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FLAME AND HEAT TRANSFER CHARACTERISTICS OF BENEFICIATED TENT MOUNTAIN-VICARY CREEK COAL REJECTS

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Flame and Heat Transfer Characteristics of Beneficiated Tent Mountain-Vicary Creek Coal Rejects

by

G.N. Banks*, H. Whaley*, R. Prokopuk** and G.K. Lee***

ABSTRACT

An experimental combustion study to establish the flame and heat transfer characteristics of beneficiated Tent Mountain-Vicary Creek coal rejects in a refractory-lined furnace is described. The pulverized coal flames ignited and burned readily, with combustion efficiencies in excess of 99.5%, compared to 99.9% efficiencies obtained with No. 6 fuel oil. Axial heat transfer patterns were relatively insensitive to either the degree of swirl or the excess air level, with about 7 to 8% less heat being transferred from the coal flames to the thermal walls of the kiln than was the case with the No. 6 fuel oil flames. NO_x and SO_x emissions were low for a refractory-lined furnace. Fly ash emissions appeared to increase with an increase in the flame swirl, but were relatively insensitive to an increase in the excess air level.

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INTRODUCTION

The Canadian Combustion Research Laboratory (CCRL) carried out a flame research project to determine the feasibility of burning beneficiated washery rejects from the Coleman region of alberta in mineral processing kilns. The beneficiated coal, a reclaimed by-product of coal from the Tent Mountain and Vicary Creek seams, had a calorific value of about 27,000 KJ/kg and is ranked as low-volatile bituminous coal by ASTM classification 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. The combustion of this coal in the CCRL pilot-scale research boiler is described in an earlier report (ERP/ERL 80-10 (CF).*

EXPERIMENTAL OBJECTIVES

The objectives of this research project were:

(a) to determine the aerodynamic requirements for a stable coal-flame condition;

(b) to evaluate the flame and heat transfer characteristics of the coal, under controlled aerodynamic and combustion condition;

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

(d) to generate combustion efficiency charts for the coal; and

(e) to compare the combustion properties of this coal with those obtained from No. 6 fuel oil.

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*Pilot-Scale Combustion Evaluation of Beneficiated Tent Mountain-Vicary Creek Coal Rejects, by R. Prokopuk, H. Whaley and G.K. Lee, Canadian Combustion Research Laboratory, Energy Research Laboratories, Canada Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources, Ottawa, Canada.

COAL PROPERTIES

Earlier work with this beneficiated coal in the CCRL pilot-scale research boiler indicated that no problems should be experienced in moving or feeding it through the laboratory coal handling system. This work also established that the coal ignited and burned readily in a water-walled steam boiler. Since stable ignition and combustion are generally easier to attain in a refractory-lined furnace, it was anticipated that no difficulty should be encountered in efficiently burning this coal in the tunnel furnace. The analyses of the coal and fuel oil used in the present experiments are given in Table 1.

DESCRIPTION OF COMBUSTION FACILITIES

CCRL Tunnel Furnace

The experimental program was carried out in the CCRL Tunnel Furnace, which is illustrated schematically in Figures 1 to 4.

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 1, were made to the furnace. A refractory-lined, water-cooled combustion chamber was installed between the burner and the tunnel furnace, and about 315^{o} of the circumference of each calorimetric section was lined with refractory brick. The remaining 45^{o} of each section was left unlined to impose a thermal load on the flames representative of a product charge.

TABLE 1. Fuel Oil and Coal Analyses

No. 6 Fuel Oil	
Specific Gravity, (15.6/15.6°C)	1.002
API (15.6°C)	9.72
Sulphur (x-ray), wt %	2.71
Ash, wt %	0.023
Water (distillation), vol. % ..	trace
Carbon, wt %	85.33
Hydrogen, wt %	10.79
Nitrogen, wt %	0.59
Viscosity (50°C), (Kinematic Centistokes)	511
Pour Point, °C	7.2
Flash Point (Pensky-Martin), °C	121.1
Calorific Value (corrected for S content)	
Btu/lb	18,250
MJ/kg	42.450

Beneficiated Coleman Rejects	
Proximate Analysis, wt %	
Ash	20.76
Volatile Matter	23.94
Fixed Carbon (by diff.) ..	55.30
Ultimate Analysis, wt %	
Carbon	69.01
Hydrogen	3.99
Sulphur	0.41
Nitrogen	1.06
Ash	20.76
Oxygen (by diff.)	4.77
Ash Analysis, wt %	
SiO_2	51.54
Al_2O_3	28.11
Fe_2O_3	4.26
TiO_2	1.62
P_2O_5	0.77
CaO	5.49
MgO	1.58
SO_3	4.15
Na_2O	0.16
K_2O	0.74
BaO	0.57
SrO	0.13
LOF	0.85
Ash Fusibility (Initial, reducing atm), °C	1350
Hardgrove Index	71
Calorific Value (dry basis)	
Btu/lb	11,574
MJ/kg	26.921

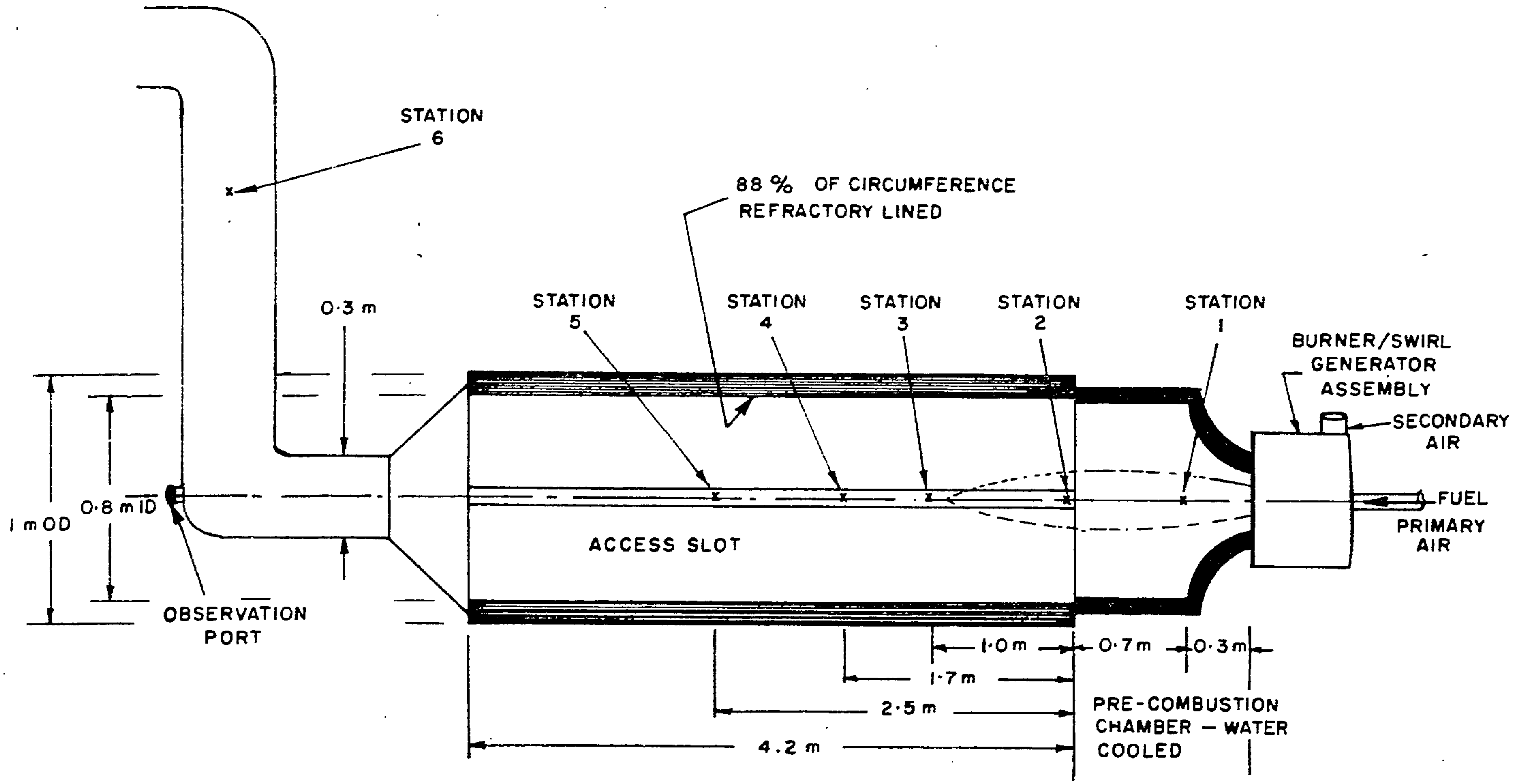

Figure 1 - Schematic view of the CCRL Flame Tunnel Furnace.

