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COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED MINTO COALS

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COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED MINTO COALS

by

G.N. Banks*, J.K.L. Wong** and H. Whaley***

ABSTRACT

The combustion performance of raw Minto coal (run of mine) and three levels of cleaned (washed) Minto coal was compared with that of a commercially available thermal bituminous coal from Western Canada. Tests were conducted in a pilot-scale pulverized coal-fired research boiler located at the Energy Research Laboratories (ERL) in Ottawa.

The three cleaned coal samples were obtained from the CANMET Coal Research Laboratories coal cleaning facility in Devon, Alberta. Chemical, physical, petrographic and thermogravimetric analyses were performed on samples of the coals as they were received in Ottawa. Each of the coals flowed readily through ERL pilot-scale conveying and coal-handling system.

The coals, which ground readily to produce a consistent size product from the pulverizer, ignited easily to produce stable flames at greater than 97% combustion efficiency. The highest combustion efficiencies (>99%) were obtained with the more finely ground coal feeds. The washed minto coal, containing the highest ash content, gave the lowest combustible content in the fly ash and the highest combustion efficiency.

The ash from each of the Minto coal samples was quite fluid and slagged readily in the refractory-lined furnace bottom, whereas the ash deposits on the water-walls and superheater surfaces were light and powdery and did not constitute a fouling problem.

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*Research Scientist, **Physical Scientist and ***Section Head, Industrial Combustion Processes, Combustion and Carbonization Research Laboratory, Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, K1A 0G1.

At a 29% reduction (highest) in the ash content of the Minto raw coal the sulphur content was reduced from 6.88 to 5.31%. This washed coal sample burned in the pilot-scale utility boiler to produce a flue gas containing 2.9 g SO_2/MJ of fuel input, compared with 4.2 g SO_2/MJ for the raw coal. If the relationship between the per cent ash and sulphur contents removal is sustained, it is estimated that a 90% reduction in the ash content would result in a 72% reduction in the sulphur content. The resulting coal product, assuming no detrimental changes, should then burn to produce a flue gas containing about 1.3 g SO_2/MJ of fuel input.

COMPARAISON ENTRE LES PROPRIÉTÉS DE COMBUSTION DES CHARBONS MINTO BRUTS ET LAVÉS

par

G.N. Banks*, J.K.L. Wong** et H. Whaley***

RÉSUMÉ

Le rendement de combustion d'un charbon Minto brut (tout venant) et trois rangs de charbons Minto lavés a été comparé avec le rendement d'un charbon thermique bitumineux de l'Ouest canadien. Des essais ont été effectués dans une chaudière expérimentale à échelle pilote chauffée avec du charbon pulvérisé, située aux Laboratoires de recherche sur l'énergie (LRE) à Ottawa.

Les trois échantillons de charbons lavés ont été obtenus de la laverie de charbon des laboratoires de recherche sur le charbon du CANMET à Devon en Alberta. Des analyses chimiques, physiques, pétrographiques et thermogravimétriques ont été effectuées sur les échantillons de charbon tel que reçu à Ottawa. Chaque charbon circulait bien à travers les systèmes de convoyeurs et de transport à échelle-pilote.

Les charbons se pulvérisaient sans difficulté pour produire un produit de taille régulière qui s'allumait facilement et produisait des flammes stables avec un rendement de combustion plus élevée que 97 %. On a obtenu des rendements de combustion plus élevés (>99 %) avec des charbons pulvérisés plus finement. Le charbon Minto lavé, contenant la plus haute teneur en cendres, a donné la plus faible teneur en combustible au niveau des cendres volantes et le rendement de combustion le plus élevé.

La cendre provenant de chaque échantillon de charbon Minto était assez fluide et formait un dépôt sur la surface réfractaire au fonds de la chaudière, tandis que les dépôts de cendres sur les surfaces du surchauffeur étaient légers et poudreux et ne présentaient pas de problème d'encrassement.

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*Chercheur scientifique,**Chercheur en science physique et ***Chef de section, Procédés de combustion industrielle, Laboratoire de recherche sur la combustion et la carbonisation, Énergie, Mines et Ressources Canada, Ottawa, K1A 0G1.

Après avoir réduit de 29 % (la plus élevée) la teneur en cendres provenant du charbon Minto brut, on a réduit la teneur en soufre de 6,88 à 5,31 %. Cet échantillon de charbon lavé a été brûlé dans une chaudière de centrale électrique à échelle-pilote et a produit un gaz de carneau contenant 2,9 g SO_2/MJ d'apport de combustible en comparaison avec 4,2 g SO_2/MJ pour le charbon brut. Si la relation entre le pourcentage obtenu pour la teneur en cendres et en soufre est maintenue, on estime qu'une réduction de 90 % de la teneur en cendres donnerait une réduction de 72 % de la teneur en soufre. Le produit de charbon qui en résulterait, en supposant aucun changement préjudiciable, brûlerait en produisant des gaz de carneau contenant environ 1,3 g SO_2/MJ d'apport de combustible.

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INTRODUCTION

As an addendum to an International Energy Agency (IEA) research program, CANMET has agreed to conduct pilot-scale combustion trials on selected raw and cleaned coals. The IEA Coal Cleanability and Combustion Characterization Project was formed to investigate the effect of coal beneficiation on the combustion properties of high ash, slagging thermal coals. Due to the diminishing quality of thermal coals and the increasing world recognition of environmental concerns, interest in the effects of coal beneficiation on the combustion performance of cleaned coals has increased significantly.

The Canadian test coal in the IEA series was from the Cape Breton Development Corporation's (CBDC) Prince mine, located on the Hub seam in the Sydney coalfield. Cleaned coal test samples were produced from the Prince mine raw coal by the Electric Power Research Institute (EPRI) Homer City coal cleaning facility in the USA and CANMET's Coal Research Laboratories (CRL) coal cleaning facility in Devon, Alberta. These coal samples were shipped to Ottawa, Ontario, where combustion performance evaluation tests were carried out by CANMET's Energy Research Laboratories (ERL) in a pilot-scale pulverized-coal-fired research utility boiler. Combustion results from the cleaned and raw Prince mine coals were compared with each other and with those from a commercially available bituminous thermal coal sample from Western Canada. The results of this testwork were reported previously (1).

A second coal was obtained from the New Brunswick Coal Company's Minto Coalfield mine located at Salmon Harbour, New Brunswick. Three cleaned coal test samples were produced from the Minto bituminous raw coal at the CRL facility in Devon, Alberta and shipped to Ottawa for combustion performance evaluation tests.

This report describes the objectives of the Minto coal project and gives the analyses of the coals. Based on these analyses, the coals' apparent quality, combustion reactivity, and potential ash slagging and fouling properties are assessed. The facilities and equipment utilized and the operational procedures selected to evaluate the coals' actual combustion performance are then described and the actual pilot plant performance is compared with predicted values.

RESEARCH OBJECTIVES

The objectives of this project were:

1. To quantify coal quality, chemistry and petrography.
2. To determine coal comminution and handling characteristics.
3. To evaluate the combustion performance of the pulverized coal at two fineness levels and at an excess air level corresponding to 4% oxygen in the flue gases.
4. To characterize the particulate and gaseous pollutants generated during combustion.
5. To assess the slagging and fouling potential of the coal ash constituents on radiant heat transfer surfaces and superheater tubes.
6. To assess the electrical resistivity characteristics of the fly ash and the ease of fly ash collection by electrostatic precipitation.
7. To generate coal combustion charts, based on heat losses calculated from the coal analyses.

COAL CHARACTERISTICS

HANDLING AND PREPARATION

Samples of the raw Minto coal and three washed products were delivered to the Energy Research Laboratories in sealed 45-gal drums. It was noted from the chemical analyses given in Table 2 that a 30% reduction in the ash content of the Minto raw coal resulted in a 24% reduction in the sulphur content. A 24% reduction in the sulphur content of the Prince mine coal required a 70% reduction in its ash content (1). Undoubtedly this is because in the Minto coal 72% of the sulphur is in the pyritic form, whereas in the Prince mine coal only 64% of the sulphur is in the pyritic form. Also, the Minto raw coal contained 10% less ash and 2% higher sulphur than the raw Prince mine coal. Similar to the Prince mine coals, the Minto coal products with their "as received" moisture were free flowing and no problems were experienced in feeding them through the pilot-scale coal handling system.

COMBUSTION REACTIVITY

The screen and the proximate, ultimate and ash analyses of the coal samples are listed in Tables 1 to 4. These analyses and the petrographic data given in Table 5 and Fig. 1 to 4 provide a guide for predicting "Combustion Reactivity". This term is generally understood as the ability of a coal to ignite readily and to produce a stable flame with acceptable carbon burn-out, without the necessity of support firing, when applied to the assessment of a potential thermal coal.

The volatile matter content of 35-38% suggests that these coals should ignite readily and the indicated percentage of reactive macerals in the coals (Table 5) is quite high (73-79%), which suggests that carbon burn-out of the coal should be good. The higher mean reflectance of the Minto coals suggests that their reactivities should be lower than that of the reference coal. Figure 1 illustrates the influence of different coal macerals on combustion reactivity and carbon burn-out. It indicates that the combustion efficiency of the Minto coals (raw and washed) should be equivalent to that obtained for the reference thermal coal, due to the equivalent or greater amount of exinite and reactive vitrinite macerals.

Another method used to predict the combustion reactivity of the coal is to determine its burn profile in air by thermogravimetric analysis (Fig. 3). The results of these analyses indicate that the Minto coal samples reached their highest devolatilization rates between 420°C and 440°C compared with about 400°C for the reference coal. For the Minto raw coal (C-2), the peak devolatilization rate was significantly higher than that of the reference coal, and also one of the Minto washed coals (C-4) peaked slightly higher than the reference coal. Similar to the Prince mine coal samples, the Minto coals exhibited an initial devolatilization peak at about 300°C, but unlike the Prince mine coal samples this peak did not diminish as the ash content decreased. The overall results of the thermogravimetric analyses are rather ambivalent but generally indicate that the combustion efficiency of the Minto coals (raw and washed) should be almost equivalent to that of the reference coal.

These bench-scale analytical tests indicate that the Minto coal samples should ignite readily to produce a stable flame, and have a combustion efficiency comparable to that of the thermal reference coal.

Combustion charts, based on the ultimate analyses of the raw Minto coal sample, are given in Appendix A. These charts provide a rapid, graphical means of determining boiler efficiency by the indirect ASME heat loss method.

HIGH TEMPERATURE ASH DEPOSITS

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

1. Slagging - fused deposits that form on surfaces exposed predominantly to radiant heat transfer, such as on refractory furnace bottoms.
2. Fouling - high temperature bonded deposits that form on surfaces exposed predominantly to convective heat transfer, such as on superheater or reheater surfaces. Such deposits are not easily removed by soot-blowing procedures.

SLAGGING INDICATORS

The slagging potential of a coal can often be assessed by using indices or composite parameters to describe the nature and severity of the slag deposits (2). Two common indices for determining the slagging potential of the coal ash and furnace deposits are described below:

1. The base/acid ratio (B/A) is defined as:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

where each oxide is expressed as a percentage of the total ash. A maximum of 0.5 for the base/acid ratio has been suggested for dry-bottom pulverized-fired units, although this is not a necessary restriction. Values below 0.27 indicate that slagging is an unlikely problem at normal furnace operating temperatures.

2. Potential slagging temperature (T_{ps}) is defined as:

$$T_{ps} = \frac{HT + 4IT}{5} \ °C$$

where IT is the minimum temperature at which initial ash deformation occurs (normally in a reducing atmosphere) and HT is the maximum temperature at which hemispherical deformation occurs (normally in an oxidizing atmosphere). Temperature values greater than 1340°C indicate a low slagging potential, whereas values less than 1150°C indicate a severe slagging potential.

The B/A ratio of 1.29 and the potential slagging temperature of 1110°C (Table 6), derived from the ash analysis and ash fusion data of the parent coal, suggest that the raw Minto coal will have a severe slagging tendency and should be burned in a wet bottom furnace. The comparative indices for the washed Minto coals indicate a similar severe slagging potential.

FOULING INDICATORS

Most indices are applied by categorizing the coal as having an "eastern type" or "western type" ash. The term "western type" is defined as an ash having more (CaO + MgO) than Fe_2O_3, on a per cent weight basis. On the above basis, the ashes from the Minto coals have (CaO + MgO): Fe_2O_3 ratios <1.0 and can be classified as "eastern type" ashes. This criterion depends solely on ash analyses and does not have any rank or geographic connotation.

There has been general agreement between research and operating practice that one of the dominant factors influencing superheater fouling is the sodium content of the coal ash. The following classification has been proposed:

Fouling category	% Na_2O in ash	
	"eastern type" ash $\frac{CaO + MgO}{Fe_2O_3}$ <1.0	"western type "ash $\frac{CaO + MgO}{Fe_2O_3}$ >1.0
Low	<0.5	<2.0
Medium	0.5 - 1.0	2.0 - 6.0
High	1.0 - 2.5	6.0 - 8.0
Severe	>2.5	>8.0

The Minto coal ashes have a Na_2O content ranging from 0.14 to 0.18% (Table 3), which indicates that they are in the low fouling category of the "eastern type" ash.

Another possible indication of the fouling potential of a coal is based on its ash content as outlined below:

Fouling potential	Ash content, wt %
Low	<15
Medium	15 - 25
High	>25

The raw and washed Minto coals have ash contents of <15% (Table 2), indicating that they are in the low fouling category.

