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FLAME AND HEAT TRANSFER CHARACTERISTICS OF BENEFICIATED OBED-MARSH COAL IN A REFRACTORY-LINED TUNNEL FURNACE

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ABSTRACT

An experimental combustion study to establish the flame and heat characteristics of beneficiated Obed-Marsh coal in a refractory furnace is described.

The pulverized coal flames ignited and burned readily, with combustion efficiencies of 99.5% or more, being achieved with swirl numbers of 0, and 1 and excess air levels corresponding to 3% and 5% O_2 in the flue gas. Axial heat transfer patterns from the flames were relatively insensitive to either the degree of swirl or the excess air level.

NO_x emissions were low for a refractory-lined furnace and adiabatic flame temperatures for this coal were comparable to No. 6 oil.

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1.0 INTRODUCTION

The Canadian Combustion Research Laboratory (CCRL) carried out a flame research project under the CANMET Energy Research Program to determine the feasibility of burning beneficiated Obed-Marsh coal in mineral process kilns. The coal, which contained about 10% total moisture, had a calorific value of about 25,500 kJ/kg and is classified as high-volatile bituminous C by ASTM ranking procedures.

This report describes the research facilities and experimental procedures used and gives an evaluation of the flame and heat transfer characteristics of the coal. This coal was burned previously in the CCRL pilot-scale research boiler under a joint project with Union Oil Company of Canada Limited (1).

2.0 EXPERIMENTAL OBJECTIVES

The objectives of the research project were:

(a) to determine the aerodynamic requirements for a stable coal flame.

(b) to evaluate the burning and heat transfer characteristics of the coal under controlled aerodynamic and combustion conditions.

(c) to assess the gaseous and particulate matter emissions produced during combustion.

(d) to generate combustion efficiency charts for the coal.

3.0 COAL PROPERTIES

The Obed-Marsh coal burned in this project had been stored in covered barrels since delivery 2 years ago for the pilot-scale boiler trials. As shown in Table 1, the coal quality was unaffected during storage except for a slight loss in moisture.

Earlier work with this low-sulphur, high volatile coal established that it was moderately to highly reactive and that it ignited and burned readily in a water-walledsteam boiler. In a refractory-lined furnace, stable ignition and combustion are generally easier to attain.

4.0 DESCRIPTION OF COMBUSTION FACILITIES

4.1 CCRL Tunnel Furnace

The experimental program was carried out in the CCRL Tunnel Furnace(2) which is illustrated in Figure 1.

The tunnel furnace consists of 28 parallel-connected calorimeters which form a cylindrical combustion chamber 1 metre in diameter and 4.25 metres long. Each calorimeter is part of a coolant circuit containing a flow control valve, a variable area flow meter, and inlet and outlet thermocouples. An axial slot, located along the entire wall of the furnace allows the use of combustion probes to measure flame properties.

To simulate a rotary kiln environment two modifications, shown in Figure 2, were made to the furnace. A refractory-lined, water-cooled combustion chamber was installed between the burner and the tunnel furnace and about 315° of the circumference of each calorimetric section was lined with refractory brick. The remaining 45° of each section was left unlined to impose a thermal load on the flames representative of a product charge.

4.2 Variable Swirl Burner

The burner used throughout these trials was a variable swirl burner of the type developed by the International Flame Research Foundation (IFRF) and illustrated in Figure 3. The swirl air register of this unit permits easy variation of the ratio of tangential to radial air flow in the burner throat at a constant pressure drop condition. The air register is capable of producing flows characterized by swirl numbers between 0 (a totally axial jet) and 5 (75% tangential flow). Swirl number is defined as

$$S = \frac{\text{Axial Flux of Angular Momentum}}{\text{Axial Flux of Axial Momentum} \;.\; R}$$

R is the exit radium of the burner nozzle.

Swirl-stablized flames are known to be effective because the internal recirculation cone of high temperature reactive species serves as an ignition source for the incoming fuel jet. In an axial flow system recirculation is external to the fuel jet and is usually at a much lower temperature. Good flame stabilization by external flame recirculation is usually easier to attain if the fuel is reactive or if an adiabatic furnace is used.

5.0 EXPERIMENTAL PROCEDURES

5.1 Independent Parameters

The following parameters were fixed for all experiments:

(a) burner Swirl No. - 0 and 1

(b) secondary combustion air temperature - 150°C

(c) coal fineness - 90% less than 250-mesh

(d) excess combustion air corresponding to 3% and 5% O_2 in the flue gas

(e) primary combustion air temperature - 90°C

(f) coal feed rate to the furnace - 60 kg/h

5.2 Furnace Operation

The operating procedure given below was used for all experiments.

(a) The cold furnace was started up with No. 6 fuel oil at 9 US gph (1600 MJ/h). When thermal equilibrium was established, the coal feed to the furnace was started and then the oil preheat burner was withdrawn.

(b) After operating on coal for 1 hour to ensure that all ancillaries were functioning properly, the coal feed was adjusted to maintain a constant thermal input to the furnace at the desired level of excess air and swirl.

(c) When all measurements were completed, the oil preheat burner was inserted and the coal feed was shut off. After a check of all furnace ancillaries the oil burner was withdrawn and the furnace shut down.

5.3 Flame and Heat Transfer Measurements

The following measurements were taken during each experiment at the locations shown in Figure 2.

(a) Proximate, ultimate, sieve analyses, ash analyses and calorific value determinations of samples taken from a bulk sample of coal obtained by hourly grab samples at the pulverizer inlet.

(b) Swirl number of the combustion air at the burner.

(c) Heat flux from the flame by calorimetric measurements along the furnace length.

(d) Temperature profiles across the flame diameter by high-velocity suction pyrometer, respectively. Station 3.

(e) Flame radiation by ellipsoidal radiometer. Stations 1, 2, 3, 4 and 5.

(f) Profiles of combustion gas components across the flame diameter. Stations 1 and 3.

(g) Flame length from visual observations through the measuring slot.

(h) CO_2 and CO by continuous infra-red monitors. Station 6.

(i) O_2 by continuous paramagnetic monitor. Station 6.

(j) NO by continuous chemiluminescent monitor. Station 6.

(k) Fly ash loading by isokinetic dust sampler. Station 6. These samples were analyzed for carbon content.

6.0 EVALUATION OF RESULTS

The furnace operating conditions for each flame experiment are summarized in Table 2.

6.1 Adiabatic Flame Temperature

The adiabatic or maximum theoretical flame temperature is often used in the cement industry to determine the suitability of a coal for use in clinker kilns. Although these peak temperatures are not attainable in industrial turbulent diffusion flames, such calculations can provide a relative indicator of the maximum flame temperature that might be produced by various fuels.

Table 3 shows that the adiabatic flame temperatures for beneficiated Obed-Marsh coal with 3% and 5% oxygen in the flue gas are only marginally different than for No. 6 oil and are within 5% of those for natural gas. This suggests that Obed-Marsh coal is an excellent alternative fuel for either No. 6 fuel oil or natural gas.

6.2 Flame Characteristics

6.2.1 Flame Length

The flame length which appeared to be unaffected by excess air level, fluctuated from 3 to 4 metres and from 2 to 3 metres downstream of the burner at Swirl No. of 0 and 1 respectively. This was expected because flame shortening with a subsequent increase in flame diameter normally occurs with an increase in swirl number.

6.2.2 Temperature Profiles

The temperature profiles across the flame at Station 3 for Swirl No. of 0 and 1 and at excess air levels corresponding to 3% and 5% O_2 in the flue gases are shown in Figure 4. Peak flame temperatures at this location regardless of Swirl No. or excess air level were about 1250°C. However, a flatter temperature profile was produced by the swirled flame because of the more rapid air/fuel mixing and the presence of rotational flow.

Attempts to obtain temperature profiles closer to the burner at Station 1 were unsuccessful because coal dust rapidly blocked the measuring probe.

6.2.3 Gas Concentration Profiles

The oxygen levels across the four flames at Station 1 and 3 are shown in Figures 5 and 6 respectively. It is immediately apparent from Figure that most of the oxygen available for combustion had not been utilized for combustion at Station 1. This measurement confirms visual observations indicating that the flame front was anchored downstream of Station 1. At Station 3, the profiles are fairly uniform and are close to the oxygen concentrations present in the exit flue gases; the combustion process should therefore be close to completion at this point.

The carbon monoxide profiles (shown in Figures 7 and 8) are essentially the reverse of the oxygen profiles with the oxygen peaks corresponding to minimum values of carbon monoxide. The carbon monoxide values at Station 3, which were close to zero at the flame edge and less than 0.1% in the flame interior further confirms that combustion is essentially completed at this point.

6.3 Combustion Efficiency

Isokinetic samples of the gas borne particulate material were collected at Station 4 during each combustion experiment and the results, presented in Table 4 were used to calculate the combustion efficiencies for each experiment.

The combustion efficiency was calculated from the following relationship:

$$\text{Combustion Efficiency } \% = 100 - \left[\frac{A}{\frac{100}{B} \quad [C + D]} \right] \times 100$$

A = % Ash in the Coal
B = % Carbon in the Fly-ash
C = % Volatile Matter in the Coal
D = % Fixed Carbon in the Coal

This relationship defines the carbon in the fly ash as a percent of the sum of the volatile matter and fixed carbon in the dry coal.

The results show clearly that increased levels of both swirl and excess combustion air produced small but consistent improvements in combustion efficiency. The combustion efficiency was in excess of 99.5% with the swirled flames and marginally less than 99.5% with the unswirled flames.

In the case of the unswirled flames, small improvements in combustion efficiency can usually be achieved by increasing air preheat temperatures.

6.4. Flue Gas Emissions

6.4.1 Fly Ash Emissions

The fly ash emissions from the furnace decreased significantly from about 8800 mg/sm^3 with the unswirled flames to about 6300 mg/sm^3 with the swirled flames. These particulate loadings, represent about 30% to 40% of the input ash; the remaining ash was removed from furnace bottom after each experiment in the form of loose, friable deposits.

Although the rotational flow of the swirled flames tended to decrease fly ash emissions, any corresponding increases in ash retention in the furnace are not critical because the total ash burden represents less than 1.5% of the total mineral charge in a dry process cement kiln.

6.4.2 Gas-phase Emissions

The carbon monoxide concentrations in the exhaust gases at the furnace exit, given in Table2, were below 100 ppm for all flames.

