, both high-ash lignites were crushed to -1/8 in. and pulverized to 70% minus 200 mesh without difficulty. Sieve analyses of the crushed and ground coals are given in Table 2. However, considerable trouble was experienced at the feed bin where the two pulverized high-ash lignites tended to compact into a cohesive solid having a 90° angle of repose. This can be attributed to the combined effects of either high ash and low moisture content, as in the case of the Estevan lignite, or medium ash and medium moisture content, as in the case of the Willow Bunch lignite. Continuous, gentle agitation by a spoked shaft was necessary to minimize "rat-holing" over the feeders and to maintain coal flow to both burners. By way of contrast, the pulverized Utility coal, which had a relatively low ash and moisture content, tended to be free flowing.

It is important to note that the aforementioned feeding problems with pulverized high-clay lignites will not occur with conventional, large-scale, moisture-separating burner systems which feed directly from the pulverizer without the intermediate bin feed.

### Combustion Performance

The combustion performance data, summarized in Table 3, show that steaming rates, superheater metal temperatures and stack gas temperatures all increased as the Btu input (i.e. fuel calorific value) increased. The Willow Bunch lignite burned with a fairly short, stable flame which required no oil support, even with 5% excess combustion air (1% O<sub>2</sub> in flue gases). However, as could be expected, the Willow Bunch flame was longer and darker than the Utility flame at any given excess combustion air level.

On the other hand, the Estevan lignite, which had the lowest calorific value of the three lignites, could not be safely burned without oil support until the furnace walls were heavily coated with ash. Even then, it was necessary to use over 30% excess combustion air (7% O<sub>2</sub> in flue gases) to maintain a stable flame. Without oil support the Estevan flame extended beyond the furnace exit and was noticeably darker than the flames from either the Willow Bunch or the Utility lignite.

With all lignites, flame temperatures were too low for wet-bottom (slag tap) operations, and boiler dust loadings were, therefore, roughly a direct function of fuel ash input. Despite their high ash content, the fireside deposits from both the Willow Bunch and Estevan lignite were easily removed to bare metal by soot blowing. Typically, the deposits from the Utility lignite with lower ash content were sintered and difficult to dislodge, particularly from the staggered screen tubes.

These observations indicate that Willow Bunch lignite can be burned as successfully and safely as higher quality lignites such as Utility, which are characterized by low sulphur, low ash and low ash softening temperatures. In the case of Estevan lignite, the experimental data suggest that high combustion efficiency and acceptable flame stability can be achieved without oil support by reducing its ash content to about 35% on a dry basis prior to burning. The high extraneous ash in the Estevan lignite, if due to fairly thick clay strata between the lignite seams, could be reduced appreciably by selectively rejecting such clay as the lignite is mined.

#### Flue Gas Analyses

The average flue gas analyses for all of the lignite tests are shown in Table 4. CO levels averaged less than 0.05% and smoke opacity was consistently below No. 1 Ringleman at all excess air levels. As would be expected, the NO levels progressively decreased with decreases in both excess air level and flame temperature, but it is important to note that the higher flame temperatures in large boiler furnaces at the same combustion conditions will produce higher concentrations of NO.

SO<sub>2</sub> levels in flue gas are normally dictated by the sulphur content of the fuel and the excess combustion air level. However, the highly alkaline ash constituents found in many lignites may trap much of the sulphur, leaving less than 50% as SO<sub>2</sub> in the flue gas. Calculations based on the data in Table 3 show that the proportion of fuel sulphur fixed by the ash ranged from 62% with Utility lignite to 66% and 79% with Willow Bunch and Estevan lignite respectively. This ash characteristic yields two important benefits - reduced SO<sub>2</sub> emissions and enhanced electrostatic precipitator efficiency.

### Low-Temperature Corrosion Potential

Repeated probing of the stack gases with a BCURA conductivity probe during each combustion test showed no evidence of an acid dewpoint and no measurable rate of acid build-up. Furthermore, analysis of the water-soluble products from the low-temperature corrosion probes, Table 5, indicates that sufficient alkaline cations are present in the fly ash of each lignite to totally neutralize any sulphuric acid condensed in the temperature range between 104°C and 138°C. These results confirm that, although gas-phase SO<sub>3</sub> levels in two tests reached a high of 10 ppm, any condensed acid would be rapidly neutralized by superfine, alkaline, fly ash particles. Thus, low-temperature corrosion should not be a problem with these three lignites.

### Fly Ash Characteristics

Gas-borne particulate material or fly ash was measured at location 7 in the pilot-scale boiler using an isokinetic sampling and collection methodology developed at CCRL. Samples were taken during each of the combustion tests summarized in Table 3.

Figure 3 shows that the fly ash concentrations in the flue gas before the electrostatic precipitator were dominated by the total ash content of the input fuel. It is significant that the Willow Bunch and Utility lignites produced proportionately less fly ash per unit weight of fuel ash than the Estevan lignite. This indicates that the Estevan ash contains a large amount of superfine material that tends to remain entrained in the flue gas.

The small influence of excess-air level on total ash concentrations in the case of the Willow Bunch and Utility lignites reflects the small changes in combustion efficiency that occurred. However, with the Estevan lignite the total fly ash in the combustion products increased progressively as the oil support firing was decreased, indicating that the increased fly ash loadings were due primarily to increased combustibles in the fly ash.

The combustible contents of the fly ash from both the Utility and the Willow Bunch lignite trials were generally between 2% and 4% wt, corresponding to a heat loss of less than 0.5% of the heat input, as shown in Figure 4. However, the combustible in the fly ash from the Estevan lignite was in excess of 5% wt with oil support equivalent to 16% of total heat input. Without oil support, combustible content of the fly ash was even higher, resulting in a 4%

heat loss. In short, the burn-out of the Willow Bunch lignite is equal to or better than that obtained in normal industrial operation, but the Estevan lignite will require upgrading if the 4% heat loss due to combustible in fly ash is to be reduced.

The fly ash sampling system included a cyclone separating stage, a coarse filtering stage and a fine filtering stage. All fly ash samples were, therefore, segregated during the sampling procedures into the three fractions illustrated in Figure 5 and described for analytical purposes as:

Coarse: the material separated in the cyclone

Medium: the material collected on the coarse filter

Fine: the material collected on the fine filter

The approximate size ranges collected in each fraction were:

Coarse: 85% greater than 20  $\mu\text{m}$

Medium: 90% in the range 20 to 2  $\mu\text{m}$

Fine: 100% below 2  $\mu\text{m}$

The size distributions of the fly ash samples are shown in Table 6 where it can be seen that most of the fly ash particles generated by all three lignites were less than 20  $\mu\text{m}$ . With the Estevan lignite, the lowest combustible content occurred with 16% oil support and coincided with a high mass fraction of particles in the coarse size range. The highest combustible content, which occurred when there was no oil support, can be attributed to a reduction in flame temperature due to the high ash content of the fuel.

Chemical analyses of the fly ash, Table 7, show that the total water solubility and water soluble sulphate content of these samples were much lower for Estevan than for Utility and Willow Bunch lignites. The total alkali, Na + K, of the fly ash from Estevan lignite was 2% and fell between the high level of 9% for the Utility lignite and the low level of 0.5% for the Willow Bunch lignite. Since the total alkali, water soluble sulphate, and water soluble alkali in the fly ash strongly influence the extent of fireside fouling, it would appear that the Utility lignite has the highest fouling tendency of the three lignites examined.

Further chemical analyses showed that for the three lignites the highest concentration of sodium was in the smallest size fraction of the fly ash, whereas potassium was concentrated in the smallest size fraction from the Willow Bunch and Estevan lignites only.

The fly ash collection efficiencies for each fuel were measured at 3% O<sub>2</sub> in the flue gas by means of a pilot-scale electrostatic precipitator which operated at an inlet gas temperature of 150°C. As shown in Table 8, collection efficiencies above 97% were achieved with each lignite despite the wide variation in solids loading at the precipitator inlet. In all three tests, the solids loading at the precipitator outlet was 0.05 gr/scf or less, indicating that when burning these lignites, solids emissions can be controlled to meet current air pollution control standards.

#### Fireside Deposits

The analyses of fireside deposits collected from the superheater and at five fireside locations throughout the pilot-scale boiler are given in Tables 9, 10, 11 and 12 and photographs of these deposits in situ are shown in Figures 6, 7 and 8.

These analyses showed that, at all sample locations, the deposits from the Utility lignite were consistently high in water soluble and alkali metal components and had initial ash deformation temperatures below 1176°C.