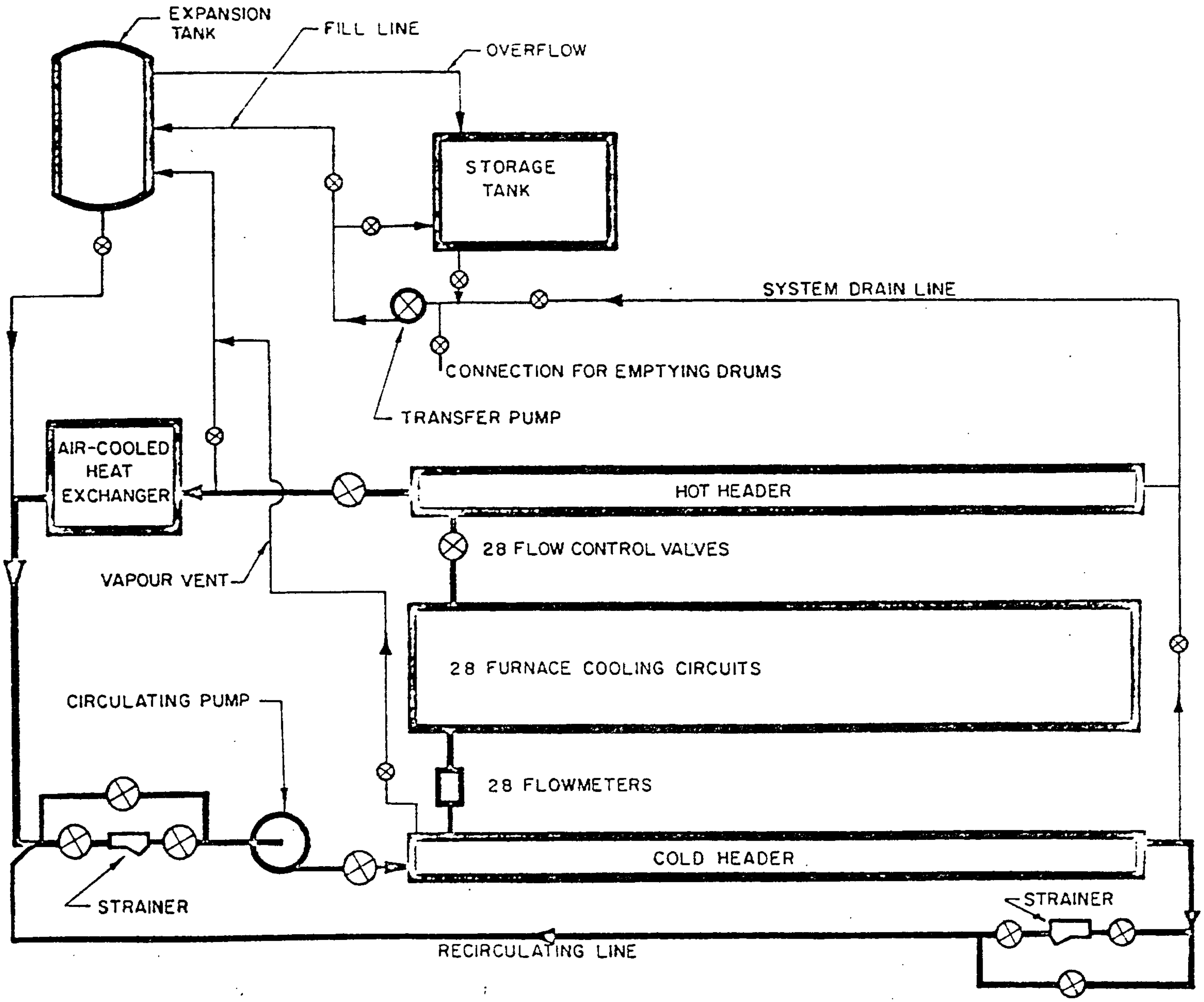

Fig. 2 - Cooling circuit of the CCRL Tunnel Furnace

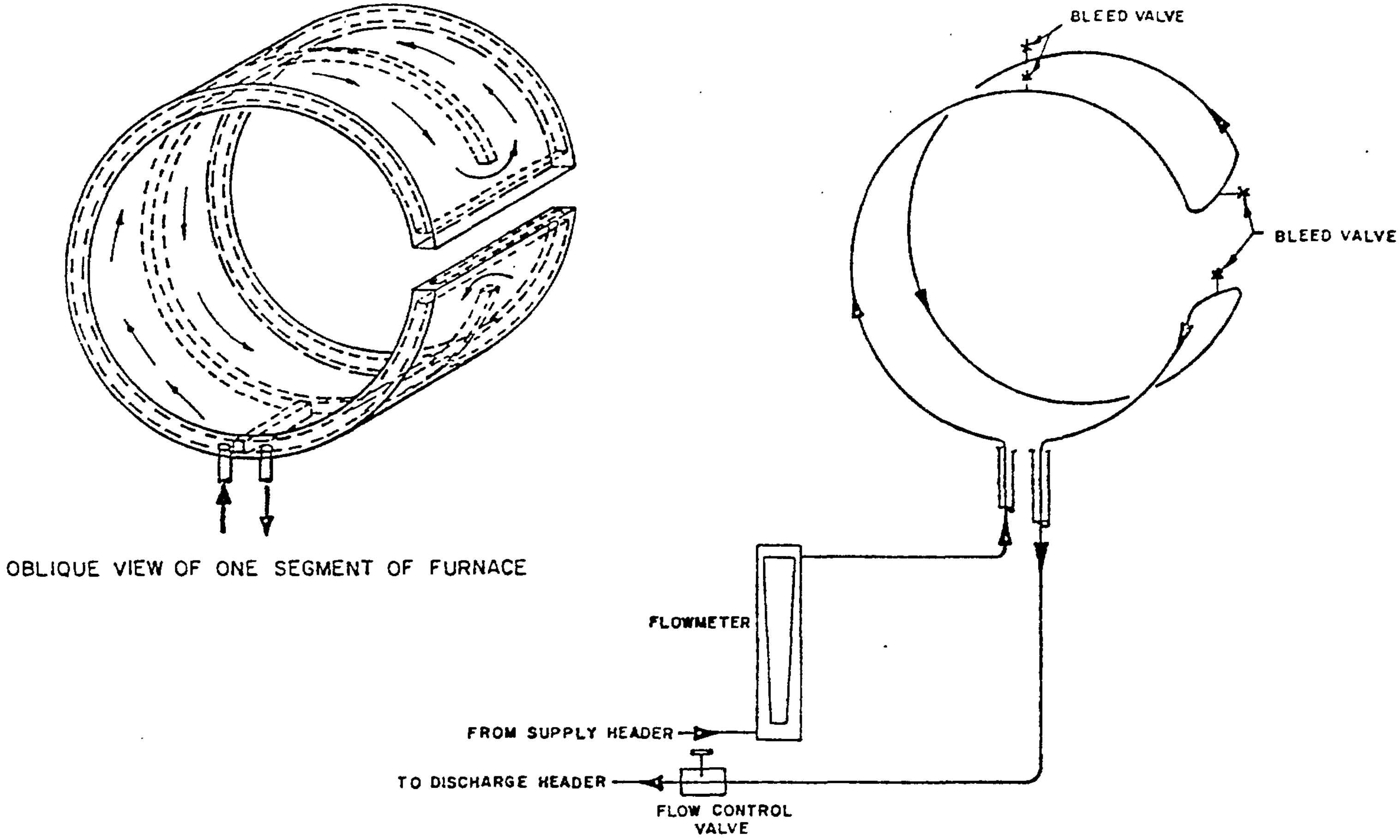

Fig. 3 - Schematic illustration of a segment of a coolant circuit on the CCRL Tunnel Furnace

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 4. 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 settings between 0 (a totally axial jet) and 5 (50% tangential flow). The Swirl number is defined as

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

R is the exit radius of the burner nozzle.

Swirl-stabilized 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.

EXPERIMENTAL PROCEDURES

Independent Parameters

The following parameters were maintained at the indicated controlled values for these experiments, using either oil or coal as a fuel:

(a) Burner swirl setting (0 and 1)

(b) Primary combustion air temperature ($80 \pm 10^{\circ}C$)

(c) Secondary combustion air temperature ($115 \pm 5^{\circ}C$)

(d) Primary to secondary air ratio (55/45 and 45/55)

(e) Excess combustion air corresponding to 3% and 5% oxygen in the flue gas

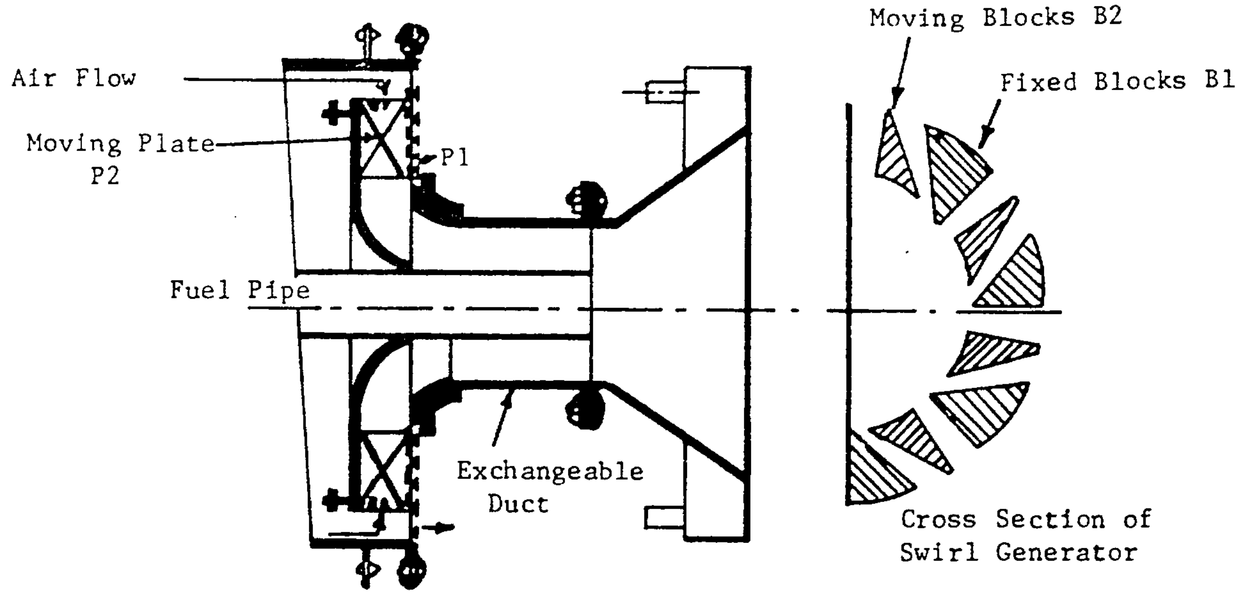

Fig. 4 - Schematic illustration of the variable swirl burner

(f) Oil feed rate (35 kg/h)

(g) Coal feed rate (55 ± 5 kg/h)

(h) Coal fineness (82% minus 74 μm)

Furnace Operation

The following operating procedure was used for all experiments:

(a) The cold furnace was started up with No. 2 fuel oil at about 20 litres per hour (approximately 900 MJ/h). When thermal equilibrium was established the coal or No. 6 fuel oil was started and the No. 2 fuel oil preheat burner was withdrawn.

(b) After operating on coal or No. 6 oil for 1 hour to ensure that all ancillaries were functioning properly, the coal or oil rate was adjusted to maintain a constant thermal input to the furnace at the desired level of excess air and swirl number.

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

Flame and Heat Transfer Measurements

The following measurements were taken during each experiment at the locations shown in Figure 1.

(a) Proximate analyses, ultimate analyses, ash analyses, sieve 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) Axial heat transfer from the flame by calorimetric measurements along the furnace length.

(d) Total heat flux and flame radiation by total heat flux meter and ellipsoidal radiometer measurements respectively at stations 1, 2, 3 and 4.

(e) Temperature profiles across the flame diameter by high-velocity suction pyrometer measurements at stations 1, 2 and 3.

(f) Profiles of combustion gas components (CO and O_2) across the flame diameter at stations 1, 2 and 3.

(g) Flame length from visual observations through the furnace's axial measuring slot.

(h) Carbon dioxide and carbon monoxide in the exhaust gas by continuous infra-red monitors at station 6.

(i) Oxygen in the exhaust gas by continuous paramagnetic monitor at station 6.

(j) Nitric oxide in the exhaust gas by continuous chemiluminescent monitor at station 6.

(k) Fly ash loading in the exhaust gas by isokinetic dust samples (these samples were analyzed for carbon content) at station 6.

EVALUATION OF RESULTS

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

Flame Characteristics

Flame length

Flame length with No. 6 oil was unaffected by variations in excess air level but varied from 2½ to 3 metres downstream from the burner at Swirl No. of 0 and 1 respectively. When coal was used as the fuel input, flame length was about 4 metres or longer and no difference could be detected visually in the length of this flame due to either variation in excess air level or swirl number.

TABLE 2. Furnace Operating Conditions

	No. 6 Fuel Oil				Beneficiated Coal Rejects			
Feed rate, kg/h	35	35	35	35	53	59	54	54
Heat input, MJ/h	1486	1486	1486	1486	1427	1588	1454	1454
Burner Swirl Setting	0	0	1	1	0	0	1	1
Coal fineness, % <74 µm ...	-	-	-	-	82	82	82	82
Primary air temp, °C	91	91	91	91	77	77	82	79
Secondary air temp, °C	121	114	121	115	119	115	117	118
Furnace exit temp, °C	705	705	700	710	925	940	900	850
Primary/Secondary air ratio	55/45	45/55	55/45	45/55	55/45	45/55	55/45	45/55
*Total Combustion air, Nm^3/h	433	489	437	474	441	537	446	503
*% Excess air	16	31	17	27	18	29	17	32
Carbon in fly ash, %	-	-	-	-	1.41	1.41	1.50	-
Combustion efficiency, % ..	>99.9	>99.9	>99.9	>99.9	99.6	99.6	99.6	-
Flue gas composition								
O_2 %	3.0	5.1	3.1	4.6	3.3	4.8	3.2	5.2
O_2 %	13.7	12.4	14.2	12.3	16.3	14.4	16.2	14.5
CO %	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.02
SO_3 ppm	<1	<1	<1	<1	<1	<1	<1	<1
SO_2 ppm	1450	1220	1410	1210	210	190	205	180
NO ppm	230	230	230	230	680	570	590	495
Fly ash emission, g/Nm^3 ...	0.275	0.297	0.206	0.137	9.884	10.914	15.009	11.875

*Calculated from % O_2 in flue gas.

Temperature Profiles

The temperature profiles across the flames at station 1 for swirl No. of 0 and 1 and at excess air levels corresponding to 3% and 5% oxygen in the flue gases are shown in figure 5 for both oil and coal. These indicate a much flatter temperature profile for the coal-fired flame at lower peak and overall flame temperatures than with the oil-fired flame. Increasing the excess air levels and/or the swirl number, when using oil as a burner fuel, appeared to increase peak temperatures of the flame profile with a corresponding increase in the average flame temperature. However, increasing the excess air levels and/or the swirl number, when using coal as a burner fuel, appeared to have little effect on flame profile and decreased the average flame temperature.

The temperature profiles for these flames at station 2, shown in figure 6, indicated similar but less significant changes on the oil-fired flames with changes in the excess air levels and/or swirl number than was evident at station 1. The coal-fired flame profile was flatter at the lower swirl number, but as at station 1 the average flame temperature decreased with the increasing excess air level and increasing swirl number. The flame profile of the coal-fired flame, at 5% oxygen in the flue gas and swirl No. 1, approaches that of the oil-fired flame but with a lower average flame temperature.

At station 3, shown in figure 7, the oil-fired burner flames have a flatter profile, at a lower average flame temperature than at either station 2 or 1. Increasing the swirl number or the excess air has a less significant effect than at the other stations. The coal-fired burner flames have a flame profile similar to that of the oil-fired burner flames with average flame temperatures, in some cases, exceeding that of the oil-fired flames; but as at other stations, increasing the swirl number decreases the average flame temperature.