Sulphur dioxide emissions, calculated from the input sulphur, were about 550 ppm. Previous work with Obed-Marsh coal established that about 10% of the fuel sulphur is retained in the coal ash. However, in lime or cement kiln operations the high alkaline content of the kiln charge should result in virtually complete fixation of the sulphur oxides and partial fixation of the nitrogen oxides.

The nitrogen oxides emissions, which remained relatively constant at 0.34 g/MJ and were not affected by either excess air or swirl levels, appear to be primarily controlled by fuel nitrogen.

7.0 HEAT TRANSFER

7.1 Radiative Heat Flux

Axial measurements of the radiative component of heat transfer from the flames are shown in Figure 9.

Excess air levels apparently had only a slight affect on radiative heat flux, but the peak heat flux values, which occurred between 1 and 1.5 m from the burner tip, were about 25% higher for the unswirled flames than for the swirled flames. The higher heat flux values obtained from the unswirled flames is consistent with practice where improved air/fuel mixing produced by swirl tends to reduce flame luminosity.

7.2 Overall Heat Transfer Rates

The axial distribution in the overall heat transfer rates to the tunnel furnace, Figures 10 and 11, showed only minor differences as the swirl numbers and excess air levels were changed. These measurements indicate that overall heat transfer rates to the refractory-lined furnace are more than an order of magnitude less than the radiative heat flux available from the flame.

8.0 CONCLUSIONS

8.1 The beneficiated Obed-Marsh coal, being highly reactive, produced an easily ignited, highly stable flame without support fuel.

8.2 Combustion efficiencies with this coal were about 99.5% in a thermally-loaded refractory furnace with unswirled and swirled flames at nominal excess air levels corresponding to 3% and 5% oxygen in flue gas. In a full-scale kiln combustion efficiencies of 100% should be readily attainable because of higher volumetric heat release rates and much longer furnace residence times.

8.3 Fly ash retention in the furnace should not be critical because the coal ash input generally comprises less than 1.5% of the mineral charge.

8.4 Nitrogen oxide emissions were unaffected by excess air or swirl level and remained relatively constant at 0.34g/MJ.

8.5 Sulphur oxide emissions from lime or cement kilns should be virtually non-existent because the alkaline minerals being processed normally have a very high potential for neutralizing fuel sulphur.

8.6 Overall axial heat transfer patterns, being only slightly affected by swirl and excess air levels typical of kiln operation, suggest that coal reactivity is more critical than burner aerodynamics in establishing heat absorption in a refractory furnace.

8.7 Beneficiated Obed-Marsh coal should be an ideal substitute fuel for No. 6 fuel oil in kiln operations. Its adiabatic flame temperature is comparable to No. 6 fuel oil.

9.0 REFERENCES

9.1 Brown, T. D. and Lee, G. K., "A Pilot-scale Combustion Evaluation of Obed-Marsh Coal". Energy Research Laboratories Report ERL/ERP 78-14, Ottawa, Canada 1978.

9.2 Friedrich, F. D., Mitchell, E. R., Lee, G. K. and Whaley, H., "The CCRL Tunnel Furnace - Design and Application" International Flame Research Foundation, 2nd Members Conference Proceedings, Chapter XV, pp XV - 1 to XV - 18, IJmuiden, Holland, 1971.

TABLE 1

COAL ANALYSIS

Sample	As Received (1977)	As Fired (1979)
Proximate (wt%)		
Moisture	10.95	9.50
Ash	12.40	13.57
Volatile Matter	33.36	32.10
Fixed Carbon (by diff)	43.29	44.83
Ultimate (dry wt%)		
Carbon	65.18	65.00
Hydrogen	4.45	3.65
Sulphur	0.53	0.67
Nitrogen	1.61	1.59
Ash	13.92	14.99
Oxygen (by diff)	14.31	14.10
Calorific Value (dry basis)		
kJ/kg	26,240	25,566
Btu/lb	11,280	10,990
Ash Analysis (wt%)		
SiO_2	60.92	58.57
Al_2O_3	20.85	18.69
Fe_2O_3	4.23	5.98
TiO_2	0.85	0.80
P_2O_5	0.39	0.30
CaO	8.11	7.68
MgO	2.00	1.90
SO_3	3.45	3.29
Na_2O	0.20	0.16
K_2O	0.60	0.68
Mercury in coal, ppm		0.12

Ash Fusion Temp., °C	Oxidizing	Reducing
Initial	1330	1371
Hemispherical	1390	1454
Spherical	1460	<1480
Fluid	<1480	<1480

TABLE 2

Furnace Operating Conditions

Flame No.	1	2	3	4
Coal Rate, kg/h	59	60	59	60
Coal Fineness, %<75 μm	89	89	89	80
Heat Input, MJ/h	1530	1561	1530	1561
Burner Swirl No.	0	0	1	1
Furnace Exit Temp., °C	743	721	743	738
Flue Gas Composition				
CO_2, %	16.3	14.2	16.5	14.4
O_2, %	3.5	5.5	3.0	5.5
CO, %	< 0.01	<0.01	<0.01	<0.01
SO_3, ppm	10	13	1	7
NO, ppm	860	730	700	720
, g/MJ	0.36	0.34	0.28	0.34
Fly Ash Emission, mg/sm^3	8441	9293	6615	6088
Combustible in Fly Ash, %	3.2	2.9	1.8	2.6
Theoretical SO_2, ppm	580	530	580	530
, g/MJ	0.51	0.53	0.51	0.53

TABLE 3

Adiabatic Flame Temperatures for Comparable Fuels

Fuel	Oxygen in Flue Gas, %	Adiabatic Flame Temperature, °C
Obed-Marsh Coal	3	1620
	5	1520
No. 6 Oil	3	1650
	5	1540
Natural Gas	3	1700
	5	1470

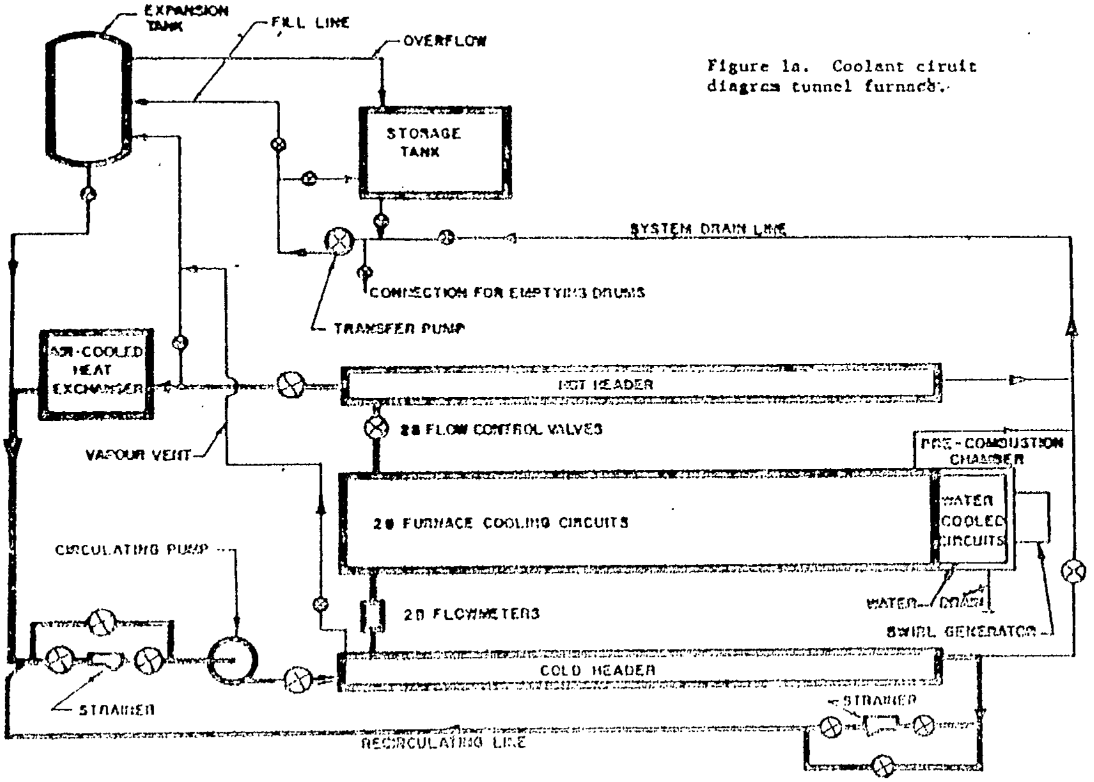
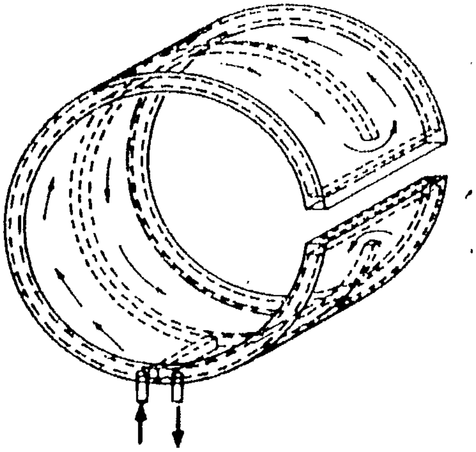


Figure 1a. Coolant ciruit diagram tunnel furnace.



OBLIQUE VIEW OF ONE SEGMENT OF FURNACE

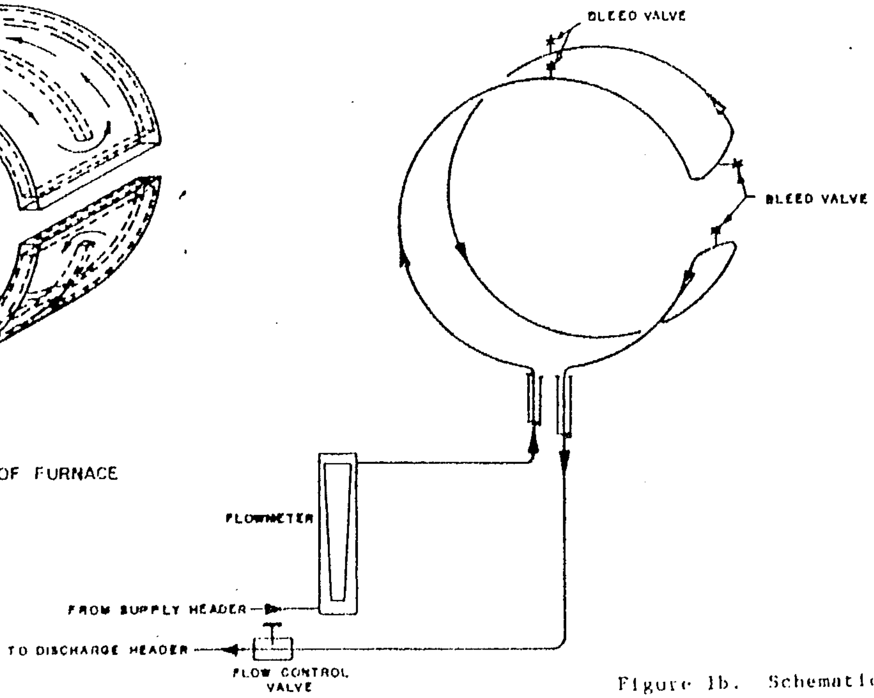


Figure 1b. Schematic of one segment of coolant circuit.

