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BURNER DESIGN CRITERIA FOR CONTROL OF NO_x FROM NATURAL GAS COMBUSTION

Volume II

Raw Data and Experimental Results

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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BURNER DESIGN CRITERIA FOR CONTROL OF NO_x FROM NATURAL GAS COMBUSTION

VOLUME II. RAW DATA AND EXPERIMENTAL RESULTS

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ABSTRACT

Volume II gives a complete discussion of the procedure used to select the test burners. Included also are detailed flame characterizations of base-line operations assembled from in-the-flame temperature, gas species, and flow direction data analysis. Similar in-the-flame studies were made for control conditions which minimized emissions for each burner type. All raw data collected from the input-output trials are also included.

A companion publication, Volume I of this final report, gives a detailed presentation and analysis of trials conducted with natural gas to determine the relationship between combustion aerodynamics and pollution emission characteristics of industrial burners. Three types of burners were studied (kiln, ported baffle, and movable-vane boiler) based on their relative gas load and estimated total industrial emissions. Experimental measurements carried out on a pilot-scale furnace included a baseline characterization of each burner and variation of primary operating parameters (air preheat, air/fuel ratio, firing rate, heat-release rate, position of gas nozzle in burner block, and air swirl intensity). Additional emissions data were gathered for suspected control conditions (fuel injector design, flue gas recirculation, fuel/air momentum ratio, and burner block angle). This volume also contains a detailed description of the experimental facility and sampling probes used to collect the data.

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BURNER SELECTION

METHODOLOGY OF ANALYSIS

In order to select three distinctly different type of burners to be investigated, a classification system was developed which would categorize a burner type by its combustion and heat-release characteristics. The relative gas loads for each of these burner types were determined from gas consumption statistics by industrial process and by an assessment of the dominant burner type used for each process. The assessment of the predominant burner type by industrial process came from industrial burner manufacturers. The gas load statistics by industrial process were available in American Gas Association publications and from nonproprietary gas supply and utilization studies conducted by IGT.

Obtaining relative NO_x emission rates by burner type was extremely difficult because of the lack of published data over the broad range of industries covered. Therefore, each of the industrial processes was assigned into one of three categories of NO_x emission levels. It was assumed that the high emission processes emitted 0. 5 lb/million Btu; intermediate emission processes, 0. 25 lb/million Btu; and low emission processes, only 0. 05 lb of NO_x/million Btu of fuel consumed. Obviously, very few processes and burner types produce exactly the quantity of NO_x of the group into which they were placed. However, for the purposes of this program evaluation, this method provides a sufficiently good relative measure of the contribution of each burner type to the national NO_x emission problem.

Each industrial processes and burner type was placed in the appropriate category based on available literature data or based on our expertise in the area of NO_x emissions developed by the field testing of burners and the testing of scaled industrial burners in our laboratory. This latter method was coupled with our knowledge of the firing rate, heat-release pattern, percent excess air, and average temperature of the industrial process. We therefore have data on the total gas load/yr and on the NO_x emission rate in lb/million Btu for each type of burner.

DISCUSSION

Burner Classification

The first step in this program was to classify burners by combustion characteristics. Product information from several of the manufacturers was consulted for the combustion-heat release characteristics. We determined that all burners could be grouped into one of seven classifications: 1) nozzle mix, nozzle premix, premix; 2) register; 3) flat flame (high intensity); 4) delayed mixing; 5) non-premix gas momentum controlled; 6) non-premix swirl; and 7) other, which includes burners of very specialized applications, such as those used in blast stoves.

Premix Burners — In the premixing type of gas burner, the primary air and gas are mixed at some point upstream from the burner ports. The mixing can be accomplished by use of an inspirator mixer, an aspirator mixer, or a fan mixer. When premixers are used, the burner serves only as a flame holder, maintaining the flame in the desired location. The cool burner port is used to stabilize the flame.

Nozzle-Mixing Burners — The nozzle-mixing gas burner keeps the gas and combustion air separated within the burner itself. The nozzle orifices are designed so as to provide rapid mixing of the fluids as they leave the burner. This burner type can supply gas through the center nozzle and air through an annular orifice around it, or supply air through the center.

Delayed-Mixing Burners — The delayed-mixing burner, usually used for radiant tube firing, injects low-velocity, nonturbulent parallel and adjacent air and gas streams into the combustion chamber. This provides a low mixing rate, which results in a long flame, because mixing occurs only along the interface between the parallel gas and air streams. If the burner is arranged so as to inject a central core of gas completely surrounded by an annular air stream, the combustion which occurs at the air-gas interface will radiate heat to the gas stream, causing it to crack (gaseous hydrocarbons being reduced to free carbon and hydrogen) and produce luminous carbon particles.

Radiant tubes are made of expensive alloys or ceramic materials, so it is important that no part of the tube is damaged by overheating; however, it is also important that every inch of their length be utilized to fullest advantage. This requires that the flame within the tube must release its heat at a uniformly high rate throughout the tube length. A delayed mixing flame accomplishes most of this requirement, except that it is rather slow in getting started. To avoid a wasteful cool section at the burner end of the tube, a partial premix is incorporated into the burner. This produces a flue flame for about the first foot of the tube length, until the luminous flame develops.

Flat-Flame Burners — When penetration of the flame and hot combustion gases is not desired, a flat-flame may be used. The radial-flame burner is a nozzle mixing type which injects the gas at a very small axial velocity, and the combustion air has a maximum tangential velocity component. The air flow thus adheres stably to the divergent burner block. A radial flame is produced which heats its own refractory tile and the refractory surface of the surrounding furnace wall or roof by convection. These hot refractory surfaces then radiate heat to the furnace load.

Swirl Burners — The non-premix swirl burner combustion characteristics can be varied from that of a nozzle-mixing to a delayed-mixing type of burner by varying the velocity components of the combustion air. The gas is injected along the axis of the burner, with the combustion air introduced through an annular orifice around it. The velocity of the air is composed of an axial and a tangential component.

Register Burners — The register burner is typically used in boilers, with the air entering through a register of guide vanes, which allows a variation in the magnitude of the axial and tangential velocity components. The gas is introduced either through a gun or ring nozzle. In the gun nozzle, there is a pipe which is concentric with the axis of the burner. The end of the pipe is plugged, and radial holes are drilled near the end to allow the gas to have a diverging velocity component. The ring nozzle is shaped like a donut with holes drilled on the inside edge of the ring. Therefore, the gas will have a converging radial velocity component.

The relative gas loads of each burner type are determined from gas consumption statistics (Table 1) by industrial process and by an assessment of the predominant burner type used for each industrial process. In some processes, more than one burner type may be used; in these cases, an additional breakdown of burner types used in any one industrial process was determined by rationing the number of each burner type sold for that process. The number of burners, by type, for a particular application was made available by the manufacturers. The gas load statistics by industrial process, as presented in Table 1, were gathered from publications of the American Gas Association and partly from non-proprietary gas supply and utilization studies conducted by IGT.

NO_x Emissions Classification

The data relating NO_x emission rates to burner types or industrial processes are relatively sparse. Therefore, to evaluate NO_x emissions by burner type, a relative NO_x emission rate had to be developed. From literature and the experimental work completed under EPA Contract No. 68-02-0216, we are able to make accurate estimates of the emissions from flat-flame, utility boilers and non-premix swirl burners. This, coupled with our experience in field testing gas-momentum-controlled non-premix burners, helped in making estimates for pollution emissions from industrial processes for which no data had been published. Because of the difficulty in obtaining absolute numbers, the NO_x emissions in lb/million Btu have been ranked into three relative categories: low, $\simeq$ 0.05 lb/million Btu; intermediate, $\simeq$ 0.25 lb/million Btu; and high, $\simeq$ 0.5 lb/million Btu.

Industrial Processes and Relative NO_x Emissions

The list of industrial processes included in Table 1 represents over 65% of the total industrial gas consumption in 1971. The remaining 35% was almost all used as feedstock. This listing also represents industries which consumed over 63% of the total U.S. energy for the same year. Each of the remaining industries consumed less than 1.3% of the total U.S. energy, with the exception of motor vehicles, which used 1.96%; however, this latter category is not applicable to our program.

Table 1. NATIONAL NATURAL GAS CONSUMPTION AND NO_x DATA BY PROCESS AND BURNER TYPE

Industrial Process	Burner Type: Nozzle Mix Nozzle Premix Premix (10^{12} Btu/yr)	Register	Flat Flame (High Intensity)	Burner Type, Delayed Mix	Non-premix: Gas Momentum Controlled	Non-premix: Swirl	Other	NO_x, lb/10^6 Btu†	Total NO_x, 10^6 lb/yr
Ironmaking									
Pelletizing	--	--	--	--	--	20.3	--	0.25	5.1
Coke Oven				Not natural gas					
Blast Furnace (injection)				Not applicable			37.4	High‡	--
Blast Air Stoves	--	--	--	--	--	--	18.0	0.25	4.5
Direct Reduction				Not applicable			19.2	0.05	1.0
Sintering	--	--	--	--	--	--	3.1	0.05	0.2
Steelmaking									
Basic Oxygen Furnace				Not applicable			15.8	0.50	7.9
Open Hearth	--	--	--	--	47.6	--	--	0.50	23.8
Electric Arc				Not applicable					
Scrap Preheat				Not available					
Ladle Heating	3.6	--	--	--	--	--	--	0.05	0.2
Soaking Pits	--	--	--	--	--	49.2	--	0.25	12.3
Slab, Bloom, and Billet Heaters	--	--	--	--	--	150.0	--	0.50	75.0
Annealing	--	--	17.0	17.0	--	--	--	0.05	1.7
Hardening	2.5	--	--	2.5	--	--	--	0.25	1.3
Carbon Control	--	--	--	2.0	--	--	--	0.05	0.1
Boilers	--	260.0	--	--	--	--	--	0.50	130.0
Foundries									
Cupolas	--	--	--	--	--	--	47.0	0.25	11.8
Electric Melting				Not applicable					
Ladle Heating				Nil					
Mold Heating				Nil					
Heat Treating	8.1	--	--	2.7	--	--	--	0.20	2.2
Space Heating				Not applicable					
Forging									
Forging and Annealing	121.5	--	40.5	--	--	--	--	0.20	32.4
Boilers				Not applicable					
Space Heating				Not applicable					
Finishing									
Plating				Nil					
Galvanizing	5.9	--	4.0	--	--	--	--	0.05	0.4
Glassmaking									
Melting	--	--	--	--	225.0	--	--	0.5	112.5
Annealing Lehrs	21.0	--	--	--	--	--	--	0.05	1.1
Cement									
Drying and Calcination	--	--	--	--	480.0	--	--	0.5	240.0
Lime									
Calcination	--	--	--	--	33.3	--	--	0.5	16.7

Table 1, Cont. NATIONAL NATURAL GAS CONSUMPTION AND NO_x DATA BY PROCESS AND BURNER TYPE

Industrial Process	Burner Type: Nozzle Mix Nozzle Premix Premix (10^{12} Btu/yr)	Register	Flat Flame (High Intensity)	Burner Type, Delayed Mix	Non-premix: Gas Momentum Controlled	Non-premix: Swirl	Other	NO_x, lb/10^6 Btu†	Total NO_x, 10^6 lb/yr
Ceramics									
Bricks	63.9	--	--	--	--	--	--	0.25	16.0
Paper									
Pulping and Papermaking	--	349.8	--	--	--	--	--	0.5	174.9
Aluminum									
Drying	--	--	--	--	81.9	--	--	0.50	41.0
Reduction				Not applicable					
Primary and Secondary Melting	16.8	--	--	--	--	--	--	0.50	8.4
Reheat	12.0	--	--	--	--	--	--	0.25	3.0
Copper and Brass									
Roasting	1.5	--	--	--	--	--	--	0.25	0.4
Smelting	--	--	--	--	27.9*	--	--	0.25	7.0
Refining	--	--	--	--	0.6	--	--	0.25	0.2
Melting Cathodes	6.1	--	--	--	--	--	--	0.25	1.5
Secondary Melting	2.0	--	--	--	--	--	--	0.25	0.5
Reheating	1.5	--	--	--	--	--	--	0.25	0.4
Lead									
Sintering	1.1	--	--	--	--	--	--	0.05	0.1
Roasting	0.6	--	--	--	--	--	--	0.25	0.2
Blast Furnace				Not applicable					
Refining	3.7	--	--	--	--	--	--	0.25	0.9
Zinc									
Roasting	0.7	--	--	--	--	--	--	0.05	--
Sintering	0.3	--	--	--	--	--	--	0.05	--
Blast Furnace				Not applicable					
Smelting	14.4	--	--	--	--	--	--	0.25	3.6
Refining	2.4	--	--	--	--	--	--	0.25	0.6
Food	--	34.6	--	--	--	--	--	0.5	17.3
Chemical									
Boilers	--	487.0	--	--	--	--	--	0.5	243.5
Feedstock				Not applicable					
Electrolysis				Not applicable					
Process Heat	49.6	--	16.4	--	--	--	--	0.05	3.3
Petroleum									
Process Heat	225.0	--	75.0	--	--	--	--	0.05	15.0
Boilers	--	439.0	--	--	--	--	--	0.50	219.5
Textiles	--	60.0	--	--	--	--	--	0.5	30.0
Rubber	--	23.1	--	--	--	--	--	0.5	11.6
Plastic	--	8.9	--	--	--	--	--	0.5	4.5
Total Gas Consumption	564.2	1662.4	152.9	24.2	896.3	219.5	139.9	--	--
Total NO_x, 10^6 lb/yr	84.3	831.2	7.6	1.4	441.0	92.4	11.9	--	--

* Older installations use an inspirated burner which is gas momentum controlled; however, newer facilities have been installing large nozzle-mixing burners similar to those used in aluminum melters.

† NO_x Categories: Low, ≃0.05 lb/10^6 Btu; Intermediate, ≃0.25 lb/10^6 Btu; High, ≃0.5 lb/10^6 Btu.

‡ Total process emissions are high. However, emissions are primarily caused by the injection of hot blast air. The contribution from hydrocarbon injection is very small.

CONCLUSIONS

The results of this evaluation are the identification of the predominate burner type associated with each of the many fuel-consuming industrial processes, a relative measure of the total national NO_x emissions by burner type, and the selection of three burners for study in this program based on the highest national NO_x emission levels.

There are eight burner types identified by combustion characteristics. These are shown in Table 2, along with the total national (estimated) NO_x emission levels established by this study. The three burners selected for further experimental study are the 1) register burner, 2) the non-premix gas-momentum-controlled burner, and 3) the non-premix swirl burner. These burners contribute significantly more NO_x to the national environment than any of the others shown. The nozzle mix, nozzle premix, and fuel premix burners were grouped together because they are very often used interchangeably by industry and therefore are difficult to evaluate separately in terms of their NO_x emissions.

The last category in Table 2, shown as "other," is made up of many burner types, usually of a very specialized design or application. Any one of these burners contributes very little NO_x.

The three burners selected for further study may be more easily recognized by their trade descriptions and applications. The register burner is the typical design used on utility power boilers and large industrial boilers. The non-premix gas-momentum-controlled burner is more commonly called a kiln burner and is used in open hearth steel furnaces, glass melting, cement kilns, lime kilns, aluminum ore drying, and non-ferrous smelting furnaces. The non-premix swirl burner is sometimes called a "baffle" burner or "large capacity" burner. It is the typical design used in steel soaking pits, steel reheat furnaces, and other material heating processes requiring temperatures up to about 2500°F.

Table 2. BASIC BURNER TYPES AND NATIONAL NO_x EMISSION LEVELS

	Burner Type	NO_x Emissions, 10^6 lb/yr
1.	Nozzle Mix Nozzle Premix Full Premix	84.3
2.	Register Burner	831.2*
3.	Flat Flame	7.6
4.	Delayed Mixing	1.4
5.	Non-Premix Gas Momentum Controlled	441.0*
6.	Non-Premix Swirl	92.4*
7.	Other	11.9

* Burners selected for further study in this research program.

IN-THE-FLAME ANALYSIS

Detailed in-the-flame data were collected for baseline and NO control operating conditions. These data are to aid in quantitative modeling of large-scale turbulent diffusion flames and provide a qualitative guide in understanding how control techniques reduce NO levels. The measurements included gas species concentrations, temperature and flow direction.

Each data set is presented in a format similar to the baseline operating conditions of the kiln burner. Table 3 lists the furnace conditions at which in-the-flame probing data were collected. This table contains a data identification header, the gas input (SCFH), the furnace wall temperature (Deg. C), the secondary combustion air preheat temperature (Deg. C), the percentage of flue gas recirculation, and a gas sample analysis taken in the flue for the listed furnace conditions. Listed next are concentration limits to be used for the ordinates of each gas species to be mapped. Iso-concentration plots of NO and NO_2 and an isothermal plot are standard printout items. The concentrations and temperatures for which these profiles will be drawn are listed next.