PILOT-SCALE RESEARCH BOILER

The CCRL pilot-scale research boiler is a pulverized coal-fired boiler incorporating two opposing low-swirl burners (Fig. 5). The furnace is U-shaped and consists of a vertical refractory shaft and a vertical steam boiler, which are connected at the bottom through a horizontal refractory tunnel. This boiler can be fired by the twin low-swirl burners located in four basic positions: known as the I, J, J_1 and U configurations. It is expected that highly reactive fuels will burn efficiently when fired in the I configuration. However, for fuels that are difficult to burn, residence times and combustion zone temperatures can be increased by locating the twin burners in the U configuration. Intermediate residence times, if required, can be obtained by locating the burners in the J or J_1 configurations. It is estimated that at full load and with the burners located in the I configuration, the combustion chamber residence time will be about one second. This residence time will increase to about three seconds with the burners located in the U configuration. The combustion chamber heat release rate is about 0.35 $MJ/s/m^3$.

All of the sections of the furnace are designed to operate at pressures up to 2.5 kPa (250 mm of water). At the full-load firing rate of

2.5 GJ/h (0.7 MW), the boiler generates about 730 kg/h of steam at 690 kPa. It is possible to control the furnace exit temperature by adding cooled-wall panels in the refractory shaft or by partially insulating the water walls of the boiler.

Crushed coal is supplied to the furnace 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 temperatures up to 230°C. If necessary, the pulverizer can be swept and pressurized with a mixture of air and flue gas at temperatures up to 400°C. The pulverizer contains a motor-driven classifier for controlling coal fineness and a riffle at the pulverizer outlet proportions the coal to each burner. Secondary air can be supplied to the burner at temperatures up to 260°C.

Combustion gases leave the furnace between 900°C-1300°C, then pass through a transition section, a test-air heater and a conventional three-pass air heater before entering a long horizontal sampling duct. A bypass from the air heater to the stack breeching and an additional heat exchanger surface in the sampling duct permit the gas temperature in the sampling duct to be varied from 150°C to 300°C.

A forced-draft fan supplies air to the air heater at 7 kPa (71 cm WC). The air, on leaving the heater, is divided into three systems: 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, can either be exhausted to the atmosphere or 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% O_2 and less than 100 ppm CO in the flue gases, with a smoke density of less than No. 1 Ringlemann.

EXPERIMENTAL PROCEDURE

OPERATING PROCEDURE

The following procedure, with minor variations in timing, was used for all trials:

1. Before each test, all boiler and air heater fireside surfaces were thoroughly cleaned by air lancing and the furnace bottom was lined with a refractory blanket. Sufficient coal was bunkered to provide 7 h continuous operation.
2. At 0800 h, the cold boiler was preheated with No. 2 fuel oil fired at 10 g/h, using two oil torches. Excess air was adjusted to provide 5% O_2 in the flue gas and the boiler was allowed to stabilize at full steaming rate and pressure. All continuous monitoring instruments were activated.
3. At 0920 h, pulverized coal was fed to the boiler at a specified classifier speed, mill temperature and excess air level. One oil torch was left in operation.
4. After flame stability was established, the oil torch was removed, allowing the boiler to operate on pulverized coal only.
5. At 1100 h, scheduled testing was begun. Boiler panel readings were monitored continuously and recorded every half hour. A specified coal feed rate, coal fineness and excess air level were maintained as closely as possible for the test duration.
6. By 1600 h, all measurements were completed and the boiler was shut down.
7. The furnace was allowed to cool overnight. The furnace bottom was then removed, the duct works were dismantled and the ash in the furnace bottom and duct work were photographed, collected, weighed and sampled.

PARAMETERS OF COMBUSTION PERFORMANCE

The following combustion performance parameters were measured at the sampling stations illustrated in Fig. 4:

1. Coal quality of a composite sample was taken from the crushed coal feed at the pulverizer inlet. Station 1.
2. Moisture and sieve analyses of pulverized coal samples were taken at the pulverizer outlet. Station 2.
3. O_2 content of the flue gas was measured continuously by a Dynatron oxygen analyzer and a paramagnetic monitor. Stations 8 and 10, respectively.

4. NO content of the flue gas was measured continuously by a chemiluminescent monitor. Station 10.
5. CO and CO_2 contents of the flue gas were measured continuously by infrared monitor. Station 10.
6. SO_2 and SO_3 contents of the flue gas were measured continuously by ultra-violet and absorption calorimetric methods. Stations 10 and 13, respectively.
7. Low-temperature corrosion potential was measured by three mild steel probes which were inserted simultaneously into the flue gas stream and maintained at three different temperatures for the duration of the combustion test. Station 9.
8. Fly ash loading was measured by an isokinetic sampling system, three samples per test. These samples were analyzed for carbon content and dust loading. Stations 15 and 16.
9. Aerodynamic size distribution was determined in a fractionating sampler and in a Cascade cyclone sampler. Station 12.
10. Fouling of heat-transfer surfaces was evaluated by visual examination and chemical composition of ash build-up on a simulated superheater, installed immediately downstream of the screen tubes. Station 7.
11. Slagging propensity was determined by examining the thickness, physical structure, chemical composition and melting characteristics of ash deposits selected from various parts of the furnace. Stations 3 to 6.
12. Fly ash resistivities were measured by an in situ, point-plane resistivity apparatus at flue gas temperatures of approximately 300°C at Station 11, and 180°C at Station 14.

COMBUSTION PERFORMANCE

COAL COMMINUTION

The Minto coals were crushed, dried, metered and pulverized to the selected degree of fineness without difficulty. The CCRL coal drying and grinding system is illustrated in Fig. 6. The pulverized coals were then transported directly to the burners without moisture separation from the carrying air. The size distribution of the pulverized coals for each of the trials is shown in Tables 7 and 8. A coarse grind (70 to 75% minus 200 mesh) was maintained for the trials (C-1A to C-5A) in Table 7, whereas a finer grind (85 to 92% minus 200 mesh) was maintained for the trials (C-1B to C-5B) in Table 8.

BOILER OPERATION AND FLAME CHARACTERISTICS

The boiler operating conditions, shown in Tables 7 and 8, remained essentially constant between 2100 and 2150 MJ/h input for all furnace trials. The flame was bright, clean and stable under reasonably steady-state conditions and an oil support flame was required for only a few minutes at the start of each trial. It should be noted that the coals were fired in the I configuration for all of the furnace trials.

GASEOUS EMISSIONS

The average flue gas analyses for each combustion trial are summarized in Tables 7 and 8. The carbon monoxide levels, at less than 100 ppm, do not constitute either an emission problem or a significant thermal penalty.

The uncontrolled sulphur dioxide emissions from the Minto Coal samples were 2.9 to 4.1 g SO_2/MJ, which is much higher than the current Canadian national emission guideline of 0.258 g SO_2/MJ of fuel input for new combustion systems (3). The nitric oxide emission rates of 0.28 to 0.35 g NO/MJ are well above the current Canadian national emission guideline of 0.168 g NO/MJ of fuel input, but this level is specific to the CCRL equipment and it can be significantly improved through the use of modern low-NO_x burner technology.

FLY ASH CHARACTERISTICS AND COAL BURN-OUT

The mass loadings, aerodynamic particle size and combustible content of the fly ash for each trial are summarized in Tables 9 and 10. As expected these data indicate that the fly ash loadings are generally higher for the coals containing a greater percentage of ash. It is also clearly evident that the more finely ground coal results in a lower combustible content in the fly ash. The combustible content obviously affects the calculated combustion efficiency of the higher ash coals more acutely than those containing less ash.

In general, high electrical resistivity (>10 log ohm-cm) indicates that precipitated fly ash will retain a strong electrical charge and repel any similarly charged particles or generate a back corona within the deposit; precipitation, conversely, is therefore difficult. A low resistivity (<7 log ohm-cm) fly ash will readily precipitate but will not adhere strongly to the collecting plates and will easily be re-entrained in the flue gas. Intermediate resistivity values of approximately 8 to 9 log ohm-cm are considered to yield the best precipitator efficiencies.

The measured in situ electrical resistivity of the fly ash from each of the trials, at the higher temperature, was approximately 5 log ohm-cm. At the lower measuring temperatures the resistivities rose slightly from about 6 to 8 log ohm-cm for the washed coals but appeared to remain essentially constant for the raw coal at 5 log ohm-cm. These values suggest that the electrostatic precipitator will operate more effectively with the washed coal than with the raw coal.

ASH SLAGGING AND FOULING

The calculated potential slagging temperature and the base/acid ratio shown in Table 6 indicate a severe slagging propensity for the Minto coal samples compared with the medium propensity of the reference coal. This severe slagging of the Minto coal samples, which was not noticeably affected by cleaning, was confirmed by the combustion trials (Fig. 6 and 7). The analytical data for the furnace products collected from the combustion trials are tabulated in Tables 13 to 16. The calculated slagging potentials of these products, shown in Tables 17 to 20, also confirm the predicted severe slagging potential of the Minto coal. The analytical data for the parent coal ashes predicted a low fouling tendency which was confirmed by the powdery, loosely adherent deposits formed on the waterwalls and convective heat transfer surfaces (Fig. 8 and 9). The 30% reduction in ash content of the coal appeared to reduce the amount of slag formed in the furnace bottom (Fig. 7). However, there was little noticeable change in the small amount of ash that collected on the superheater tubes (Fig. 9). There were no material changes to the furnace operating temperatures (Tables 7 and 8) that could be attributed to the reduction in ash content of the coal.

CONCLUSIONS

The Minto coal samples handled and flowed without difficulty. The resulting ground coal product ignited readily to produce stable combustion flames. These flames appeared similar to each other and to those of the reference thermal coal.

The petrographic data and coal analyses suggested that the carbon burn-out from the Minto coals (raw and washed) should be favourable and thermogravimetric analyses suggested that the combustion reactivity of these coals will be equivalent to that of the reference coal. Combustion studies in the utility boiler indicated that the raw Minto coal can be burned to less than 6% combustible content in the fly ash with a fine grind (87% minus 200 mesh) whereas the ash from the finely ground washed coals contained from 3 to 5.5% combustible content, depending on the ash content of the coal. These figures compare to a 2.1% combustible content in the fly ash from the thermal reference coal, containing 10.5% ash and fired at a grind of 90% minus 200 mesh, to give a 99.9% combustion efficiency (higher than any of the Minto coal samples). The reduction in ash content of the coal did not appear to affect the furnace operating temperatures or the severity of the coal ash to slag.

Washing the Minto coal reduced the sulphur content of the coal from 6.88% to 5.31%, depending on the amount of ash removed. The overall reduction in SO_2 evolved in the flue gas (g/MJ of fuel input) compared with the raw coal varied from 16 to 35% with the highest SO_2 reduction occurring with the highest ash removal. However, the lowest emission rate of 2.858 g SO_2/MJ is still well above the current Canadian emission guideline of 0.258 g SO_2/MJ of fuel input.

The tendency of the coal ash to slag was predicted to be severe from the analytical data on the parent Minto raw and washed coal samples. This prediction was confirmed by the fluid slag produced in the refractory-lined furnace bottom. The analytical data also indicated a low fouling tendency, which was consistent with the powdery, easily removed ash material deposited on the water-walls and the superheater tubes during the combustion trials.