The lower water solubility and alkali metal concentrations in the Estevan and Willow Bunch lignites gave rise to deposits with initial ash deformation temperatures above 1200°C and 1247°C respectively. In all cases the lowest initial ash deformation temperatures were associated with the deposits from the highest temperature region (the simulated superheater), indicating the existence of a eutectic. The minimum initial ash deformation temperatures were:

Utility Lignite:	1082°C
Willow Bunch Lignite:	1249°C
Estevan Lignite:	1204°C

The chemical analyses of the fireside deposits have been plotted as a series of enrichment ratios in Figures 9, 10 and 11, and their ash fusion characteristics are given in Figure 12. "Enrichment ratio" is defined as the ratio of the percentage of cation or anion in the deposit sample to the percentage of the same ion in the coal ash.

The low-melting superheater deposits from Utility lignite were characterized by a substantial enrichment in water soluble calcium and water soluble sodium. The deposits on the air heater tubes showed similar low melting characteristics and a significant enrichment in water soluble calcium, but did not show any sodium or total alkali enrichment. The calcium to sodium ratio observed in the superheater deposits was maintained in the air heater deposits and is considered to be responsible for the eutectic observed at both locations.

The most significant enrichment in the deposits from Willow Bunch lignite occurred in the water soluble sodium content of the superheater deposits. The absence of any dramatic effect on the ash fusion characteristics can be attributed to the low concentration levels, 0.02% to 0.36%, across which the enrichment occurred.

In the case of the Estevan lignite, a significant enrichment in both soluble sulphate and soluble calcium occurred in the superheater deposits. It appears likely, therefore, that the eutectic observed in the superheater deposits from the Estevan and Utility lignites is due to calcium enrichment and that the overall low levels of ash fusion temperatures observed in deposits from the Utility lignite are due to the high concentration of both water soluble calcium and alkali metal components.

#### CONCLUSIONS

1. The combustion performance of Willow Bunch lignite, which was comparable to Utility lignite, shows that it is eminently suitable for a boiler fuel. On the other hand, the Estevan lignite, because of its high extraneous ash content, required an oil support flame to maintain stable ignition and to reduce the combustible content of the fly ash to acceptable levels. Beneficiation of the Estevan lignite by separation of clay either during mining or at the coal preparation plant will, in all probability, permit this lignite to be burned successfully without oil support.

2. The fireside deposits produced by Willow Bunch and Estevan lignites were non-adherent and powdery throughout the boiler and were easily removed by soot-blowing. These observations, in conjunction with the thermo-chemical characteristics of their ash deposits, indicate that both high-ash lignites have a low fouling and slagging potential and that any build-up of fireside deposits can be controlled by properly located soot blowers. By comparison, Utility lignite produced relatively thick, sintered deposits on the screen tubes and simulated superheater tubes. In a large steam boiler the rate of ash build-up with the high-ash lignites should be much lower than with Utility lignite.
3. All three lignites can be burned with minimal impact on the environment. It was found that, for each lignite, over 60% of the input sulphur was neutralized by alkaline constituents in the fly ash and that collection efficiencies of fly ash exceeded 97% in a pilot-scale electrostatic precipitator.
4. If de-ashing of Estevan lignite is feasible, a combustion trial will be necessary with the cleaned coal to determine whether the fouling characteristics have been affected.

TABLE 1

Lignite Analytical Data

Lignite Sample Condition	Utility		Willow Bunch		Estevan	
	As Pulverized	As Fired	As Pulverized	As Fired	As Pulverized	As Fired
<b>Proximate Analysis</b>						
Moisture .....	17.06	5.36	34.89	19.18	17.71	6.89
Ash .....	11.11	14.89	16.04	22.57	34.61	51.16
Volatile Matter .....	32.51	36.08	25.55	30.98	22.64	21.45
Fixed Carbon (By Diff) .....	39.32	43.67	23.52	27.27	25.04	20.50
<b>Ultimate Analysis</b>						
Carbon .....	50.60	56.90	34.59	39.75	33.62	29.42
Hydrogen .....	3.31	3.68	2.30	2.82	2.52	2.23
Sulphur .....	0.48	0.62	0.88	1.42	0.57	0.58
Nitrogen .....	0.87	0.98	0.49	0.59	0.57	0.53
Ash .....	11.11	14.89	16.04	22.57	34.61	51.16
Oxygen (By Diff) .....	16.57	17.57	10.81	13.67	10.40	9.19
Calorific Value (Btu/lb Gross).	8230	9290	5600	6380	5600	4760
<b>Fusibility of Ash</b>						
Initial Deformation Temp ... °C	1182	1093	1288	1304	1188	1171
Softening Temp .....	1193	1149	1327	1360	1371	1371
Hemispherical Temp .....	1227	1171	1349	1404	1427	1480+
Fluid Temp .....	1427	1316	1415	1432	1477	1480+
Grindability, Hardgrove .....	56 (5.2% Moist)		74 (6.4% Moist)		85 (3.7% Moist)	
<b>Ash Analysis</b>						
Water Soluble Components ... %		4.89		26.54		3.58
S .....		1.22		6.64		0.90
Mg .....		0.02		0.13		0.01
Na .....		2.09		0.59		1.00
K .....		0.05		0.10		0.06
Ca .....		2.65		3.12		2.35
Acid Soluble Components ... %		16.0		14.9		8.91
Fe .....		0.98		0.97		0.60
Mg .....		0.46		0.44		0.14
Na .....		0.28		0.04		0.10
K .....		0.01		0.03		0.12
Ca .....		7.40		4.10		2.84
Al .....		1.55		1.72		1.59
<b>Acid Insoluble Components</b>						
SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> .....		79.11		58.56		87.51



TABLE 2

Sieve Analyses of Crushed and Pulverized Lignites

Lignite (Screen Size)	Utility		Willow Bunch		Estevan	
	Crushed	Pulverized	Crushed	Pulverized	Crushed	Pulverized
‡ 1/8"	2.18		0.33		0.94	
-1/8" x 10	39.75		16.68		24.29	
10 x 20	32.86		21.08		33.75	
20 x 28	8.08		7.79		7.66	
28 x 48	8.98		14.41		12.31	
48 x 0	8.15		39.71		21.05	
>140		17.3		19.2		18.0
140 x 200		14.1		12.1		11.1
200 x 325		17.1		18.7		14.4
325 x 0		51.5		50.0		56.6

TABLE 3

## Lignite Combustion Data

Operating Parameter Lignite	Coal Rate lb/hr	Oil Support Rate US gph	O <sub>2</sub> in Flue Gas %	Steam Flow lb/hr	Comb Air °C	Flue Gas Out °C	Superheater Tube Metal °C	Pulverizer Air In °C	Pulverizer Air Out °C
Utility	343	-	5.9	1150	204	271	571	271	85
		-	3.2	1180	203	320	551	279	84
		-	1.1	1220	199	366	532	263	82
Willow Bunch	340	-	4.8	950	177	270	502	207	51
		-	2.8	1100	191	274	502	213	51
		-	1	1050	171	248	460	191	50
Estevan	347	5	2.7	1450	202	321	543	263	77
		3	2.7	1350	204	346	527	321	77
		1½	2.8	1200	204	344	518	311	73
		-	6.5	900	160	327	443	304	74

TABLE 4

## Average Flue Gas Analyses

Lignite	Coal Rate lb/hr	Oil Rate US gph	O <sub>2</sub> %	CO <sub>2</sub> %	CO %	SO <sub>2</sub> ppm	SO <sub>3</sub> ppm	NO ppm	Ringleman Smoke No
Utility	343	-	5.9	15.8	0.01	211	10.5	330	<1
		-	3.2	17.2	0.01	235	4.9	330	<1
		-	1.1	19.2	0.02	267	-	200	<1
Willow Bunch	340	-	4.8	16.6	0.02	619	5.9	213	<1
		-	2.8	17.0	0.02	704	3.4	243	<1
		-	1.8	18.2	0.02	789	1.6	228	<1
Estevan	347	5	2.7	16.8	0.03	317	3.9	175	<1
		3	2.7	17.0	0.03	309	9.4	140	<1
		1½	2.8	17.2	0.04	320	6.3	150	<1
		-	6.5	13.0	0.05	200	-	138	<1