The raw data collected as a function of axial sampling position are listed in Tables 4 through 8. The radial position (cm) where the data were collected is listed first, followed by the gas species for which the sample was analyzed. Because of the time involved in using the chromatograph to analyze gas samples (approximately 45 minutes), only selected samples are analyzed for all the chemical components listed in the tables. Samples which have not been analyzed for a certain component have a question mark (?) listed for the concentration of that component. The criterion for a chromatographic analysis of a gas sample is based on the carbon monoxide concentration. If the concentration measured by a nondispersive infrared analyzed is greater than 0.5%, then a chromatographic analysis is made. If the concentration is less than 0.5%, the gas sample is only analyzed for oxygen, carbon monoxide, carbon dioxide, methane, nitric oxide, and nitrogen dioxide.

Table 3. KILN BURNER IN-THE-FLAME SAMPLING CONDITIONS WITHOUT FLUE GAS RECIRCULATION

KILN BURNER - COMBINATION NOZZLE JULY 31,1974

NUMBER OF SETS OF DATA = 5.
MINIMUM GRID VALUE OF AVERAGE TEMPERATURE = 500. DEG.C
MAXIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1700. DEG.C

POSITION OF OUTSIDE EDGES OF BURNER BLOCK
MINIMUM POSITION = -18. CM
MAXIMUM POSITION = 18. CM

GAS INPUT, AXIAL 876. CF/HR RADIAL 1830. CF/HR
WALL TEMPERATURE 1362. DEG.C
PREHEAT TEMPERATURE 460. DEG.C
FLUE GAS RECIRCULATION 0.0 %

GAS SAMPLE ANALYSIS IN THE FLUE

NITROGEN OXIDE	265.0 PPM
NITROGEN DIOXIDE	36.0 PPM
OXYGEN	3.1 %
CARBON DIOXIDE	10.0 %
CARBON MONOXIDE	.0365 %

LIMITS FOR CONCENTRATION PLOTS

LOWER LIMIT OF NO =	0. PPM	UPPER LIMIT = 300. PPM
LOWER LIMIT OF NO2 =	0. PPM	UPPER LIMIT = 50. PPM
LOWER LIMIT OF O2 =	0. %	UPPER LIMIT = 21. %
LOWER LIMIT OF CH4 =	0. %	UPPER LIMIT = 29. %
LOWER LIMIT OF CO2 =	0. %	UPPER LIMIT = 11. %

ISOCONCENTRATION VALUES

OBTAIN VALUE OF RADIAL POSITION AT NO PPM CONCENTRATION	100.	150.	200.	250.	275.
OBTAIN VALUE OF RADIAL POSITION AT NO2 PPM CONCENTRATION	10.	20.	30.	40.	

Table 4. KILN BURNER IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 5.1 cm

KILN BURNER - COMBINATION NOZZLE JULY 31,1974

AXIAL POSITION = 5.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	5.5	?	255.	34.	8.5	.0041	?	?	?	?	?	?	1328.	1332.	4.
-48.	5.7	?	245.	29.	8.6	.0040	?	?	?	?	?	?	1325.	1334.	9.
-36.	6.4	?	265.	22.	8.4	.0040	?	?	?	?	?	?	1321.	1328.	7.
-30.	6.8	?	245.	27.	8.1	.0038	?	?	?	?	?	?	1270.	1311.	41.
-27.	8.2	?	245.	24.	7.8	.0034	?	?	?	?	?	?	1256.	1291.	35.
-24.	11.8	?	180.	17.	5.3	.0028	?	?	?	?	?	?	1072.	1109.	37.
-18.	19.9	?	3.	0.	.1	.0021	?	?	?	?	?	?	605.	609.	4.
-15.	19.7	?	2.	0.	.1	.0021	?	?	?	?	?	?	581.	592.	11.
-12.	20.2	?	2.	0.	0.0	.0019	?	?	?	?	?	?	576.	600.	24.
-9.	19.2	?	5.	0.	.4	.0200	?	?	?	?	?	?	646.	721.	75.
-6.	12.2	78.6	15.	26.	3.7	1.5000	1.5	2.0	.3	.1	0.0	0.0	1216.	1357.	141.
-3.	11.1	60.2	10.	8.	1.8	2.3000	3.8	18.1	.6	.8	0.0	1.2	1072.	1127.	55.
0.	12.8	55.3	8.	2.	.8	.5000	.4	28.4	.1	1.3	.4	0.0	825.	834.	9.
3.	11.9	56.7	6.	5.	1.1	.9000	1.2	20.8	.3	1.0	0.0	6.1	1084.	1166.	82.
6.	10.8	60.4	14.	29.	3.7	4.7000	5.3	11.3	1.1	.5	2.1	.1	1437.	1484.	47.
12.	18.9	?	7.	3.	.5	.0056	?	?	?	?	?	?	721.	791.	70.
18.	19.5	?	5.	0.	.3	.0020	?	?	?	?	?	?	664.	709.	45.
20.	20.4	?	7.	5.	.1	.0016	?	?	?	?	?	?	656.	768.	112.
24.	19.9	?	12.	8.	.4	.0010	?	?	?	?	?	?	778.	936.	158.
36.	4.1	?	225.	22.	10.2	.0040	?	?	?	?	?	?	1364.	1374.	10.

Table 5. KILN BURNER IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 26.0 cm

KILN BURNER - COMBINATION NOZZLE JULY 31,1974

AXIAL POSITION = 26.0 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	8.4	?	250.	22.	7.2	.0024	?	?	?	?	?	?	1291.	1339.	48.
-50.	9.1	?	225.	18.	6.9	.0023	?	?	?	?	?	?	1273.	1336.	63.
-45.	9.3	?	230.	16.	6.8	.0021	?	?	?	?	?	?	1221.	1302.	81.
-40.	10.7	?	190.	13.	5.8	.0015	?	?	?	?	?	?	1183.	1291.	108.
-30.	14.3	?	140.	8.	3.6	.0011	?	?	?	?	?	?	994.	1144.	150.
-20.	19.1	?	35.	2.	.8	.0008	?	?	?	?	?	?	728.	933.	205.
-10.	15.5	79.9	48.	16.	2.6	.6000	.5	.2	.1	.6	0.0	0.0	1306.	1405.	99.
-5.	6.4	64.0	11.	35.	3.5	5.0000	6.4	11.2	1.2	.5	1.2	.6	1232.	1295.	63.
0.	13.7	56.3	6.	13.	1.2	2.4000	3.1	21.3	.7	.9	0.0	.4	945.	1022.	77.
5.	6.1	63.6	10.	30.	3.2	5.2000	7.7	12.3	1.3	.5	0.0	.1	1441.	1463.	22.
10.	11.6	78.9	85.	50.	4.9	1.7000	1.5	.9	.5	0.0	0.0	0.0	1300.	1429.	129.
20.	15.9	?	75.	13.	4.0	.0015	?	?	?	?	?	?	1008.	1191.	183.
25.	16.9	?	112.	15.	4.4	.0021	?	?	?	?	?	?	1102.	1284.	182.
30.	13.5	?	150.	21.	5.3	.0025	?	?	?	?	?	?	1188.	1292.	104.
40.	10.1	?	200.	23.	6.9	.0025	?	?	?	?	?	?	1331.	1355.	24.

Table 6. KILN BURNER IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 57.2 cm

KILN BURNER - COMBINATION NOZZLE JULY 31,1974

AXIAL POSITION = 57.2 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	9.5	?	235.	24.	7.0	.0022	?	?	?	?	?	?	1325.	1383.	58.
-56.	9.1	?	215.	23.	7.2	.0027	?	?	?	?	?	?	1315.	1382.	67.
-48.	9.6	84.1	195.	20.	6.3	.0043	0.0	0.0	0.0	0.0	0.0	0.0	1270.	1373.	103.
-36.	11.2	?	155.	15.	5.7	.0051	?	?	?	?	?	?	1213.	1301.	88.
-24.	13.4	?	160.	12.	4.3	.0098	?	?	?	?	?	?	1253.	1377.	124.
-18.	11.8	81.6	170.	18.	5.4	.5000	.3	.3	0.0	.1	0.0	0.0	1389.	1517.	128.
-12.	4.7	81.6	180.	33.	5.7	2.6000	3.2	.3	.1	1.8	0.0	0.0	1520.	1586.	66.
-11.	3.4	78.1	168.	31.	6.6	4.2000	5.1	1.2	.3	1.1	0.0	0.0	1503.	1544.	41.
-10.	3.7	79.5	157.	29.	6.4	4.1000	5.0	1.0	.3	0.0	0.0	0.0	1473.	1526.	53.
-9.	2.2	75.7	130.	27.	6.0	5.9000	7.6	2.0	.6	0.0	0.0	0.0	1414.	1465.	51.
-6.	2.0	68.5	60.	27.	4.5	7.6000	10.2	5.2	1.3	0.0	.7	0.0	1294.	1329.	35.
-3.	3.4	63.7	30.	24.	3.6	7.1000	10.5	9.0	1.7	.2	.6	.2	1223.	1282.	59.
0.	4.0	62.9	20.	24.	3.1	6.6000	10.0	10.4	1.7	.3	.7	.3	1282.	1312.	30.
3.	3.1	64.5	25.	25.	3.8	7.2000	10.3	8.1	1.6	.2	.9	.3	1429.	1488.	59.
6.	1.9	69.1	70.	22.	5.1	7.0000	11.6	4.1	1.1	.1	0.0	0.0	1507.	1583.	76.
9.	2.4	77.8	138.	22.	6.5	4.9000	6.3	1.6	.5	0.0	0.0	0.0	1539.	1593.	54.
12.	5.9	81.8	155.	22.	7.0	2.1000	2.5	.6	.1	0.0	0.0	0.0	1457.	1516.	59.
15.	8.8	83.2	175.	18.	6.8	.7000	.1	.4	0.0	0.0	0.0	0.0	1344.	1433.	89.
20.	9.8	83.9	160.	19.	6.3	.0444	0.0	0.0	0.0	0.0	0.0	0.0	1288.	1386.	98.
24.	10.4	?	150.	18.	6.2	.0041	?	?	?	?	?	?	1273.	1370.	97.
28.	10.0	?	143.	18.	6.4	.0011	?	?	?	?	?	?	1331.	1397.	66.
31.	9.5	?	144.	20.	6.7	.0024	?	?	?	?	?	?	1328.	1382.	54.
35.	8.3	?	160.	20.	7.3	.0025	?	?	?	?	?	?	1325.	1391.	66.
38.	7.4	?	158.	19.	7.8	.0031	?	?	?	?	?	?	1361.	1393.	32.
40.	7.1	?	153.	23.	7.9	.0028	?	?	?	?	?	?	1331.	1377.	46.

Table 7. KILN BURNER IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 146.1 cm

KILN BURNER - COMBINATION NOZZLE JULY 31,1974

AXIAL POSITION = 146.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.8	?	220.	49.	9.1	.0191	?	?	?	?	?	?	1481.	1506.	25.
-55.	5.1	?	215.	48.	8.8	.0311	?	?	?	?	?	?	1477.	1508.	31.
-50.	4.5	?	233.	47.	9.3	.0488	?	?	?	?	?	?	1477.	1514.	37.
-45.	4.9	?	228.	44.	9.1	.1000	?	?	?	?	?	?	1498.	1531.	33.
-35.	4.6	?	240.	44.	9.0	.3000	?	?	?	?	?	?	1539.	1578.	39.
-25.	2.2	84.7	230.	41.	9.3	2.3000	1.5	0.0	0.0	0.0	0.0	0.0	1577.	1641.	64.
-20.	1.6	?	255.	34.	8.7	3.3000	?	.3	?	?	?	?	1592.	1635.	43.
-15.	.6	80.3	230.	28.	7.6	5.6000	5.1	.7	.1	0.0	0.0	0.0	1572.	1629.	57.
-10.	.5	75.5	180.	24.	7.0	6.6000	9.7	.6	.1	0.0	0.0	0.0	1553.	1636.	83.
0.	.6	75.7	180.	20.	6.9	7.0000	8.7	1.0	.1	0.0	0.0	0.0	1572.	1625.	53.
5.	1.3	78.5	210.	26.	7.8	5.4000	6.2	.7	.1	0.0	0.0	0.0	1597.	1641.	44.
10.	2.6	80.6	240.	31.	8.4	3.6000	4.0	.8	0.0	0.0	0.0	0.0	1591.	1649.	58.
15.	4.0	84.3	200.	29.	8.5	1.6000	1.6	0.0	0.0	0.0	0.0	0.0	1562.	1633.	71.
20.	6.2	84.7	205.	33.	7.9	.6000	.6	0.0	0.0	0.0	0.0	0.0	1520.	1602.	82.
23.	6.7	?	202.	34.	7.8	.4000	?	?	?	?	?	?	1448.	1509.	61.
26.	7.5	?	188.	37.	7.8	.2000	?	?	?	?	?	?	1429.	1500.	71.
30.	7.1	?	180.	39.	7.8	.0576	?	?	?	?	?	?	1399.	1456.	57.
36.	7.6	?	173.	34.	7.4	.0280	?	?	?	?	?	?	1389.	1433.	44.

Table 8. KILN BURNER IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 385.4 cm

KILN BURNER - COMBINATION NOZZLE JULY 31,1974

AXIAL POSITION = 385.4 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	3.4	?	285.	47.	9.8	.1000	?	?	?	?	?	?	1567.	1592.	25.
-50.	3.0	?	267.	46.	10.0	.2000	?	?	?	?	?	?	1572.	1608.	36.
-40.	2.9	?	275.	46.	9.9	.4000	?	?	?	?	?	?	1602.	1602.	0.
-30.	2.7	?	276.	48.	10.1	.2000	?	?	?	?	?	?	1587.	1604.	17.
-20.	2.7	?	281.	40.	10.0	.4000	?	?	?	?	?	?	1597.	1612.	15.
-10.	2.7	?	283.	40.	9.9	.3000	?	?	?	?	?	?	1587.	1602.	15.
0.	3.1	?	288.	40.	9.8	.3000	?	?	?	?	?	?	1577.	1608.	31.
10.	3.2	?	276.	33.	9.8	.1000	?	?	?	?	?	?	1557.	1601.	44.
20.	3.2	?	294.	38.	9.6	.4000	?	?	?	?	?	?	1548.	1580.	32.
25.	3.4	?	276.	36.	9.9	.0585	?	?	?	?	?	?	1534.	1548.	14.
30.	3.3	?	281.	33.	9.8	.0540	?	?	?	?	?	?	1534.	1558.	24.
35.	3.6	?	253.	37.	9.7	.0449	?	?	?	?	?	?	1516.	1544.	28.
40.	3.6	?	258.	17.	9.7	.0675	?	?	?	?	?	?	1516.	1545.	29.

Listed next in the tables are the measured temperature. We wanted to use a fast-response thermocouple for temperature measurements, because we believe that the key to determining the location of pollutant formation in the flame may be directly related, not to the highest time-averaged temperature, but to the highest instantaneous temperature, which may have a duration of only a few milliseconds. In order to decrease the response time of our temperature probe to 1 millisecond, we must electronically compensate our thermocouple. Although we have been experimenting with electronic compensators, we have only been able to increase the response time by a factor of 10. Further improvements have been difficult because of the interference caused by stray high-frequency signals. This problem can be overcome, but not without additional design work. We used subminiature thermocouples during data collection on the kiln burner. The lifetime of the couple was less than 3 minutes, making continuous data collection impossible. Thus, we returned to using a shielded suction pyrometer identical to the one used in EPA Contract No. 650/2-73-033a and described in Volume I of this report.

Figures 1 through 34 present plots of nitric oxide, nitrogen dioxide, oxygen, methane, carbon dioxide, composite gases, temperature, and flow direction versus radial position. In these figures, the two dotted parallel lines perpendicular to the abscissa represent space projections of the burner-block edges into the furnace chamber.

Figures 35, 36, and 37 are isothermal and isoconcentration plots of the data presented in the preceding tables. These figures were prepared as a useful tool in visualizing flame development patterns and to permit a comparison of flame and emission profiles for different burner and flame types.

KILN BURNER

In-the-flame probings for the kiln burner were conducted with two different operating conditions. The baseline flame data were collected with a fuel/air momentum ratio similar to that found in industry. Control-case data were gathered from a flame whose NO flue emission level had been reduced by 61% with a 12% by total volume addition of flue products to the secondary combustion air. Both of these flames displayed a Type I directional flow profile.