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Table 1 - Screen analysis of the coal head samples

Screen size (mm)	Weight % (cumulative)				
	Ref. coal	Raw Minto	Washed Minto		
	C-1	C-2	C-3	C-4	C-5
+25.4	1.75	44.94	-	-	-
+19.1	3.70	55.57	-	-	-
+12.7	9.84	66.88	1.74	0.43	1.51
+6.4	28.86	80.27	22.77	8.61	16.01
+3.2	54.32	88.06	64.16	44.91	59.14
-3.2	45.68	11.94	35.84	55.09	40.86
Bulk density (kg/m^3)......	881	877	699	710	766
Moisture wt %	8.4	1.8	2.4	3.8	6.8

Table 2 - Coal analyses

Component	Analyses					Pacific rim specifications	
	Ref. coal	Raw Minto coal	Washed Minto coal				
			No. 9	No. 5	No. 3		
	C-1	C-2	C-3	C-4	C-5	KECO	EPDC
Moisture, wt %							
As received	6.04	0.97	7.76	3.93	2.94	<15	<10
Equilibrium	8.72	1.57	1.80	2.14	1.73	-	-
Proximate, wt %							
Ash	10.50	15.40	12.35	11.51	10.89	<17	<20
Volatile matter	33.39	35.09	36.69	36.93	37.64	22-36	$\frac{VM}{FC} \geq 0.4$
Fixed carbon	56.11	49.51	50.96	51.56	51.47	50-60	
Ultimate, wt %							
Carbon	71.04	70.23	73.01	73.76	75.10	-	-
Hydrogen	4.46	4.67	4.89	5.07	4.97	-	-
Sulphur	0.22	6.88	6.03	5.84	5.31	<1.0	<1.0
Nitrogen	1.16	1.07	1.11	1.09	1.12	<2.0	<1.8
Ash	10.50	15.40	12.35	11.51	10.89	-	-
Oxygen (by diff)	12.62	1.75	2.61	2.73	2.61	-	-
Sulphur forms							
Pyritic	-	5.43	3.81	3.64	3.29	-	-
Sulphate	-	0.10	0.43	0.43	0.28	-	-
Organic	-	1.35	1.79	1.77	1.74	-	-
Calorific value, MJ/kg	28.20	29.75	30.72	31.05	31.40	>25.12	>25.12
Hardgrove grindability index	52	62	62	59	59	>45	>45
Chlorine in coal, wt %	<0.01	<0.01	<0.01	<0.01	<0.01	-	-
Free swelling index	N.A.*	6.5	6.0	6.0	6.0	-	-
Ash fusibility, °C							
Reducing atmosphere							
Initial deformation	1218	1024	1035	1038	1029	>1250	-
Spherical deformation	1313	1038	1041	1043	1041	-	-
Hemispherical deformation.	1391	1043	1046	1049	1049	-	-
Fluid temperature	1454	1104	1146	1102	1160	-	-
Oxidizing atmosphere							
Initial deformation	1266	1321	1329	1335	1349	-	-
Spherical deformation	1377	1393	1416	1413	1413	-	>1200
Hemispherical deformation.	1424	1402	1421	1418	1416	-	-
Fluid temperature	1479	1410	1424	1427	1418	-	>1300

Table 3 - Analysis of parent coal ashes

Major elemental oxides (wt %)	Ref. coal	Raw coal	Washed Minto coal		
	C-1	C-2	C-3	C-4	C-5
SiO_2	60.01	30.20	31.94	30.71	31.71
Al_2O_3	18.09	9.21	10.02	9.66	9.93
Fe_2O_3	3.60	46.13	48.69	47.32	47.45
TiO_2	0.86	0.53	0.58	0.53	0.62
P_2O_5	0.25	2.13	1.81	1.85	1.86
CaO	7.85	5.14	4.05	4.14	3.80
MgO	1.59	<0.50	-	-	-
SO_3	3.90	1.97	1.52	1.85	1.32
Na_2O	1.35	0.20	0.23	0.19	0.18
K_2O	0.41	0.61	0.65	0.63	0.58
BaO	0.15	0.22	0.23	0.18	0.22
SrO	0.11	-	-	-	-
L.O.F.	0.81	0.74	0.59	0.81	0.54

Table 4 - Trace elements determined in coal samples (ppm)

Element	Ref. coal	Raw Minto coal	Washed Minto coal		
	C-1	C-2	C-3	C-4	C-5
Antimony (Sb)	0.7	5.5	4.7	4.6	4.5
Arsenic (As)	3.1	151	108	105	85
Barium (Ba)	265	33	22	41	31
Bromine (Br)	0.4	3.6	3.5	3.4	3.6
Caesium (Cs)	0.5	<0.5	<0.5	0.6	0.6
Cerium (Ce)	14.3	13.5	9.6	9.2	9.6
Chlorine (Cl)	29.0	321	325	322	356
Chromium (Cr)	5.4	8.7	12.0	10.0	10.0
Cobalt (Co)	1.7	3.7	3.0	2.8	2.6
Copper (Cu)	8.7	20.9	25.7	18.7	21.8
Dysprosium (Dy)	1.1	1.5	1.4	1.3	1.2
Europium (Eu)	0.2	0.4	0.3	0.3	0.3
Hafnium (Hf)	1.0	0.7	0.5	0.5	0.5
Holmium (Ho)	0.2	<0.5	<0.5	<0.5	<0.5
Iodine (I)	<0.5	<0.6	0.5	<0.5	0.5
Lanthanum (La)	6.5	6.3	4.7	4.4	4.1
Lutecium (Lu)	0.1	0.1	<0.1	<0.1	<0.1
Manganese (Mn)	31.1	259	149	147	89.7
Mercury (Hg)	<0.3	<0.7	<0.7	<0.9	<0.9
Molybdenum (Mo)	2.1	18.5	13.6	13.4	12.6
Neodymium (Nd)	4.7	6.1	<2.8	<4.0	<3.7
Nickel (Ni)	<26	<56	<54	<54	<50
Rubidium (Rb)	<4.3	<10	<9.2	<9.0	<8.6
Samarium (Sn)	1.1	1.9	1.2	1.2	1.1
Scandium (Sc)	1.7	1.5	1.4	1.3	1.3
Strontium (Sr)	130	<45	56	<36	<31
Tantalum (Ta)	<0.2	0.2	0.2	0.1	0.1
Thorium (Th)	2.5	1.2	1.0	0.8	0.7
Uranium (U)	1.4	0.6	0.7	0.6	0.6
Vanadium (V)	10.5	17.8	18.5	17.1	16.8
Zinc (Zn)	<10	<17	68	20	<15

Table 5 - Petrographic examination of coal macerals

Maceral form	C-1	C-2	C-3	C-4	C-5
<u>Reactives</u>					
Exinite	3.9	3.4	4.4	5.1	5.5
Vitrinite	64.8	65.7	67.4	67.4	69.8
Reactive semifusinite	5.5	4.1	4.3	3.9	3.8
Sub-total	74.2	73.2	76.1	76.4	79.1
<u>Inerts</u>					
Fusinite	6.5	3.9	2.0	3.0	1.9
Semifusinite	11.0	8.2	8.7	7.7	7.6
Micrinite	2.4	3.9	4.6	4.9	3.9
Mineral matter	5.9	10.8	8.6	8.0	7.5
Sub-total	25.8	26.8	23.9	23.6	20.9
Mean reflectance, %	0.60	0.82	0.85	0.83	0.81

Table 6 - Comparative indices of slagging potential of parent coals

Slagging propensity	Reference limits	Parent coal ash				
		Ref. coal	Raw Minto coal	Washed Minto coal		
		C-1	C-2	C-3	C-4	C-5
Base/Acid (B/A) Ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15-0.30	0.19	-	-	-	-
High	0.27-0.50	-	-	-	-	-
Severe	>0.50	-	1.32	1.26	1.28	1.14
Potential slagging temp, (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340-1230	1259	-	-	-	-
High	1230-1150	-	-	-	-	-
Severe	<1150	-	1100	1112	1114	1106

Table 7 - Boiler operating conditions (coarse grind)

Components	Ref. coal	Raw Minto coal	Washed Minto coal		
	C-1A	C-2A	C-3A	C-4A	C-5A
Furnace configuration	I	I	I	I	I
Fuel rate, kg/h	75.0	71.8	68.5	68.6	67.4
Fuel moisture, wt %	0.37	0.40	0.14	0.00	0.40
Coal fineness, wt % (Cdn std)					
+100 mesh	0.3	2.0	1.0	1.0	1.0
-100 + 140 mesh	5.3	9.0	6.0	6.0	7.0
-140 + 200 mesh	22.4	19.0	18.0	19.0	18.0
-200 + 325 mesh	48.0	46.0	44.0	46.0	44.0
-325 + 400 mesh	10.4	13.0	15.0	12.0	15.0
-400 mesh	13.6	11.0	16.0	16.0	15.0
-200 mesh	72.0	70.0	75.0	74.0	74.0
Heat input, MJ/h	2107	2132	2120	2117	2122
Furnace exit temp, °C	1000	969	987	932	901
Air temperature, °C					
Pulverizer in	209	203	209	191	194
Pulverizer out	111	117	109	105	105
Secondary	268	243	254	237	234
Steam rate, kg/MJ	0.209	0.217	0.209	0.216	0.212
Flue gas rate, Nm^3/MJ	0.306	0.306	0.307	0.310	0.308
Flue gas analyses, volume					
CO_2 %	14.9	14.3	14.3	14.7	14.2
O_2 %	4.0	3.9	4.0	4.0	4.0
CO ppm	43	91	54	97	64
NO ppm	833	759	789	664	780
SO_2 ppm	220	4784	4010	3956	3309
SO_3 ppm	-	1.8	0.5	1.11	0.7
Emission rates, g/MJ					
NO	0.341	0.311	0.324	0.275	0.322
SO_2	0.192	4.187	3.517	3.504	2.916

Table 8 - Boiler operating conditions (fine grind)

Components	Ref. coal	Raw Minto coal	Washed Minto coal		
	C-1B	C-2B	C-3B	C-4B	C-5B
Furnace configuration	I	I	I	I	I
Fuel rate, kg/h	78.8	71.7	69.3	68.6	67.9
Fuel moisture, wt %	0.00	0.18	0.13	0.16	0.34
Coal fineness, wt % (Cdn std)					
+100 mesh	0.1	1.0	1.0	1.0	1.0
-100 + 140 mesh	1.4	1.0	2.0	2.0	1.0
-140 + 200 mesh	9.1	11.0	8.0	12.0	6.0
-200 + 325 mesh	59.4	48.0	48.0	57.0	62.0
-325 + 400 mesh	13.7	23.0	21.0	14.0	15.0
-400 mesh	16.3	16.0	20.0	14.0	15.0
-200 mesh	89.4	87.0	89.0	85.0	92.0
Heat input, MJ/h	2101	2134	2100	2114	2139
Furnace exit temp, °C	1023	940	999	967	954
Air temperature, °C					
Pulverizer in	212	192	200	203	199
Pulverizer out	119	105	110	100	100
Secondary	259	229	251	256	250
Steam rate, kg/MJ	0.198	0.199	0.208	0.207	0.215
Flue gas rate, Nm^3/MJ	0.306	0.308	0.310	0.310	0.308
Flue gas analyses, volume					
CO_2 %	14.9	14.2	14.2	14.2	14.3
O_2 %	4.0	4.0	4.0	4.0	4.0
CO ppm	40	61	48	53	46
NO ppm	859	784	795	769	855
SO_2 ppm	216	4873	4128	3653	3243
SO_3 ppm	0.1	1.6	-	0.5	1.4
Emission rates, g/MJ					
NO	0.352	0.323	0.330	0.319	0.353
SO_2	0.189	4.378	3.655	3.236	2.858

Table 9 - Fly ash characteristics (coarse grind)

	C-1A	C-2A	C-3A	C-4A	C-5A
Precipitator inlet loading,					
g/Nm^3	2.50	4.04	2.78	3.09	2.53
g/MJ	0.77	1.24	0.85	0.96	0.78
Combustible content, wt % ...	5.71	14.6	4.61	12.94	8.39
Aerodynamic particle size, wt %					
+30 µm	-	-	-	-	-
+10 µm	53	50	43	40	52
+1 µm	98	93	95	93	95
Electrical resistivity, log ohm-cm					
@ 165 - 170°C	7.73	4.51	7.82	7.52	6.38
@ 310 - 340°C	5.18	5.16	5.34	5.18	5.36
Combustion efficiency, %* ...	99.24	97.18	99.36	98.12	99.04

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where: A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

Table 10 - Fly ash characteristics (fine grind)

	C-1B	C-2B	C-3B	C-4B	C-5B
Precipitator inlet loading,					
g/Nm^3	2.26	4.51	2.88	2.56	2.58
g/MJ	0.69	1.39	0.89	0.79	0.80
Combustible content, wt % ...	2.14	5.80	3.22	5.52	5.03
Aerodynamic particle size, wt %					
+30 µm	-	-	-	-	-
+10 µm	55	53	45	46	53
+1 µm	98	97	96	96	97
Electrical resistivity, log ohm-cm					
@ 165 - 170°C	10.18	5.27	8.48	7.65	8.36
@ 310 - 340°C	7.48	5.17	5.34	5.34	5.34
Combustion efficiency, %* ...	99.86	98.98	99.55	99.26	99.44

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where: A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

Table 11 - Fly ash analysis (coarse grind)

Major elemental oxides (wt %)	Combustion trial				
	C-1A	C-2A	C-3A	C-4A	C-5A
SiO_2	58.91	29.20	33.90	27.88	26.34
Al_2O_3	20.08	11.66	10.53	11.76	10.08
Fe_2O_3	4.27	44.99	45.93	47.02	49.55
TiO_2	1.11	0.65	0.61	0.69	0.71
P_2O_5	0.44	2.45	1.75	2.77	2.38
CaO	8.30	5.72	4.19	5.63	4.52
MgO	1.51	-	0.29	-	-
SO_3	0.45	2.58	3.01	0.30	2.40
Na_2O	1.46	0.31	0.22	0.26	0.23
K_2O	0.46	0.83	0.66	0.78	0.69
BaO	0.61	0.32	-	-	-
SrO	0.15	-	-	0.01	-

Table 12 - Fly ash analysis (fine grind)

Major elemental oxides (wt %)	Combustion trial				
	C-1B	C-2B	C-3B	C-4B	C-5B
SiO_2	56.94	27.05	28.49	29.70	26.14
Al_2O_3	19.79	11.69	12.66	12.16	11.37
Fe_2O_3	4.52	45.62	46.83	45.99	48.10
TiO_2	1.33	0.63	0.68	0.75	0.83
P_2O_5	0.44	2.52	2.64	2.38	2.59
CaO	9.48	6.34	5.95	5.24	4.94
MgO	1.89	0.46	-	0.33	-
SO_3	0.73	2.82	0.78	0.46	3.26
Na_2O	1.23	0.26	0.20	0.23	0.24
K_2O	0.46	0.81	0.78	0.75	0.78
BaO	0.76	0.38	0.19	0.14	0.81
SrO	0.16	-	0.01	0.01	-

Table 13 - Analyses of furnace bottom deposits (coarse grind)