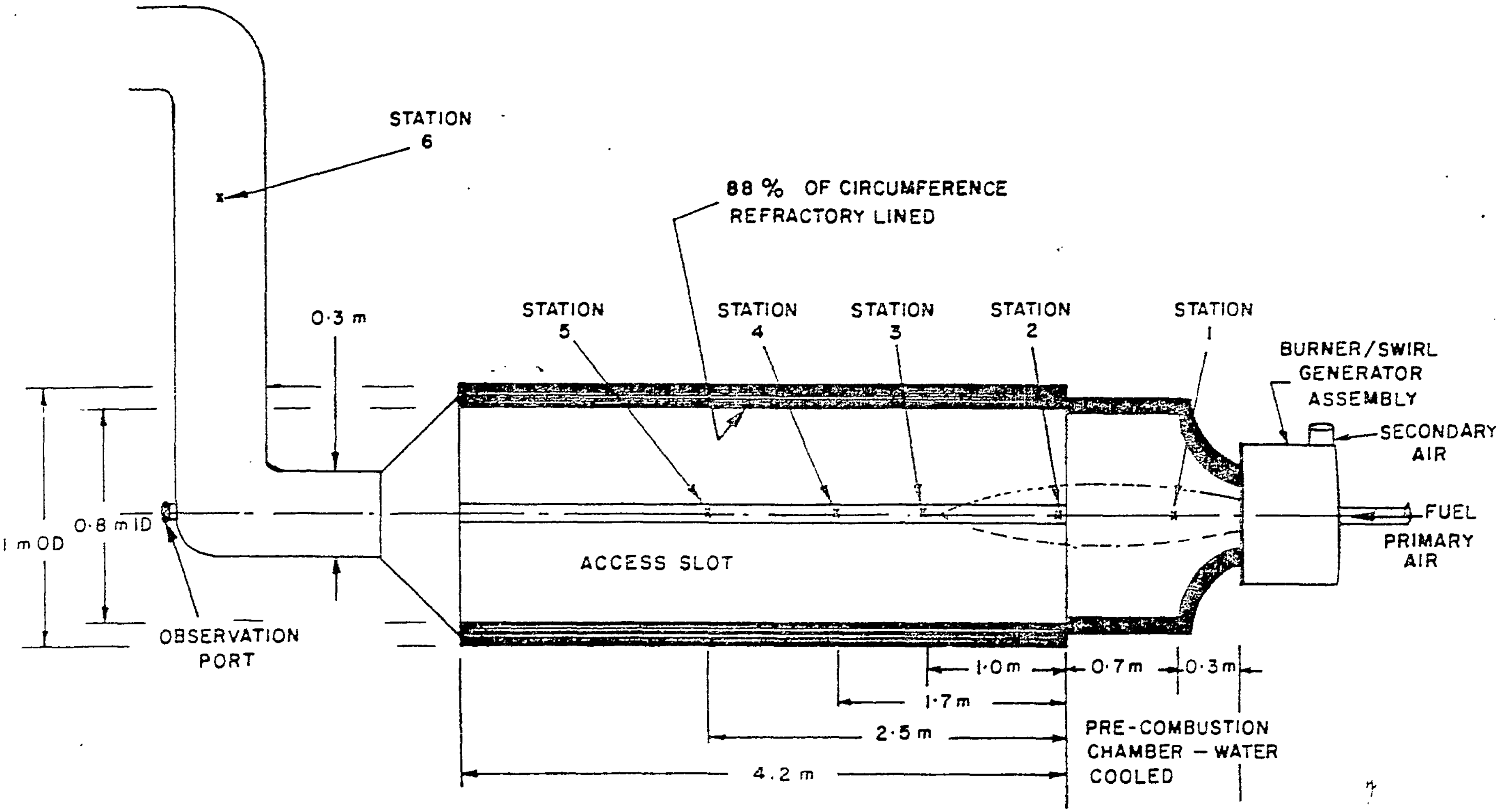


Figure 2. Schematic view of the CCRL Flame Tunnel Furnace.

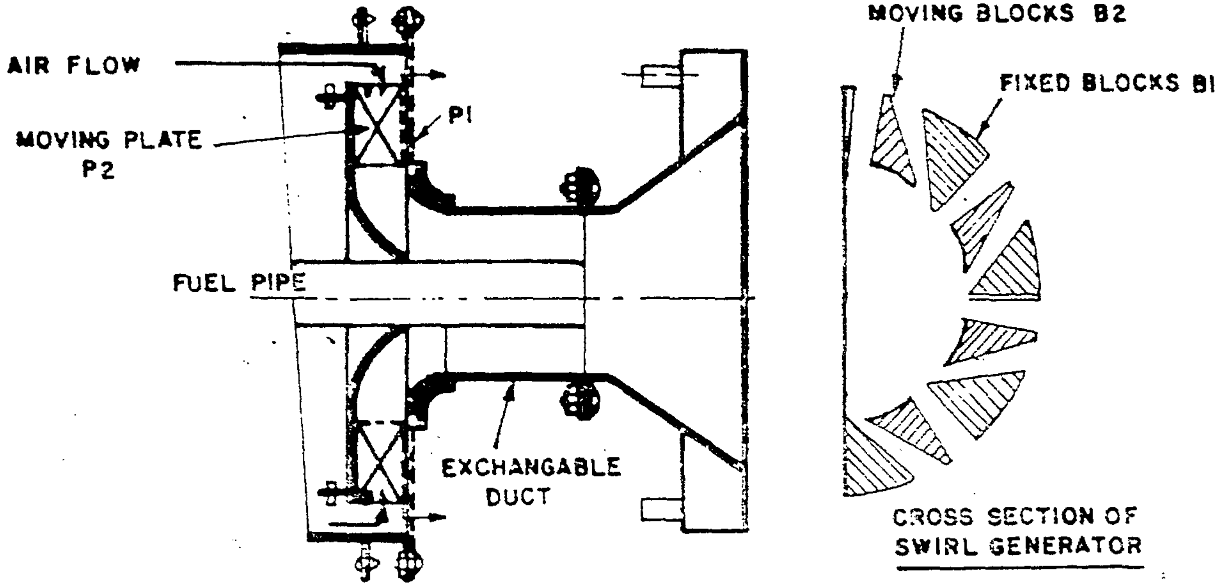
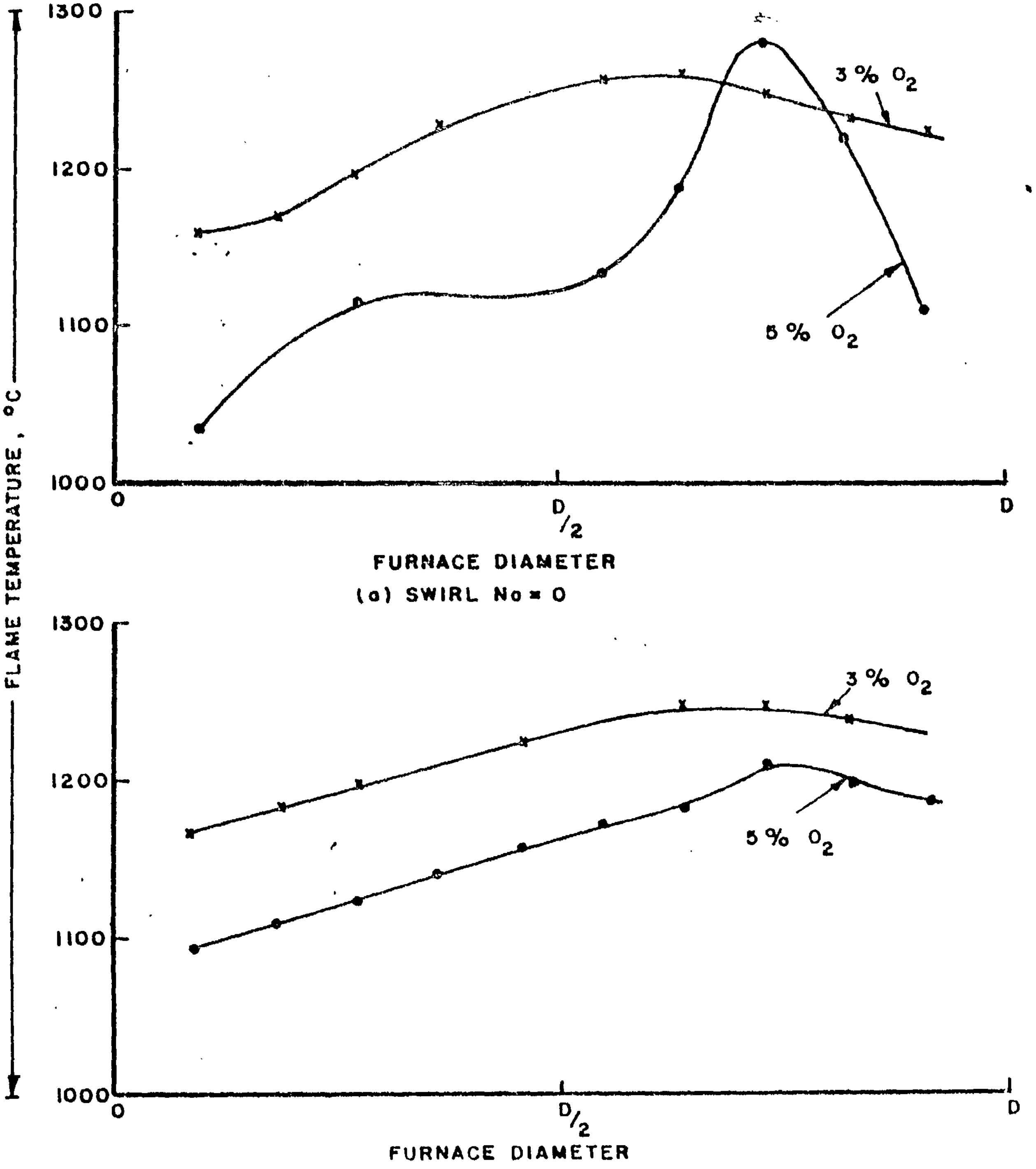