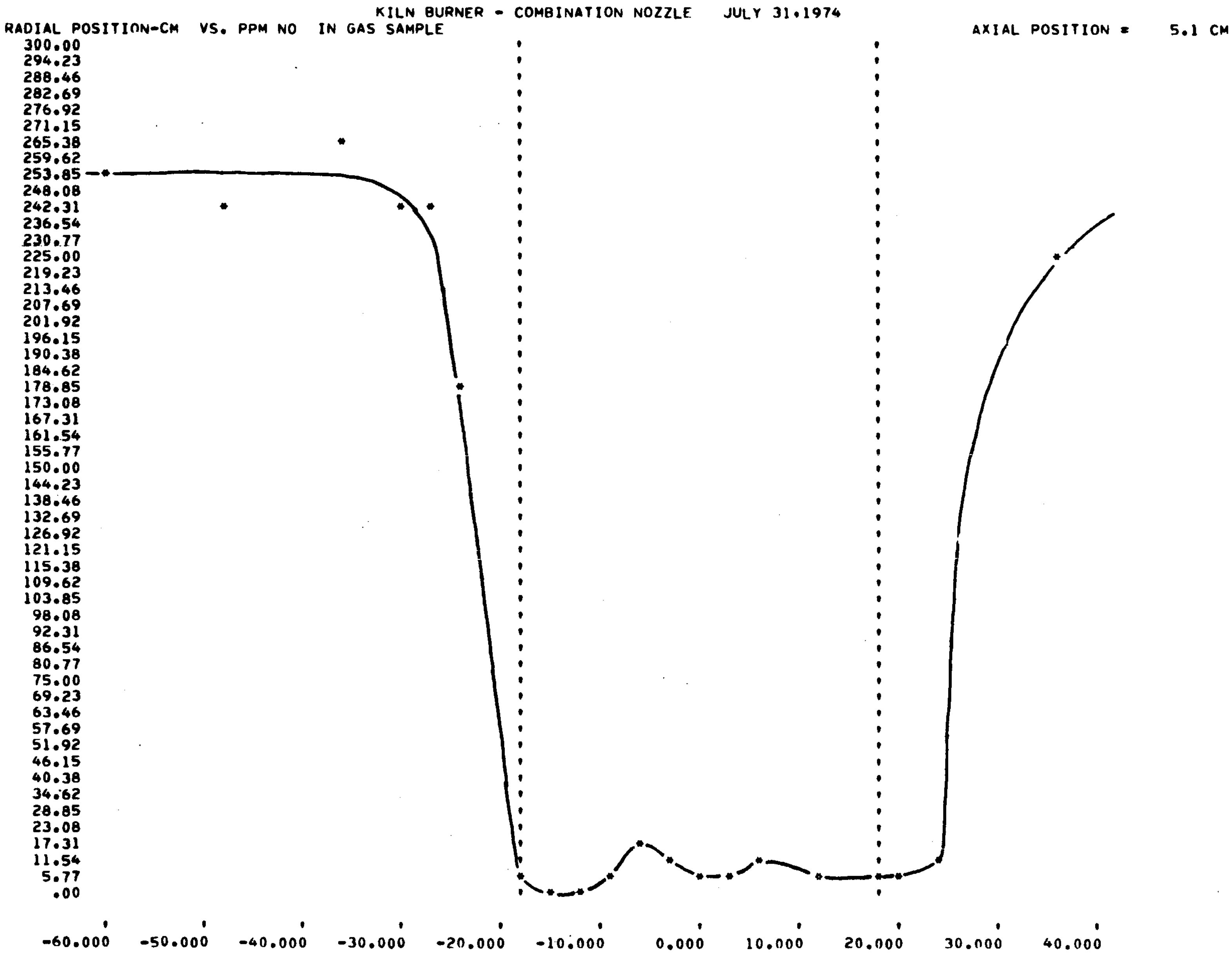

Figure 1. Combination kiln burner nozzle — radial profile of NO at an axial position of 5. 1 cm

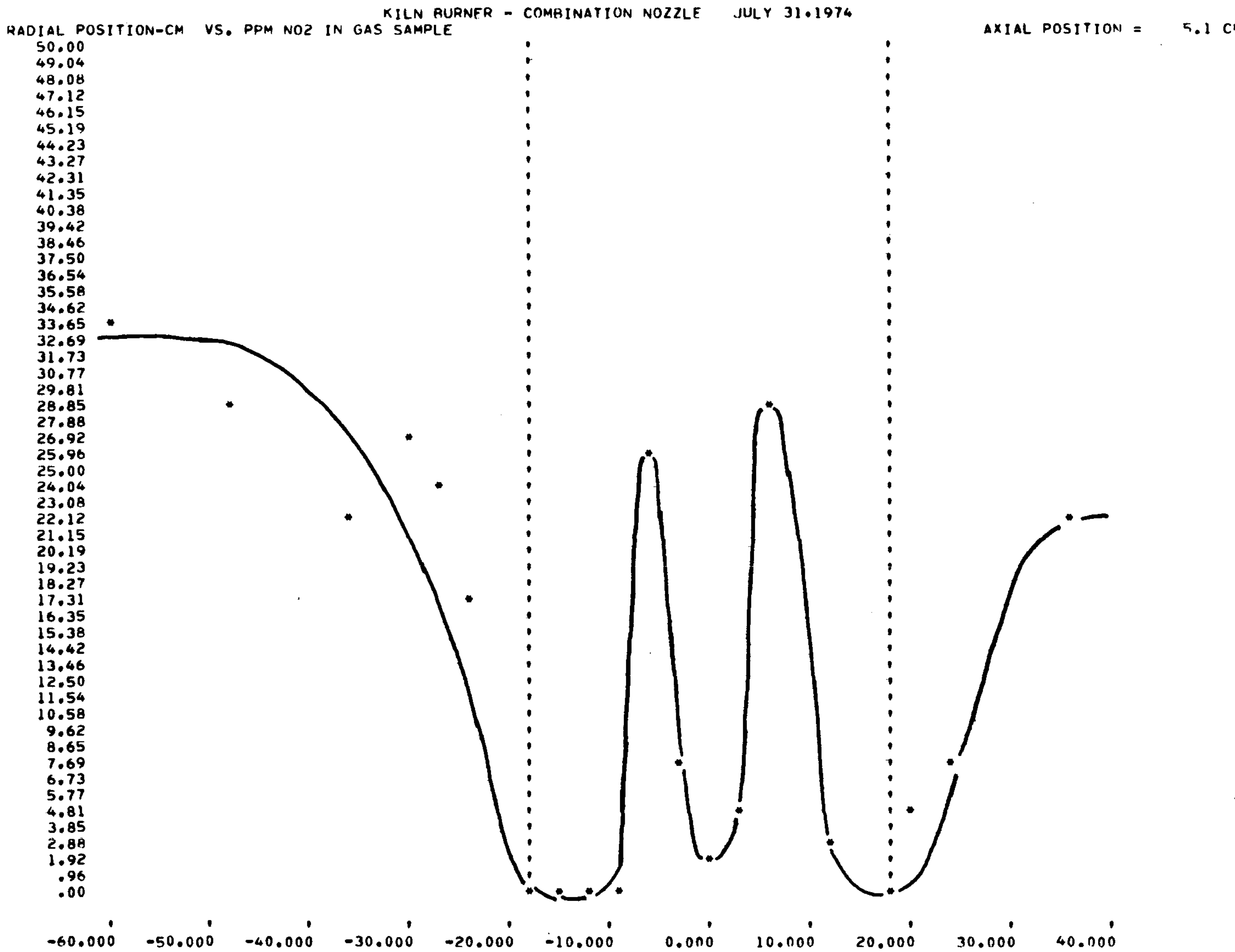

Figure 2. Combination kiln burner nozzle – radial profile of NO_2 at an axial position of 5.1 cm

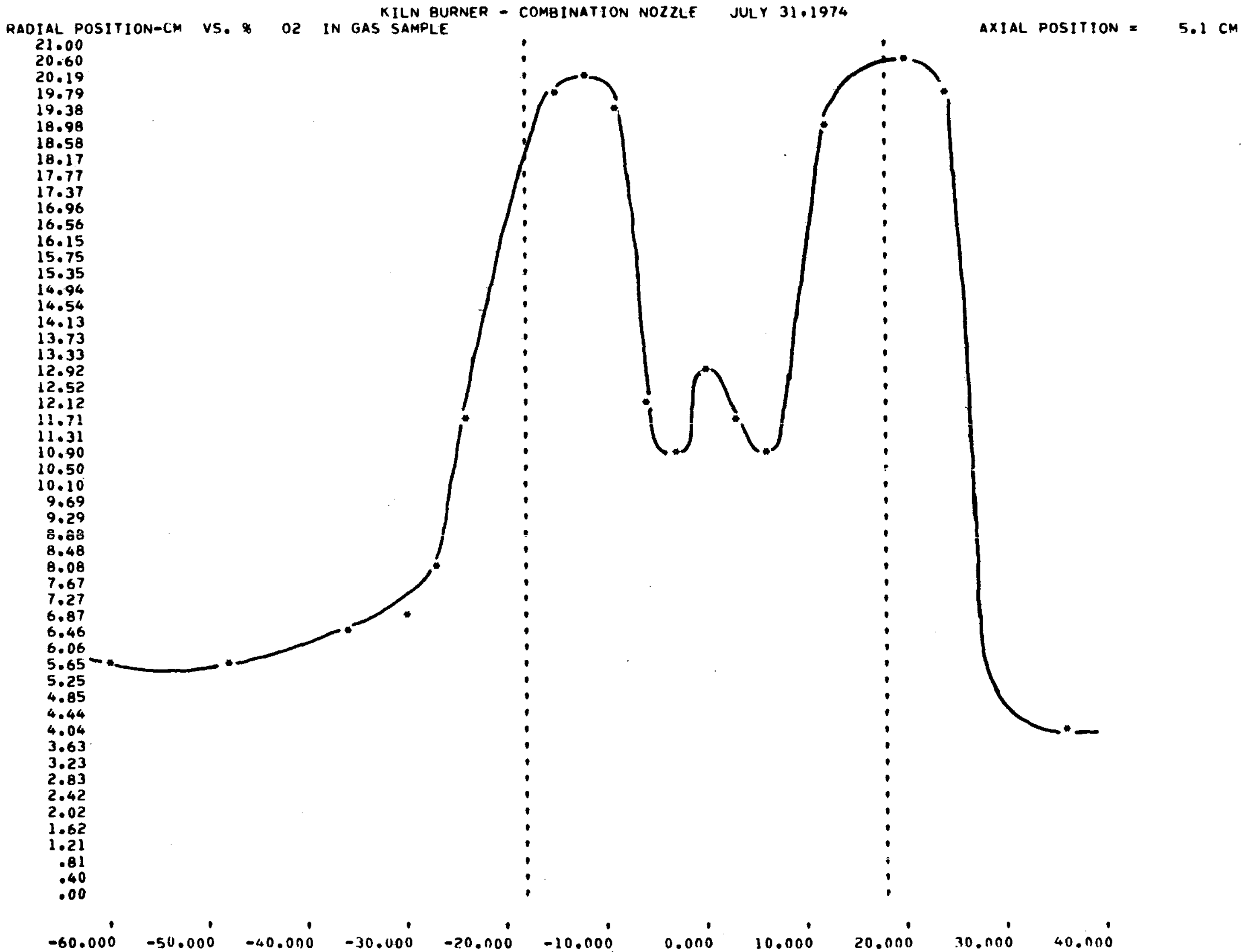

Figure 3. Combination kiln burner nozzle — radial profile of O_2 at an axial position of 5.1 cm

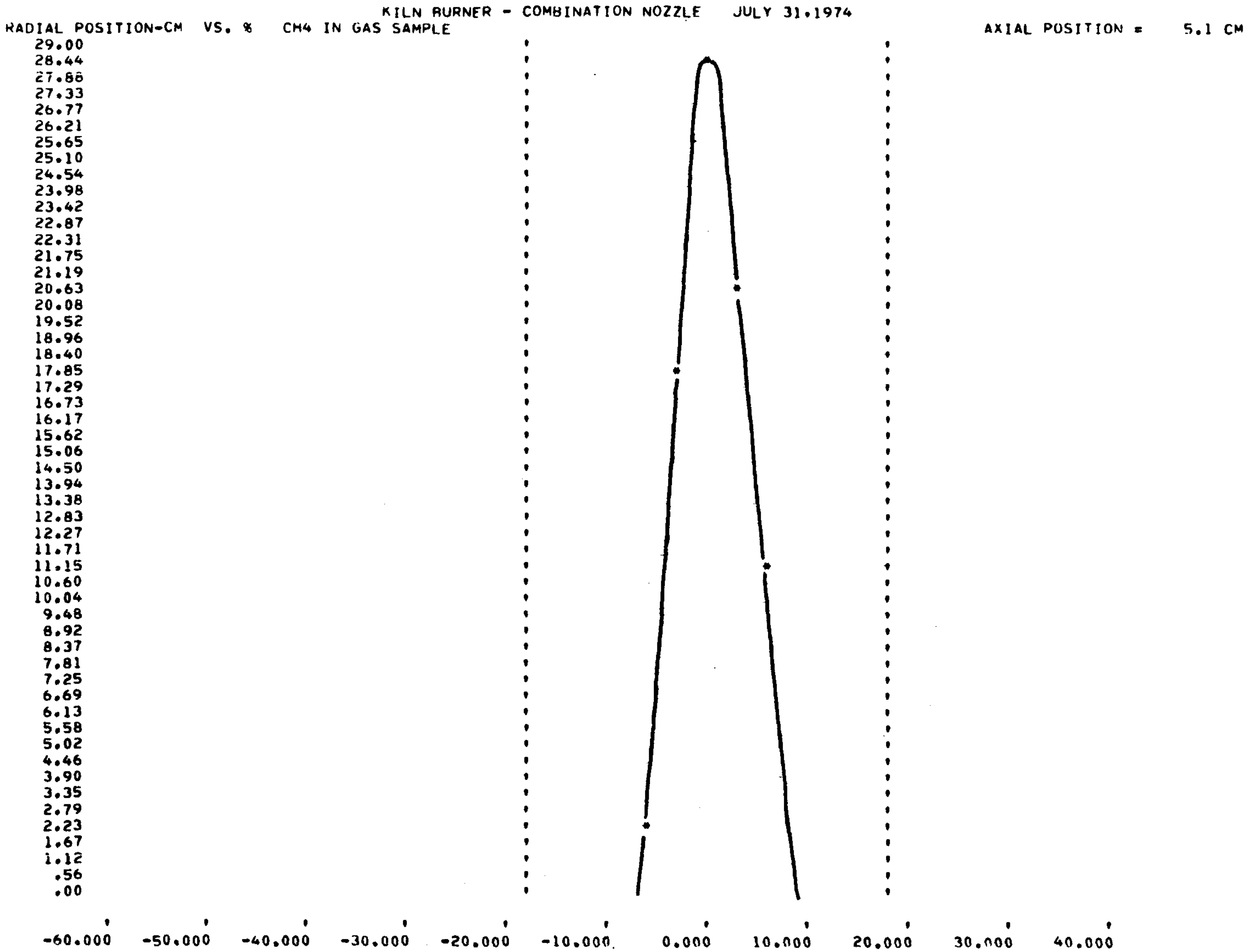

Figure 4. Combination kiln burner nozzle – radial profile of CH_4 at an axial position of 5. 1 cm

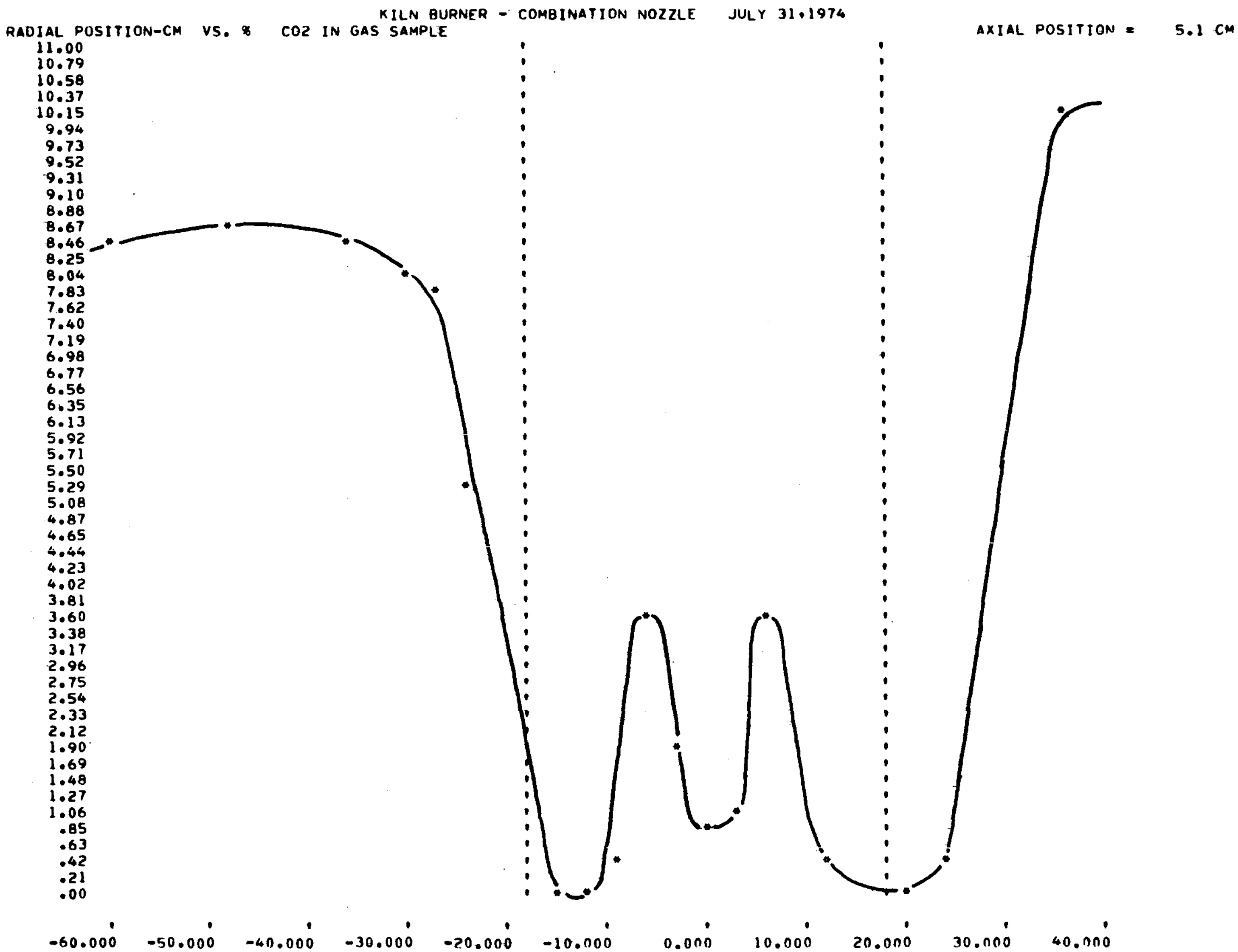

Figure 5. Combination kiln burner nozzle — radial profile of CO_2 at an axial position of 5.1 cm