	Combustion trial				
	C-1A	C-2A	C-3A	C-4A	C-5A
Major elemental oxides (wt %)					
SiO_2	65.36	36.65	37.81	47.26	35.09
Al_2O_3	18.74	15.48	16.59	15.87	17.02
Fe_2O_3	3.89	36.98	38.03	24.83	39.82
TiO_2	0.67	0.57	0.74	0.73	0.65
P_2O_5	0.26	0.05	0.85	0.76	0.95
CaO	6.84	4.22	3.26	6.87	3.12
MgO	1.15	0.25	-	-	-
SO_3	0.43	0.10	0.43	0.36	0.28
Na_2O	0.54	0.55	0.09	0.35	0.23
K_2O	0.32	0.53	0.42	0.39	0.36
BaO	0.07	-	-	0.20	-
SrO	0.09	-	0.01	0.03	-
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1260	1107	1060	1079	1041
Spherical deformation	1293	1129	1113	1096	1066
Hemispherical deformation	1382	1153	1138	1110	1091
Fluid temperature	>1482	1261	1246	1268	1235
Oxidizing atmosphere					
Initial deformation	1263	1241	1357	1274	1346
Spherical deformation	1363	1331	1399	1335	1407
Hemispherical deformation	1432	1379	1404	1377	1418
Fluid temperature	>1482	1416	1429	1421	1429

Table 14 - Analyses of furnace bottom deposits (fine grind)

	Combustion trial				
	C-1B	C-2B	C-3B	C-4B	C-5B
Major elemental oxides (wt %)					
SiO_2	62.11	37.95	40.80	43.73	38.47
Al_2O_3	18.90	17.42	19.08	17.54	19.72
Fe_2O_3	4.60	36.17	30.91	28.41	34.31
TiO_2	0.63	0.67	0.81	0.78	0.58
P_2O_5	0.27	0.04	0.73	0.77	0.05
CaO	7.65	4.45	4.73	5.59	2.91
MgO	1.15	0.37	-	-	0.26
SO_3	0.34	0.20	0.39	0.38	0.10
Na_2O	0.51	0.67	0.19	0.22	0.72
K_2O	0.37	0.58	0.35	0.35	0.43
BaO	0.49	-	0.30	-	-
SrO	0.08	-	0.01	0.01	-
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1254	1059	1079	1057	1078
Spherical deformation	1299	1067	1096	1082	1097
Hemispherical deformation..	1388	1073	1110	1093	1105
Fluid temperature	>1482	1105	1282	1254	1167
Oxidizing atmosphere					
Initial deformation	1268	1244	1349	1310	1309
Spherical deformation	1335	1322	1391	1363	1382
Hemispherical deformation..	1460	1376	1404	1393	1400
Fluid temperature	>1482	1405	1432	1432	1443

Table 15 - Analyses of superheater deposits (coarse grind)

	Combustion trial				
	C-1A	C-2A	C-3A	C-4A	C-5A
Major elemental oxides (wt %)					
SiO_2	58.39	25.68	22.30	21.93	25.46
Al_2O_3	18.88	8.32	9.12	9.19	8.02
Fe_2O_3	4.67	54.48	59.67	58.49	58.60
TiO_2	1.10	0.45	0.53	0.51	0.49
P_2O_5	0.40	1.38	1.61	1.68	1.23
CaO	8.80	4.53	3.96	3.90	3.02
MgO	1.13	0.25	0.30	-	-
SO_3	1.65	1.56	1.86	2.03	1.25
Na_2O	1.50	0.26	0.12	0.14	0.08
K_2O	0.37	0.49	0.46	0.42	0.34
BaO	0.62	-	0.22	0.21	0.34
SrO	0.14	-	0.01	0.01	0.01
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1232	1086	1049	1041	1063
Spherical deformation	1285	1105	1071	1082	1077
Hemispherical deformation	1329	1113	1077	1099	1082
Fluid temperature	>1482	1118	1182	1213	1146
Oxidizing atmosphere					
Initial deformation	1277	1328	1379	1349	1399
Spherical deformation	1335	1411	1441	1446	1435
Hemispherical deformation	1410	1422	1443	1449	1441
Fluid temperature	>1482	1430	1457	1457	1443

Table 16 - Analyses of superheater deposits (fine grind)

	Combustion trial				
	C-1B	C-2B	C-3B	C-4B	C-5B
Major elemental oxides (wt %)					
SiO_2	59.45	28.55	23.46	22.64	27.86
Al_2O_3	20.16	8.91	9.00	8.95	10.83
Fe_2O_3	4.38	51.66	58.07	57.35	52.19
TiO_2	0.88	0.48	0.47	0.48	0.29
P_2O_5	0.31	1.49	1.35	1.48	1.12
CaO	9.94	4.74	3.85	3.69	3.22
MgO	1.38	-	-	0.25	0.23
SO_3	1.65	1.69	1.94	1.62	0.99
Na_2O	0.88	0.17	0.13	0.11	0.20
K_2O	0.30	0.49	0.45	0.40	0.46
BaO	0.47	0.26	0.26	-	-
SrO	0.12	-	-	0.01	-
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1199	1041	1063	1054	1099
Spherical deformation	1285	1046	1088	1077	1134
Hemispherical deformation	1360	1052	1102	1099	1142
Fluid temperature	1404	1143	1182	1191	1174
Oxidizing atmosphere					
Initial deformation	1252	1349	1379	1371	1314
Spherical deformation	1329	1421	1443	1449	1432
Hemispherical deformation	1371	1424	1446	1452	1443
Fluid temperature	>1482	1429	1454	1463	1454

Table 17 - Comparative indices of slagging potential
- furnace bottom deposits (coarse grind)

Slagging propensity	Reference limits	Original ash source				
		Ref. coal	Raw Minto coal	Washed Minto coal		
		C-1A	C-2A	C-3A	C-4A	C-5A
Base/acid (B/A) ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15-0.30	0.15	-	-	-	-
High	0.27-0.50	-	-	-	0.49	-
Severe	>0.50	-	0.81	0.76	-	0.82
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340-1230	1294	-	-	-	-
High	1230-1150	-	1161	-	-	-
Severe	<1150	-	-	1129	1085	1116

Table 18 - Comparative indices of slagging potential - furnace bottom deposits (fine grind)

Slagging propensity	Reference limits	Original ash source				
		Ref. coal	Raw Minto coal	Washed Minto coal		
		C-1B	C-2B	C-3B	C-4B	C-5B
Base/acid (B/A) ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15-0.30	0.17	-	-	-	-
High	0.27-0.50	-	-	-	-	-
Severe	>0.50	-	0.91	0.60	0.56	0.66
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340-1230	1295	-	-	-	-
High	1230-1150	-	-	-	-	-
Severe	<1150	-	1097	1144	1124	1142

Table 19 - Comparative indices of slagging potential
- superheater deposits (coarse grind)

Slagging propensity	Reference limits	Original ash source				
		Ref. coal	Raw Minto coal	Washed Minto coal		
		C-1A	C-2A	C-3A	C-4A	C-5A
Base/acid (B/A) ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15-0.30	0.21	-	-	-	-
High	0.27-0.50	-	-	-	-	-
Severe	>0.50	-	1.75	2.02	1.99	1.83
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340-1230	1267	-	-	-	-
High	1230-1150	-	1153	-	-	-
Severe	<1150	-	-	1128	1123	1139

Table 20 - Comparative indices of slagging potential superheater deposits (fine grind)

Slagging propensity	Reference limits	Original ash source				
		Ref. coal	Raw Minto coal	Washed Minto coal		
		C-1B	C-2B	C-3B	C-4B	C-5B
Base/acid (B/A) ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15-0.30	0.21	-	-	-	-
High	0.27-0.50	-	-	-	-	-
Severe	>0.50	-	1.50	1.90	1.96	1.45
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340-1230	1233	-	-	-	-
High	1230-1150	-	-	-	-	1168
Severe	<1150	-	1118	1140	1134	-

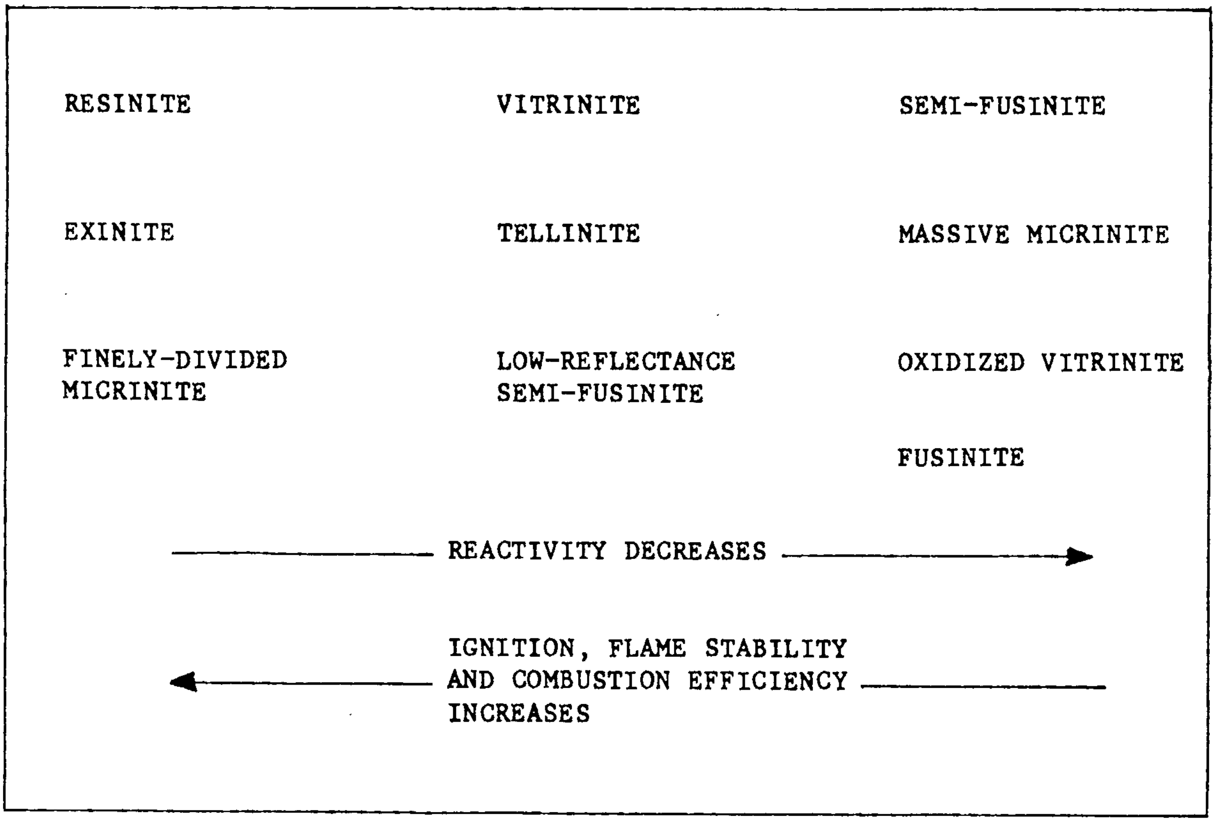


Fig. 1 - Influence of coal maceral type on combustion

CLASSIFICATION OF COAL BY RANK

Canada uses the systems and procedures of the American Society for Testing and Materials (ASTM) for sampling, analysing and classifying coals by rank, as detailed in the Annual Book of ASTM Standards. Basically coals are ranked according to their degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite.

Classification in the ASTM system is a function of fixed carbon content and calorific value calculated on the mineral-matter-free basis. The high rank coals are classed according to calorific value on the moist basis. The agglomerating characteristics of coals (i.e. their binding and/or swelling qualities when heated in the absence of oxygen) are used to differentiate between certain adjacent groups in the ranking.

