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for Mineral   de la technologie
and Energy   des minéraux
Technology   et de l'énergie

PILOT-SCALE COMBUSTION STUDIES WITH HAT CREEK COAL

B.C. HYDRO-CANMET JOINT RESEARCH PROJECT

F.D. Friedrich, T.J. Cyr, G.K. Lee and T.D. Brown
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SUMMARY

This two-volume report describes a series of pilot-scale combustion tests carried out with Hat Creek coal under a research project sponsored jointly by B.C. Hydro and CANMET. Volume 1 discusses the tests and the results in terms of the project objectives which were:

    a)   to evaluate the feasibility of burning various qualities of Hat Creek coal by means of conventional pulverized-fired technology,

    b)   to determine the effects on combustion performance of reducing the coals' ash content by washing, and

    c)   to establish, insofar as possible, design parameters for a utility-scale steam generator to burn Hat Creek coal.

Volume 2 is an appendix containing all of the progress reports issued during the project.

It is concluded that Hat Creek coals having a higher heating value of 6000 Btu/lb or more on an equilibrium moisture basis can be successfully burned using conventional pulverized-fired technology. However, in the design of steam generators for this coal, it is imperative that reliable facilities be provided for removing the vast quantities of ash that will be produced.

All three samples of raw Hat Creek coal burned in the project produced stable flames without support fuel. However, an obstacle to their successful utilization is a combination of high clay content and high moisture content which makes handling difficult. This problem can be minimized by drying the coal to less than equilibrium moisture. The lower the heating value of the coal, the more it must be dried. Coal having a higher heating value of 6000 Btu/lb on an equilibrium moisture basis can be adequately handled if the moisture content is about 20%, but coal having a higher heating value of 4000 Btu/lb, again on an equilibrium moisture basis, will likely have to be dried to approximately 10% residual moisture before it can be reliably handled.

The three samples of washed Hat Creek coals burned in the project generally produced hotter, more stable flames than the raw coals. The removal of much of the extraneous clay by washing facilitated handling and drying noticeably. Reactivity was also improved. In a full-scale coal handling

system washed coals subjected to normal drainage of surface moisture would likely flow freely without further drying.

The fly ash produced by Hat Creek coal, either raw or washed, has a high electrical resistivity. However, it can be collected efficiently in either a hot or a cold precipitator designed to accommodate the physico-chemical properties of the fly ash. Washing the coal produced no major differences in either the mineral composition or the physical structure of the ash residues.

Neither high- nor low-temperature corrosion of heat transfer surfaces should be a problem when burning Hat Creek coal.

Resource conservation makes it desirable to utilize as much of the Hat Creek coal deposit as possible. By beneficiating all coal with a heating value between 3500 and 6000 Btu/lb on an equilibrium moisture basis, up to 80% of the currently recoverable deposit could be burned. This upgraded coal could be fired separately, or it could be dried and blended with dried raw coal of higher quality; that is, raw coal having a higher heating value greater than 6000 Btu/lb on an equilibrium moisture basis. The blending of high-grade and low-grade raw coals to obtain an average higher heating value of 6000 Btu/lb should not be undertaken without further study. Bands or lenses of extraneous clay in the low-grade coal may create handling problems after blending. Alternatively, it may prove more economical to wash all of the raw coal, blend it to produce a fuel containing approximately 6000 Btu/lb on an equilibrium moisture basis, and burn it without thermal drying.

Compared to raw coal, washed coal would appear to provide a number of benefits. These include a smaller materials handling system at the power plant, smaller steam generators with smaller auxiliaries and smaller dust collectors, and lower pollutant emissions. In addition, there would be substantial reductions in the erosion of heat transfer surfaces and in the volume of ash deposits to be removed from the furnace bottom. The overall result would be reduced cost and increased availability of steam generator plant.

Although Hat Creek coal of reasonable quality can probably be burned in steam generators as large as 750 MWe, the absence of direct experience with high-clay coals in equipment of this size makes it prudent to limit the first unit at Hat Creek to a size somewhere between 300 and 500 MWe. Should

scheduling permit, such a first unit could be built and proven before further expansion is undertaken; units installed subsequently, could be scaled up with a high degree of confidence.

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1. INTRODUCTION

Under an agreement dated August 3, 1976, with the British Columbia Hydro and Power Authority (subsequently referred to as BC Hydro) the Canadian Combustion Research Laboratory (CCRL) carried out a series of combustion tests using coal from the Hat Creek area of British Columbia. This coal is ranked as sub-bituminous C by ASTM classification procedures, and in addition to the high moisture content typical of low-rank coals it has a high and variable ash content. Prior to 1947 Hat Creek coal was mined at the rate of 2000 to 3000 tons per year, but it was never burned in industrial-size equipment. Thus, there were no combustion performance data pertinent to the design of modern utility boilers, and the purpose of the CCRL tests was to assist in determining the technical feasibility of using Hat Creek coal for thermal power generation.

The research program covered by the agreement specified that combustion tests be carried out with seven different coals, six of which were from the Hat Creek deposit. The seventh coal was tested to provide a reference against which the performance of the Hat Creek coal could be compared. A well-known Alberta sub-bituminous coal from the Edmonton formation, known as Sundance, was chosen as the reference coal. BC Hydro provided five-to-ten-ton samples of each coal. The properties of the samples are described in a later section.

The present report summarizes seventy-five research and progress reports that have already been submitted to BC Hydro. It describes the objectives of the program, the test coals, the CCRL facilities used, and the experimental procedures employed. Also, the test results are reported and evaluated, conclusions are presented, and recommendations are made for the design of full-scale boilers, insofar as appropriate, considering that the drill-core samples provided by BC Hydro cannot be guaranteed to be representative of the Hat Creek deposit.

2. OBJECTIVES OF THE RESEARCH PROJECT

Combustion research on a pilot-scale offers several advantages such as low cost, rapid generation of results, convenient modification of conditions, and flexibility of approach. Quantitatively reliable results can be obtained with respect to a number of parameters including formation of pollutants, potential for low temperature corrosion, and fly ash characteristics relating

to electrostatic precipitation. With respect to other parameters, pilot-scale results must be viewed as qualitative only, because of distortions in residence time, heat release rates and surface-volume ratios imposed by the scale of operation. Examples are flame temperature profiles, fireside fouling by coal ash, and carbon carryover. Consequently pilot-scale tests cannot be used directly to generate data needed for furnace design, such as minimum dimensions, flame length and heat absorption patterns. Nonetheless, reliable trends can be established by obtaining data from pilot-scale burns of a coal for which the above data are known, and comparing the results to data from pilot-scale test burns of the test coals. This approach was used in the present trials, and within the limitations imposed by the CCRL pilot-scale research boiler, it enabled the following objectives to be set:

1. To establish whether the various qualities of raw Hat Creek coal could be successfully burned using conventional pulverized-firing technology without supplementary fuel.

2. To establish whether combustion performance was likely to be improved through upgrading the coal by water washing;

3. To determine, insofar as possible, major design features required in a utility-type steam generator burning Hat Creek coal.

To achieve the foregoing objectives, a series of eighteen combustion test were done to investigate the independent and dependent parameters listed below. The selection of the parameters and the techniques used to measure them are described in Section 5.

Independent Parameters

1. Seven coal samples; three grades of Hat Creek raw coal, the same three coals, but washed, and a reference coal.

2. Each coal at two or more levels of moisture content.

3. Each coal at two excess air levels, corresponding to 3% and 5% oxygen in the flue gas.

Dependent Parameters

1. Coal comminution and handling characteristics of each level of moisture content.

2. Generation of particulate and gaseous pollutants during combustion;

3. Corrosion potential of condensed sulphuric acid on "cold end" boiler surfaces;

4. Fouling potential of ash constituents, both in liquid and solid state, on refractory and heat-transfer surfaces at various temperatures;

5. Collection efficiency of the fly ash by electrostatic precipitation;

6. In-situ electrical resistivity of the fly ash;

7. Flame temperature profiles in the furnace.

3. COAL PROPERTIES

3.1 Description of Coal Samples and Handling Properties

The coal samples, five to ten tons each, were delivered to CCRL in plastic bags, sealed in 45 gal drums. These drums were labelled as follows:

Hat Creek	"A"	raw
Hat Creek	"B"	raw
Hat Creek	"C"	raw
Hat Creek	"A"	washed, S.G. 1.65
Hat Creek	"B"	washed, S.G. 1.65
Hat Creek	"C"	washed, S.G. 1.55
Sundance		

The washed coals were beneficiated by heavy media separation in water and were shipped without being dewatered. Consequently, when the drums were opened, they were found to contain several gallons of free water. It is significant that these washed coals, which poured and drained freely, had much

better handling properties than the raw Hat Creek coals. The latter coals, which were wet with surface moisture, were very cohesive and could not be poured. In general, the raw "A" and "B" Hat Creek coals came out of the barrels as a single cylindrical lump with a very steep angle of repose; very little free water drained from these coals.

Although the Sundance coal, which was received with 17% moisture, could be handled and fired by the CCRL equipment, the Hat Creek coal had to be dried before it would pass through the chutes and hoppers with acceptable reliability. Drying was accomplished in two ways; either air-drying, by spreading a thin layer of coal on a paved surface exposed to the sun, or kiln-drying, using a small, oil-fired rotary kiln. Both methods were used on some samples, and other samples were passed through the kiln twice to reduce moisture to the desired level.

The moisture levels and corresponding handling properties of the samples at various stages in the drying process are summaried in Table 3.1.

The poor handling qualities of the Hat Creek coals, when moisture in excess of equilibium levels is present, is attributed to the high clay content of the ash. Fine plastic clays can absorb much water and in so doing, may provide sufficient cohesion to effect an angle of repose greater than 90°. In general, for those samples having lower ash content, adequate handling characteristics were observed at higher moisture levels.

It should be noted that the handling qualities of the coal received by CCRL may be quite different from mine-run coal at Hat Creek. Whereas the coal received by CCRL was $-\frac{1}{4}$ in. mesh and fairly well mixed, coal delivered to a power station is typically $1\frac{1}{2}$ in. or larger. The handling properties are markedly affected by size consist, and if the coal should contain large lumps of wet clay, difficulties can be expected.

3.2 Petrography

According to ASTM Method D388-66, the Hat Creek coal samples were all classified as sub-bituminous C. The equilibrium moisture ranged from 22% to 25% except for A-raw coal which had a value of 27%. When the washed coals were air-dried, the moisture content rapidly dropped to sub-equilibrium levels and decrepitated while drying.

TABLE 3.1

Coal Handling Properties* and Moisture Content
of the Sample Coals When Crushed to 1/8 in. x 0

Coal	Moisture in Coal %	Condition	Remarks
Sundance	16	As received	Adequate
A-Raw	27	As received	Not adequate, formed cakes and balls in hoppers
A-Raw	16	Kiln dried	Not adequate, hung in hopper and feed chute to pulverizer, pulverized easily
A-Raw	7	Kiln dried twice	Adequate
A-Washed	25	As received	Not adequate, hung in hoppers
A-Washed	16	Air & kiln dried	Adequate
B-Raw	22	As received	Not adequate, hung in hoppers
B-Raw	17	Kiln dried	Adequate, but required constant attention to feed chute to pulverizer, pulverized easily
B-Raw	9	Kiln dried twice	Adequate
B-Washed	23	As received	Not adequate, appeared to cake, pulverized easily
B-Washed	20	Air dried	Adequate
B-Washed	9	Air & kiln dried	Adequate
C-Raw	24	As received	Not adequate, appeared to cake
C-Raw	20	Air dried	Adequate
C-Raw	9	Air & kiln dried	Adequate
C-Washed	24	As received	Not adequate, appeared to cake
C-Washed	22	Air dried	Adequate
C-Washed	13	Air & kiln dried	Adequate

*Coal judged not adequate for the small-scale CCRL feeding mechanisms may have adequate handling properties in larger equipment.

Macerals are the organic components of coal that are distinguishable by microscopic examination. They are classified according to their optical and morphological properties and experience has shown that the combustion characteristics of the macerals may be used to describe those of the coal.

Samples of A-raw, B-raw and C-raw coals were prepared according to ASTM Method - D2797-72 and were examined according to ASTM Method D2798-72, and 2796-72, and also as outlined briefly in Stach's Textbook of Coal Petrology[1]. For convenient comparison, the proximate ultimate and calorific analyses of the three coals are shown in Table 3.2. The maceral analyses shown in Table 3.3 were done in two laboratories, the Energy Research Laboratories of CANMET, and the laboratories of Bergbau-Forschung, Essen, West Germany. When corrected for mineral matter content, the results of the two analyses are nearly identical, as shown in Table 3.4.

On a mineral-matter-free basis, the coals were almost entirely composed of vitrinite, but the vitrinite was not homogeneous due to variations in original plant materials in their degree of preservation. Some cellular structures derived from vegetable material were visible in the vitrinite. The cell walls, called tellinite had collapsed where they had not been filled with collinite or with clay, sand, pyrites and other mineral matter. Tellinite and collinite are components of vitrinite.

The material classified as vitrinite by both laboratories was not homogeneous in any of the coal samples; it contained a multiplicity of differently structured components showing remnants of the parent plant materials, Figure 3.1. These materials were identified as tellinite, Figure 3.2, and resinite, Figure 3.3, interspersed between lamellations of a high reflectance vitrinite. All the coals were characterized by the absence of significant amounts of well developed inert macerals, fusinite and semi-fusinite. The maceral count showed unusually low exinite macerals, Figure 3.4, for this rank of coal where typical values lie in the range of 6 - 10%.

The coal macerals shown in Tables 3.3 and 3.4 may be listed in order of their ignitability or reactivity as follows:

$$
\left.\begin{array}{l} \text{resinite} \\ \text{exinite} \\ \text{micrinite} \end{array}\right\} > \left.\begin{array}{l} \text{vitrinite} \\ \text{structured vitrinite} \\ \text{tellinite} \end{array}\right\} > \begin{array}{l} \text{semifusinite} \\ \\ \text{fusinite} \end{array}
$$

TABLE 3.2

Proximate and Ultimate Analyses of
Three Samples of Raw Hat Creek Coal

		A-Raw	B-Raw	C-Raw
Proximate Analysis				
Air-dried Moisture	wt %	15.64	13.53	18.99
Ash	wt %	44.51	29.94	20.57
Volatile Matter	wt %	22.16	30.55	31.34
Fixed Carbon	wt %	16.69	25.98	29.10
Ultimate Analysis				
Carbon	wt %	35.88	39.02	42.35
Hydrogen	wt %	2.23	3.07	3.20
Sulphur	wt %	0.80	1.04	0.58
Nitrogen	wt %	0.54	0.82	0.93
Ash	wt %	44.51	29.94	20.57
Oxygen	wt %	10.51	12.58	13.38
Calorific Value (Gross)				
Cal/gm		2355	3601	4006
Btu/lb		4239	6482	7211
Btu/lb dry, mineral-matter-free basis		8318	9665	9319
ASTM Classification		Sub-bituminous C	Sub-bituminous C	Sub-bituminous C

TABLE 3.3

Maceral Composition of Samples of Raw Hat Creek Coal

Coal Sample	Maceral Type, vol %	A	B
A-Raw	Vitrinite	36.0	38 } 55
	Structured vitrinite		17
	Exinite	0.8	3
	Resinite & Telinite		3
	Micrinite	1.2	
	Semi-fusinite	0.4	
	Pyrite	0.4	
	Fusinite		
	Mineral Matter	61.2	39
	Mean max reflectance, Ro	0.38	0.46
B-Raw	Vitrinite	27.6	27 } 50
	Structured Vitrinite		23
	Exinite		2
	Resinite & Telinite		3
	Micrinite		3
	Semi-fusinite	0.4	2
	Pyrite		
	Fusinite		
	Mineral Matter	72.0	43
	Mean max reflectance, Ro	0.34	0.41
C-Raw	Vitrinite	55.6	40 } 73
	Structured Vitrinite		33
	Exinite	1.2	2
	Resinite & Telinite		1
	Micrinite	1.8	
	Semi-fusinite	5.6	1
	Pyrite	0.2	
	Fusinite	2.2	
	Mineral Matter	33.4	23
	Mean max reflectance, Ro	0.34	0.43

A: Energy Research Laboratories
B: Bergbau-Forschung

TABLE 3.4

Maceral Composition of Samples of Raw Hat Creek Coal
(Mineral-Matter-Free basis)

Coal Sample	Maceral Type, vol %	A	B
A-Raw	Vitrinite Structured vitrinite Exinite Resinite & Telinite Micrinite Semi-fusinite Pyrite Fusinite	93 2 3 1 1 –	62 ⎫ 28 ⎬ 90 5 5
B-Raw	Vitrinite Structured vitrinite Exinite Micrinite Semi-fusinite Pyrite Fusinite	99 1	47 ⎫ 40 ⎬ 87 5 4 4
C-Raw	Vitrinite Structured vitrinite Exinite Resine & Telinite Micrinite Semi-fusinite Pyrite Fusinite	83 2 3 8 <1 3	52 ⎫ 43 ⎬ 95 3 1

It is probable that the most reactive of the macerals is micrinite, which consists of the micron-sized, hydrogen-rich rounded grains which are embedded in vitrinite or collinite. It devolatilizes at the lowest temperatures and is the richest in volatile matter.

The ignitability of a maceral is determined by its degree of oxidation. For example, coal oxidation can occur by exposure to air or to intrusions of igneous rock during some period in its formation. Increased oxidation of vitrinite is characterized by increased reflectivity, and by means of this parameter the vitrinite maceral of the Hat Creek coals has been classified as a mixture of reactive and oxidized (less reactive) vitrinite. The results are shown in Table 3.5. All three samples were highly reactive vitrinite with the A-raw coal containing the largest proportion and the C-raw coal containing the least.

The following is a simplified description of the role played by the various coal macerals prior to and during combustion. As coal is heated it devolatilizes. It may also become plastic and then resolidify. The plastic phase occurs over the temperature range $350^{o}C$ to $600^{o}C$ which corresponds to the greatest rate of devolatilization. If the rate of devolatilization is very high such as would occur in a flame, then the non-volatile residue that is mostly carbon char and mineral matter has an open structure ressembling foamed plastic. Vitrinite, the maceral with the highest volatile content, expands the most and produces a char with a high surface area. On heating to $550^{o}C$ in a Ruhr dilatometer at a rate of $3^{o}C/min$, vitrinite normally undergoes an initial contraction on becoming plastic and then expands as the bulk of the sample devolatilizes to produce a semi-coke with high surface area and a volume equal to or greater than its original level. This characteristic contraction due to the plasticity of vitrinite was totally absent in all of the Hat Creek coals. No dilatation was recorded.

After heating, the vitrinite structures of all three raw Hat Creek coals disappeared and all samples retained this structurally modified vitrinite with small amounts of fusinite and semi-fusinite which do not expand, Figures 3.5 and 3.6. Because of its high surface area, char from vitrinite has a significantly higher rate of combustion than char from semi-fusinite. Consequently, the carbon carryover from a furnace fired by pulverized coal will contain

FIGURE 3.1 - Vitrinite showing remnants of parent plant materials.

FIGURE 3.2 - Tellinite-like structure.

FIGURE 3.3 - Resinite (oxidized) structure.

FIGURE 3.4 - Exinite and vitrinite structure.

FIGURE 3.5 - Semi-coke on heating to 550°C. Vitrinite and semi-fusinite structure.
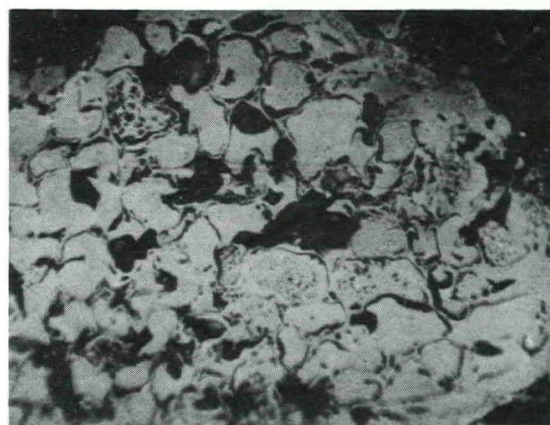
FIGURE 3.6 - Semi-coke on heating to 550°C. Low reflectance fusinite and oxidized resinitic structure.

proportionately more char from semi-fusinite and fusinite macerals than from vitrinite. The quantity of semi-fusinite and fusinite in the A-raw coal is negligible, and that in the B-raw and C-raw coal is small, less than 10%. Therefore, for conventional pulverized fuel combustion, Hat Creek coals need not be so finely ground as many higher-grade coals that are either more oxidized or contain fusinite or semi-fusinite.

Much of the mineral matter appeared to be finely dispersed in the coal. It was composed of sand, clay and pyrites. The clay was primarily in the form of kaolin tonstein, with about 10% bentonite or montmorillonite. Some of the clay appeared as large balls or lenses indicating that a Bradford breaker should be considered for primary coal crushing. The montmorillonitic or bentonitic clay, although the minor clay component, would adversely affect recovery of water and iron oxides in a heavy media coal washing plant. Therefore, coal beneficiation by simple jigging or treatment in a water cyclone would appear to be more appropriate for Hat Creek coal.

TABLE 3.5

Nature of the Vitrinite Component in Samples of Raw Hat Creek Coal
(Mineral-Matter-Free Basis)

Coal Sample	Vitrinite Content, % vol		
	Reactive	Oxidized	Total
A-Raw	76-80	13-14	90-93
B-Raw	38-56	43-49	87-99
C-Raw	29-48	47-54	83-95

*The data are presented as a range by considering the
vitrinite analyses from the two different laboratories.

The pyrites observed in the coal substance were mostly occluded, micron-sized particles which would not be removed easily by coal beneficiation. Fortunately, only about 40% of the sulphur in Hat Creek coal is pyritic, and a substantial portion is found in the mineral matter, where it can be removed by beneficiation.

Coals containing high concentrations of finely dispersed pyrites are prone to spontaneous combustion. In the case of Hat Creek coals, it is felt that the concentrations of pyrites are not great enough to warrant concern. A greater potential for spontaneous combustion is presented by the highly reactive vitrinite maceral, and substantial precautions will have to be taken in the coal storage and handling system. Vitrinite is most susceptible to spontaneous combustion when the moisture content of the coal has decreased below the equilibrium value by more than 10%. For Hat Creek coals the equilibrium moisture value is approximately 24%, a level at which the coal exhibits difficult handling characteristics. If the coal is dried to improve handling, storage between drying and firing will have to be minimized and precautions will have to be taken to control any fires due to spontaneous combustion. Beneficiation may be a preferable alternative because the wet washed coal would probably not require thermal drying.

3.3 Physico-Chemical Analyses

3.3.1 Proximate and Ultimate Analyses

A variety of standard ASTM analyses were carried out on the coal samples provided by B.C. Hydro. Some were carried out on grab samples taken from the drums shortly after delivery. Ash, moisture and heating value data for these are shown in Figure 3.7.

Additional coal samples were taken in each combustion test. Samples of crushed coal for conventional analyses such as proximate, ultimate, sulphur and ash were extracted incrementally of the pulverizer, primarily to determine the particle size distribution.

The calorific data in Table 3.6, which are superimposed on Figure 3.7, show that the raw Hat Creek coals range on a dry basis from 25 to 52% ash, and 11 to 20 Mj/kg (4740 to 8620 Btu/lb) higher heating value, while equilibrium moisture is typically 24%. All this indicates a low quality coal. On the other hand, the volatile matter content is fairly high, the sulphur content is approximately 1%, and the petrographic studies indicate a high reactivity. Washing appears to upgrade the coal significantly, both with respect to increased heating value and reduced pyritric and sulphatic sulphur content.

3.3.2 Ash and Chlorine Analyses

Ash and chlorine analyses for the test coals are given in Table 3.7. The maximum concentration of chlorine found was 0.02%. This value is well below the threshold of 0.6% at which chlorine is considered to present corrosion and fouling problems. The following comments can be made about the ash composition:

1. Typically, 80% or more of the ash when analyzed as oxides consisted of silica and alumina. This suggests a fairly refractory ash, which may also be abrasive.

2. Iron compounds comprised 5 to 11% of the ash, and their concentration tended to be lower in the washed samples.

TABLE 3.6

Analytical Data for the Test Coals

Proximate and Ultimate Analyses, Heating Values, and Sulphur Form Determinations

Coal	Test No.	Equil. Moist. %	Proximate, % 107 ± 3°C Dried			Ultimate, % 107 ± 3°C Dried						Cal.Value Dry Basis Mj/kg	Sulphur Forms in Coal, %			
			Ash	VM	FC	C	H	S	N	Ash	O		SO$_3$	FeS	Org.	Tot.
Sundance	1.1	16	14.61	34.71	50.68	63.29	3.90	0.21	0.82	14.61	17.17	24.20	–	–	–	–
Sundance	1.2	18	15.16	34.38	50.46	62.75	3.88	0.18	0.86	15.16	17.17	23.96	–	–	–	–
A-raw	2.1	22	52.98	25.04	22.88	30.60	2.58	1.12	0.62	52.08	13.00	11.32	0.12	0.47	0.45	1.04
A-raw	2.2		47.39	26.88	25.73	34.17	2.82	1.08	0.73	47.39	13.81	12.89	0.13	0.38	0.50	1.01
A-washed	3.1	25	30.27	33.15	36.58	47.92	3.41	1.20	0.96	30.27	13.24	18.65	0.12	0.29	0.61	1.02
A-washed	3.2		29.75	32.61	37.64	48.19	3.37	1.20	0.96	29.75	16.53	18.85	0.12	0.31	0.60	1.03
B-raw	4.1	22	37.43	33.13	29.44	42.10	3.28	1.10	0.93	37.43	15.16	16.44	0.11	0.51	0.40	1.02
B-raw	4.2		30.84	35.35	33.81	47.80	3.62	0.91	1.00	30.84	15.84	15.83	0.06	0.32	0.46	0.84
B-raw	4.3		28.80	35.95	35.25	49.21	3.67	0.92	1.03	28.80	16.37	19.27	0.08	0.24	0.44	0.76
B-washed	5.1	23	23.81	53.69	22.50	53.23	3.77	0.78	0.10	23.81	18.31	18.72	0.05	0.17	0.50	0.72
B-washed	5.2		21.91	47.70	30.39	54.91	3.93	0.90	1.08	21.91	17.27	21.58	0.04	0.14	0.64	0.82
B-washed	5.3		20.68	45.99	33.33	56.13	3.88	0.77	1.10	20.68	17.44	21.48	0.04	0.10	0.49	0.63
C-raw	6.1	24	28.32	35.42	36.26	48.62	3.62	0.70	0.12	28.32	18.61	19.39	0.05	0.12	0.46	0.63
C-raw	6.2		25.84	36.03	38.13	51.39	3.73	1.17	1.11	25.84	16.76	20.28	–	–	–	–
C-raw	6.3		30.26	34.68	35.06	48.62	3.47	0.62	1.08	30.26	15.95	19.05	–	–	–	–
C-washed	7.1	24	19.09	37.61	43.30	57.33	4.07	0.71	1.21	19.09	17.59	22.73	–	–	–	–
C-washed	7.2		18.16	38.36	43.48	57.71	3.98	0.75	1.24	18.16	18.16	22.65	–	–	–	–
C-washed	7.3		19.00	38.36	42.64	57.89	3.96	0.74	1.20	19.00	17.21	22.60	–	–	–	–
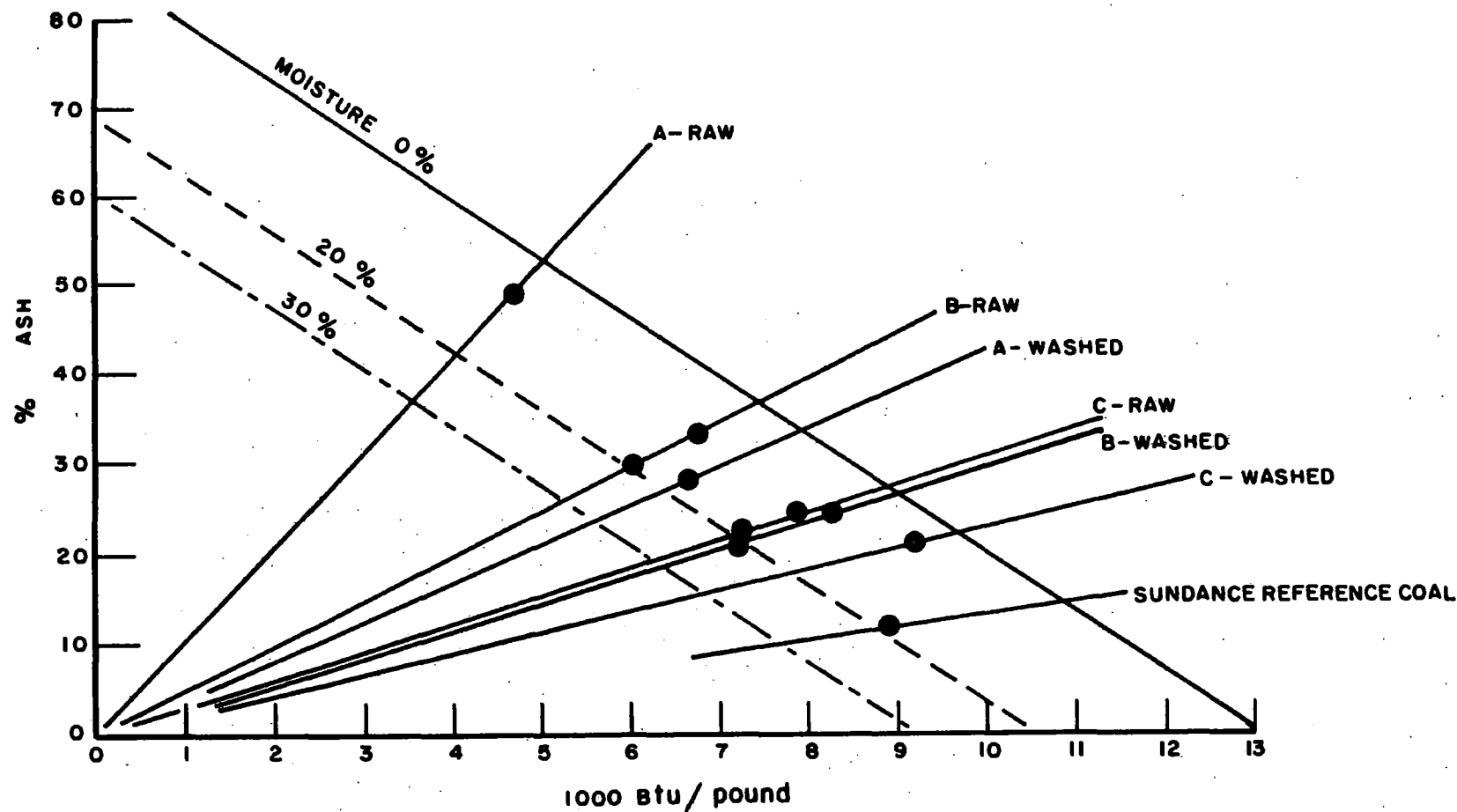
FIGURE 3.7   The ash-calorific value graph of Hat Creek coal for moisture contents of 0%, 20% and 30%. The load lines extending outwards from the origin show the effect of moisture on the ash-calorific value for each of the coals, A-raw, B-raw, A-washed, etc. The dark circles on the load lines represent the coals burned. Note that 1 Btu/pound equals 2.32 kjoules/kgram.

