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PILOT-SCALE COMBUSTION EVALUATION OF JUDY CREEK NORTH COAL

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by

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ABSTRACT

The combustion performance of a small sample of Judy Creek North coal was evaluated in a pilot-scale, pulverized-fired research boiler. The coal, which contained 22% total moisture and was moderately reactive, handled and pulverized easily, ignited readily and produced a bright, stable flame. The coal ash did not slag or sinter on high-temperature boiler surfaces and low-temperature corrosion due to sulphuric acid was not detected on probe surfaces controlled at 104°C, 120°C and 138°C.

The coal produced moderate levels of nitric oxide (about 0.56 lbs/ 10^6 Btu). Sulphur oxide emissions were considerably less than theoretical because about 40% of the input sulphur was retained in the boiler ash and fly ash. The resistivity of the fly ash, being generally between 10^9 and 10^{10} ohm-cm, indicates that the performance of cold electrostatic precipitators will be good.

The combustion, fouling and emission characteristics of Judy Creek North coal were similar in many respects to those of a Sundance reference coal.

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CONTENTS

TABLES

TABLES

FIGURES

1. INTRODUCTION

Under an agreement with the Production Research Division of Imperial Oil Limited, the Canadian Combustion Research Laboratory (CCRL) carried out a combustion performance evaluation to determine the feasibility of using coal from an undeveloped deposit near Whitecourt, Alberta as a boiler fuel. This coal, known as Judy Creek North, is ranked as sub-bituminous C by ASTM classification procedures and has not previously been burned in industrial-sized equipment. Sundance, a commercially-mined coal of slightly higher rank from the Edmonton formation, was also included in the evaluation to provide a reference against which the performance of the Judy Creek North coal could be compared.

The joint project formed part of the CANMET Energy Research Program and included an analytical investigation of the coal and coal ash properties as well as combustion studies in the CCRL pilot-scale, pulverized-fired boiler under conditions representing those in large steam boilers.

This report describes the objectives of the project, the analyses of the coals burned, the facilities used and the operational procedures selected. An evaluation of the experimental results is also given together with the conclusions reached.

2. RESEARCH OBJECTIVES

The objectives of this study were:

(a) to determine the comminution and handling characteristics of the coal;

(b) to evaluate the combustion performance of the pulverized coal at a fineness level of 75% less than 200-mesh and at an excess air level corresponding to 5% O_2 in the flue gases;

(c) to characterize the particulate and gaseous pollutants generated during combustion;

(d) to assess the slagging and fouling potential of ash constituents on radiant heat transfer surfaces and superheater tubes;

(e) to assess the corrosion potential of condensed sulphuric acid on cold-end boiler surfaces;

(f) to determine the fly-ash resistivity characteristics and the ease of fly-ash collection by electrostatic precipitator; and

(g) to compare the above measurements with those obtained from an identical combustion trial with Sundance coal.

3. COAL CHARACTERISTICS

A 500-kg sample of Judy Creek North coal was delivered to CCRL in sealed, plastic-lined drums. The coal with its "as received" moisture content of 22% was found to be free of surface moisture, uniformly blended and free flowing. No problems were experienced in moving or feeding it through the CCRL pilot-scale handling system.

Table 1 shows the proximate and ultimate analyses of both the Judy Creek North and the Sundance coals as fed to the pulverizer after pre-crushing to minus 3.2 mm in a hammer mill. Although both coals are of the same rank, the Judy Creek coal's lower volatile matter content and lower calorific value suggest that it could be more difficult to ignite and burn than the Sundance coal.

However, past experience has shown that a better indicator of coal reactivity is the volatile matter combustion temperature or the adiabatic gas temperature achieved by a stoichiometric mixture of coal and air. In this calculation, the coal is considered to be dry, the combustion air is considered to carry all the moisture in the coal as fed to the pulverizer, and the combustion of volatile matter is considered to be complete prior to combustion of the fixed carbon. The volatile-matter combustion temperatures for the Judy Creek North and Sundance coals, shown in Table 2, lie in the range 800°C - 900°C. Any value above 800°C suggests that the coal will ignite easily and that combustion will be stable; it should also be possible to operate low loads (25% of full load) without oil or gas support.

According to the volatile-matter combustion temperature, Judy Creek North coal would be almost as reactive as Sundance coal which is being burned successfully at Wabamun Generating Station in Alberta.

4. PILOT-SCALE RESEARCH BOILER

The CCRL research boiler, illustrated schematically in Figure 1, is a pulverized-coal-fired boiler incorporating two opposed in-shot burners that tilt downward over a refractory chamber. The furnace is of membrane-wall construction and operates at pressure of up to 2.5 kPa (10 in. WC). At the full-load firing rate of 2500 MJ/h (0.7 MW) the boiler generates 730 kg/h steam at 690 kPa (6.8 atm.). The heat is dissipated in an air cooled condenser. Because of the limited amount of Judy Creek North coal available, it was necessary to reduce the firing rate to approximately 1650 MJ/h to obtain six hours of continuous boiler operation. Operating times of less than six hours do not permit the range of measurements necessary for a meaningful combustion evaluation.

Crushed coal is supplied from a 4500-kg hopper, mounted on an electronic weigh scale, through a variable-speed worm feeder to a ring-and-roller type of pulverizer, which is normally swept and pressurized by air at any temperature up to 230°C. If necessary, the pulverizer can be swept and pressurized with a mixture of air and flue gas at any temperature up to 490°C. The pulverizer contains a motor-driven classifier for controlling coal fineness, and a riffle at the pulverizer outlet proportions the coal to each burner. Secondary air can be supplied to the burner at any temperature up to 260°C.

Combustion gases leave the furnace between 760°C and 860°C and then pass through a transition section, a test-air heater and a conventional three-pass air heater before entering a long horizontal sampling duct. At the end of the sampling duct, either the gas flow can be passed entirely into the stack or, if necessary, a portion of the gas flow to the stack can be diverted isokinetically into a small two-stage electrostatic precipitator. A by-pass from the air heater to the stack breeching and additional heat exchanger surface in the sampling duct permit the gas temperature in the sampling duct to be varied between 150°C and 300°C.

A forced-draft fan supplies air to the air heater at 7 kPa (28 in. WC). The air, on leaving the heater, is divided into three streams: primary air to the pulverizer, secondary air to the burners and cooling air to the test-air heater. The last stream, after leaving the test-air heater, either can be exhausted to the atmosphere or can be blended with the primary-air supply to the pulverizer.

The research boiler is manually controlled, except for electrical interlocks to ensure that safe start-up and shutdown procedures are followed. When burning high-grade coals, it has been possible to operate with as little as 1.0% O_2 and no more than 0.1% CO in the flue gases, with a smoke density of less than No. 1 Ringelmann. When severe fouling of the convective heat-transfer surfaces occurs, firing-rate or excess-air level must be reduced to control furnace pressure.

5. EXPERIMENTAL PROCEDURES

5.1 Operating Procedure

The operating procedure given below was used for both tests, with some minor variations in timing as necessary.

1. Before starting each test, all boiler and air heater fireside surfaces were thoroughly cleaned by air lancing and the feed rate was adjusted to provide six hours of operation.
2. At 0700 h, the cold boiler was fired up on No. 2 fuel oil at 16 gph. Excess air was adjusted to provide 5% O_2 in the flue gas and the boiler was allowed to stabilize at full steaming rate and pressure. All continuous monitoring instruments were put into service.
3. At 0830 h, pulverized coal feed to the boiler was started with the specified classifier speed, mill temperature and excess oxygen in the flue gas. One oil torch was left in operation.
4. At 0845 h, the oil torch was removed, leaving the boiler operating on pulverized coal only.
5. At 0900 h, scheduled testing was begun. Boiler panel readings were recorded hourly. The specified coal feed rate and excess oxygen level were maintained as closely as possible.
6. By 1400 h all measurements were completed. When the coal bunker was empty, the boiler was shut down.
7. The furnace was allowed to cool overnight. Then the furnace bottom was removed and the ash remaining in the furnace bottom and boiler hoppers was collected and weighed.

5.2 Parameters of Combustion Performance

The following parameters of combustion performance were measured in each test at appropriate measuring stations.