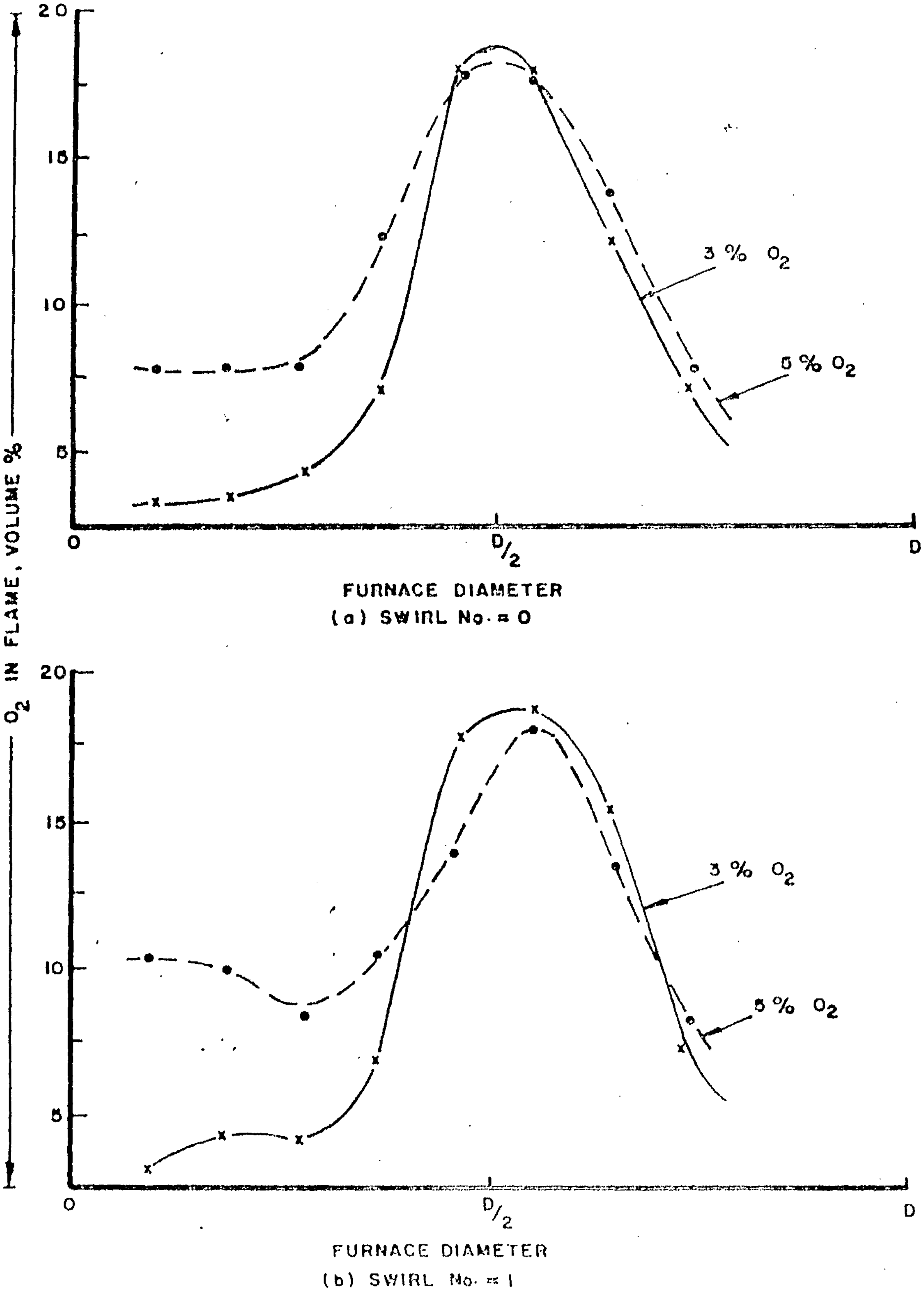
Figure 3. Side view of the variable swirl burner.



(a) SWIRL No = 0

(b) SWIRL No = 1

Figure 4. Temperature profiles through the flame at Station 3 for two levels of swirl and excess combustion air.



(a) SWIRL No. = 0

(b) SWIRL No. = 1

Figure 5. Oxygen profiles through the flame at Station 1 for two levels of swirl and excess combustion air.

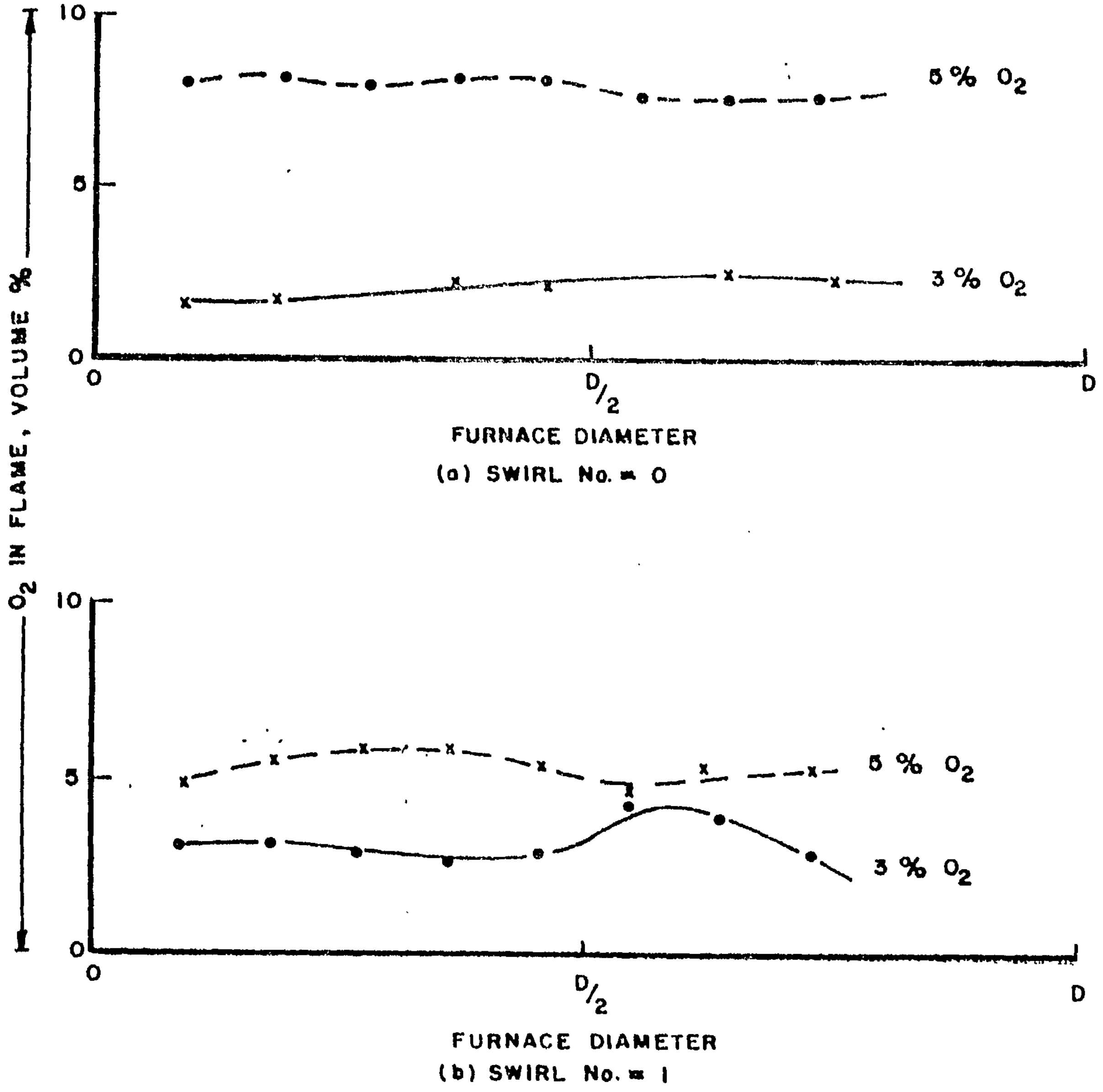
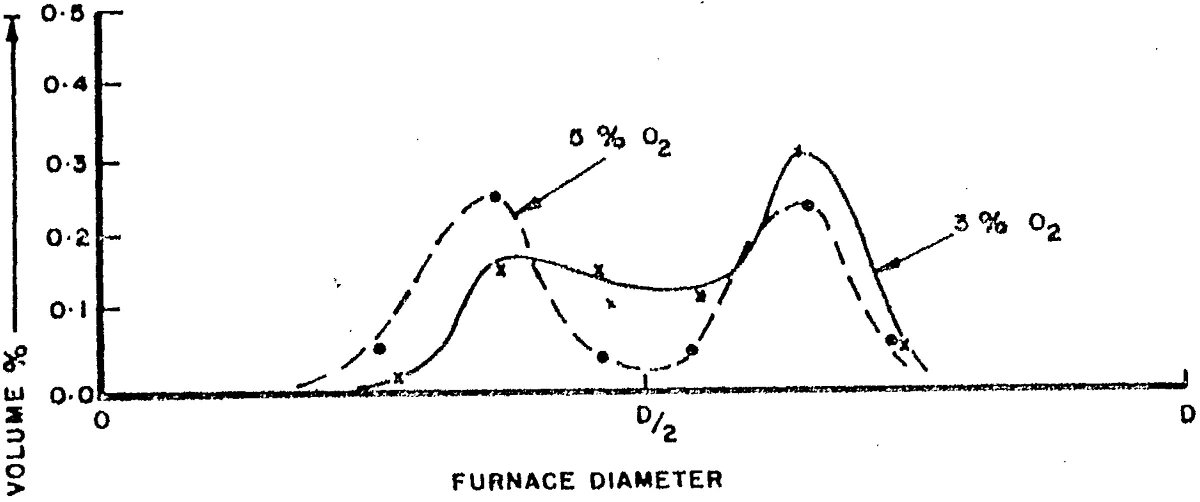
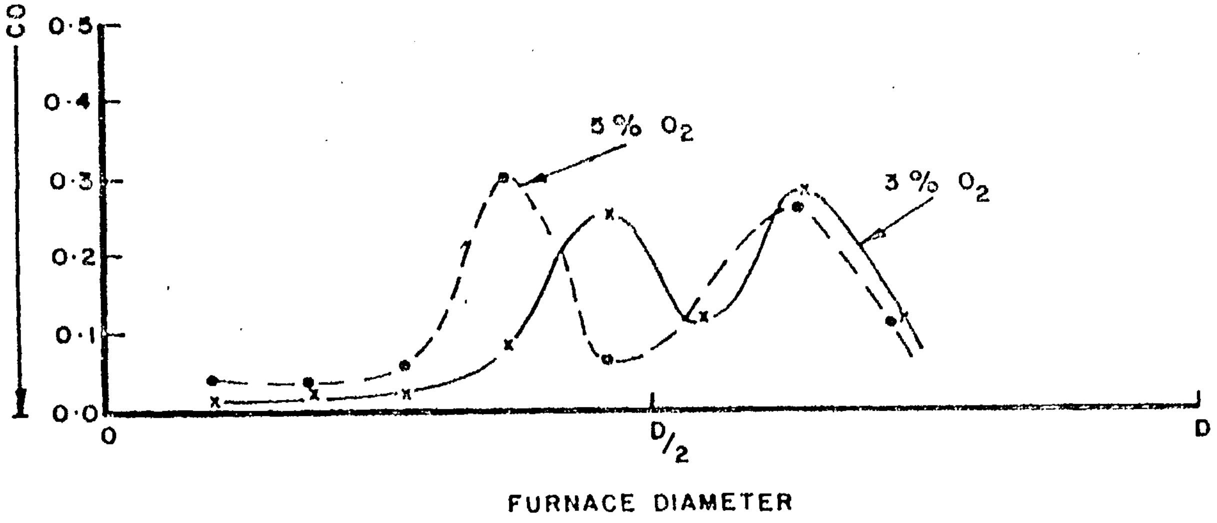