TABLE 3.7   Chlorine Content and Ash Analyses for the Test Coals

Coal	Test No.	Ash Analysis, wt %											
		SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O	Cl
Sundance	1.1	48.42	23.64	4.58	1.03	0.50	0.20	13.58	0.93	2.42	2.45	0.26	0
Sundance	1.2	49.76	23.96	4.35	0.93	0.47	0.17	12.60	0.85	2.50	2.26	0.26	0.01
A-raw	2.1	56.18	28.26	6.69	0.30	0.89	0.13	1.23	1.34	0.97	0.47	0.94	0.01
A-raw	2.2	56.94	31.38	7.53	0.03	1.31	0.12	1.51	1.19	1.10	0.47	0.79	0.00
A-washed	3.1	53.57	28.76	8.68	0.02	1.63	0.20	2.57	1.34	1.77	0.56	0.73	0.01
A-washed	3.2	55.67	30.13	8.01	0.02	1.70	0.19	2.53	1.04	2.12	0.54	0.74	0.01
B-raw	4.1	48.24	29.14	11.11	0.13	1.18	0.37	3.82	1.10	3.62	0.28	0.37	–
B-raw	4.2	50.85	29.84	9.36	0.12	1.31	0.37	4.11	0.94	3.17	0.31	0.36	0.01
B-raw	4.3	50.82	30.53	8.43	0.10	1.29	0.35	4.06	1.59	3.31	0.33	0.38	–
B-washed	5.1	48.28	31.41	6.80	0.06	1.42	0.38	4.54	1.30	2.70	0.29	0.37	–
B-washed	5.2	48.42	31.07	6.61	0.07	1.45	0.37	4.47	1.64	3.12	0.29	0.35	–
B-washed	5.3	49.43	31.85	6.57	0.06	1.52	0.41	4.66	1.51	3.00	0.31	0.36	–
C-raw	6.1	49.98	32.10	7.89	0.16	1.30	0.18	2.59	1.43	1.87	0.50	0.47	–
C-raw	6.2	51.20	29.06	6.78	0.10	1.10	0.16	2.81	1.20	2.67	0.54	0.60	0
C-raw	6.3	51.22	29.00	6.84	0.09	1.03	0.14	2.33	1.39	2.87	0.48	0.59	0
C-washed	7.1	50.61	29.57	5.28	0.07	1.26	0.27	3.48	1.50	3.66	0.60	0.58	0
C-washed	7.2	51.23	30.19	5.11	–	1.26	0.36	3.64	1.44	2.96	0.64	0.63	0.02
C-washed	7.3	50.20	28.66	6.88	–	1.24	0.43	3.63	1.81	2.98	0.67	0.63	0.02

3. In all the Hat Creek coals, alkali and calcium oxide content of the ash represented less than 5% of the ash. This suggests that the potential for sulphur retention in the ash is very limited.

4. None of the Hat Creek coal samples showed as much as 1% sodium oxide in the ash. This suggests minimal difficulties with fireside fouling.

3.3.3   Grindability and Particle Size Distribution

Table 3.8 presents data on grindability and on particle size distribution upstream and downstream of the pulverizer. Grindability as determined by the Hardgrove test was much the same for the Hat Creek coals as for the Sundance coal. An exception was the A-raw coal, which because of its high-clay content, appeared to be easier to grind than any of the others. The data also show that moisture adversely affects grindability. However, the reduced grindability does not appear to be reflected in the fineness of the pulverized coal. It would appear that experience with Sundance coal can be used to size pulverizers for Hat Creek coal. The same throughput and fineness can be assumed, but allowance must be made for the inferior heating value of Hat Creek coal.

3.3.4   Coal Reactivity Parameters

Coal reactivity is a major consideration in furnace design. Reactivity is a loosely-defined term denoting the ability of a coal to burn-out without support firing by oil or gas, without excessively fine grinding, and with a minimum of refractory in the furnace. Over the years a variety of parameters have been suggested as means for predicting reactivity, and while none have achieved universal recognition, a number of them offer useful guidelines. A very simple one, for example, equates increased reactivity to increased volatile matter as indicated by the proximate analysis. The logic of this is supported by coal petrography which has demonstrated that the coal macerals when ranked from highest to lowest reactivity, are exinite, vitrinite, macrinite and fusinite. When the macerals are ranked from highest to lowest volatile matter content, the same order applies.

As pointed out by Burbach and Bogot (2) some coals contain non-organic volatile matter, such as carbonates, which show up in the volatile

TABLE 3.8 Grindability and Size Analyses of Crushed and Pulverized Coals

Coal	Test No.	Hardgrove Grindability[a]	Coal Feed[b] to Pulverizer, % Size Fractions in inches					Pulverized Coal[b], % Size Fractions in mesh/in.					Residual[c] Moisture, %
			+1/4	1/4 x 1/8	1/8 x 1/16	1/16 x 1/32	1/32 x 0	+100	100 x 200	140 x 200	200 x 325	325 x 0	
Sundance	1.1	43	0	3.2	36.3	32.8	27.7	0.7	4.4	7.9	16.8	70.1	17.1
Sundance	1.2	43	0	4.5	46.8	31.1	17.6	0.7	5.8	12.9	14.0	66.5	16.0
A-raw	2.1	61	0	0.3	16.5	28.1	55.1	1.5	6.8	9.2	18.8	63.6	7.1
A-raw	2.2	58	0	0.8	25.9	28.7	44.6	3.0	10.2	13.0	19.9	53.8	7.4
A-washed	3.1	44	0	2.9	34.0	32.1	31.0	1.9	7.2	8.5	33.4	49.0	16.3
A-washed	3.2	44	0	2.8	35.2	33.4	28.6	7.4	21.0	9.4	17.5	44.7	16.5
B-raw	4.1	48	0	0.4	12.0	39.3	48.3	3.9	15.1	9.9	24.2	46.9	8.6
B-raw	4.2	47	0	0.9	32.3	38.5	28.3	3.8	16.8	8.6	23.3	47.4	9.3
B-raw	4.3	42	0	4.8	49.2	24.3	21.7	16.9	12.8	6.4	16.2	47.7	16.6
B-washed	5.1	45	0	3.9	30.2	33.2	32.7	12.4	17.1	8.2	14.0	48.0	8.6
B-washed	5.2	44	0	6.1	40.1	31.1	22.7	11.2	17.5	8.2	14.9	48.2	8.6
B-washed	5.3	39	0	15.4	51.7	19.0	13.9	3.1	17.1	9.7	23.7	46.4	20.3
C-raw	6.1	45	0	2.6	20.4	28.1	48.9	9.2	15.0	7.0	16.0	52.8	11.0
C-raw	6.2	43	0	4.5	41.2	29.5	27.8	8.5	15.2	6.7	17.2	52.5	13.0
C-raw	6.3	43	0	1.6	15.9	24.8	57.7	2.3	12.2	10.9	17.1	57.5	19.6
C-washed	7.1	40	0	3.0	32.1	34.7	30.2	2.5	13.3	10.7	18.6	55.0	12.8
C-washed	7.2	38	0	6.8	55.3	25.1	12.8	1.6	11.6	11.3	22.5	53.0	13.8
C-washed	7.3	36	0	5.8	33.1	25.1	36.0	2.1	9.5	16.1	12.1	60.4	21.8

a/ The test for grindability of coal by the Hardgrove-machine method is ASTM D 409-71. The coal feed to the pulverizer and the pulverized coal were sampled at regular intervals. The accumulated samples were the quartered and riffled to ASTM standards before testing.

b/ ASTM E11-70 specifies the wire cloth sieves that were used for testing. Crushed coal was tested according to ASTM D 311-30 (1969) and pulverized coal using a "Sonic Sifter".

c/ Residual moisture is moisture in coal fed to pulverizer.

matter determination, but do not contribute to the heating value. To avoid being misled by this, the heat content of the volatile matter is sometimes used as a reactivity parameter. It is simply the heating value of the coal less the heating value of the fixed carbon, (32.8 Mj/kg) and can be readily calculated from the proximate analysis. An example is given in parts A and B of Table 3.9.

Table 3.10 gives values of volatile-matter heat content calculated for several Canadian coals. These values in may cases give misleading indicators about ease of burning. For example, char from the Great Canadian Oil Sands process, is shown to have nearly twice the volatile-matter heat content of Hat Creek A-raw coal, whereas, in the CCRL furnace equipped with a small refractory-lined bottom (grey bottom) the A-raw coal burned readily, but the GCOS char required oil support to maintain ignition. The char did maintain self-supporting combustion when the CCRL furnace was equipped with a large, nearly-adiabatic, refractory bottom. Similarly, Canmore coal, a semi-anthracite relatively unsuitable for pulverized firing, is shown to have a higher volatile-matter heat content than Sundance coal which is known to perform well in utility boilers.

A better parameter of coal reactivity appears to be the calculated adiabatic gas temperature resulting from the combustion of the volatile matter alone. This is reasonable if one considers a simplistic two-stage model for the combustion of coal, in which the first stage is the rapid combustion of the volatile matter together with devolatilization and heating of the fixed carbon and ash. The second stage is the relatively slow combustion of fixed carbon, which is affected by a number of factors, of which a major one is temperature. Temperature affects the time (t) required for combustion of a particle approximately according to the Arrhenius relationship $t = B \exp (27500/T)$ where T = temperature, $^{\circ}K$ and B is a geometric parameter related to the surface texture and size of the particle. Thus if T is low, the reaction time t will be relatively long.

In the simple model under discussion, T is determined by the combustion of the volatile matter and can be determined for adiabatic conditions by considering the mean values of specific heat appropriate to the ash, fixed carbon, moisture and combustion air for the fuel in question. An example of how this is done is given in parts C and D of Table 3.9 and results are presented in Table 3.10.

TABLE 3.9   Sample Calculation of Volatile-Matter Heat Content
and Adiabatic Gas Temperature

Sundance Coal, 16% Moisture

A)   Heat content of volatile matter

Calorific value of coal	24.202 Mj/kg
Fraction fixed carbon	0.5068
Calorific value – Fixed carbon x 32.8 Mj/kg	7.58 Mj/kg

B)   Heat content of volatile matter corrected for moisture (16% H_2O)

$$\text{Heat content} \times \frac{100 - \% \ H_2O}{100} \qquad 6.37 \ \text{Mj/kg}$$

C)   Approximate value of mean specific heat

% Ash x 1.09 x 10^{-7} x (100 – % H_2O)	4.77 x 10^{-5} Mj/^{o}C
% Volatile matter x 1.2 x 10^{-7}x (100 – % H_2O)	2.52 x 10^{-4} Mj/^{o}C
% Fixed carbon x 10^{-7}x (100 – % H_2O)	1.92 x 10^{-4} Mj/^{o}C
% Moisture x 2.42 x 10^{-5}	3.87 x 10^{-4} Mj/^{o}C
Kg Combustion air$\underline{^{a/}}$ x 1.2 x 10^{-5} (100 – % H_2O)	8.64 x 10^{-3} Mj/^{o}C
TOTAL –	9.37 x 10^{-3} Mj/^{o}C

D)   Calculated gas temperature

Corrected heat content/mean specific heat	=	6.37 (9.37 x 10^{-3})^{o}C
	=	680°C

$\underline{a/}$ The combustion air is the quantity required for the complete combustion
of the coal and may be calculated from the ultimate analyses shown in
Table 3.6.

TABLE 3.10   Volatile-Matter Heat Content and Gas Temperature

Calculated for Several Canadian Fuels

Coal	% H_2O	Heat Content Mj/kg	Gas Temperature $^\circ C$
Sundance	16	7.58	680
Hat Creek raw			
A	7	3.82	630
A	16	3.82	600
B	9	6.78	850
B	17	6.78	830
C	12	7.50	870
C	20	7.50	840
Hat Creek washed			
A	16	6.65	760
B	9	13.67	1470
B	20	13.67	1410
C	13	8.53	830
C	22	8.53	800
GCOS char	2	6.08	420
" "	2	6.08	420
Luscar (Coal Valley)	6	8.10	690
Battle River (Sheerness)	25	10.32	830
Forestburg (Castor)	20	9.84	820
" (Castor)	25	9.84	810
Canmore (Cascade)	10	8.63	590
Springhill, N.S.	20	10.25	830
Battle River, Estevan, Sask.	25	9.75	820

Other factors affecting combustion time for a coal particle are particle size, diffusion of oxygen to the combustion zone, and rate of heat loss from the particle. Halving the particle size of a given mass of coal doubles the surface area available for reaction. Thus finer grinding reduces the time required for combustion. The effects of particle size distribution are discussed further in Section 6.1. The rate of reaction will be retarded by localized shortage of oxygen resulting from inadequate mixing, and will be retarded if the temperature of the burning particle is reduced by radiation to surrounding surfaces at lower temperatures. Indeed, if cooling is severe the burning of the particle may be quenched before combustion is complete. Thus, several factors may combine to modify the influence of volatile-matter gas temperature on the time required for the second stage of combustion.

Nonetheless, practical experience can be used to assess the significance of the gas temperatures presented in Table 3.10. The Hat Creek coals and the Sundance coal were fired in the CCRL boiler under similar conditions of excess air, heat absorption and fineness of grind. Sundance coal burned well, therefore, a gas temperature of $680^{o}C$ can be viewed as representative of a reactive coal. By that standard, only the Hat Creek A-raw coal has a reactivity inferior to Sundance. Furthermore, this criterion rates the A-raw coal as being somewhat more reactive than Canmore, and substantially more reactive than GCOS char, which agrees with experience.

In summary, the volatile-matter gas temperature appears to be a dependable parameter of coal reactivity. The Hat Creek A-raw coal, when dried to 7% moisture, burned well in the CCRL boiler, therefore, a volatile-matter gas temperature of $625^{o}C$ may be the threshold of acceptable reactivity. In that case, the B-raw, C-raw and all the washed coals can be considered highly reactive.

3.3.5 Ash Fusion Data

ASTM ash fusion determinations were carried out under both oxidizing and reducing conditions on ashed coal samples. The results are presented in Table 3.11 and indicate that all of the sample coals had a medium to high initial deformation temperature, and high softening and fusion temperatures. Fusion temperatures under oxidizing conditions were generally 50 to $100^{o}C$

TABLE 3.11   Fusion Temperatures of Ash from Test Coals

Coal	Test No.	Oxidizing Atmosphere Temperature, °C				Reducing Atmosphere Temperature, °C			
		ID	SS	HS	F	ID	SS	HS	F
Sundance	1.1	1338	1365	1407	1438	1271	1310	1360	1438
Sundance	1.2	1310	1360	1388	+	1277	1316	1388	1443
A-raw	2.1	+1500	+	+	+	1332	+	+	+
A-raw	2.2	+	+	+	+	1410	+	+	+
A-washed	3.1	1460	+	+	+	1377	1466	+	+
A-washed	3.2	1438	+	+	+	1327	1477	+	+
B-raw	4.1	1438	+	+	+	1360	1427	1460	+
B-raw	4.2	+	+	+	+	1416	1477	+	+
B-raw	4.3	1454	+	+	+	1371	1471	+	+
B-washed	5.1	1427	+	+	+	1382	+	+	+
B-washed	5.2	1410	+	+	+	1354	+	+	+
B-washed	5.3	+	+	+	+	1399	+	+	+
C-raw	6.1	+	+	+	+	1454	+	+	+
C-raw	6.2	1471	+	+	+	1388	+	+	+
C-raw	6.3	1460	+	+	+	1332	+	+	+
C-washed	7.1	1438	+	+	+	1282	1460	+	+
C-washed	7.2	+	+	+	+	1410	+	+	+
C-washed	7.3	1399	+	+	+	1288	+	+	+

a) Ash Fusion Tests were done according to D 157 – 74.
   ID = Initial Deformation
   SS = Spherical Softening
   HS = Hemispherical Softening
   F = Fluid

higher than under reducing conditions. This can be attributed to the lower melting temperature of FeO and FeS which is likely to be present under reducing conditions, compared to Fe_2O_3, which is likely to be present under oxidizing conditions.

It would be unwise to deduce from the ash fusion data that Hat Creek coals are non-fouling. The small quantities of iron and alkali in the ash, while insufficient to significantly influence the behaviour of the ASTM ash fusion cones, can reach melting temperatures and act as a cement, binding more refractory ash components into massive, porous sinters. This was demonstrated during the combustion trials, and is discussed in detail later.

3.3.6   Slagging and Fouling Indicators

Two general types of high temperature ash deposition can occur on gas-side surfaces of coal-fired boilers:

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.

The assessment of slagging and fouling 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 ash deposition. 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 fouling indices are described as being applicable only to coals with "eastern type" ash or to coals with "lignite type" ash. The term "lignite type" ash is defined as an ash having more CaO + MgO than Fe_2O_3 when all are measured as a weight per cent of the coal ash.

The ash analyses of the coals used in the Canadian Combustion Research Laboratory (CCRL) combustion evaluation of Hat Creek coal show

(Table 3.7) that the only coal which unequivocally had a lignite type ash was the Sundance reference coal. It is also clear that washing of the Hat Creek coals moves the ash towards the lignite characteristic.

The washed B and C coals show a CaO + MgO : Fe_2O_3 ratio in the ash close to unity and cannot be classified as either lignite or eastern. The remaining coals clearly fall into the "eastern" classification. It must be remembered that the 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 analyses of five common indices for determining the slagging or fouling potential of a coal ash.

(a)   The Base : Acid Ratio as a Slagging Indicator

One slagging index, (Rs), has been reported to have been used with success to identify four types of slagging coal. It was developed from pilot-scale tests using coals for which extensive plant experience was available.

$$\text{Slagging Index (Rs)} = \frac{\text{Base}}{\text{Acid}} \times [S]$$

$$\text{Base} = Fe_2O_3 + CaO + MgO + Na_2O + K_2O$$

$$\text{Acid} = SiO_2 + Al_2O_3 + TiO_2$$

$$S = \text{Sulphur}$$

All oxides as weight % in the ash; sulphur as weight % in the coal. The types of slagging associated with this slagging factor are shown below:

Slagging Type	Slagging Index Rs
Low	< 0.6
Medium	0.6 - 2.0
High	2.0 - 2.6
Severe	> 2.6

The slagging index for all the coals used in the CCRL combustion evaluation was below 0.25. The probability of producing a hard, adherent slag is seen to be low.

(b)   Ash Fusion Characteristics as Slagging Indicators

Ash fusion characteristics determined according to proceedures 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, normal reference is to the reducing atmosphere which usually generates lower temperatures and is therefore a more restrictive condition.

High ash fusion temperatures - particularly the initial deformation temperature - generally lead to minimal slagging problems. The ideal situation for dry bottom firing is represented by a high initial deformation with a wide temperature difference to the ash softening temperature.

In the case of the Hat Creek coals all the initial deformation (reducing atmosphere) temperatures of the coal ash were in the range $1300^{\circ}C$ - $1375^{\circ}C$ and the softening temperatures are above $1425^{\circ}C$. Further, the initial deformation temperatures of the furnace bottom ash collected during the combustion trials are all above $1200^{\circ}C$ and the softening temperatures are above $1400^{\circ}C$. These fusion temperatures are normally associated with a low slagging potential.

Experience with Sundance coal, which has an initial deformation temperature of $1270^{\circ}C$ and a fluid temperature of $1440^{\circ}C$, indicates that slagging is not a problem. The Hat Creek coals should not therefore present major slagging problems in the combustion chamber provided that soot blowing facilities are adequate to control the accelerated deposit build up due to the high ash content of the fuel.

(c)   Sodium Content of the Coal Ash as a Fouling Indicator

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 classifications have been proposed:

Fouling Characteristic	% 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

[*] i.e., those with lignite type ash.

The great differences between the reference values of % Na_2O for the two types of coals emphasizes the difficulty in using these fouling indicators. Since the Hat Creek coals define generally as "eastern" type, this classification suggests that the fouling characteristic of the coals used in the CCRL trials is as follows:

Sundance   : Medium

A, B raw, B washed : Low

A washed, C raw, C washed : Medium

It must be borne in mind that the B and C washed coals did not classify unequivocally as having either lignitic or eastern ashes and the fouling characteristic of these coals will therefore be over-estimated by this classification.

(d)   Total Alkali Content of the Coal as a Fouling Indicator

Since sodium and potassium behave similarly in wet chemical reactions the assumption can be made that they behave similarly in pyro-chemical reactions within a boiler. The total alkali can then be calculated from the proximate and ash analysis of the coal and reported as equivalent Na_2O.

Total Alkali   = $[Na_2O] + 0.6589\ [K_2O] \quad \dfrac{A}{100}$
(equivalent Na_2O
as weight % of coal)

A is the ash content (weight %) of the dry coal, the oxides are expressed as weight %.

For coals with "eastern" type ash the following values have been proposed as a guide.

Total Alkali (weight % of coal)	Fouling Type
< 0.3	Low
0.3 – 0.45	Medium
0.45 – 0.6	High
> 0.6	Severe

Using this classification the only Hat Creek coal which shows a fouling characteristic other than "low" is the A coal in the unwashed condition. The reason for this does not lie in the composition of the ash but rather in the massive ash content of the coal which is incorporated into the calculation of the total alkali.

(e)   The Base to Acid Ratio as a Fouling Indicator

A fouling index (R_f) using the base : acid ratio of the coal ash has been used to categorize coals into the usual four fouling categories.

$$R_f = \frac{Base}{Acid} [Na_2O]$$

$$Base = Fe_2O_3 + CaO + MgO + Na_2O + K_2O$$

$$Acid = SiO_2 + Al_2O_3 + TiO_2$$

All oxides are expressed as weight % of the ash.

| Fouling Index	Fouling Type
R_f	
< 0.2	Low
0.2 – 0.5	Medium
0.5 – 1.0	High
> 1.0	Severe

All the Hat Creek coals show a fouling index below 0.11 and indicate a low fouling potential. The reference Sundance coal shows a fouling index of 0.7.

4.   THE PILOT-SCALE RESEARCH BOILER

The CCRL research boiler illustrated schematically in Figure 4.1, 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 pressures of up to 25 cm W.C. At the full-load firing rate of 2500 Mj/hr (0.7 MWt) the boiler generates 730 Kg/hr steam at 6.8 atm. The heat is dissipated in an air cooled condenser. Because of limitations in pulverizer capacity, the firing rate for the tests with Hat Creek coal was reduced to approximately 2150 Mj/hr (0.6 MWt) which corresponds to a volumetric heat release rate of approximately 2050 Mj/m^3 (55,000 Btu/cu ft).

For tests with high ash coals, the boiler has been equipped with a furnace bottom that permits bottom ash to be removed while the boiler is on the line. A sheet metal skirt encloses a 50 cm square opening in the refractory-lined furnace bottom and extends downward into a quench tank filled with water. The water serves to seal the slight pressure of the furnace, and eliminates the hazards of handling hot ash. Since the opening in the furnace bottom occupies approximately half the bottom area, it would normally impose a substantial and undesired thermal load on the flame. This is minimized by a pair of dump plates installed on hinges at the upper end of the skirt. In normal operation, the plates are fixed in the horizontal position screening the flame from the quench tank. Periodically the plates are swung to the vertical position, allowing accumulated ash to fall through the skirt into the quench tank. The ash is then manually removed from the quench tank.

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
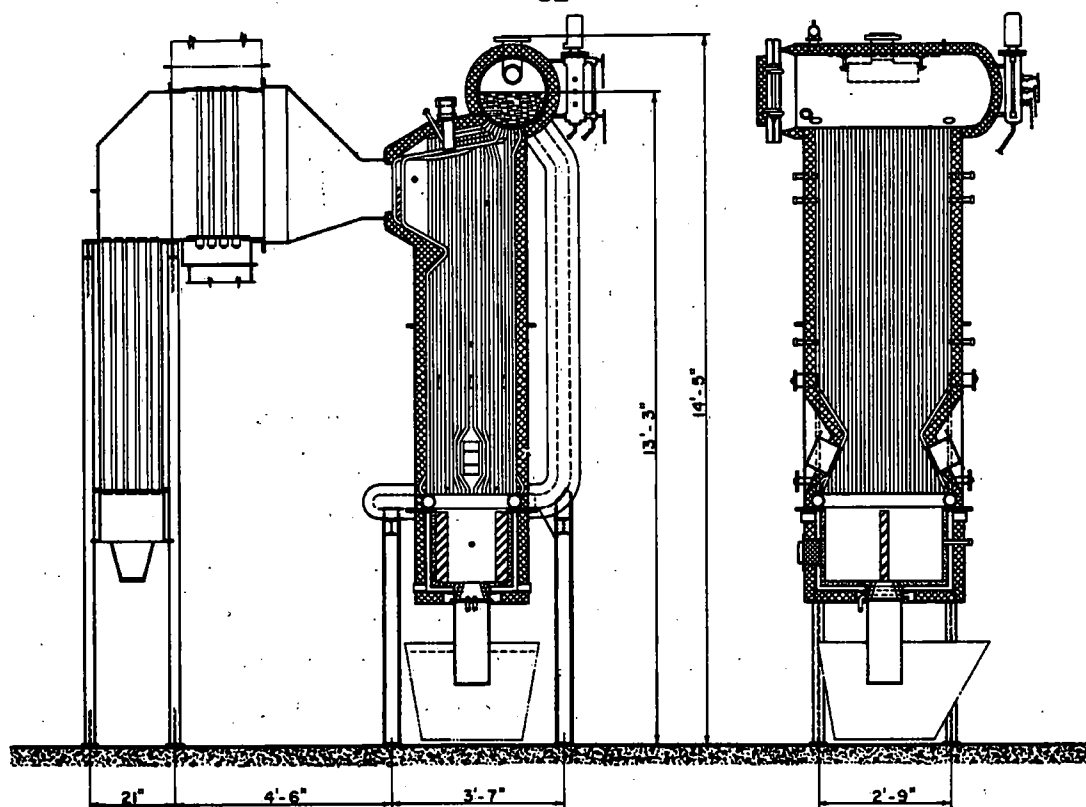
SCALE - ¼ = 1'-0"

FIGURE 4.1   Schematic view of the CCRL pilot-scale
research boiler

coal fineness, and a riffle at the pulverizer outlet proportions the coal to
each burner. Secondary air can be supplied to the burners 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, the gas flow can either 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 bypass 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 and 300°C.

A forced-draft fan supplies air to the air heater at 0.07 atm. 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 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 startup and shutdown procedures are followed. When burning high-grade coals, it has been possible to operate with as little as 1.0 per cent O_2 and no more than 0.1 per cent CO in the flue gases, with a smoke density of less than No. 1 Ringelmann. However, the boiler gas-side pressure drop between the furnace exit and the stack normally limits full-load operation to maximum O_2 levels in the flue gases of between 3.5 and 5 per cent. 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 Control Parameters

It was agreed with B.C. Hydro that the major input variable, besides the seven samples of coal, was to be excess air level. Another variable that had to be considered was coal moisture content.

The 180 Kg/hr coal-handling system for the CCRL research boiler is not capable of maintaining a reliable, uniform feed to the pulverizer if the coal is wet. Furthermore, previous experience with other low-quality Canadian coals has shown that acceptable combustion conditions cannot be expected when the gross calorific value is low and the moisture content is high. Thus, it was recognized that the coal had to be dried partially before burning.

Drying was accomplished in two ways; air-drying, by spreading a thin layer of coal on a asphalt driveway in suitable weather and by thermal drying, using a small oil-fired rotary kiln. To avoid the danger of fire while using this kiln, the feed rates and temperature were held at levels which limited moisture extraction to 6% per pass. To achieve the desired

moisture level some coals had to be passed through the dryer twice; i.e., double-dried. However, to assess the effect of moisture content on combustion performance, some tests were scheduled with coal that had either been (a) passed through the dryer only once, (b) air dried only or (c) air-dried and then passed through the dryer once. After drying, coal samples were stored in sealed drums.