1. Proximate, ultimate and ash analyses and ash fusion determinations of samples taken from a bulk sample of crushed coal obtained by hourly grab samples at the pulverizer inlet. Station 1.

2. Moisture and sieve analyses of samples of pulverized coal taken every two hours at the pulverizer outlet. Station 2.

3. CO_2 and CO content of the flue gas, measured continuously by infrared monitors. Station 10.

4. O_2 content of the flue gas, measured continuously by a paramagnetic monitor. Station 10.

5. NO content of the flue gas, measured continuously by a chemiluminescent monitor. Station 13.

6. SO_2 content of the flue gas, measured continuously by a chemifluorescent monitor. Station 14.

7. SO_2 and SO_3 content of the flue gas, measured by the API and the modified Shell-Thornton methods, respectively, two or three times per test. Station 15.

8. Low-temperature corrosion potential, measured by three mild-steel probes inserted simultaneously into the flue-gas stream and maintained at three different temperatures for the duration of the combustion test. Station 13.

9. Fly-ash loading, measured by an isokinetic sampling system, two to four samples per test. These samples were analyzed for carbon content, chemical composition and size distribution. Station 16.

10. Ash fouling of heat-transfer surfaces evaluated by examination of deposits on a simulated superheater, installed immediately downstream of the screen tubes to accommodate studies of fly-ash build-up on high-temperature boiler tube surfaces. A second

method of evaluating ash fouling was by examining the thickness, physical structure, chemical composition and melting characteristics of ash deposits selected from various parts of the furnace and air heater after shutdown. Stations 7, 8, 9, 11, 19 and 20.

11. Electrostatic precipitator efficiency, measured by passing part of the flue gas through a small electrostatic precipitator for 45 min, three samples per test. The efficiency was calculated from the measured inlet and outlet dust loadings. Station 17.

12. Fly-ash resistivity, measured by an in-situ, point-plane resistivity apparatus at flue gas temperatures of 200°C and 400°C, two measurements at each location per test. A series of static isothermal measurements on selected samples of fly ash extracted from the gas stream at the precipitator inlet were also made. Station 18.

In addition, qualitative observations on flame appearance and length were logged. After each trial, areas of ash build-up on the superheater and furnace walls of the cold boiler were photographed.

6. COMBUSTION PERFORMANCE

6.1 Coal Comminution

The "as received" Judy Creek North coal was crushed, metered and pulverized to the selected degree of fineness without difficulty. It was then transported directly to the burner without moisture separation from the carrying air; no blockage or segregation occurred in either of the coal pipes to the boiler. The size distribution of the pulverized coals used in each combustion test is shown in Table 3.

6.2 Flame Characteristics

The boiler operating conditions, shown in Table 4, remained essentially constant throughout each combustion trial and confirmed that the handling characteristics of both coals were excellent. The flames from both coals were bright, clean and extremely stable under the experimental conditions selected and an oil support flame was required for only about five minutes after the start of each trial.

The Judy Creek North coal, as would be expected from the combined effect of its lower volatile matter adiabatic flame temperature and lower calorific input, yielded consistently lower gas temperatures inside the furnace than did the Sundance coal (Figure 2).

6.3 Flue Gas Analyses

The average flue gas analyses for each combustion trial are summarized in Table 4. The carbon monoxide level was generally about 0.01% or less and did not constitute either an emission problem or a significant thermal penalty.

The sulphur dioxide content of the flue gas on a dry basis from both coals was significantly less than theoretical. In the case of Judy Creek North about 60% of the input sulphur was emitted in the flue gas and the remaining 40% was retained in the boiler ash; the latter percentage was confirmed by analysis of deposit samples taken throughout the boiler.

Fixation of SO_2 by alkali and alkaline earth elements in the coal ash is known to depend on both excess-air level and local combustion gas temperatures. Previous work at CCRL with lignitic coals has shown that sulphur retention is enhanced by high excess-air levels which tend to increase furnace exit temperatures, reduce residence times in the furnace, and improve the oxidation of fuel sulphur to sulphur oxides.

Nitric oxide concentrations, as expected, were much lower for Judy Creek North than for Sundance coal. This reflects both the lower fuel nitrogen content and the lower flame temperatures obtained with Judy Creek North coal. During combustion, nitric oxide concentrations are increased by enhanced oxidation of both atmospheric nitrogen due to higher flame temperatures and fuel nitrogen due to burner mixing patterns. It is important to note that although the trend of the nitric oxide levels is valid, the absolute level of nitric oxide emissions is also strongly dependent on burner geometry, burner arrangements, boiler configurations and boiler heat release rates.

6.4 Fly-ash Resistivity

The in-situ fly ash resistivities and particulate concentrations for both coals over a narrow range of flue gas temperatures are given in Table 6. The fly-ash size distributions of both coals are shown in Figure 3.

In general, high electrical resistivity ($>10^{10}$ ohm-cm) indicates that a precipitated fly ash will retain a strong electrical charge and repel any similarly charged particle or generate a back corona within the deposit. Conversely, a low resistivity ($<10^{7}$ ohm-cm) fly ash will readily precipitate but will not adhere strongly to the collecting plates and will easily be re-entrained in the flue gas. Intermediate resistivity values of approximately 10^{8} ohm-cm to 10^{9} ohm-cm are considered to yield the best precipitator efficiencies. Since the resistivity values of the fly ash from both Judy Creek North and Sundance coals fell within the optimum range of 10^{8} ohm-cm to 10^{9} ohm-cm, electrostatic precipitators should perform well with either fuel.

A series of bulk resistivity measurements were made in an electric furnace to determine the temperature at which the fly ash from each coal would reach a maximum resistivity value. These data, plotted in Figure 4 and 5, show maximum resistivity values of 3×10^{10} ohm-cm at 165°C and 5×10^{11} ohm-cm at 125°C for Sundance and Judy Creek North coals respectively. Although bulk resistivity values are typically an order of magnitude higher than in-situ measurements because of procedural differences, the two curves are usually parallel. It follows that flue gas temperatures corresponding to the peak resistivity values should be avoided during boiler operation to ensure good precipitator performance.

6.5 Precipitator Performance and Coal Burn-out

With each coal, the efficiency of fly ash collection in the small electrostatic precipitator was about 97% (Table 5). This indicates that the precipitator performance was unaffected by the high inlet dust loadings from Judy Creek North coal which were three times as great as those from Sundance coal. It should be remembered,however, that dust emissions to atmosphere from Judy Creek North were three times those for Sundance coal and that a precipitator designed for collecting fly ash from Judy Creek North coal would have to be larger than one for Sundance coal, if the same dust concentrations to atmosphere are to be achieved.

The fly ash from Judy Creek North and Sundance coal contained 0.6% and 1.7% combustible respectively, corresponding in each case to a thermal penalty of less than 1% of the input fuel. These were slightly higher than utility operating standards but are typical of the performance of good boiler fuels in the pilot-scale boiler.

In large furnaces, carbon burn-out is superior because flame quenching is slow and overall residence times are commonly around 1.5 s, whereas on the pilot-scale system, burn-out tends to be inhibited by a high surface to volume ratio, rapid flame quenching and maximum residence times of about 0.35 s.

7. HIGH TEMPERATURE ASH DEPOSITS

Two types of high-temperature ash deposition can occur on the surfaces of coal-fired boilers exposed to combustion gases:

1. Slagging - fused deposits that form on surfaces exposed predominantly to radiant heat transfer;
2. Fouling - high temperature bonded deposits that form on surfaces exposed predominantly to convective heat transfer Particularly troublesome areas are superheaters and reheaters.

An assessment of the slagging and fouling potential of the Judy Creek North and Sundance coals used in these pilot-scale experiments has been done using accepted empirical indices based on the ash analysis of the raw coal, the analysis of the fireside deposits and the visual assessment of the deposits produced within the boiler (1).

7.1 Ash Fusion Characteristics

The deposits produced in the furnace bottom and on the refractory quarls surrounding the burners were bulky and granular (Figure 6). The fusion temperatures of the deposits and the ash of the two parent coals are in Table 7.

Ash fusion characteristics determined according to procedures described in ASTM D1857 define four temperatures at which physical changes in a standard specimen become apparent. The test can be carried out in either a reducing or an oxidizing atmosphere, but normal reference is to the reducing atmosphere which usually generates lower temperatures and is therefore a more restrictive condition.