VM%*	FC%*	CLASS	GROUP	CALORIFIC VALUE**	
				Btu per lb	Mj/kg
2	98	Anthracite(1)	Meta Anthracite		
8	92		Anthracite		
14	86		Semianthracite		
22	78	Bituminous(2)	Low Volatile Bituminous		
31	69		Medium Volatile Bituminous		
			High Volatile A Bituminous	14 000	32.6
			High Volatile B Bituminous	13 000	30.2
			High Volatile C Bituminous		
		Sub-bituminous(4)	Sub-bituminous A(3)	11 500	26.7
			Sub-bituminous B	10 500	24.4
			Sub-bituminous C	9 500	22.1
		Lignitic(4)	Lignite A	8 300	19.3
			Lignite B	6 300	14.7

* Dry, mineral-matter-free basis

**Moist, mineral-matter-free basis

(1) Non-agglomerating; if agglomerating classified as low volatile bituminous

(2) Commonly agglomerating

(3) If agglomerating classified as high volatile C bituminous

(4) Non agglomerating

VM: Volatile matter

FC: Fixed carbon

Source: Energy, Mines and Resources, Canada CANMET Report 83-20E

Fig. 2

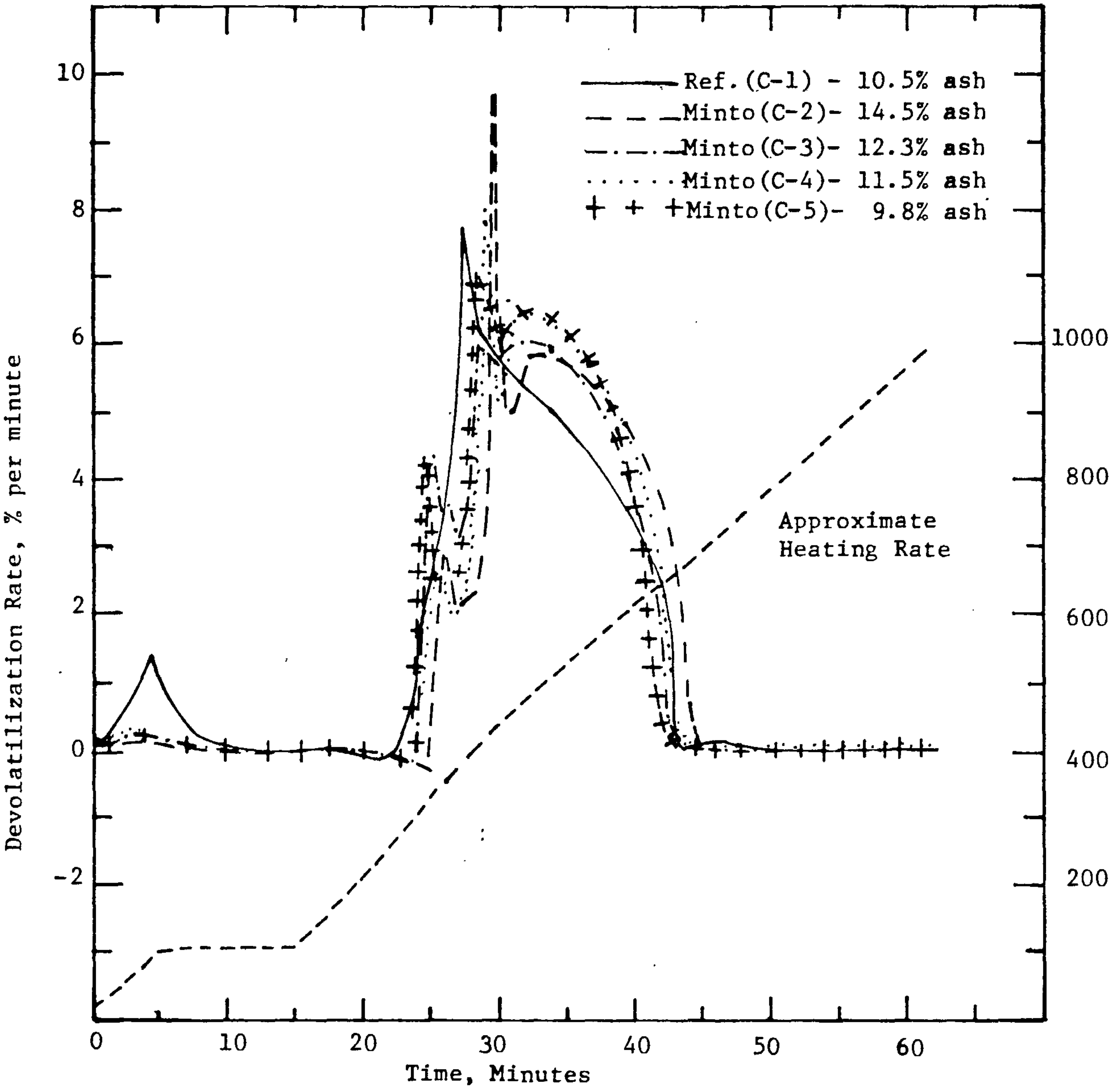


Fig. 3 - Comparative thermogravimetric analysis of minto coals and a thermal reference coal

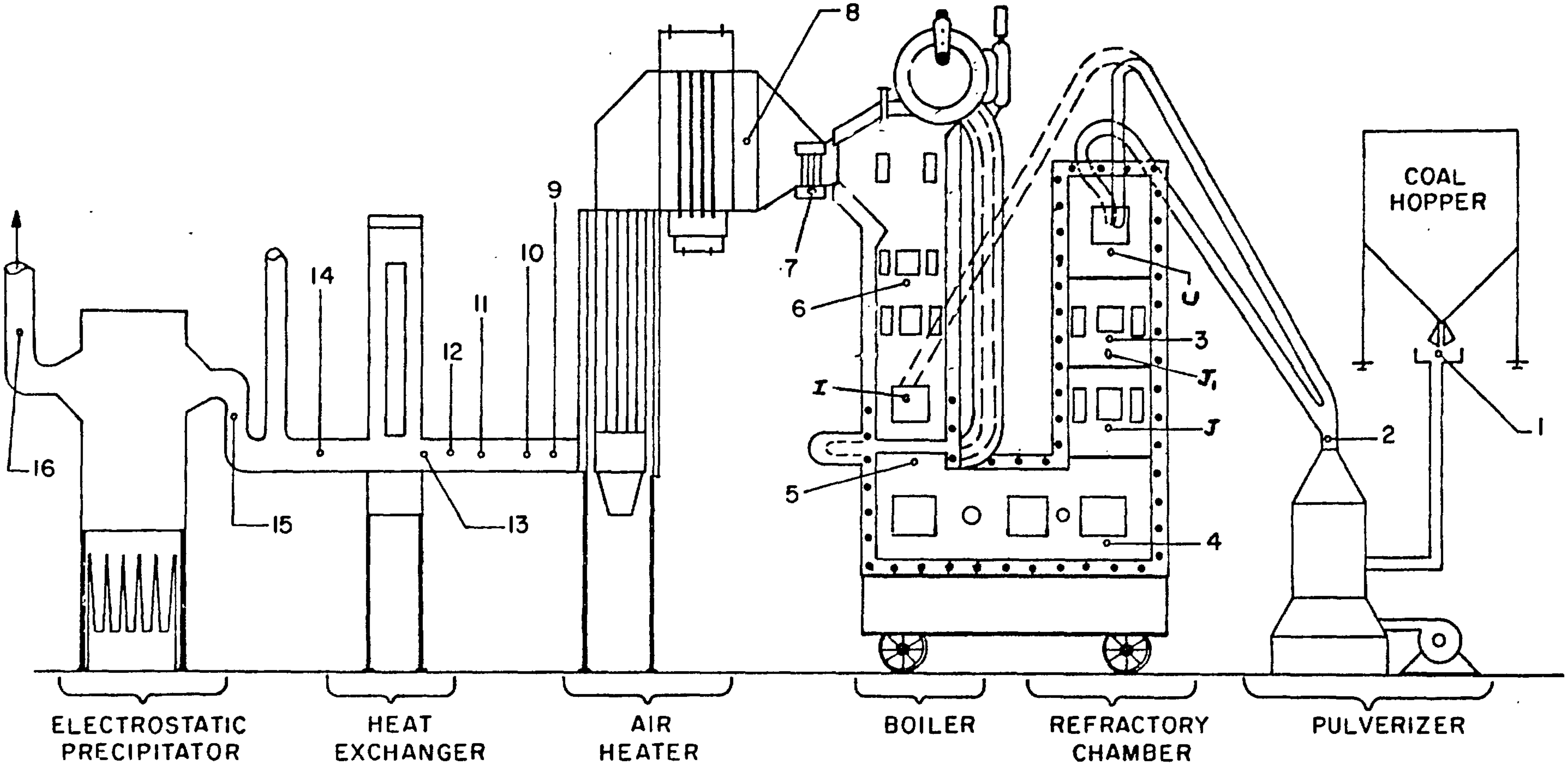


Fig. 4 - Schematic illustration of the pilot-scale boiler - showing sampling stations

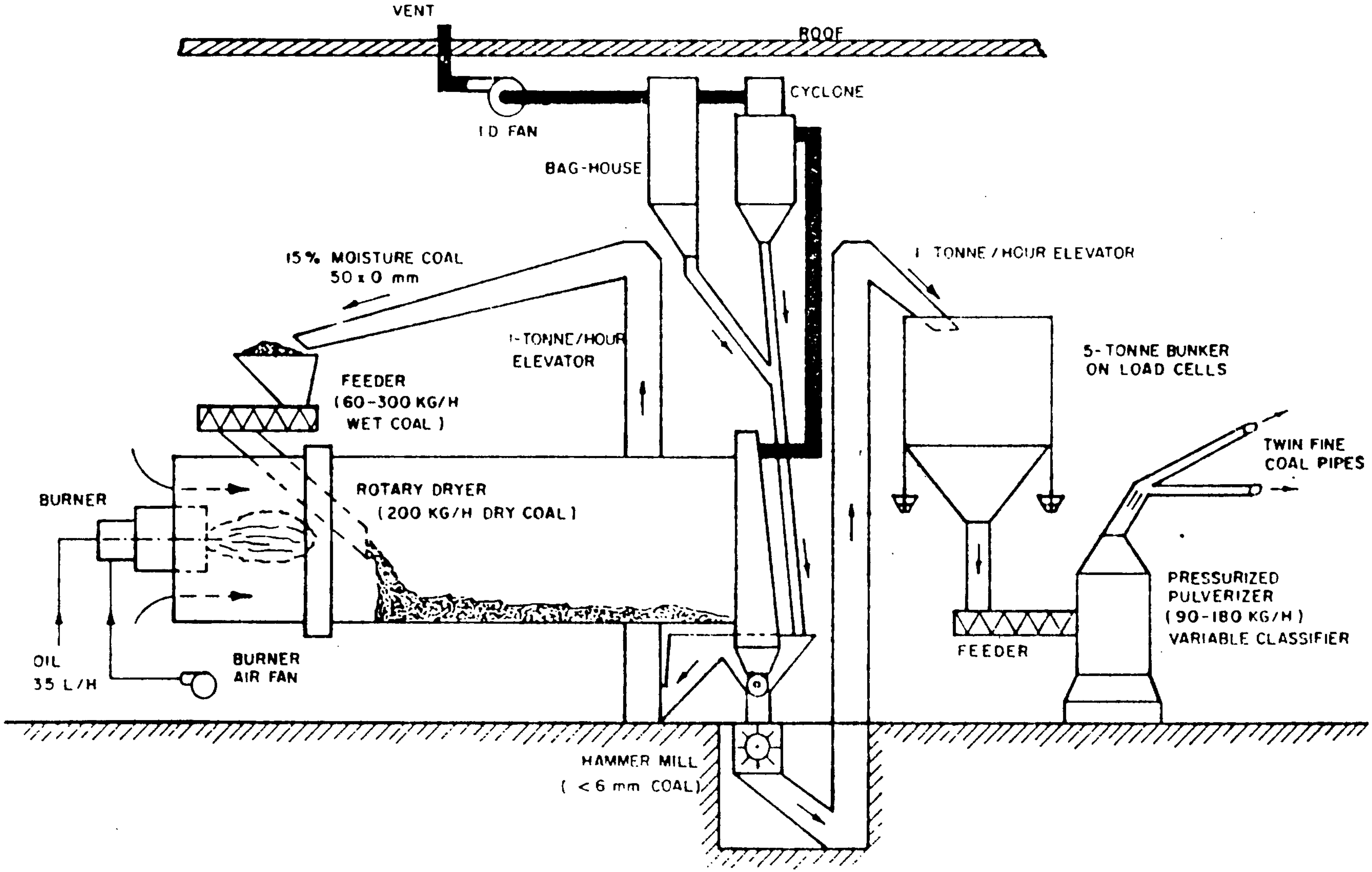
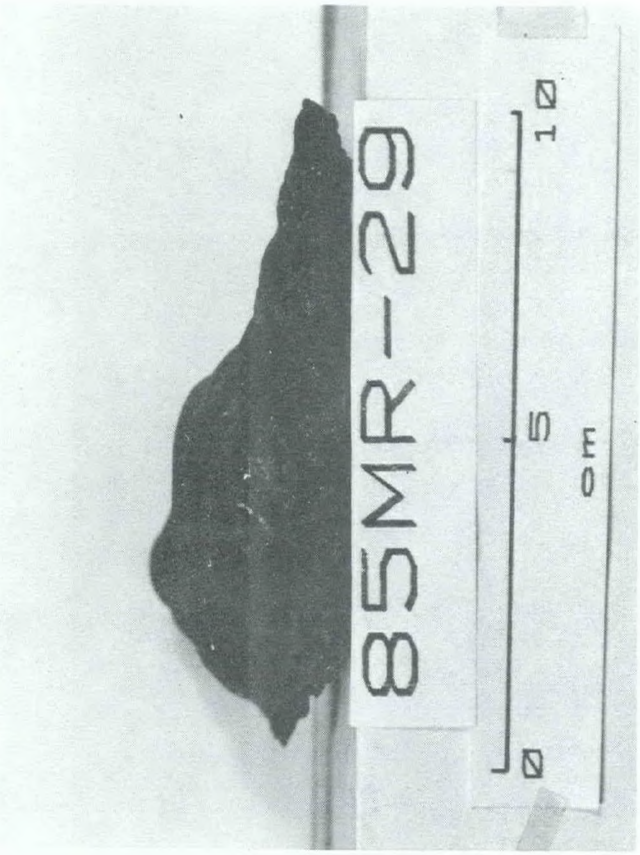
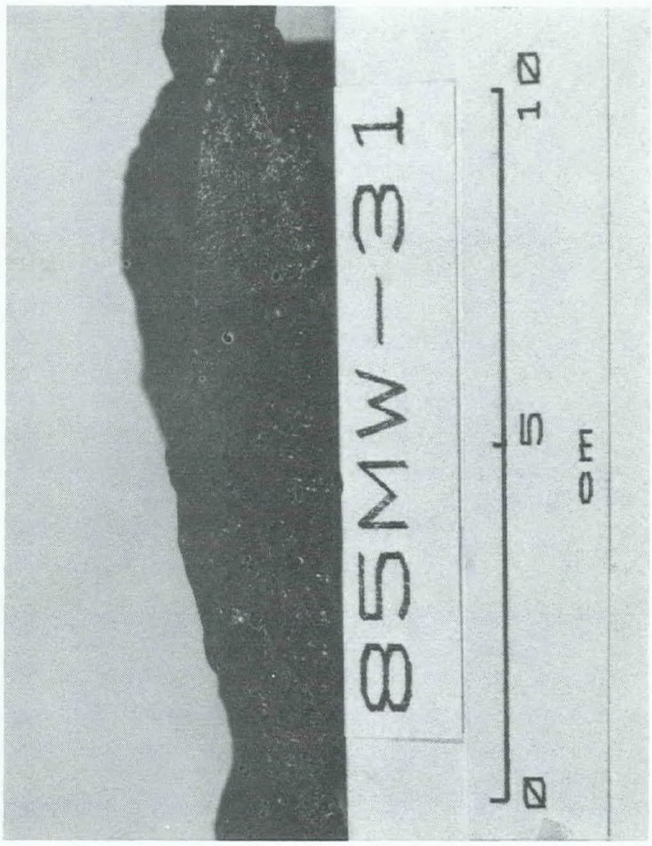