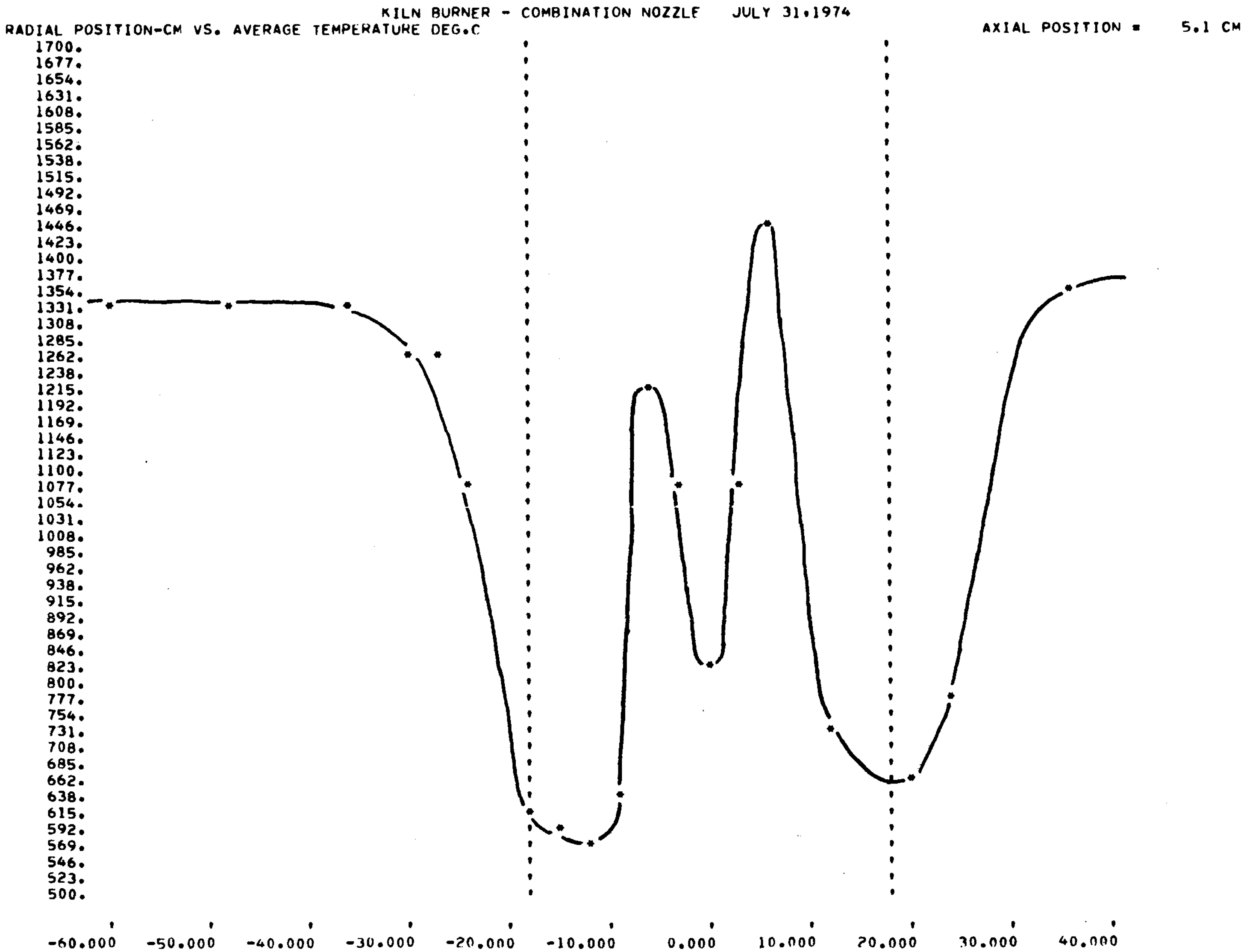

Figure 6. Combination kiln burner nozzle – radial profile of temperature at an axial position of 5. 1 cm

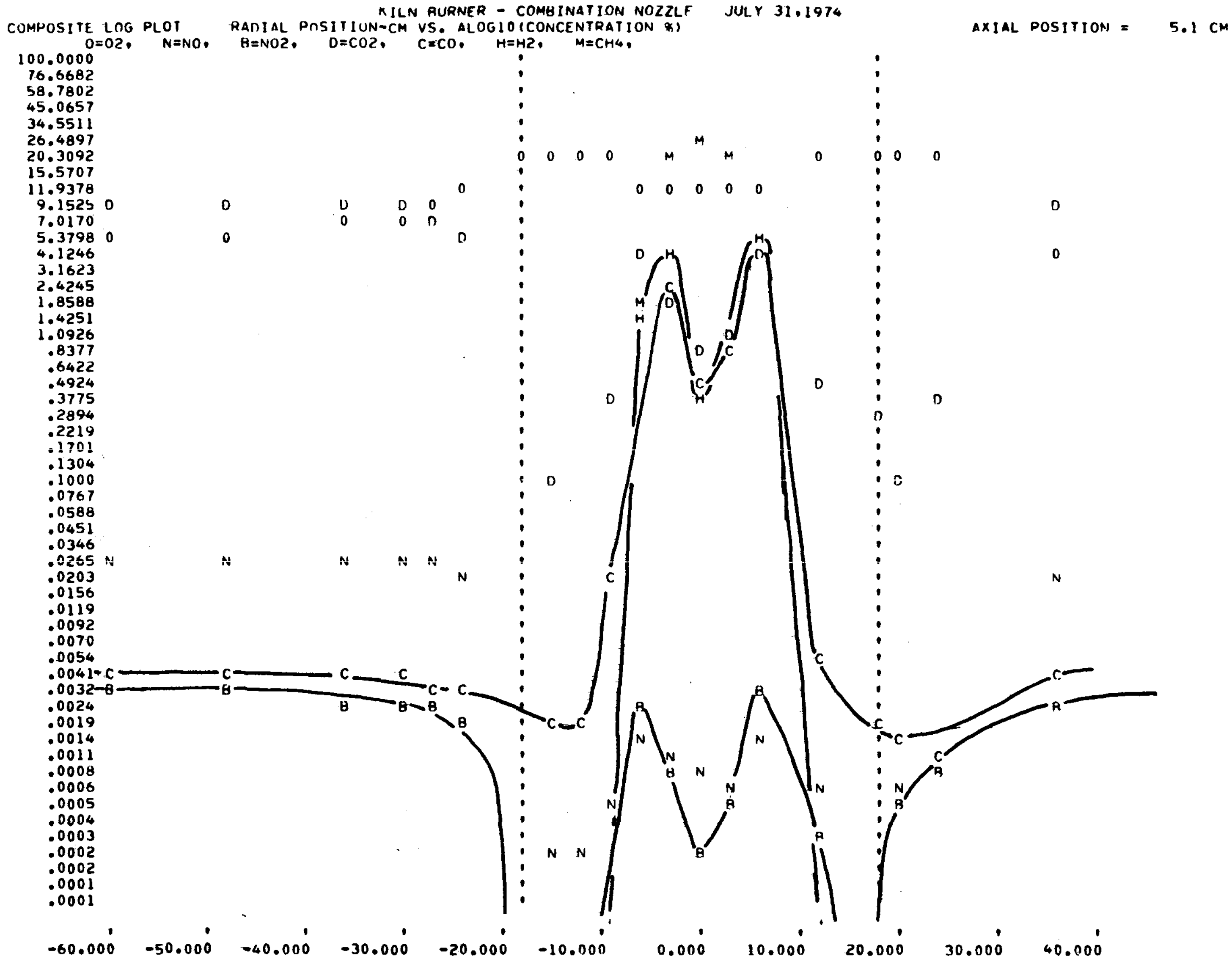

Figure 7. Combination kiln burner nozzle – radial profile of all the gases at an axial position of 5.1 cm

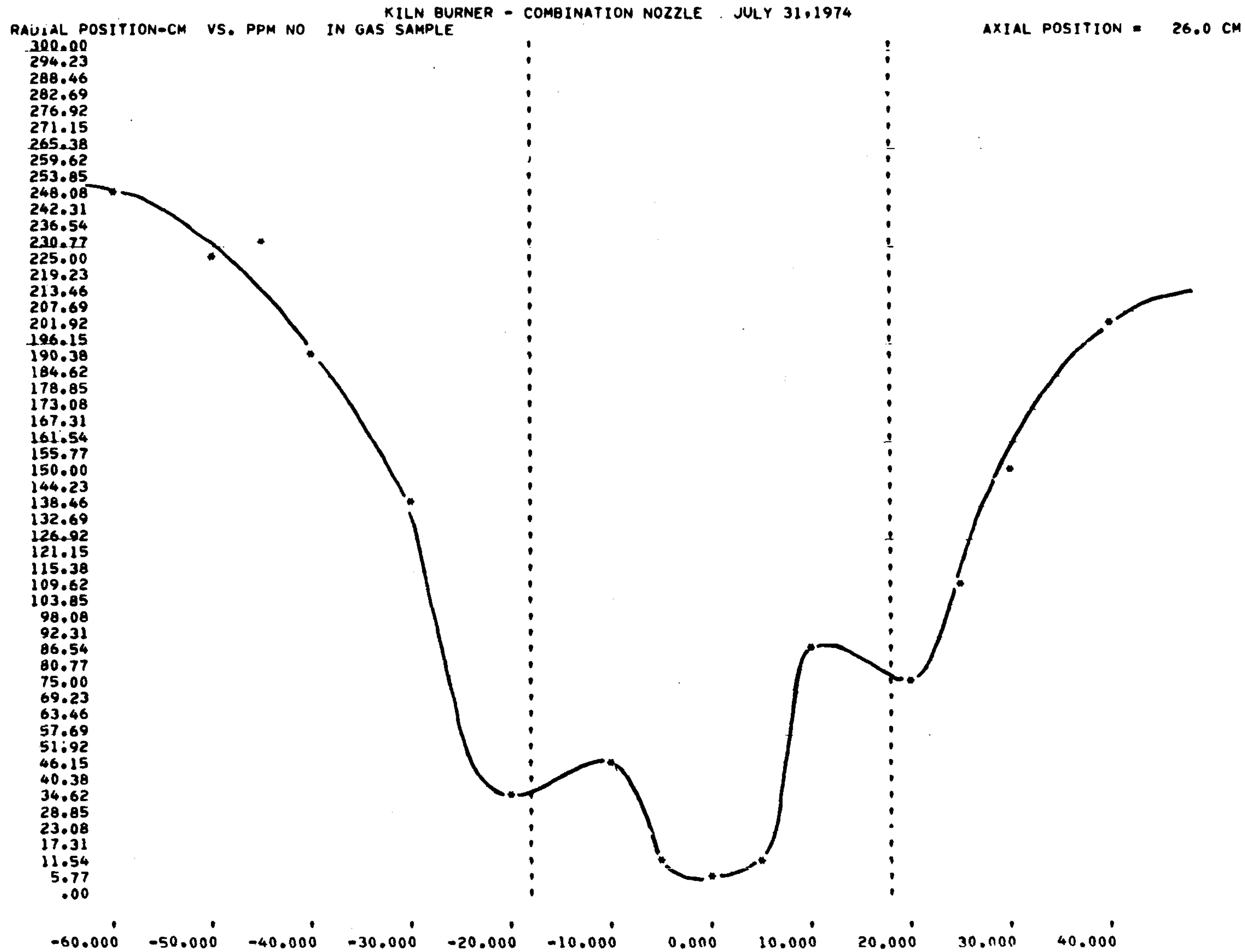

Figure 8. Combination kiln burner nozzle – radial profile of NO at an axial position of 26. 0 cm

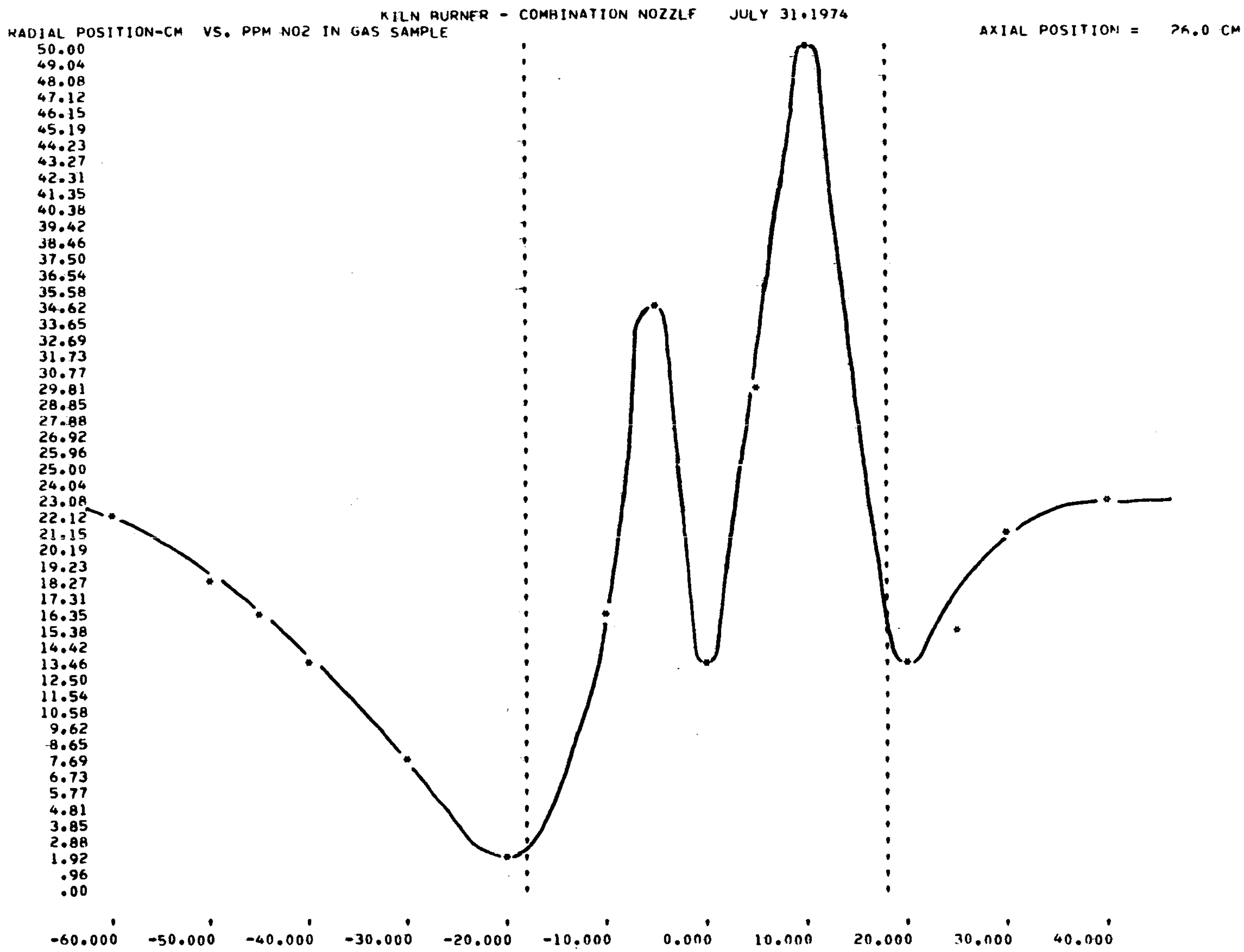

Figure 9. Combination kiln burner nozzle — radial profile of NO_2 at an axial position of 26.0 cm

