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COMBUSTION PERFORMANCE AND SULPHUR CAPTURE DURING FLUID BED COMBUSTION
OF A WESTERN SUB-BITUMINOUS COAL AND AN EASTERN BITUMINOUS COAL

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by

N.S.H. Stover*, E.J. Anthony**, D.L. Desai* and F.D. Friedrich**

ABSTRACT

The carbon combustion efficiency and solid phase sulphur retention of low-sulphur Alberta sub-bituminous coal and a high sulphur New Brunswick bituminous coal were examined in an atmospheric fluidized-bed combustor. Input variables were energy release (35 KW to 130 KW), bed temperature (750°, 850° and 950°C), and flue gas oxygen concentrations (2.5, 5%). The resulting range of superficial fluidizing velocities was 1 to 4 m/s which produced vigorous bubbling bed conditions.

The sub-bituminous coal proved more reactive with a once through combustion efficiency in the range of 96% to 99%. Comparable figures for the bituminous coal were in the range of 90% to 98%.

Attempts to correlate burn-out with bed temperature, excess air and fluidizing velocity indicate that burn-out with the sub-bituminous coal is primarily dependent on bed temperature. For the bituminous coal burn-out is chiefly dependent on bed temperature and fluidizing velocity.

For both coals, sulphur capture in 'coal ash constituents' appear to be best below 750°C. With the high-sulphur bituminous coal (sulphur content of 9%) limestone was also used to vary the Ca/S mole ratio in the range of 2 to 5 and was able to produce up to a 90% reduction in sulphur emission. The degree of sulphur retention, Ret, followed the relationship:

$$\text{Ret} = 100 \quad 1 - \exp(-0.46 [\text{Ca/S}])$$

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NOMENCLATURE

cc	carbon carryover (%)
Ca/S	calcium to sulphur mole ratio
g	acceleration due to gravity (m/s^2)
H	bubbling bed height (m)
L	characteristic length for the bed chosen as the bed diameter (m)
M	empirical constant
Ret	sulphur retention (%)
T	bed temperature (K)
U	superficial gas velocity (m/s)
W_c	concentration of calcium oxide in the bed (wt %)
Z	Dimensionless velocity (gL/U^2)
ϕ	mixture strength, the ratio of air available for combustion to that required for complete combustion

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INTRODUCTION

Fluid bed combustion (FBC) is well suited to burn coals containing any combination of high sulphur, high ash or high moisture. By using limestone as a sulphur sorbent reductions of about 90% in SO₂ emissions can be achieved and because fluidized-bed combustors typically operate at temperatures of 750° to 950°C they avoid the problems of slagging frequently encountered with conventional combustion technology (1,2). In addition high heat transfer coefficients in the fluidized bed (200 - 510 W/m²/°C) (3) allow for more compact boiler designs.

Energy, Mines and Resources Canada is encouraging the development and application of FBC by sponsoring demonstration projects, (4), the first of which will be a heating plant at the Canadian Forces Base Summerside, containing two boilers rated at 18 tph of steam each (5). The demonstration projects are supported by in-house pilot-scale research at the Canadian Combustion Research Laboratory (CCRL) to study the performance of various Canadian fuels in fluidized-bed combustors. This paper describes pilot-scale research on a high-sulphur bituminous coal from eastern Canada, and on a low-sulphur sub-bituminous coal from western Canada.

The major objectives were:

1. To evaluate the combustion performance of a high-sulphur, high-ash bituminous coal typical of eastern Canada and of a low-sulphur but high-ash and high-moisture sub-bituminous coal typical of western Canada, in terms of carbon carryover and pollutant emissions.
2. To compare the extent of sulphur capture by the ash constituents of the eastern coal, which are high in iron, and by the ash constituents of the western coal, which are high in alkali.
3. To determine, for the eastern coal, the effect on sulphur capture of limestone addition.

THE PILOT-SCALE COMBUSTOR

The major components of CCRL's AFBC are shown schematically in Figure 1. Combustion air is supplied to the wind box at the base of the combustor and enters the bed through a stainless steel distributor plate

which holds an array of 36 bubble caps arranged in concentric circles. The bubble caps were fabricated from conventional stainless-steel pressure-jet oil-burner nozzles by removing the internals and drilling a 1.8 mm diam. hole in each of the hexagonal faces. Thus air enters the bed horizontally and the possibility of solids backflow is minimized.

The combustor has an inside diameter of 0.24 m and a height of 1.2 m. It consists of a liner fabricated from 4.5 mm thick Inconel 601, backed by a 22 mm thick layer of insulating castable refractory, surrounded in turn by a water jacket. On top of the combustor is mounted a freeboard section having an inside diameter of 0.6 m and an overall height of 1.8 m. It is fabricated of stainless steel, with a refractory lining on the conical section which adapts to the combustor top. Externally, the freeboard section is insulated with a 50 mm thick silica-alumina blanket. The combustor and freeboard are penetrated by ports for temperature and pressure measurement, fuel injection, gas sample extraction, and a propane-fired light-up burner. Bed temperature and pressure are measured at distances of 0.1, 0.3, 0.6 and 0.9 m above the distributor plate. Freeboard temperatures are also measured at 1.5 m and 2.4 m above the distributor plate.

A flexible 0.15 m diameter stainless steel duct connects the top of the freeboard to a small multi-cyclone dust collector which has a hopper and double-valve arrangement to permit on-line extraction of the cyclone product. From the dust collector flue gases are ducted to a waste heat boiler and thence to an exhaust system. Dust loading in the gases leaving the dust collector can be measured in the duct between it and the waste heat boiler.

The fuel supply system consists of a hopper with a capacity of 160 kg discharging onto a horizontal rotating-plate feeder. A variable-speed drive connected to the rotating plate controls the fuel feed rate, and a pneumatic system transports the fuel from the feeder into the bed at a point 0.1 m above the distributor plate. The fuel hopper and feeder rest on an electronic weigh scale, in order to provide a simple means of determining fuel feed rate. This feed system is only suitable for dry fuels crushed to about minus 6 mm.