For Judy Creek North coal the results show that initial deformation for both the ash and the furnace bottom ash occurs in the range 1300°C to 1320°C irrespective of the nature of the atmosphere. The fusion temperatures of the furnace bottom and wall deposits were about the same as those recorded from the parent coal ash, indicting that preferential volatilization of fluxing components (e.g. Na_2O, K_2O) during combustion was minimal. The fusion temperatures recorded are normally associated with a low slagging potential. The low slagging tendency experienced with Sundance coal, which has an initial deformation temperature of 1249°C and a fluid temperature of 1480°C, indicates that furnace slagging with Judy Creek North coal should not be a problem since the ash is considerably more refractory in nature than that of Sundance coal.

7. Slagging Indicators

The assessment of slagging potential in pulverized or crushed coal-fired boilers has been attempted by several workers who have produced indices or composite parameters to describe the nature and severity of the slag deposits (1). These indices are frequently described as "specific" in the sense that they reflect the type of combustion equipment used in a particular unit.

Many ash slagging indices are described as being applicable only to coals with "eastern type" ash or to coals with "western type" ash. "Western type" ash is defined as having more CaO + MgO than Fe_2O_3 when all are measured as a weight per cent of the coal ash.

The results presented in Table 8 show clearly that both the Judy Creek North and Sundance coals have a [CaO + MgO]:[Fe_2O] ratio between 2.0 and 3.0. The coals can therefore be classified as "western" or lignitic-type coals. This criterion is dependent on ash analysis and does not have any rank or geographic connotation. The importance of this will become apparent in the following discussion of three common indices for determining slagging potential.

7.2.1 The Base:Acid Ratio

The Base:Acid Ratio is defined as $\frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$

where each oxide is expressed as a percentage of the total ash.

A maximum value of 0.5 for the Base:Acid ratio has sometimes been specified for dry bottom-pulverized-fired units although this is not a necessary restriction.

Values below 0.27 indicate that the coal is not generally suitable for use in wet-bottom units since slag viscosity will not be low enough. The low values shown in Table 8 for both the coal ash and the furnace bottom deposit lie in the range 0.13 to 0.14 for Judy Creek North coal and 0.23 to 0.28 for Sundance coal. Wet-bottom operation is therefore precluded and the upper limit for dry-bottom firing is not exceeded for either coal.

7.2.2 Ash Viscosity and Slagging

Further evaluation of the potential of the bottom ash to slag can be made by calculating the viscosity/temperature relationship for both the coal and the bottom ash deposits using the method outlined below:

$$T_{250}\ (°C) = \left(\frac{10^7 M}{2.3979 - C}\right)^{\frac{1}{2}} + 150,$$

where T_{250} is the temperature in °C at which the viscosity of a potential bottom ash slage is 250 poise with 20% of the iron in ferrous form,

$$M = 0.00835(SiO_2) + 0.00601(Al_2O_3) - 0.109,$$

and

$$C = 0.0415(SiO_2) + 0.0192\ (Al_2O_3) + 0.0276\ (Fe_2O_3) + 0.016\ (CaO) - 3.92,$$

where $SiO_2 + Al_2O_3 + Fe_2O_3 + MgO + CaO = 100$

For wet-bottom furnaces the preferred slag viscosity for easy tapping is below 100 poise and the T_{250} temperature should not normally exceed 1425°C.

For dry-bottom furnaces the T_{250} temperature can be one factor used to rate the coal ash in relation to furnace slagging.

One suggested rating system is shown below:

Slagging Category	T_{250} °C
Low	>1275
Medium	1400 - 1150
High	1250 - 1120
Severe	<1205

It should be noted that there is considerable overlap between the categories.

The results, illustrated in Figure 7, show that reactions during combustion and after deposition have modified the coal ash and produced a slag of higher viscosity. The critical viscosity temperature (T_{cv}) shown in Figure 7 is the temperature at which molten slag will run freely from the furnace walls. It can be calculated from the ash analysis by the following relationship:

$$T(C_v)°C = 2990 - 1470\left(\frac{SiO_2}{Al_2O_3}\right) + 360\left(\frac{SiO_2}{Al_2O_3}\right)^2 - 14.7\,(Fe_2O_3 + CaO + MgO) + 0.15\,(Fe_2O_3 + CaO + MgO)^2$$

T_{cv} is also the temperature limit above which the viscosity/temperature relationship can be confidently calculated from the ash analysis. With Judy Creek North coal the extrapolation of the results to below 1500°C is unreliable, but the indicated values of T_{250} confirm the low ash slagging potential obtained from the other slagging indices.

7.3 Fouling Indicators

A most convincing indicator of the low fouling tendency of the coals was the visible inspection of the deposits on the simulated superheater which was controlled at a surface temperature of 550°C. The deposits from Judy Creek North coal were light and powdery whereas those from Sundance coal showed some evidence of weak sintering. Photographs of the in-situ deposits

(Figure 8) shows the difference in deposit build-up. The Judy Creek North and the Sundance coals were therefore tentatively classified as having low and moderately low fouling tendencies respectively. The following calculation of fouling indicators was made to confirm this conclusion.

7.3.1 Sodium Content of the Coal Ash

There has been general agreement between research and operating practice that the dominant factor correlating with superheater fouling is the sodium content of the coal ash.

The following classification has been proposed:

Fouling Category	% Na_2O in Ash	
	"Eastern" coals	"Western" coals
Low	<0.5	<2.0
Medium	0.5 - 1	2.0 - 6.0
High	1.0 - 2.5	6.0 - 8.0
Severe	>2.5	>8.0

As shown previously in Table 1 the parent coal ash from the Judy Creek North had about 1.0% Na_2O, thus classifying the coal as having a low fouling potential. Sundance coal ash with 2.7% Na_2O is classified as having medium fouling potential. Moreover, the furnace bottom ash for Judy Creek North and Sundance coals contained 0.9% and 1.9% Na_2O respectively, indicating little change during the combustion process.

8. LOW TEMPERATURE CORROSION

Low temperature corrosion problems are due to the condensation of gas-phase sulphur trioxide on metal surfaces below the acid dewpoint. The condensed acid (H_2SO_4) can then react with air heater and/or economizer tubes to produce an $FeSO_4$ corrosion product.

Table 9 gives the analysis of the deposits collected on cylindrical corrosion probes which were controlled at temperatures of 104°C, 120°C and 138°C during exposure to flue gas at 270°C. Because no free acid accumulated on any of the probes during either trial the potential for low-temperature corrosion would appear to be very low or non-existent.

9. CONCLUSIONS

9.1 The Judy Creek North coal handled and flowed readily at 22% moisture and produced easily ignitable and stable flames throughout the trial period.

9.2 Based on the sulphur content of the Judy Creek North coal on a dry basis, it is important to note that about 40% of the input sulphur was neutralized by alkali metal ions in the coal ash during combustion.

9.3 Nitrogen oxide emissions, which were moderately low, reflected the low calorific value and low fuel nitrogen content of the Judy Creek North coal.

9.4 The burn-out of this coal with 5% oxygen in the flue gas was excellent. Combustible matter in the fly ash was only 0.6% and represented a thermal loss of less than 1% of the heat input.

9.5 The electrical resistivity of the Judy Creek North fly ash, being between 10^9 ohm-cm and 10^{10} ohm-cm at 200°C, indicates that precipitability will be good.

9.6 The tendency for the ash from Judy Creek North coal to slag boiler surfaces or to cause fouling of superheater surfaces is very low. This coal should perform well in a dry-bottom furnace using normal soot blowing procedures to remove high-temperature fireside deposits.

9.7 The coal has virtually no low-temperature corrosion potential. The test results indicated that metal heat transfer surfaces can be operated at temperatures as low as 121°C without risking sulphuric acid attack.

9.8 Judy Creek North coal, having similar combustion, fouling and emission characteristics to the Sundance reference coal, should burn readily and efficiently in pulverized-coal-fired boilers of conventional design. Fly-ash loadings will be considerably higher with Judy Creek North and for Sundance coal, but dust emissions can be held within acceptable limits with available precipitator design.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

1. E. C. Winegartner, "Procedures and Definitions of Fouling and Slagging Parameters for Coal-fired Boilers"; ASME Research Committee on Corrosion and Deposits from Combustion Gases and published by the American Society of Mechanical Engineers (ASME) New York, November 1972.