Fig. 5 - Schematic illustration of solid fuel drying and grinding system



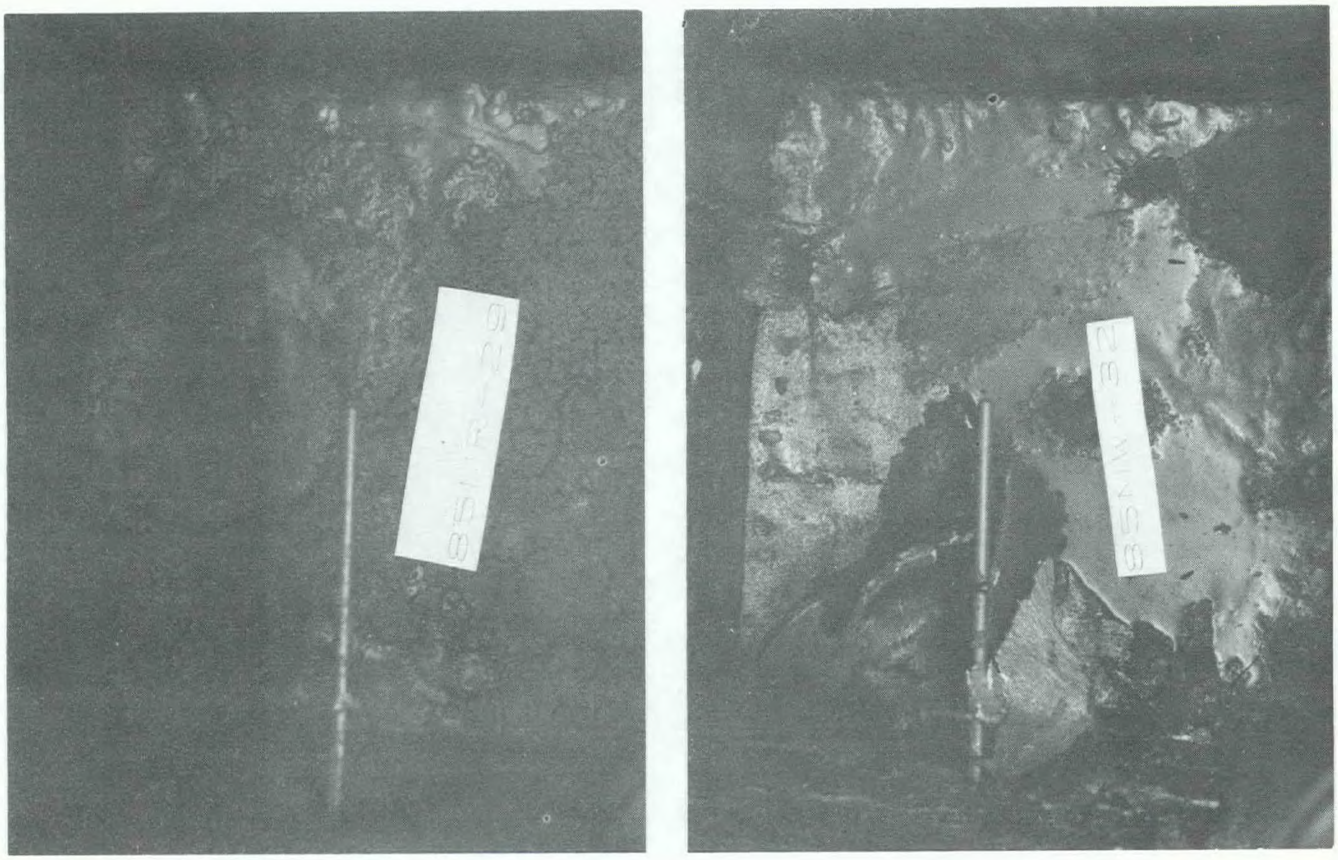
Raw Coal (C-2)



Washed Coal (C-5)

Reference Coal (C-1)

Fig. 6 - Cross-sectional photographs of furnace bottom deposits

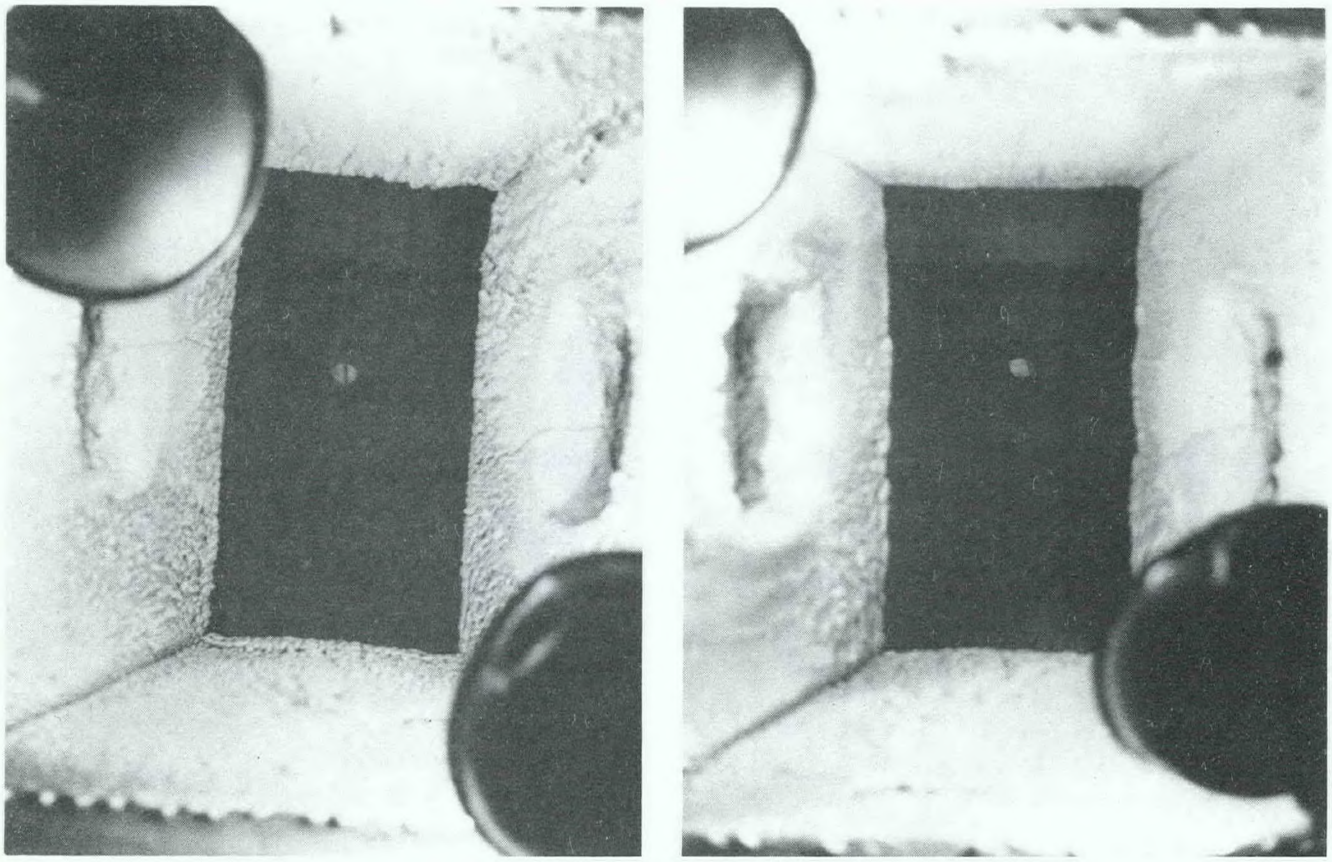


Raw Coal (C-2)

Washed Coal (C-5)

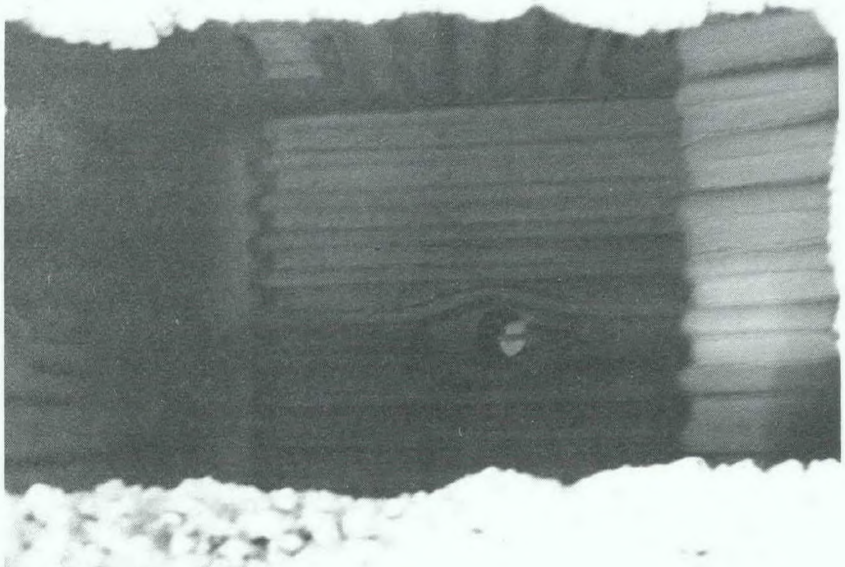
Reference Coal (C-1)

Fig. 7 - Deposits in furnace bottom



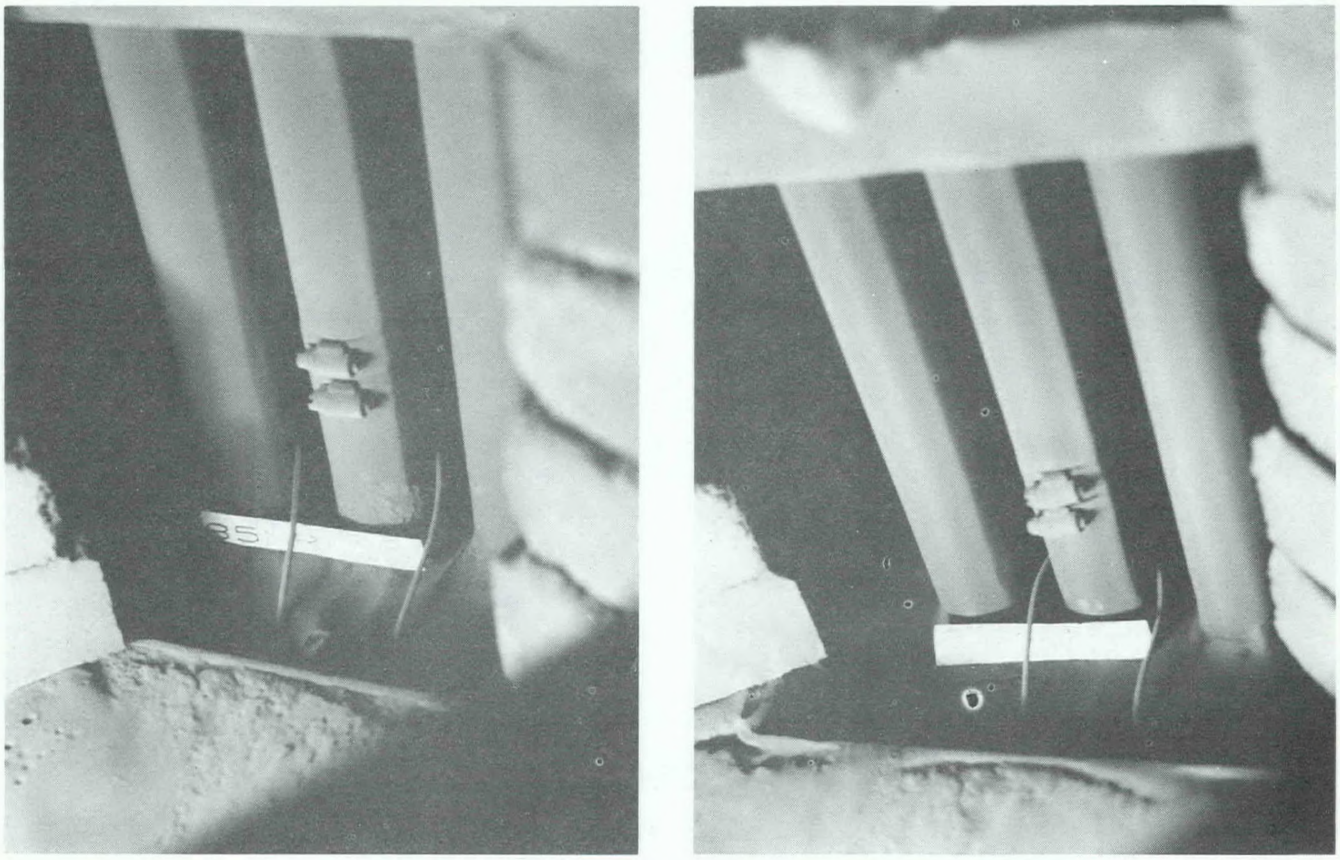
Raw Coal (C-2)