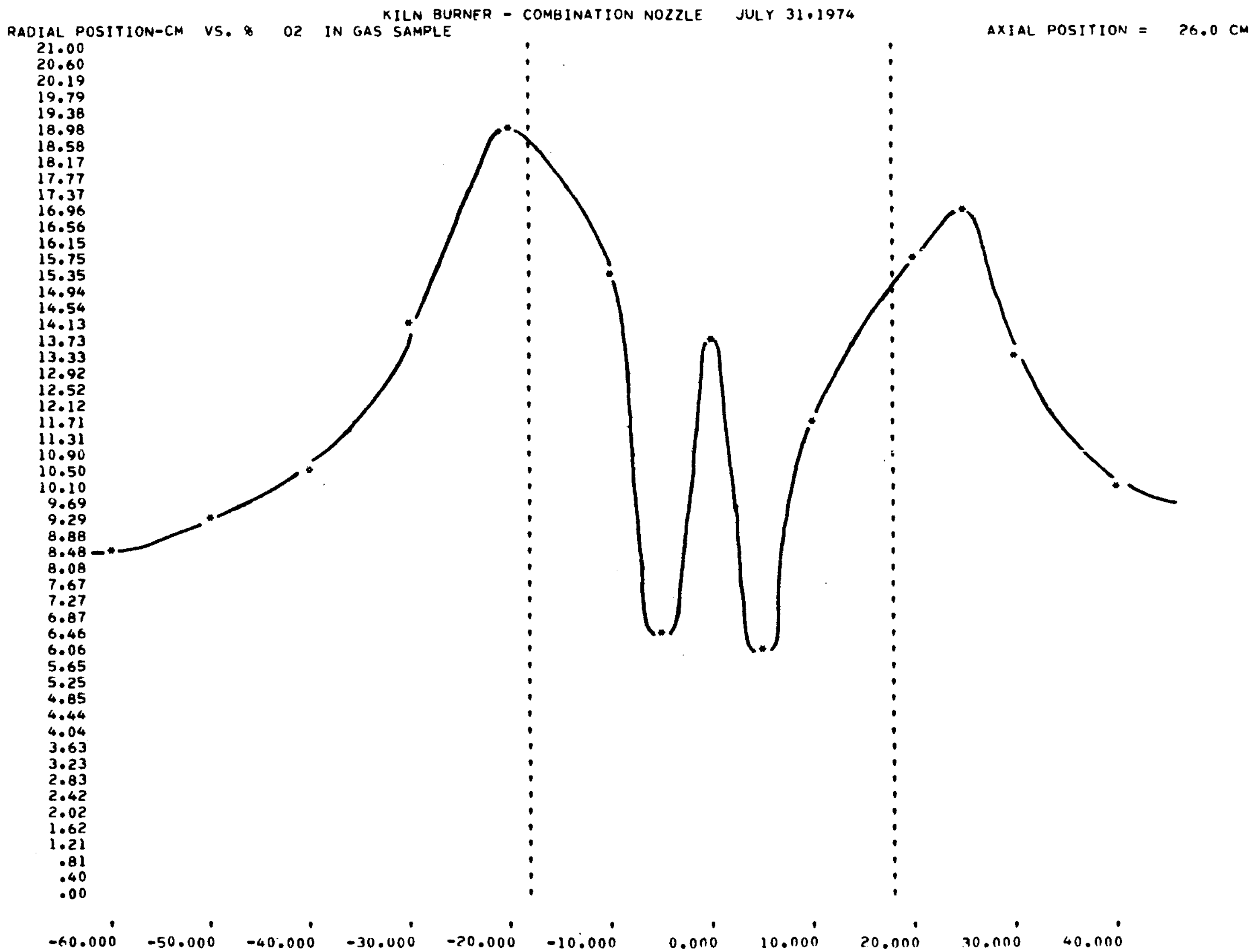

Figure 10. Combination kiln burner nozzle — radial profile of O_2 at an axial position of 26.0 cm

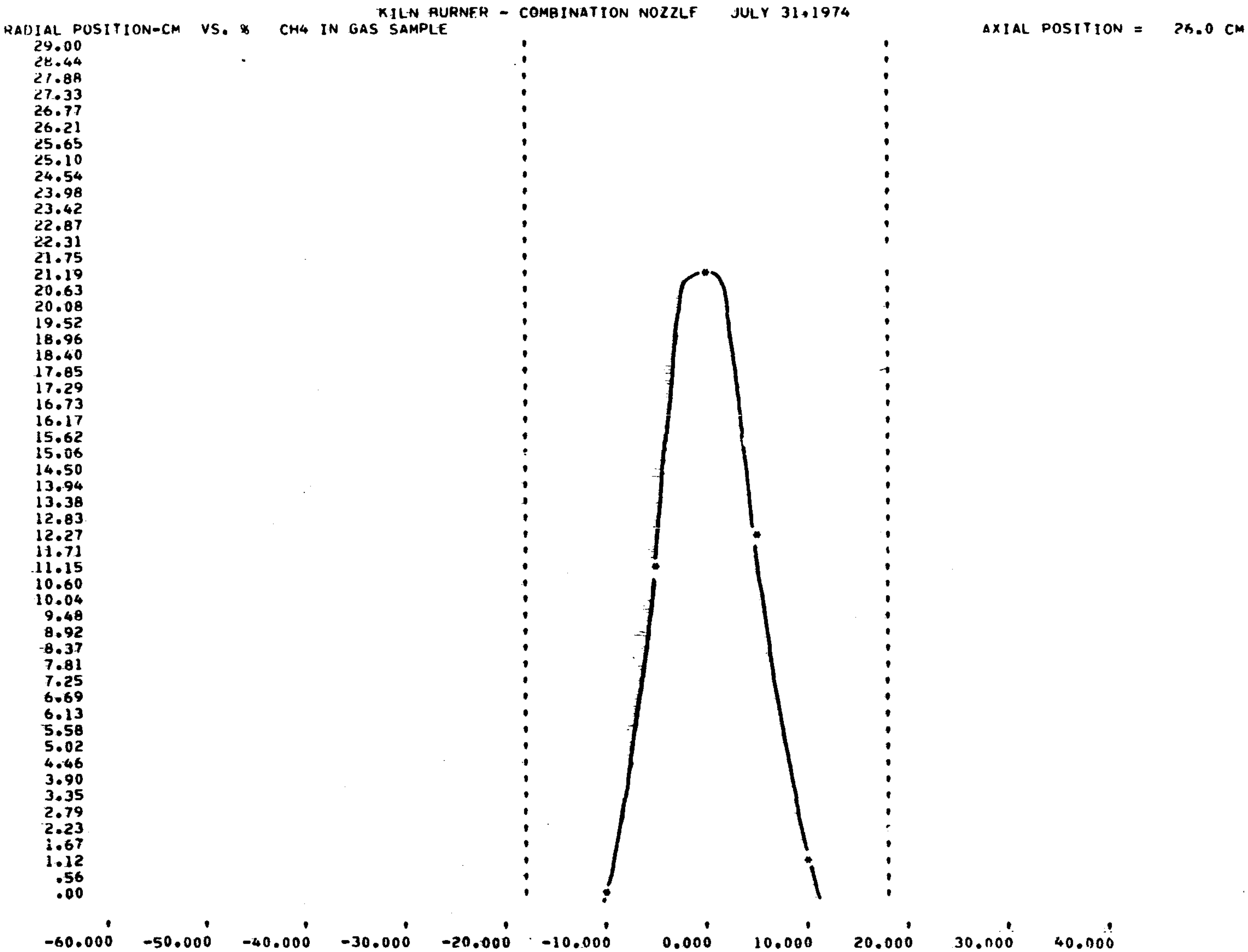

Figure 11. Combination kiln burner nozzle – radial profile of CH_4 at an axial position of 26.0 cm

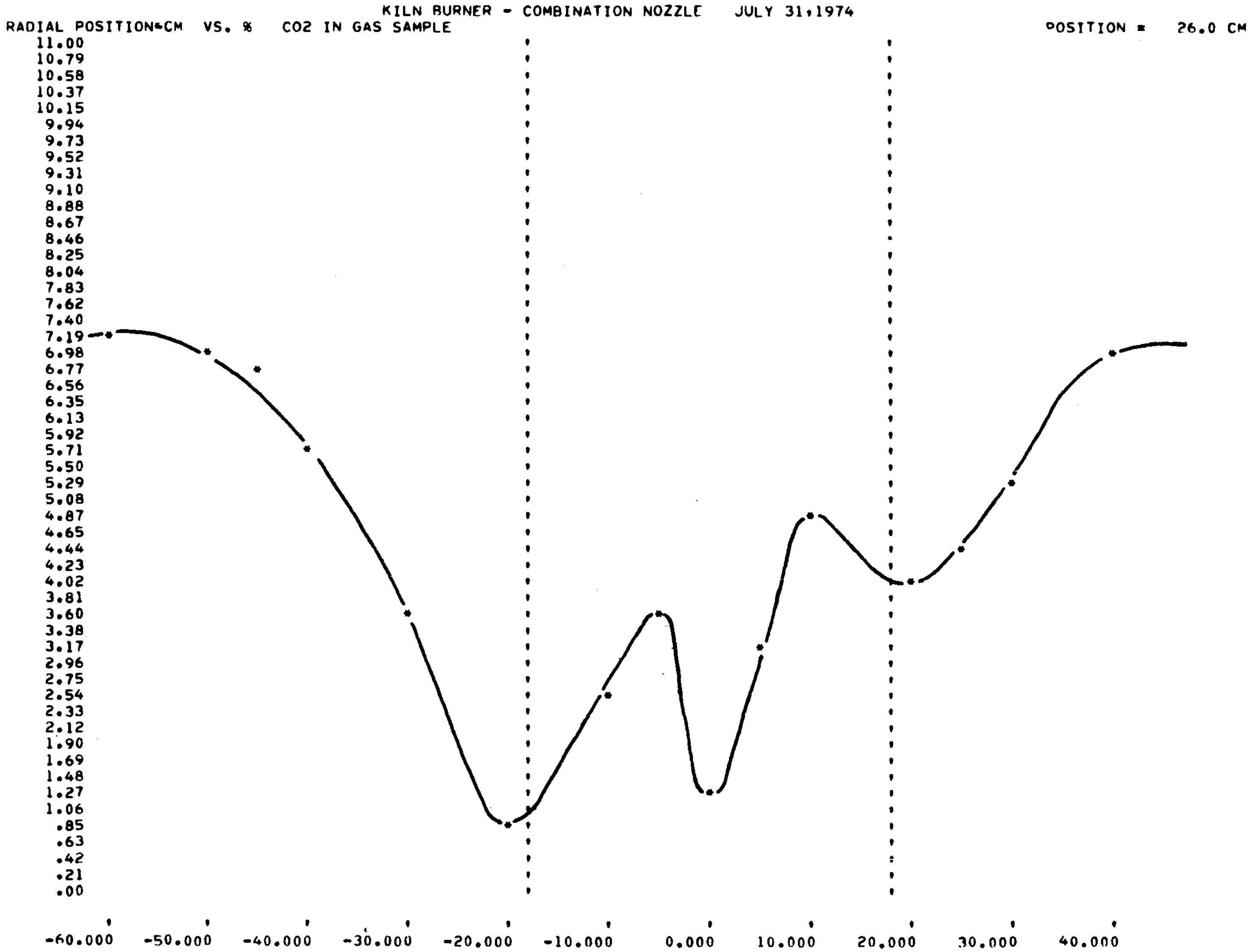

Figure 12. Combination kiln burner nozzle – radial profile of CO_2 at an axial position of 26.0 cm

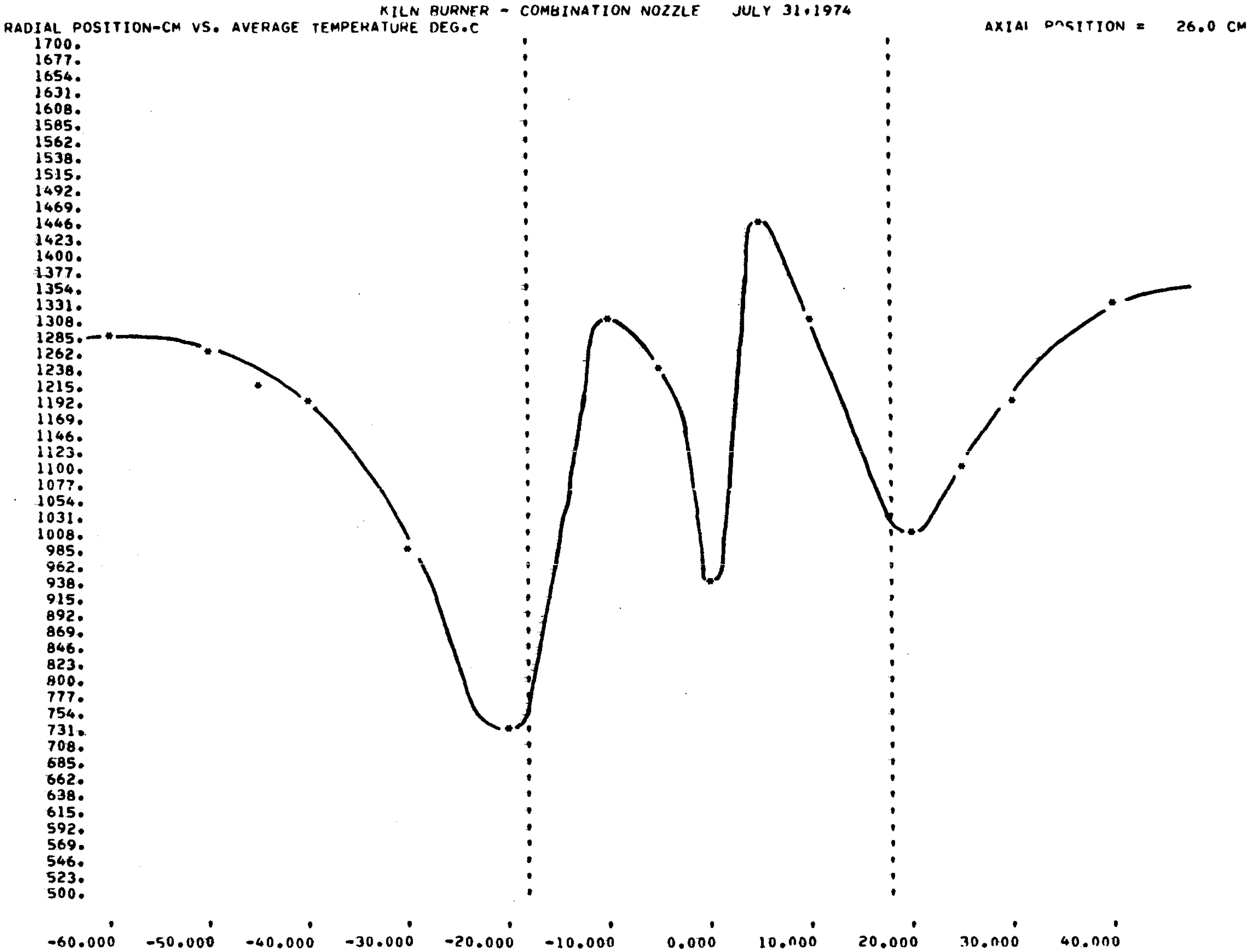

Figure 13. Combination kiln burner nozzle — radial profile of temperature at an axial position of 26.0 cm

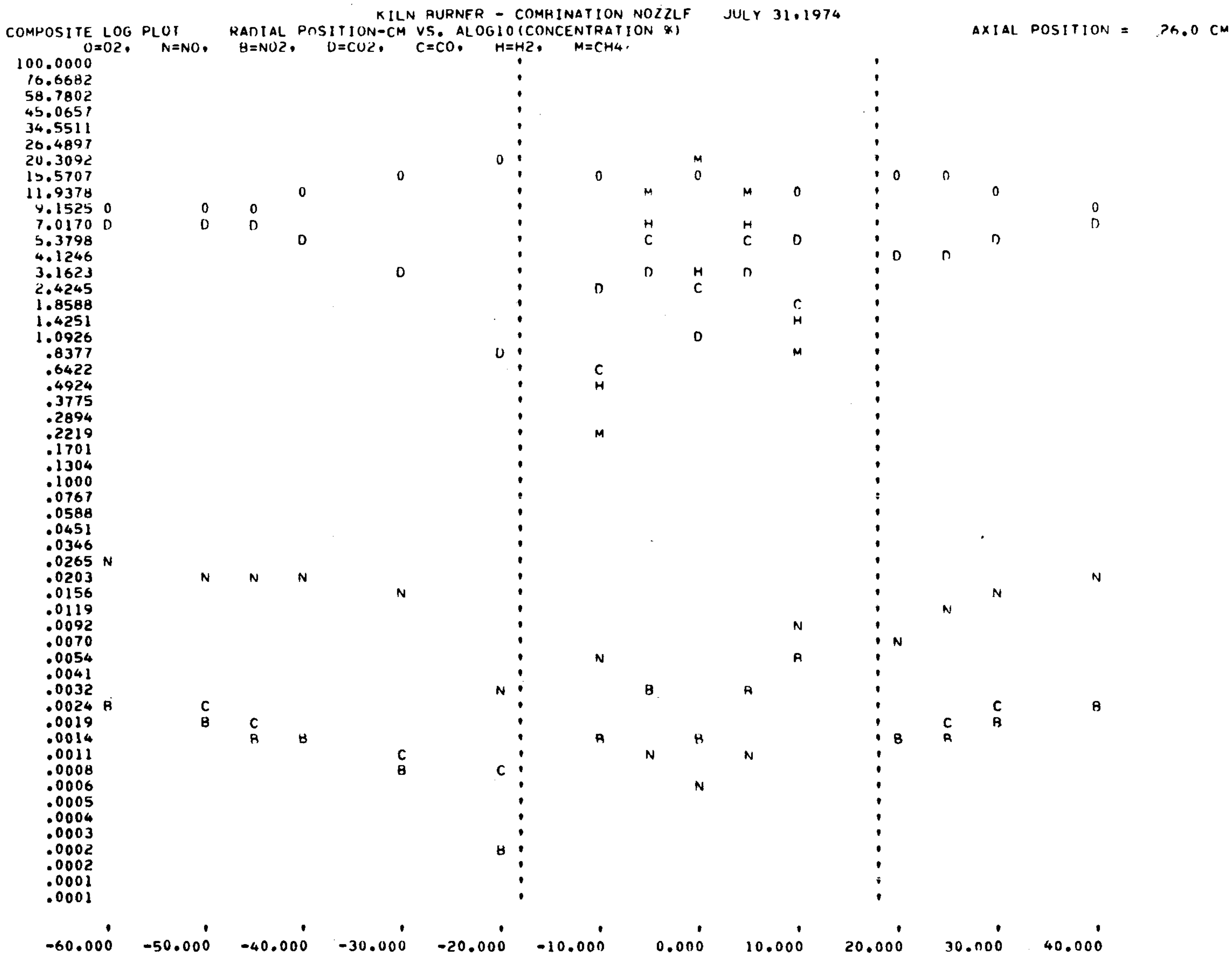

Figure 14. Combination kiln burner nozzle — radial profile of all the gases at an axial position of 26.0 cm