To determine the effect of excess air level on combustion performance, tests were done with oxygen in the flue gas held at two levels; 5% and 3%, corresponding to approximately 38% and 20% excess air, respectively.

Another potential variable was heat input to the furnace, but this was fixed for all tests at approximately 0.55 Megawatts (two million Btu/hr) and the feed rate for each coal was adjusted accordingly.

After consideration of the above control parameters and of the constraint imposed by the small quantities of coal available, B.C. Hydro and CCRL agreed to a basic program of 18 tests. The target control conditions for these tests are summarized in Table 5.1.

5.2   Operation of the Research Boiler

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

1. Before each test, all boiler and air heater fireside surfaces were cleaned by air lancing. Ash deposits sintered to refractory surfaces were manually removed. Sufficient coal was bunkered to provide approximately 10 hr of operation at the desired feed rate.

2. At 0400 hr, the cold boiler was fired up on No. 2 fuel oil at 16 gph. Excess air was adjusted to provide 3% 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 0630 hr, feed of pulverized coal 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.

TABLE 5.1

Control Conditions for the Test Program

Test No.	Coal	Degree of Drying	Excess O_2 Level, %	Feed Rate Kg/hr
1.1	Sundance	None	5	100
1.2	"	"	3	100
2.1	Hat Creek "A" raw	KD* twice	5	196
2.2	" "	"	3	196
3.1	Hat Creek "A" washed	AD**+ KD	5	134
3.2	" "	"	3	134
4.1	Hat Creek "B" raw	KD twice	5	131
4.2	" "	"	3	131
4.3	" "	KD	5	142
5.1	Hat Creek "B" washed	AD + KD	5	120
5.2	" "	"	3	120
5.3	" "	AD	5	120
6.1	Hat Creek "C" raw	KD twice	5	110
6.2	" "	"	3	110
6.3	" "	KD	5	120
7.1	Hat Creek "C" washed	AD + KD	5	110
7.2	" "	"	3	110
7.3	" "	AD	5	110

*KD = kiln-dried

**AD = air-dried

4. At 0730 hr, the oil torch was removed, leaving the boiler operating on pulverized coal only.

5. At 0800 hr, bottom ash was dumped and 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. Bottom ash was dumped as necessary into a water-filled hopper, and the frequency of dumping was noted. Suitable steps were taken to present ash deposits in the furnace from interfering with combustion conditions. This sometimes involved inserting a rod through the sight port at the top of the furnace to clear away sintered deposits just below the furnace throat.

6. By 1500 hr, scheduled tests were usually nearing completion. If repeat measurements were required, these were begun.

7. When all measurements were completed, an oil torch was inserted and coal feed to the pulverizer was shut off. When the pulverizer was empty, the boiler was shutdown. The last laod of bottom ash was not dumped, because of a B.C. Hydro requirement for samples of dry bottom ash.

8. The furnace was allowed to cool overnight. Then the quench tank was removed and the ash remaining in the furnace bottom was dumped on the floor. All the bottom ash was weighed. Ash samples were taken from designated locations in the boiler and air heaters, and photographs were taken.

5.3 Parameters of Combustion Performance

By agreement between B.C. Hydro and CCRL the following parameters of combustion performance were measured in each test at the sampling or measuring stations shown in Figure 5.1.
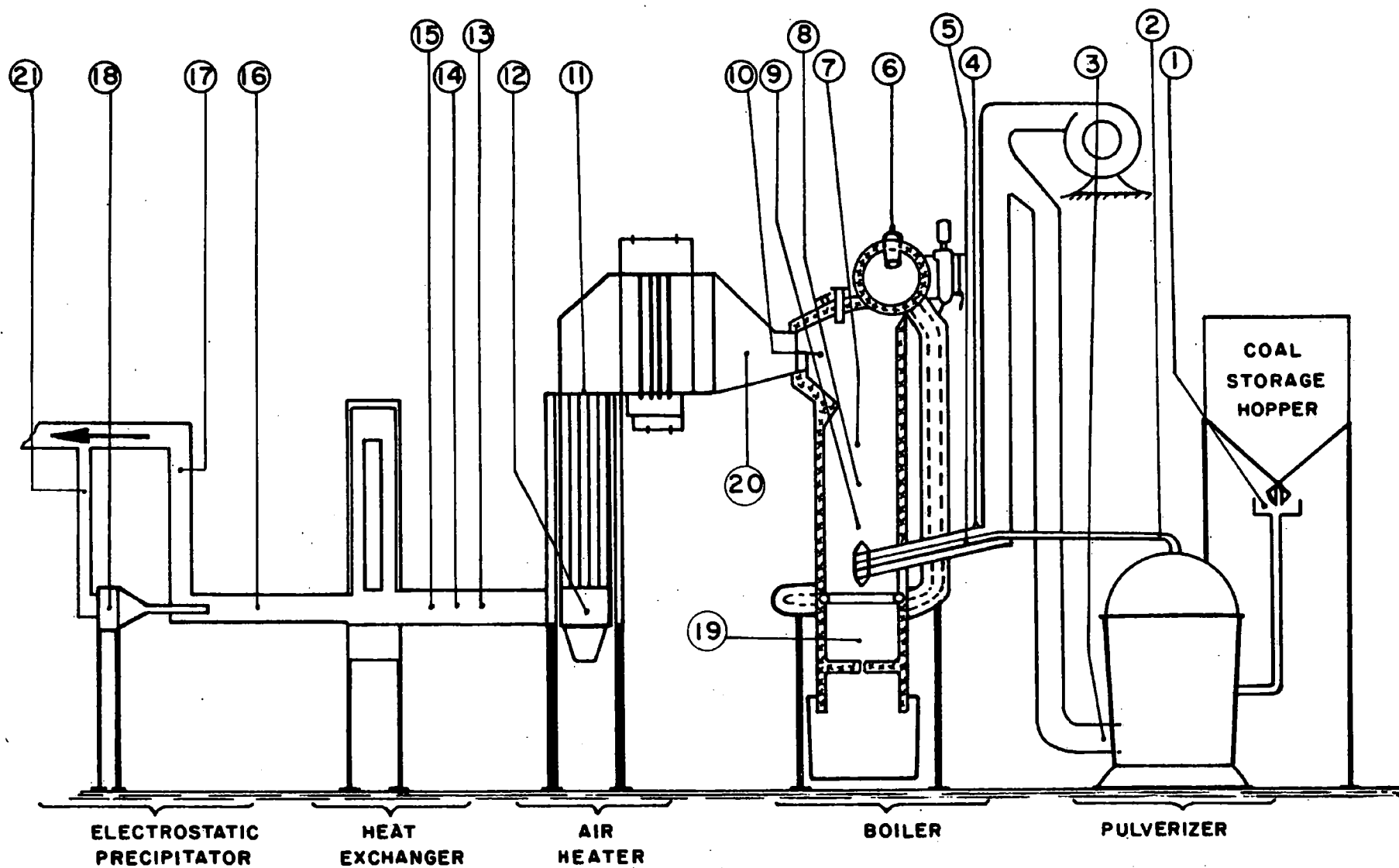
FIGURE 5.1   Schematic illustration of the pilot-scale boiler showing the sampling stations.

1. Proximate, ultimate, 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. Petrographic examinations were also conducted on some samples.

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 infra-red monitors, Station 20.

4. O_2 content of the flue gas, measured continuously by a paramagnetic monitor, Station 20.

5. NO content of the flue gas, measured continuously by a chemiluminescent monitor, Station 14.

6. SO_2 content of the flue gas, measured continuously by a chemifluorescent monitor, Station 15.

7. SO_2 and SO_3 content of the flue gas, measured by the API and the 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 about four hours, one set per test, Station 13.

9. Fly ash loading, measured isokinetically by an automated sampling system, shown in Figure 5.2, two to four samples per test, Station 16. These samples were analyzed for carbon content, chemical composition and size distribution.

10. Ash fouling of heat-transfer surfaces, evaluated by two methods. The first method was by examination of thickness, structure and chemical composition of deposits on three pairs of temperature-monitored probes located in the furnace bottom (Station 19), above the furnace throat
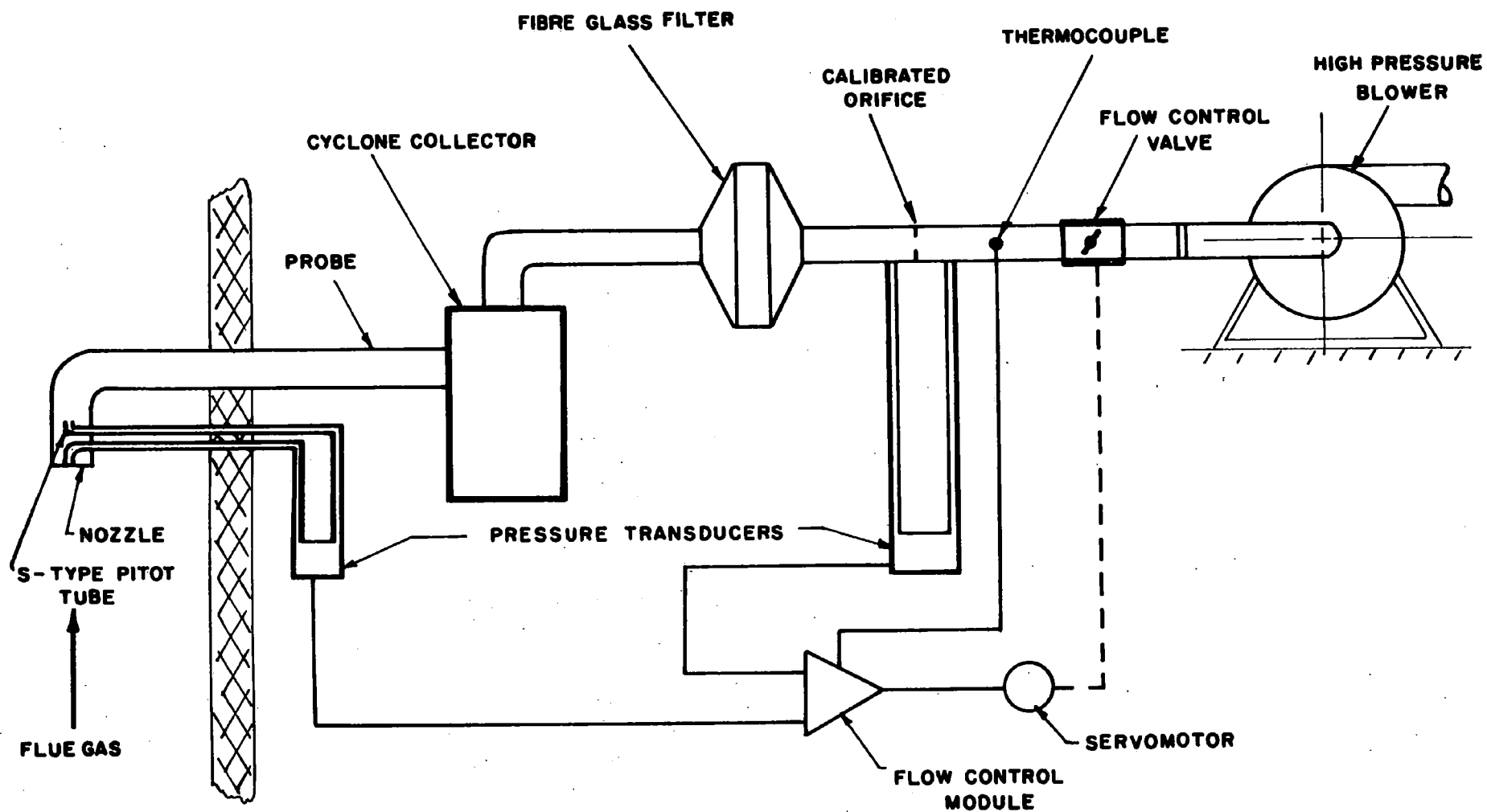
FIGURE 5.2   Illustration of automated isokinetic dust sampling system.

Station 9, and in the transition section Station 20;
each pair consisted of an air-cooled stainless steel
probe and an uncooled refractory probe. These probes
were in place for the duration of each test. The second
method of evaluating ash fouling was by examination of
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 8, 11, 19 and 20.

11. Electrostatic precipitator efficiency, measured by passing
part of the flue gas through a small electrostatic
precipitator for a period of 45 minutes, three samples per
test, Station 18. The efficiency was calculated from the
measured inlet and outlet dust loadings at Stations 16
and 21, respectively. The fly ash collected was analyzed
for carbon content, chemical composition and particle size
distribution.

12. Fly ash resistivity, measured by an in-situ, point-plane
resistivity apparatus at flue gas temperatures, of $150^{o}C$
and $315^{o}C$ at Stations 17 and 13 respectively, two
measurements at each location per test. In addition,
one measurement was taken with the flue gas temperature
at $120^{o}C$. A series of static measurments on selected
samples of fly ash extracted from the gas stream at the
precipitator inlet were also taken by Research Cottrell.

13. Acid or water dewpoint of the flue gas, by BCURA dewpoint
meter, one or two determinations per test, Station 21.

14. Furnace temperature by suction pyrometer traversed along
the vertical furnace centreline twice per test,
Stations 7, 8 and 9.

In addition, qualitative observations on flame appearance and
length, deposit build-up and appearance of ash were logged. When the furnace
was sufficiently cooled after a test, the deposition probes, furnace walls, and
second pass tube sheet of the air heater were photographed. The deposition
probes were then removed and photographed. The low-temperature corrosion probes
were also photographed.

6. EVALUATION OF TEST RESULTS

6.1 Pulverizer Performance

Grab samples of pulverized coal from each test were analyzed for moisture content, Hardgrove grindability index and size distribution. In addition, loss on ignition, which is approximately equal to the combustible content, was determined for each size fraction. The results are presented in Table 6.1. Some typical results, plotted in Figure 6.1, show a clear-cut tendency for the ash to concentrate in the smaller size fraction. This tendency, which becomes more evident as ash content increases, is related to the high clay content of the coal. When subjected to dehydration and grinding, clay can be expected to readily decrepitate into micron-size particles.

As shown in Table 6.2, the heat content of all the Hat Creek coals and the Sundance coal is much the same, 26.7 ± 1.3 Mj/kg, when calculated on a dry, mineral-matter-free basis. Since the smaller size fractions are rich in ash, for the same size distribution the higher-ash coals have less surface area available for reaction than the lower-ash coals. This can be determined by calculating a relative fineness parameter as follows:

$$S = \sum \frac{Km \, Q(1 - A)}{D}$$

where S = Relative fineness parameter, summed over the size fractions

m = Size fraction

Q = Higher heating value of the coal on mineral-matter-free basis

A = Ash content of the size fraction

D = Geometric mean particle diameter of the size fraction

K = Available surface for combustion

The results for the test coals, assuming identical surface availability for combustion are given in Table 6.2, and show that the Hat Creek coals had only 50 to 85% of the reactive surface area that Sundance coal presented. This

TABLE 6.1

Size Distribution and Loss on Ignition of Pulverized Coal Samples

Hardgrove Grindability Index	Test	RM[2] %	+ 100 [3]		100 x 140		140 x 200		200 x 325		325 x 0	
			Wt %	LOI %	Wt %	LOI %	Wt %	LOI %	Wt %	LOI %	Wt %	LOI %
43	1.1 Sundance	17.1	0.7	–	4.4	89.3	7.9	86.9	16.8	85.3	70.1	82.7
43	1.2 Sundance	16.0	0.7	–	5.8	89.4	12.9	86.1	14.0	84.9	66.5	82.6
61	2.1 A-raw	7.1	1.5	–	6.8	65.1	9.2	52.9	18.8	49.7	63.6	42.2
58	2.2 A-raw	7.4	3.0	–	10.2	66.2	13.0	54.4	19.9	48.1	53.8	42.3
44	3.1 A-washed	16.3	1.9	–	7.2	76.5	8.5	72.5	33.4	67.4	49.0	58.6
44	3.2 A-washed	16.5	7.4	82.6	21.0	76.7	9.4	73.0	17.5	70.1	44.7	61.8
48	4.1 B-raw	8.6	3.9	79.3	15.1	72.5	9.9	67.0	24.2	60.2	46.9	54.6
47	4.2 B-raw	9.3	3.8	84.1	16.8	76.6	8.6	70.5	23.3	66.6	47.4	60.2
42	4.3 B-raw	16.6	16.9	77.7	12.8	72.5	6.4	66.2	16.2	60.6	47.7	53.8
45	5.1 B-washed	8.6	12.4	80.6	17.4	78.8	8.2	76.4	14.0	75.3	48.0	68.2
44	5.2 B-washed	8.6	11.2	80.3	17.5	80.6	8.2	78.7	14.9	77.7	48.2	71.2
39	5.3 B-washed	20.3	3.1	–	17.1	83.0	9.7	79.9	23.7	76.2	46.4	69.1
45	6.1 C-raw	11.0	9.2	80.0	15.0	75.3	7.0	71.1	16.0	69.6	52.8	63.9
43	6.2 C-raw	13.0	8.5	84.2	15.2	79.4	6.7	76.8	17.2	74.9	52.5	68.6
43	6.3 C-raw	19.6	2.3	–	12.2	82.2	10.9	75.0	17.1	72.2	57.5	65.5
40	7.1 C-washed	12.8	2.5	–	13.3	84.0	10.7	81.2	18.6	81.4	55.0	76.9
38	7.2 C-washed	13.8	1.6	87.8	11.6	85.3	11.3	82.6	22.5	81.3	53.0	78.4
36	7.3 C-washed	21.8	2.1	84.6	9.5	85.5	16.1	83.7	12.1	83.0	60.4	76.2

1/ Size analyses were done on grab samples according to ASTM D197-30 (1971)
2/ RM is residual moisture in coal fed to pulverizer
3/ The mesh openings for the sieves are as follows: 149μ for 100 mesh, 105μ for 140 mesh, 74μ for 200 mesh and 44μ for 325 mesh where 1μ = 10^{-6} metres.

TABLE 6.2

Heat Content of Coal and Fineness Parameter of Reactivity

| Coal	Test Number	Heat Content Mj/kg		Coal Fineness Parameter Dry Basis
		As-fired basis	Dry, Mineral-matter-free basis	
Sundance	1.1	20.1	28.3	1.02
Sundance	1.2	20.1	28.2	0.99
A-raw	2.1	10.5	23.6	0.52
A-raw	2.2	11.9	24.5	0.48
A-washed	3.1	15.6	26.8	0.67
A-washed	3.2	15.7	26.8	0.62
B-raw	4.1	15.0	26.3	0.58
B-raw	4.2	16.9	27.0	0.64
B-raw	4.3	16.1	27.1	0.52
B-washed	5.1	17.1	24.6	0.66
B-washed	5.2	19.7	27.6	0.70
B-washed	5.3	17.1	27.1	0.73
C-raw	6.1	17.3	27.1	0.66
C-raw	6.2	17.6	27.4	0.71
C-raw	6.3	15.3	27.3	0.74
C-washed	7.1	19.8	28.1	0.84
C-washed	7.2	19.5	27.7	0.86
C-washed	7.3	17.7	27.9	0.87
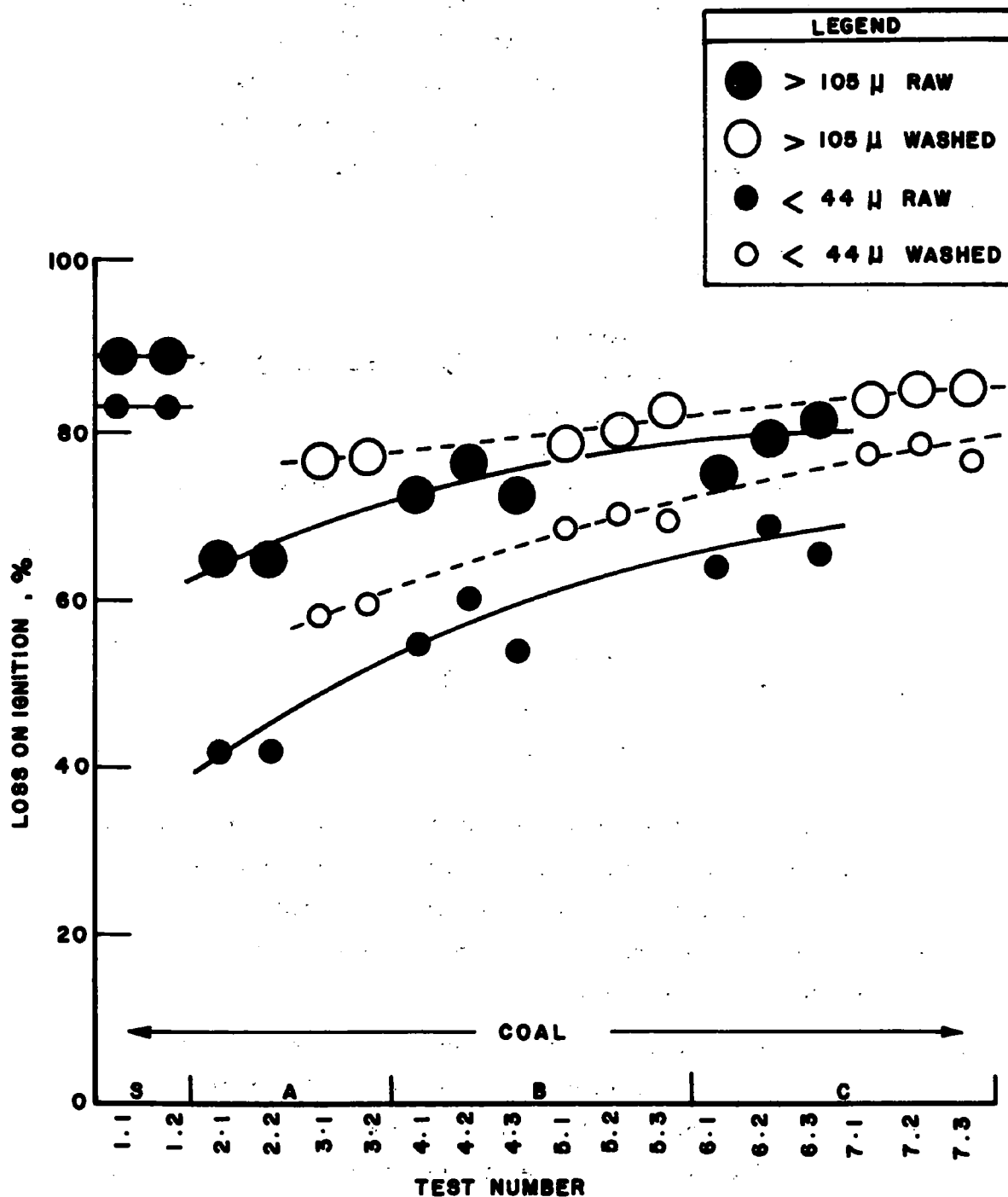
FIGURE 6.1   Loss on ignition of different size fractions of pulverized
            coal samples, moisture-free basis.

indicates the extent to which particle size distribution influences reaction
time for the various coal samples. The fact that the Hat Creek coals,
with the exception of A-raw, presented less reactive surface area to the
flame than Sundance coal but produced substantially similar flame
patterns in the CCRL furnace, reinforces the conclusion of Section 3.3.4 that
most of the Hat Creek coal samples were more reactive than Sundance coal.
The probable order of reactivity is as follows:

B-washed > $\left.\begin{array}{l} \text{B-raw} \\ \text{C-washed} \\ \text{C-raw} \\ \text{A-washed} \end{array}\right\}$ > Sundance > A-raw

This is substantially different from the order of heat content, which is as
follows:

$\left.\begin{array}{l} \text{Sundance} \\ \text{C-washed} \end{array}\right.$ > $\left.\begin{array}{l} \text{B-raw} \\ \text{C-washed} \\ \text{C-raw} \\ \text{A-washed} \end{array}\right\}$ > A-raw

It can be concluded from the foregoing that when burning Hat Creek
coal, the higher the ash content, the finer the grind should be. Or, instead,
a larger furnace could be employed in order to increase residence time. In
practise, both approaches are expensive, and beneficiation to reduce the ash
content may be a desirable alternative.

In addition to the combustion tests, some additional experiments
were carried out in which power consumption of the CCRL pulverizer was
monitored for different feed rates of B-raw coal. However, no identifiable
correlation was found, indicating that other variables such as mill temperature
and the coal's clay and moisture content had more effect on power consumption
than the feed rates used.

6.2 Combustion Performance

6.2.1 Steaming Rate

Sundance coal, the reference for the combustion tests, is sub-
bituminous in rank like the Hat Creek coals, and has a similar mineral-matter-
free heat content, as shown in Table 6.2. Thus, steaming rate can be
expected to be proportional to combustible content. The data in Table 6.3
show this to be the case. The same table shows steaming rates measured for
each test, based on the as-fired weight of coal. As expected, the steaming
rates were higher in the "3% oxygen" tests than in the corresponding "5%
oxygen" tests.

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

6.2.2 Flame Observations

Both the flame and burnout patterns for each test are shown in
Figures 6.2, 6.3, 6.4 and 6.5. Below each illustration is the test number,
the name of the coal, its residual moisture and its size analysis. The flame
pattern shown contains approximately that region where the carbon monoxide
concentration is more than 0.1% and the carbon dioxide concentration is no
more than 95% of the value measured in the flue gas. The burnout pattern,
the zone in which all combustion is completed, was estimated from what test
personnel were able to see through the various viewing ports in the furnace.
The gas temperature was measured by a suction pyrometer at L (the throat),
M (below the nose) and N (at the nose). For example, the right hand
illustration in Figure 6.2 corresponds to what was observed in test number
1.2, in which Sundance coal containing 16.0% residual moisture was burned.
The pulverized coal was 93.4% less than 200 mesh (75 microns) in size.
Glowing embers were observed in the furnace, above the nose and in the
transition piece of the furnace ahead of the test air heater tubes which are
indicated by the vertical dotted lines at the left of the illustration.
Note that the temperature determined by the suction pyrometer is significantly

TABLE 6.3

Comparison of Steaming Rates (Kg Steam per Kg Coal)

Test	$\%O_2$ in Flue gas	$RM^{a)}$ $\%$	Combustible Content, as fired, $\%$	Steaming Rate	Relative Steaming Rate[b]	Relative Firing Rate[c]
Sundance						
1.1	5	17.1	70.8	5.84	94.8	1.05
1.2	3	16.0	71.3	6.16	100.0	1.0
A-raw						
2.1	5	7.1	44.5	3.01	48.9	2.04[d]
2.2	3	7.4	48.7	3.54	57.5	1.74[d]
A-washed						
3.1	5	16.3	58.4	4.02	65.2	1.53
3.2	3	16.5	58.6	4.75	77.1	1.30
B-raw						
4.1	5	8.6	57.2	4.50	73.0	1.34
4.2	3	9.3	62.7	4.90	79.5	1.26
4.3	5	16.6	59.4	4.22	68.5	1.46
B-washed						
5.1	5	8.6	69.6	5.48	89.0	1.23
5.2	3	8.6	74.4	5.92	96.1	1.04
5.3	5	20.3	63.2	4.77	77.4	1.29
C-raw						
6.1	5	11.0	63.8	5.17	83.9	1.19
6.2	3	13.0	64.5	5.74	93.2	1.07
6.3	5	19.6	56.1	4.86	78.9	1.27
C-washed						
7.1	5	12.8	70.6	5.73	93.0	1.08
7.2	3	13.8	70.6	6.02	97.7	1.02
7.3	5	21.8	63.3	5.03	81.7	1.22

a) Residual moisture in coal as fed to the pulverizer
b) To designed firing capacity as % of the Sundance 3% steaming rate
c) To designed steaming capacity as % of Sundance 3% firing rate
d) These firing rates are judged not acceptable for designed firing capacity of B raw coal.
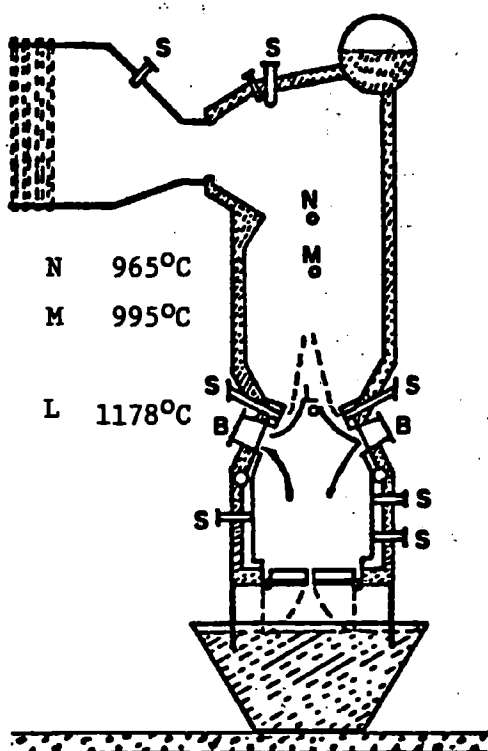
Test 1.1, RM   17.1%

    5.1% O_2 in flue gas

    82% below 200 mesh
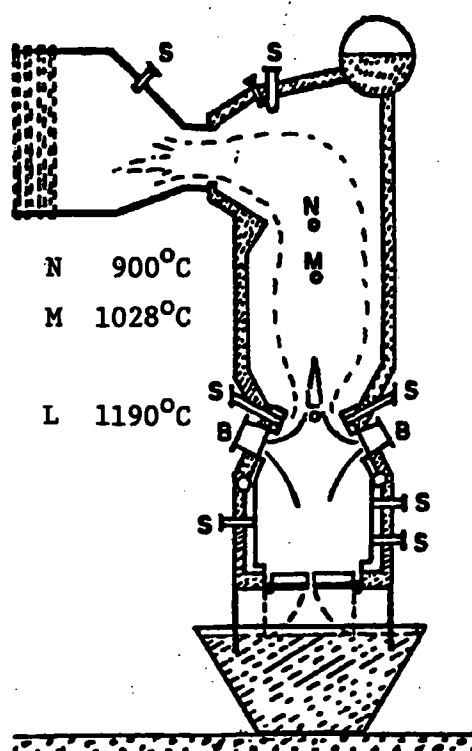
Test 1.2, RM   16.0%

    3.1% O_2 in flue gas

    93.4% below 200 mesh

FIGURE 6.2   Illustration of flame pattern (——) and burnout pattern (---) for Sundance coal.