TABLE 1

Judy Creek North and Sundance Coal Analyses

As-Fired Coal Analyses	Judy Creek North	Sundance
Proximate Analysis, wt %		
Moisture	16.24	13.61
Ash	24.98	13.84
Volatile Matter	32.88	43.43
Fixed Carbon	25.90	29.12
Ultimate Analysis, wt % (dry basis)		
Carbon	49.06	63.67
Hydrogen	1.71	2.54
Sulphur	0.35	0.24
Nitrogen	0.54	0.78
Ash	29.73	16.04
Oxygen	18.29	16.94
Calorific Value		
cal/g	3778	5020
Btu/lb	6800	9036
Ash Analysis, wt %		
SiO_2	60.15	54.97
Al_2O_3	21.57	20.08
Fe_2O_3	2.54	4.77
TiO_2	0.77	0.68
P_2O_5	0.18	0.43
CaO	7.04	11.93
MgO	0.56	1.31
SO_3	2.96	3.08
Na_2O	0.98	2.66
K_2O	0.31	0.35
ASTM Classification	Sub-bituminous C	Sub-bituminous B

TABLE 2

Volatile Matter

Adiabatic Flame Temperature*

Coal		V. M. Flame Temperature
Judy Creek North	@ 16% Moisture	841°C
Sundance	@ 13.6% Moisture	868°C

*The temperature achieved by combustion of the volatile matter in an adiabatic stoichiometric flame.

TABLE 3

Particle Size Distribution

of Pulverized Coal

Screen Size	Judy Creek North			Sundance	
% in Range	Sample No.			Sample No.	
	1	2	3	4	5
>100-mesh	0.4	0.5	0.4	0.5	0.6
100 - 140	4.9	6.2	12.1	5.2	8.8
140 - 200	17.1	15.7	12.1	15.4	11.6
200 - 325	26.6	28.8	34.5	27.1	27.4
325 - 400	7.1	7.7	2.8	3.0	3.4
<400-mesh	44.0	41.1	38.0	48.8	48.1
% below 200-mesh	77.7	77.6	75.3	78.9	79.0

TABLE 4

Boiler Operating Conditions

Fuel	Coal Firing Rate kg/h	Thermal Input to Boiler MJ/h	Steam Flow kg/h	CO_2 %	O_2 %	CO %	NO ppm	SO_2* Theoretical ppm	SO_2* Measured ppm
Judy Creek North	94.1 ±3.3	1486	460 ±4.8	15.0 ±0.1	5.1 ±0.1	< 0.01	483 ±54	443	275
Sundance	87.3 ±11.2	1832	498 ±3.4	14.7 ±1.1	5.1 ±0.1	< 0.01	643 ±22	223	113

±values are standard deviations

*on a dry basis

TABLE 5

FLY-ASH RESISTIVITY "IN-SITU" MEASUREMENTS

Coal	Temperature °C	Resistivity ohm-cm
Judy Creek North	180	1.4×10^{10}
	200	6.5×10^{9}
	230	9.6×10^{9}
	260	2.4×10^{9}
Sundance	250	9.9×10^{7}
	310	4.1×10^{7}
	310	7.7×10^{7}

TABLE 6

Fly-ash Precipitation in a
Pilot-Scale Electrostatic Precipitator

Coal	Fly-ash Loading in Gas Streams		Precipitator Efficiency %
	Before Precipitator	After Precipitator	
Judy Creek North	8258 mg/nm^3	212 mg/nm^3	97.4
	7806 mg/nm^3	275 mg/nm^3	96.5
	7598 mg/nm^3	151 mg/nm^3	98.0
Mean Values	7887 mg/nm^3	212 mg/nm^3	97.3
Sundance	2822 mg/nm^3	83 mg/nm^3	97.1
	2931 mg/nm^3	52 mg/nm^3	98.2
	2717 mg/nm^3	69 mg/nm^3	97.5
Mean Values	2823 mg/nm^3	68 mg/nm^3	97.6

TABLE 7

ASH FUSION CHARACTERISTICS OF

THE EXPERIMENTAL COALS

Oxidizing Atmosphere	Judy Creek North		Sundance	
	Coal Ash	Furnace Bottom Ash	Coal Ash	Furnace Bottom Ash
Temperature, °C				
Initial	1320	1320	1230	1280
Spherical	1370	1380	1300	1330
Hemispherical	1461	1480	1340	1400
Fluid Temp	1480	>1480	1480	1480
Reducing Atmosphere				
Temperature, °C				
Initial	1320	1300	1200	1249
Spherical	1366	1370	1250	1310
Hemispherical	1480	1480	1310	1400
Fluid	>1480	>1480	1340	1480

TABLE 8

ASH SLAGGING INDICES

Coal	$\frac{CaO + MgO}{Fe_2O_3}$ (1)	$\frac{Base}{Acid}$ (2)
Judy Creek North		
Coal Ash	3.0	0.14
Furnace Ash	2.5	0.13
Sundance		
Coal Ash	2.8	0.28
Furnace Ash	2.5	0.23

(1) $\frac{CaO + Mg}{Fe_2O_3} < 1 < \frac{CaO + MgO}{Fe_2O_3}$ Eastern Type Ash < 1 < Western Type Ash

(2) $\frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} = \frac{Base}{Acid}$ B/A < .5 Dry Bottom Firing

TABLE 9

ANALYSES OF WATER SOLUBLE MATERIAL
IN LOW TEMPERATURE DEPOSITS

Coal	Water Soluble Deposit Components mg	Corrosion Probe Temperature		
		104°C	120°C	138°C
Judy Creek North	Fe	1.15	1.24	0.09
	Mg	0.03	0.01	0.01
	Ca	6.35	5.45	6.35
	Na	0.17	0.10	0.11
	K	0.01	0.01	0.01
	Free H_2SO_4	-	-	-
Sundance	Fe	0.98	0.58	0.30
	Mg	0.03	0.04	0.03
	Ca	7.05	6.55	7.25
	Na	0.30	0.29	0.27
	K	0.01	0.01	0.00
	Free H_2SO_4	-	-	-