Figure 6. Oxygen profiles across the flame at Station 3 for two levels of swirl and excess combustion air.



(a) SWIRL No. = 0



(b) SWIRL No. = 1

Figure 7. Carbon monoxide profiles through the flame at Station 1 for two levels of swirl and excess combustion air.

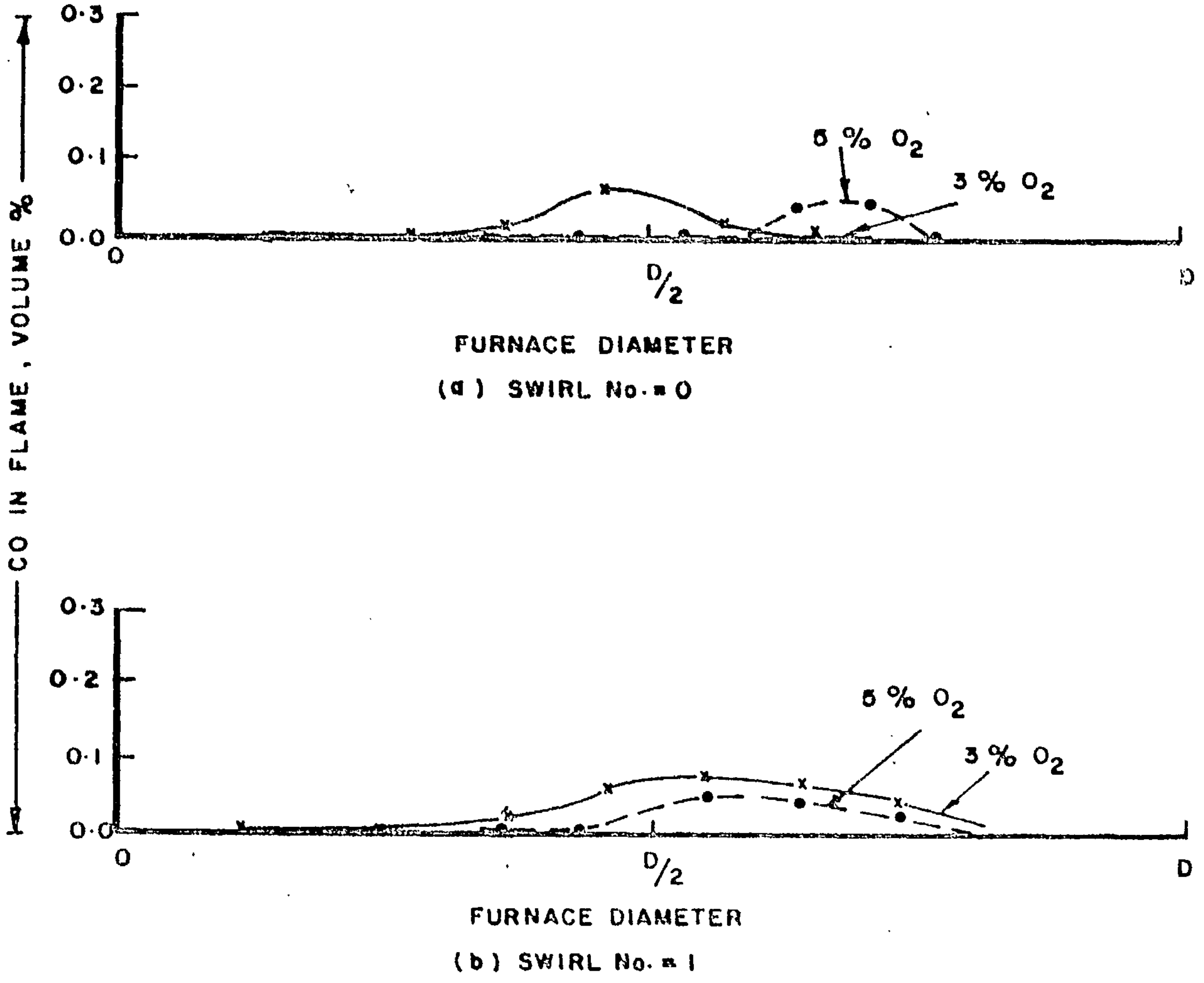
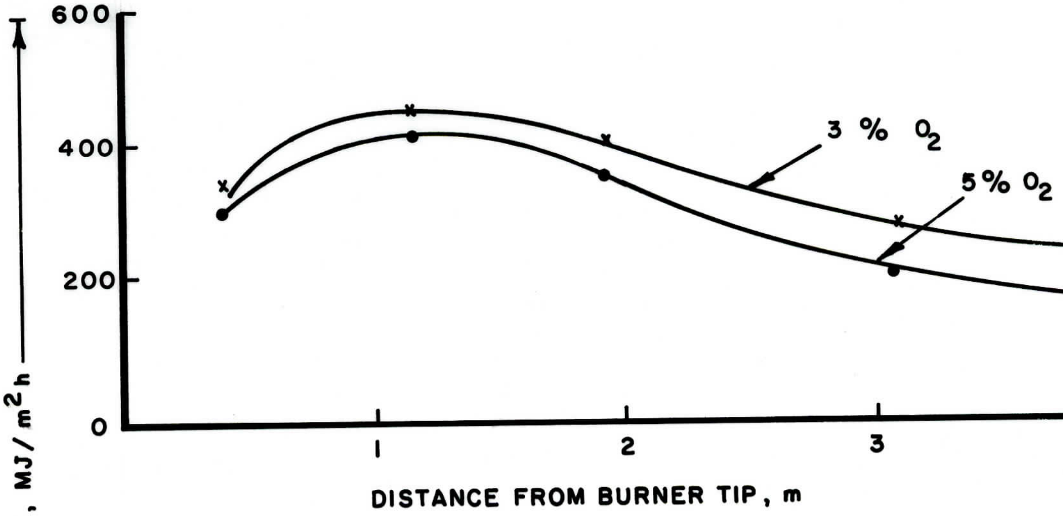
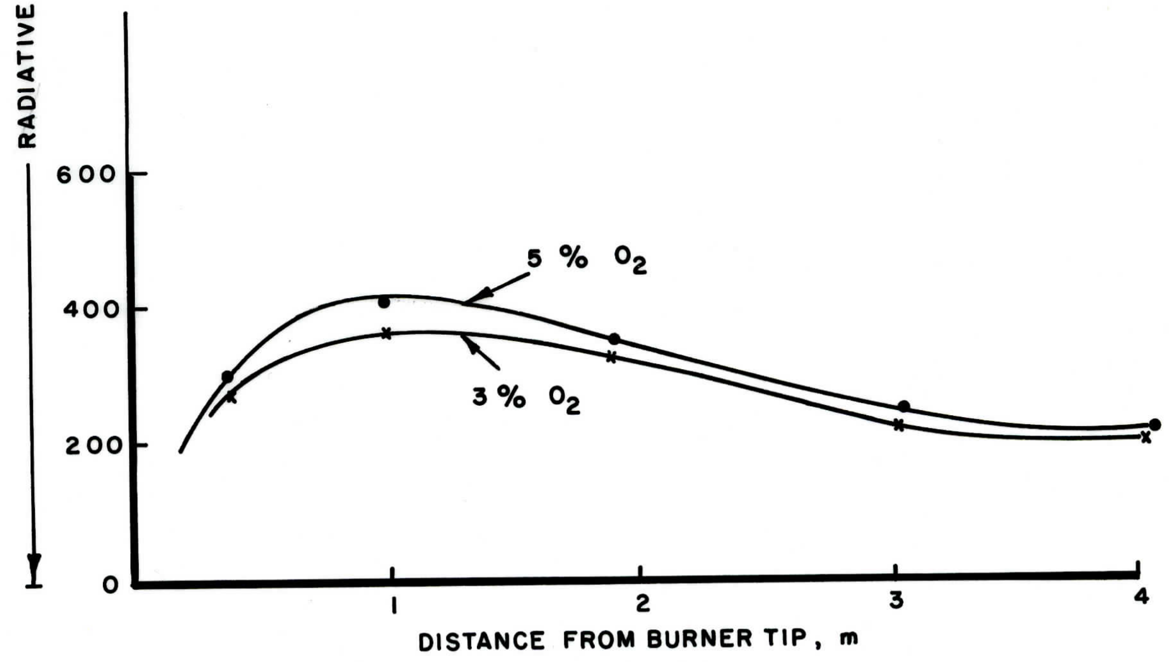


Figure 8. Carbon monoxide profiles through the flame at Station 3 for two levels of swirl and excess combustion air.