    Legend: B burner

            S sightport

          RM residual moisture of coal feed to pulverizer

Test 2.1, A raw, RM 7.1%
76% below 200 mesh

Test 3.1, A washed, RM 16.3%
87% below 200 mesh

Test 4.1, B raw, RM 8.6%
83.6% below 200
mesh

Test 5.1, B washed, RM 8.6%
72.8% below 200 mesh

Test 6.1, C raw, RM 11.0%
73.6% below 200 mesh

Test 7.1, C washed, RM 12.8%
70.4% below 200
mesh

FIGURE 6.3   Illustration of flame pattern (——) and burnout pattern (---) of Hat Creek
coals.   Oxygen content of flue gas was 5%.

Test 2.2, A raw, RM 7.4%
76% below 200 mesh

Test 3.2, A washed, RM 16.5%
74% below 200 mesh

Test 4.2, B raw, RM 9.3%
75% below 200 mesh
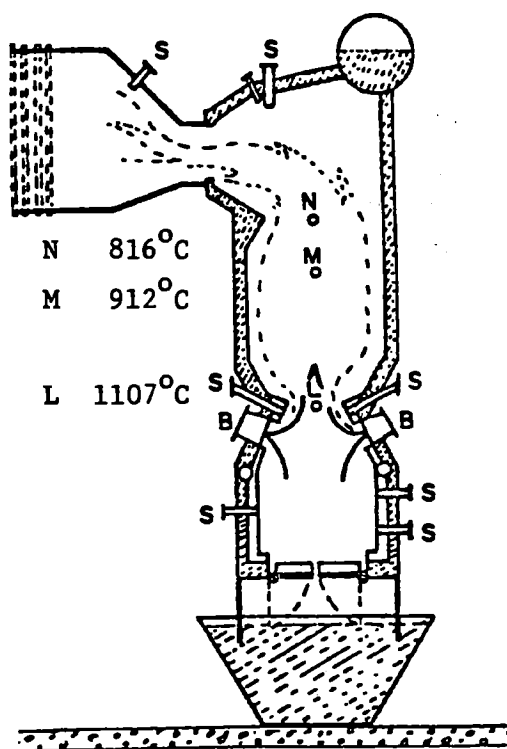
Test 5.2, B washed, RM 8.6%
74% below 200 mesh
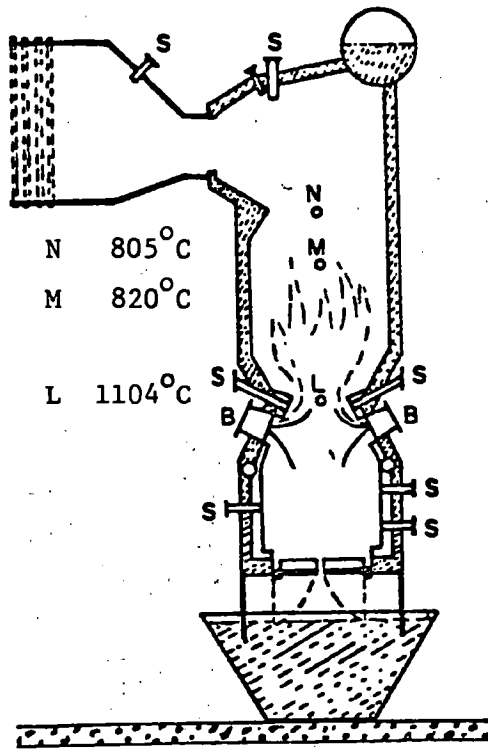
Test 6.2, C raw, RM 13.0%
67% below 200 mesh
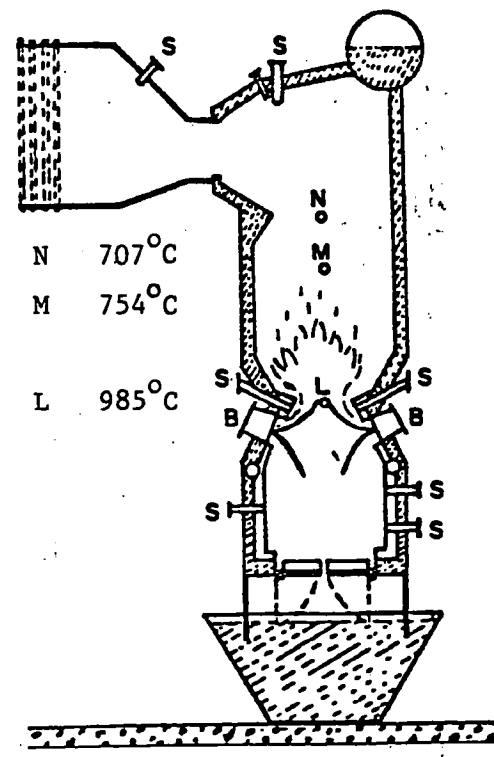
Test 7.2, C washed, RM 13.8%
75% below 200 mesh

FIGURE 6.4   Illustration of flame pattern (——) and burnout pattern of Hat Creek coals.
Oxygen content of flue gas was 3%.

N 780°C

M 855°C

L 960°C
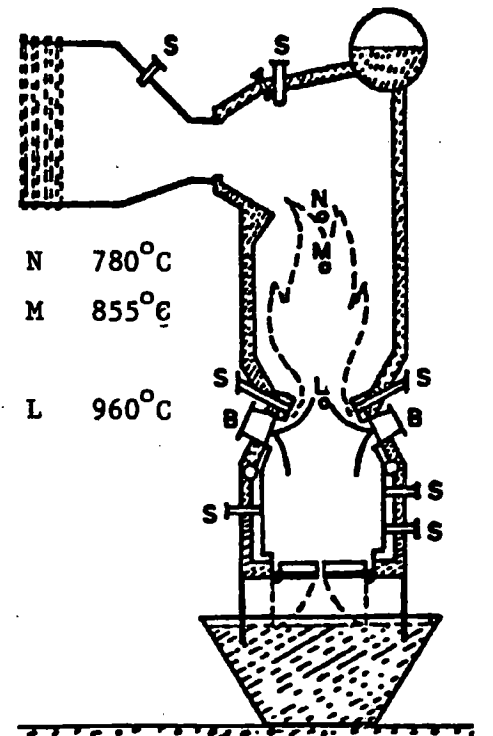
Test 4.3, B raw, RM 16.6%

82% below 200 mesh

N 799°C

M 835°C

L 976°C
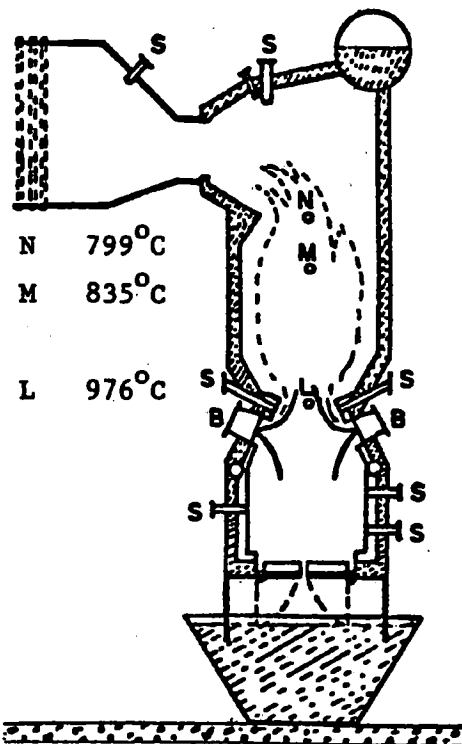
Test 5.3, B washed, RM 20.3%

83% below 200 mesh

N 909°C

M 955°C

L 1074°C
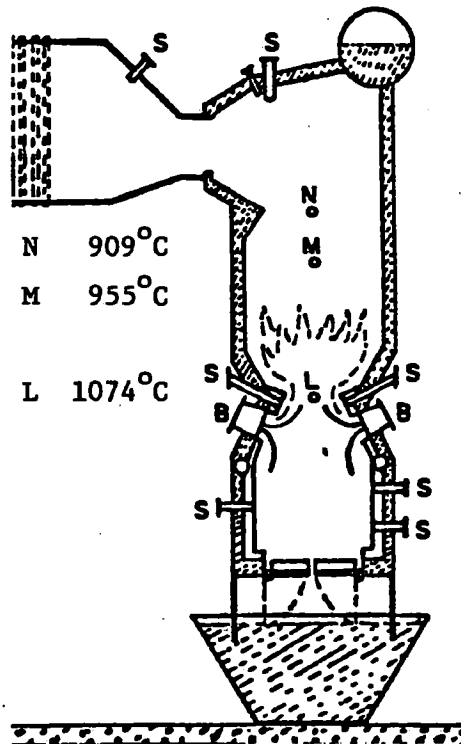
Test 6.3, C raw, RM 19.6%

72% below 200 mesh

N 770°C

M 895°C

L 1060°C
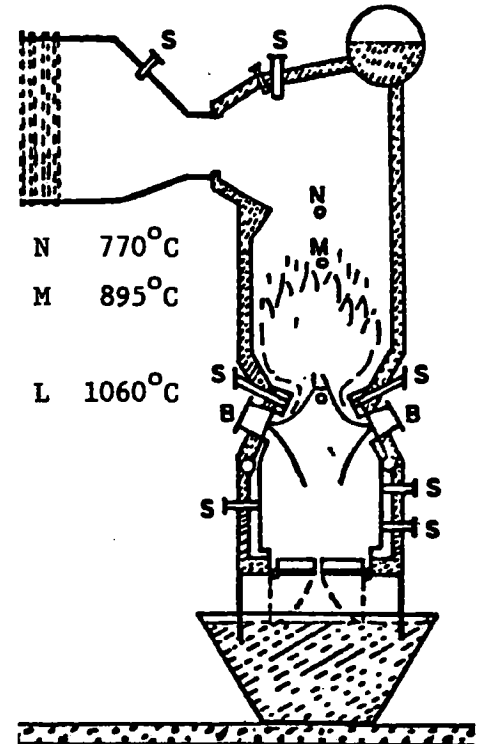
Test 7.3, C washed, RM 21.8%
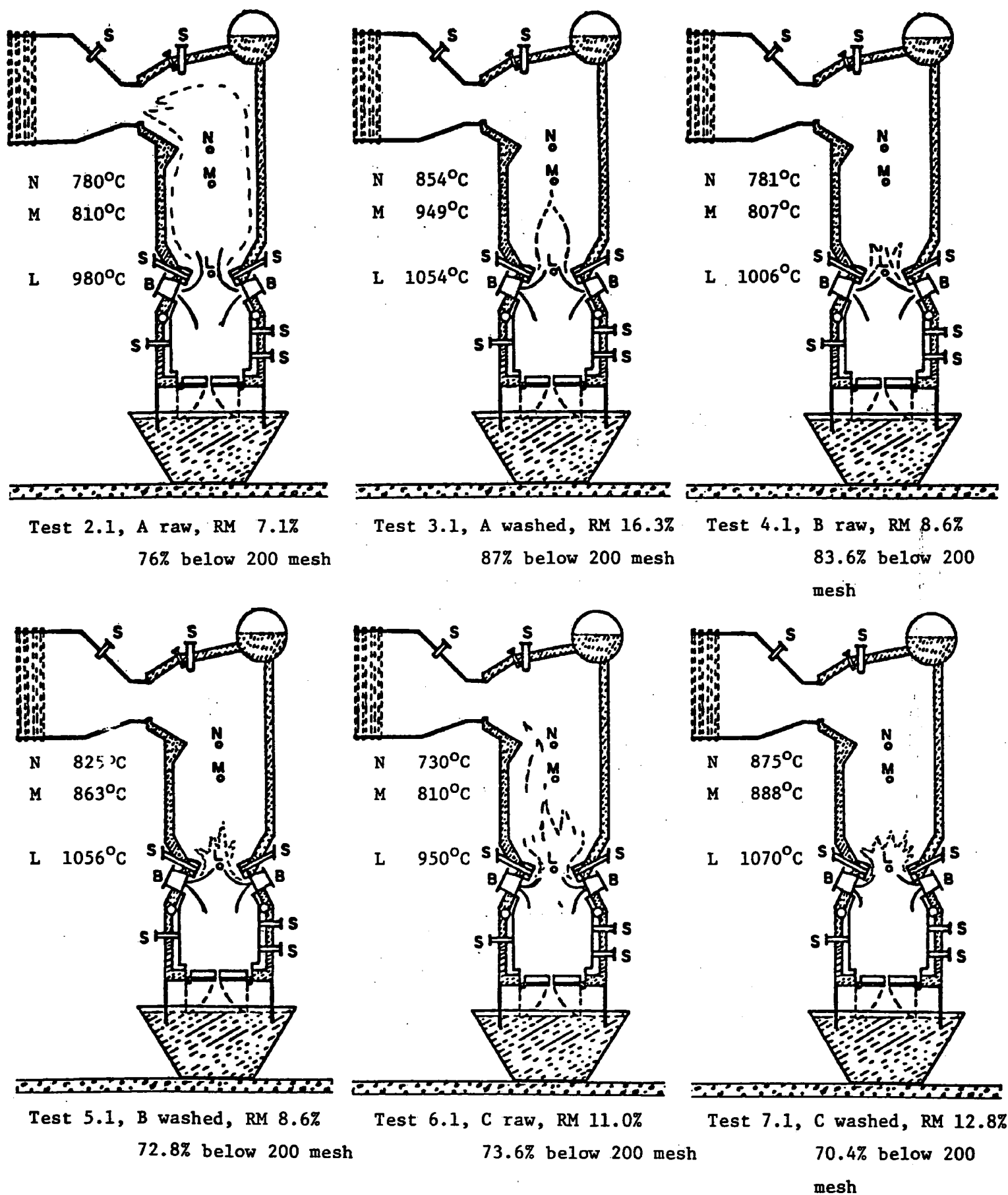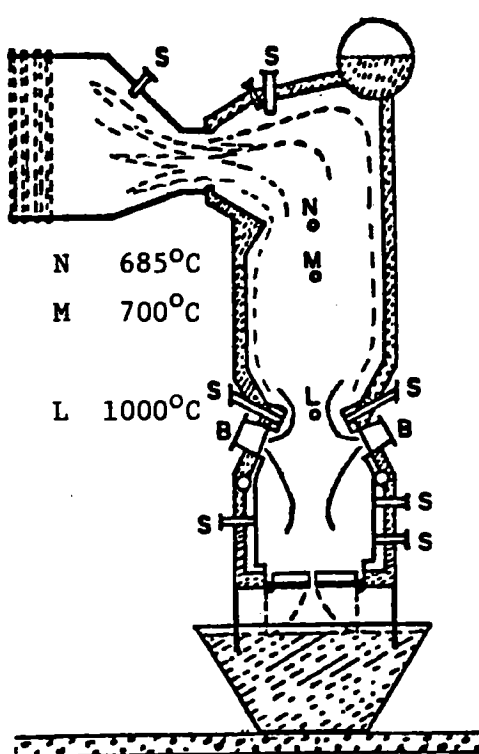
72% below 200 mesh
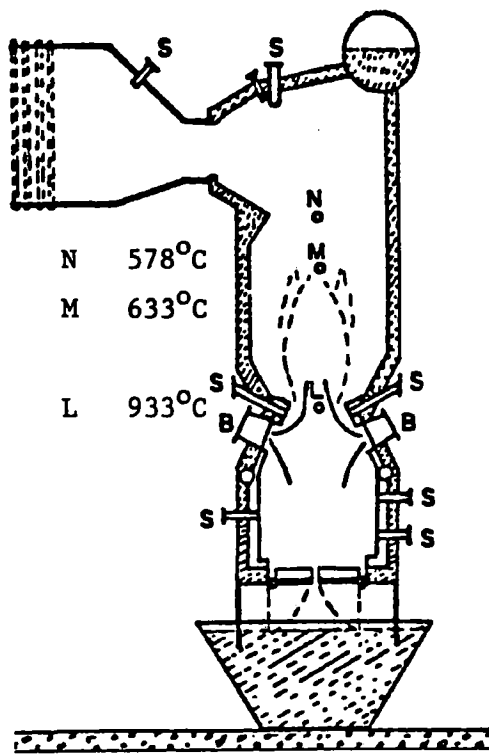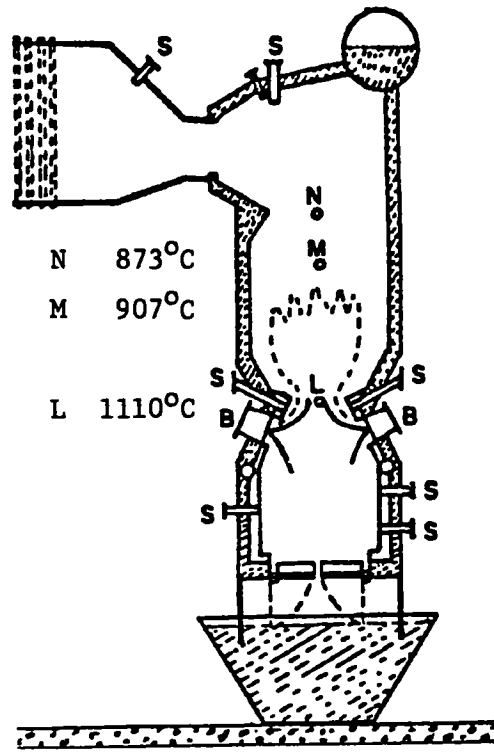
FIGURE 6.5   Illustration of flame pattern (——) and burnout pattern (---) of Hat Creek

coals.   Oxygen content of flue gas was 5%. High moisture (RM).

lower than the temperature of the flame front around a burning coal particle.

Comparison of Figures 6.3, 6.4 and 6.5 show that the burnout pattern and the flame pattern are extended when the excess air is decreased or when either the ash content or the residual moisture content of the coal are increased. This indicates that an excess air level, corresponding to 5% oxygen in the flue gas, is desirable and that beneficiation either alone or in combination with drying will reduce the furnace size. However, Table 6.3 and Table 6.4 show that the steaming rate improved at 3% oxygen while at the same time, the carbon content of the fly ash (burnout) remained reasonable.

It should be noted that the size analyses shown in Figure 6.1 have a root mean square deviation of approximately 5%, and it is reasonable to believe that the long burnout pattern of A-raw coal in test number 2.1 was due to the fact that the large size fraction was predominatly coal while the small size fraction was predominantly clay. Coarse particles collected in the transition piece and the heat exchanger and did not reach the electrostatic precipitator, whereas the fine ash particles carried over by the flue gases were the major constituent of the fly ash. This is discussed in greater detail in Section 6.2.3.

6.2.3   Carbon Carryover

The carbon content in the fly ash constitutes an energy loss which can reduce steam generator efficiency by about 3%. In Table 6.4, the loss for each test is given as per cent of heat input, calculated as follows:

$$\text{Thermal loss} = \frac{32.8 \times C \times A (1 - B)}{Q (1 - C)} \times 100\%$$

Where Q is the calorific value of the coal, Mj/kg

A is the fractional ash content of the moisture free coal

B is the fraction of the ash retained by the bottom, and

C is the fractional weight loss on ignition (LOI) of the fly ash sample.

TABLE 6.4

Thermal Loss by Carbon Carryover as % of Heat Input

Coal	Test Number	% LOI	Thermal Loss % of Heat Input	Coal Fineness			Combustion Conditions		
				(%-200m)	D µm	Deff µm	%O$_2$	% Ash	% Moisture
Sundance	1.1	1.3	0.2	82	60	71	5.1	14.6	17.1
Sundance	1.2	2.4	0.4	93	64	75	3.1	15.2	16.0
A-raw	2.1	2.0	2.7	76	65	132	5.3	52.0	7.1
A-raw	2.2	3.5	2.9	76	75	142	2.9	47.4	7.4
A-washed	3.1	4.0	1.4	64	71	105	5.1	30.3	16.3
A-washed	3.2	5.6	2.2	74	92	127	3.2	29.8	16.5
B-raw	4.1	3.8	2.3	75	81	126	5.1	37.4	8.6
B-raw	4.2	4.5	1.5	84	82	117	3.1	30.8	9.3
B-raw	4.3	3.3	1.2	82	101	150	5.0	28.8	16.6
B-washed	5.1	6.3	2.0	73	97	127	5.0	23.8	8.6
B-washed	5.2	8.6	2.1	74	95	122	3.0	21.9	8.6
B-washed	5.3	4.0	1.0	83	81	104	5.0	20.7	20.3
C-raw	6.1	4.6	2.1	74	88	122	5.1	28.3	11.0
C-raw	6.2	4.3	1.3	67	86	114	3.0	25.8	13.0
C-raw	6.3	4.5	1.9	72	73	99	4.9	30.3	19.6
C-washed	7.1	4.1	0.8	70	75	92	5.0	19.1	12.8
C-washed	7.2	4.5	0.7	75	73	89	3.0	18.2	13.8
C-washed	7.3	2.2	0.4	72	72	89	5.0	19.0	21.8

Deff $= \left(\sum \dfrac{mC}{D'} \right)^{-1}$ where m is fraction of size consist, D' is size of opening in sieve and C is the combustible content of the coal particles.

D is obtained graphically from the cumulative particle size distribution of the pulverized coal for each test.

The calorific value of carbon is assumed to be 32.8 Mj/kg.

As shown in Table 6.4, the thermal loss ranges from near zero to approximately 3%. No clear-cut trends are evident from the data, but it is reasonable to expect the loss to increase with increasing ash and moisture content of the coal, and decrease with increasing excess air. Within the range of excess air tested, however, the increase in carbon loss at low excess air is overridden by the decrease in dry flue gas loss.

Figures 6.6 and 6.7 show plots of thermal loss by carbon carryover versus the fineness parameter, described in Section 6.1, and the effective mean diameter of the pulverized coal particles. It is reasonable to suppose that particles of coal that contain much ash will burn slowly since the ash inhibits diffusion of oxygen to the reactive surface. Although A-raw coal was ground more finely than, for example, C-washed coal, its effective mean diameter was much larger and its coal fineness parameter, a measure of its reactive surface area, was much smaller. It is evident that if the high ash coals are to be burned with the same thermal loss by carbon carryover as the lower ash coals, they must be ground finer, or burned in a much larger furnace than would be required for Sundance coal.

When examined petrographically, the fly ash from the Hat Creek A coals was found to contain mostly mineral matter in the form of hollow spheres, Figure 6.8, with small amounts of carbonaceous material. As shown in Figure 6.9, this carbonaceous material consisted of partially burnt vitrinite with sparse populations of oxidized vitrinite.

The fly ash from the Hat Creek B and C coals was also mostly mineral matter, but their shape was not well defined, Figure 6.10. The small amount of carbonaceous or char material present consisted of a filamented structure, Figure 6.11, similar to the lamellations of high reflectance observed in the raw Hat Creek coals. Figure 6.12 shows that the reactives resinous material, that was originally interspersed between the filaments, apparently burned out in the flame leaving a lamellar residue. These relatively large filamented particles of char in the fly ash from the Hat Creek B and C coals can be attributed to swelling of the coal particles during initial stages of combustion.
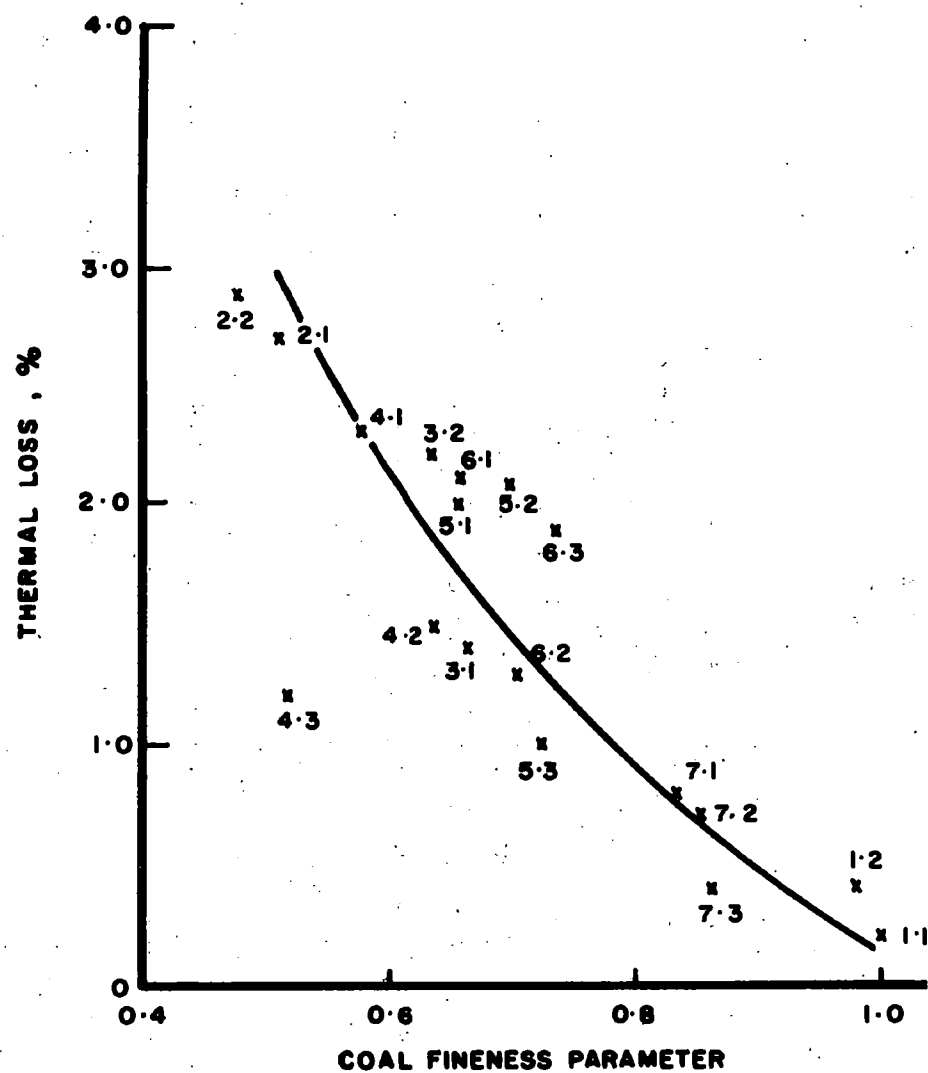
FIGURE 6.6   Influence of coal fineness parameter on thermal loss by carbon carryover.
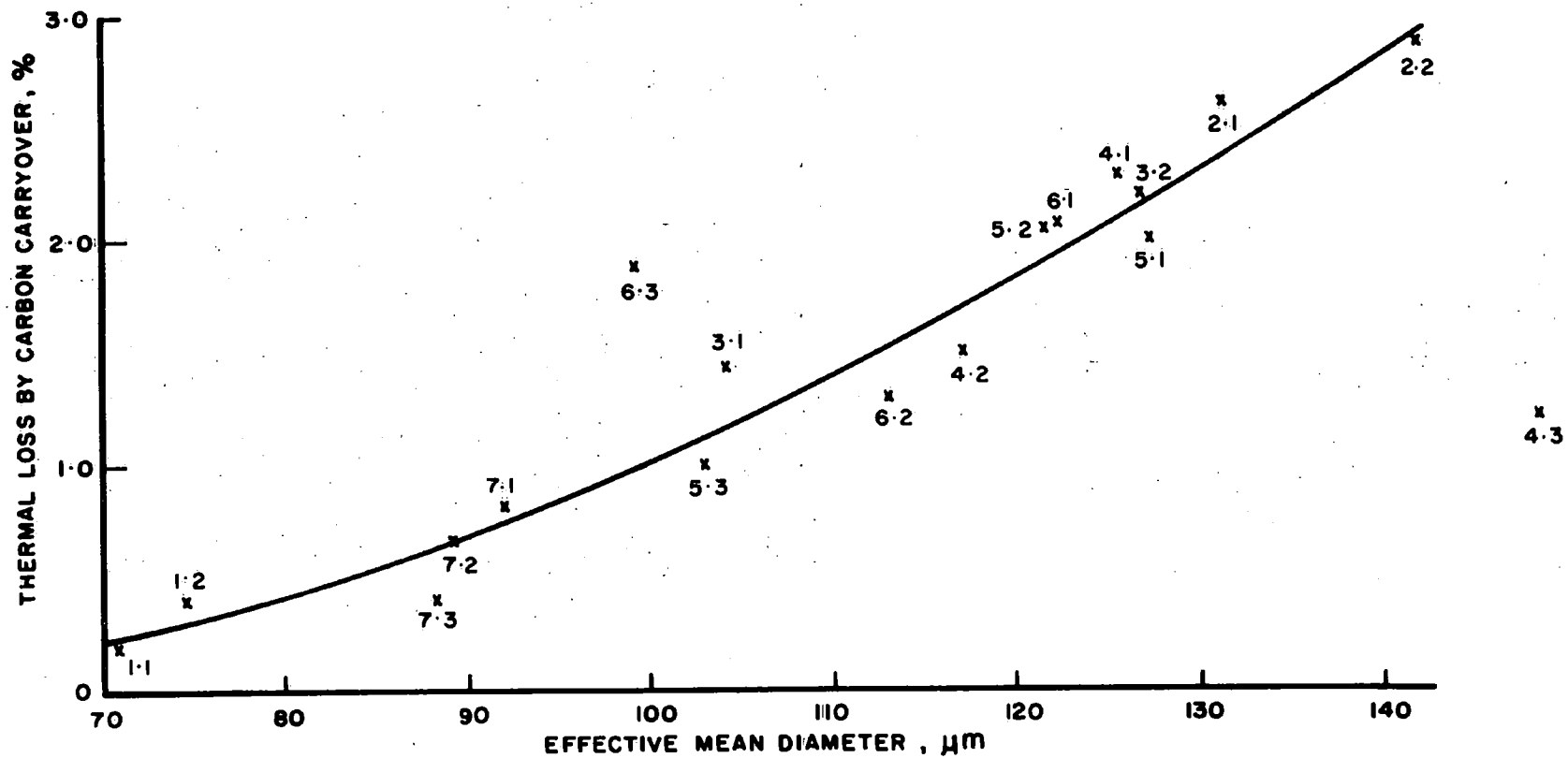
FIGURE 6.7   Influence of effective mean diameter of pulverized coal particles on thermal loss by carbon carryover.
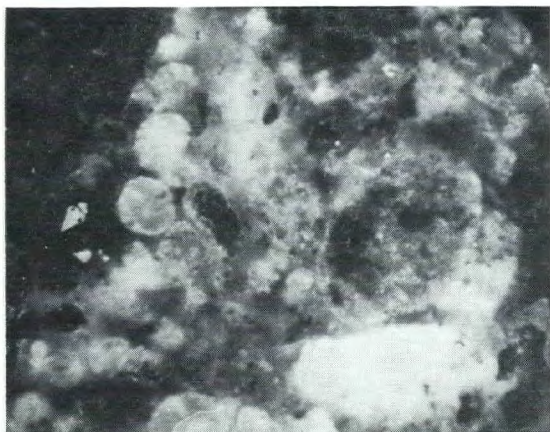
FIGURE 6.8 - Fly ash from Hat Creek
A-coal showing hollow
spheres of mineral matter.
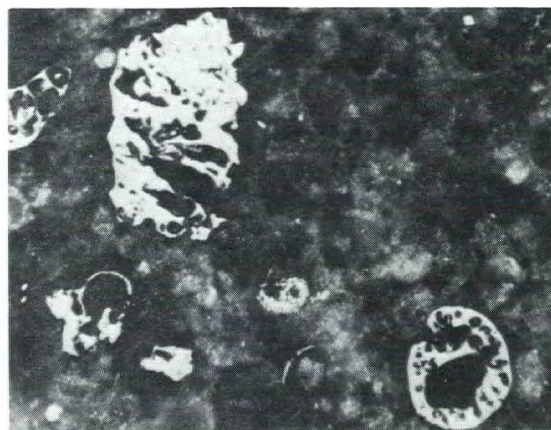
FIGURE 6.9 - Partially reactive
vitrinite(V) and
fusinite(F) in fly ash
from Hat Creek A-coal.