Bed material can be added to the combustor through the top of the freeboard section and can be removed through a 25 mm discharge pipe in the

centre of the distributor plate. The removal system includes a valve, a cooler, a small cyclone and a vacuum system.

THE TEST FUELS AND LIMESTONE

The bituminous coal used in the research program is surface-mined in New Brunswick and sold under the trade name of Minto, primarily as a fuel for thermal power generation. It is the highest-sulphur coal presently used in Canada and has the additional drawbacks of high ash content and low ash fusion temperatures. However, it is a reactive fuel and performs well in conventional pulverized-fired systems. The ash composition with its high iron content is typical of eastern Canadian coals. The sub-bituminous coal, Highvale, is surfaced-mined in central Alberta to fuel the Sundance thermal generation station. Its ash composition, low in iron but high in calcium, is typical of the low-rank plains coals of western Canada. It is also a reactive fuel and performs well in pulverized-fired systems but, as with most Canadian plains coals, generous furnace sizing is required to avoid ash fouling. Analytical data for both coals are given in Table 1.

Limestone from Havelock, New Brunswick was chosen as the sulphur sorbent for the research program mainly because other work (5) has shown it to be moderately good for this application, but also because it is located in the same geographic area as the high sulphur Minto coal. Its analysis together with its particle size distribution, are given in Table 2.

THE TEST PROGRAM AND PROCEDURES

To meet the objective of evaluating the combustion performance of the two coals, a test matrix was planned in which fuel firing rate, bed temperature and excess air level were the input variables. The ranges were as follows:

Fuel input rate:	35 to 130 kW
Bed temperature:	750° 850° and 950°C
Excess air level:	2.5 and 5.0 % O ₂ in the flue gas

Eighteen combustion tests were carried out with each coal, using combinations of the foregoing variables which yielded a 1 to 4 m/s range of superficial fluidizing velocities.

To determine the effect of limestone addition on sulphur capture six

additional combustion tests were conducted with Minto coal. Nominal values for the input variables were:

Fuel input rate:	75 kW
Bed temperature:	850°C
Excess air level:	2.5 and 5% O ₂ in the flue gas
Ca/S mole ratio:	1.7, 3.0 and 4.3

The coals were prepared by crushing and air-drying prior to charging the fuel hopper. Particle size distributions are given in Table 3. For the tests with limestone addition, the appropriate proportions of limestone and coal were thoroughly mixed in a barrel mixer before charging into the hopper. For each test the fluidized bed was charged with approximately 26 kg of fresh, sharp silica sand, the size distribution of which is also given in Table 3.

The combustor was brought into operation by fluidizing it at close to the minimum fluidizing velocity and then preheating it by means of a submerged propane burner to the temperature required for stable combustion of coal. This was found to be about 500°C for the sub-bituminous Highvale coal and about 750°C for the bituminous Minto coal. When coal feed was initiated and ignition was stabilized the propane burner was taken out of service. Coal feed and combustion air rates were then adjusted to the target conditions and bed temperature was regulated by injecting water into the bed as necessary.

Test measurements were begun when steady-state conditions had been achieved. Typically during each test three batch samples of flue gas were extracted from the top of the freeboard and analyzed for SO₂ and SO₃ using the West-Gaeke Method (6). Also, three measurements were made of solids loading in the flue gas at the cyclone outlet. Concentrations of CO, CO₂, O₂ and NO_x in the flue gas were monitored continuously using NDIR analyzers for CO and CO₂, a paramagnetic analyzer for O₂, and a chemiluminescent analyzer for NO_x. The gas sample was extracted from the cyclone exit to ensure that it was well mixed. Bed and freeboard temperatures were also monitored continuously, whereas pressures were manually logged at frequent intervals.

In the combustion tests with limestone addition some bed material was removed periodically to maintain the expanded bed depth at about

410 mm. In the tests without limestone addition most of the ash appeared to elutriate, for bed depth remained constant without operator intervention.

At the end of each test the cyclone product and the bed material were analyzed for sulphur and carbon. The results of which, together with similar analyses of the fly ash escaping the cyclone collector, permitted calculation for inventories of sulphur and carbon.

Average conditions for the combustion tests with Minto and Highvale coals are given in Tables 4 and 5 respectively.

RESULTS AND DISCUSSION

A. Sulphur Capture Without Limestone Addition

Sulphur balances calculated for the eighteen combustion tests carried out with Minto coal without limestone addition produced an average sulphur accountability of 76%. For the eighteen tests with Highvale coal the average accountability was substantially better; 92%. One possible explanation for the low accountability with the high-sulphur eastern bituminous coal may lie in limitations of the Leco furnace technique (7) which was employed to determine the sulphur content of the solids samples. This method has been shown to have an inherent negative bias when applied to "ash-like" materials (8). Another factor is variation in the sulphur content of the Minto coal used in the tests. Sulphur content of spot samples was found to range from 8.46 to 9.44%. For the sulphur balance calculations an average value of 9.03% was used.

For both coals, the amount of sulphur retained in the bed material and the elutriated solids is given in Table 6. In the case of Minto, although the amount of sulphur retained is small, 2 to 7%, it cannot be explained by chemical fixation, for both the Ca/S ratio and the (Ca + Na + K)/S ratio are too small, being 0.025 and 0.042 respectively. It seems more likely that before oxidation of the pyrite is completed, some is elutriated from the bed and quenched in the cyclone.