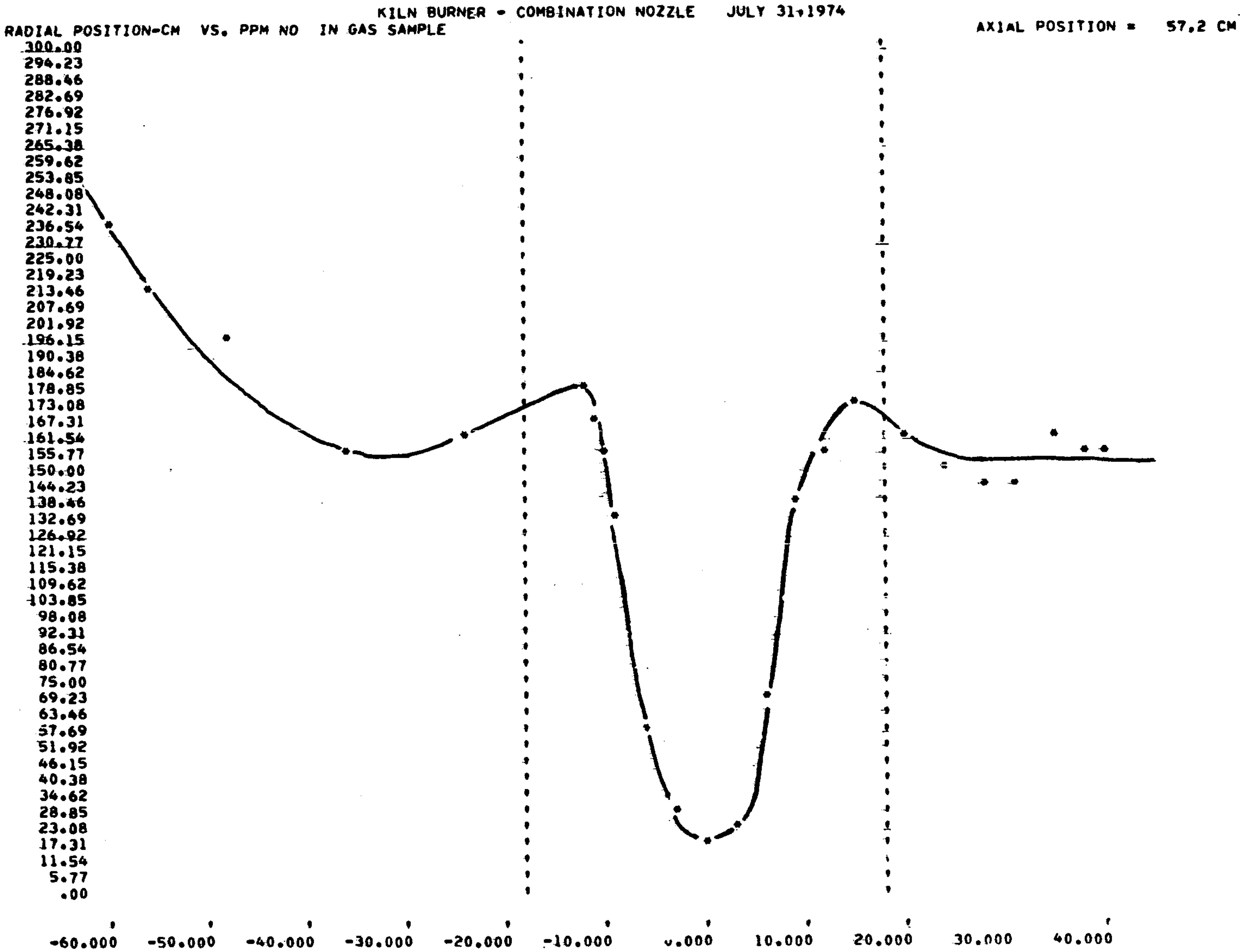

Figure 15. Combination kiln burner nozzle – radial profile of NO at an axial position of 57. 2 cm

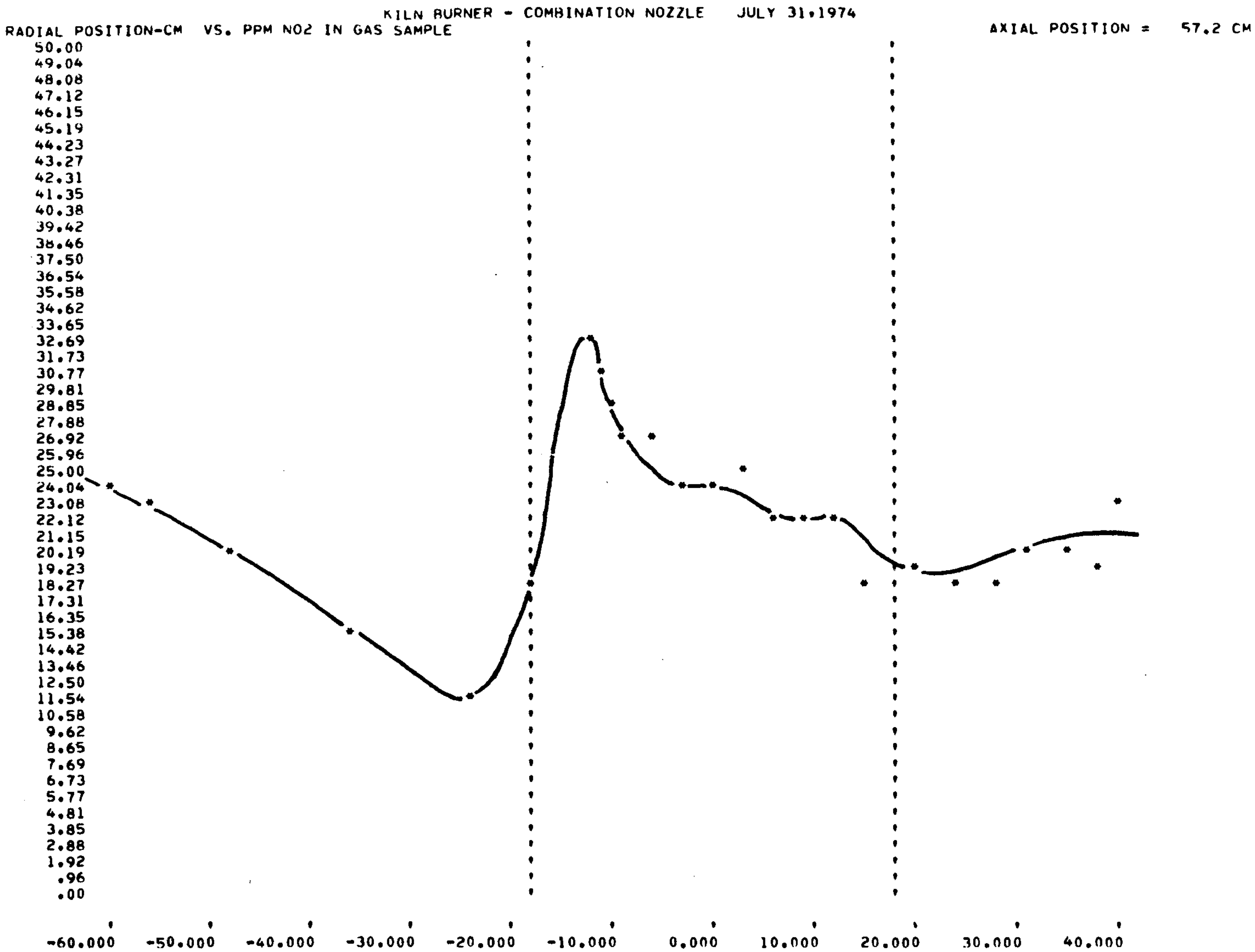

Figure 16. Combination kiln burner nozzle — radial profile of NO_2 at an axial position of 57.2 cm

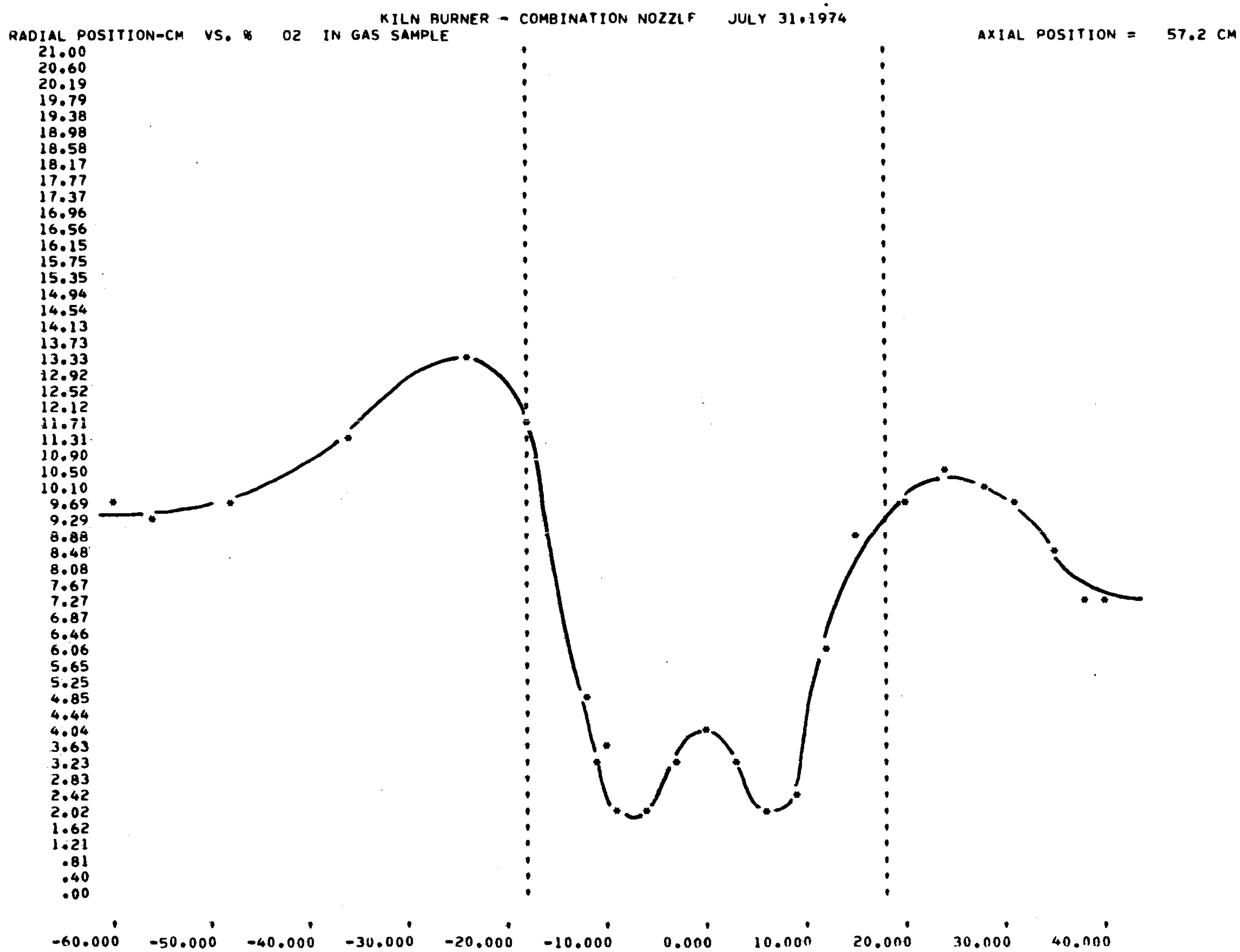

Figure 17. Combination kiln burner nozzle – radial profile of O_2 at an axial position of 57.2 cm

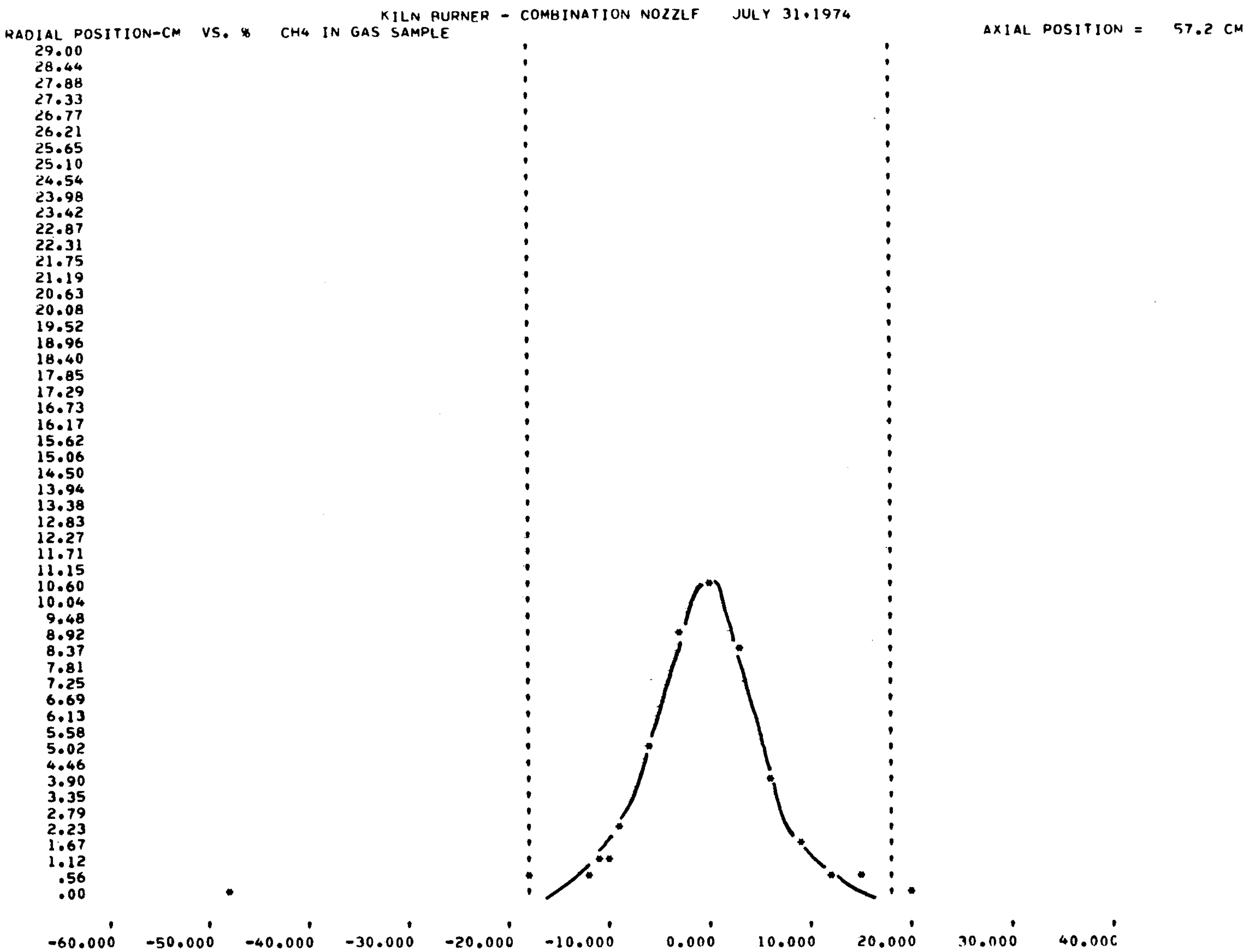

Figure 18. Combination kiln burner nozzle — radial profile of CH_4 at an axial position of 57. 2 cm