FIGURE 6.10 - Mineral matter in fly ash
from Hat Creek B-coal. Well
defined spheres are absent.
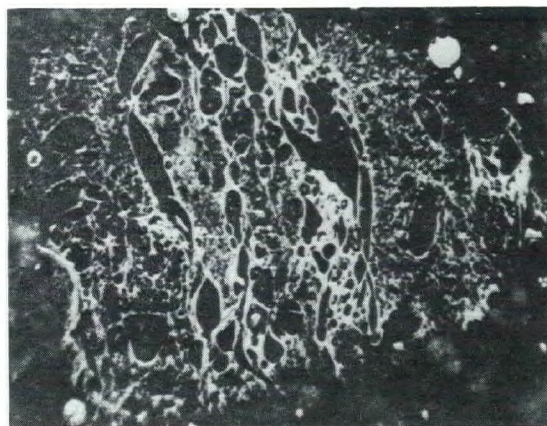
FIGURE 6.11-Carbonaceous residue in
fly ash from Hat Creek
B-coal.

FIGURE 6.12 - High reflectance carbonaceous lamellae
in the unburnt fly ash from Hat Creek
B-coal.

6.4   Fireside Deposits

6.4.1   Furnace Fouling Observations

In the course of each test, subjective observations were made concerning furnace fouling by ash. Similar observations were made concerning the appearance of the furnace after each test and both sets of observations are detailed in "A" series of progress reports.

Although no true slagging was observed, the ash formed sinter in all the tests and this affected the operation in varying degrees. With Sundance coal it posed no problem, although it might have, had operation continued for longer periods. With most of the Hat Creek coal samples, however, sinter tended to build-up on the refractory under the furnace throat and had to be removed periodically, by means of a poker inserted through the top of the furnace to prevent the deposits from blocking the gas passage to the waterwall section of the boiler. The sinters were typically light, porous and brittle; a tacky consistency indicative of partial melting was only observed in the tests with C-washed coal. In all cases they were readily knocked loose with a poker. Large sinters tended to bridge across the ash removal port in the furnace bottom, requiring the use of a poker to supplement the ash dumping mechanism, Figure 6.13.

Observations on furnace fouling are summarized in Tables 6.5 and 6.6. In terms of operational difficulties, the severity of sintering, can be ranked as follows:

Sundance	No sinter
A-raw	
A-washed, C-raw	
B-raw, B-washed	
C-washed	Moderate sinter

The fact that this ranking does not match the measured ash fusion characteristics can be attributed to the effects of moisture, ash content and coal reactivity on flame temperature.
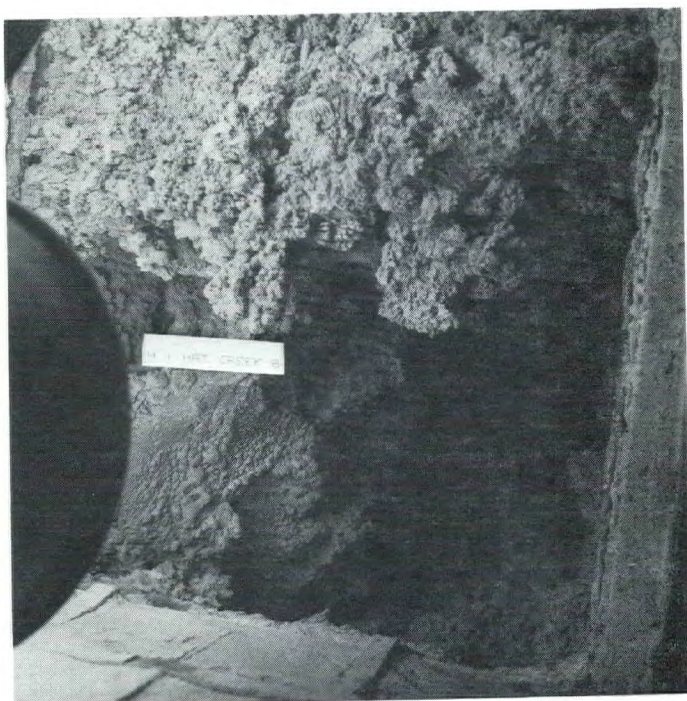
(a) Hat Creek B-raw coal

(b) Hat Creek B-washed coal

FIGURE 6.13 Build-up of sinter in the furnace bottom after about
two hours of operation.

TABLE 6.5

Furnace Deposition During Test

Test	Coal	Furance Bottom	Throat Refractory
1.1	Sundance RM : 17% O_2 : 5%	Light sinter. No dumping during test.	Sinter up to 15 cm thick
1.2	Sundance	Uniform moderate sinter on walls. Bottom $\frac{1}{2}$ full No dumping during test.	Heavy sinter blocking throat by $\frac{1}{2}$ and lengthening flame.
2.1	A-raw	Ash bridged, requiring shut-down to dump. Then operated with dump plates open. Moderate sinter on walls.	Weak sinter broke loose clearly from throat refractory when manually removed.
2.2	A-raw RM : 7.4% O_2 : 3%	Ash dumped every $\frac{1}{2}$ hr. Walls remained free of sinter.	A few large sinters up to 10 cm thick formed but fell off.
3.1	A-washed RM : 16.3% O_2 : 5%	Ash dumped every hour. Moderate sinter deposits on walls. Sinters fallen from throat were manually removed once.	Heavy sinter deposits tended to block the throat, and were manually removed once.
3.2	A-washed RM : 16.5% O_2 : 3%	Ash dumped every hour. Moderate sinter deposits on walls. Sinters fallen from throat were manually removed once.	Heavy sinter deposits tended to block the throat and were manually removed twice.

Table 6.5 (Continued)

Test	Coal	Furnace Bottom	Throat Refractory
4.1	B-raw RM : 8.6% O_2 : 5%	Ash dumped every hour. Heavy sinter deposition walls. Sinter tended to bridge the bottom opening and was manually removed three times.	Heavy sinter deposits built up rapidly, blocking the throat once. They were manually removed three times.
4.2	B-raw RM : 9.3% O_2 : 3%	Ash was dumped four times. Heavy sinter deposits on walls. Sinter bridged the bottom opening and was manually removed twice.	Heavy sinter deposits built up rapidly and were manually removed four times.
4.3	B-raw RM : 16.6% O_2 : 5%	Ash dumped every hour. Heavy sinter whiskers on walls. Fallen ash deposits were manually removed once.	Heavy sinter deposits built up periodically and were manually removed once.
5.1	B-washed RM : 8.6% O_2 : 5%	Ash dumped three times. Heavy sinter deposits on two walls. Fallen sinter and ash deposits were manually removed twice.	Heavy sinter deposits built up and were manually removed three times.
5.2	B-washed RM : 8.6% O_2 : 3%	Ash dumped three times. Heavy sinter deposits on three walls. Deposits and fallen ash tended to block sight ports, and was manually removed twice.	Heavy sinter deposits built up and were manually removed three times.
5.3	B-washed RM : 20.3% O_2 : 5%	Ash dumped twice. Sinter deposits 2 to 4 cm thick on walls, thicker in places.	Fairly heavy sinter deposits built up and were manually removed once.

Table 6.5 (Continued)

Test	Coal	Furnance Bottom	Throat Refractory
6.1	C-raw RM : 11% O_2 : 5%	Ash dumped approx. every hour. Heavy sinter deposit on one wall only tended to block sight port and was manually removed once.	Sinter deposits built up and usually fell off but were manually removed once.
6.2	C-raw RM : 13% O_2 : 3%	Ash dumped three times. Heavy sinter deposit on one wall only tended to block sight port and was manually removed once.	Sinter deposits built up and usually fell off but were manually removed once.
6.3	C-raw RM : 19.6% O_2 : 5%	Ash dumped three times. Sinter deposit 5 to 8 cm thick on one wall, less on other walls. Fallen deposits bridged and were manually removed once.	Sinter deposits built up and usually fell off but were manually removed once.
7.1	C-washed RM : 12.8% O_2 : 5%	Ash dumped three times. Fairly heavy deposit of sinter whiskers on all walls. Deposits which fell from throat were somewhat plastic.	Heavy sinter deposits of a tacky consistency built up rapidly and were manually removed four times.
7.2	C-washed RM : 13.8% O_2 : 3%	Ash dumped four times. Sinter deposits up to 20 cm thick, somewhat plastic on the surface on all walls.	Sinter deposits of a slightly tacky consistency built up rapidly and were manually removed four times.
7.3	C-washed RM : 21.8% O_2 : 5%	Ash dumped twice. Sinter whiskers 2 to 4 cm long on all walls. Some larger sinters which fell appeared to be plastic.	Ragged sinter deposits formed fairly rapidly. Some fell off but manual removal was required twice.

TABLE 6.6

Furnace Deposits After Test

Test	Coal	Furnace Bottom	Throat Refractory	Waterwalls
1.1	Sundance RM : 17% O_2 : 5%	Large lumps of friable sinter	Cohesive sinter. Some fallen off cleanly.	Thin layer of dust
1.2	Sundance RM : 16% O_2 : 3%	Most of sinter fell off leaving refractory clean.	Most of sinter fell off. Some large pieces of weak sinter.	Thin layer of dust
2.1	A-raw RM : 7% O_2 : 5%	Mostly clean. Some strong sinter 8 to 10 cm thick.	Mostly clean. Some strong sinter 8 to 10 cm thick.	Heavy layer of dust which fell off readily
2.2	A-raw RM : 7.4% O_2 : 3%	Walls clean exept for a few whiskers of sinter up to 5 cm long.	Mostly clean. A few whiskers of sinter up to 5 cm long.	Loose dust up to 2 cm thick.
3.1	A-washed RM : 16.3% O_2 : 5%	Walls clean except for a deposit of sinter in one corner.	Heavy sinter all around 20 to 40 cm thick. Sinter bridged over one burner.	Thin layer of dust
3.2	A-washed RM : 16.5% O_2 : 3%	Large lumps of weak sinter lying loose. Walls clean.	Fairly clean	Thin layer of dust

Table 6.6 (Continued)

Test	Coal	Furnace Bottom	Throat Refractory	Waterwalls
4.1	B-raw RM : 8.6% O_2 : 5%	Some large sinters adhered weakly to the walls.	Clean except for some small whiskers of sinter.	Thin layer of dust Minor sintering just above throat.
4.2	B-raw RM : 9.3% O_2 : 3%	Sinter deposits on walls 5 to 20 cm thick. One sinter 30 x 30 x 15 cm, partly supported by deposition probe.	Sinter deposits 5 to 20 cm thick.	Thin layer of dust. A few globules of sinter just above throat.
4.3	B-raw RM : 16.6% O_2 : 5%	Rough sinter deposits on walls 5 to 8 cm thick.	Some sinter deposits 5 to 8 cm thick.	Clean and shiny.
5.1	B-washed RM : 8.6% O_2 : 5%	Sinter deposit 25 cm thick on one wall. Sinter whiskers 3 cm thick on remaining walls.	Friable sinter up to 3 cm thick.	Heavy layer of dust and small sinters just above throat. Light layer of dust or remainder.
5.2	B-washed RM : 8.6% O_2 : 3%	Heavy sinter deposits on walls and large sinter bridged across.	Heavy, rough deposits of friable sinter.	Thin layer of black dust and some small globules of sinter.

Table 6.6 (Continued)

Test	Coal	Furnace Bottom	Throat Refractory	Waterwalls
5.3	B-washed RM : 20.3% O_2 : 5%	A few sinters 2 to 5 cm diam on walls.	A few sinters 2 to 5 cm diam.	Heavy layer of dust.
6.1	C-raw RM : 11% O_2 : 5%	Walls fairly clean. Loose sandy ash in corners.	Some patches of sinter 3 cm thick.	Heavy layer of grey and black dust.
6.2	C-raw RM : 13% O_2 : 3%	Weak sinter whiskers 2 to 7 cm long on walls. Several large sinters bridged across bottom opening.	Clean except for a few sinter whiskers 2 to 7 cm long.	Heavy layer of grey dust.
6.3	C-raw RM : 19.6% O_2 : 5%	Walls fairly clean. Dust and small sinters in bottom corners.	Sinter deposits 2 to 5 cm thick under each burner.	Heavy layer of dust on part of one wall. Thin layer elsewhere.
7.1	C-washed RM : 12.8% O_2 : 5%	Walls covered with sinter whiskers 5 cm long. Large, strong sinters bridged across bottom opening.	Deposits of sinter whiskers 5 to 7 cm long. On one wall, a large deposit 8 cm thick with a slagged surface.	Moderate layer of grey and black dust.
7.2	C-washed RM : 13.8% O_2 : 3%	Sinter deposit on one wall 10 cm thick. Sinter whiskers 1 to 3 cm long on other walls. Large, strong, partially slagged sinter bridged across opening.	Heavy sinter deposits all around, 15 cm thick above burners.	Thin layer of grey and black dust.

Table 6.6 (Continued)

Test	Coal	Furnace Bottom	Throat Refractory	Waterwalls
7.3	C-washed RM : 21.8% O_2 : 5%	Walls fairly clean. Some sinter whiskers 1 to 3 cm long.	Sinter deposits all around up to 15 cm thick, slagged on the surface.	A bond partway up walls heavily layered with grey dust. Remainder lightly layered.

In all tests with Hat Creek coal the furnace bottom filled with bulky sintered deposits in two to three hours. Periodic ash dumping was therefore necessary to prevent the depth of bottom ash from reaching the furnace zone where flame impingement would cause the top surface of the already sintered bottom ash to start slagging.

6.4.2   Furnace Bottom Ash

Although furnace bottom ash was periodically dumped into the water lock below the furnace bottom during the combustion trials with both Sundance and Hat Creek coals, the dry bottom ash from the final two hours of each combustion trial was retained for chemical analyses.

The wet bottom ash consisted mostly of grey-coloured mud which contained some large (20 cm) pieces of friable sinter. This muddy residue drained rapidly leaving a damp pile of sand-like granules containing about 30% water.

After every test, the dry bottom ash contained several large pieces of friable tan-coloured sinter as well as a considerable quantity of powdery material; no evidence of any molten slag residues was detected. Photomicrographs of the dry ash, typical of that shown in Figure 6.14 revealed that the sinter was an aggregation of particle agglomerates and fused spheres each with dimensions less than 100 microns and separated by many interconnecting voids. The agglomerates consisted of several micron-sized spheres cemented to one another.

The chemical analysis of the furnace bottom ash, given in Table 6.7, when compared with that of the coal ash produced according to ASTM D3176, showed that only small changes in ash composition had occurred. The Sundance reference coal showed a reduction of 1% in Na_2O content between its ASTM ash and its furnace bottom ash whereas the largest reduction occurring with the Hat Creek coals was only 0.08%. Changes in K_2O content were equally small with the sole exception of the A-raw coal where a reduction of 0.3% was recorded. The Fe_2O_3 content of the bottom ash did not show a consistent trend of depletion or enrichment when compared to the coal ash from the ASTM ashing procedure.

These changes in composition of the bottom ash can under certain furnace conditions cause the sintered bottom ash to become plastic or molten. To evaluate the potential of the bottom ash to slag the analytical data have been used to calculate the T_{250} temperature which is defined as that temperature in $^{\circ}C$ at which the viscosity of a potential slag from the bottom ash is 250 poise when 20% of the iron is present in the ferrous form. In

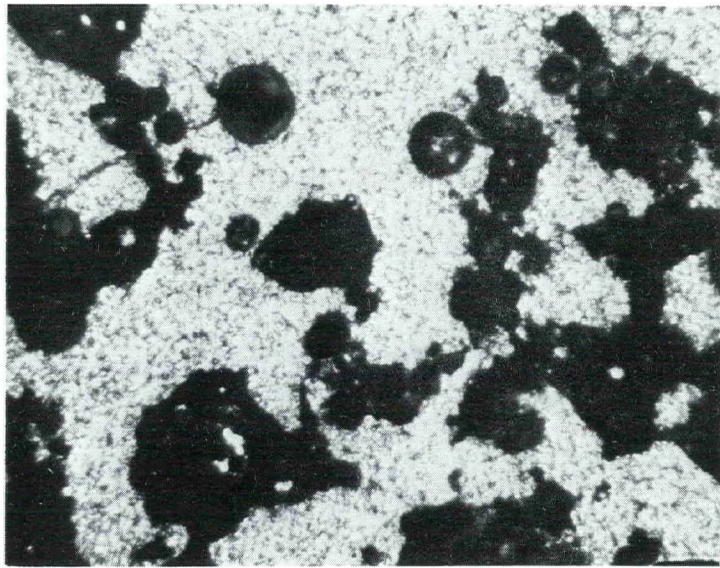FIGURE 6.14   Thin section of sintered bottom ash from
Hat Creek B-washed coal.

TABLE 6.7

Chemical Analysis of Furnace Bottom Ash

Coal	Test No.	Ash Analysis %										
		SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
Sundance	1.1	50.25	24.31	4.92	–	0.68	0.34	12.52	2.01	0.06	1.61	0.25
Sundance	1.2	52.92	25.22	4.11	–	0.71	0.33	12.31	1.26	0.08	1.15	0.27
A-raw	2.1	60.60	29.18	7.58	–	0.99	0.06	1.25	1.01	0.44	0.48	1.09
A-raw	2.2	61.40	30.01	6.54	–	1.08	0.08	1.29	1.40	0.14	0.50	1.08
A-washed	3.1	54.69	26.15	8.13	–	1.15	0.12	2.03	1.23	–	0.51	0.84
A-washed	3.2	56.52	26.64	8.04	–	1.22	0.08	2.26	1.55	–	0.56	0.82
B-raw	4.1	52.77	28.01	10.79	–	0.96	0.23	3.71	1.44	–	0.29	0.47
B-raw	4.2	55.17	30.02	8.34	–	1.02	0.28	3.66	1.25	–	0.31	0.45
B-raw	4.3	55.18	29.51	9.29	–	1.03	0.24	3.70	1.35	–	0.31	0.52
B-washed	5.1	52.17	29.38	7.69	–	1.06	0.36	3.99	1.77	0.27	0.37	0.47
B-washed	5.2	55.14	31.71	5.55	–	1.22	0.38	4.24	1.60	0.10	0.33	0.46
B-washed	5.3	54.78	30.97	6.88	–	1.19	0.33	4.29	1.39	0.17	0.31	0.49
C-raw	6.1	55.49	31.31	7.95	–	1.03	0.19	2.38	1.37	0.23	0.47	0.61
C-raw	6.2	53.61	30.85	6.97	–	1.08	0.24	2.68	1.91	0.14	0.48	0.61
C-raw	6.3	54.16	30.80	6.93	–	1.03	0.17	2.44	1.09	0.15	0.51	0.58
C-washed	7.1	55.56	32.44	6.07	–	1.16	0.30	3.33	1.58	0.12	0.54	0.68
C-washed	7.2	52.26	31.20	5.63	–	1.73	0.38	1.97	1.97	0.06	0.53	0.67
C-washed	7.3	54.78	31.34	6.84	–	1.17	0.32	3.39	1.52	0.07	0.54	0.67

the absence of experimental measurements, the value of T_{250} is generally calculated from the coal ash analysis by the method outlines below.

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

where $M = 0.00835 \ (SiO_2\%) + 0.00601 \ (Al_2O_3\%) - 0.109$

$C = 0.0415 \ (SiO_2\%) + 0.0192 \ (Al_2O_3\%) + (Fe_2O_3\%)$

$+ \ 0.016 \quad (CaO\%) \quad - 3.92$

and $SiO_2\% + Al_2O_3\% + Fe_2O_3\% + CaO\% + MgO\% = 100$

For wet-bottom furnaces the preferred slag viscoscity for easy tapping is below 100 poise and the T_{250} temperature should not normally exceed 1425^oC

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.

Severity of Slagging	$T_{250}, \ ^oC$
Low	> 1275
Medium	1400 - 1150
High	1250 - 1120
Severe	< 1205

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

Table 6.8 lists the values of Tcv and T_{250} calculated from the coal ash analysis and also the values of T_{250} calculated from the furnace bottom ash analysis.

The minimum temperature recorded for T_{250} for the ash from the Hat Creek coals was 1415^oC. This classifies all the coals as having a low to medium slagging potential. The values of T_{250} for the furnace bottom ash showed an average increase of only 16^oC in the T_{250} value for the corresponding

TABLE 6.8

Calculated Viscosity Characteristics of Hat Creek Coal Ash

Test No.	Critical Viscosity Temperature, $^{\circ}C$			
	Tcv = Hemispherical T + 110	Tcv from Ash Analysis	$T_{250\ Poise}$ from Ash Analysis	$T_{250\ Poise}$ from Bottom Ash Analysis
1.1	1470	1250	1380	1380
1.2	1498	1260	1400	1415
2.1	+ 1600	1360	1525	1530
2.2	+ 1600	1370	1515	1540
3.1	+ 1600	1330	1475	1470
3.2	+ 1600	1350	1495	1505
4.1	+ 1600	1335	1415	1435
4.2	+ 1600	1345	1440	1485
4.3	+ 1600	1355	1435	1460
5.1	+ 1600	1410	1435	1455
5.2	+ 1600	1400	1435	1475
5.3	+ 1600	1405	1435	1470
6.1	+ 1600	1410	1455	1480
6.2	+ 1600	1365	1485	1475
6.3	+ 1600	1365	1485	1490
7.1	+ 1600	1380	1475	1485
7.2	+ 1600	1380	1475	1450
7.3	+ 1600	1405	1460	1475

The critical viscosity temperature, Tcv, is the point where molten runs freely from the furnace walls.

$$Tcv\ (C^{\circ}) = 2990 - 1470 \left(\frac{SiO_2}{Al_2O_3} \right) + 360 \left(\frac{SiO_2}{Al_2O_3} \right)^2$$

$$- 14.7\ (Fe_2O_3 + CaO + MgO) + 0.15\ (Fe_2O_3 + CaO + MgO)^2$$

coal ash. This implies that the slagging potential of Hat Creek coal can be predicted reasonably well by the procedure for calculating T_{250}. The minimum value of T_{250} recorded for the bottom ash was $1440^{\circ}C$ for the Hat Creek B-raw coal which also recorded the minimum T_{250} based on the coal ash analysis. This confirms the classification of the Hat Creek coals as having a low to medium slagging potential.

Comparison of the ash fusion temperatures of the coal ash, Table 3.11, and the bottom ash, Table 6.9 , shows that in the reducing atmosphere test, the initial deformation temperature of the bottom ash averaged $100^{\circ}C$ less than that determined for the parent coal ash. The spherical softening temperature of the bottom ash was also lower than that of the coal ash; the extent of reduction measurable in the A-washed and B-raw coals was only $38^{\circ}C$. Both of these differences are within the normal variation expected for the test procedure, however, since the differences are consistent in a sense, i.e., a lower temperature was recorded for the bottom ash and since alkali metal oxide concentrations remained essentially constant, it can be concluded that the iron content of the bottom ash was higher in ferrous content than the ash prepared by the ASTM procedure. This difference did not in any way modify the prediction that the Hat Creek coals have a low to medium slagging potential.

The results of differential thermal analyses of the bottom ash from tests 1.1, 2.1, 3.1, 4.1 and 4.3 are summarized in Table 6.10. The only sample which unquestionably underwent melting at a temperature below $1160^{\circ}C$ was that from the B-raw coal during test 4.3. The other samples probably had some minor liquid phases present, however, these phases had no noticeable effect on their potential slagging properties. The absence of peaks suggests that limited fusion had occurred over a broad temperature range.

The bottom ash samples from tests 2.1, 3.1, 4.1 and 5.1 were examined under a hot stage microscope at a standard heating rate of $300^{\circ}C/hr$. All the samples behaved in a similar manner and exhibited the same physical changes at closely similar temperatures;

$1380^{\circ}C$ ± 25   Edge deformation, slight sagging

$1400^{\circ}C$ ± 25   General softening

$1550^{\circ}C$ ± 25   Flow and deformation

$1600^{\circ}C$ ± 25   Liquid flow

TABLE 6.9

Fusion Temperatures of Furnace Bottom Ash

Coal	Test No.	Oxidizing (°C)				Reducing (°C)			
		ID[a]	SS	SH	F	ID	SS	SH	F
Sundance	1.1	1332	1360	1388	1443	1310	1354	1382	1421
Sundance	2.2	1338	1371	1393	1449	1332	1360	1388	1432
Hat Creek									
A-raw	2.1	1382	1500 +	1500 +	1500 +	1260	1500 +	1500 +	1500 +
A-raw	2.2	1388	+	+	+	1238	+	+	+
A-washed	3.1	1349	+	+	+	1288	1432	+	+
A-washed	3.2	1321	+	+	+	1232	1421	+	+
B-raw	4.1	1343	+	+	+	1249	1410	+	+
B-raw	4.2	1332	+	+	+	1238	1438	+	+
B-raw	4.3								
B-washed	5.1	1310	+	+	+	1277	1399	1460	+
B-washed	5.2	1299	+	+	+	1277	1460	1500 +	+
B-washed	5.3	1338	+	+	+	1321	1477	+	+
C-raw	6.1	1421	+	+	+	1199	1500 +	+	+
C-raw	6.2	1388	+	+	+	1299	+	+	+
C-raw	6.3	1360	+	+	+	1288	+	+	+
C-washed	7.1	1399	+	+	+	1288	+	+	+
C-washed	7.2	1366	+	+	+	1332	+	+	+
C-washed	7.3	1377	+	+	+	1338	1482	+	+

a) Ash Fusion Tests were done according to D1857-74. The abbreviated titles are: ID = initial deformation; SS = softening spherical; SH = softening hemispherical; F = fluid.

TABLE 6.10

Differential Thermal Analyses of Selected Samples of Furnace Bottom Ash

Test No.	Commentary
1.1	No peaks observed; exothermic shift at $1360^{o}C$
2.1	No peaks observed; endothermic shift at $1450^{o}C$
3.1	No peaks observed; endothermic shift at $1340^{o}C$
4.1	No peaks observed; exothermic shift at $1330^{o}C$
4.3	No peaks observed; endothermic shift at $1160^{o}C$

These physical characteristics are in accord with the calculated slag viscosities given in Table 6.8.

6.4.3   Air Cooled and Refractory Probe Deposits

Descriptions of the deposits produced on air cooled stainless steel probes exposed to the combustion gases and maintained at controlled temperatures throughout each combustion trials are summarized in Table 6.11. The nomenclature used in this table is as follows:

Sinter : A deposit which had sintered throughout its entire thickness and was loosely bonded to the surface.

Crust : A deposit of sintered material overlying a scale, powder or dust deposit.

Scale : An unsintered deposit with a weakly adherent character, on removal these deposits which retained a flake-like configuration were friable.