This is supported by an analysis of the sulphur retention data for Minto considering mixture strength ϕ , a dimensionless fluidizing velocity Z where $Z = \frac{gL}{U^2}$, and bed temperature T . These were combined in a relationship

of the form

$Ret = a\phi^b Z^c \exp(d/T)$ where a, b, c and d are arbitrary constants which when determined from multilinear regression produced the following:

$$Ret = 0.11 Z^{-0.3} \exp\left(\frac{3500}{T}\right) \quad (\text{Eq. 1})$$

Multiple correlation coefficient $R = 0.7$, F ratio = 14

This equation shows sulphur retention to be dependent on fluidizing velocity but not on excess air, and it can be inferred that the degree of retention depends upon the time it takes the sulphur to oxidize compared to the time it takes for particles to become small enough to elutriate. Since most of the sulphur in Minto coal is pyrite, its oxidation can be expected to be relatively slow.

In the case of Highvale coal 78% of the sulphur is in organic form and therefore is bound up in the volatile matter. It seems reasonable to assume that this will be oxidized rapidly. In addition the Ca/S ratio at 4.55 and the (Ca + Na + K)/S ratio at 5.66 are approximately two orders of magnitude greater than for Minto coal. A high degree of sulphur retention via chemical fixation can therefore be expected, and this is supported by the data in Table 6. It should be borne in mind that the combustion tests were conducted without fly ash recycle. In a system with recycle higher levels of sulphur retention for Highvale might be seen and lower values for Minto without limestone.

An attempt to fit the sulphur retention data for Highvale coal to the same relationship used for Minto coal resulted in the following equation

$$Ret = 0.28 \exp\left(\frac{5800}{T}\right) \quad (\text{Eq. 2})$$

Multiple correlation coefficient $R = 0.87$, F ratio = 101

In this case sulphur retention is independent of fluidizing velocity and mixture strength which is understandable if one assumes that a significant amount of the alkaline constituents are bound up in the organic fraction, i.e., the volatiles, and thus are available for immediate reaction. This phenomenon has been observed by Goblirsch, et al (9) who also found, for their coals, a peak neutralization efficiency by ash alkali at a bed temperature of about 700°C.

The existence of two different mechanisms for sulphur retention is significant because the effect of alkali components on sulphur retention by

natural ash in fluidized bed combustors remains as one of the major unknowns in modelling studies (10). Also, if as other workers have found, the fixation of sulphur by some naturally-occurring coal ash components is reversible even at ambient conditions (11) then the fate of the sulphur in discarded fly ash and bed material will be of more than academic interest and further work in the area is clearly needed.

B. Sulphur Capture with Limestone Addition

As explained previously, six combustion tests were carried out with Minto coal mixed with limestone to give Ca/S ratios of 1.7, 3.0 and 4.3. Test conditions and results are presented in Table 4 and Table 7. Fuel input rate, bed temperature, bed height, excess air level and superficial velocity were held as nearly constant as possible to isolate the effect of the Ca/S ratio. Its effect on sulphur retention is described by the following equation:

$$\text{Ret} = 100 [1 - \exp [-0.46 (\text{Ca/S})]] \quad (\text{Eq. 3})$$

Multiple correlation coefficient $R = 0.98$, F ratio = 203

These results are very similar to those of Wright (12) and Zhang Xu-Yi (13) who were able to fit their data to the following equations respectively:

$$\text{Ret} = 100 [1 - \exp [-M(\text{Ca/S})]] \quad (\text{Eq. 4})$$

$$\text{Ret} = 100 [1 - \exp (-1.97 W_c H/U)] \quad (\text{Eq. 5})$$

With the highest dosage of limestone employed, which gave a Ca/S ratio of 4.3 a sulphur capture of 88% was achieved based on measurements of sulphur in solids. This brought the SO_2 emissions down from a calculated theoretical level of 8220 ppm to an average measured level of 150 ppm for test No. 6. These results suggest the actual sulphur capture is significantly higher perhaps by as much as 10% in some cases and that sulphur in the solid phase is being systematically underestimated by the analytical techniques employed, as discussed previously (8). The problem of achieving good accountability and determining the source of error is not clear cut however because of the variability of sulphur in the fuel.

C. Efficiency of Carbon Combustion

Without fly ash recycle, the measured combustion efficiencies were 90 to 98% with Minto coal and 96 to 99% with Highvale coal. The test results relating to carbon carryover are given in Table 8, and Figure 2 shows carbon carryover plotted against fluidizing velocity. Using these data attempts were made to correlate carbon carryover (cc), to the bed operating parameters of mixture strength ϕ , dimensionless fluidizing velocity Z , and bed temperature T . The following equations resulted:

$$\text{For Minto coal: } cc = 0.314 Z^{-0.5} \phi^{-1} \exp\left(\frac{3500}{T}\right) \quad (\text{Eq. 6})$$

Multiple correlation coefficient $R = 0.93$, F ratio = 59

$$\text{For Highvale coal: } cc = 5.6 \times 10^{-4} \exp\left(\frac{8400}{T}\right) \quad (\text{Eq. 7})$$

Multiple correlation coefficient $R = 0.49$, F ratio = 15

Thus, in the case of Minto coal the combustion efficiency or the degree of burnout is inversely proportional to the fluidizing velocity, directly proportional to the excess air level and exponentially dependent on bed temperature. The reactivity of the coal is such that increasing residence time by reducing fluidizing velocity improves the combustion efficiency. In the case of Highvale coal the correlation is very poor and is given for the sake of completion. Nevertheless one can conclude that the Highvale shows a stronger temperature dependence than Minto and no observable effect of fluidizing velocity or mixture strength on carbon carryover. This indicates that the sub-bituminous Highvale coal is substantially more reactive than the bituminous Minto coal; so much so that thermodynamic, rather than kinetic factors predominate in determining its combustion characteristics.

Temperature data from the freeboard region confirm the higher reactivity of the Highvale coal. A significant amount of the Minto coal burns in the freeboard, as evidenced by temperature rises of up to 200°C. With Highvale coal the highest temperature rise observed in the freeboard was less than 100°C, indicating that combustion is largely completed within the bed. Figures 3 and 4 show freeboard temperature profiles for the tests in which bed temperature was 750°C, when freeboard combustion was most apparent.