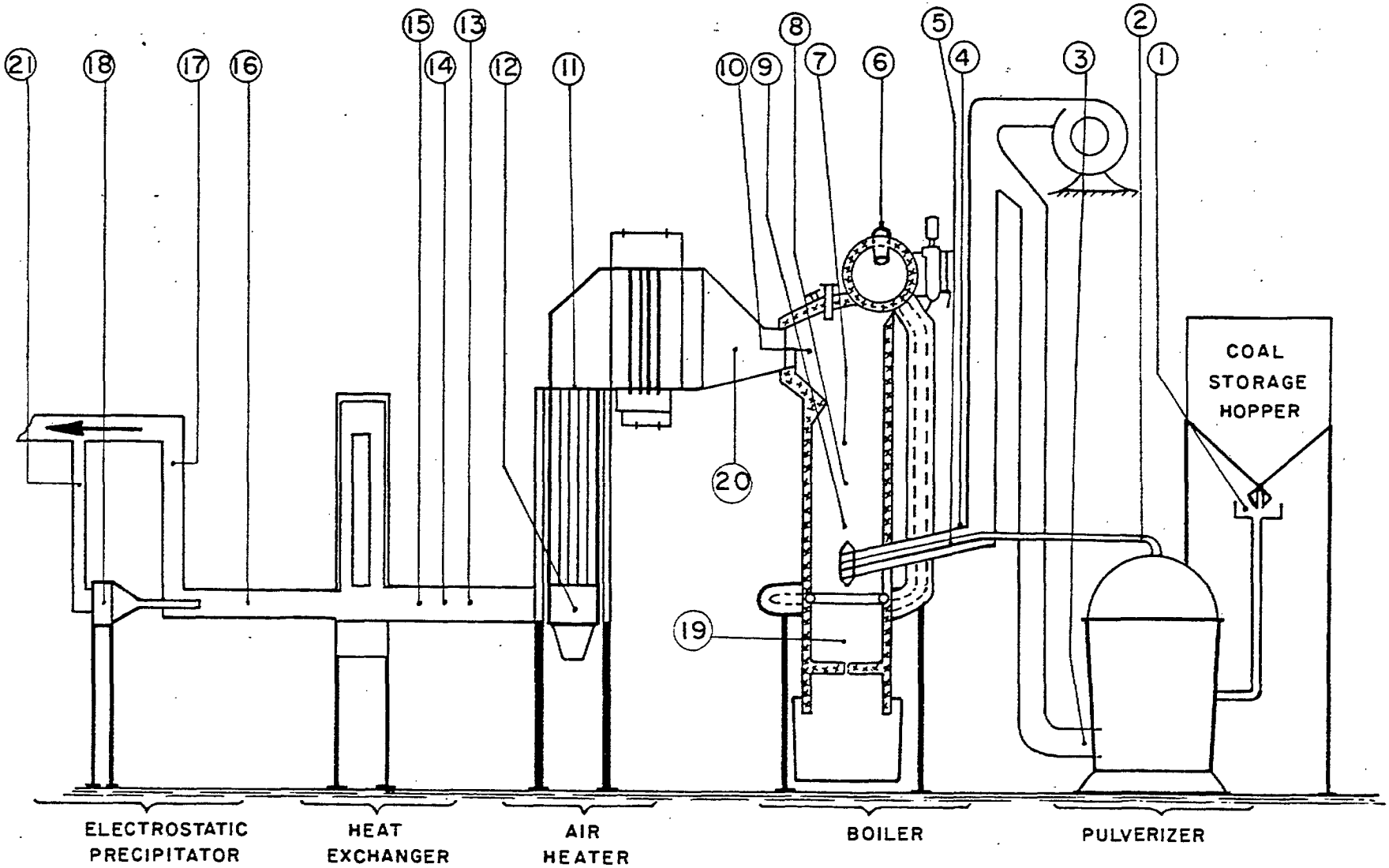


FIGURE 1. Schematic illustration of the pilot-scale research boiler showing the sampling locations.

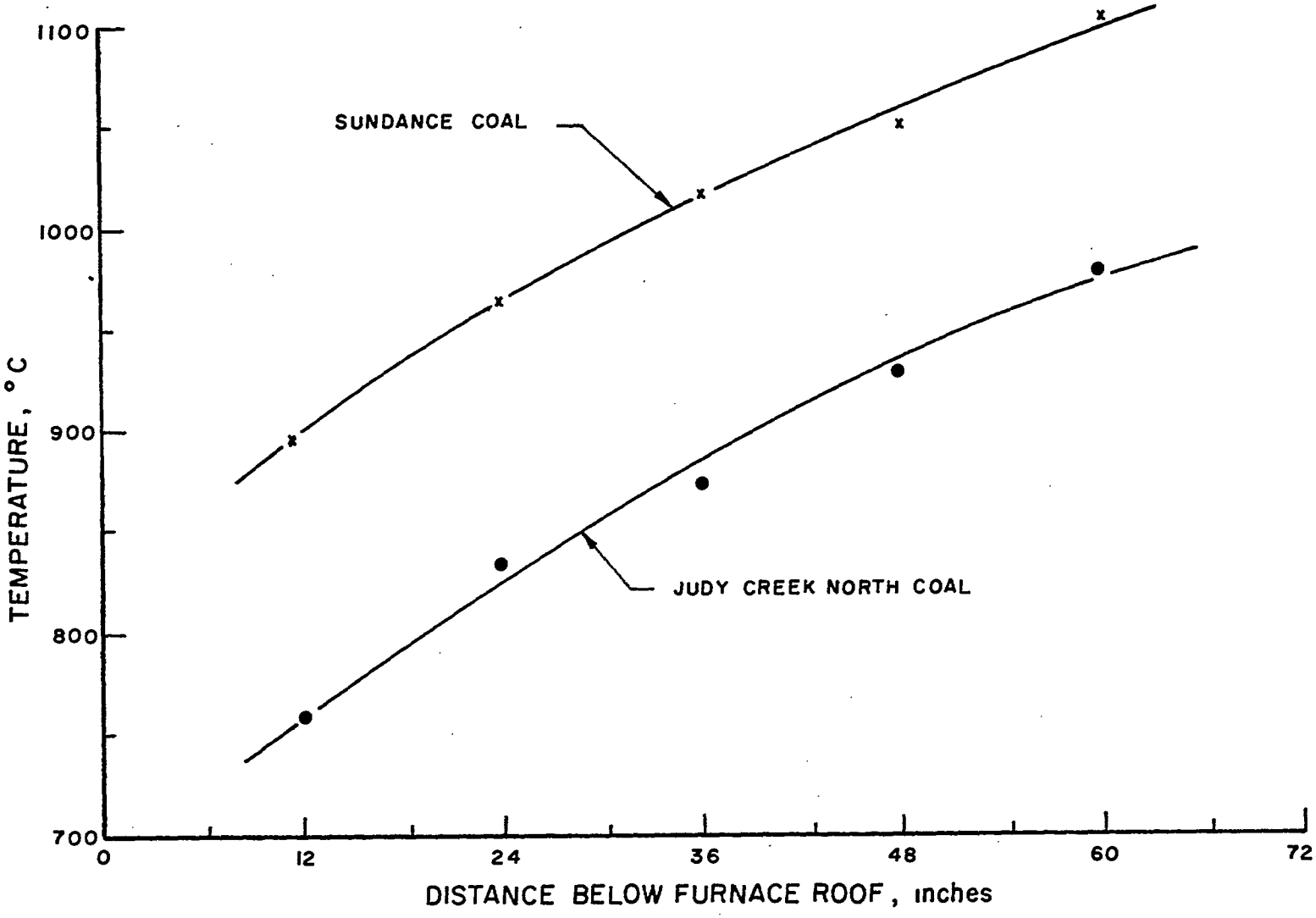


FIGURE 2. Temperatures measured in the pilot-scale research boiler during the combustion trials.