TABLE 5

Low-Temperature Corrosion Probe Data

Lignite	Probe Temp °C	Water-Soluble Constituents in Deposits mg/hr with 3% O <sub>2</sub> in Flue Gas				
		Fe	Ca	Mg	Na	SO <sub>4</sub>
Utility	104	1.9	1.7	0.1	2.1	5.0
	121	2.2	1.1	0.1	0.7	1.9
	138	0.8	1.5	1.7	2.2	5.2
Willow Bunch	104	0.2	0.4	0.0	0.0	1.4
	121	0.2	0.3	0.0	0.0	1.2
	138	0.1	0.4	0.0	0.0	0.9
Estevan	104	0.2	1.2	0.0	0.2	0.4
	121	0.3	0.8	0.0	0.1	0.6
	138	0.1	1.0	0.1	0.3	0.8

TABLE 6

Size Distribution of Fly Ash

Lignite	O <sub>2</sub> in Flue Gas %	Oil Support %	Size Distribution, % wt in Fraction		
			Coarse >20 microns	Medium 20-2 microns	Fine <2 microns
Utility	5.9	-	43.2	35.4	21.4
	3.2	-	44.5	43.3	12.2
	1.1	-	53.4	30.8	15.8
Willow Bunch	4.8	-	46.1	38.0	15.9
	2.8	-	62.2	13.8	24.0
Estevan	2.7	25	68.0	16.1	15.9
	2.7	16	77.0	15.1	7.9
	2.8	8	73.1	16.8	10.1
	6.5	-	69.2	20.2	10.6

TABLE 7

Chemical Analyses of Fly Ash

	Utility Lignite			Willow Bunch			Estevan		
% O <sub>2</sub> in Flue Gas	5.9	3.2	1.1	4.8	2.8	2.7	2.7	2.8	6.5
% Oil Support	0	0	0	0	0	25	16	8	0
Water Soluble Components, % wt									
Total Water Soluble	10.25	7.18	6.10	7.60	6.78	1.89	2.27	2.04	1.54
S (as SO <sub>4</sub> )	4.91	3.13	2.54	3.30	2.53	0.91	1.18	1.18	1.16
Fe	-	-	-	0.08	0.07	0.04	0.03	0.04	0.13
Mg	0.01	0.03	0.02	0.01	0.01	0.03	0.03	0.02	0.02
Na	1.39	0.92	1.23	0.02	0.02	0.44	0.18	0.30	0.76
K	0.38	0.46	0.41	0.03	0.06	0.04	0.02	0.05	0.07
Ca	0.05	0.05	0.05	1.44	1.66	1.63	1.09	2.63	2.27
Acid Soluble Components, % wt									
Fe	2.23	2.71	3.11	1.35	2.61	1.15	1.48	1.25	1.17
Mg	1.54	1.75	1.75	1.17	2.20	0.38	0.44	0.32	0.31
Na	5.91	7.21	7.41	0.08	0.10	0.66	0.71	0.63	0.62
K	0.51	0.54	0.48	0.19	0.21	0.78	0.69	0.61	0.70
Ca	9.62	11.16	7.05	3.68	6.12	0.54	0.69	0.35	0.51
Al	9.74	11.07	10.68	13.90	13.60	6.79	6.28	6.98	9.16
Acid Insoluble, % wt									
Al + Si	41.6	37.29	33.86	49.05	46.97	83.84	82.52	83.06	83.72
Total Alkali, % wt									
(Na + K)	8.19	9.13	9.53	0.32	0.39	1.92	1.60	1.59	2.16

TABLE 8

Fly Ash Collection Efficiencies

Lignite	O <sub>2</sub> in Flue Gas %	Average Fly Ash Concentration in Flue Gases gr/scf		Electrostatic Precipitator Collection Efficiency %
		Precipitator Inlet	Precipitator Outlet	
Utility	3.2	1.17	.03	97.4
Willow Bunch	2.8	3.08	.05	98.4
Estevan	2.7	16.3	.01	>99

TABLE 9

Analyses of Furnace Deposits  
from Utility Lignite

Station No.	Furnace Bottom 1	Furnace Wall 2	Screen Tubes 3	Superheater 4	Air Heater 6
Water Soluble % wt	5.74	17.40	7.01	9.66	6.42
SO <sub>4</sub>	2.12	10.79	4.31	4.30	2.31
Fe	0.04	0.05	0.03	-	0.59
Mg	0.02	0.03	0.02	0.05	0.89
Na	0.13	1.98	0.76	4.36	0.48
K	0.01	0.01	0.01	0.37	0.04
Ca	0.18	0.20	0.17	2.75	0.32
Acid Soluble % wt					
Fe	2.57	3.65	2.81	0.70	2.55
Mg	1.28	1.35	1.85	2.17	1.90
Na	3.95	2.43	3.88	4.58	2.62
K	0.12	0.12	0.15	0.06	0.12
Ca	5.22	3.31	11.72	6.84	12.59
Al	16.39	13.85	21.25	6.44	18.36
Acid Insoluble % wt	45.61	36.83	28.11	27.80	31.93
Deposit Fusion Temperatures					
Initial Softening, °C		1182	1188	1077	1104
Spherical, °C		1227	1216	1121	1138
Hemispherical, °C		1249	1804	1160	1260
Liquid, °C		1299	1349	1182	1282



TABLE 10

Analyses of Furnace Deposits  
from Willow Bunch Lignite

Station No.	Furnace Bottom 1	Furnace Wall 2	Screen Tubes 3	Superheater 4	Air Heater 6
Water Soluble % wt	7.73	7.93	5.87	5.58	4.46
SO <sub>4</sub>	5.25	5.85	6.55	3.29	2.87
Fe	0.07	0.08	0.06	-	0.24
Mg	0.04	0.04	0.02	0.04	0.23
Na	0.05	0.07	0.05	0.36	0.05
K	0.02	0.02	0.02	0.08	0.02
Ca	0.78	0.74	0.56	1.91	0.83
Acid Soluble % wt					
Fe	5.12	5.48	2.95	0.73	4.59
Mg	1.94	2.08	2.54	2.72	2.43
Na	0.12	0.11	0.08	0.03	0.11
K	0.17	0.28	0.33	0.16	0.27
Ca	4.45	3.95	5.77	0.43	5.58
Al	10.24	12.04	17.58	5.45	11.74
Acid Insoluble % wt	53.76	52.66	50.85	51.40	54.00
Deposit Fusion Temperatures					
Initial Softening, °C		1282	1249	1243	1260
Spherical, °C		1327	1304	1277	1316
Hemispherical, °C		1360	1316	1327	1399
Liquid, °C		1471	1449	1366	1482

TABLE 11

Analyses of Furnace Deposits  
from Estevan Lignite

Station No.	Furnace Bottom 1	Furnace Wall 2	Screen Tubes 3	Superheater 4	Air Heater 6
Water Soluble % wt	3.70	2.62	2.77	1.46	3.14
SO <sub>4</sub>	1.51	0.99	1.03	0.80	0.47
Fe	0.09	0.17	1.13	-	0.34
Mg	0.03	0.70	0.72	0.03	0.37
Na	0.10	0.14	0.18	0.17	0.14
K	0.01	0.02	0.02	0.02	0.02
Ca	0.52	0.55	0.49	1.88	0.49
Acid Soluble % wt					
Fe	1.00	1.42	1.06	0.34	1.04
Mg	0.48	0.41	0.46	0.45	0.56
Na	0.52	0.53	0.58	0.39	0.52
K	0.60	0.83	0.94	0.64	0.76
Ca	0.58	0.44	0.62	0.56	0.84
Al	6.30	8.84	7.92	2.61	9.25
Acid Insoluble % wt	82.93	80.81	79.62	81.35	78.68
Deposit Fusion Temperatures					
Initial Softening, °C		1260	1288	1193	1304
Spherical, °C		1427	1432	1377	1438
Hemispherical, °C		1482+	1480+	1480+	1471
Liquid, °C		1480+	1480+	1480+	1480+