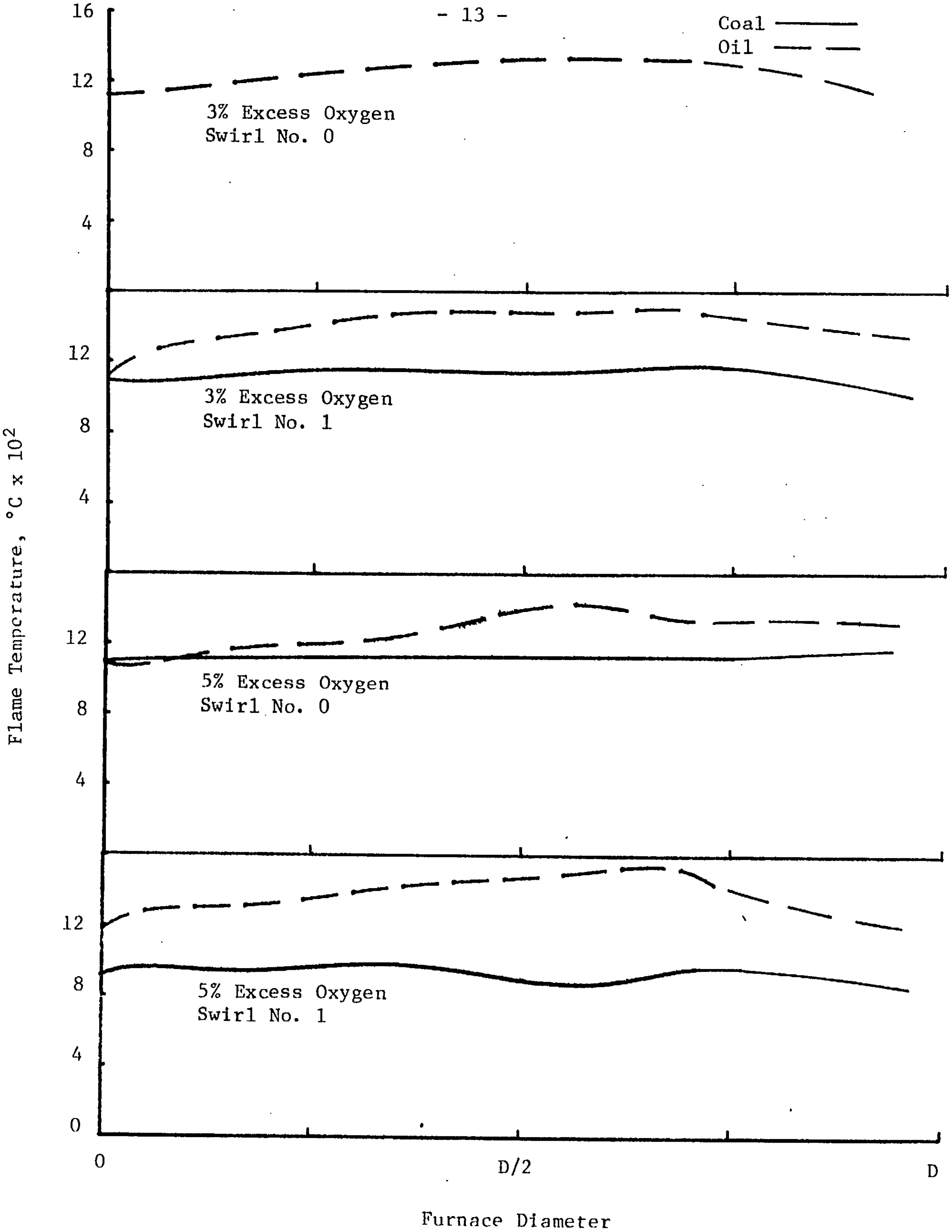

Fig. 5 - Comparative flame temperature profiles at Station 1 for two levels of swirl and two levels of excess combustion air

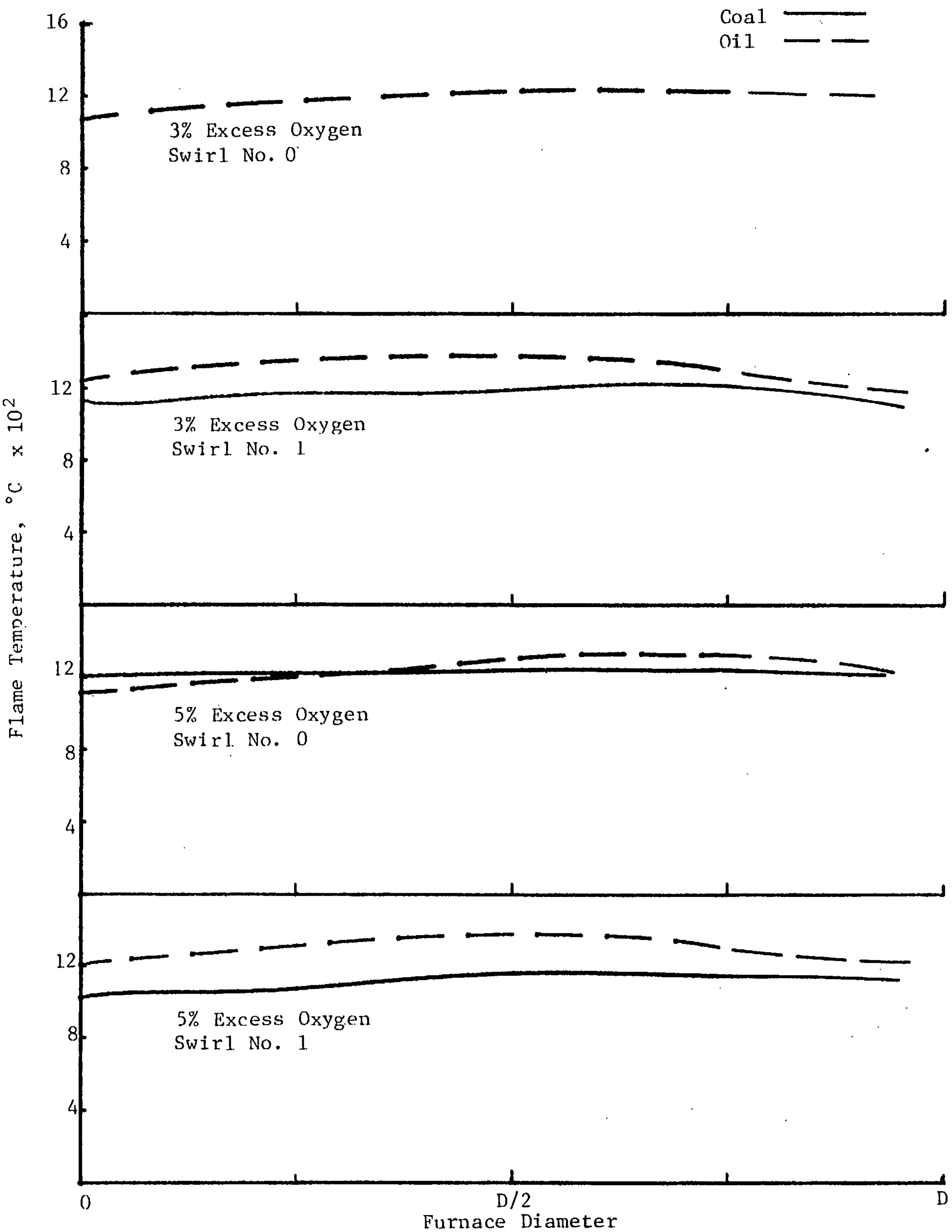

Fig. 6 - Comparative flame temperature profiles at Station 2 for two levels of swirl and two levels of excess combustion air

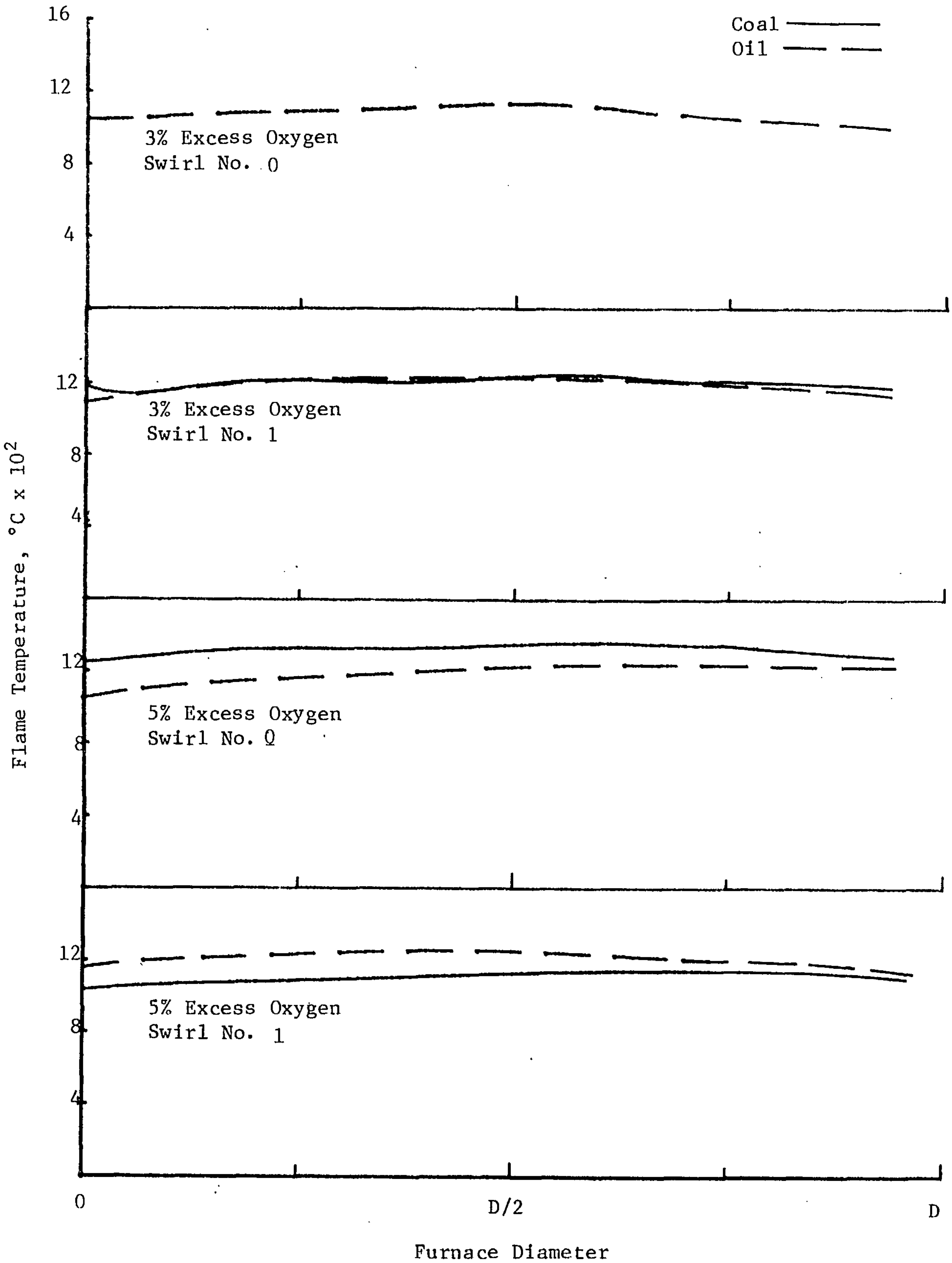

Fig. 7 - Comparative flame temperature profiles at Station 3 for two levels of swirl and two levels of excess combustion air

It is significant to note that the average temperature of the coal flame increases with distance from the burner tip, whereas the average temperature of the oil flame decreases with distance.

Gas Concentration Profiles

The variation in oxygen levels across the oil and coal flames are shown in Figures 8, 9 and 10. It is evident from these concentration profiles that a considerable amount of the oxygen available for combustion was not utilized at station 1. This was much more evident with the coal flames than with the oil flames. At station 3, the oxygen concentrations of the oil flames are closer to their respective concentrations in the exit flue gases than is the case with the coal flames. This indicates that the combustion process on No. 6 oil is closer to completion at this point than when coal is utilized. This was confirmed by visual observations of the flame length.

The carbon monoxide profiles across the flames at the three stations are shown in Figures 11 to 13. These figures again indicate the relative completion of combustion in the oil flames compared to the coal flames at station 3. In every case, the carbon monoxide values are higher in the coal flames than in the oil flames. These figures also show that the carbon monoxide value decreased across the diameter of the coal flame when the swirl number increased from 0 to 1, at 3% excess oxygen in the flue gas, indicating a relatively complete combustion.

Combustion Efficiency

Isokinetic samples of the gas borne particulate material was collected at station 6 during each combustion experiment, and the results, presented in Table 2, were used to evaluate the combustion efficiencies for each experiment.