Washed Coal (C-5)



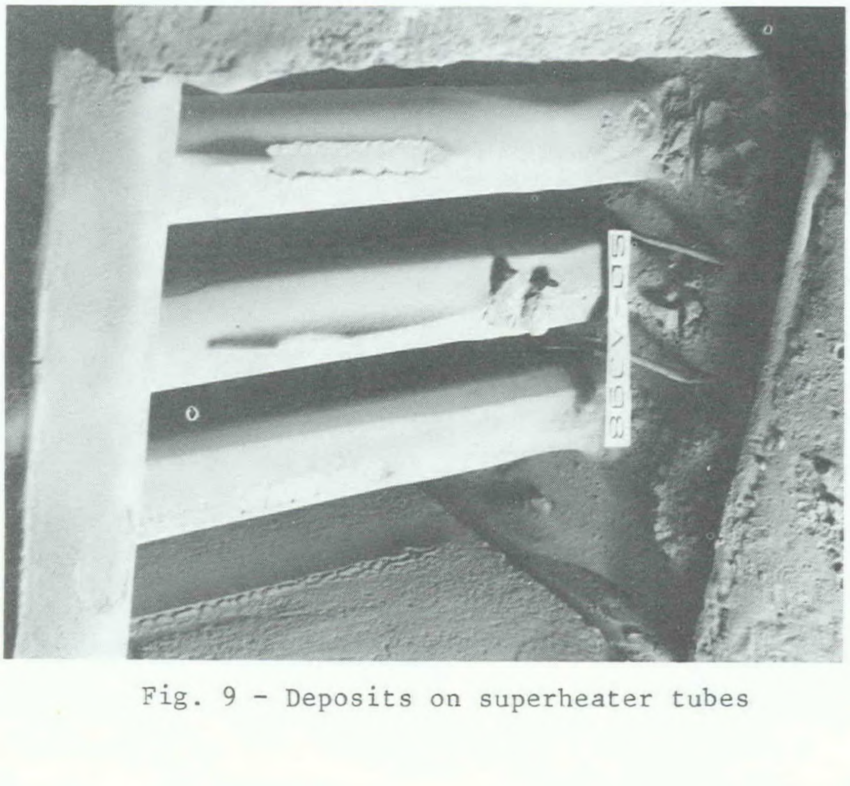
Reference Coal (C-1)

Fig. 8 - Deposits on refractory and water-walls of furnace



Raw Coal (C-2)

Washed Coal (C-5)



Reference Coal (C-1)

Fig. 9 - Deposits on superheater tubes

APPENDIX "A"