(a) SWIRL No. = 0



(b) SWIRL No. = 1

Figure 9. Axial variation in radiative heat flux from the flame for two levels of swirl and excess combustion air.

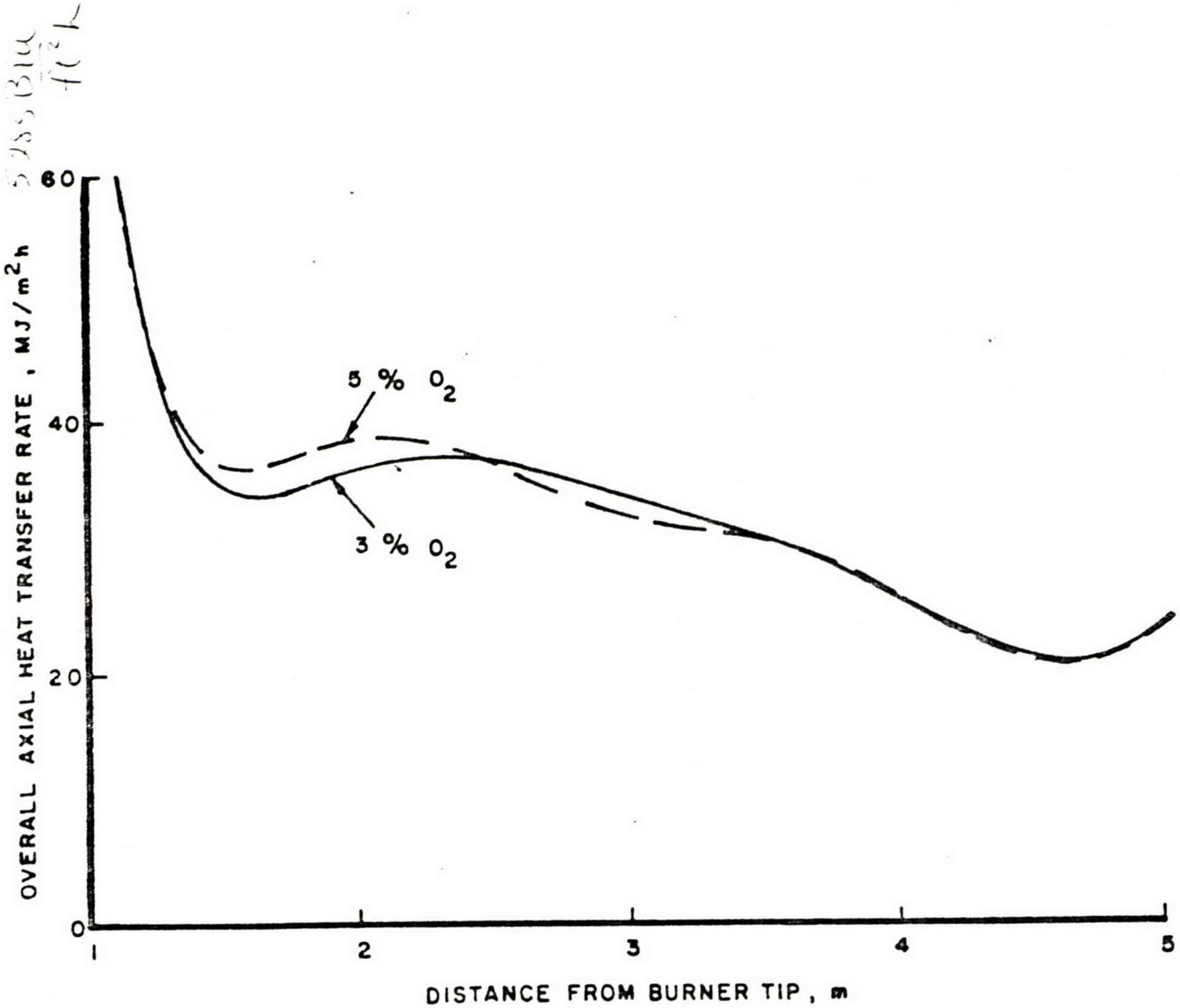


Figure 10. Overall axial heat transfer rates to the furnace for flames at Swirl No. = 0.

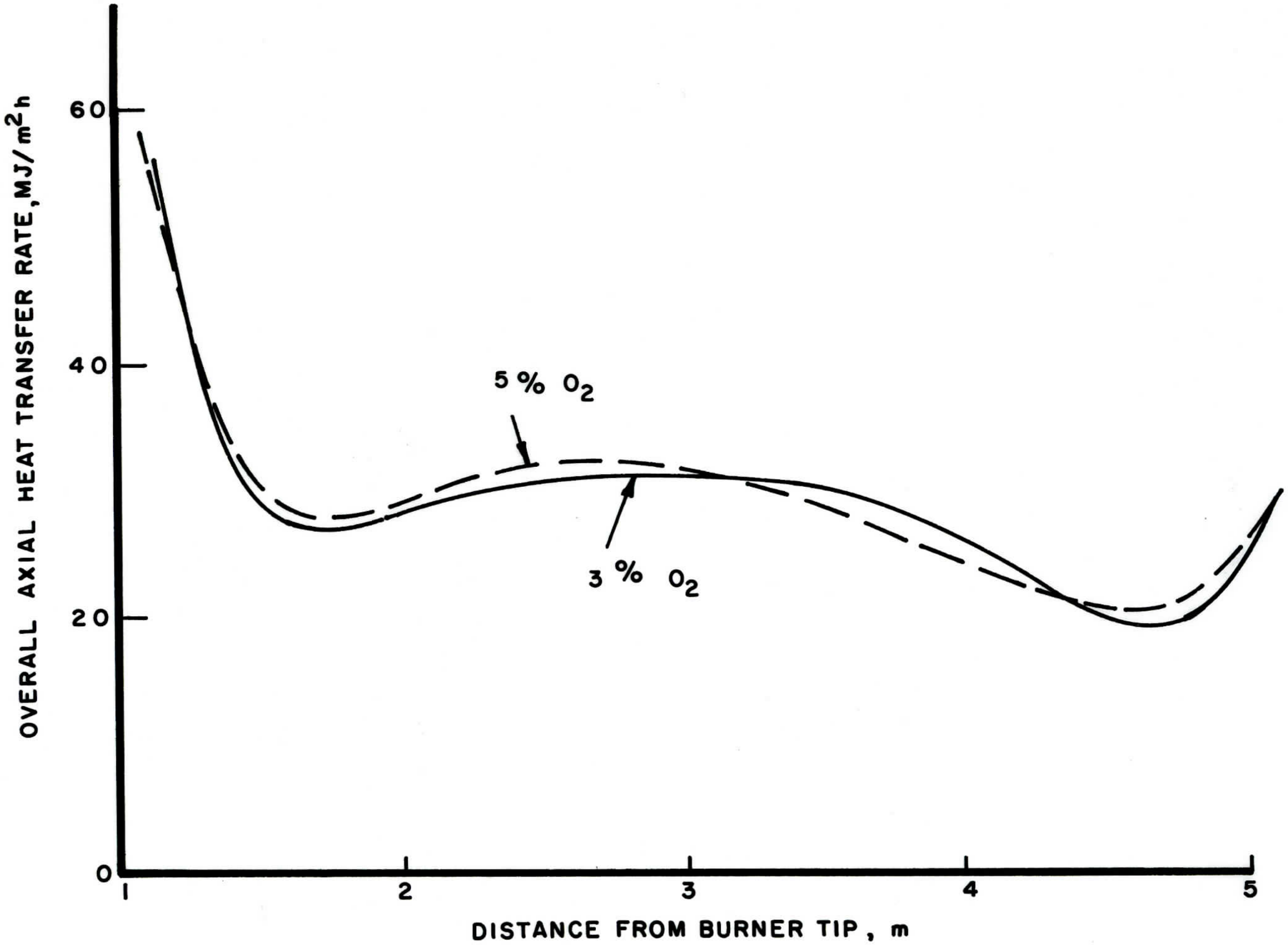


Figure 11. Overall axial heat transfer rates to the furnace for flames at Swirl No. = 1.

APPENDIX "A"