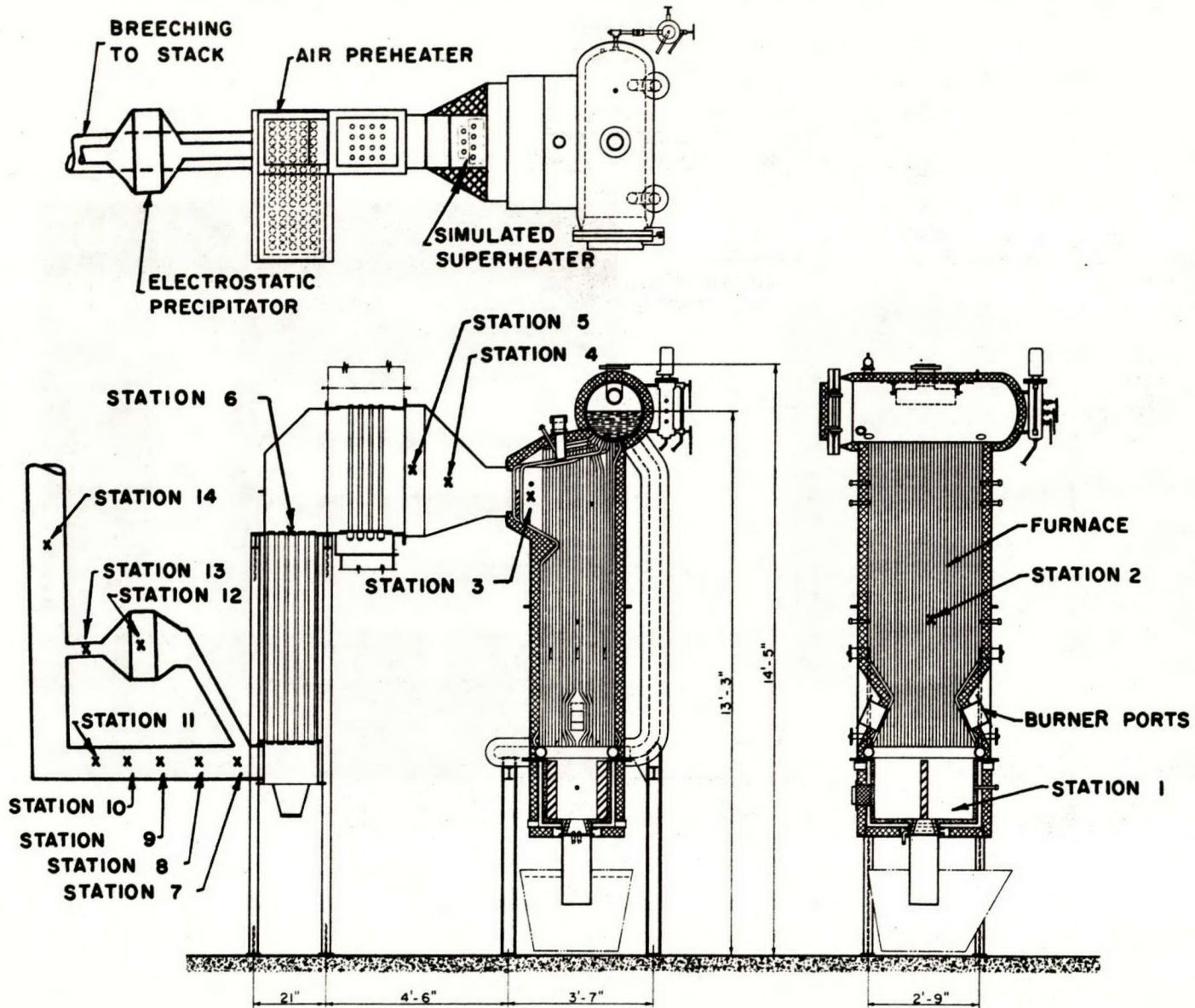
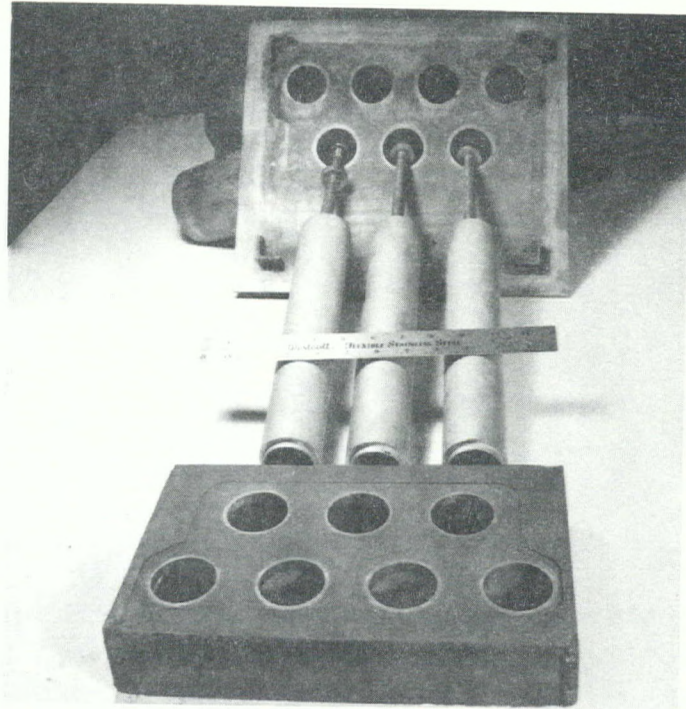
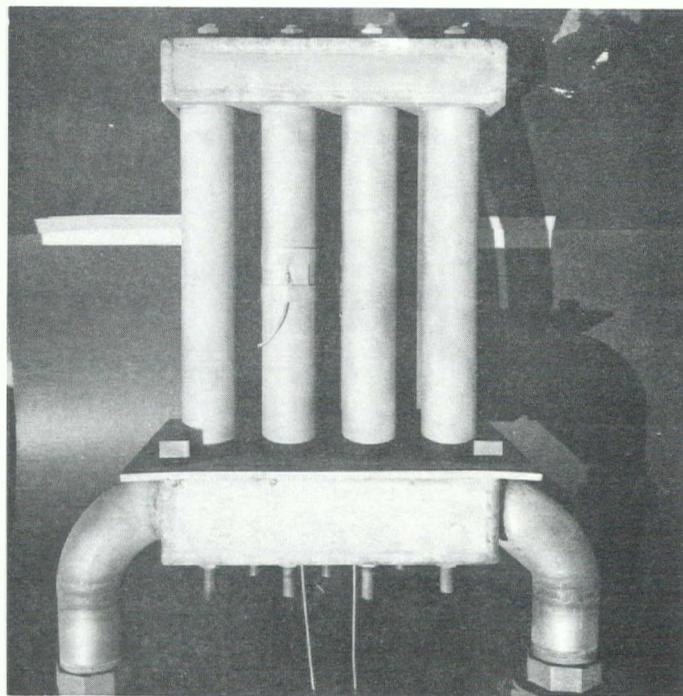


Figure 1. Pilot-scale research boiler, showing location of sampling stations.



(a) Exploded View



(b) Assembled View

Figure 2. Simulated air-cooled superheater designed for operation with metal-tube temperatures up to 600°C.

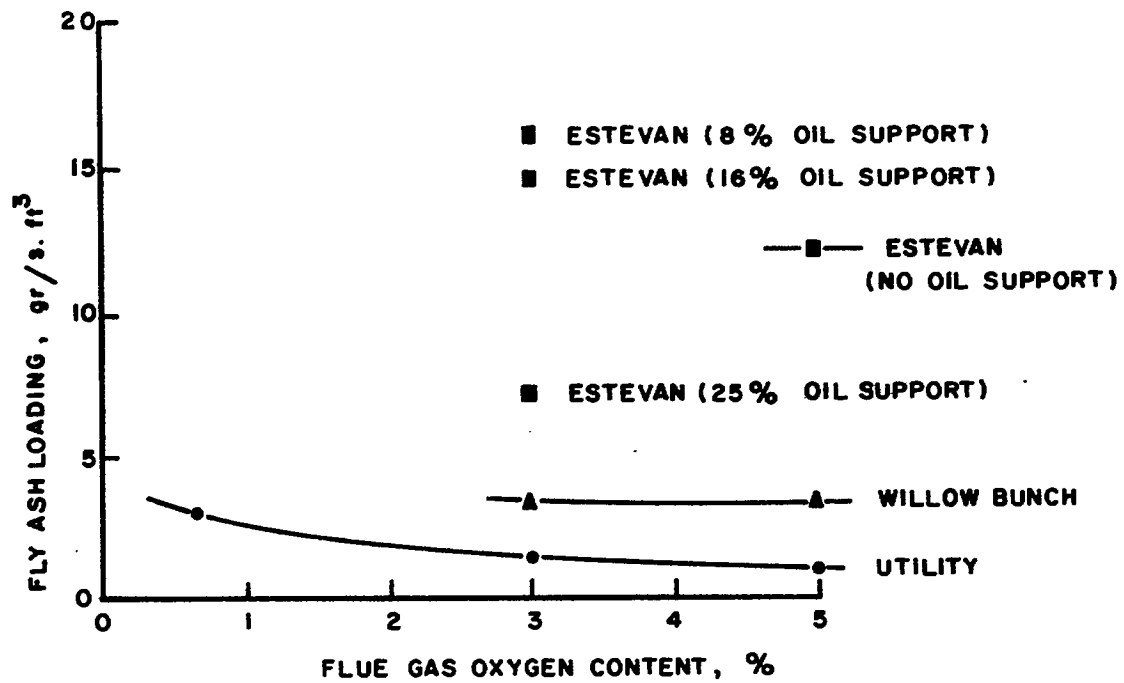


Figure 3. Fly ash loading in flue gases before the electrostatic precipitator.