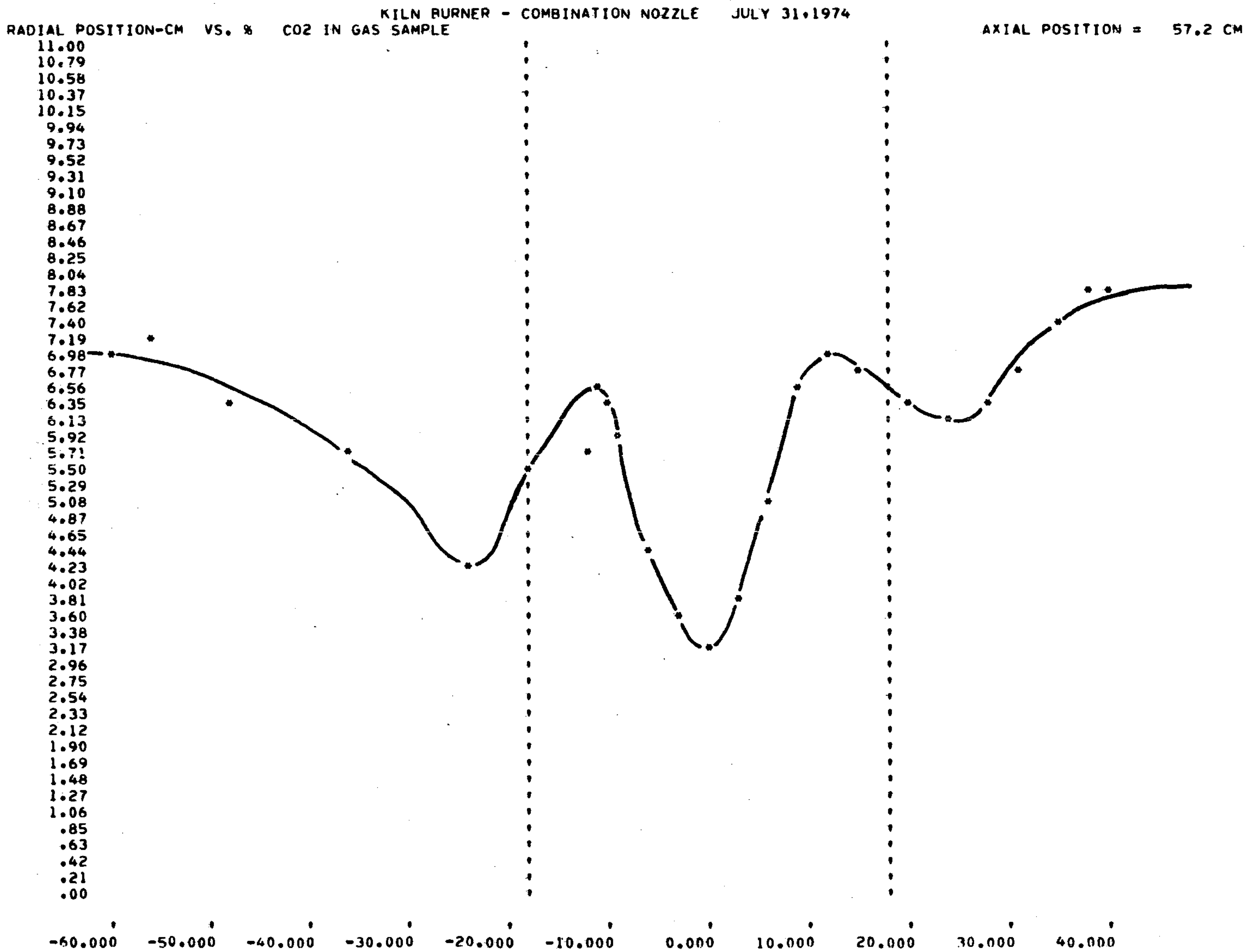

Figure 19. Combination kiln burner nozzle — radial profile of CO_2 at an axial position of 57. 2 cm

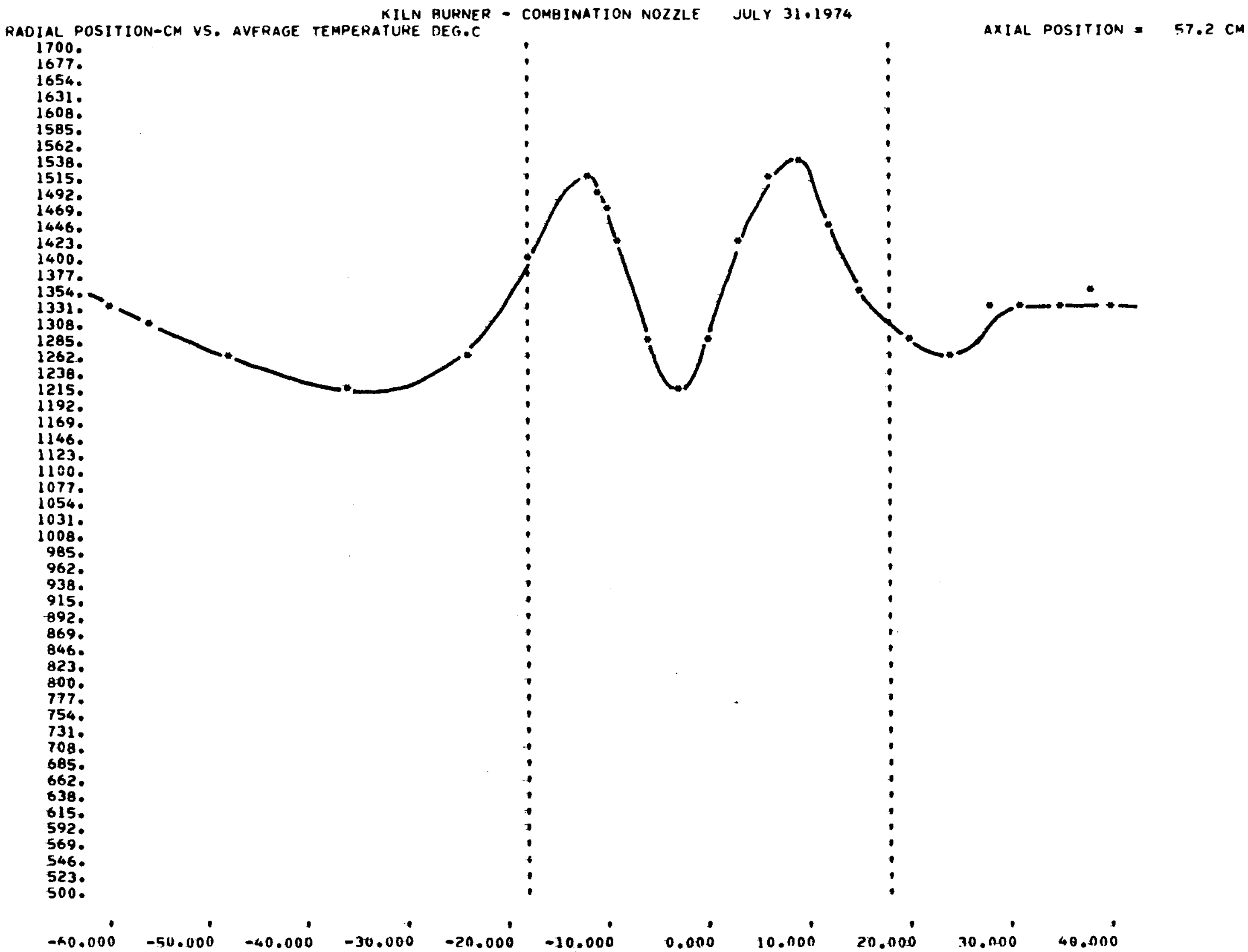

Figure 20. Combination kiln burner nozzle – radial profile of temperature at an axial position of 57.2 cm

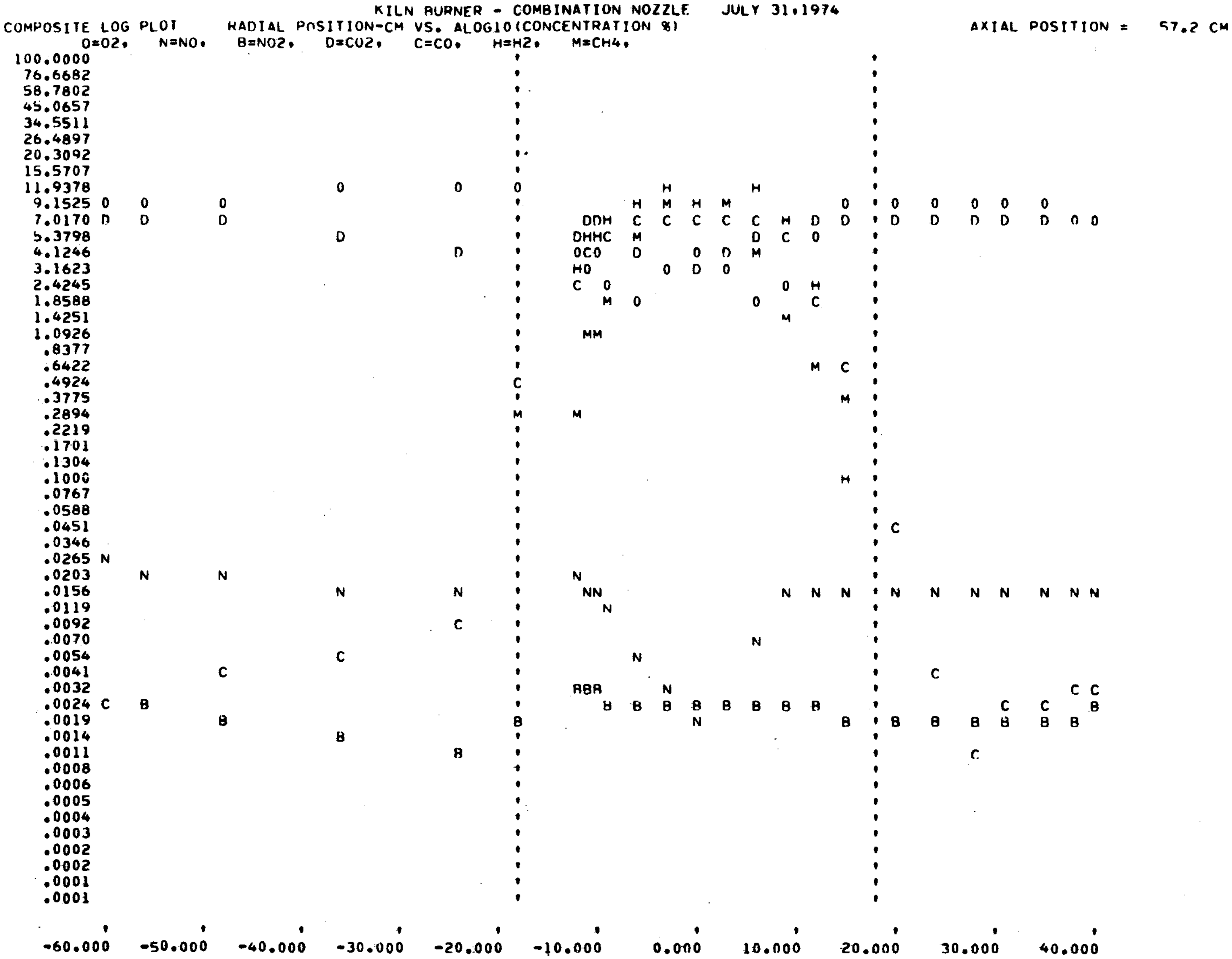

Figure 21. Combination kiln burner nozzle — radial profile of all the gases at an axial position of 57.2 cm

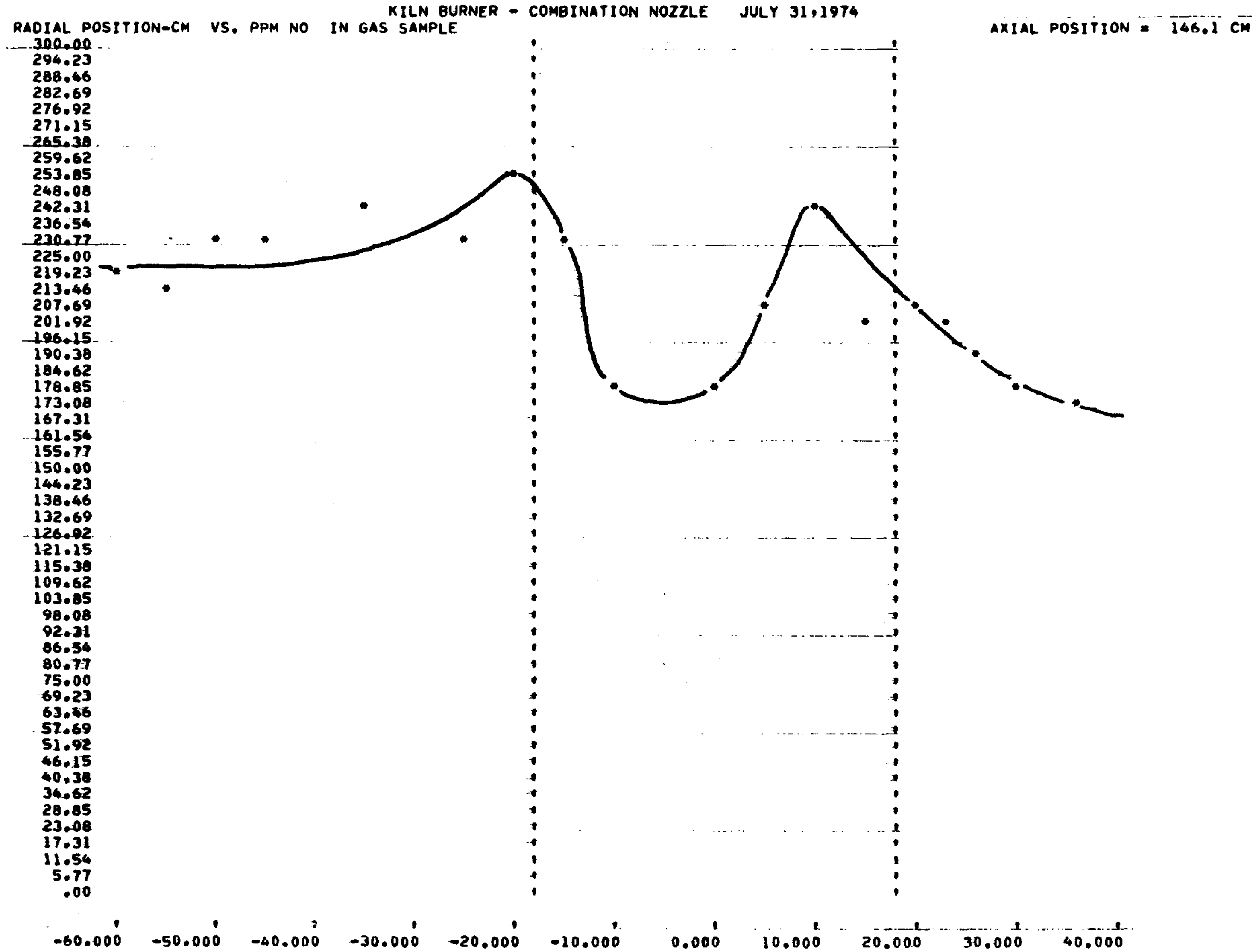

Figure 22. Combination kiln burner nozzle – radial profile of NO at an axial position of 146.1 cm

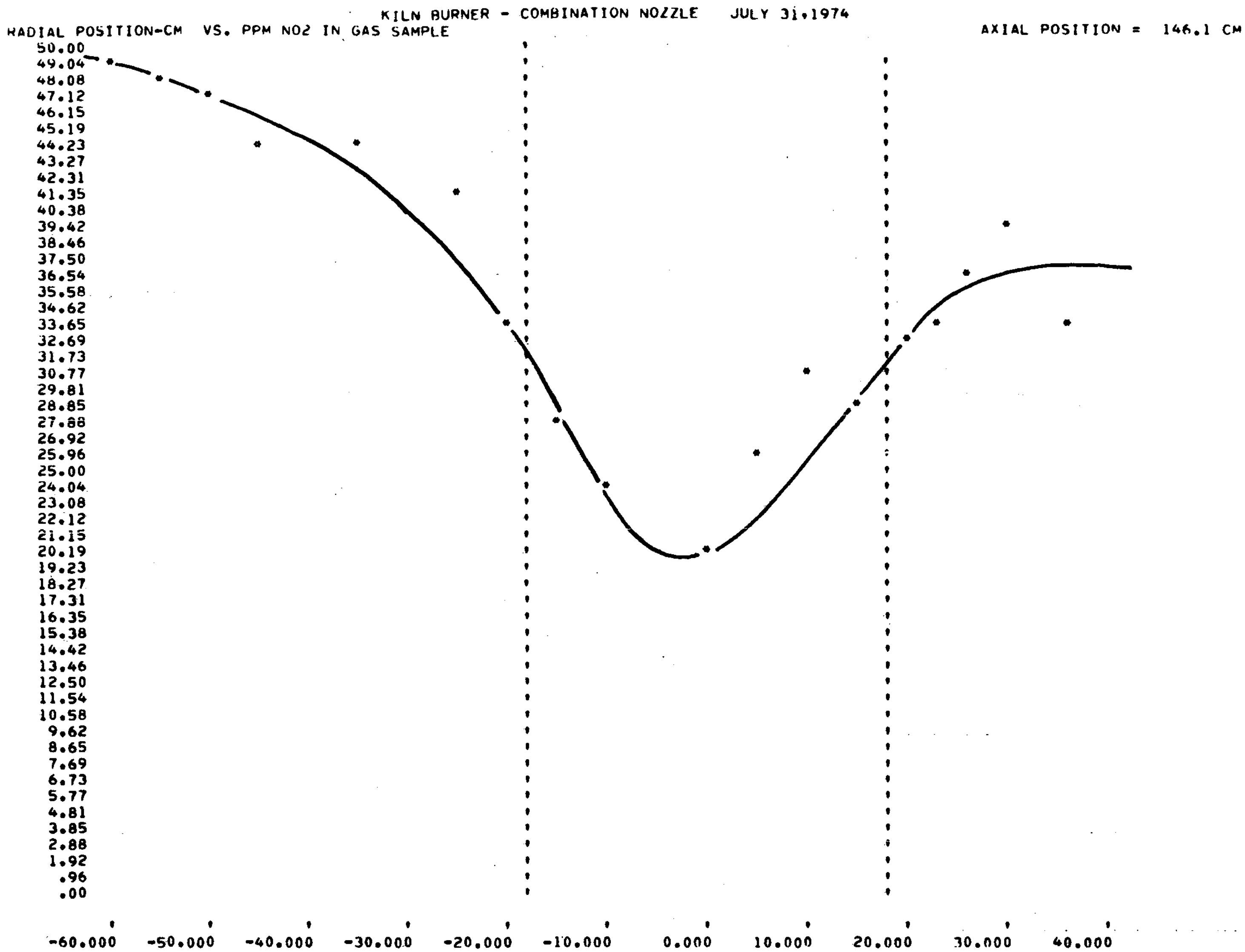

Figure 23. Combination kiln burner nozzle — radial profile of NO_2 at an axial position of 146. 1 cm