COMBUSTION CHARTS FOR OBED-MARSH COAL

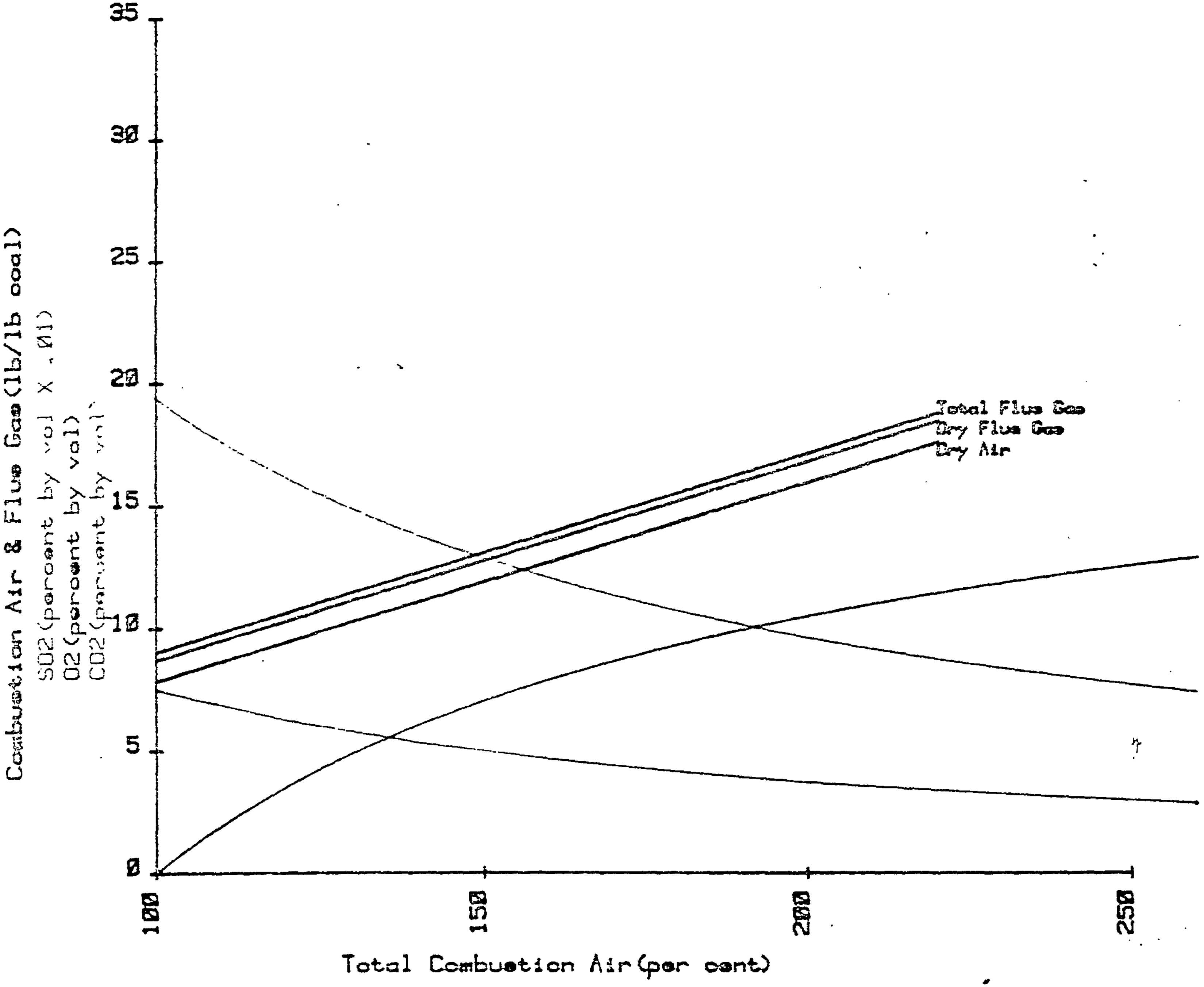


Figure 1A. Combustion Data, Weight Basis

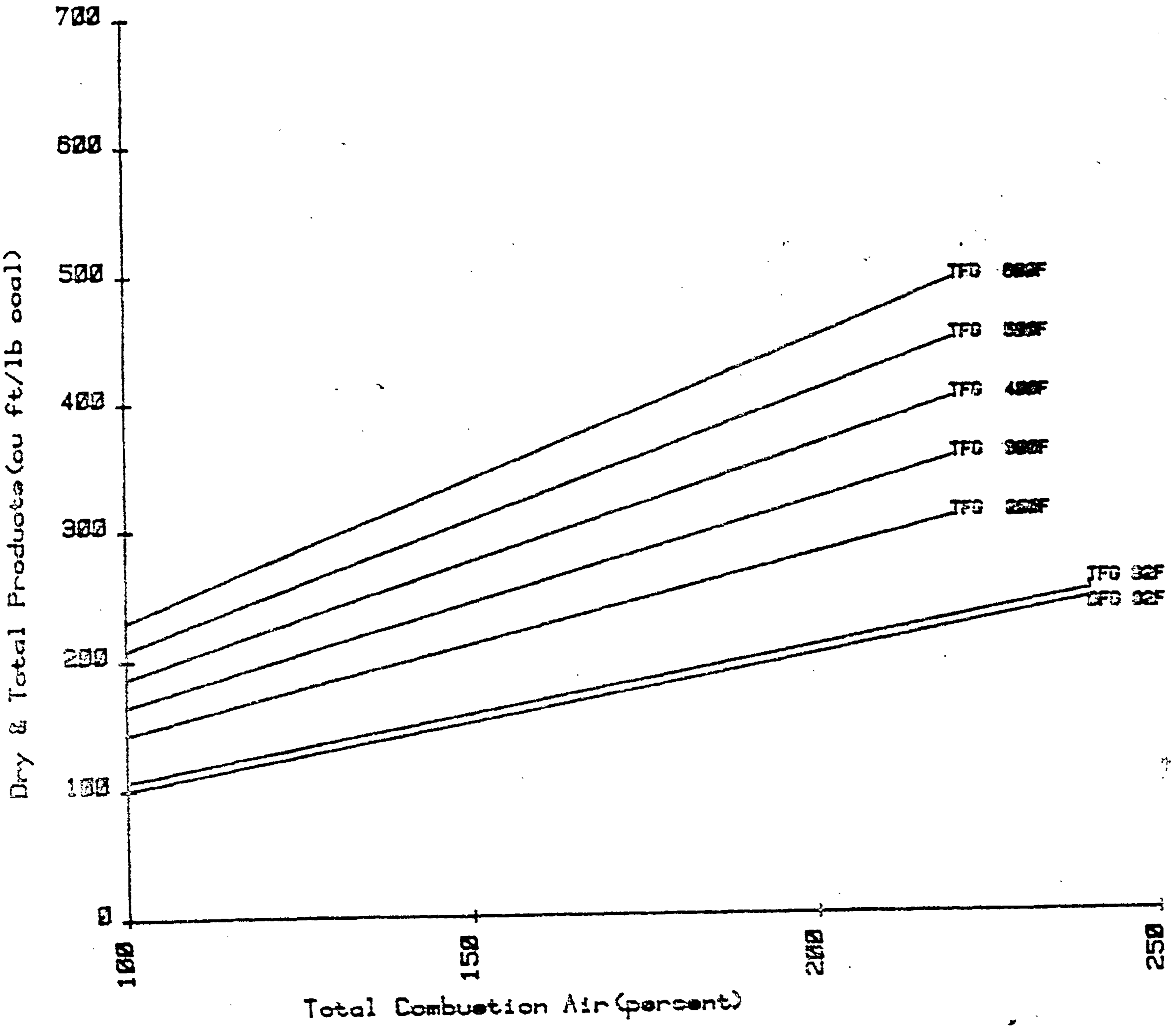


Figure 2A. Combustion Data, Volume Basis

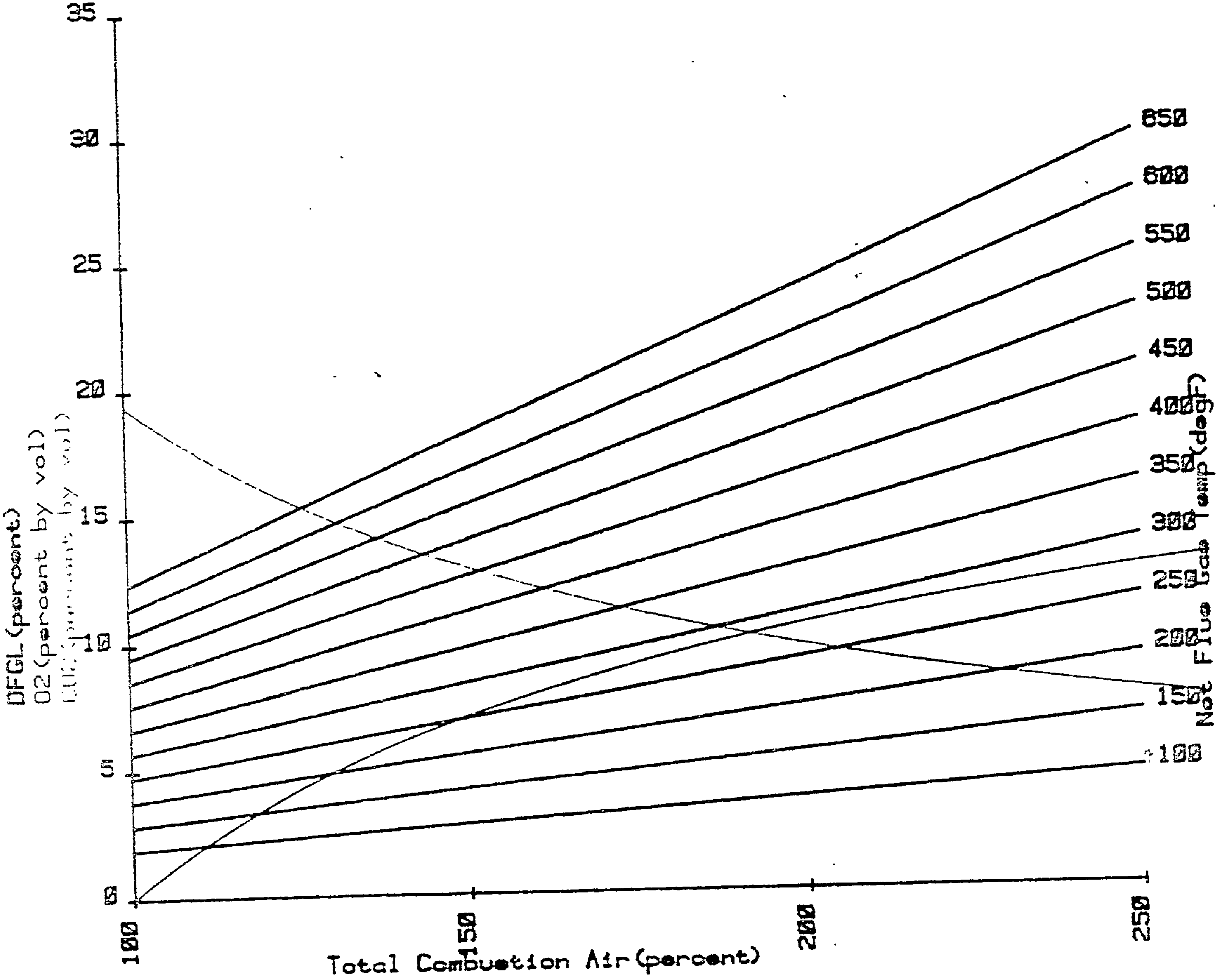


Figure 3A. Dry Flue Gas Loss for a Range of Temperature Differentials