Powder : A deposit which was easily removed.

Dust : A deposit which was totally non-adherent to the probes.

Table 6.11 shows that in the majority of cases, the deposit was an easily removed non-adherent powder. In all instances, the accumulation of deposit was small. This was due in part to the unbonded nature of the deposit which was observed to fall off the probe in the furnace bottom during several of the tests. It was only in rare cases that deposits became thick enough on the air-cooled probes in the furnace bottom for surface melting to occur; X-ray diffraction analyses of the deposits accumulated on these probes revealed that they consisted of the following identifiable components:

Major: Mullite, Quartz, Cristobalite

Minor: Magnetite or an analagous spinel
          Feldspar and Hematite

TABLE 6.11

Description of High-Temperature Deposits on Air-Cooled Stainless Steel Probes

Test No.	Probe Temp. °C	Furnace Bottom	Probe Temp. °C	Combustion Chamber	Probe Temp. °C	Transition Piece
1.1	.525	Orange Powder	451	Orange Powder	523	Orange Powder
1.2	426	Tan Powder	444	Tan Powder	473	Tan Powder
2.1	559	Tan Powder	549	Crust, Grey Powder	534	Tan Powder
2.2	493	Crust, Tan Powder	527	Crust, Tan Powder	543	Tan Powder
3.1	474	Mauve Powder	462	Grey Powder	505	Beige Dust
3.2		Probe Disintegrated	527	Scale, Tan Powder	545	Tan Powder
4.1	534	Grey Scale	538	Grey Scale	536	Tan Powder
4.2	(711)	Tan Scale	482	Grey Dust	504	Grey Powder
4.3	486	Mauve Scale	496	Mauve Scale	415	Black Scale
5.1	579	Grey Scale	516	Grey, + Mauve Scale	493	Beige Powder
5.2	495	Grey Scale	552	Grey Scale	550	Black Scale
5.3	561	Grey Scale	441	Grey Scale	586	Beige Dust
6.1	549	Grey Scale	543	Grey Scale	556	Beige Powder
6.2	545	Black Scale	529	Clean	559	Clean
6.3	469	Grey Scale + Powder	502	Black Sinter	424	Grey Powder
7.1	442	Grey Scale		Probe Broken	565	Clean
7.2	462	Grey Brown Scale	500	Black Scale	496	Grey - Beige Powder
7.3	529	Grey Sinter	523	Grey Scale	525	Clean

All were identified with approximately the same frequency and are listed in relative order of abundance.

The mullite and cristobalite both represent thermal transformation products of kaolinite and montmorillinite which existed in the parent coal ash. The quartz and some cristobalite, both of which were also present in the parent coal ash, appeared to have passed through the flame without change.

The uncooled refractory probes located adjacent to the air cooled stainless steel probes also accumulated heavy sintered deposits. These probes, which tended to equilibrate close to the combustion gas temperature at that point, were used to simulate conditions at the outer layer of a thick deposit on a cooled tube where initial melting of ash may occur. A summary description of the deposits is given in Table 6.12, using the same nomenclature employed on page 75.

The probes in the furnace bottom consistently accumulated a sintered deposit which periodically fell off the probe under its own weight during furnace operation. No fused deposits were produced during any of the tests. At the lower temperatures of the combustion chamber, the uncooled probes were all coated with a powdery ash except in Test 5.2 when a sintered deposit formed. In the transition section, all of the deposits were generally loose and powdery.

In general, deposits formed on all deposition probes throughout the test program were characterized as friable and easy to remove and were typical of those shown in Figure 6.15.

6.4.4   High Temperature Corrosion Potential

The occurrence of corrosive high temperature deposits on super-heaters and reheaters is associated with the presence of water soluble sodium and potassium salts which react at the deposit and tube interface to to produce alkali metal trisulphates [$Na_3 Fe (SO_4)_3$]. The analytical evidence from the combustion trials of the Hat Creek coals is that the total water soluble material produced on stainless-steel deposition probes controlled at $520 - 560°C$ was below 5% of the total deposit compared to the 16% from the Sundance reference coal. In addition, the water soluble sodium content of these deposits was below 0.2% and potassium was not detectable in
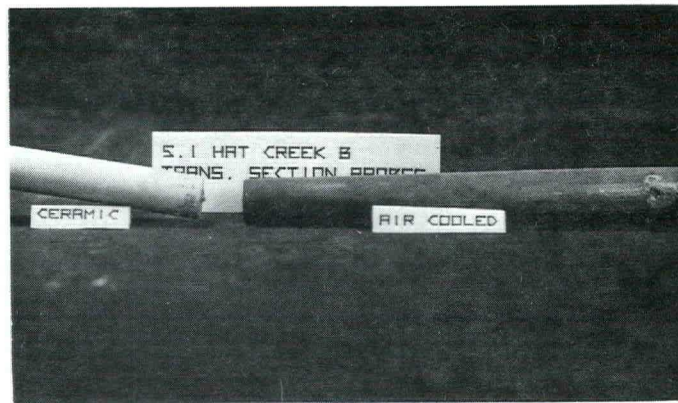
(a)   Transition Section
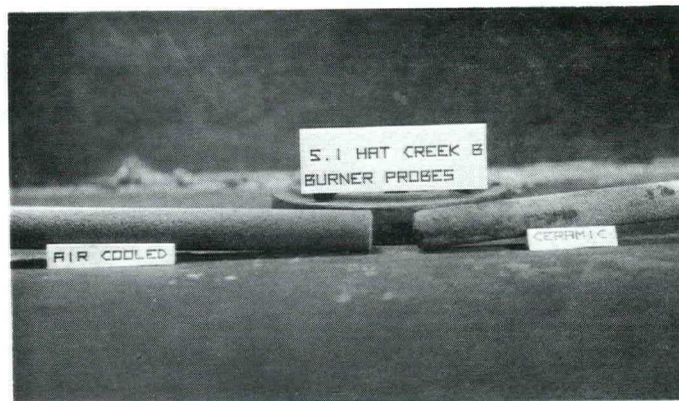
(b)   Burner
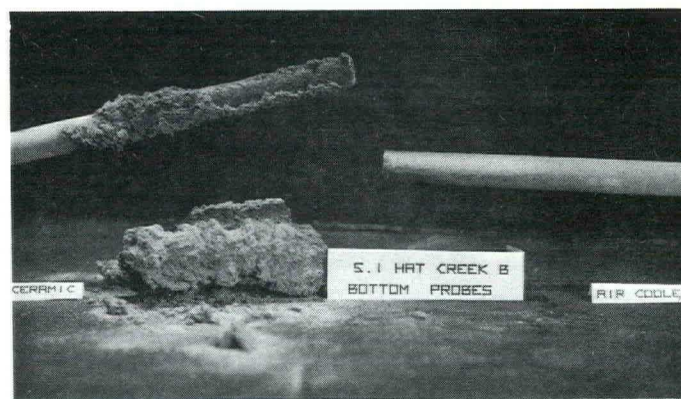
(c)   Bottom

FIGURE 6.15 High-temperature deposition probes after Test No. 5.1.

TABLE 6.12

Description of High Temperature Deposits on Uncooled Refractory Probes

Combustion Test No.	Probe Temp. °C	Furnace Bottom	Probe Temp. °C	Combustion Chamber	Probe Temp. °C	Transition Piece
1.1	1173	Tan Powder	590	Tan Powder	685	Tan Powder
1.2	1135	-	815	Tan Powder	682	Tan Powder
2.1	928	-	835	Tan Scale	619	Tan Scale
2.2	1031	Tan Crust	766	Clean	577	Tan Scale
3.1		-	860	Grey Powder	626	Tan Powder
3.2	1058	Orange Sinter	774	Tan Sinter	612	Tan Scale
4.1	1101	Brown Crust	784	Grey Scale	601	Grey-Tan Powder
4.2	1220	Grey Sinter	781	Black Scale	640	Tan Dust
4.3	1123	Tan Sinter	829	Grey Scale	617	Clean
5.1	1080	Tan Sinter	743	Grey Scale	621	Tan Powder
5.2	-	Tan Sinter	768	Tan Sinter	624	Tan Dust
5.3	990	Tan Scale	745	Grey Scale	622	Tan Dust
6.1	1000	Grey Scale	761	Grey Scale	581	Grey-Tan Powder
6.2	1008	Grey Sinter	792	Grey Scale	572	Clean
6.3	1114	-	655	Grey Scale	563	Grey Powder
7.1	990	Blade Scale	489	Grey Scale	628	Clean
7.2	1051	Tan Sinter	750	Grey Scale	630	Grey Scale
7.3	968	Grey Sinter	858	Scale	635	Clean

other than trace quantities, i.e., less than 0.05%. Since postulated mechanisms for high temperature corrosion involve an SO_3 transport across a molten interface between the bulk combustion products and the tube metal, these results suggest that the Hat Creek coals all have a lower potential for high temperature corrosion problems than posed by the Sundance reference coal.

6.4.5   Low Temperature Corrosion

Low temperature corrosion is produced by condensation of gas-phase SO_3 onto metal surfaces below the acid-dewpoint. The condensed acid (H_2SO_4) can react with air heater and/or economizer tubes to give rise to $FeSO_4$.

The measured SO_3 concentrations in the combustion products from the Hat Creek coals were all below 3 ppm - a level normally associated with minimal low temperature corrosion. No acid dewpoints were measurable.

The deposits produced on cylindrical probes exposed to the flue gases at controlled probe temperatures of 104°C, 121°C and 138°C, Figure 6.16, were all dry non-adherent powders which were easily removed by a soft brush. These deposits were dominantly collected on the upstream face of the probes.

Analyses of the water soluble components of these deposits were used to calculate the deposition rate of free acid (mg/m^2 hr) for each test as summarized in Table 6.13.

The persistence of the free acid increased as the excess-air level and the sulphur content of the various Hat Creek coals increased. The most significant modifying effect was the amount of CaO persent in the coal ash. Major quantities of water soluble calcium were recorded in the low temperature deposits from the Sundance and the Hat Creek A coals. In all other cases the dominant water soluble cation on the corrosion probes was iron.

Although an acid dewpoint was not detected in the flue gases, the presence of free sulphuric on low temperature probes exposed for over eight hours is not surprising. Conversion to acid can occur "in situ" after deposition and be accelerated by the presence of iron oxide(s).

The existence of free acid indicates some potential for low temperature corrosion on surfaces designed to operate at temperatures below 120°C (250°F).   The analysis of the water soluble deposits shows that

TABLE   6.13

Free Acid in Low-Temperature Corrosion Probe Deposits

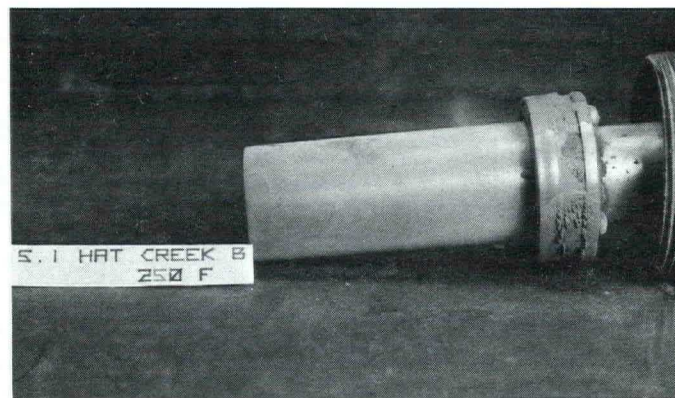| Test No.	Sulphur Content of Coal %	Free Acid; mg/m² hr H₂SO₄ at Controlled Temperature T		
		T = 138°C	T = 121°C	T = 104°C
1.1	0.21	Nil	Nil	Nil
1.2	0.18	Nil	Nil	Nil
2.1	1.12	13.7	26.5	17.3
2.2	1.08	Nil	43.5	Nil
3.1	1.2	148	125	104
3.2	1.2	Nil	Nil	Nil
4.1	1.1	129	83	73.4
4.2	0.91	34.3	Nil	27.8
4.3	0.92	6.1	29.7	4.3
5.1	0.78	176	38.4	16.6
5.2	0.90	Nil	Nil	Nil
5.3	0.77	Nil	Nil	Nil
6.1	0.70	Nil	Nil	Nil
6.2	1.17	Nil	5.8	5.0
6.3	0.62	Nil	Nil	7.2
7.1	0.71	Nil	Nil	Nil
7.2	0.75	9.1	Nil	Nil
7.3	0.74	2.2	Nil	Nil

FIGURE 6.16   Low-temperature corrosion probe

free acid accumulation and hence low temperature corrosion will be minimized
by operation of the system at an excess-oxygen level of 3% and by maintaining
all heat transfer surfaces above $130^{o}C$ ($265^{o}F$). At 5% excess oxygen the
minimum acceptable surface temperature will be about $5^{o}C$ higher.

6.5 Gas-Phase Pollutants

6.5.1 Behaviour of Sulphur during Combustion

The oxidation of sulphur during the combustion process can lead to
the production of both sulphur dioxide and sulphur trioxide. The dioxide is
the primary product of the oxidation of fuel sulphur and the trioxide is the
product of reaction between the dioxide and atomic oxygen which is generated
in the high temperature flame. Further production of sulphur trioxide can
occur at lower temperatures by reaction between sulphur dioxide and
molecular oxygen. This low temperature oxidation is catalyzed by clean
metallic (Fe) surfaces or by such ash constituents as Fe_2O_3 or V_2O_5.

It is generally observed that the production of sulphur trioxide
in boiler combustion systems represents less than 5% of the gas phase sulphur
oxides. There is also potential for the removal of both sulphur oxides from
the gas phase by reaction with the basic constituents of the ash, e.g. Na_2O
K_2O, CaO, to produce sulphates. The extent of this neutralization is
dependent on the concentration of the available basic oxides and the extent
to which they can be volatilized during the combustion process. Small
reductions in the gas phase sulphur oxides can also occur by absorption on
and reaction within high and low temperature deposits and by physical
absorption on acidic ash constituents such as SiO_2 and Al_2O_3.

6.5.2 Sulphur Trioxide Emissions

Measured sulphur trioxide levels during the pilot-scale combustion
trials at CCRL were all below 4 ppm. The absence of a measurable acid
dewpoint confirms this low level of SO_3 production. This is an extremely low
level and cannot be considered to pose an emission problem.

6.5.3   Sulphur Dioxide Emissions

The range of sulphur contents of the Hat Creek coals (0.62 to 1.2%) means that the theoretical maximum emission of sulphur dioxide ranges from 24.8 to 48 lbs SO_2 per ton of dry coal. The actual emissions shown in Table 6.14, ranged between 20.7 and 38.6 lbs SO_2 per ton of dry coal. The difference between the theoretical and measured values can, in part, be accounted for by the neutralization processes outlined in Section 6.5.1.

A sulphur balance based on the measured concentrations of gas phase sulphur dioxide and the chemical analysis of the ash retained in the various parts of the boiler are presented in Table 6.15. These results show that the sulphur balance accounts for about 70% of the input sulphur for the B and C coals with the exception of C-raw coal at 3% oxygen. Since the tests with C-raw coal were all performed using the same coal and the sulphur content reported on a moisture free basis, the high sulphur content (1.17%) reported for Test 6.2 must be regarded as anomalous. Short term variations in the sulphur content of the coal fed to the pulverizer can be sufficient to account for a sulphur balance between 75 and 110% of the input sulphur, but it is unlikely that a well-blended coal sample would lead to an error of over 45% in the sulphur balance.

The results for the A-raw coal show that the gas phase sulphur dioxide accounts for less than 50% of the input sulphur. The reason for this is not clear since the fuel sulphur analyses for all of the A-raw coals are both self-consistent and consistent with the sulphur content of all of the A-washed coals.

The retention of sulphur within the pilot-scale boiler was generally low. When expressed as a percentage of the input sulphur, maximum retentions of 0.9% in the furnace bottom, 5.2% in the gas-borne fly ash and 6.0% in the airheater deposits were recorded for all Hat Creek coals except A-raw.

The high degree of sulphur retention in the fly ash of the Sundance reference coal, with a consequent reduction in the gas phase sulphur dioxide concentration, was expected because of its high alkali and alkali-earth content.

In summary, it appears that if the sulphur neutralization characteristics recorded in the pilot-scale furnace are duplicated in a full

TABLE   6.14

Theoretical and Measured Sulphur Dioxide Emissions

Pilot-Scale Combustion Test No.	Excess Oxygen %	Fuel Sulphur %	Sulphur Dioxide Emissions					
			Theoretical Maximum			Measured Concentrations		
			ppm	lb SO_2/ton Coal dry	lb $SO_2/10^6$ Btu	ppm	lb SO_2/ton Coal dry	lb $SO_2/10^6$ Btu
1.1	5.1	0.21	185	8.4	0.40	80	3.7	0.18
1.2	3.1	0.18	179	7.2	0.35	88	3.5	0.17
2.1	5.3	1.12	1964	44.8	4.60	909	20.7	2.13
2.2	2.9	1.08	1957	43.2	3.90	1158	25.6	2.31
3.1	5.1	1.2	1374	48.0	2.99	968	33.8	2.11
3.2	3.2	1.2	1537	48.0	2.96	1000	31.3	1.93
4.1	5.1	1.1	1420	44.0	3.11	937	29.1	2.06
4.2	3.1	0.91	1164	36.4	2.27	1016	31.8	1.98
4.3	5.0	0.92	1025	36.8	2.22	1076	38.6	2.33
5.1	5.0	0.78	815	31.2	1.72	731	28.0	1.54
5.2	3.0	0.90	1014	36.0	1.94	707	25.1	1.35
5.3	5.0	0.77	758	30.8	1.67	691	28.1	1.52
6.1	5.1	0.70	798	28.0	1.68	745	26.1	1.57
6.2	3.0	1.17	1407	46.8	2.68	768	25.6	1.47
6.3	4.9	0.62	709	24.8	1.51	706	24.7	1.50
7.1	5.0	0.71	681	28.4	1.45	685	28.6	1.46
7.2	3.0	0.75	810	30.0	1.54	677	25.1	1.29
7.3	5.0	0.74	705	29.6	1.52	612	25.7	1.32

TABLE 6.15

Sulphur Retention in CCRL Pilot-Scale Boiler

Test No.	Fuel Sulphur	Sulphur Distribution			
		Furnace Bottom	Air Heater Section	Fly Ash	Gas Phase
	%	%	%	%	%
1.1	0.21				45.0
1.2	0.18				48.6
2.1	1.12				46.3
2.2	1.08				59.2
3.1	1.20		2.6	1.9	70.5
3.2	1.20		2.6	1.7	65.2
4.1	1.10		6.8	3.6	66.2
4.2	0.91		3.0	2.7	87.2
4.3	0.92		5.7	5.2	[105.0]
5.1	0.78	0.9	3.7	1.8	89.5
5.2	0.90	0.3	2.7	1.9	69.6
5.3	0.77	0.5	2.6	0.3	91.0
6.1	0.70	0.4	4.5	3.0	93.5
6.2	1.17	0.4	2.4	1.1	54.9
6.3	0.62	0.5	6.0	2.2	99.3
7.1	0.71	0.4	3.4	1.5	[100.7]
7.2	0.75	0.3	4.0	1.2	83.8
7.3	0.74	0.2	4.0	1.1	86.8

scale system the sulphur dioxide emission will be 80 ± 10% of the input sulphur. This applies to coals with the general specification of the A-washed and both of the B and C coals. The test results indicate that the A-raw coal behaves differently and offers a higher chemical neutralization or physical absorption capacity due to the large amount of extraneous clay in this coal.

6.5.4   Nitric Oxide Emissions

Nitric oxide is the dominant oxide of nitrogen formed in combustion processes and its role in the formation of photochemical smogs has been well documented in the past two decades. In addition, nitrogen dioxide, which is a product of the atmospheric oxidation of nitric oxide, is toxic in its own right.

The flame reactions which lead to nitric oxide production in flames can be grouped into the following two categories:

1.   reactions involving atmospheric nitrogen
2.   reactions involving fuel nitrogen

Yields of nitric oxide from atmospheric nitrogen are increased by increasing flame temperatures and increasing oxygen availability. Since increased excess-air levels produce a decrease in flame temperature it could be expected that an optimum excess-air level will exist at which a maximum nitric concentration will occur in the combustion products. This maximum has been observed in gas-fired systems. Yields of nitric oxide from fuel nitrogen reactions are increased by increasing fuel nitrogen content and increased oxygen availability.

In coal fired boilers, where both reaction processes leading to nitric oxide production can occur, it has been found that the effects of oxygen availability are dominant. The practical result is that increasing the excess-air level increases the nitric oxide emission.

These trends are followed in the nitric oxide yields from the combustion experiments at CCRL. In those instances where there is a negligibly small change in fuel nitrogen content, i.e., Tests 1.1, 1.2, 3.1, 3.2, 7.1 and 7.2, the reduction in excess oxygen level from 5% to 3% resulted in lower nitric oxide emissions. In the other tests the effects of

reduced excess-air level were offset by increases in the fuel nitrogen content.

In all instances the combustion of the washed coal produced higher nitric oxide emissions on a thermal basis than did combustion of the raw coal. This reflects the higher combustion intensities with washed coal which lead to a higher conversion of atmospheric nitrogen to nitric oxide.

The effect of coal moisture content on the emission of nitric oxide was not consistent. When the coal nitrogen content remained constant - as in Tests 7.1 and 7.3, the nitric oxide emission per ton of coal was reduced at the higher moisture content. This effect, due to reductions in flame temperature from the thermal load of the moisture in the coal, was more than offset in all other experiments by conversion of the increased fuel nitrogen content to nitric oxide.

The concentrations of nitric oxide measured in the CCRL combustion trials are shown in Table 6.16. Again the results are presented for both the "dry" and "as pulverized" moisture content. It is significant that the best quality Hat Creek coal (C-washed) yielded the highest furnace temperatures and gave the highest nitric oxide emission in the pilot scale unit. It can be anticipated that this trend will be duplicated in large scale systems although the actual emission levels will be different depending on the furnace and burner design. The mechanisms of nitric oxide formation are strongly system and burner dependent; for example, tangentially fired units consistently produce lower nitric oxide emissions than do front or opposed wall fired units[3].

It is unlikely that there will be any requirement for nitric oxide control by staged combustion, external flue gas recirculation or flue gas scrubbing. The first two of these control techniques produce a deterioration in the degree of burn-out of the carbonaceous material in the fuel which cannot be tolerated in a low quality fuel. The last technique, in addition to the energy penalties associated with its implementation, may result in a liquid waste disposal problem.

TABLE 6.16

Nitric Oxide Emissions

Test No.	Excess Oxygen %	Measured Nitric Oxide (NO) ppm	Calculated Nitrogen Dioxide (NO$_2$)	
			lb/ton Coal (dry)	lb/10^6 Btu
1.1	5	600	19.3	0.77
1.2	3	567	16.9	0.69
2.1	5	276	4.7	0.45
2.2	3	450	6.6	0.55
3.1	5	595	14.8	0.77
3.2	3	608	14.2	0.73
4.1	5	519	11.7	0.76
4.2	3	580	12.1	0.68
4.3	5	587	13.5	0.68
5.1	5	563	15.4	0.78
5.2	3	667	17.2	0.85
5.3	5	644	17.6	0.76
6.1	5	581	14.5	0.77
6.2	3	693	16.0	0.80
6.3	5	690	17.2	0.84
7.1	5	958	29.1	1.29
7.2	3	741	20.5	0.90
7.3	5	653	19.8	0.80

6.6.   Fly Ash Characteristics

6.6.1   Dust Loading and Particle Size Distribution

The dust loadings measured at the inlet of the electrostatic precipitator are shown in Figure 6.17 and Table 6.17. Table 6.17 also shows the amount of total input ash calculated from the ultimate analysis of each coal and the weight percentage of ash retained in both the furnace bottom and in the flue gas ducting.

In the Hat Creek tests, about 27% of the total ash was retained in the furnace bottom with another 50% being retained in the ducts and boiler hoppers. The remaining 23% of the total ash was entrained in the flue gas at Station 7, the inlet to the precipitator. This apportionment of ash, which is specific to the CCRL pilot-scale boiler, will vary from boiler to boiler depending on aerodynamic factors such as system geometry and gas velocity. It is, however, significant that a large proportion (> 75%) of the ash settled out upstream of the precipitator with all of the Hat Creek coals except A-raw.

These data indicate that dust loadings at the dust collector inlet of a full-scale boiler can be reduced substantially by designing the boiler system to trap as much ash as possible in the furnace, economizer and air-heater hoppers.

Particle size analysis of fly ash samples taken from the tube sheet between the second and third pass of the airheater and the electrostatic precipitator, showed that most of the large fly ash particles were trapped in the airheater hopper by inertial separation. A typical plot of the particle size distribution for fly ash from B-washed coal is shown in Figure 6.18. When plotted on log-normal graph paper, the results of these particle size analysis closely approximate a straight line as shown in Figure 6.19; the data from all of the other tests showed the same log-normal distribution. Consequently, rather then show a separate graph for each of the 18 tests, the volume geometric mean diameters (Dg) and the geometric standard deviations (σg), which is defined by

$$\log \sigma g = \tfrac{1}{2} \log \frac{Dg(84)}{Dg(16)} \, ,$$

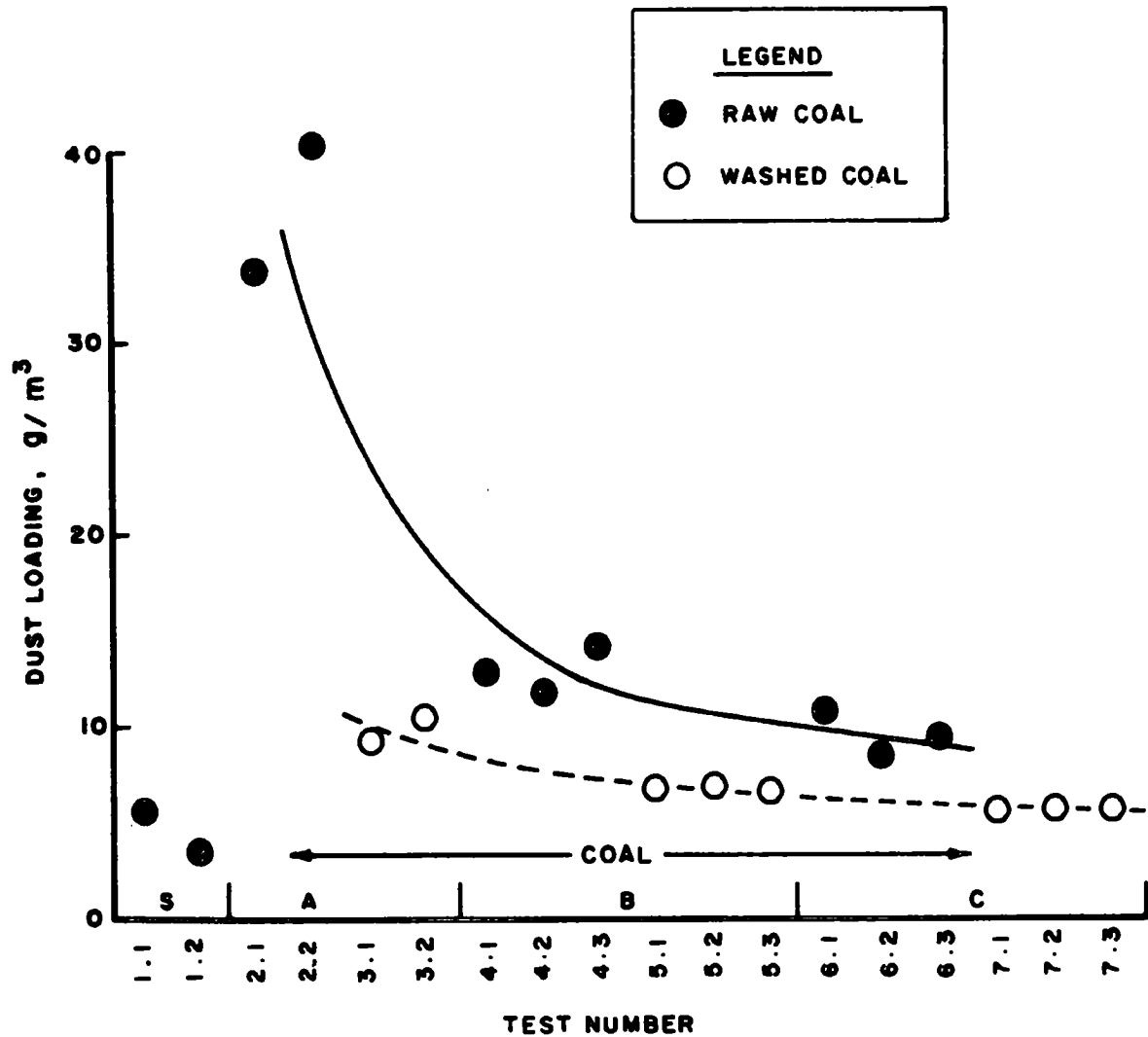are summarized in Table 6.18.

FIGURE 6.17   Dust loading of the flue gas measured at entry to
electrostatic precipitator, corrected to 20°C and
1 atm. pressure.