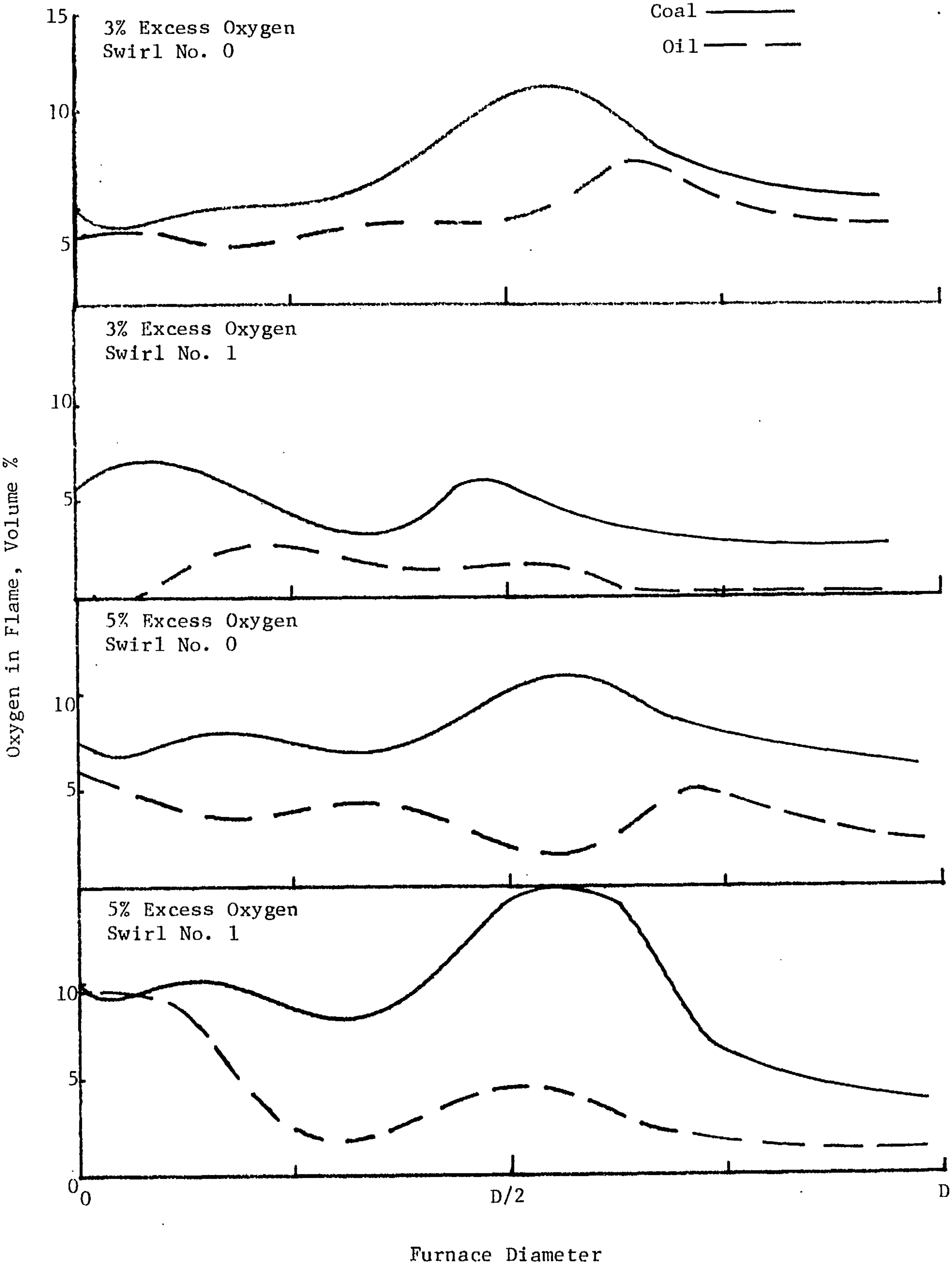

Fig. 8 - Comparative oxygen profiles through the flame at Station 1 for two levels of swirl and two levels of excess combustion air

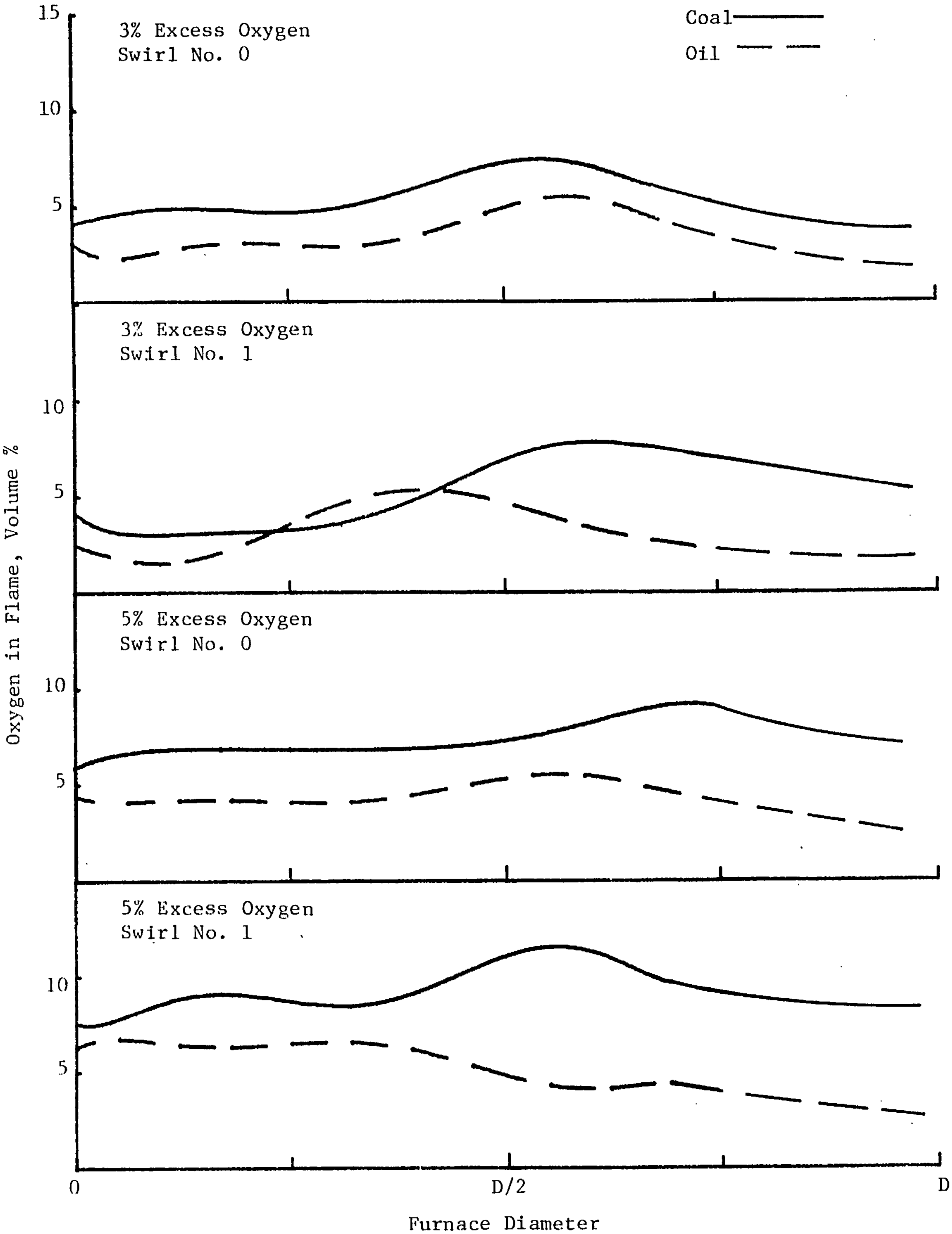

Fig. 9 - Comparative oxygen profiles through the flame at Station 2 for two levels of swirl and two levels of excess combustion air

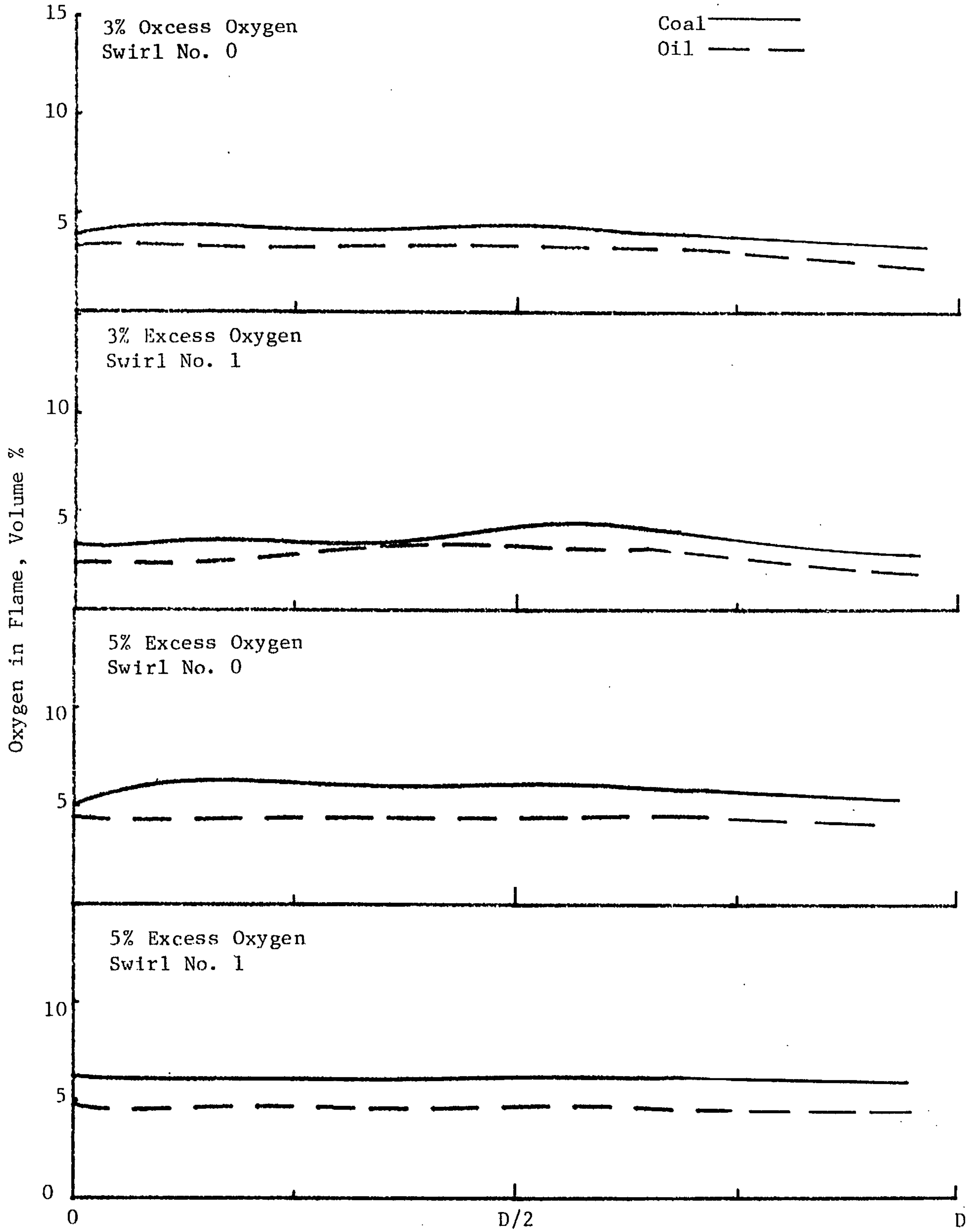

Fig. 10 - Comparative oxygen profiles through the flame at Station 3 for two levels of swirl and two levels of excess combustion air