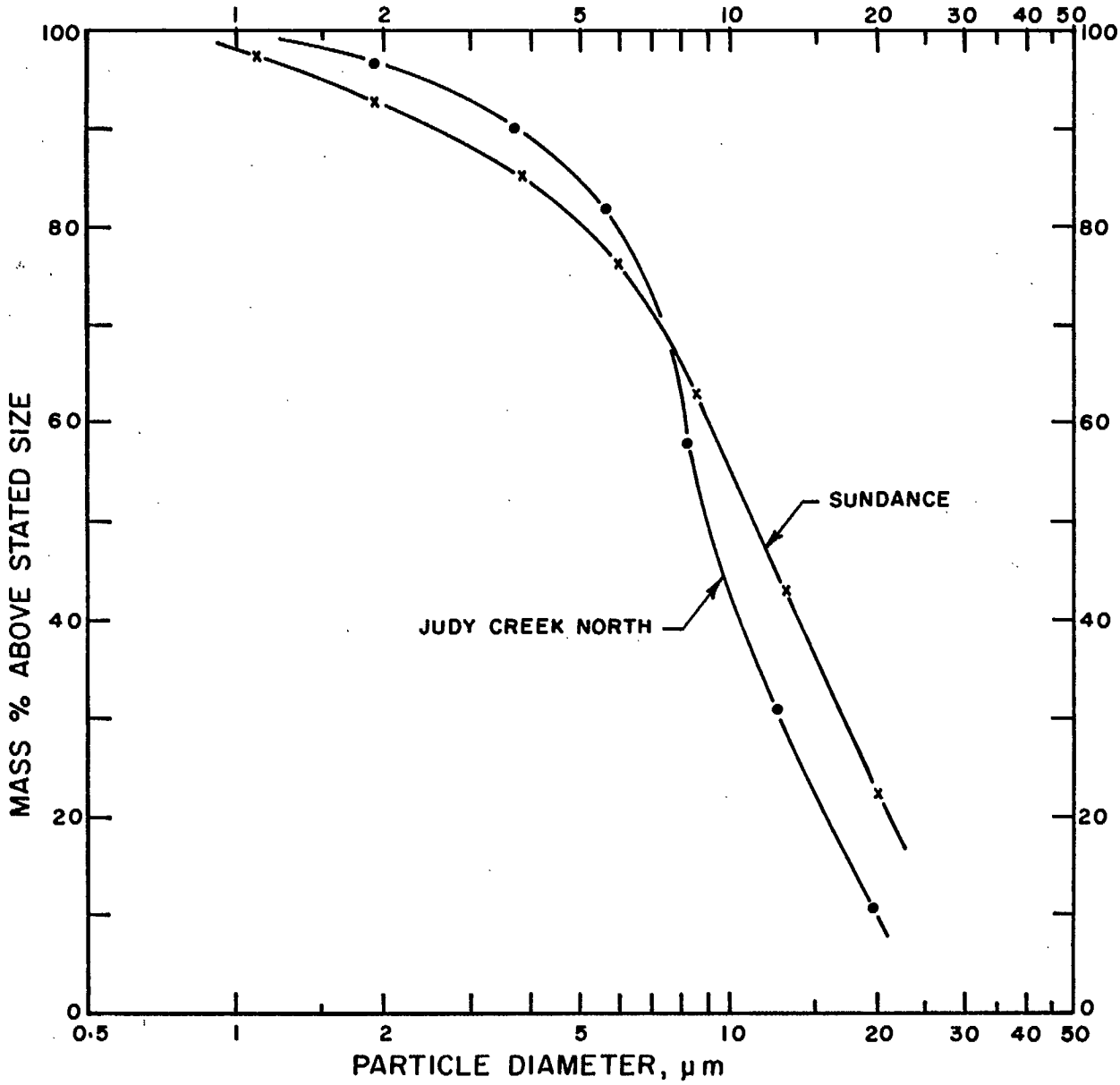


FIGURE 3. Size distribution of the fly ash obtained during the combustion trials.

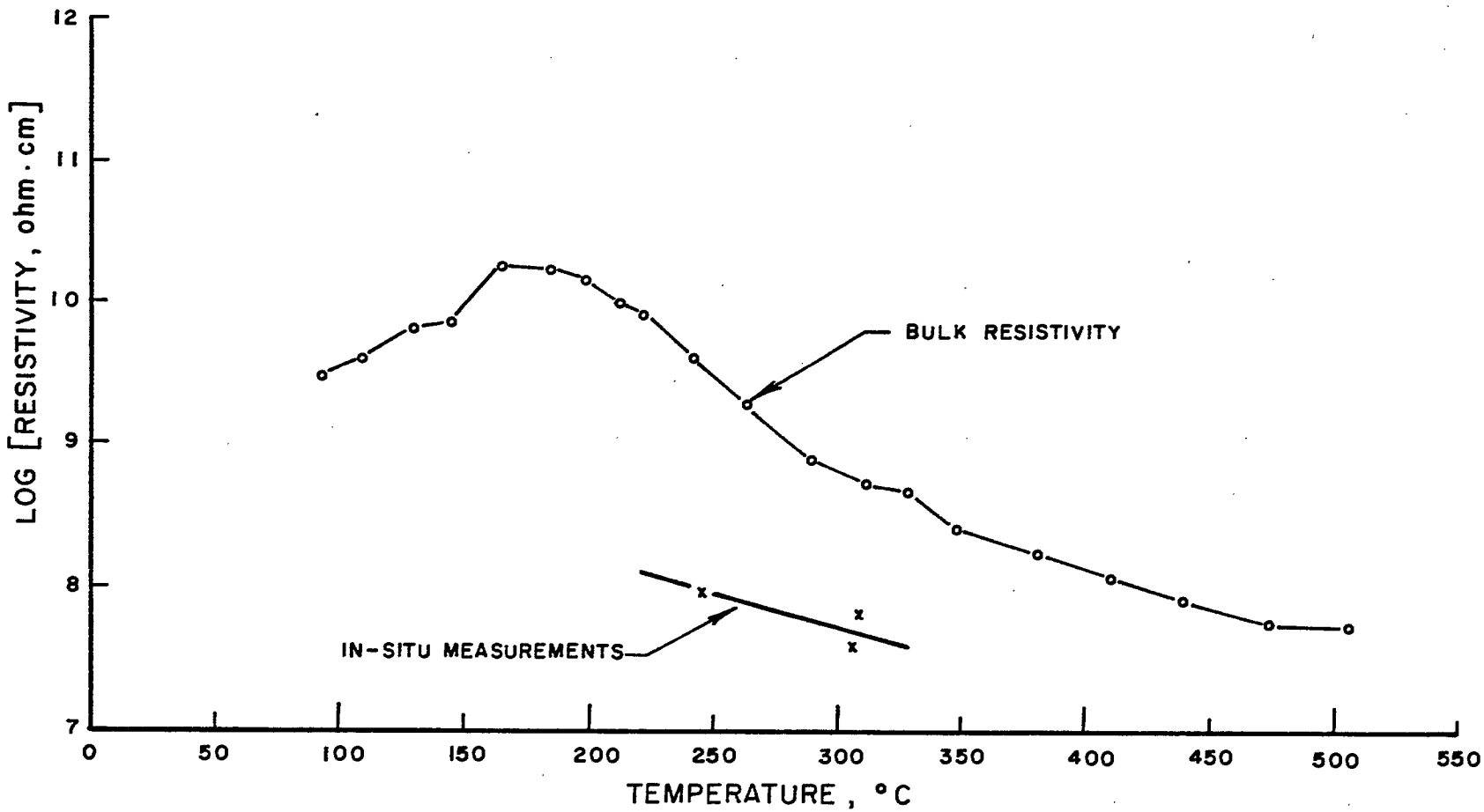


FIGURE 4. Bulk and in-situ resistivity measurements with a point-plane; Sundance coal.