TABLE 6.17

Dust Loading at Precipitator Inlet and Ash Retention in CCRL Pilot-Scale Boiler

Coal		Test No.	Dust Loadings, g/m³ at 20°C		Ash Retention, wt %		
			Calculated Input	Measured at Precipitator Inlet	In Furnace Bottom	In Flue Gas Ducting	At Precipitator Inlet
Sundance		1.1	17.8	3	17.3	65.8	31.7
Sundance		1.2	20.4	3.1	15.5	69.5	15.0
Hat Creek	A-raw	2.1	107.3	34	30*	38.3*	31.7
	A-raw	2.2	99.4	40.3	32.7	26.8	40.5
	A-washed	3.1	46.3	9.1	37.3	43.0	19.7
	A-washed	3.2	51.0	10.4	29.1	50.5	20.4
	B-raw	4.1	58.6	12.9	21.7	56.3	22.0
	B-raw	4.2	48.8	11.6	39.5	36.7	23.8
	B-raw	4.3	42.9	14.1	26.6	40.5	32.9
	B-washed	5.1	30.1	7.0	27.2	49.5	23.3
	B-washed	5.2	30.4	7.0	32.4	44.6	23.0
	B-washed	5.3	28.7	6.7	26.9	49.8	23.3
	C-raw	6.1	39.7	10.6	9.7	63.6	26.7
	C-raw	6.2	39.9	8.2	32.1	47.3	20.6
	C-raw	6.3	47.7	9.1	20.8	60.1	19.1
	C-washed	7.1	23.7	5.1	31.3	47.2	21.5
	C-washed	7.2	25.5	5.4	47.6	31.2	21.2
	C-washed	7.3	26.2	5.2	28.5	51.7	19.8
Average values for Hat Creek coal					27.2	49.4	23.4

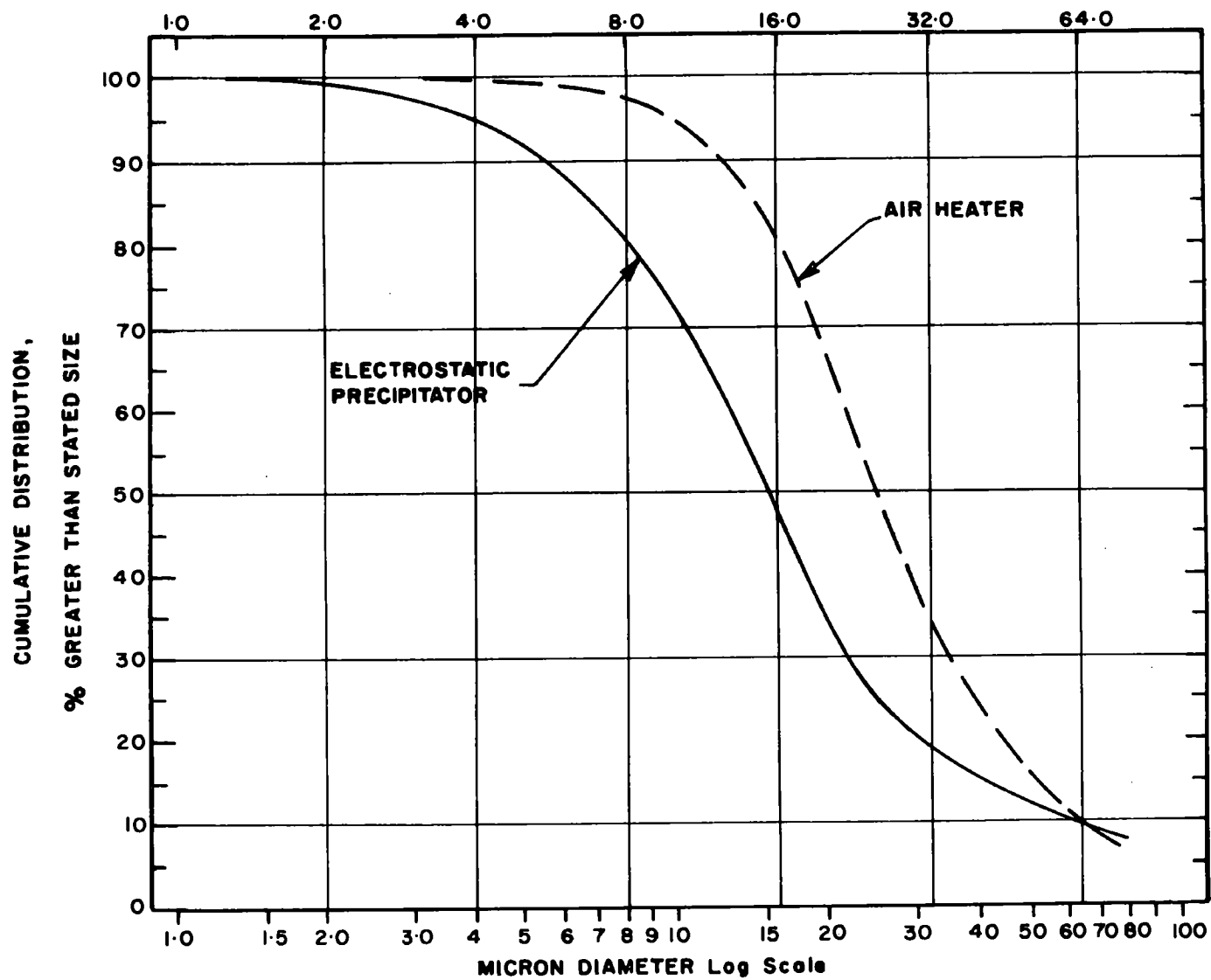*Corrected to compensate for ash lost during removal

FIGURE 6.18   Particle size distribution of fly ash from Hat Creek B—washed
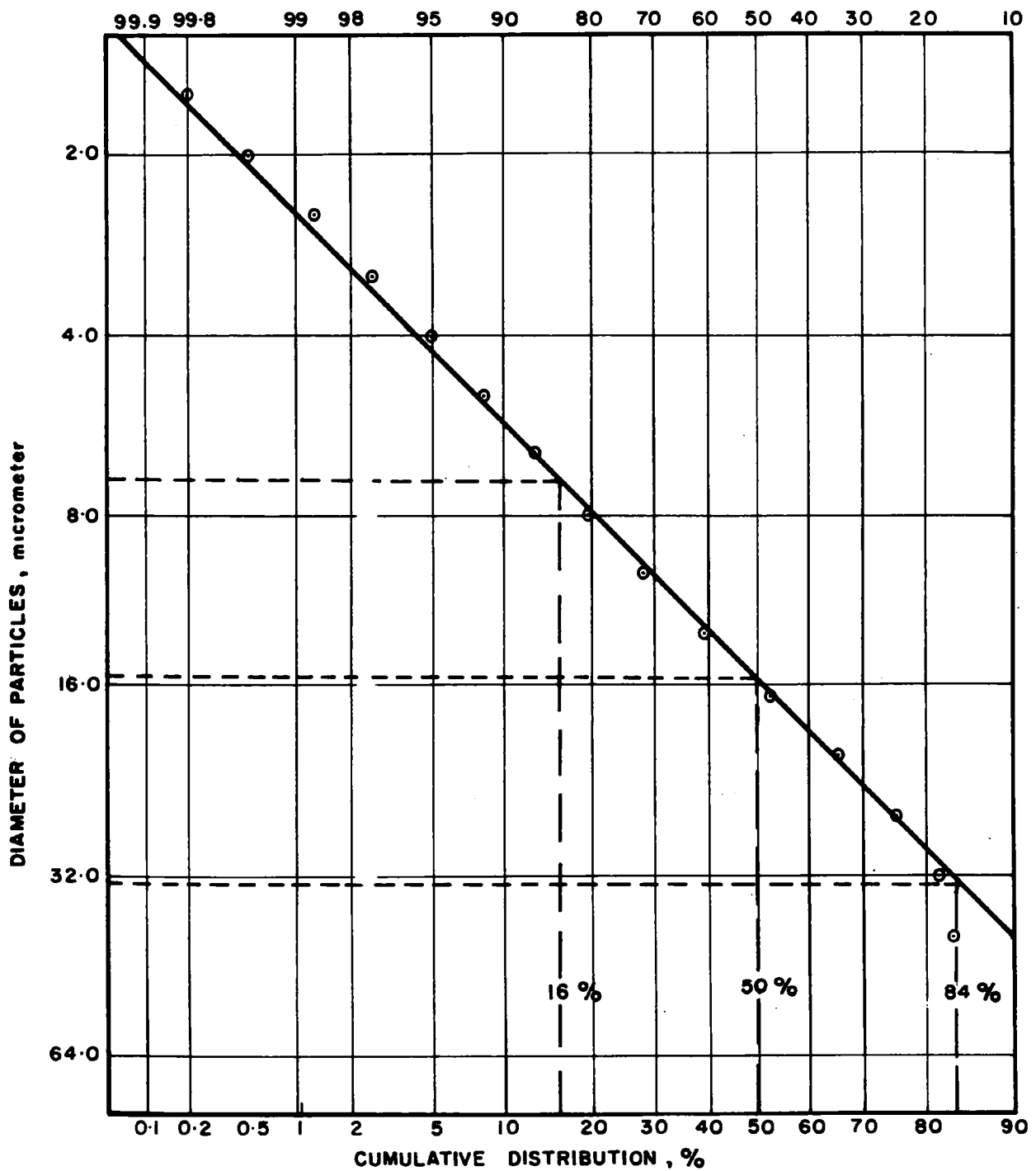coal, Test 5.1.

FIGURE 6.19   Cumulative distribution of particle sizes for fly ash
from Hat Creek B-washed coal, Dg = 15.3 μm and σg = 2.1.

TABLE 6.18

Mean Size Characteristics of Fly Ash Collected in Airheater and Electrostatic Precipitator

Coal	Test No.	Air Heater		Electrostatic Precipitator	
		Dg, μm[a)]	σg[a)]	Dg, μm[a)]	σg[a)]
Sundance	1.1	27.8	1.0	10.1	1.90
Sundance	1.2	31.2	1.0	10.6	2.2
A-raw	2.1	33.50	1.7	19.0	2.4
A-raw	2.2	20.0	1.7	17.9	2.6
A-washed	3.1	21.6	1.7	12.7	2.1
A-washed	3.2	25.4	1.8	13.0	2.2
B-raw	4.1	24.4	1.8	11.5	2.2
B-raw	4.2	21.6	1.7	15.0	2.1
B-raw	4.3	32.0	1.8	13.7	2.1
B-washed	5.1	25.4	1.8	15.3	2.1
B-washed	5.2	20.0	1.6	14.6	2.3
B-washed	5.3	23.2	1.6	13.3	2.1
C-raw	6.1	22.7	1.7	14.3	2.1
C-raw	6.2	23.7	1.6	15.6	2.0
C-raw	6.3	24.3	1.7	13.9	2.2
C-washed	7.1	33.1	1.8	13.3	2.1
C-washed	7.2	21.7	1.6	14.6	2.1
C-washed	7.3	21.1	1.6	13.3	2.2
a) Average for all Hat Creek coals except A-raw.		24.3	1.7	13.9	2.1

Dg = Volume geometric mean diameter
σg = Geometric standard deviation

This table shows that the volume geometric mean diameters of the particles of fly ash collected from the electrostatic precipitator could be divided easily into three groups:

1) Sundance coal, D_g = 10.4 μm, σ_g = 2.1,

2) Hat Creek A-raw coal, D_g = 19 μm, σ_g = 2.5,

and 3) All other Hat Creek coals, D_g = 14 μm, σ_g = 2.1

The particle sizes of the fly ash from A-raw coal, being much larger than those from the other Hat Creek coals, suggests the presence of either unburned char or coarse grains of extraneous coal ash.

Classification of fly ash deposition behaviour into three groups based on the particle geometric mean diameters in the precipitator also applied to the amounts of ash retained in different parts of the boiler system. As shown below, the same three groups can be abstracted from the data in Table 6.17.

Boiler Location	Furnace Bottom	Ducting & Hoppers	Precipitator Inlet
1) Sundance	16%	68%	16%
2) Hat Creek A-raw coal	31%	33%	36%
and 3) All other Hat Creek coals	29%	48%	23%

Thus, the dust loadings at the inlet to the precipitator, which must decrease with decreases in the geometric mean diameter of the fly ash, are consistent with the measured particle size distributions of the precipitated fly ash.

The size distributions of the particles of fly ash collected from the airheater were not multimodal but were slightly skewed to favour particles having a diameter larger than approximately 12 μm. The geometric standard deviation of the particles, smaller than 12 μm was typically 2.1, the same value as that of the size distribution of particles of fly ash collected from the precipitator. However, the fraction of small particles having this distribution was typically about 5%.

Figure 6.20 illustrates the dust loading at the inlet to the precipitator for particles having a diameter between 1 and 5 μm did not vary by more than 50% from an average value. Since these particles are considered
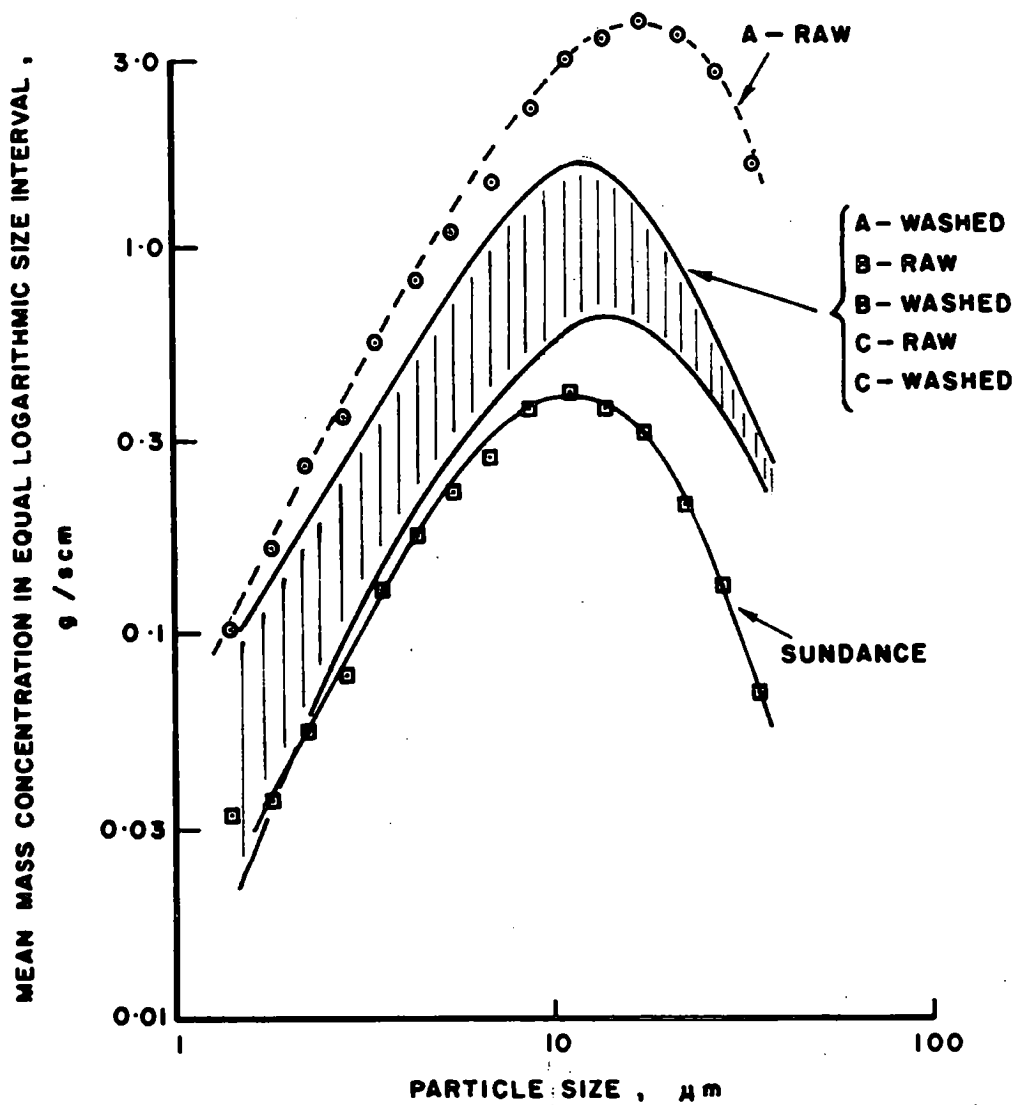
FIGURE 6.20   Variation in fine particle sizes of the fly ash
entering the electrostatic precipitator.

to be "difficult to collect" it is reasonable to suppose that any inefficiency in the function of the electrostatic precipitator can be related to these particles.

6.6.2   Bulk Density and Mineral Analyses

The bulk density of fly ash samples from both Sundance and the six Hat Creek coals which were collected at the precipitator inlet were measured by Research Cottrell. As shown in Table 6.19, the bulk densities of Hat Creek fly ash were only about one-half that of the Sundance fly ash. Although, this suggests that structural requirements for fly ash hoppers and ducts for a boiler designed to burn Hat Creek coal could be less severe than those for Sundance coal, it should be noted that the capacity of the hoppers for Hat Creek fly ash must be much larger to compensate for the combined effect of the lower bulk density and a higher dust loading in the flue gas. An examination of Table 6.17 show that beneficiation of the Hat Creek coals was effective in reducing the fly ash loadings at the precipitator inlet by at least 50% and that the fly ash loadings for both the A-raw and B-raw Hat Creek coals were much higher than for the other higher quality Hat Creek coals.

The chemical analyses of the fly ash collected by the precipitator, Table 6.20 shows that the chemical composition of the fly ash from the B-washed, C-raw and C-washed coals were essentially the same and that beneficiation of the B-raw coal resulted in a noticeable reduction in both the iron and sulphur content in the collected fly ash.

Microphotographs of fly ash from Sundance and the Hat Creek B-washed coals are shown in Figure 6.21. The Sundance fly ash consisted mostly of non-agglomerated glassy spheres that were generally less than 25 μm in diameter whereas the fly ash from all six Hat Creek coals were characterized by fused agglomerates of micron-sized particles and numerous cenospheres which were generally less than 20 μm in diameter. These microscopic observations are consistent with the bulk density data reported in Table 6.19.

TABLE 6.19

Bulk Density of Fly Ash at Precipitator Inlet

Coal		Test No.	Bulk Density Kg/m^3
Sundance		1.1	1.42
Hat Creek	A-raw	2.1	0.74
	A-washed	3.1	0.77
	B-raw	4.1	0.81
	B-washed	5.1	0.82
	C-raw	6.1	0.71
	C-washed	7.1	0.74

6.6.3   Electrical Resistivity

In-situ electrical resistivity measurements of the fly ash at the precipitator inlet at nominal gas temperatures of $150^{\circ}C$ and $270^{\circ}C$ are shown in Figures 6.22 and 6.23 respectively. At flue gas temperatures of $150^{\circ}C$ the resistivity values of Sundance fly ash ranged from 10^9 and 10^{11} ohm - cm whereas those from the Hat Creek coals generally fell between 10^{11} and 10^{12} ohm - cm. The values for both the Sundance and the Hat Creek coals decreased by about one order of magnitude when resistivity measurements were taken at a flue gas temperature of $270^{\circ}C$. Thus, a slight improvement in resistivity can be obtained by precipitating the fly ash from Hat Creek coal at $270^{\circ}C$ rather than at $150^{\circ}C$.

Although resistivity values between 5×10^8 and 5×10^9 ohm - cm are considered to yield the best precipitator efficiency, these values are known to decrease rapidly to less than 10^5 ohm - cm if the char content of the fly ash rises above 5% by weight. Previous work at CCRL has not only confirmed this general observation, but has also demonstrated that resistivity values can still be very low even when the char content is less than 3%. These low values of resistivity indicate that fly ash will readily precipitate, but that

TABLE 6.20

Ash Analyses of Deposits Collected from the Electrostatic Precipitator

Coal	Test No.	Chemical Composition, %									
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
Sundance	1.1	40.8	21.4	5.0	1.0	0.4	21.8	2.4	1.1	3.5	0.4
Sundance	1.2*	49.6	23.5	4.7	0.8	0.3	15.5	1.5	0.5	1.6	0.3
A-raw	2.1	58.8	28.2	6.5	1.2	0.1	1.8	1.3	0.9	0.7	1.0
A-raw	2.2*	57.5	27.6	7.2	1.1	0.1	1.5	1.1	0.6	0.5	1.0
A-washed	3.1	55.6	25.7	7.3	1.6	0.2	3.0	1.4	1.0	0.6	0.9
A-washed	3.2	55.5	25.5	6.7	1.8	0.2	3.5	1.8	1.0	0.8	1.1
B-raw	4.1	50.3	27.0	9.4	1.2	0.4	5.0	1.9	1.3	0.4	0.5
B-raw	4.2	53.3	29.2	7.4	1.3	0.3	5.0	1.5	0.8	0.4	0.5
B-raw	4.3	52.5	28.9	7.9	1.3	0.3	4.7	1.5	1.1	0.4	0.6
B-washed	5.1	50.8	29.4	6.5	1.6	0.4	5.6	1.8	0.6	0.5	0.7
B-washed	5.2	51.4	29.9	5.6	1.6	0.5	5.8	1.9	0.8	0.4	0.5
B-washed	5.3	51.8	30.3	6.0	1.6	0.5	5.6	1.8	0.1	0.4	0.5
C-raw	6.1	53.3	30.9	6.5	1.4	0.4	3.8	1.7	0.7	0.7	0.6
C-raw	6.2	52.3	30.8	5.9	1.5	0.4	4.0	1.9	0.6	0.7	0.6
C-raw	6.3	51.4	29.8	6.2	1.4	0.3	3.6	1.7	0.7	0.7	0.6
C-washed	7.1	50.9	30.1	6.2	1.7	0.5	5.1	2.0	0.7	0.9	0.6
C-washed	7.2	56.1	32.8	5.6	1.2	0.3	3.4	1.3	0.6	0.9	0.6
C-washed	7.3	52.2	31.0	6.3	1.6	0.4	4.9	1.7	0.6	0.8	0.7

*The analysis that is shown is for the deposit collected from the sheet between the second and third passes of the airheater.
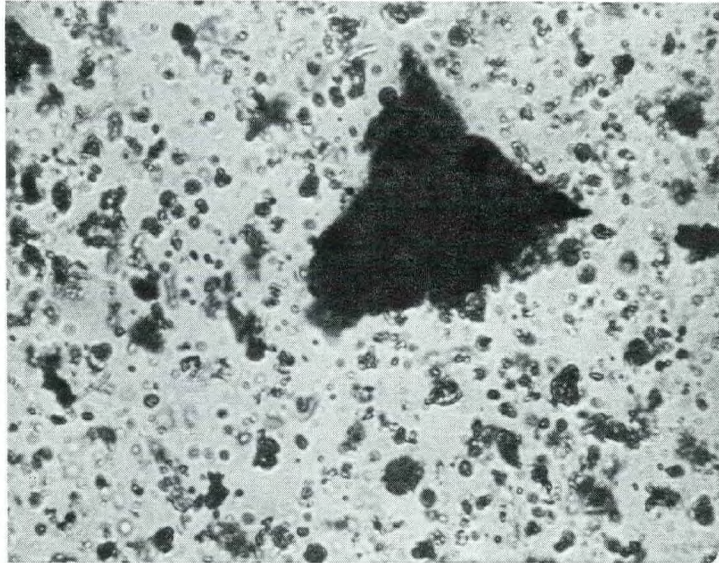
(a) Sundance Coal
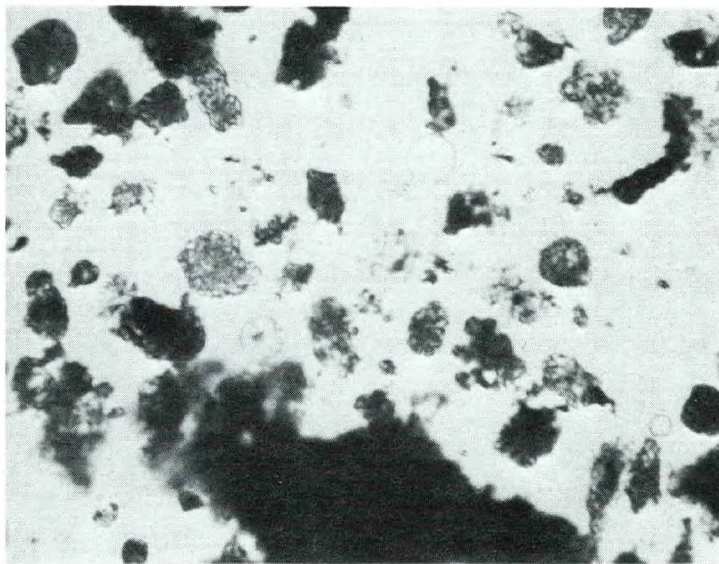
(b) Hat Creek B-Washed Coal

FIGURE 6.21   Microphotographs of fly ash from Sundance
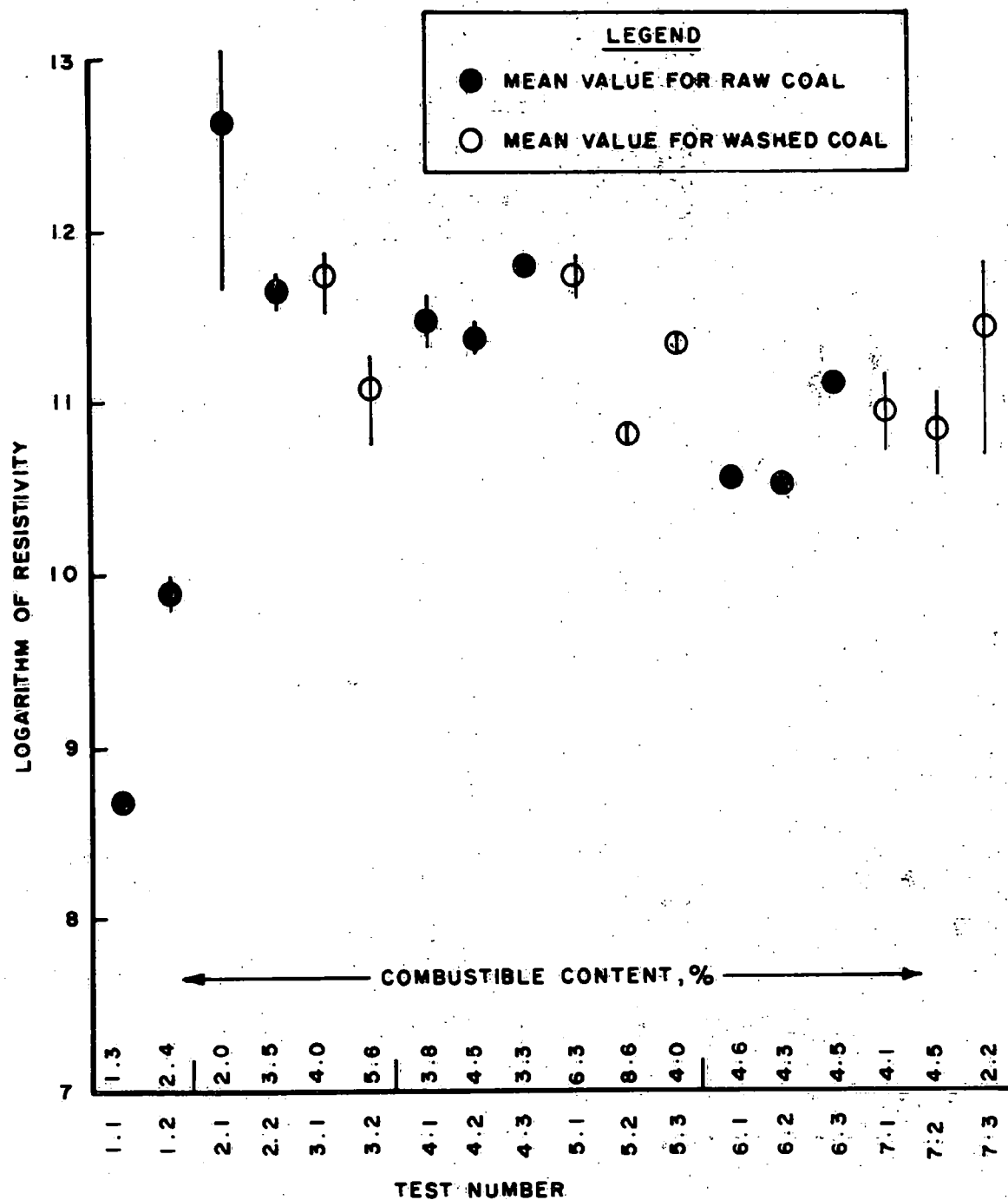and Hat Creek B-Washed Coal.