D. Emissions of NO_x and CO

As can be seen from the data in Table 4, NO_x emissions in the test with Minto coal ranged from near zero to 230 ppm, increasing generally with bed temperature, but with a great deal of scatter. No relationship to excess air level is apparent. CO emissions fluctuated from 100 to 1600 ppm. No correlations with bed temperature or excess air level were attempted, since these are likely to be overshadowed by variations in the fines content of the fuel.

In the case of Highvale coal, the data in Table 5 show that NO_x varied from about 100 to 300 ppm with the higher levels fairly consistently associated with higher bed temperatures. CO emissions, at 50 to 200 ppm were lower and more uniform than from Minto coal, further evidence that Highvale is the more reactive coal.

CONCLUSIONS

Two coals, a high-sulphur high-ash bituminous coal from eastern Canada known as Minto, and a low-sulphur, high-ash sub-bituminous coal from western Canada known as Highvale, have been successfully burned in a pilot-scale atmospheric fluidized-bed combustor. Combustion performance, pollutant emissions and neutralization of sulphur by natural ash constituents were evaluated.

In the case of Minto coal, combustion efficiency without recycle ranged from 90 to 98%, the higher values being obtained at low fluidizing velocities and high bed temperatures. Without limestone addition, only 2 to 7% of the fuel sulphur was retained by the ash, and analysis of the data indicates that this was due to incomplete oxidation of pyrites rather than chemical neutralization of SO₂. When limestone was added to give a Ca/S ratio of 4.3, a sulphur capture of 88% was achieved. NO_x emissions were generally under 200 ppm, and CO emissions were generally under 400 ppm, with some excursions to about 1600 ppm. Clean, efficient combustion of this coal in a full-scale FBC system would require limestone addition and fly ash recycle.

In the case of Highvale coal, combustion efficiency without recycle ranged from 96 to 99%, and was found to be strongly dependent upon bed temperature but independent of fluidizing velocity and excess air, indicating that the coal is highly reactive. The calcium content of the ash was such

that the Ca/S ratio for the coal as fired was 4.55, and 25 to 80% of the fuel sulphur was accordingly trapped in the ash by chemical fixation. The lower levels of capture correspond to higher bed temperatures. NO_x emissions were generally about 200 ppm and CO emissions were generally about 100 ppm. In a full-scale FBC system this coal could be efficiently burned without fly ash recycle at a bed temperature of about 950°C, and SO_2 emissions would be about 100 to 150 ppm. With fly ash recycle and a bed temperature of about 800°C, high combustion efficiency would be maintained and SO_2 emissions would probably be reduced to less than 100 ppm.

The following empirical correlations have been developed from the data:

For Minto coal without limestone addition

$$\% \text{ Sulphur retention} = 0.11 Z^{-0.3} \exp\left(\frac{3500}{T}\right)$$

$$\% \text{ Carbon Carryover} = 0.314 Z^{-0.5} \phi^{-1} \exp\left(\frac{3500}{T}\right)$$

For Minto with limestone addition

$$\% \text{ Sulphur Retention} = 100 [1 - \exp[-0.46 (\text{Ca/S})]]$$

For Highvale coal

$$\% \text{ Sulphur Retention} = 0.28 \exp\left(\frac{5800}{T}\right)$$

$$\% \text{ Carbon Carryover} = 5.6 \times 10^{-4} \exp\left(\frac{8400}{T}\right)$$

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Table 1 - Analytical data for the test coals

Rank	Minto		Highvale		
	High volatile bituminous A		Sub-bituminous		
Proximate Analysis, dry basis, wt %					
Ash	22.01		16.02		
Volatile matter	30.72		33.71		
Fixed Carbon (by diff.)	47.27		50.27		
Ultimate Analysis, dry basis, wt %					
Carbon	62.59		63.54		
Hydrogen	4.34		2.54		
Sulphur	9.03		0.24		
Nitrogen	0.76		0.78		
Ash	22.01		16.02		
Oxygen (by diff.)	1.27		16.88		
Calorific Value, dry basis, MJ/kg	27.40		24.31		
Moisture "as fired" wt %	0-0.5		13-19		
Ash Fusion Temperatures, °C					
	Oxidizing	Reducing	Oxidizing	Reducing	
Initial Deformation	-	1077	-	1227	
Spherical Softening	-	1116	-	1299	
Hemispherical Softening	-	1199	-	1338	
Fluid	-	1227	-	1482	
Ash Composition, wt %					
SiO ₂	(CaO)	31.38	(1.80)	52.71	(11.93)
Al ₂ O ₃	(MgO)	15.61	(1.26)	23.08	(1.31)
Fe ₂ O ₃	(SO ₃)	45.63	(0.84)	4.77	(3.08)
TiO ₂	(Na ₂ O)	0.54	(0.16)	0.68	(2.66)
P ₂ O ₅	(K ₂ O)	0.96	(1.82)	0.43	(0.35)
Sulphur Forms, wt % of totals					
Sulphate	1.11		0.0		
Pyrite	84.3		21.7		
Organic (by diff.)	14.6		78.3		

Table 2 - Analysis of Havelock Limestone

	<u>As Element, wt %</u>	<u>As Oxide, wt %</u>
Loss on Ignition at 982°C	42.60	42.60
Si (SiO ₂)	0.63	1.35
Al (Al ₂ O ₃)	0.08	0.15
Fe (Fe ₂ O ₃)	0.12	0.17
Ca (CaO)	39.52	55.33
Mg (MgO)	0.41	0.68
S	<u><.01</u>	<u> </u>
Total	83.37	100.28
Est. Ca present as CaO + Ca(OH) ₂	:	0.05%
Est. Mg present as MgO + Mg(OH) ₂	:	0.01%
Est. Ca present as CaSO ₄ , assuming all S present as CaSO ₄	:	0.01%
CaCO ₃	:	>98%
Size Distribution, as fired, wt %		
> 1.7 mm	33.4	
1.7 x 1.2 mm	14.2	
1.2 x 0.8 mm	18.5	
0.8 x 0.6 mm	13.4	
< 0.6 mm	20.5	