COMBUSTION CHARTS
FOR
RAW MINTO COAL

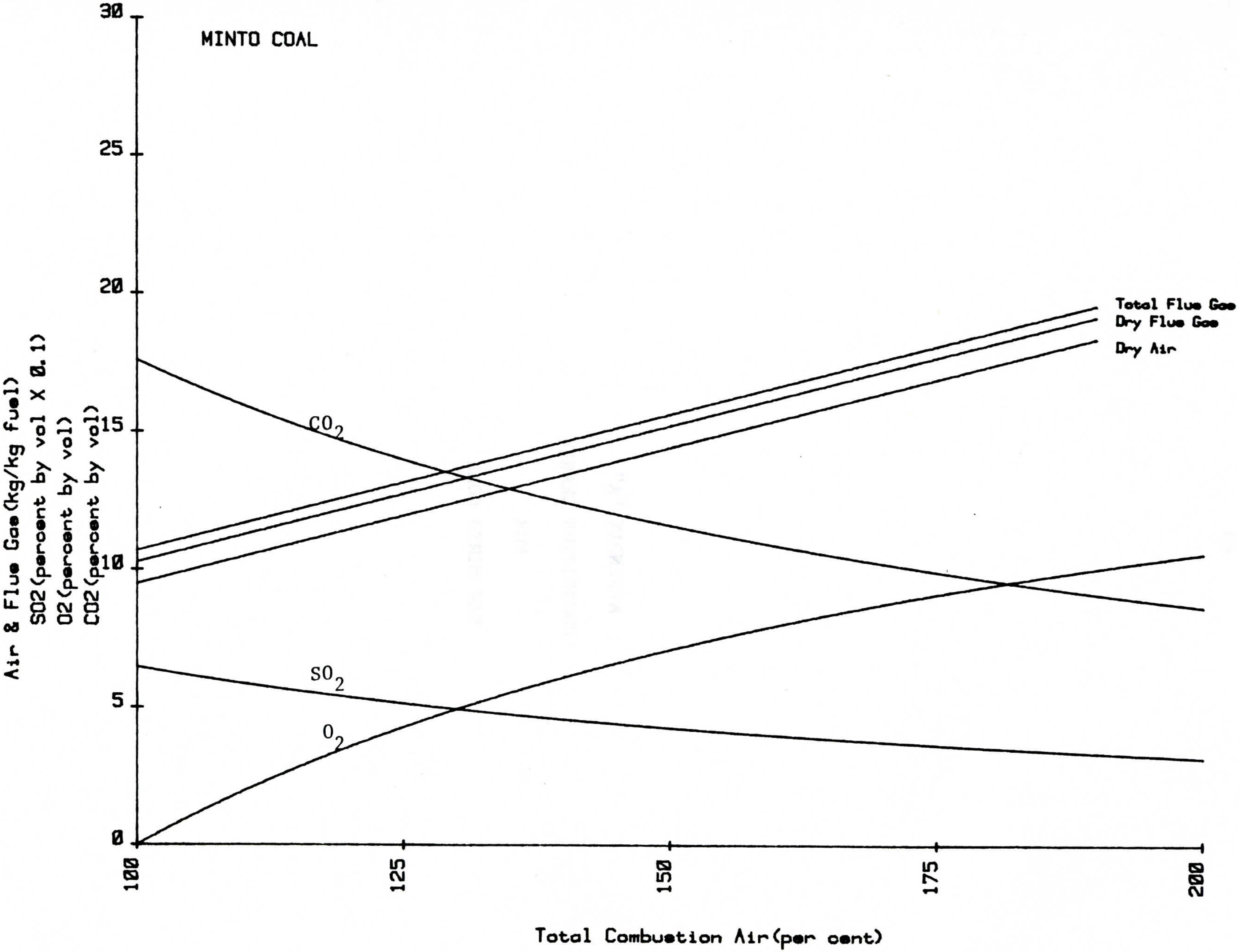


Fig. 1A - Combustion data, weight basis

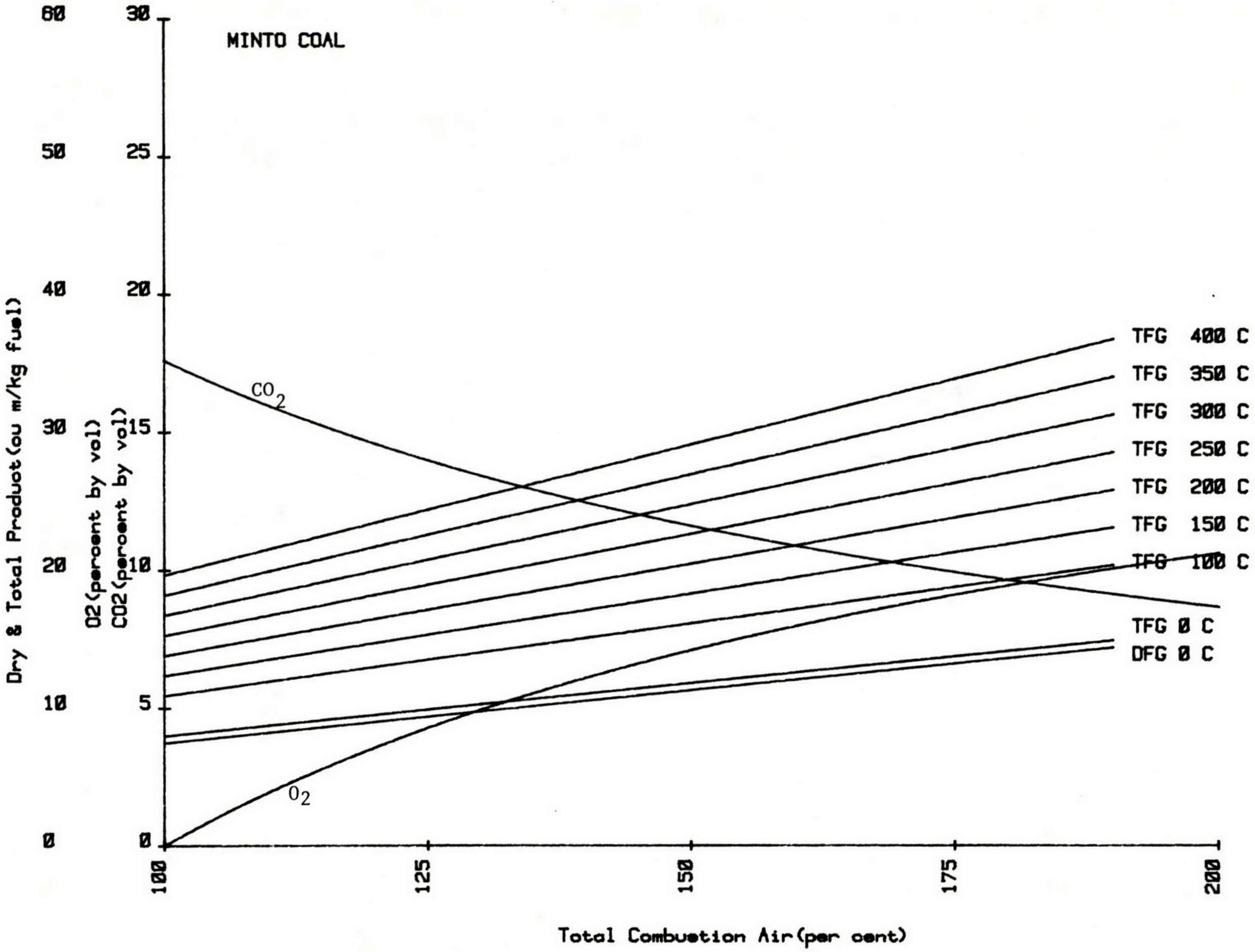


Fig. 2A - Combustion data, volume basis

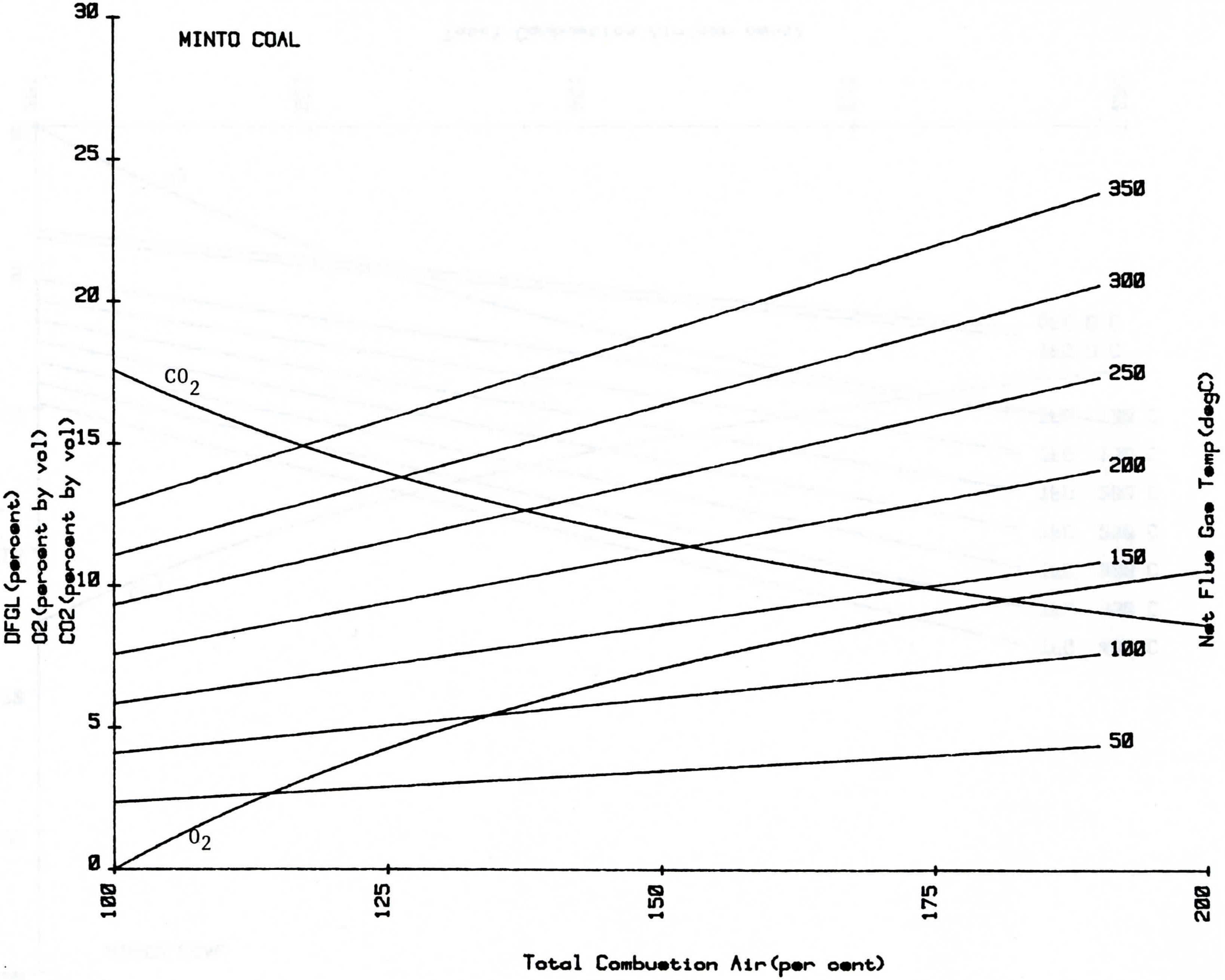


Fig. 3A - Dry flue gas loss for a range of temperature differentials

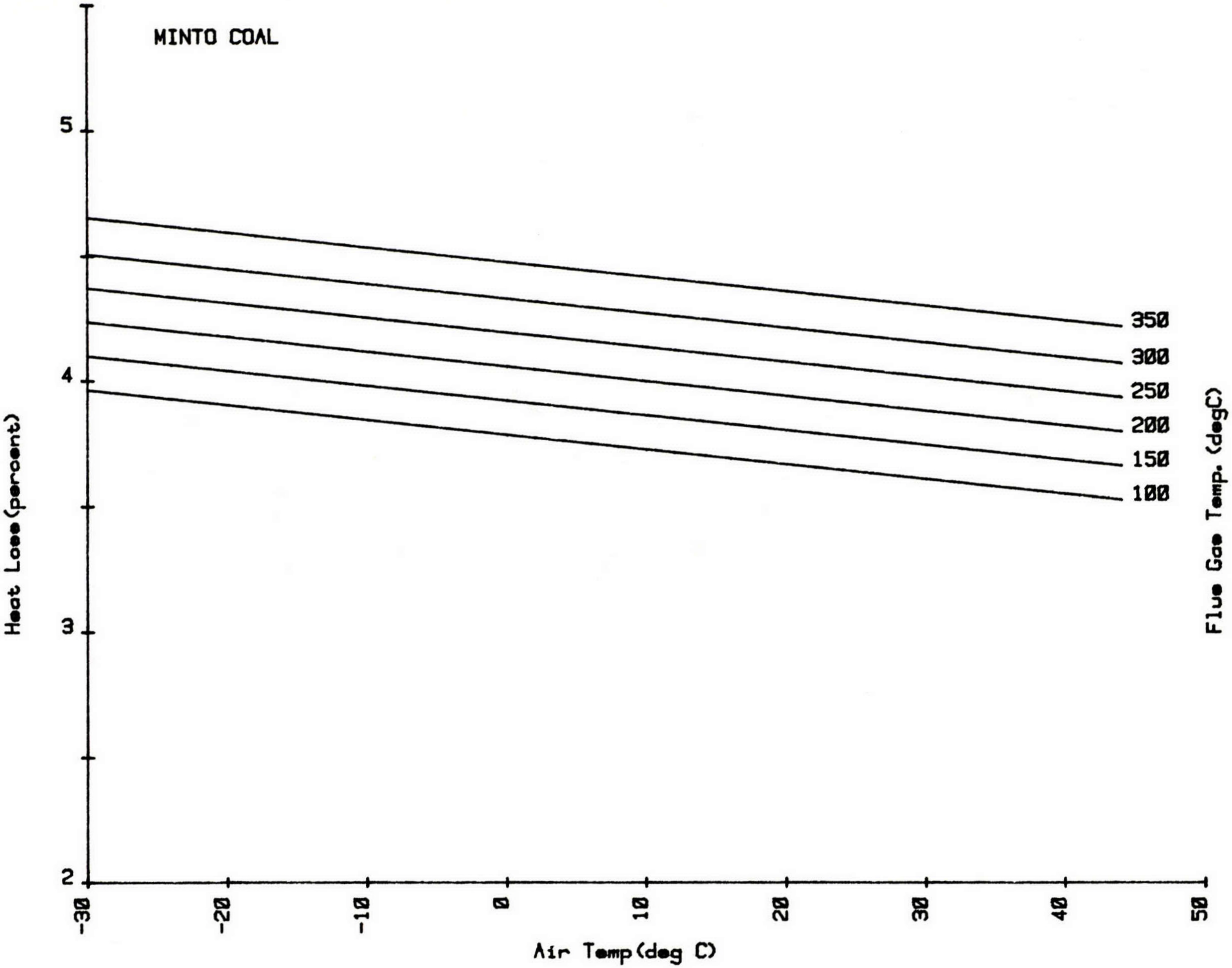


Fig. 4A - Hydrogen loss for a range of stack gas temperatures

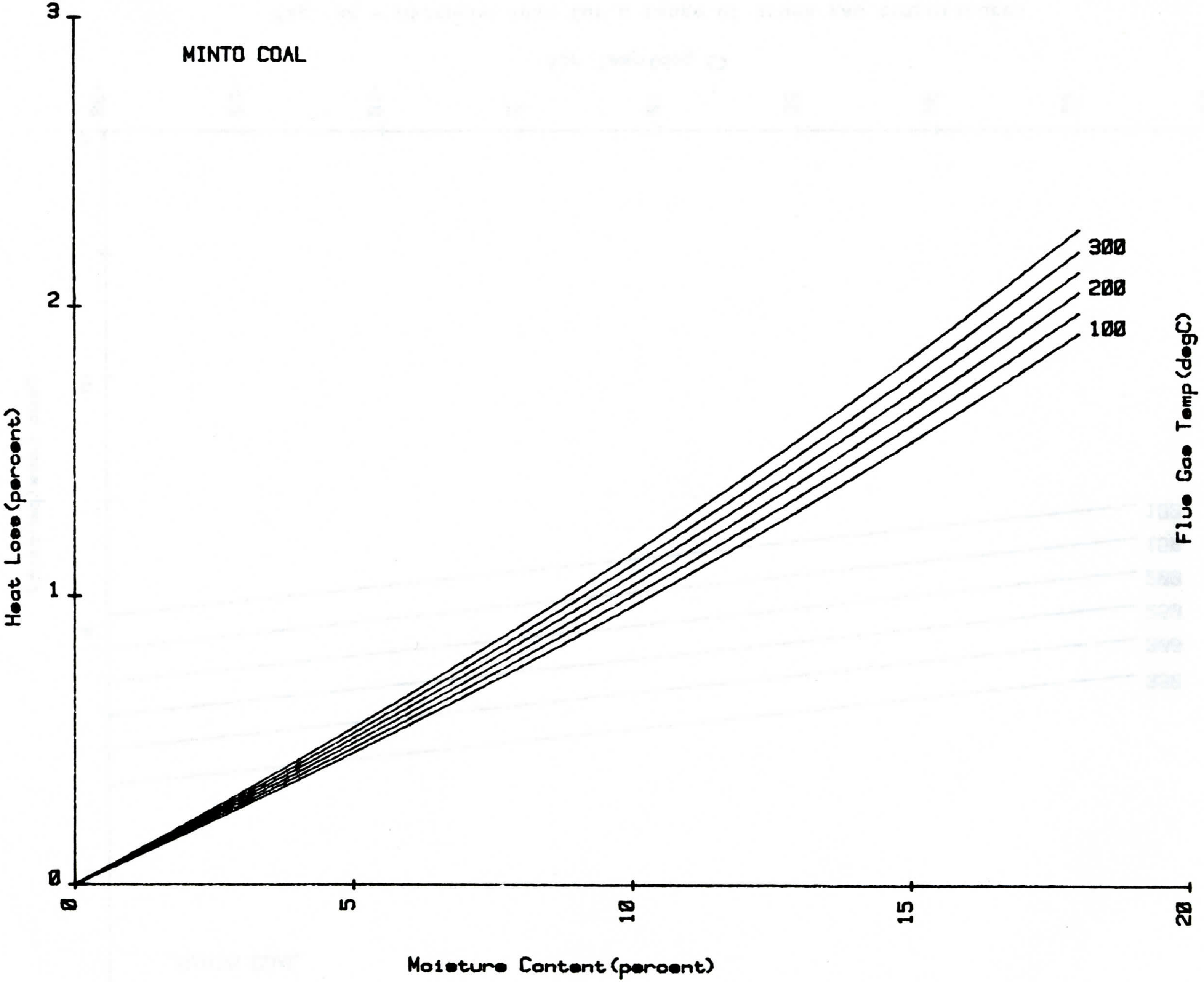


Fig. 5A - Heat loss due to moisture in coal

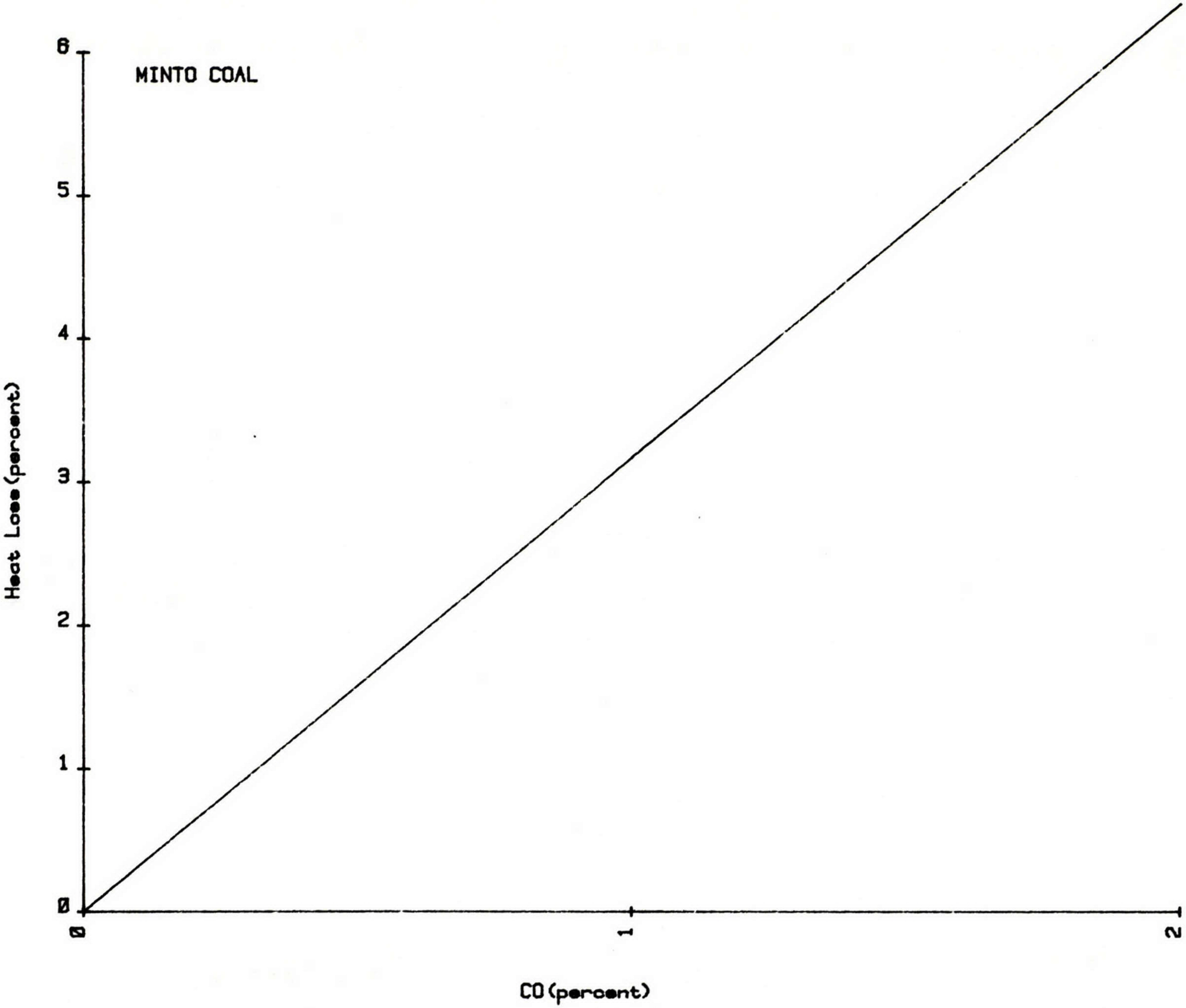


Fig. 6A - Heat loss for a range of CO concentration
(assuming negligible excess air)