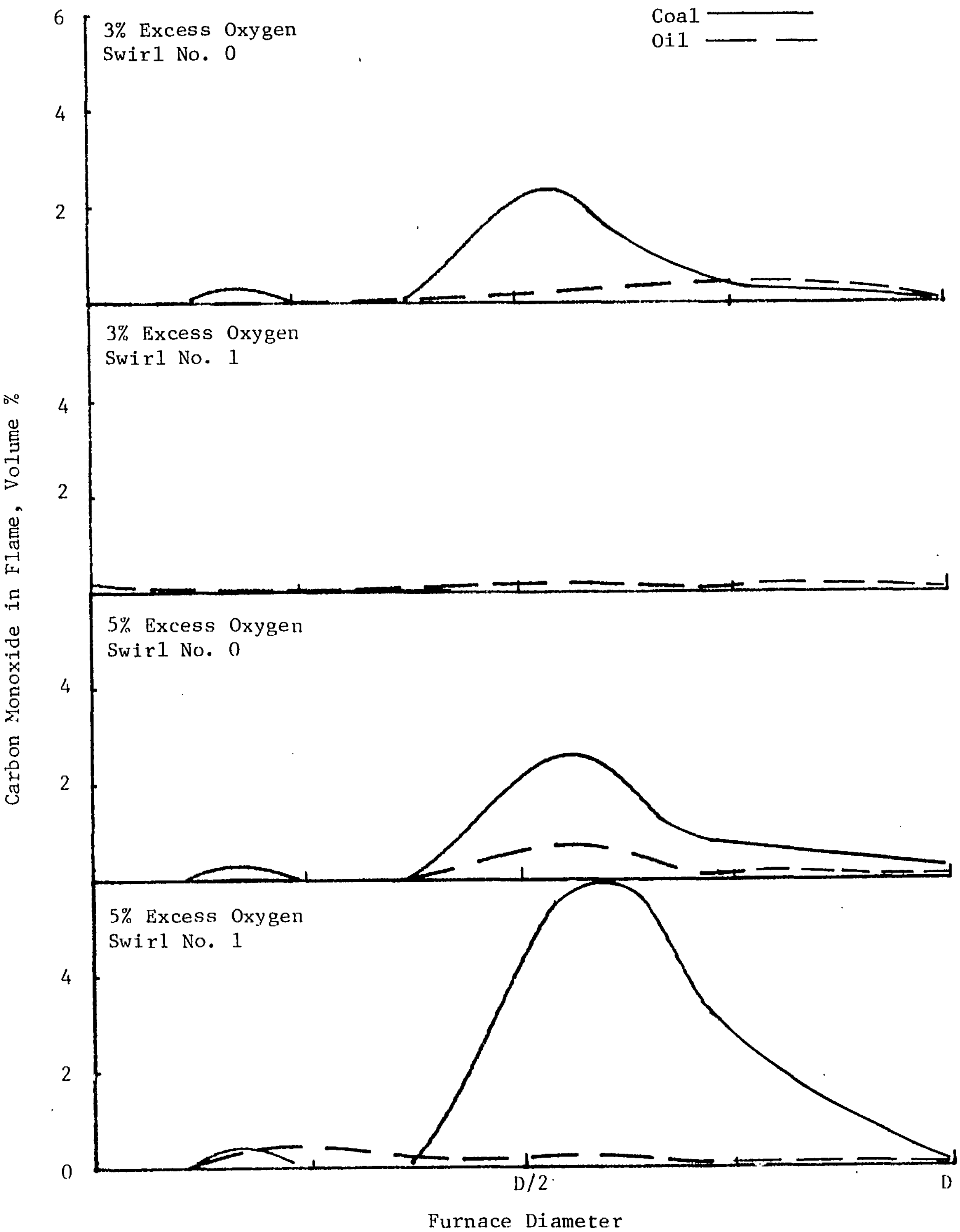

Fig. 11 - Comparative carbon monoxide profiles through the flame at Station 1 for two levels of swirl and two levels of excess combustion air

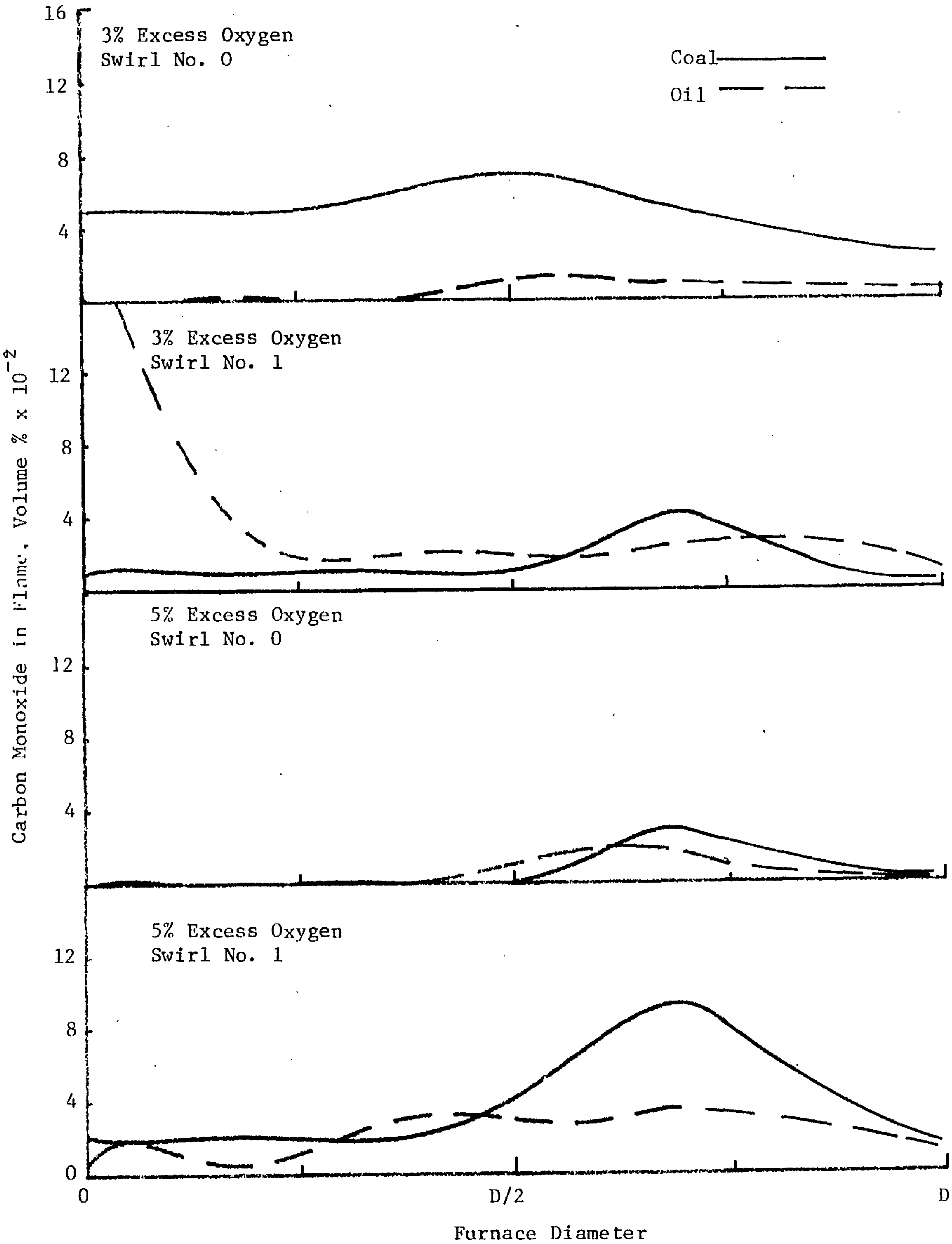

Fig. 12 - Comparative carbon monoxide profiles through the flame at Station 2 for two levels of swirl and two levels of excess combustion air

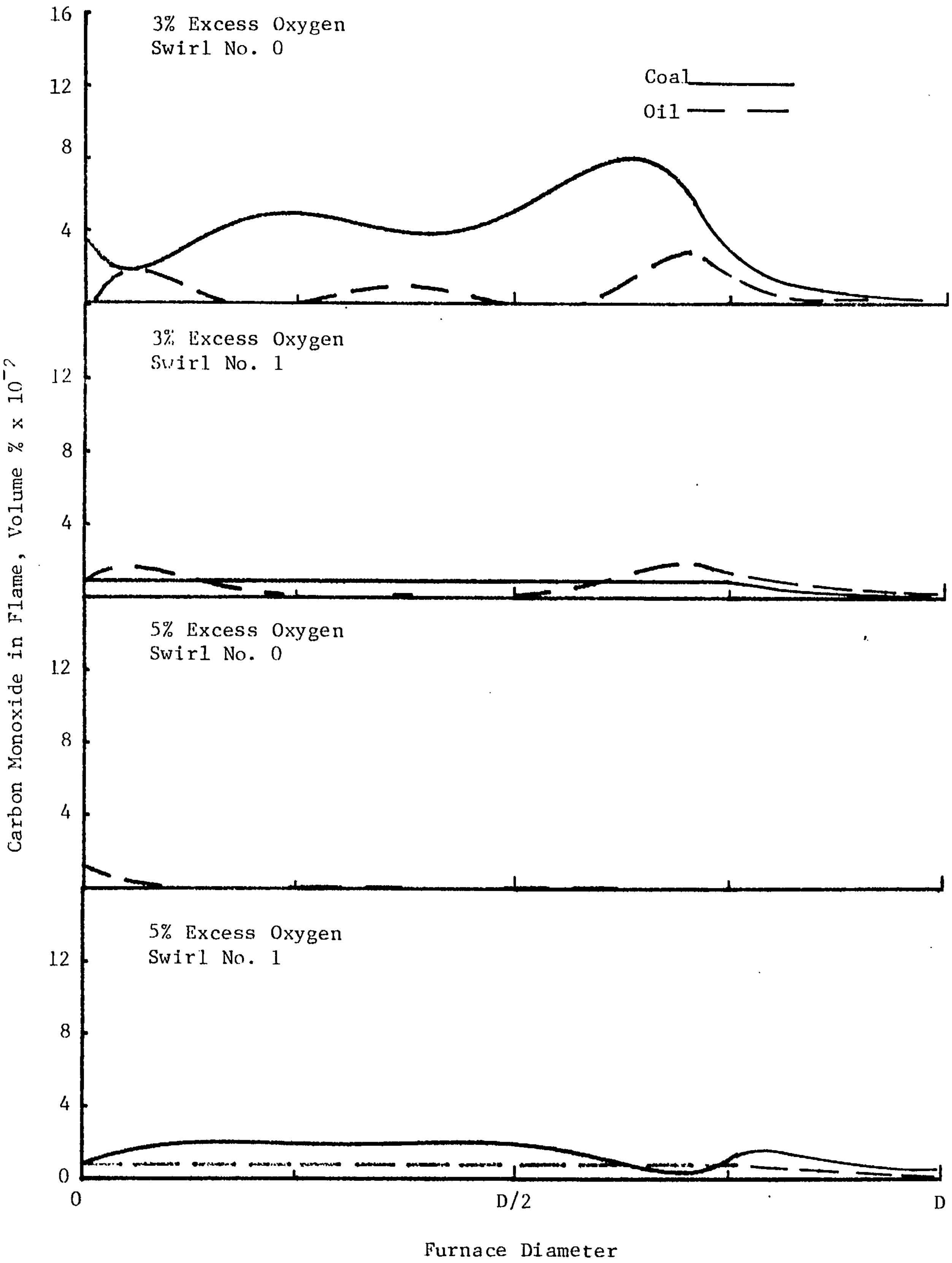

Fig. 13 - Comparative carbon monoxide profiles through the flame at Station 3 for two levels of swirl and two levels of excess combustion air

The combustion efficiencies were calculated from the following relationships:

$$\text{Combustion Efficiency for Coal, \%} = 100 - \frac{14500\ CA}{(100-C)\ C_v}$$

where 14,500 = Calorific Value of Pure Carbon, Btu/lb

C = % Carbon in Fly Ash

A = % Ash in Coal

C_v = Calorific Value of Coal, Btu/lb

This relationship defines the combustion efficiency in terms of the percentage of input heat lost due to carbon in the fly ash emissions.

In the case of oil, which has negligible ash, combustion efficiency is simply defined by estimating the amount of thermal input lost due to carbon emitted. In oil combustion the particulate emissions are more than 99% carbon.

$$\text{Combustion Efficiency for Oil, \%} = 100 - \frac{14500\ CD}{C_v}$$

where C = Concentration of Soot in Emissions, lb/sft^3

D = Dry Flue Gas Produced by Oil, sft^3/lb oil

C_v = Calorific Value of Oil, Btu/lb

The results, given in Table 2, indicate that the combustion efficiency, using coal, was slightly lower than that of the oil and was not significantly effected by changes in levels of either swirl or excess combustion air.

Flue Gas Emissions

Fly Ash Emissions

The fly ash emissions from the furnace were much greater with coal than with oil, increasing by a factor of 35 to 90, depending on conditions. Increasing the swirl setting from 0 to 1 tended to decrease the emissions from the oil flames, but increased the emissions from the coal flames. Increasing the excess combustion air from 3 to 5% oxygen in the flue gas appeared to have little effect on the fly ash emissions.

Gas-Phase Emissions

The carbon monoxide concentrations in the exhaust gases were less than 0.02% volume for all flames. Sulphur dioxide emissions were 1210 to 1450 ppm for the oil flames and 180 to 210 ppm for the coal flames. These sulphur dioxide emissions appeared to decrease in concentration with an increase in swirl number and/or excess air. The nitric oxide emissions from the oil-fired burner flames remained constant at about 230 ppm whereas those from the coal flames decreased from 680 to 495 ppm, with an increase in swirl number and/or excess air.