Table 3 - Particle size distribution of the test coals and bed material, as fired

<u>Size Distribution</u>	<u>wt %</u>		
	<u>Minto Coal</u>	<u>Highvale Coal</u>	<u>Silica Sand</u>
>1.7 mm	28.0	28.1	5.8
1.7 x 1.2 mm	12.6	17.6	39.4
1.2 x 0.8 mm	11.9	14.2	41.6
0.8 x 0.6 mm	10.0	10.7	10.4
<0.6 mm	37.5	29.4	2.8

Table 4 - Average conditions for the tests with Minto coal and Minto coal plus limestone

TEST	FUEL FEED kg/hr (DRY)	AIR FEED m ³ /hr	MEAN O ₂ %	MEAN CO ₂ %	MEAN NO _x ppm	MEAN CO ppm	MEAN SO ₂ ppm	MEAN COAL H ₂ O % wt	MEAN ENERGY INPUT kW	MEAN BED TEMP °C	MEAN SO ₃ ppm	DURATION hr	LIMESTONE FEED RATE kg/hr
1	4.94	48.72	5.32	12.76	-	350	5343	0.2	36.7	949	48	6.25	N/A
2	4.86	42.79	2.61	13.91	-	300	6002	0.1	35.9	952	25	3.23	
3	4.73	46.53	4.98	11.72	-	400	5243	0.5	34.8	852	41	2.83	
4	4.32	43.66	2.36	13.61	-	500	5630	0.2	32.0	855	22	6.30	
5	9.60	88.74	4.94	12.23	-	250	4389	0.3	70.9	951	106	5.92	
6	11.02	69.51	2.45	15.64	-	100	6585	0.3	81.5	953	34	7.62	
7	9.69	72.28	4.85	14.86	230	650	5976	0.3	69.2	849	49	4.28	
8	9.74	66.14	2.51	15.28	200	1600	6610	0.3	68.9	853	29	5.03	
9	9.70	70.47	5.07	14.74	90	300	5928	0.3	67.8	763	40	5.60	
10	9.16	60.99	2.44	14.15	55	400	6642	0.2	63.9	752	36	3.67	
11	14.78	110.74	5.09	13.53	200	200	5704	0.3	104.0	955	58	2.45	
12	15.49	101.99	2.54	15.13	200	150	6489	0.3	108.3	956	25	3.15	
13	15.22	105.68	5.01	13.74	60	150	5781	0.0	105.5	856	30	2.05	
14	15.26	97.41	2.38	15.19	25	100	6399	0.0	103.5	851	27	2.67	
15	16.00	106.23	4.90	15.61	10	350	6505	0.0	109.4	745	27	2.52	
16	15.53	98.47	2.28	14.04	13	400	6797	0.0	108.3	760	27	2.70	
17	5.17	42.49	5.04	15.22	60	350	6506	0.0	39.0	764	40	3.72	
18	4.80	37.59	2.46	16.14	22	150	6693	0.0	32.7	758	61	2.10	
A1	10.39	77.62	5.08	14.64	23	200	1750	0.0	79.1	846	0	3.27	5.61
A2	19.61	68.37	2.53	16.25	130	175	2175	0.0	73.1	845	0	3.53	5.12
A3	10.05	76.98	4.93	15.90	180	175	661	0.0	76.5	854	0	3.05	9.55
A4	9.13	67.89	2.49	17.34	140	210	788	0.0	69.5	842	0	3.77	8.67
A5	8.86	72.35	5.34	16.04	230	260	75	0.0	67.4	845	0	5.10	12.04
A6	9.45	70.27	2.28	17.94	193	175	150	0.0	71.9	852	0	3.78	12.85

Table 5 - Average conditions for the tests with Highvale coal

TEST	FUEL FEED kg/hr (DRY)	AIR FEED m ³ /hr	MEAN O ₂ %	MEAN CO ₂ %	MEAN NO _x ppm	MEAN CO ppm	MEAN SO ₂ ppm	MEAN COAL H ₂ O % wt	MEAN ENERGY INPUT kw	MEAN BED TEMP °C	DURATION hr
1	5.60	42.49	4.96	16.15	100	150	46.9	19.2	36.5	760	3.58
2	6.04	37.92	2.50	18.48	95	200	56.0	16.1	40.4	759	2.32
3	5.42	41.30	5.03	16.41	170	100	106.3	16.6	36.3	863	2.70
4	5.62	39.75	2.57	18.38	150	50	115.2	16.8	37.7	862	2.92
5	5.71	42.10	4.69	15.61	200	50	124.3	14.9	38.4	935	3.53
6	5.40	41.60	2.32	18.63	170	50	149.5	14.5	36.1	949	3.63
7	11.28	75.34	4.95	15.44	280	75	138.2	15.4	75.9	954	3.92
8	12.00	79.34	7.54	17.62	180	50	141.6	14.6	80.0	948	4.28
9	10.85	75.28	4.71	16.81	210	100	104.1	15.8	72.9	857	3.88
10	12.39	76.22	2.64	16.98	190	75	113.2	14.8	83.0	857	2.37
11	10.62	75.95	5.19	15.46	135	50	42.3	14.9	70.9	754	3.43
12	10.88	73.03	2.63	17.58	100	100	56.9	15.0	71.9	759	3.15
13	17.88	118.61	4.87	16.27	285	50	271.0	14.2	119.9	953	3.05
14	18.38	119.80	2.24	17.50	230	100	167.2	13.1	123.3	954	2.57
15	19.06	131.54	5.00	16.16	235	120	71.9	13.2	128.2	852	3.27
16	18.83	114.56	2.59	17.64	180	75	135.9	13.4	124.9	856	2.93
17	18.22	127.18	5.18	15.98	160	100	53.2	13.4	121.2	756	2.63
18	17.83	117.98	2.48	17.85	165	100	57.6	15.1	118.3	761	3.83