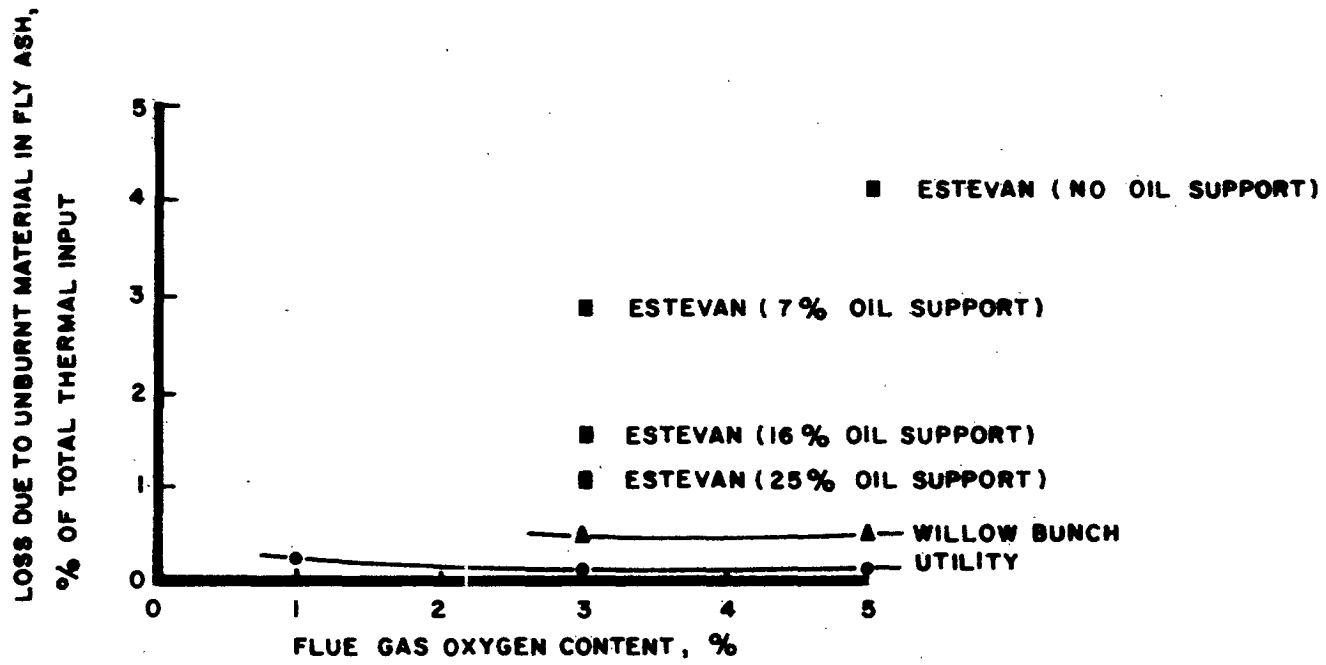
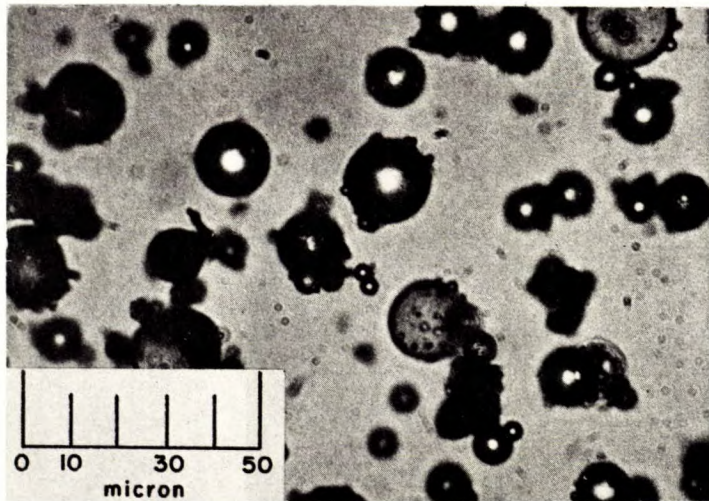
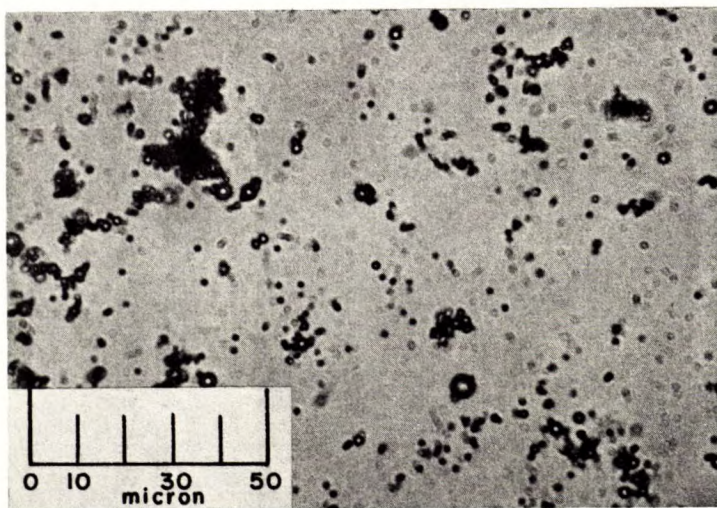
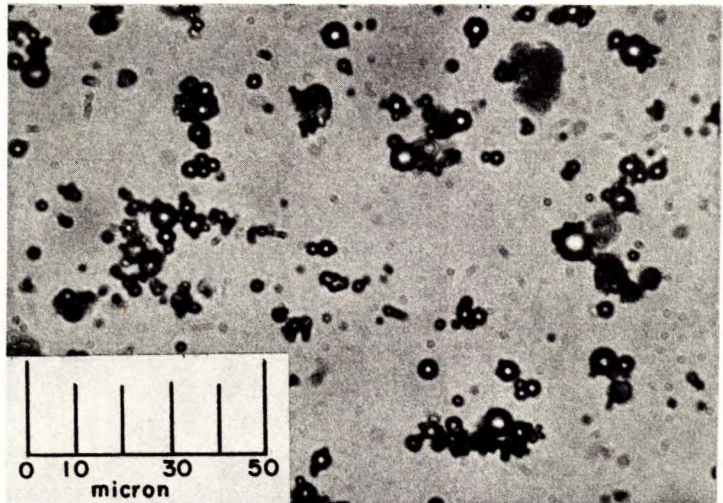


Figure 4. Heat loss due to combustible content of fly ash before the electrostatic precipitator.



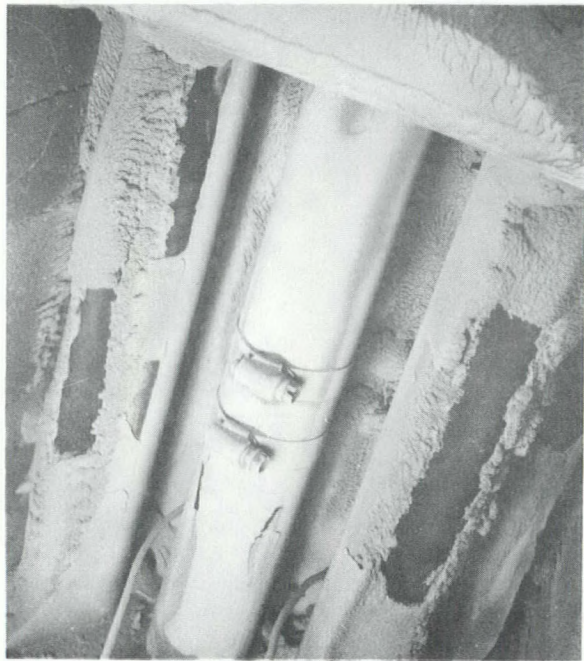
(a) Fly ash separated in the cyclone; the coarse fraction.