Heat Transfer

Total and Radiative Heat Flux

Comparative axial measurements of the total and radiative heat flux measurements are shown in Figures 14 and 15. Increasing excess air levels decreased the total heat flux levels and radiative heat flux levels from both the coal and oil flames. This appeared to be much more significant with the coal flames than with the oil flames, especially at zero swirl. At swirl setting 1, increasing the excess air levels appeared to decrease the peak total heat flux value, but had little effect on the average total heat flux value. The average value of the radiative component of the total heat flux value was 47 to 58% for the coal flames and 40 to 47% for the oil flames, depending on the swirl number.

With 3% excess oxygen in the flue gas, increasing the flame swirl decreased the average total and radiative heat flux values, whereas with 5% excess oxygen, increased swirl increased the average total and radiative heat flux values of the coal flames and decreased those of the oil flames.

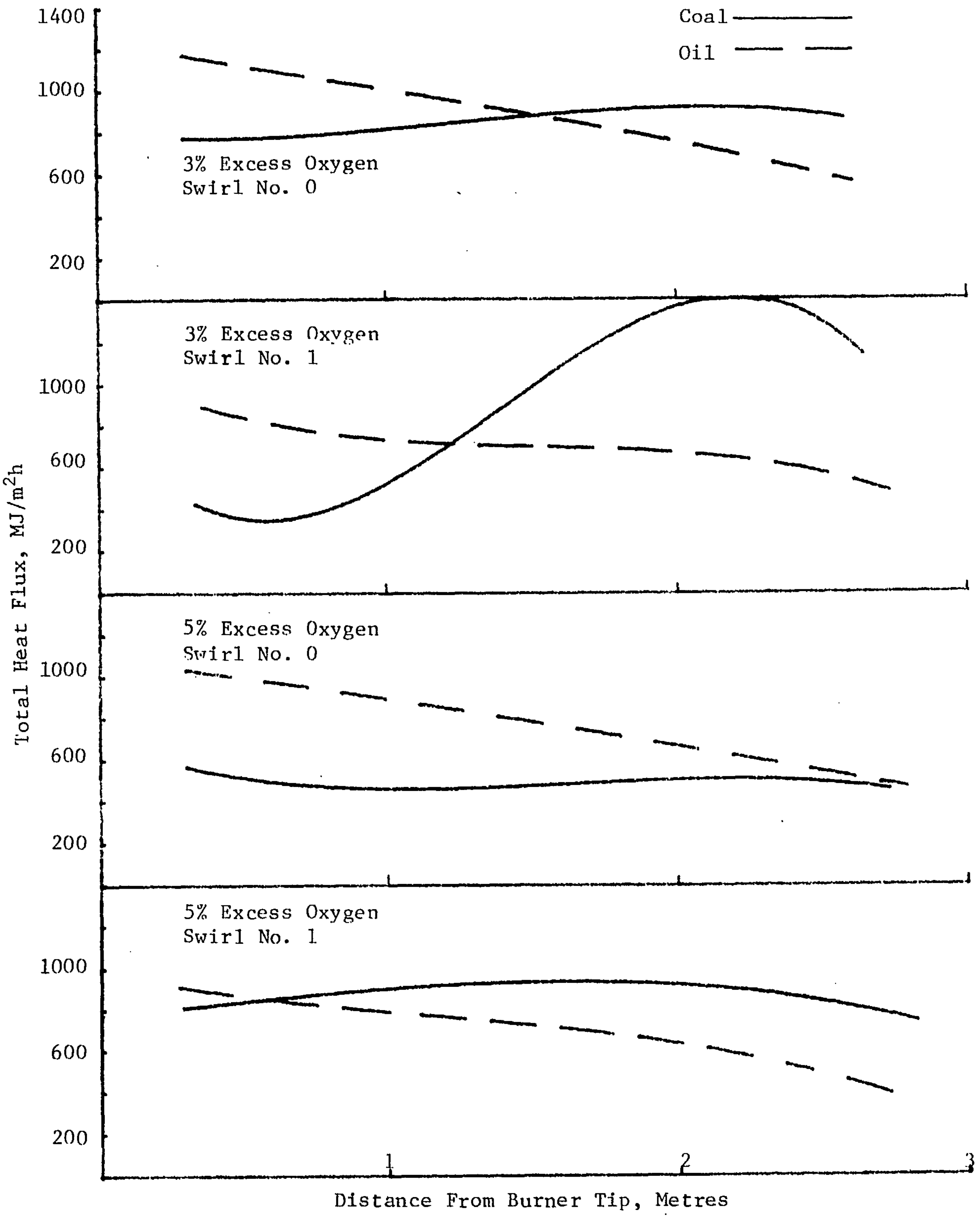

Fig. 14 - Comparative axial variation of total heat flux at two levels of excess combustion air and two levels of swirl

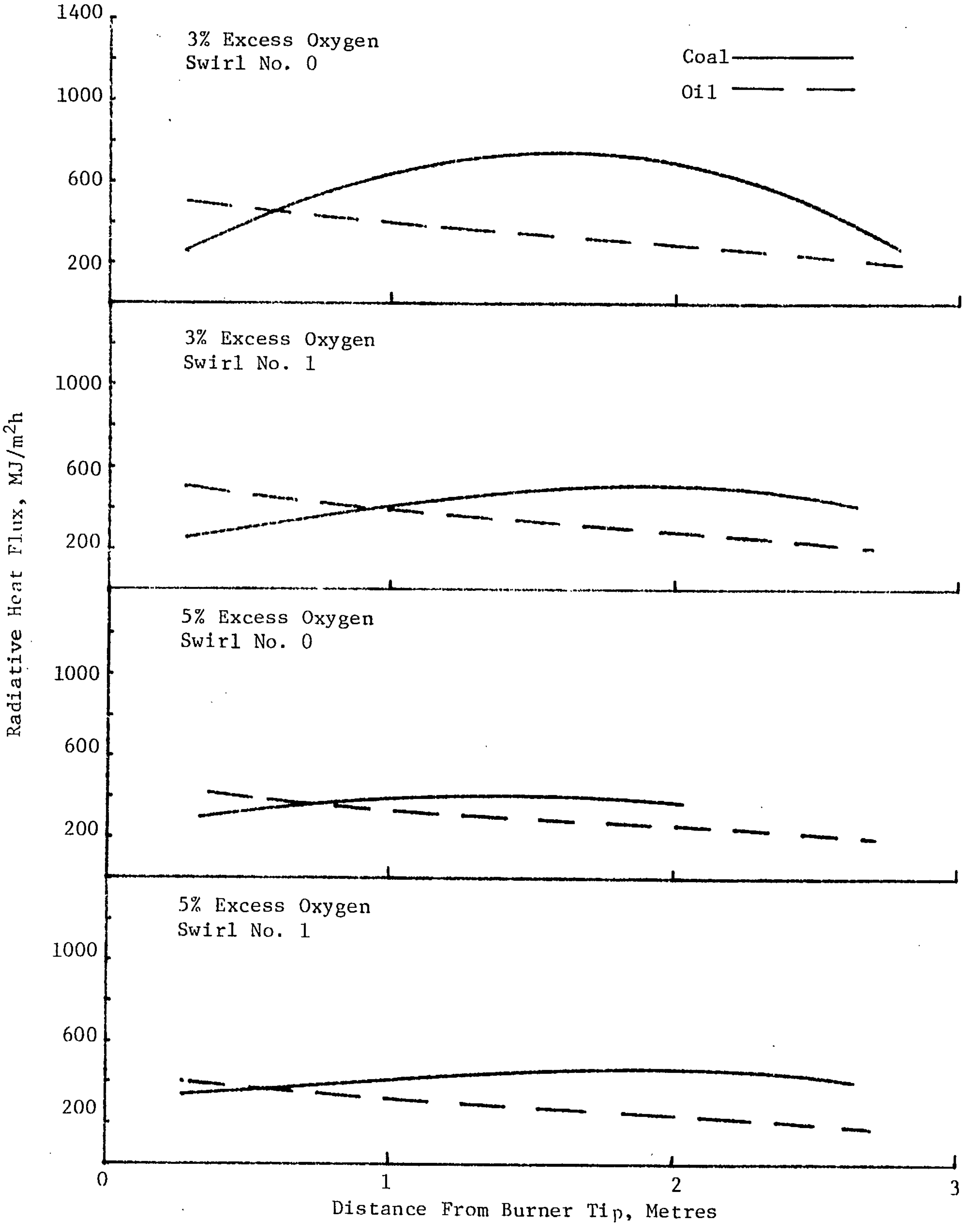

Fig. 15 - Comparative axial variation of radiative heat flux at two levels of excess combustion air and two levels of swirl

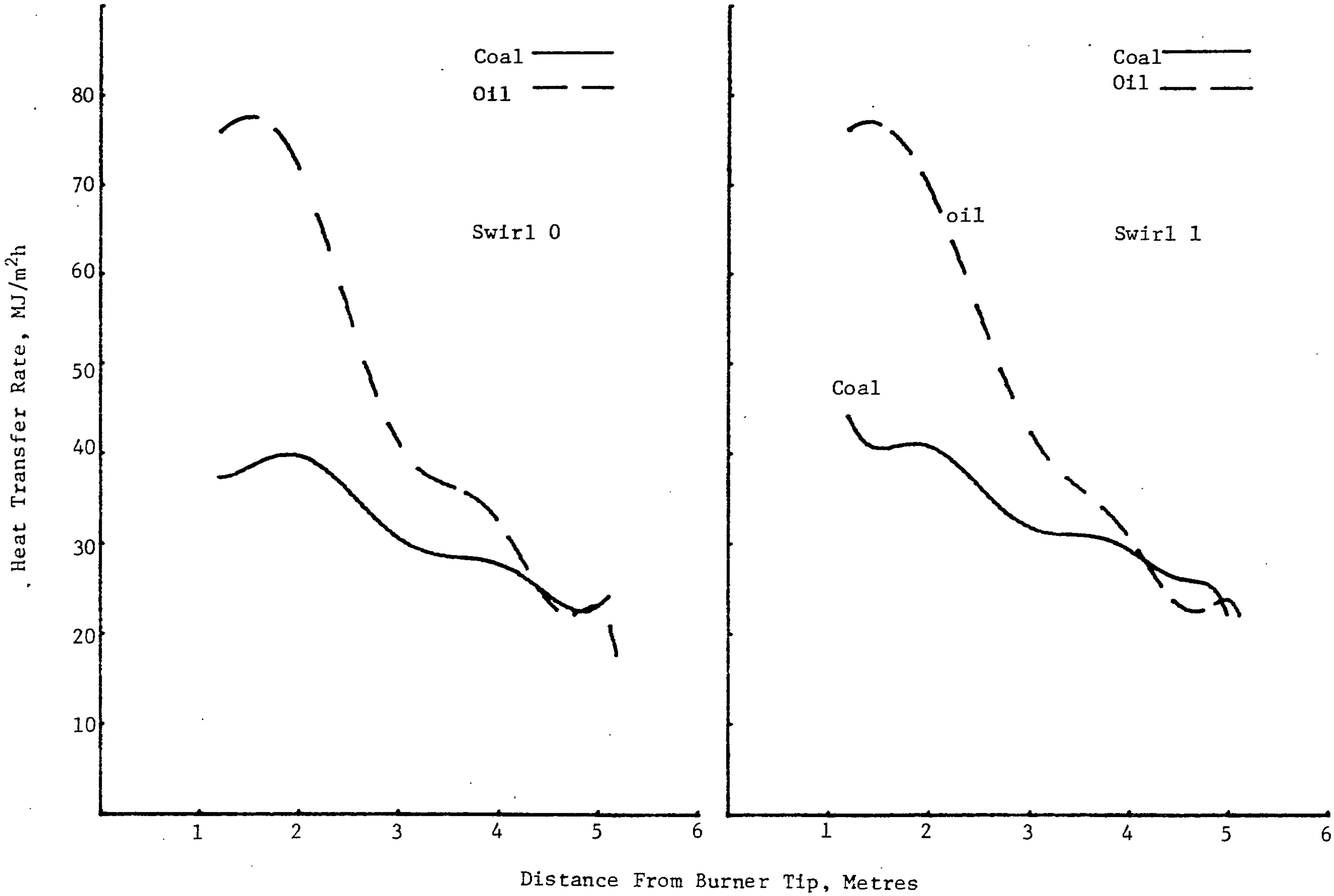

Fig. 16 - Comparative axial heat transfer rates at 3% excess oxygen in flue gas and two levels of swirl

Fig. 17 - Comparative axial heat transfer rates at 5% excess oxygen in flue gas and two levels of swirl

Overall Heat Transfer Rate

The axial distribution in the overall heat transfer rates to the tunnel furnace, Figures 16 and 17, showed only minor differences as the excess air levels were changed, but a slightly improved rate of heat transfer with swirled flames. Based on the heat input to this experimental furnace, about 26% of the heat was transferred to the cooling coils using coal with an unswirled flame and about 28% using coal with a swirled flame. This compares with the oil fired flames which transferred about 34% of the heat to the cooling coils with an unswirled flame and about 35% with a swirled flame. Swirl therefore had little effect on the total heat absorbed in the furnace.