Table 6 - Sulphur retention in elutriated solids and bed material

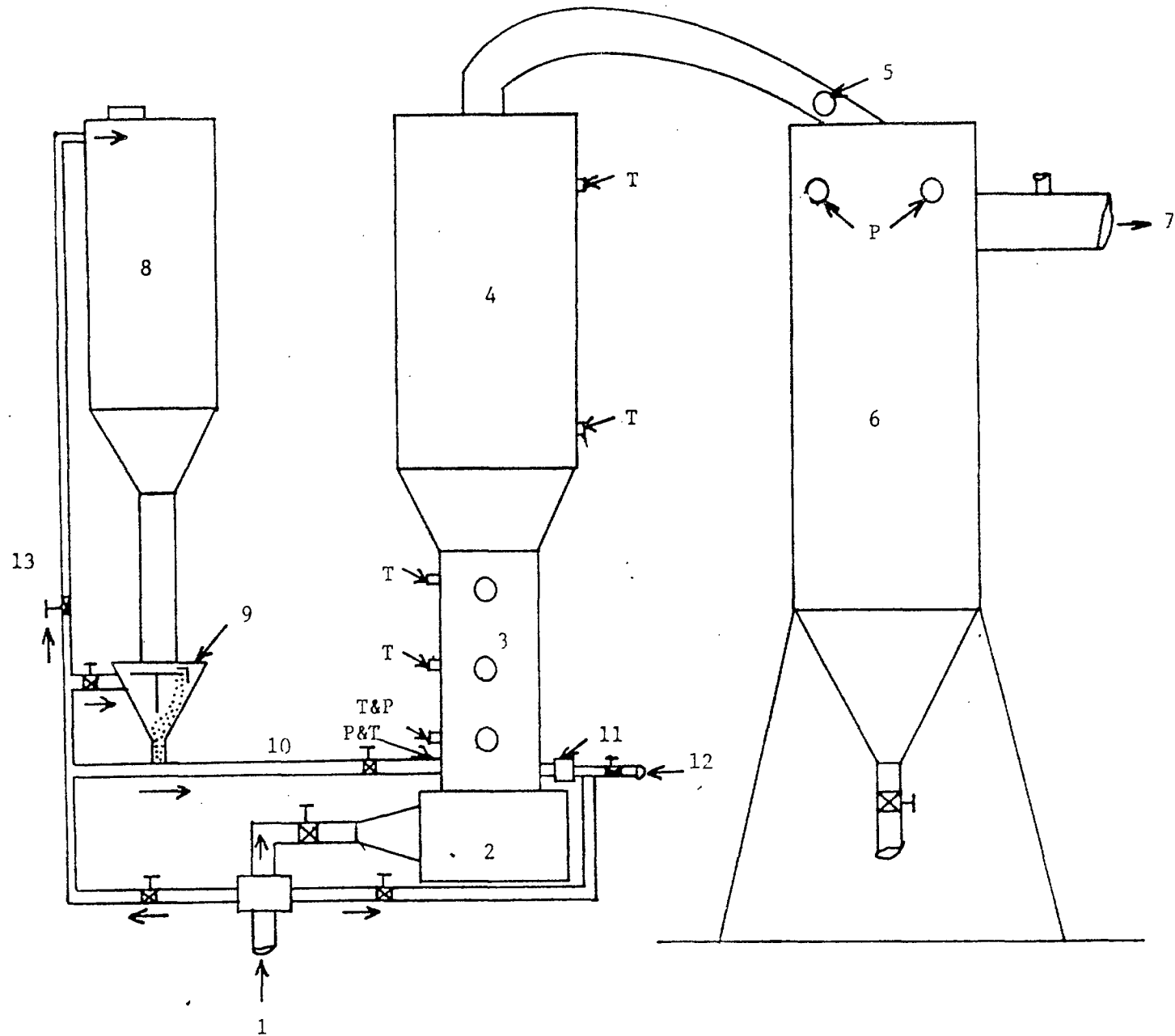
Test	% of Total Sulphur Retained	
	Minto	Highvale
1	2.1	75.3
2	2.5	75.9
3	2.7	45.4
4	2.4	43.2
5	2.1	34.9
6	2.0	25.9
7	2.9	36.4
8	2.9	31.7
9	3.9	51.7
10	4.4	67.1
11	3.6	80.8
12	4.0	74.0
13	3.9	-
14	4.5	27.4
15	5.4	65.8
16	5.5	45.3
17	2.1	75.1
18	6.9	74.1

Table 7 - Test conditions and sulphur retention for mixtures of Minto coal and Havelock limestone

Test	Velocity m/s	Mixture Strength ϕ	Bed Temperature °C	Ca/S Mole Ratio	Ca Utilization wt %	S Retention wt %	Energy Input kw
1	2.36	1.11	845	1.72	32.2	55.3	79.1
2	2.11	1.06	845	1.72	33.6	57.7	73.9
3	2.36	1.18	853	3.02	24.2	73.1	76.5
4	2.08	1.14	842	3.02	25.6	77.4	69.5
5	2.20	1.30	848	4.32	20.6	89.0	67.4
6	2.23	1.20	853	4.32	20.7	89.3	71.9