FIGURE 6.22 In-situ electrical resistivities of fly ash between 150°C and 160°C. The vertical lines represent the degree of scatter.
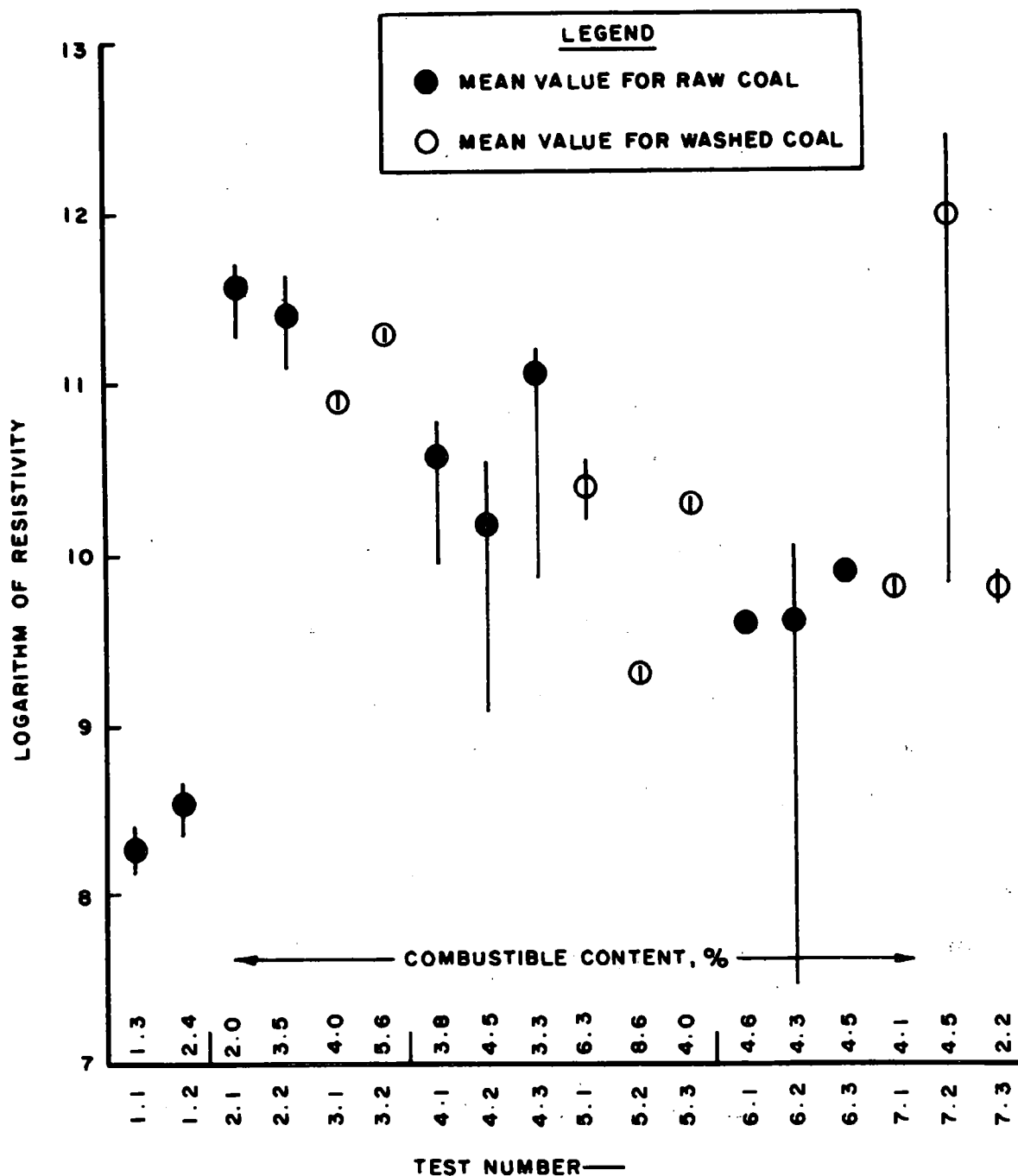
FIGURE 6.23   In-situ electrical resistivities of fly ash between
250°C and 270°C. The vertical lines represent the
degree of scatter.

re-entrainment of the agglomerated dust will occur. On the other hand, high resistivity values indicate that the precipitated dust will retain a strong electrical charge and either repel any similarly charged particles or cling so strongly to the collector plates that back corona occurs. Thus, precipitator collection efficiency is strongly dependent on the electrical resistivity of the fly ash as well as other factors such as the size, shape and surface characteristics of the dust particles.

The bulk electrical resistivity of fly ash collected at the inlet of the precipitator were also measured by Research Cottrell using the procedure given in Section 4.05 of the ASME Power Test Code No. 28 - 1965. These resistivities were measured over a temperature range of $93^{\circ}C$ to $371^{\circ}C$, and as shown in Figures 6.24 and 6.25, the values at $150^{\circ}C$ and $270^{\circ}C$ are about one order of magnitude higher than those measured in-situ at CCRL.

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

6.6.4   Correlation Between Precipitator Efficiency and Fly Ash Resistivity

The electrostatic precipitator employed in these measurements was a research model which was modified temporarily to reduce its efficiency. In its original state, it collected essentially all of the particulate matter in the flue gas. Consequently, alternate plates of the precipitator were placed at ground potential with respect to the charging wires and the discharging plates.

As shown in Figure 6.26, the precipitator efficiencies with fly ash from Hat Creek coal were superior to that obtained with fly ash from Sundance coal. These results appear to be anomolous because the fly ash resistivity values for Sundance coal, which bracketed 10^9 ohm - cm, are generally associated with the highest precipitator efficiencies, whereas those for the Hat Creek coals, being all above 10^{11} ohm - cm, suggest that precipitator efficiencies will be low. The apparent discrepancy can, however, be explained by the differences in particle size distribution of the fly ash.

As described in Section 6.6.1, the particles of Hat Creek fly ash were not only generally larger than those of Sundance fly ash, but a smaller fraction
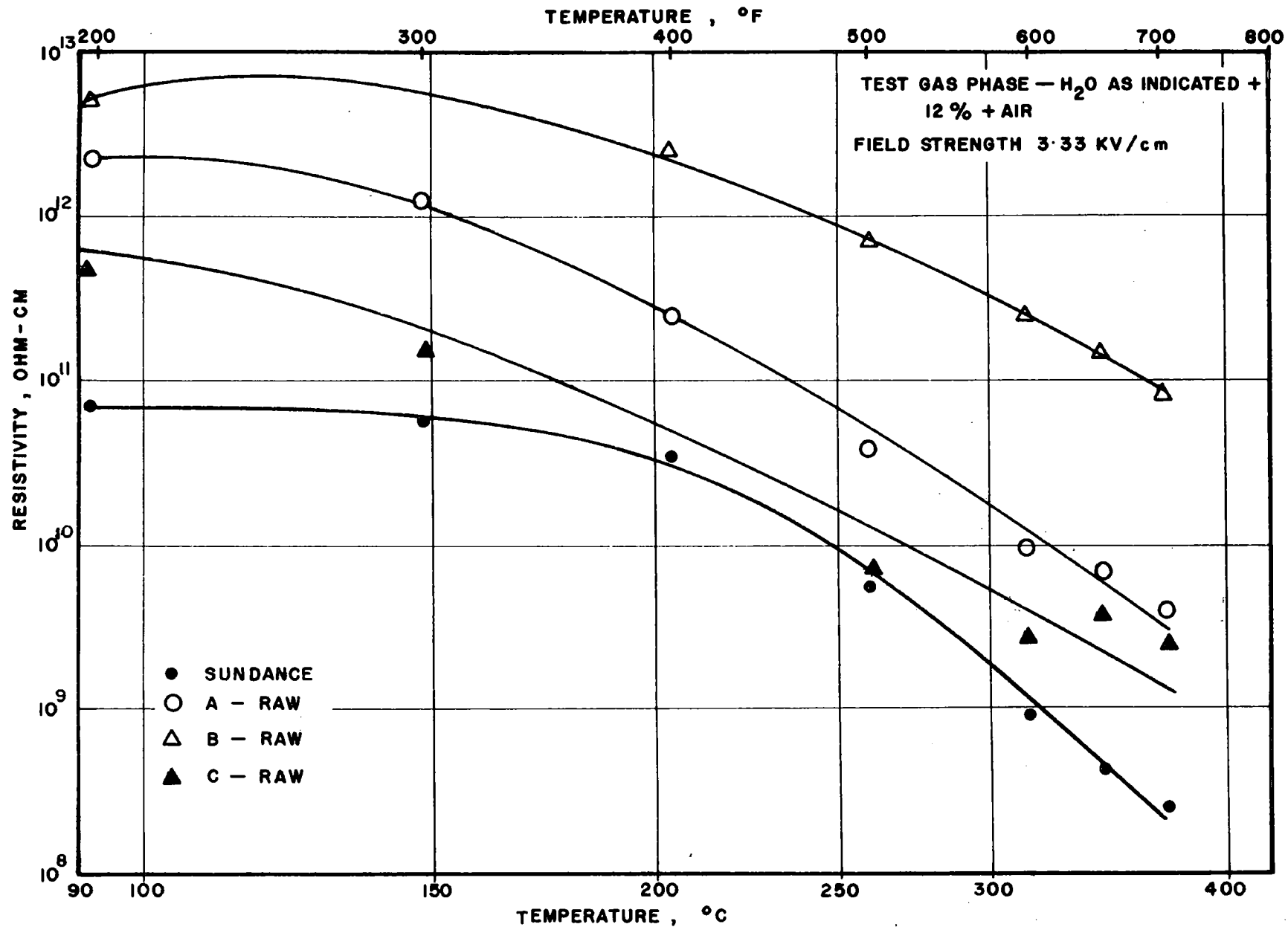
FIGURE 6.24　Bulk electrical resistivity of fly ash from Sundance and Hat Creek raw coals (Research – Cottrell data).
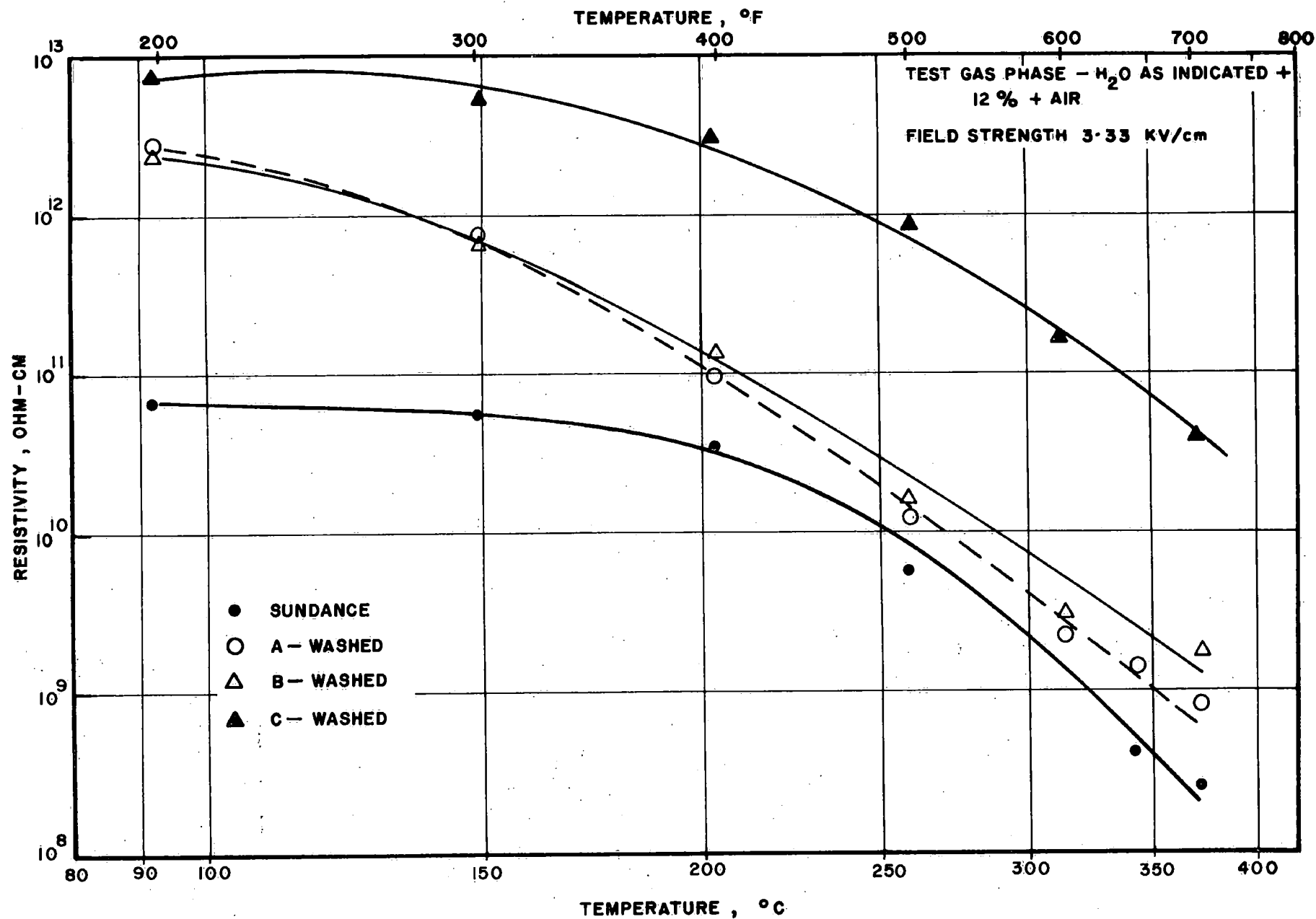
FIGURE 6.25   Bulk electrical resistivities of fly ash from Sundance and Hat Creek washed coals
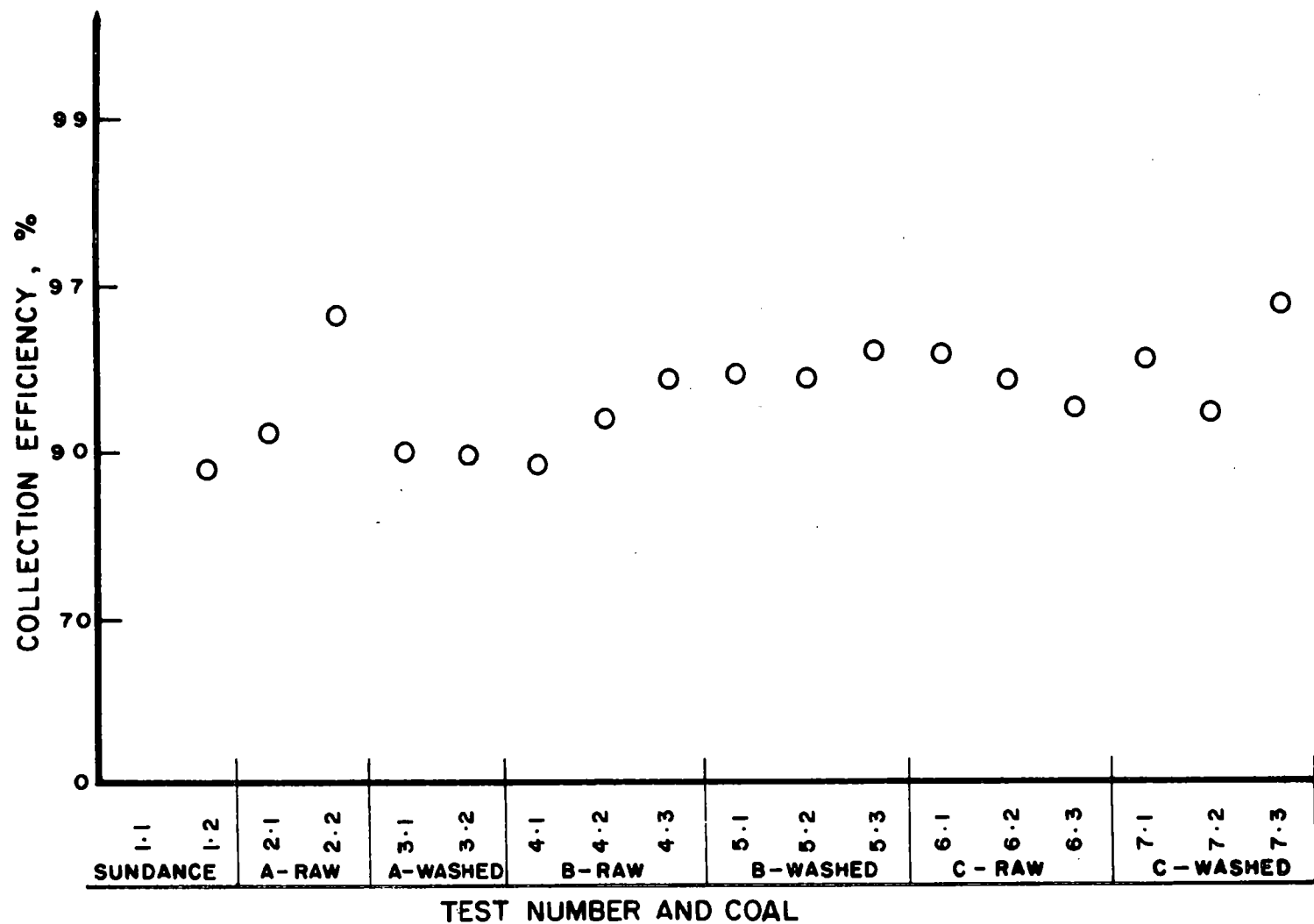(Research - Cottrell data).

FIGURE 6.26   Collection efficiency of fly ash from Sundance and Hat Creek coal in the CCRL
model precipitator.

of the Hat Creek fly ash was between 0.1 μm and 3μm, the "difficult-to-collect" size range. Thus, the small size characteristics of the Sundance fly ash suggest a difficult-to-collect ash, whereas, the large size of the Hat Creek fly ash appears to favour precipitability and efficiency.

This explanation agrees with an empirical relationship developed by Research Cottrell which indicates that precipitator efficiency decreases inversely with the square root of the particle size. In addition, if gravitational settling mechanisms can be considered in the overall performance of a precipitator, then the fly ash from Hat Creek coal would be more easily collected than those from Sundance coal. Thus, any reduction in the clay or fine mineral content of Hat Creek coal by beneficiation would favour both an increase in precipitator efficiency and a significant reduction in precipitator size.

The bulk and in-situ resistivities, both being in the $10^{11} - 10^{13}$ ohm - cm range at 150°C, indicate that a cold precipitator may require an extremely large specific collection area to meet environmental objectives for dust emission. If these specific collection areas prove to be abnormally large, consideration should be given to either cold precipitators with an appropriate flue gas conditioning agent to reduce the fly resistivity or a hot precipitator. The effectiveness of various flue gas conditioning agents in improving the fly ash resistivities of a Western Canadian sub-bituminous coal are shown in Figure 6.27.
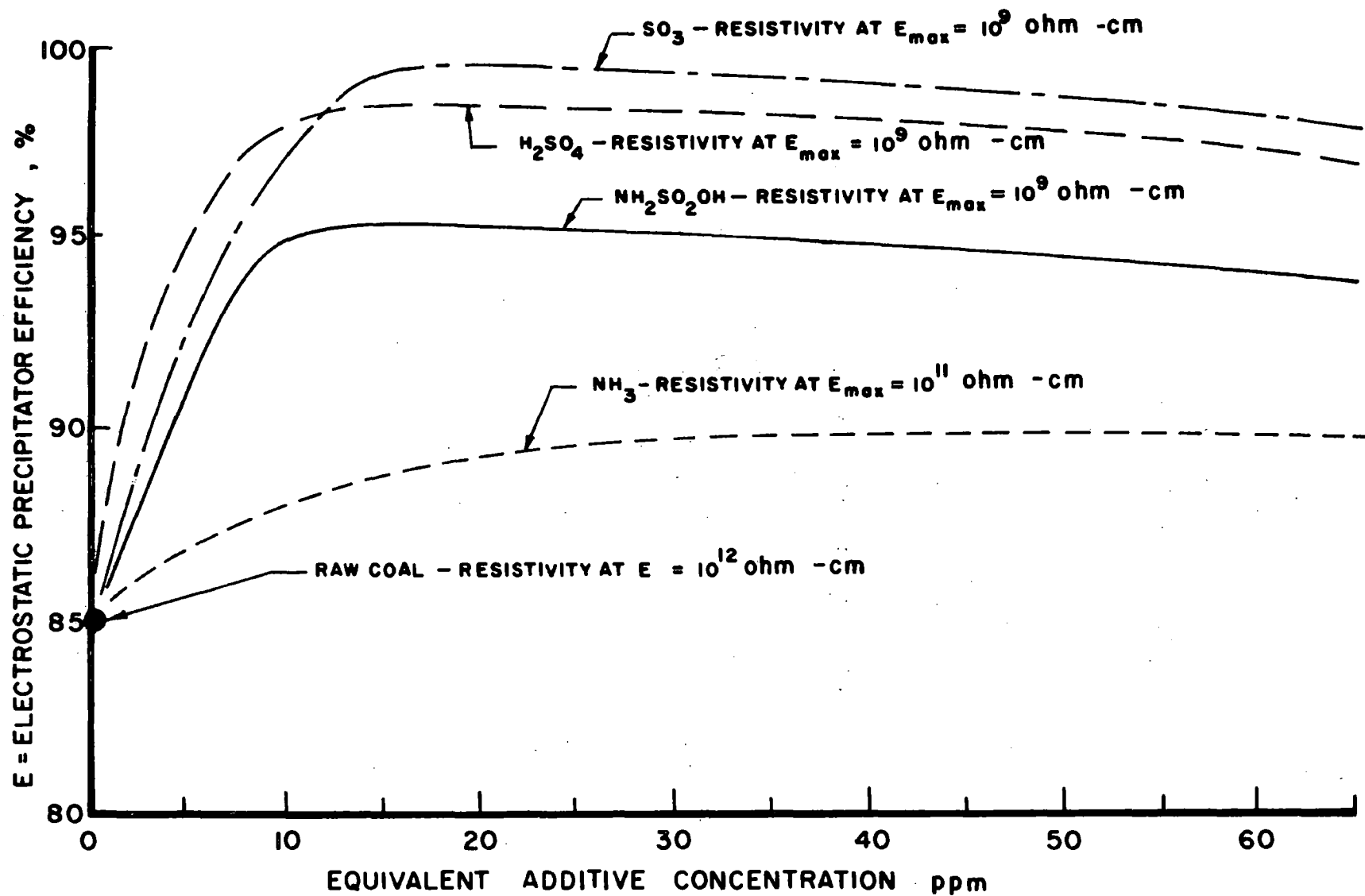
FIGURE 6.27   Improvement in electrical resistivity of fly ash from western Canadian coal by flue gas conditioning agents.

7. CONCLUSIONS

7.1 Characteristics of Raw Coal

7.1.1   A-raw coal does not appear to be suitable for use in a conventional pulverized-fired boiler. In the samples received, which contained higher than equilibrium levels of moisture, large sticky lumps of extraneous clay effectively cemented the coal into a cohesive, mass having a 90° angle of repose. Even when dried to 10% residual moisture the coal was difficult to handle. The high ash content made grinding difficult, and although the coal was burned without support fuel in the CCRL boiler, the flame pattern was excessively long.

7.1.2   The B-raw and C-raw coals handled satisfactorily after being dried to slightly below equilibrium moisture level of 23%. They ignited readily and produced bright, stable flames without support fuel. Both coals are considered to be more reactive than the Sundance reference coal despite their higher ash content.

7.1.3   Raw Hat Creek coals can cause excessive erosion of boiler heat transfer surfaces because of the large quantities of clay and quartz in the ash. The clay converts to highly abrasive mullite in the flame, while the quartz is abrasive in its natural state.

7.1.4   During the combustion tests all three raw coals produced bulky, porous deposits of sinter that adhered weakly to the refractory furnace walls. Depending on ash composition sintering can occur at temperatures as low as 1160°C due to small quantities of low-melting-point constituents which cement quantities of refractory material together. In the pilot-scale tests no true slagging was observed with any of these coals, but in a full-scale boiler molten ash deposits may develop in areas of flame impingement or high heat release.

7.1.5   The potential for superheater corrosion when burning raw coal is considered to be very low. This conclusion is based on the fact that there were no well-defined liquid phases in ash deposits collected on a series of furnace probes which were controlled at temperatures ranging from 500 to 800°C.

7.1.6 The potential for low-temperature corrosion is also low. No acid dewpoint was detected in the flue gas, and in every test with raw coal, gas-phase concentrations of SO_3 were below 4 ppm. Furthermore, measurements with low-temperature corrosion probes indicated minimal corrosion at temperatures of 122 and $138°C$.

7.1.7 With all of the raw coals, in-situ measurement of electrical resistivity of the fly ash yielded values higher than 10^{11} ohm - cm at $150°C$, and higher than 10^{10} ohm - cm at $270°C$. Although these values indicate that precipitation efficiencies should be low, it was found that, in the CCRL pilot-scale electrostatic precipitator, the fly ash from the Hat Creek raw coals was collected at a slightly better efficiency than the fly ash from the Sundance reference coal. The electrical resistivity for the latter was 10^9 ohm - cm at $150°C$, a value which is normally associated with high precipitation efficiencies. The apparent anomaly can be explained by the fact that the fly ash from the Hat Creek coals was coarser than that from the Sundance coal.

7.1.8 In the tests with A-raw coal, approximately 50% of the fuel sulphur was retained in the bottom ash and fly ash. For the B-raw and C-raw coals the corresponding value was only 10%. It is not clear why such a high degree of sulphur neutralization was achieved with the A-raw coal, but absorption of gas-phase SO_2 on the surfaces of fly ash particles is one possibility.

7.1.9 With all of the raw coals, nitric oxide emissions were below 700 ppm even with 5% O_2 in the flue gas. NO_x concentration decreased as excess air decreased, as fuel moisture content increased, and as ash content increased.

7.2   Characteristics of Washed Coal

7.2.1 All of the samples of washed coal poured freely from the shipping containers even though the latter contained large quantities of free water remaining from the beneficiation process. The coals subsequently drained and air-dried readily at $20°C$.

7.2.2 The combustion performance of the washed coals was excellent. They ignited readily and burned with bright, stable flames that were generally shorter and hotter than those from the corresponding raw coals. Support fuel was not required.

7.2.3   In addition to reducing the ash content and improving the reactivity, water washing of Hat Creek coal apparently reduces the sulphur content by approximately 30%. It may also partially remove inorganic salts and water-soluble trace element constituents.

7.2.4   As would be expected, loadings of bottom ash and fly ash were significantly lower with the washed coals than with the raw coals. Of greater importance, there was no evidence of erosion on boiler heat transfer surfaces after burning the washed coals.

7.2.5   In general, furnace deposits from the washed coals were less voluminous but more strongly sintered than those from the raw coals. This is to be expected; reducing the ash content tends to produce a hotter flame.

7.2.6   Washing the coals effected no measurable difference in mineralogical or morphological properties of the fly ash, or in the SO_3 content of the flue gas. It is therefore understandable that both the raw and the washed coals showed the same properties with respect to bulk density and electrical resistivity of fly ash, electrostatic precipitator efficiencies, and corrosion potential at both high and low temperatures.

7.2.7   In all the tests with washed coals, sulphur retention in the bottom ash and fly ash was about 10%, the same as with the B-raw and C-raw coals. However, the sulphur oxides emitted by the washed coals would be approximately 30% lower than emissions from the raw coals, because of the sulphur removed during washing.

7.2.8   The washed coals, because of their higher flame temperatures, produced higher nitric oxide emissions than the raw coals. As with the raw coals, NO_x was reduced somewhat by decreases in excess air and increases in fuel moisture.

7.3   Design Considerations for Full-scale Plant

7.3.1   The extraneous clay in the raw coals was primarily in the form of kaolin with about 10% montmorillinite. Some of this clay was in the form of large balls or lenses which could be removed during primary crushing by means of a Bradford-type breaker.

7.3.2   Hat Creek coal, being very reactive, may ignite spontaneously in storage, especially when its residual moisture content is less than 15%. Therefore suitable fire protection strategies such as compacted stockpiles and provision for flooding the bunkers are required if relatively dry coal is stored.

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

7.3.4   A steam generator designed to tolerate no more than 10% deviation from the firing rate for Sundance coal will be restricted to burning B-washed, C-raw and C-washed Hat Creek coals. However, a steam generator designed to burn B-raw coal, which requires a firing rate 25% higher than Sundance coal, will, if it has the same 10% tolerance, be capable of burning all the Hat Creek coals except A-raw.

7.3.5   If the steam generators are designed for a coal having 6000 Btu/lb on a equilibrium moisture basis, it should be possible to supply a coal of uniform quality with optimum resource recovery. For example, all coal between 3500 and 6000 Btu/lb could be beneficiated and then blended with the higher quality coals, with whatever drying appears appropriate. Alternatively, all the coal could be beneficiated to obtain an average of 6000 Btu/lb. The latter approach would produce fewer rejects without the requirement to dry.

7.3.6   It was characteristic of all the Hat Creek coals, but particularly of the B-raw and C-raw coals, that large porous sinters formed on the furnace walls and subsequently fell off, filling the furnace bottom. To avoid true slag formation, a full-scale furnace must be designed to eliminate flame impingement and zones of high temperature. Also, to cope with the large volumes of sinter and low-bulk-density fly ash, the furnace must have a generously-proportioned bottom hopper designed to prevent ash bridging,

and it must have a high-capacity mechanical ash removal system incorporating some form of sinter crusher.

7.3.7   Because Hat Creek coal tends to produce large quantities of fly ash having a low bulk density, dust loadings at the precipitator inlet will be very high unless gravitational settling of fly ash in the flow passages of the steam generator is optimized. If 40% or more of the ash can be trapped in the steam generator, the size of the precipitator can be significantly reduced.

7.3.8   Judging from the electrical resistivity of Hat Creek fly ash at $150^{\circ}C$, and its morphological features, it appears that in order to achieve the same collection efficiency as for Sundance coal, the specific collection area of a cold precipitator for Hat Creek coal containing 25 to 30% ash would have to be at least 30% greater than for Sundance coal. For a given specific collection area, precipitator efficiency can be improved either by using a suitable flue gas conditioning agent in a cold precipitator, or by using a hot precipitator which takes advantage of the lower fly ash resistivities prevailing above $250^{\circ}C$.

7.3.9   Because the sulphur content of Hat Creek coal is generally less than 1%, there are not likely to be problems with acid mist emissions or low temperature corrosion. Nitric oxide emissions can probably be kept within acceptable limits by operating at 3% O_2 in the flue gas, and by controlling flame temperature through appropriate burner and furnace design, or through burning coal with a high moisture content, i.e., washed but not dried.

7.3.10   Construction schedules permitting, there would be considerable merit in incorporating the foregoing considerations into the design of one steam generator having a capacity of approximately 300 - 500 MWe. Experience gained in operating this unit would lead to a reliable design for units as large as 750 MWe.

8. REFERENCES

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9. ACKNOWLEDGEMENTS