(b) Fly ash separated on the coarse filter, the medium fraction.

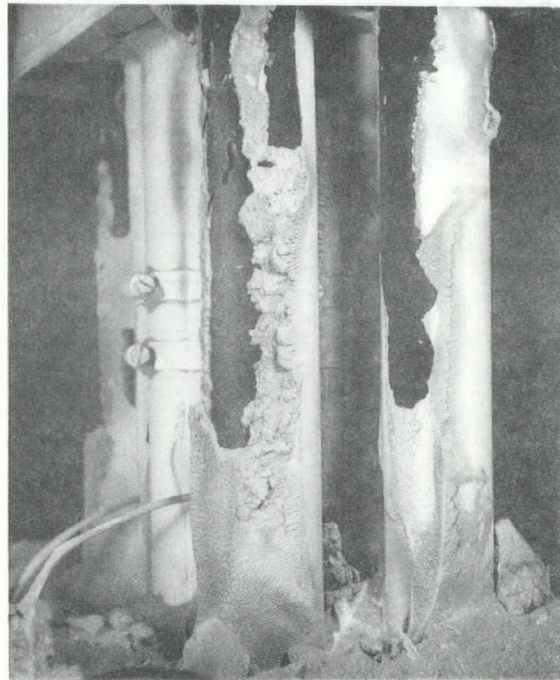


(c) Fly ash separated on the fine filter; the fine fraction.

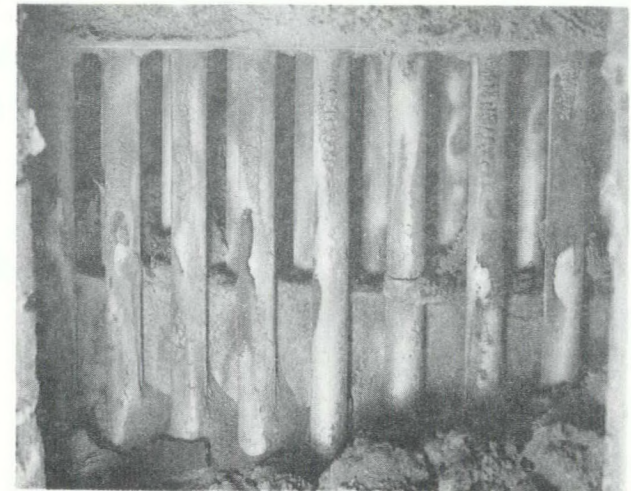
Figure 5. Size distribution of a typical fly ash sample.



(a) Rear view of superheater tubes.



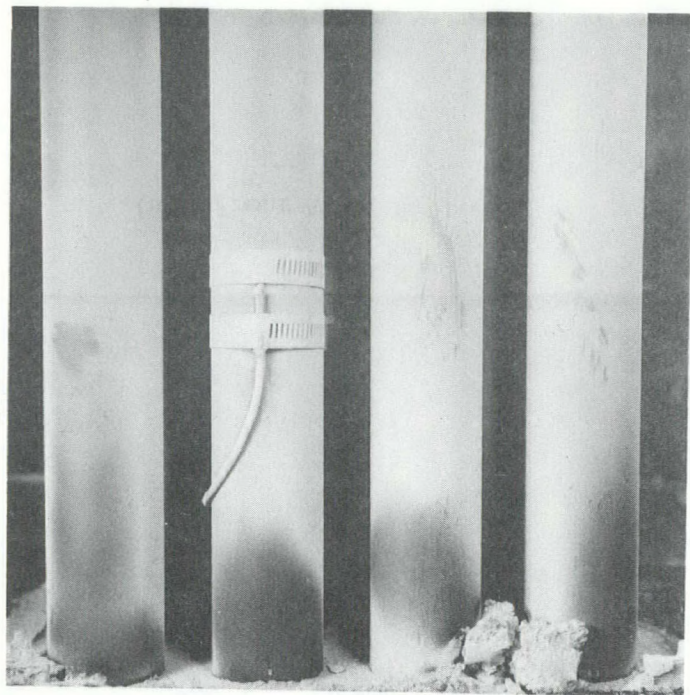
(b) Side view of superheater tubes.



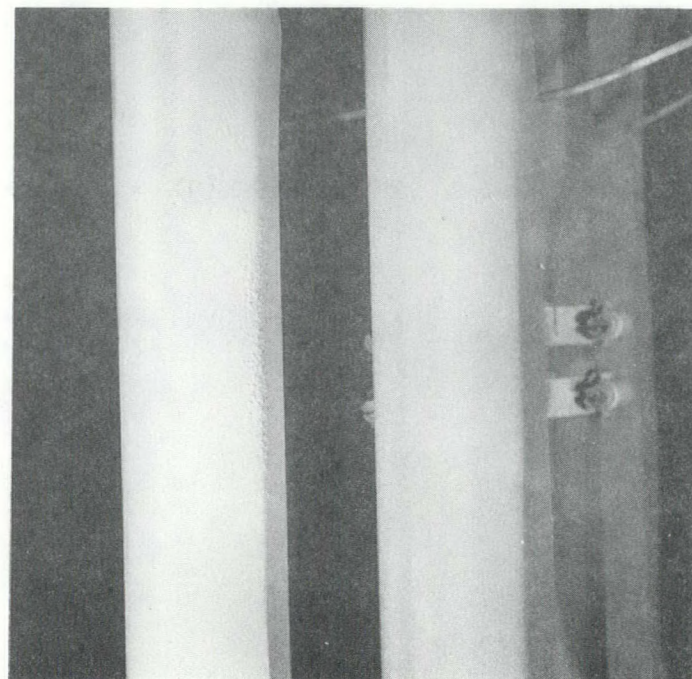
(c) Rear view of screen tubes.

Figure 6. Simulated superheater and screen tubes showing the thick build-up of sintered ash deposits from Utility lignite.



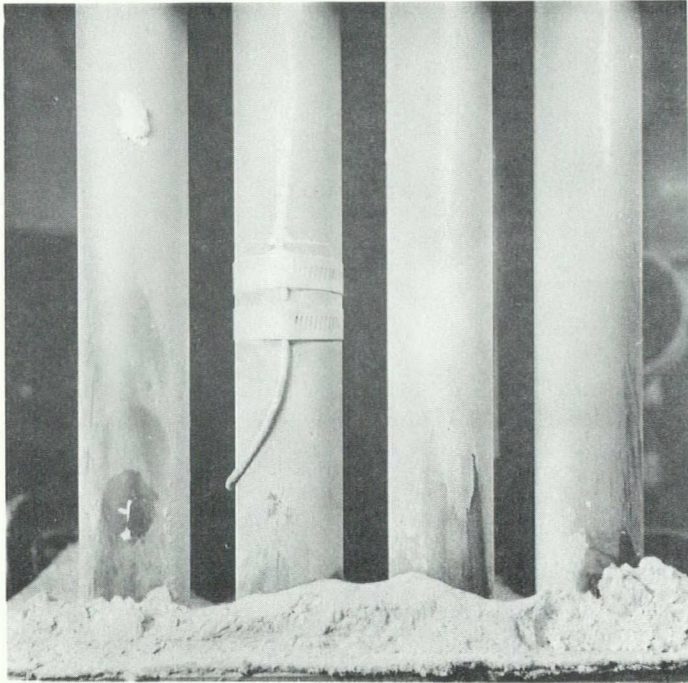


(a) Front View

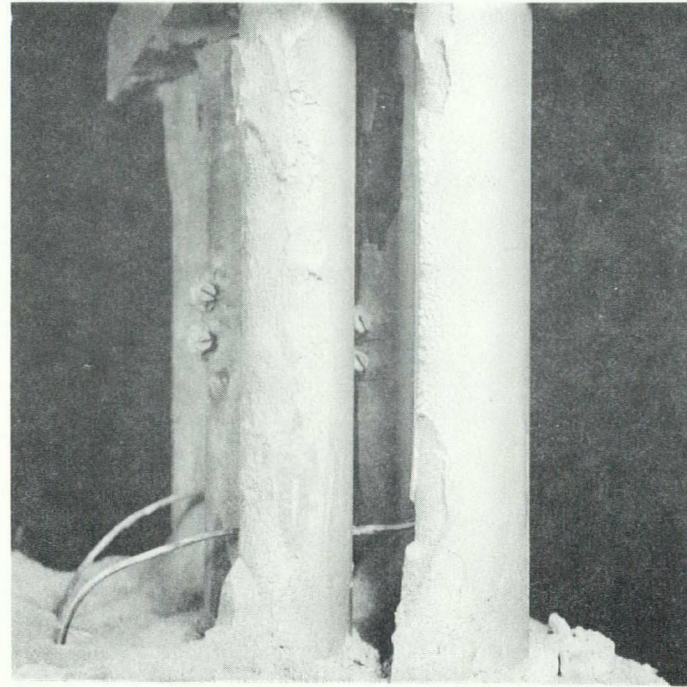


(b) Side View

Figure 7. Simulated superheater showing the thin build-up of powdery deposits from Willow Bunch lignite.