CONCLUSIONS

1. The beneficiated Tent Mountain-Vicary Creek coal rejects produced an easily ignited, highly stable flame without the use of support fuel.

2. Flue gas emissions were normal for a typical coal fuel with the fly ash emissions and nitric oxide composition higher and the sulphurous oxide composition lower than when No. 6 fuel oil is burned.

3. Overall axial heat transfer patterns indicate a more rapid release of heat from oil-fired burner flames than from the coal-fired burner flames, which are only slightly affected by swirl and excess air levels.

4. Combustion efficiencies of this coal were 99.6% compared to No. 6 fuel oil at >99.9% under the same operating conditions. Swirling the flame or increasing the excess air levels had no apparent affect on these efficiencies. Because of the much longer furnace residence times and higher volumetric heat release rates in full-scale equipment, combustion efficiencies close to 100% with this coal should be readily attainable in industrial process kilns.

APPENDIX "A"

COMBUSTION CHARTS

FOR

BENEFICIATED TENT MOUNTAIN - VICARY CREEK COAL REJECTS

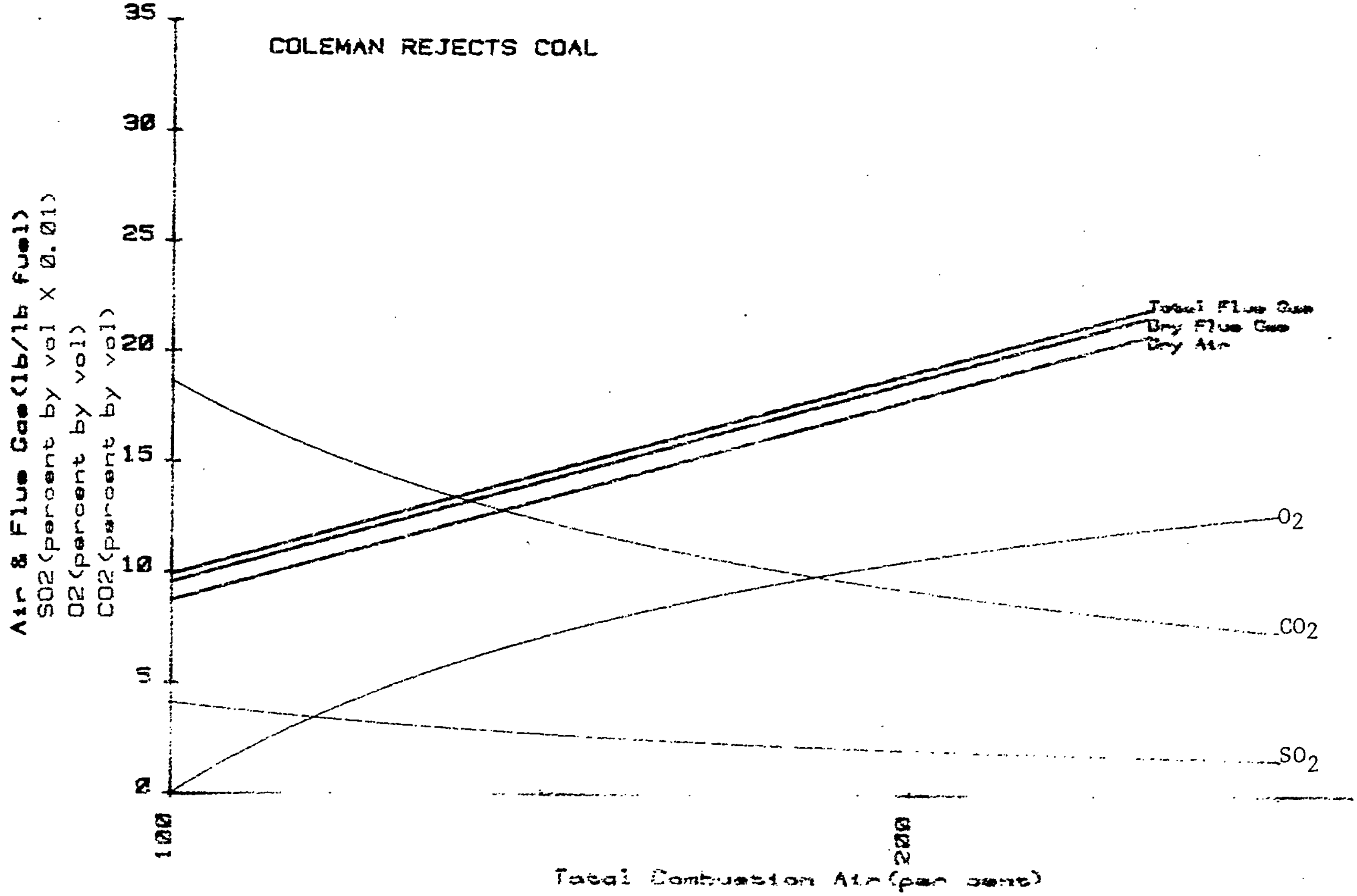

Fig. 1A - Combustion data, weight basis

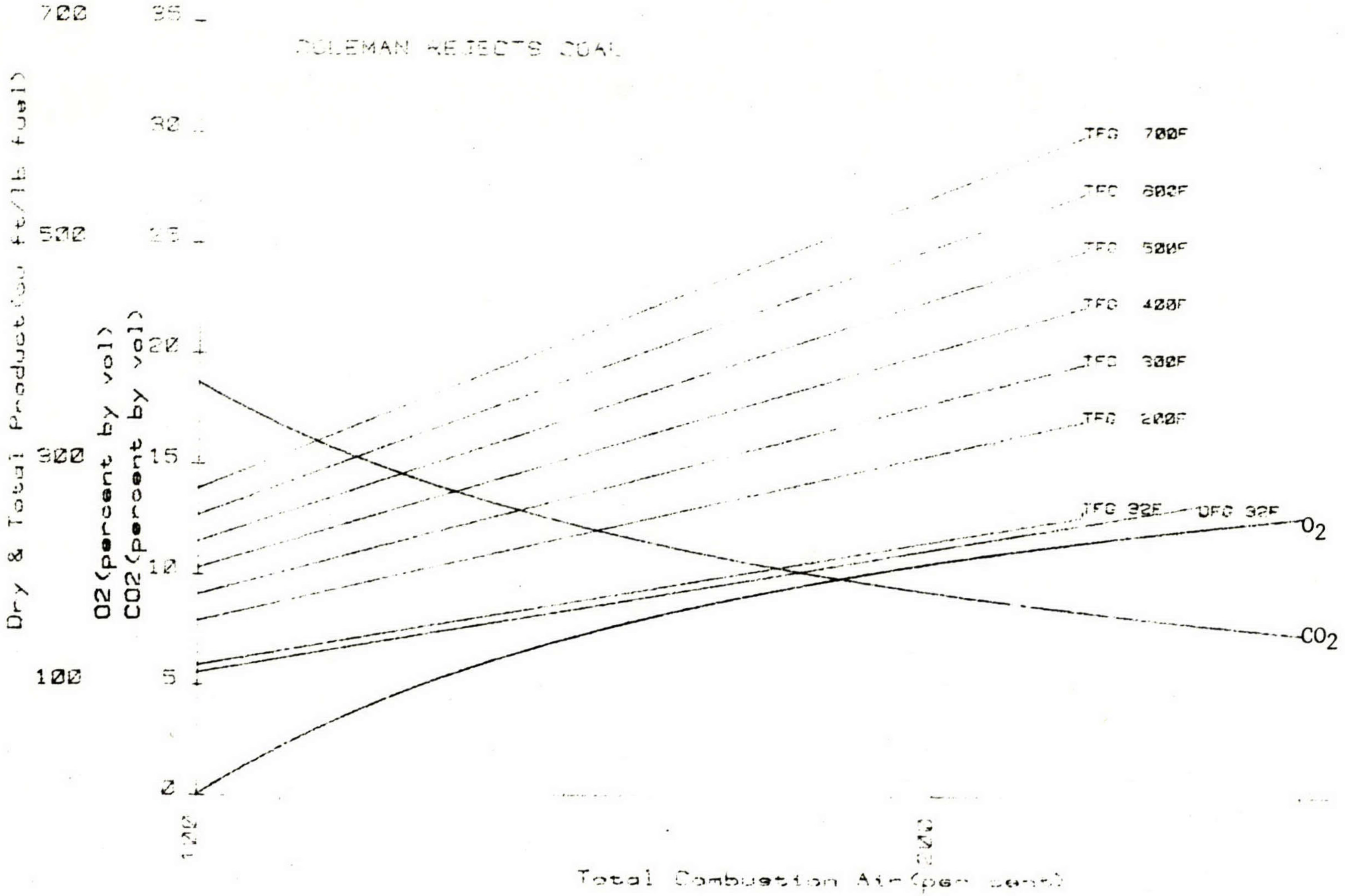

Fig. 2A - Combustion data, volume basis

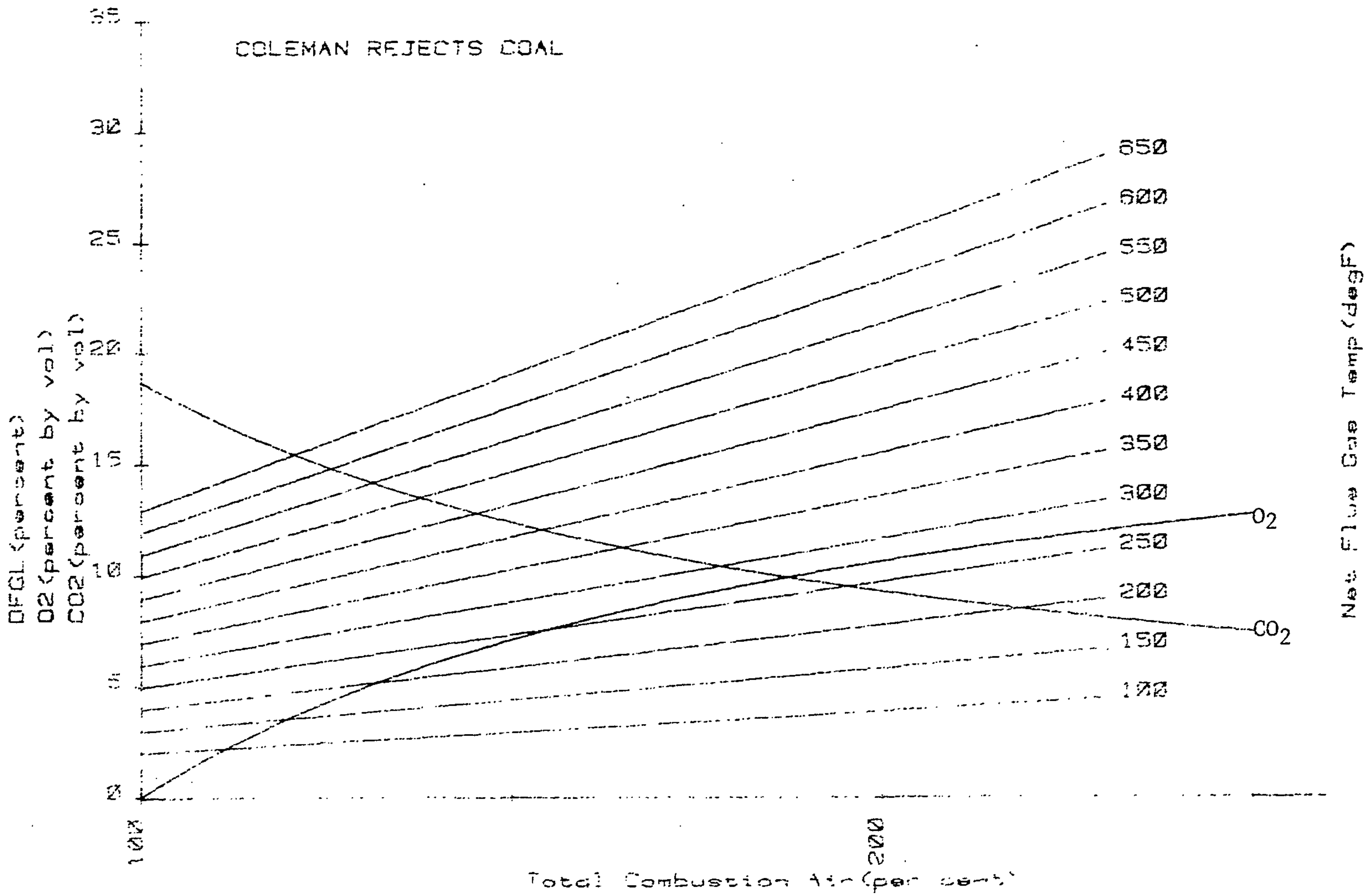

Fig. 3A - Dry flue gas loss for a range of temperature differentials

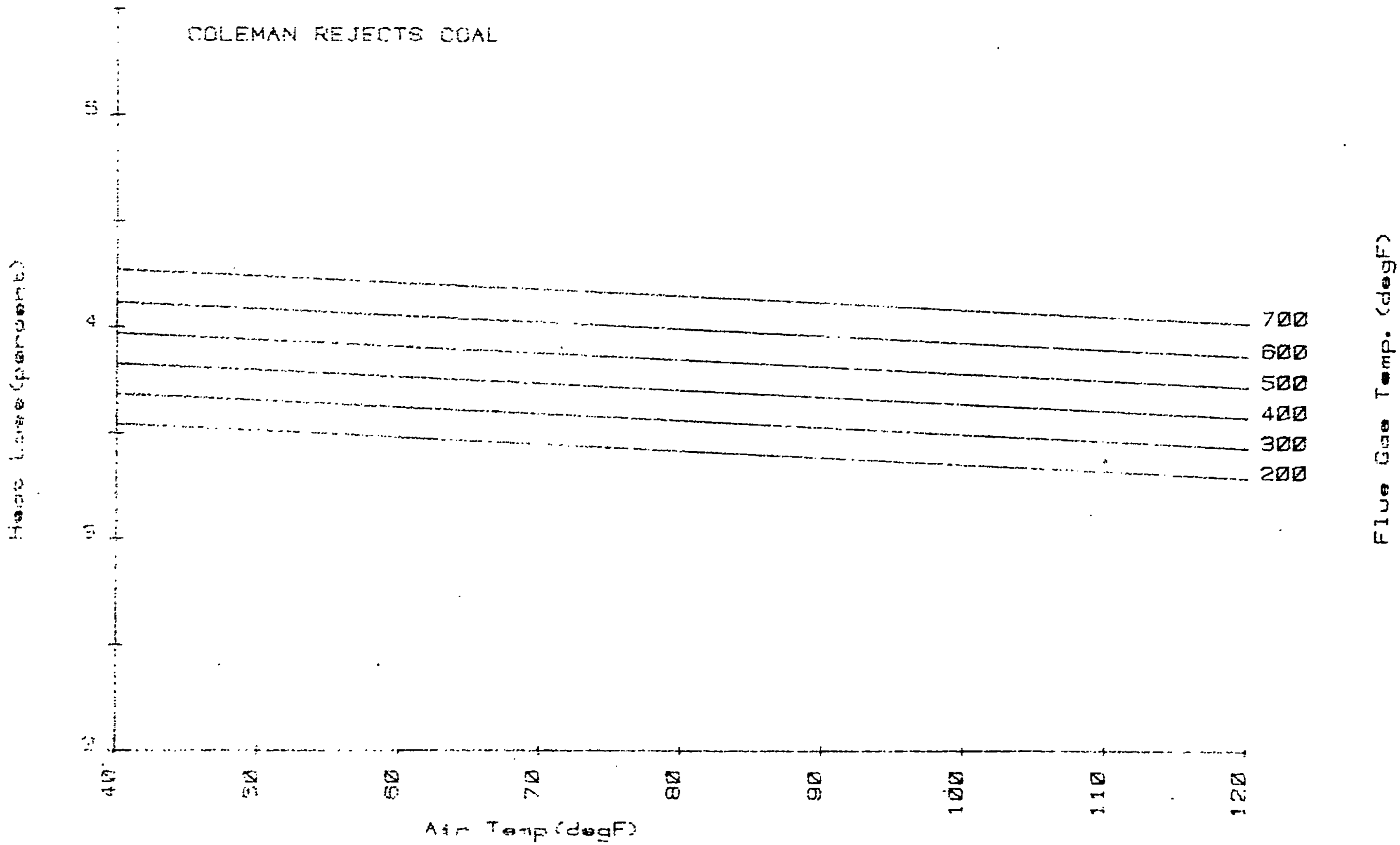

Fig. 4A - Hydrogen loss for a range of stack temperatures

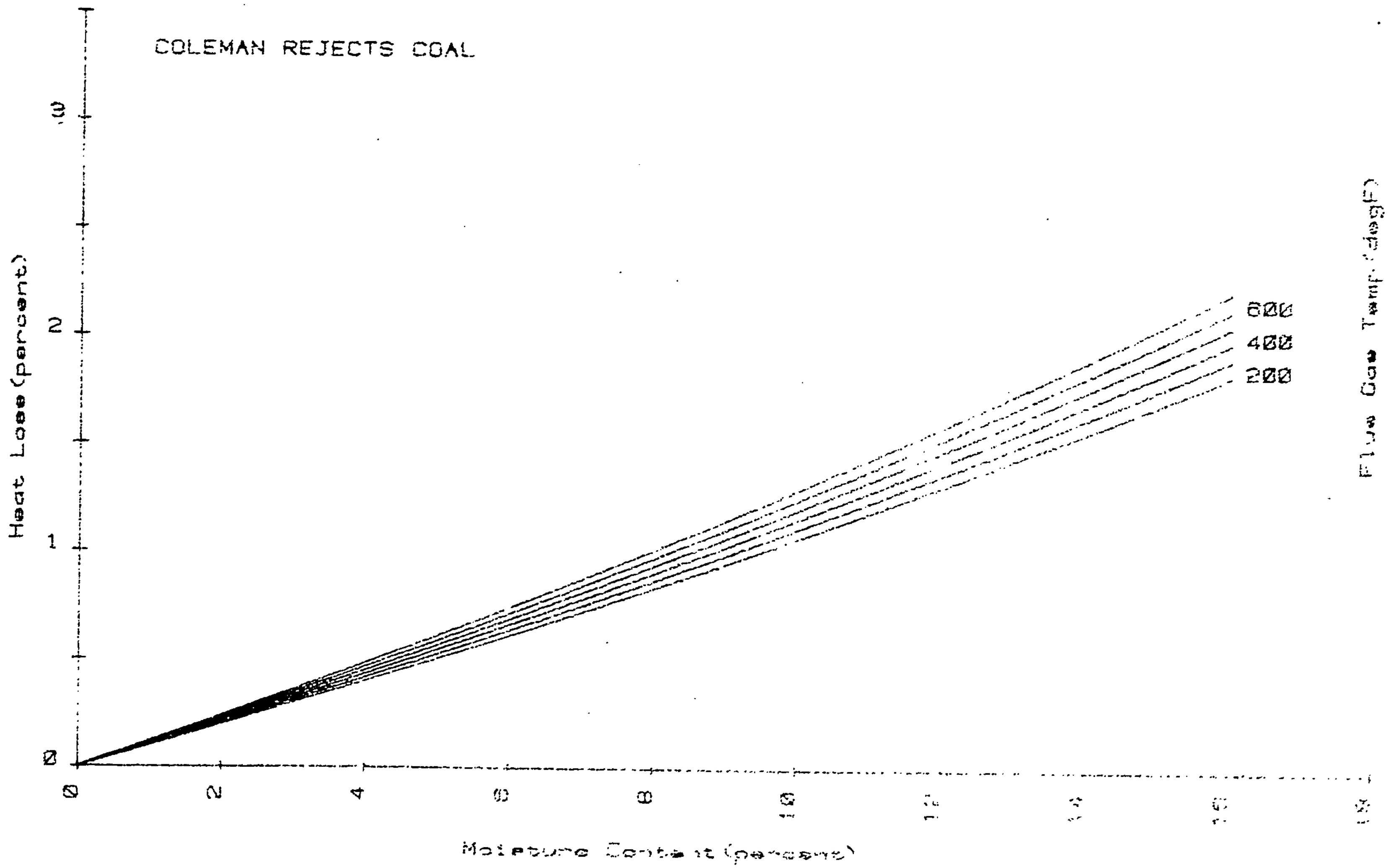

Fig. 5A - Heat loss due to moisture in coal at 70°F

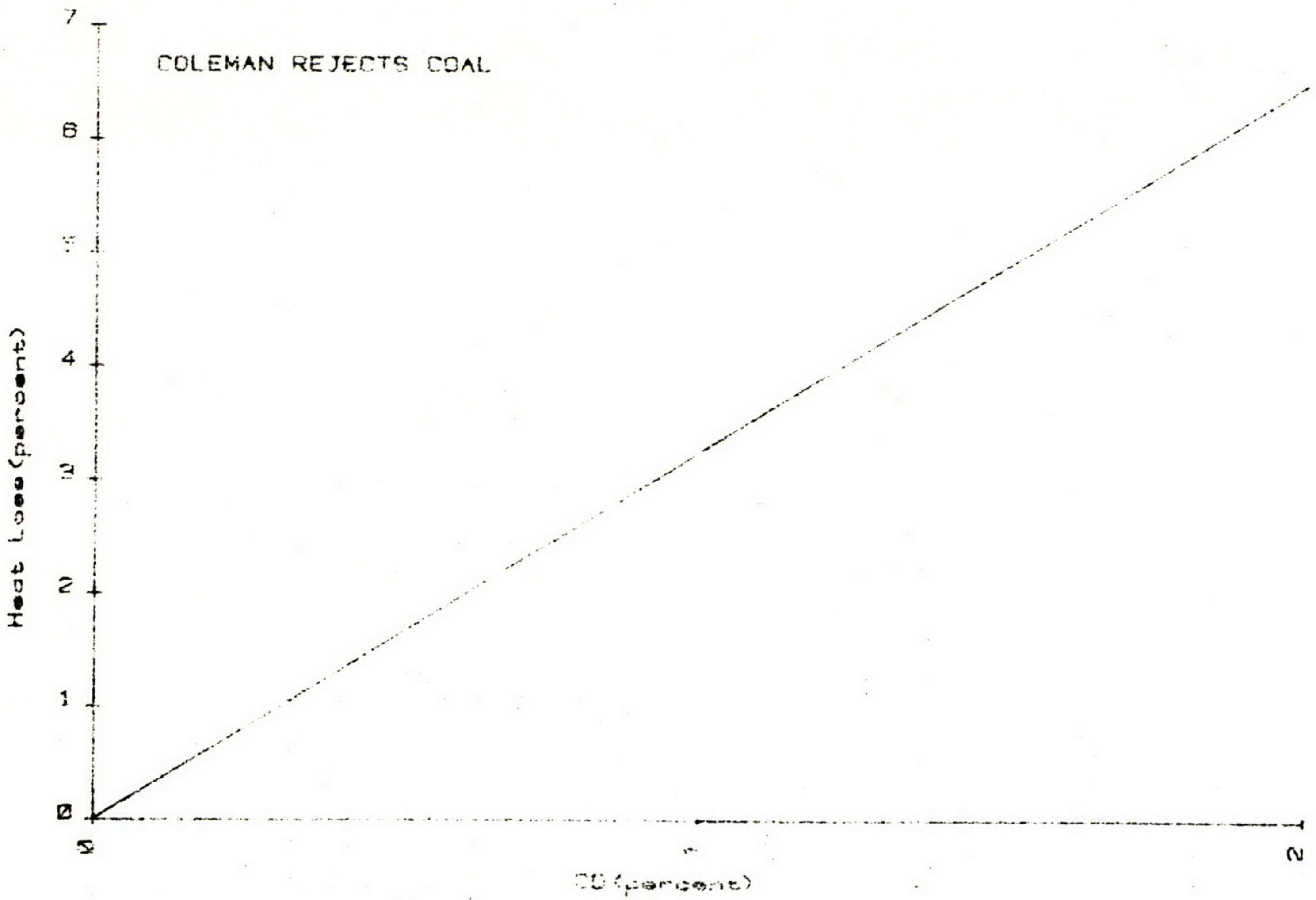

Fig. 6A - Heat loss for a range of CO concentrations, assuming negligible excess air