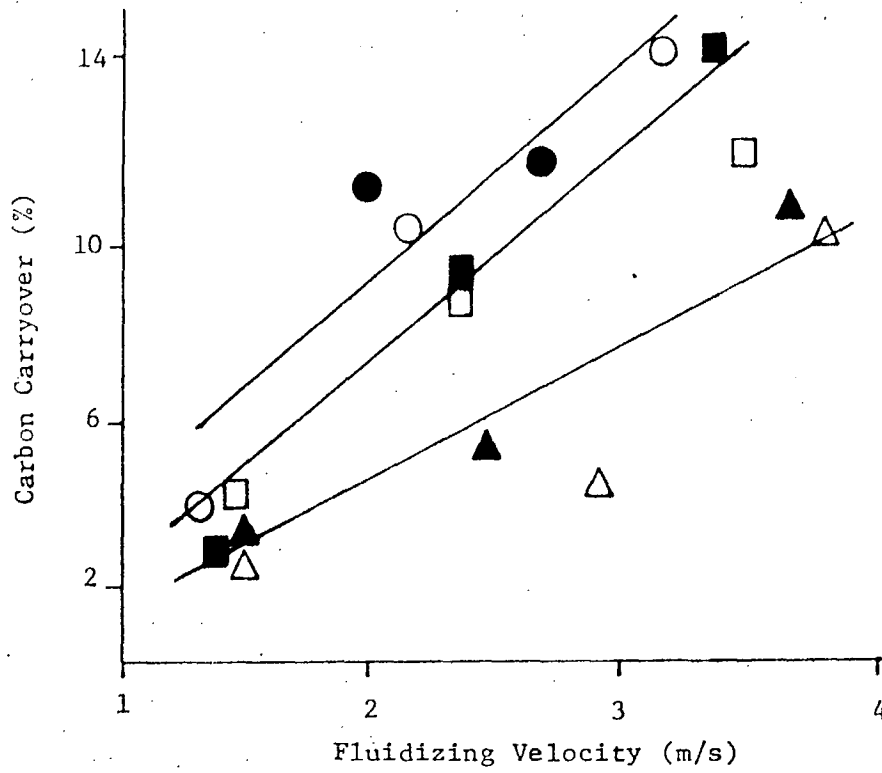
Table 8 - Carbon carryover data for Minto and Highvale coals

Test	Minto				Highvale			
	U m/s	T °C	ϕ	cc %	U m/s	T °C	ϕ	cc %
1	1.56	949	1.64	3.02	1.29	760	1.43	4.3
2	1.44	952	1.47	3.88	1.21	759	1.18	1.3
3	1.45	852	1.64	4.46	1.31	863	1.43	0.9
4	1.39	855	1.68	3.48	1.27	862	1.33	0.7
5	2.87	951	1.54	4.94	1.16	935	1.39	0.4
6	2.44	953	1.05	5.65	1.16	949	1.46	0.3
7	2.35	849	1.24	8.85	2.42	954	1.26	0.4
8	2.26	853	1.13	9.35	2.48	948	1.25	1.5
9	2.14	763	1.21	10.31	2.32	857	1.31	0.5
10	1.98	752	1.11	11.17	2.39	857	1.16	0.7
11	3.82	955	1.25	10.08	-	-	-	-
12	3.69	956	1.10	10.82	2.16	759	1.26	2.5
13	3.50	856	1.16	11.94	3.89	953	1.25	0.9
14	3.38	851	1.06	14.45	3.98	954	1.22	0.8
15	3.18	745	1.11	14.24	4.24	852	1.30	0.5
16	2.65	760	1.06	11.71	3.79	856	1.15	2.0
17	1.31	764	1.37	4.52	3.90	756	1.31	1.8
18	-	-	-	-	3.69	761	1.25	2.0



- 1 Air Supply
- 2 Windbox
- 3 Combustor
- 4 Freeboard
- 5 O₂, CO, CO₂ Sample Ports
- 6 Dust Collector
- 7 Flue Gas
- 8 Fuel Hopper
- 9 Fuel Meter
- 10 Pneumatic Fuel Feed
- 11 Light-up Burner
- 12 Propane
- 13 Pressure Equalization Line
- P Pressure Port
- T Thermocouple

Figure 1 - A schematic overview of the fluid bed combustor and ancillary equipment



OXYGEN RANGE	TEMPERATURE RANGE °C		
	950	850	750
5%	△	□	○
2.5%	▲	■	●

Figure 2 - Per cent carbon carryover versus the fluidizing velocity for Minto coal