(a) Front View



(b) Side View

Figure 8. Simulated superheater showing the moderate build-up of powdery deposits from Estevan lignite.

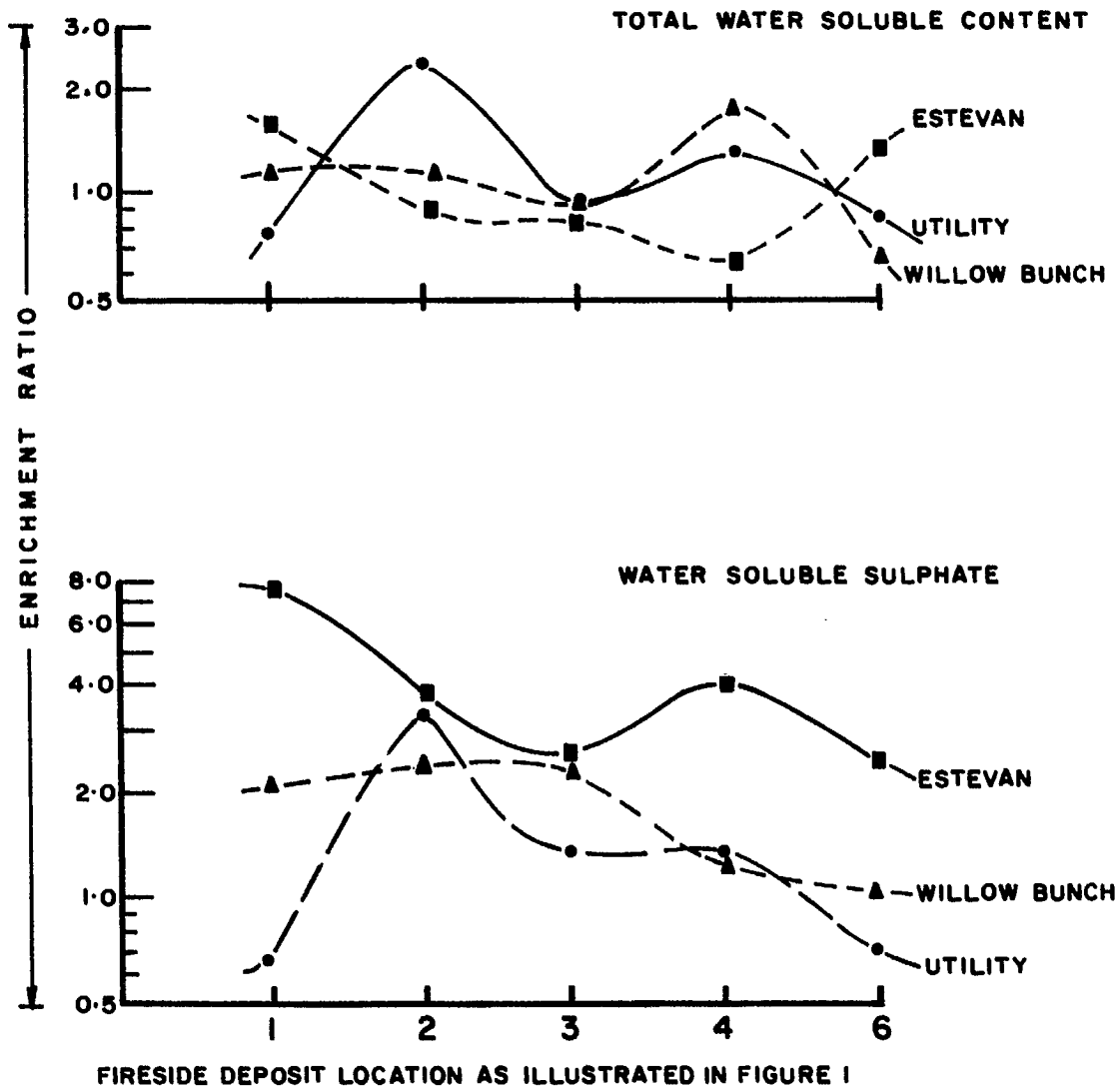


Figure 9. Total water-soluble matter and water-soluble sulphate contents of fireside deposits at various boiler locations.

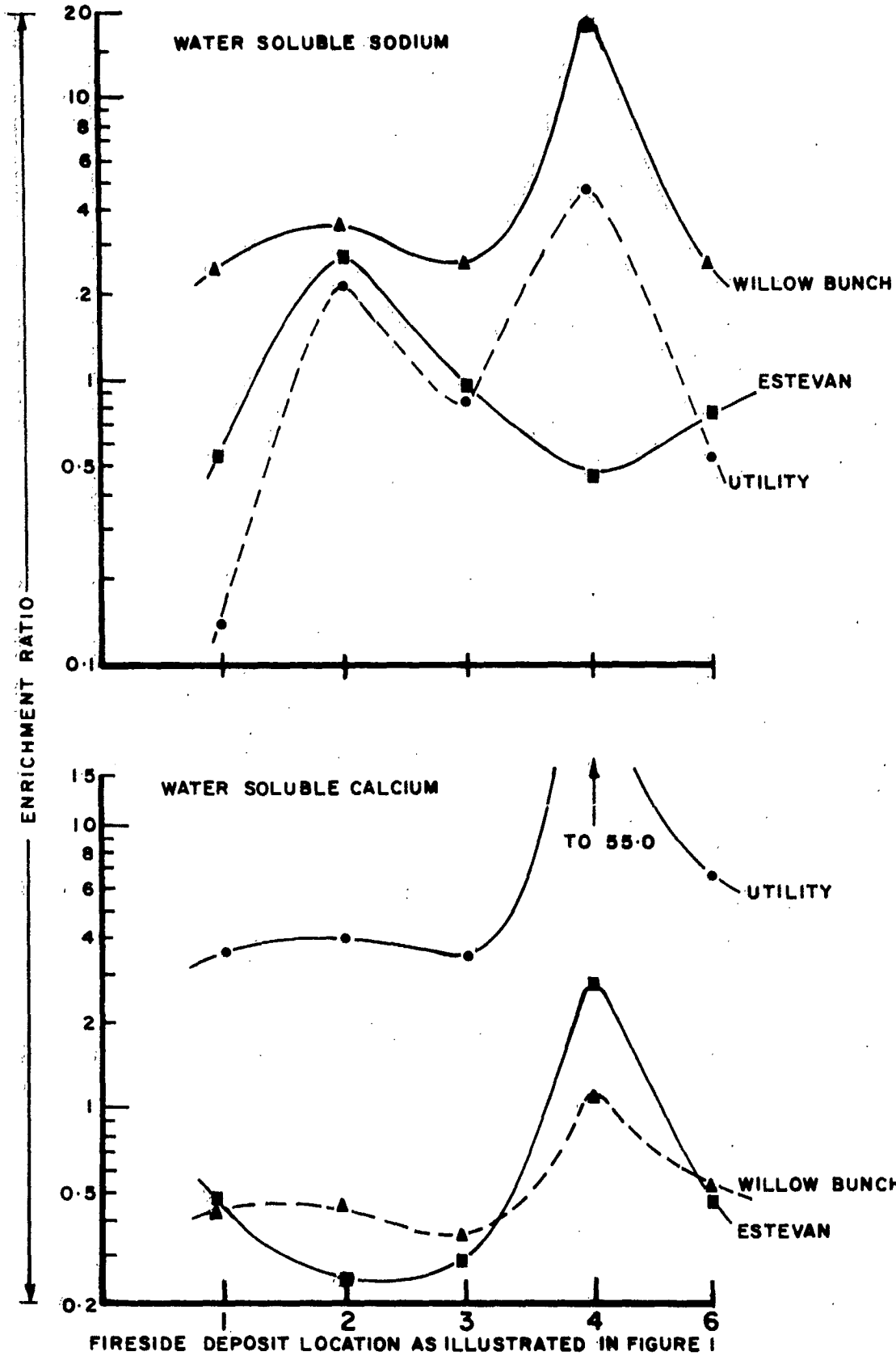


Figure 10. Water-soluble sodium and water-soluble calcium contents of fireside deposits at various boiler locations.