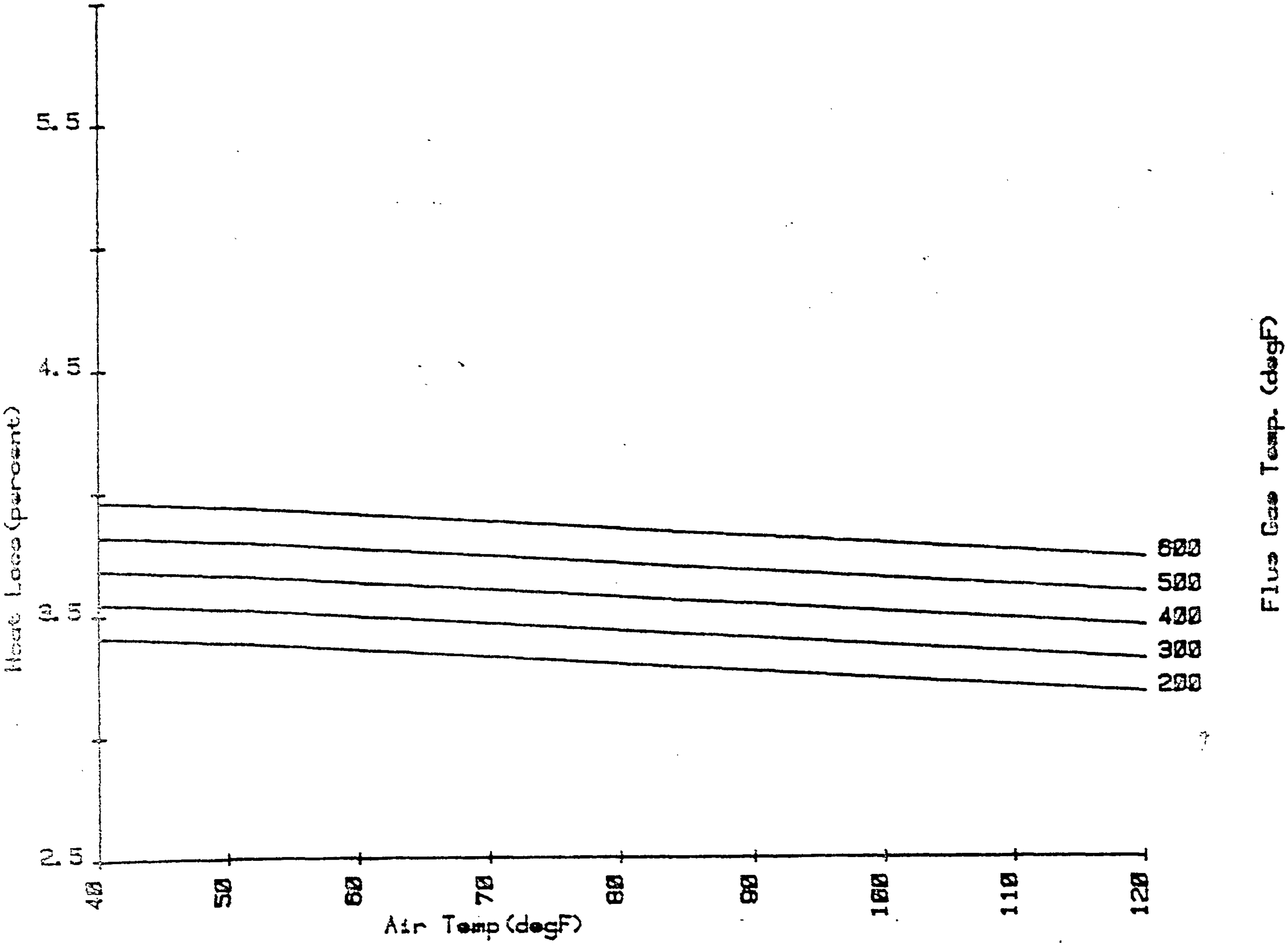


Figure 4A. Hydrogen Loss for a Range of Stack Temperatures

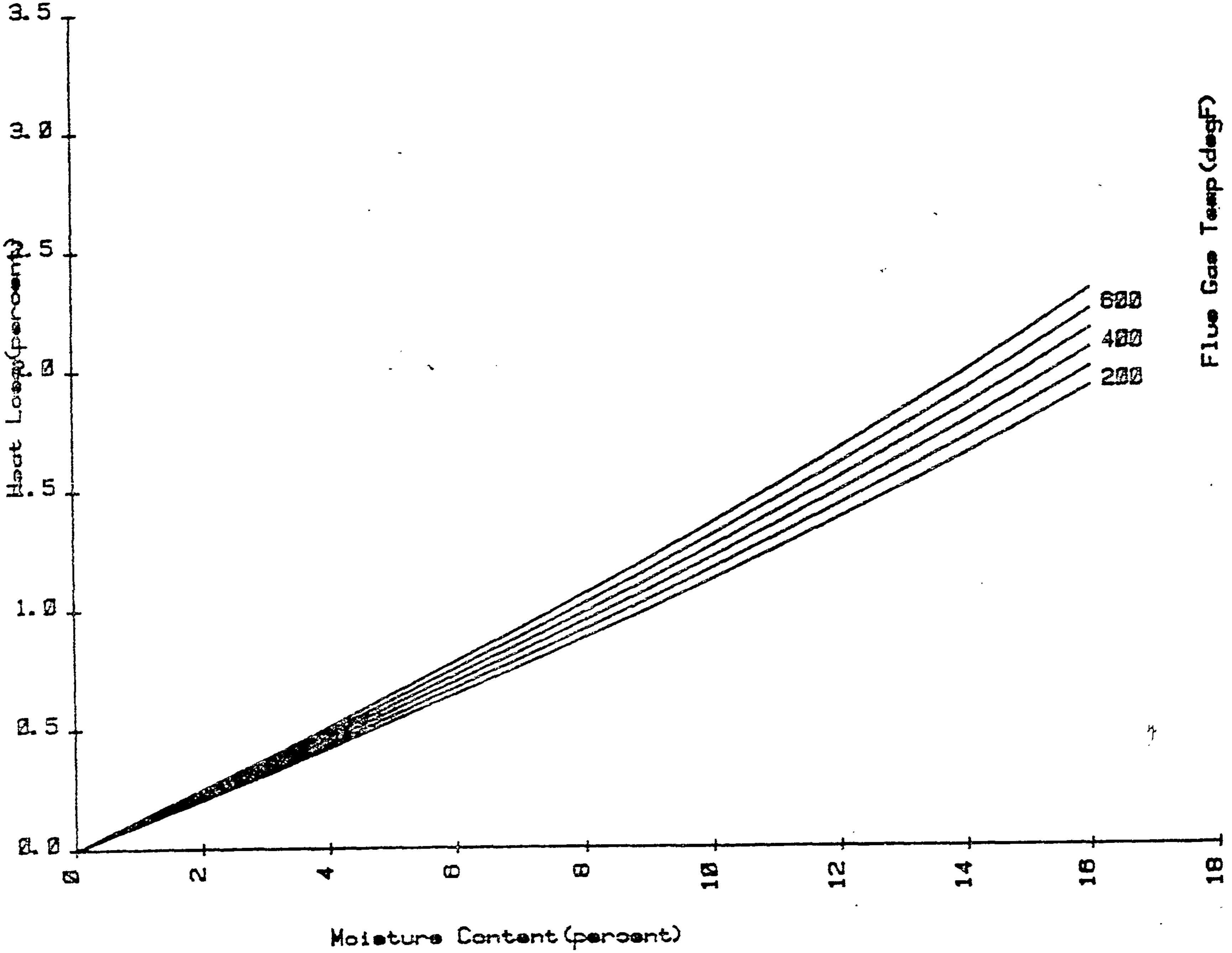


Figure 5A. Heat Loss Due to Moisture in Coal at 70°F

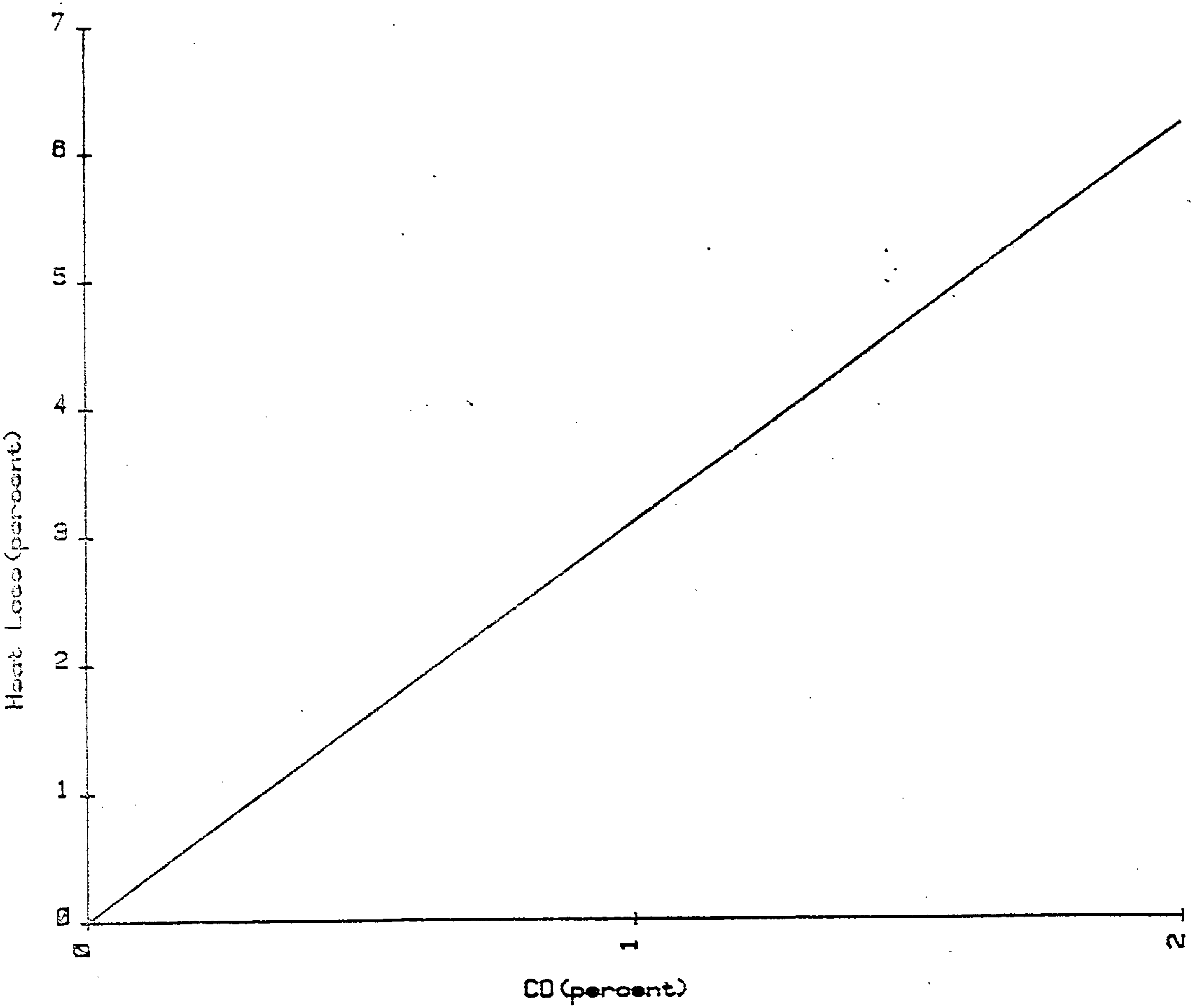


Figure 6A. Heat Loss for a Range of CO Centrations, Assuming Negligible Excess Air