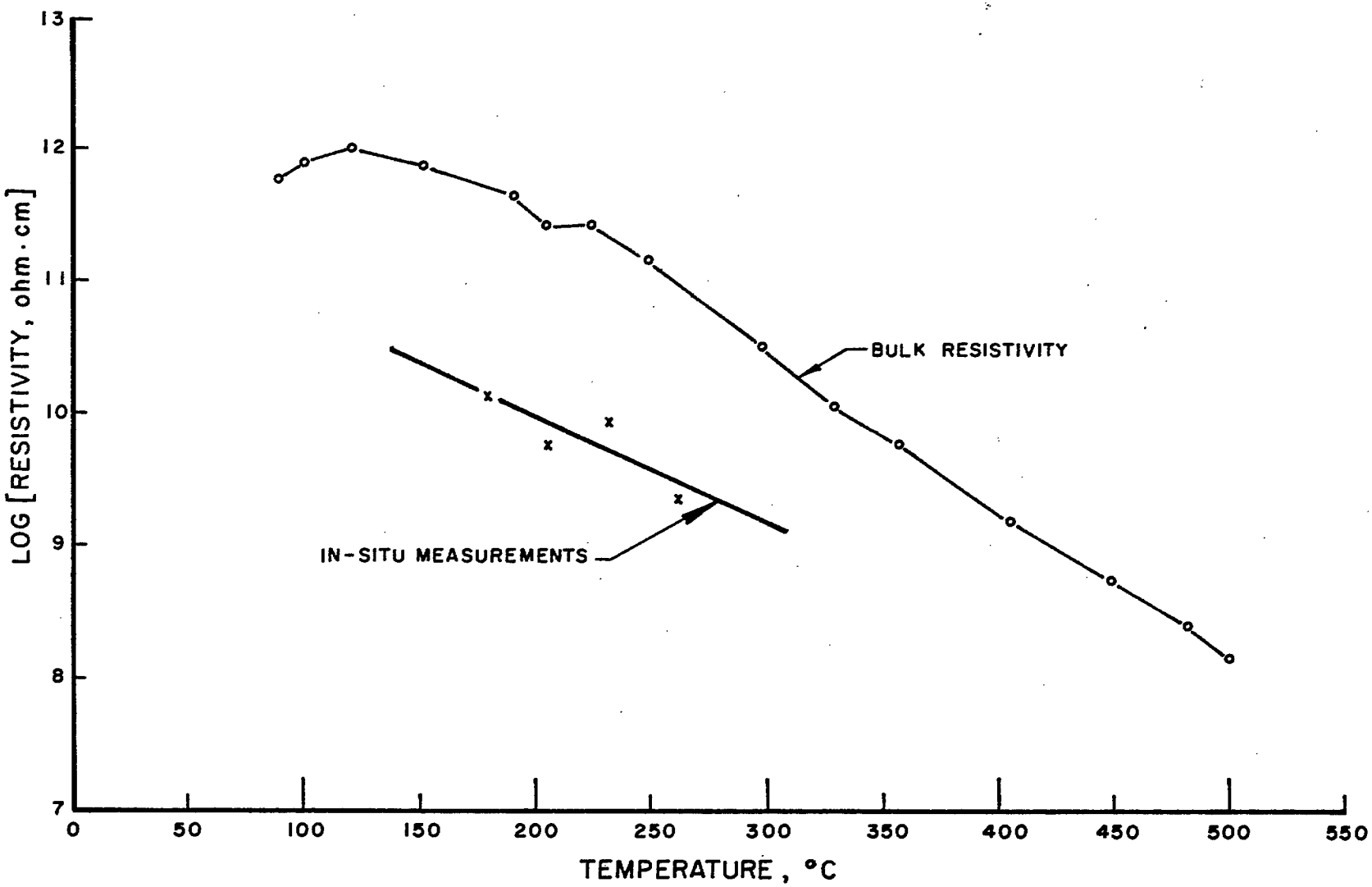
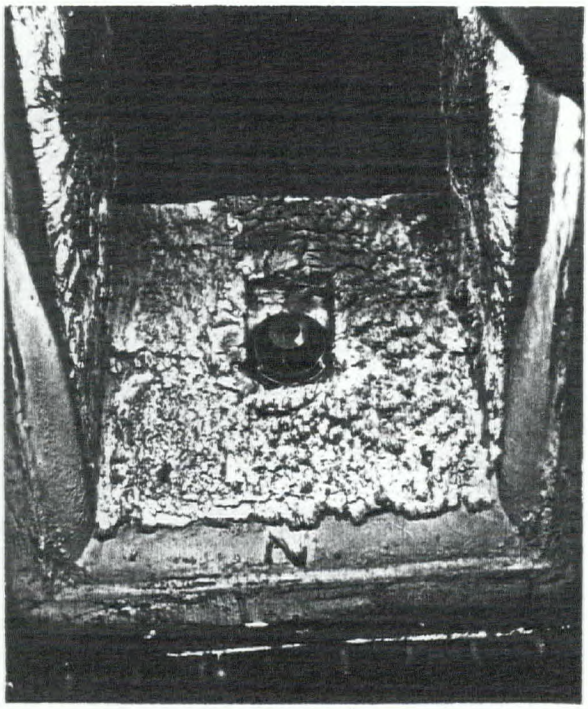
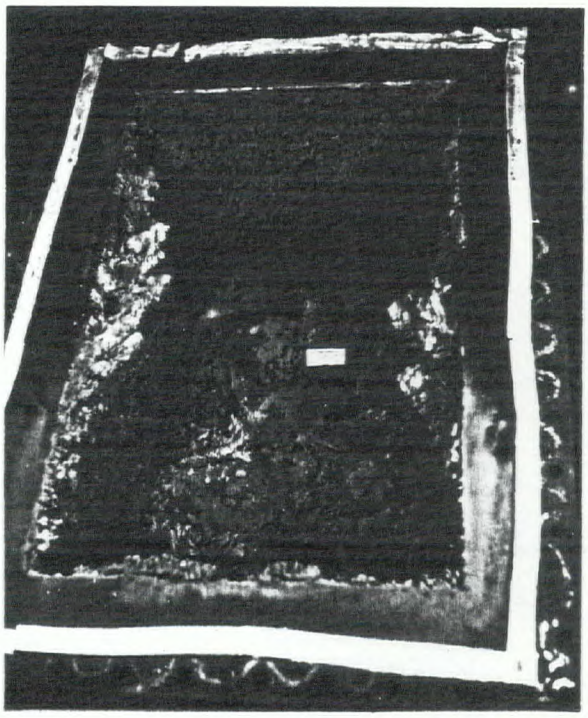


FIGURE 5. Bulk resistivity and in-situ resistivity measurements with a point-plane probe; Judy Creek North coal.

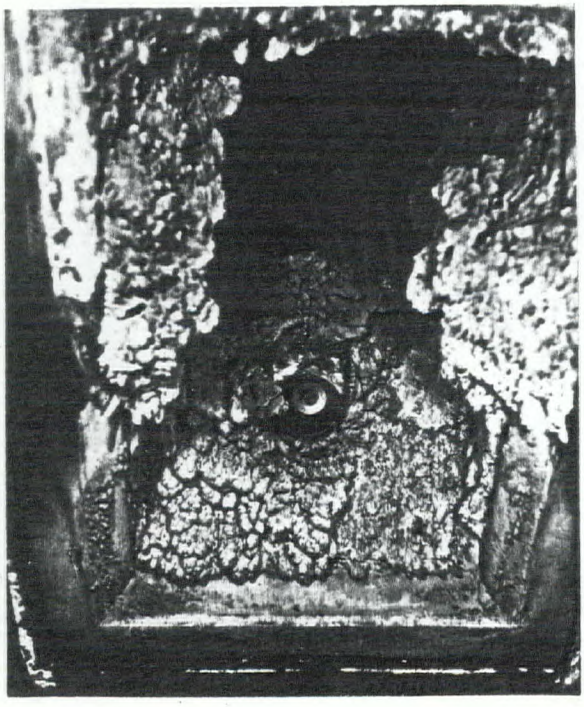


Burner Wall

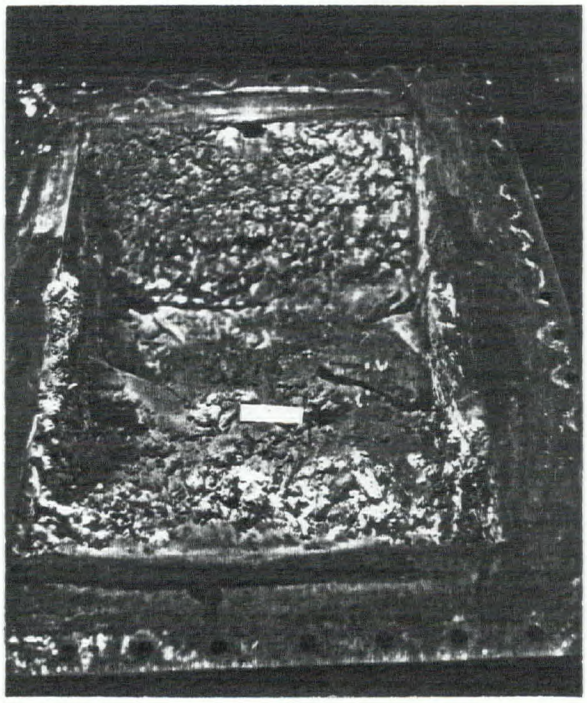


Furnace Bottom

Sundance



Burner Wall



Furnace Bottom

Judy Creek

FIGURE 6. Photographs of boiler deposits after combustion trials.