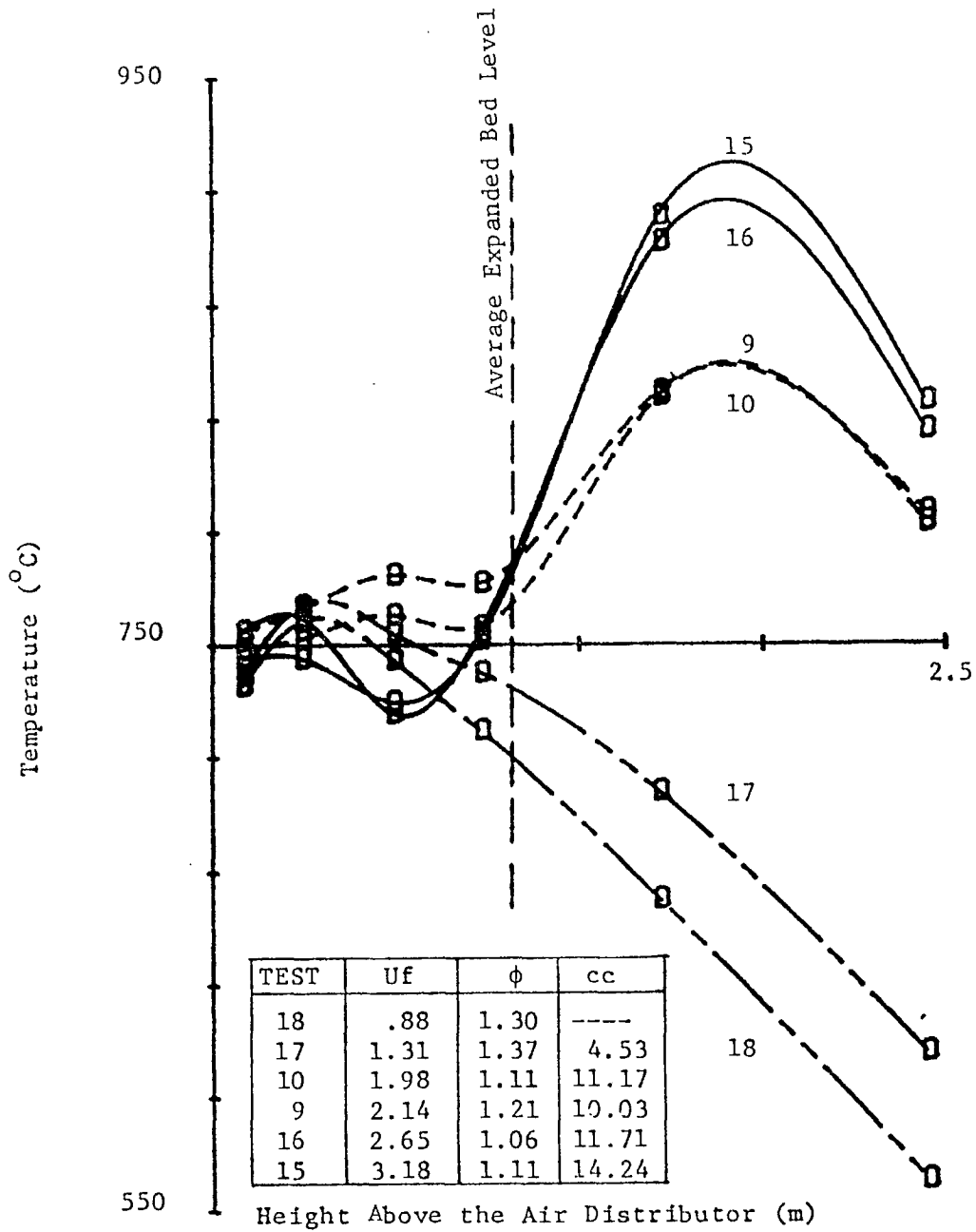


Figure 3 - Bed and freeboard temperature profiles for the tests with Minto coal at 750°C

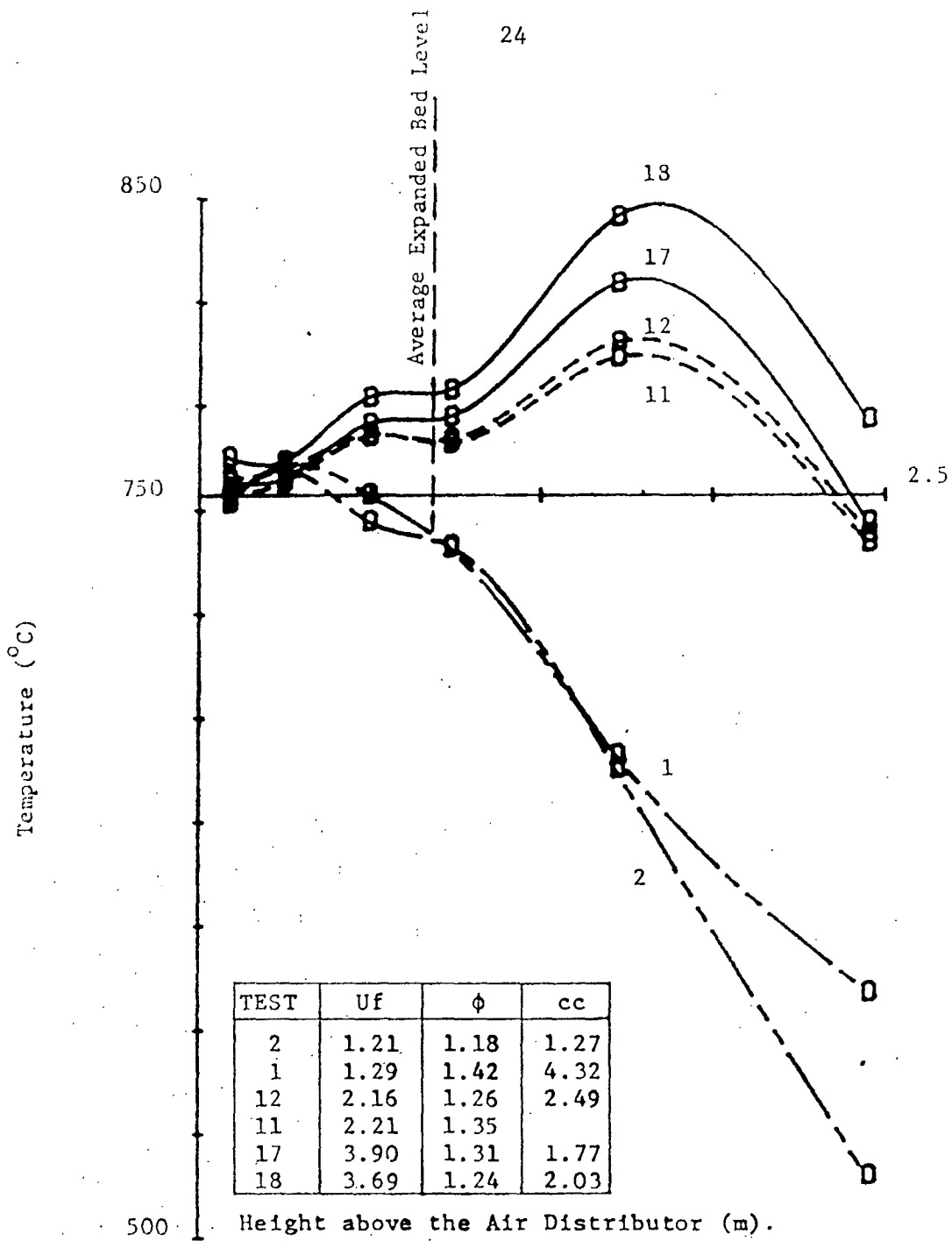


Figure 4 - Bed and freeboard temperature profile for the tests with Highvale coal at 750°C