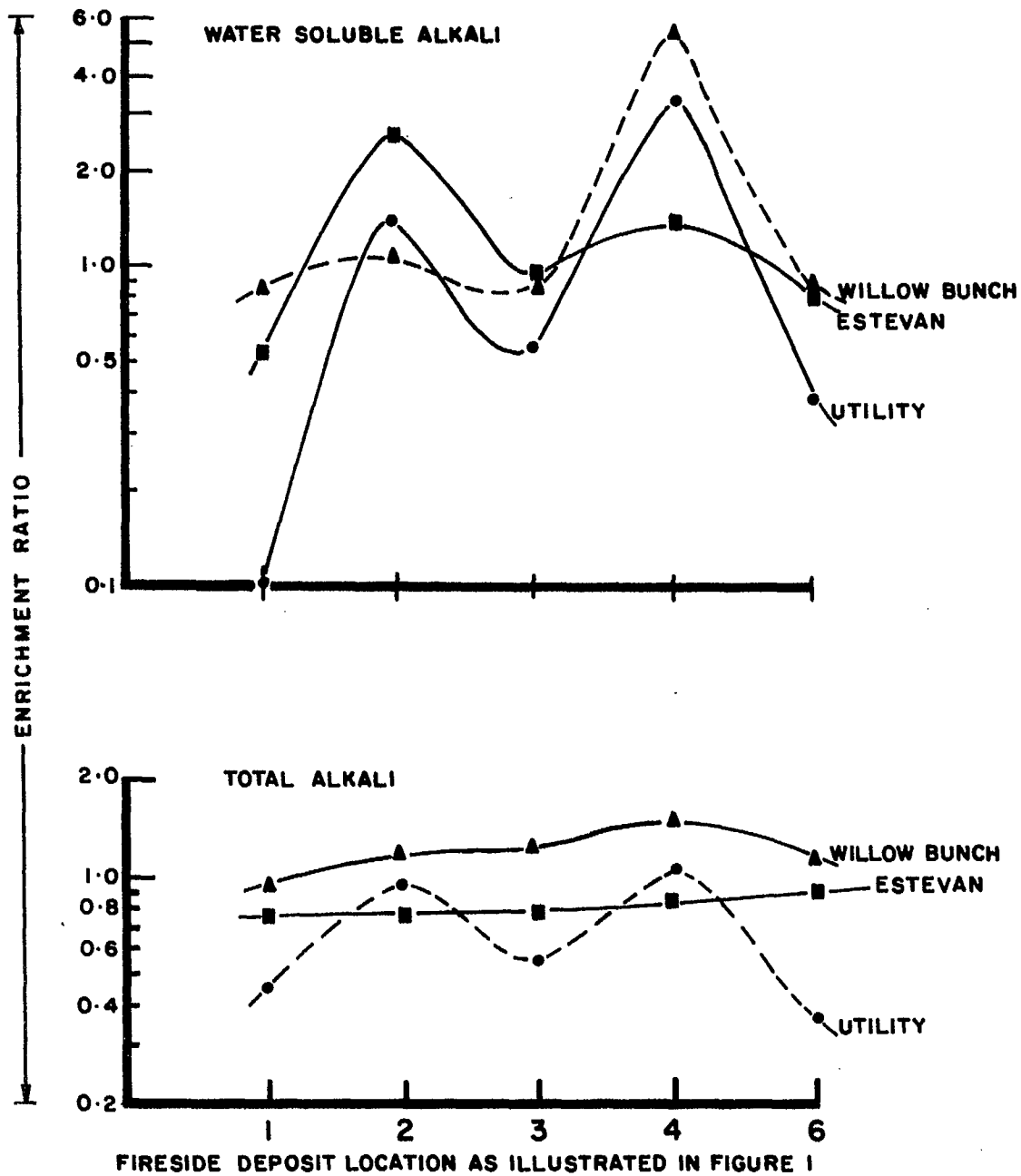


Figure 11. Water-soluble alkali and total alkali contents of fireside deposits at various boiler locations.

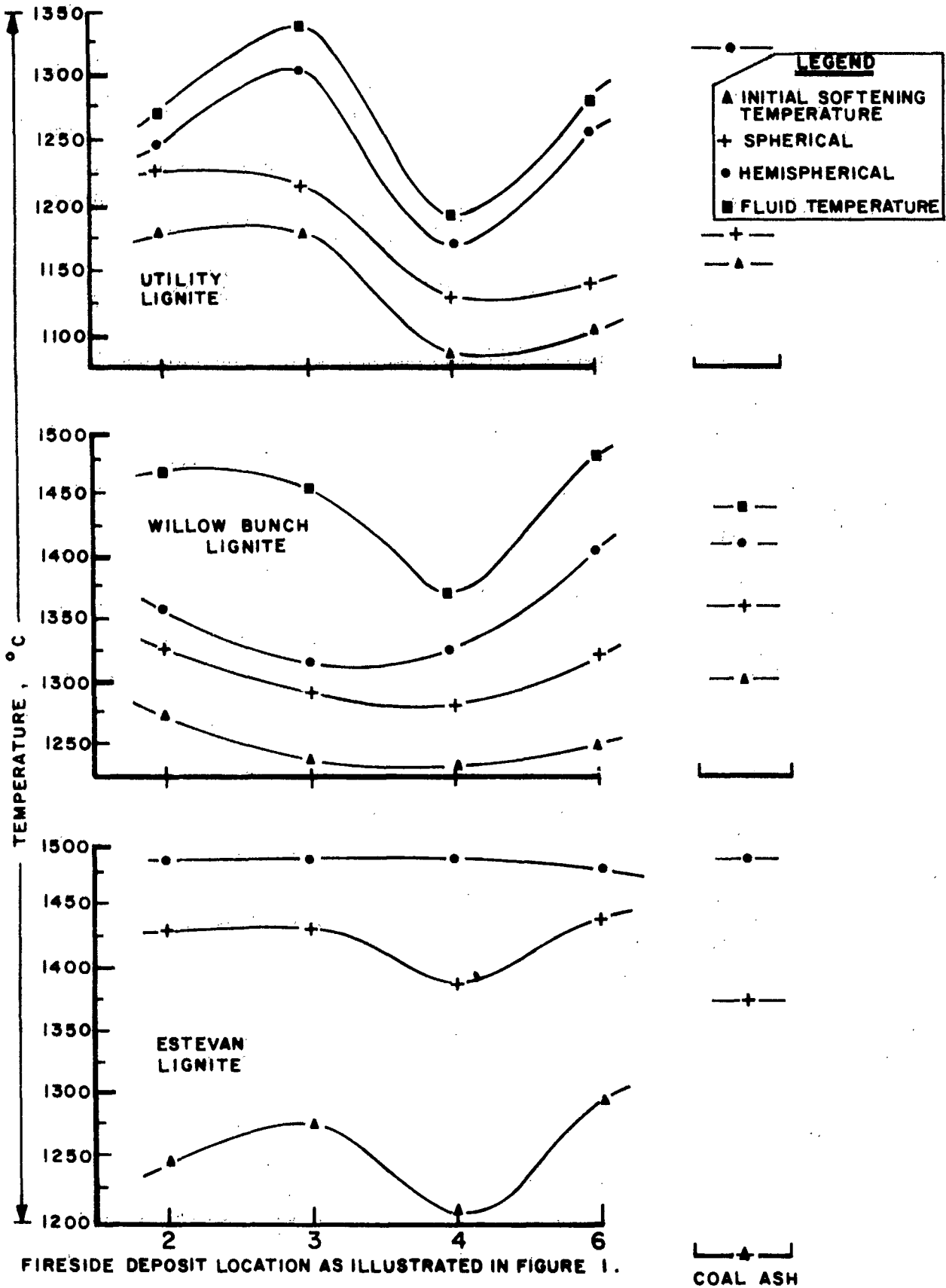


Figure 12. Fusion temperature of ash at various boiler locations.