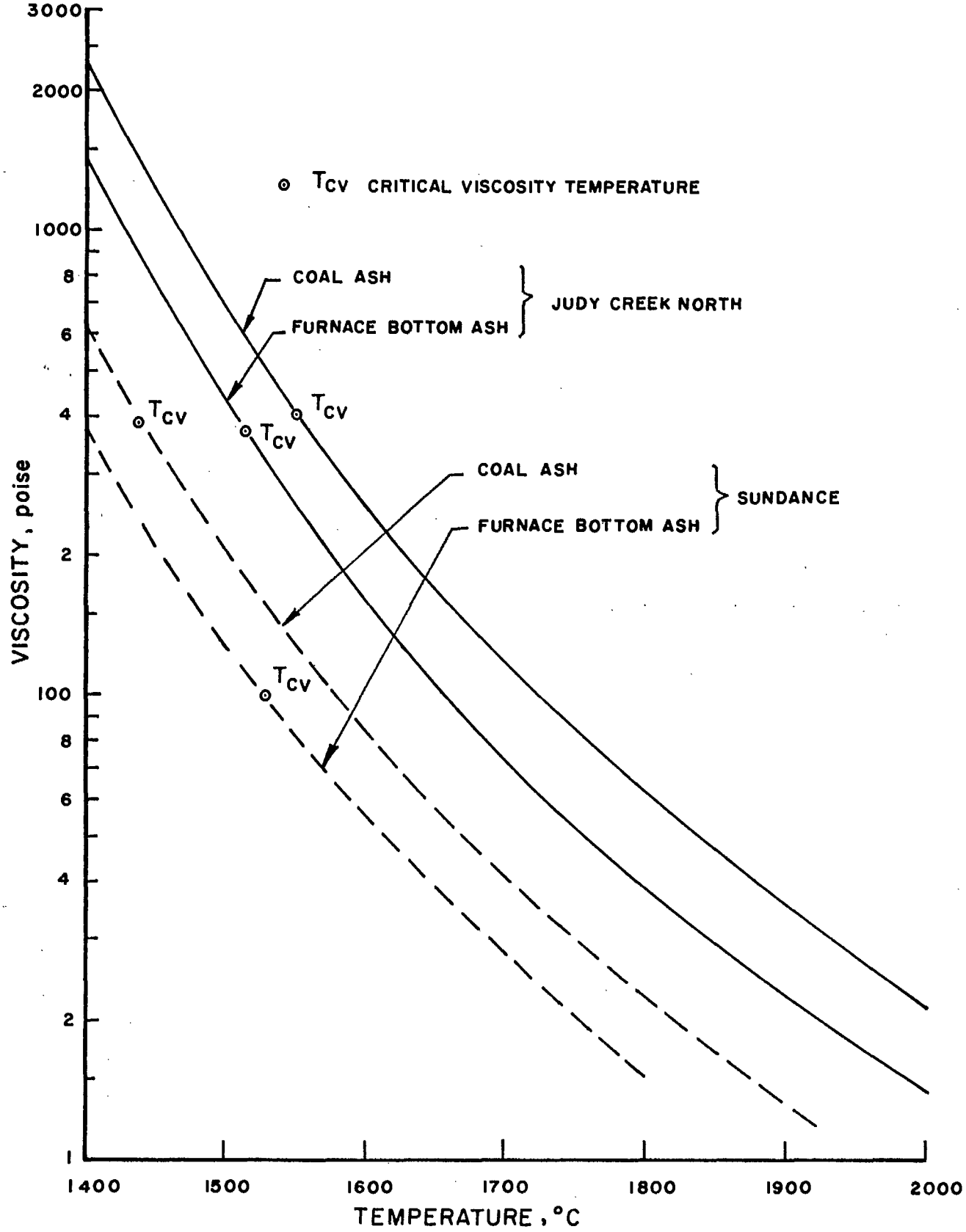
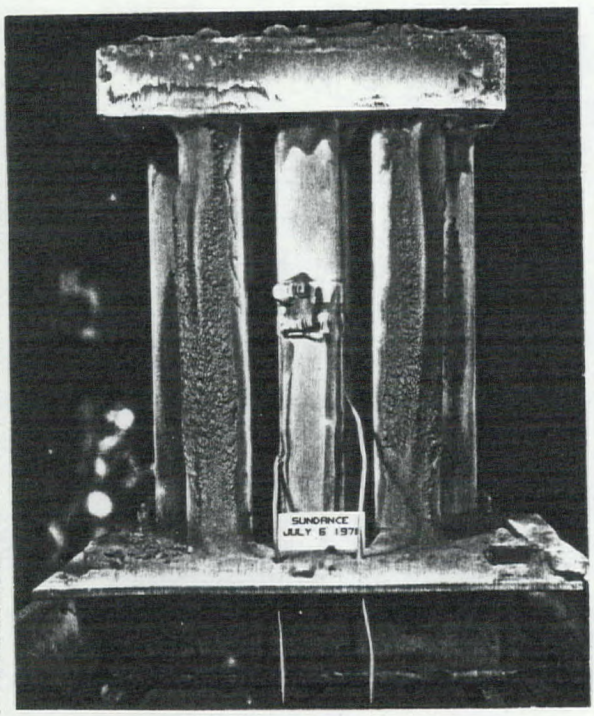
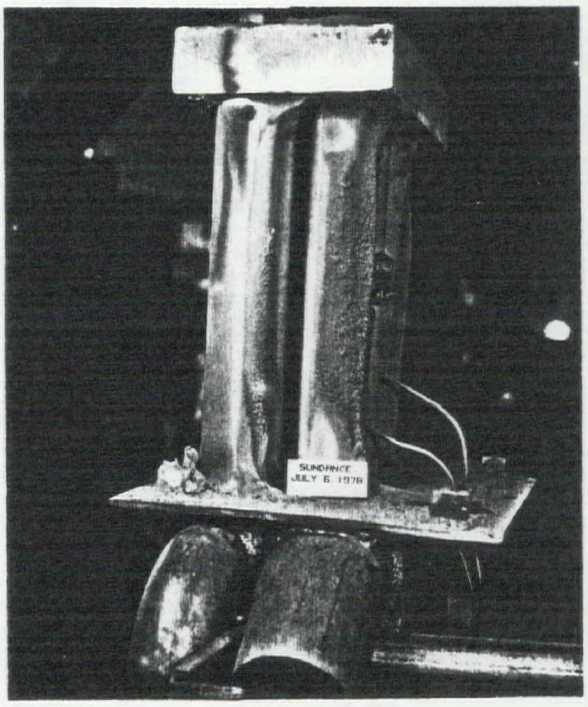


FIGURE 7. Relationship between slag viscosity and temperature; calculation based on ash analyses.

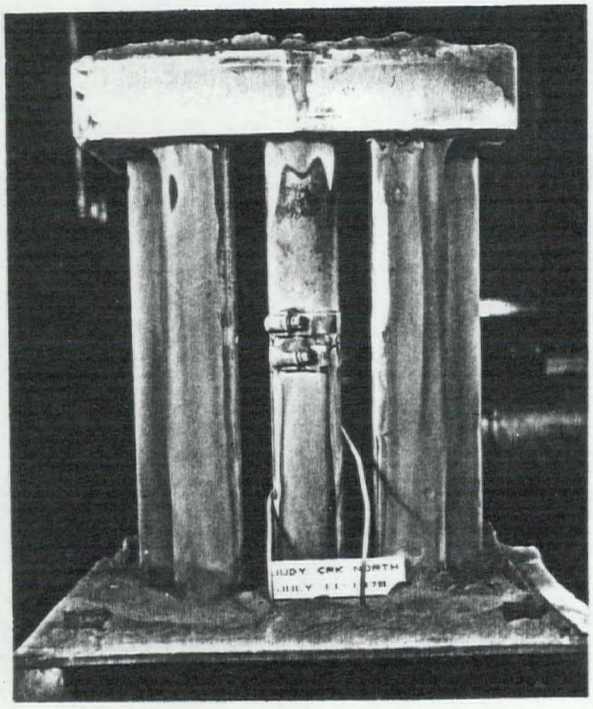


Front View

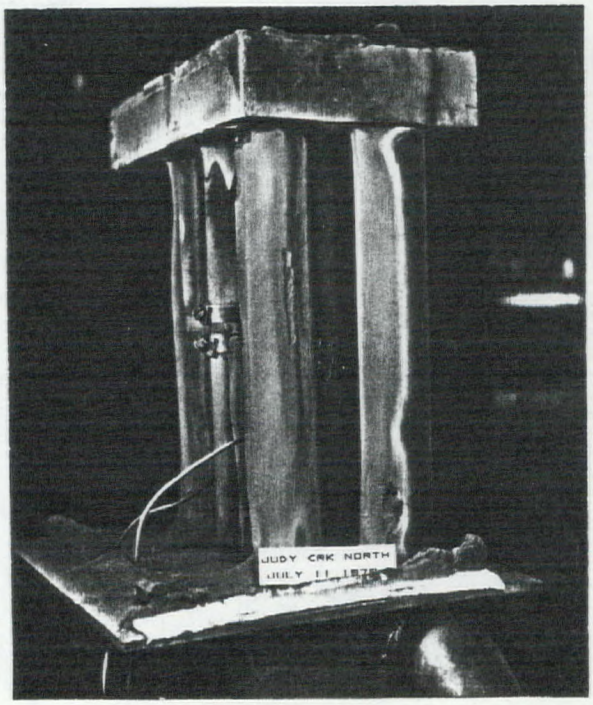


Side View

Sundance



Front View



Side View

Judy Creek

FIGURE 8. Photographs of simulated superheater tubes showing deposits after the combustion trials.