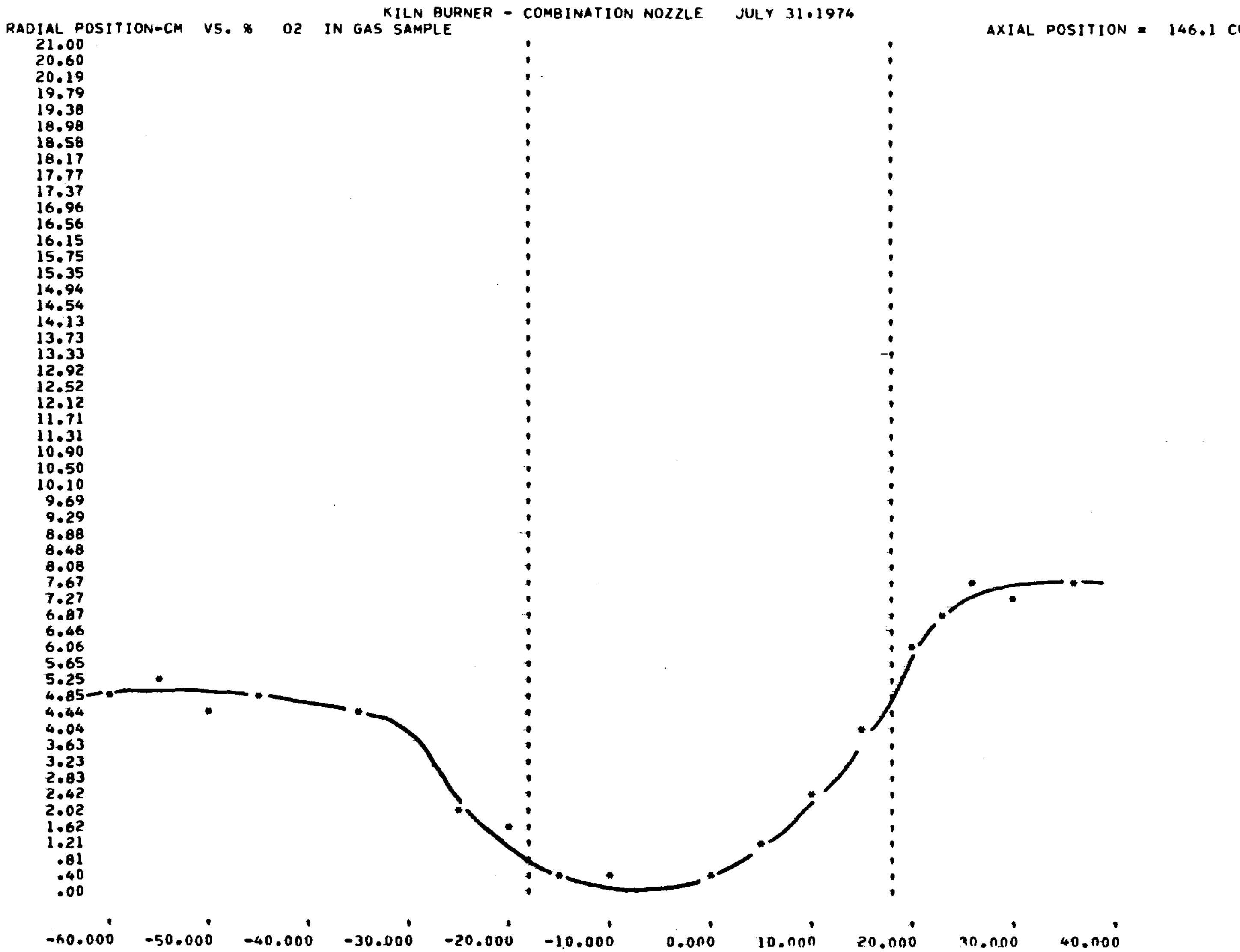

Figure 24. Combination kiln burner nozzle – radial profile of O_2 at an axial position of 146.1 cm

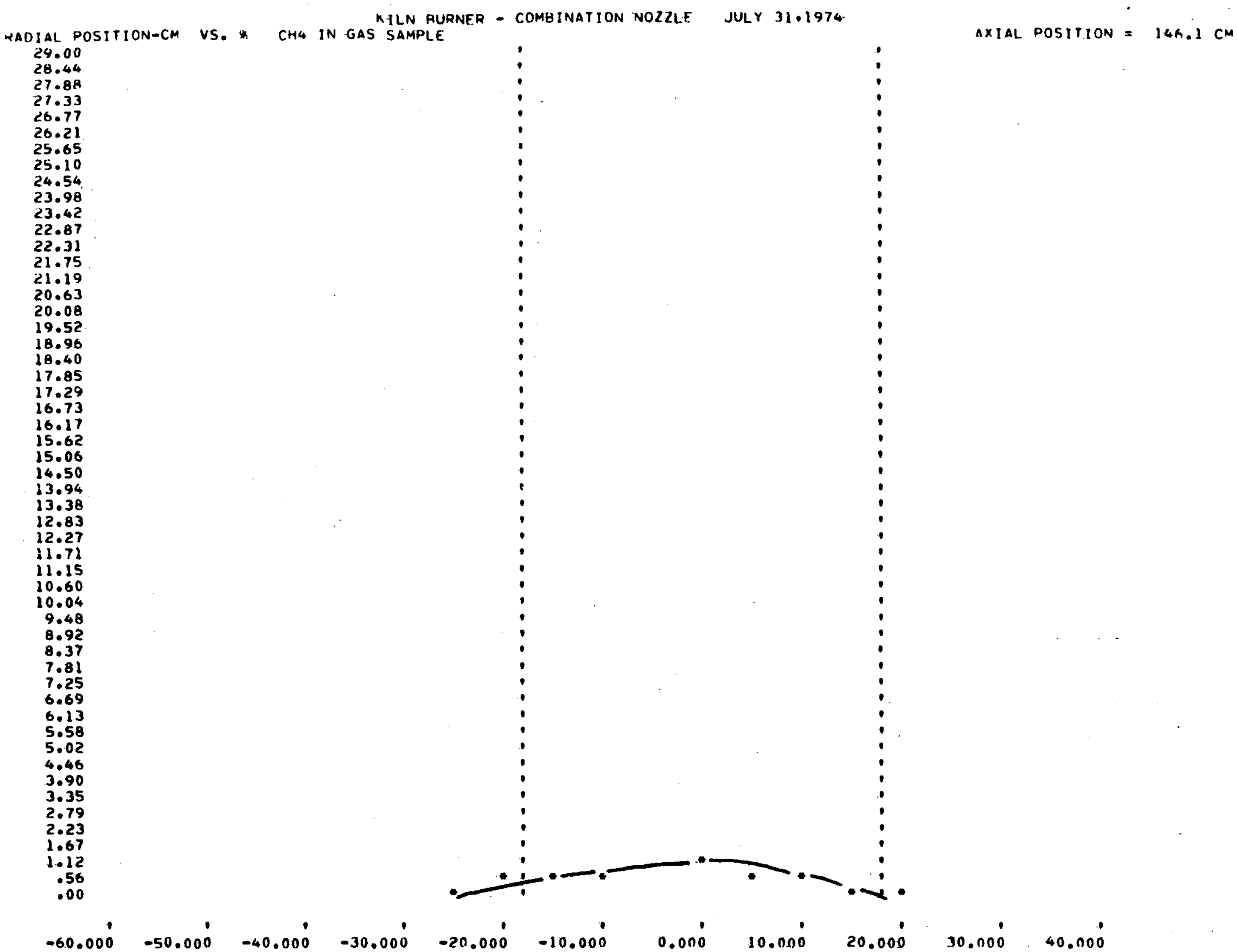

Figure 25. Combination kiln burner nozzle – radial profile of CH_4 at an axial position of 146.1 cm

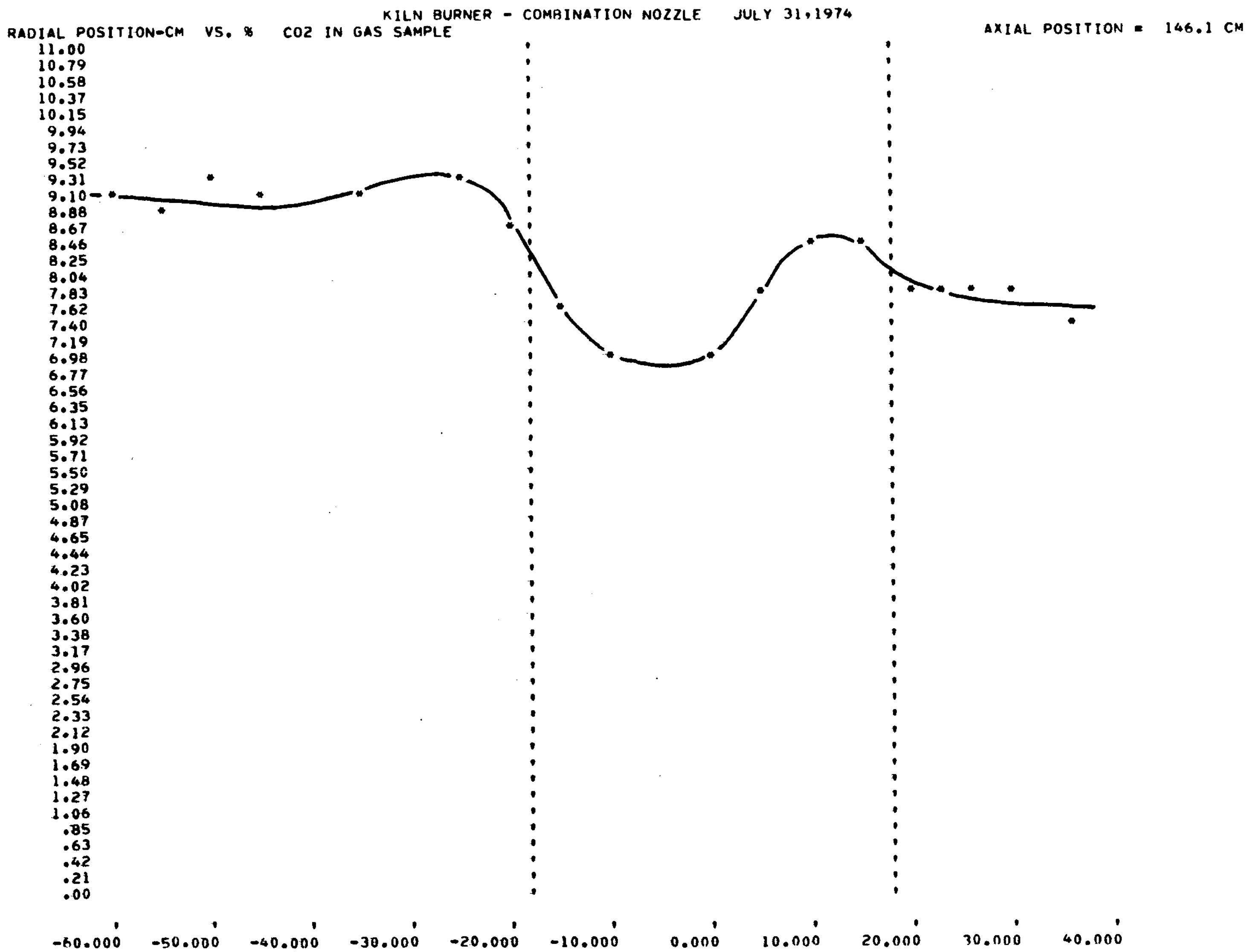

Figure 26. Combination kiln burner nozzle – radial profile of CO_2 at an axial position of 146. 1 cm

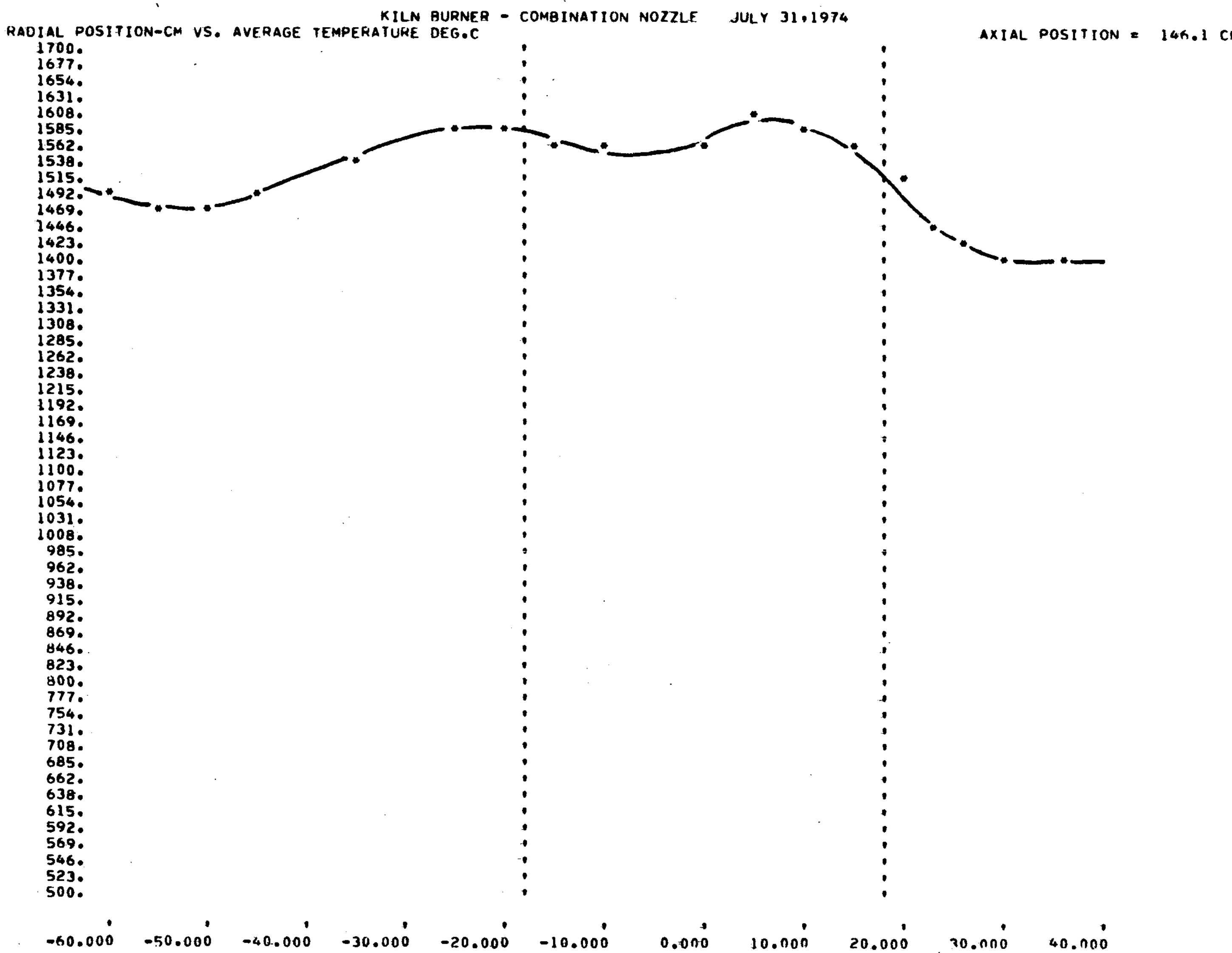

Figure 27. Combination kiln burner nozzle – radial profile of temperature at an axial position of 146.1 cm

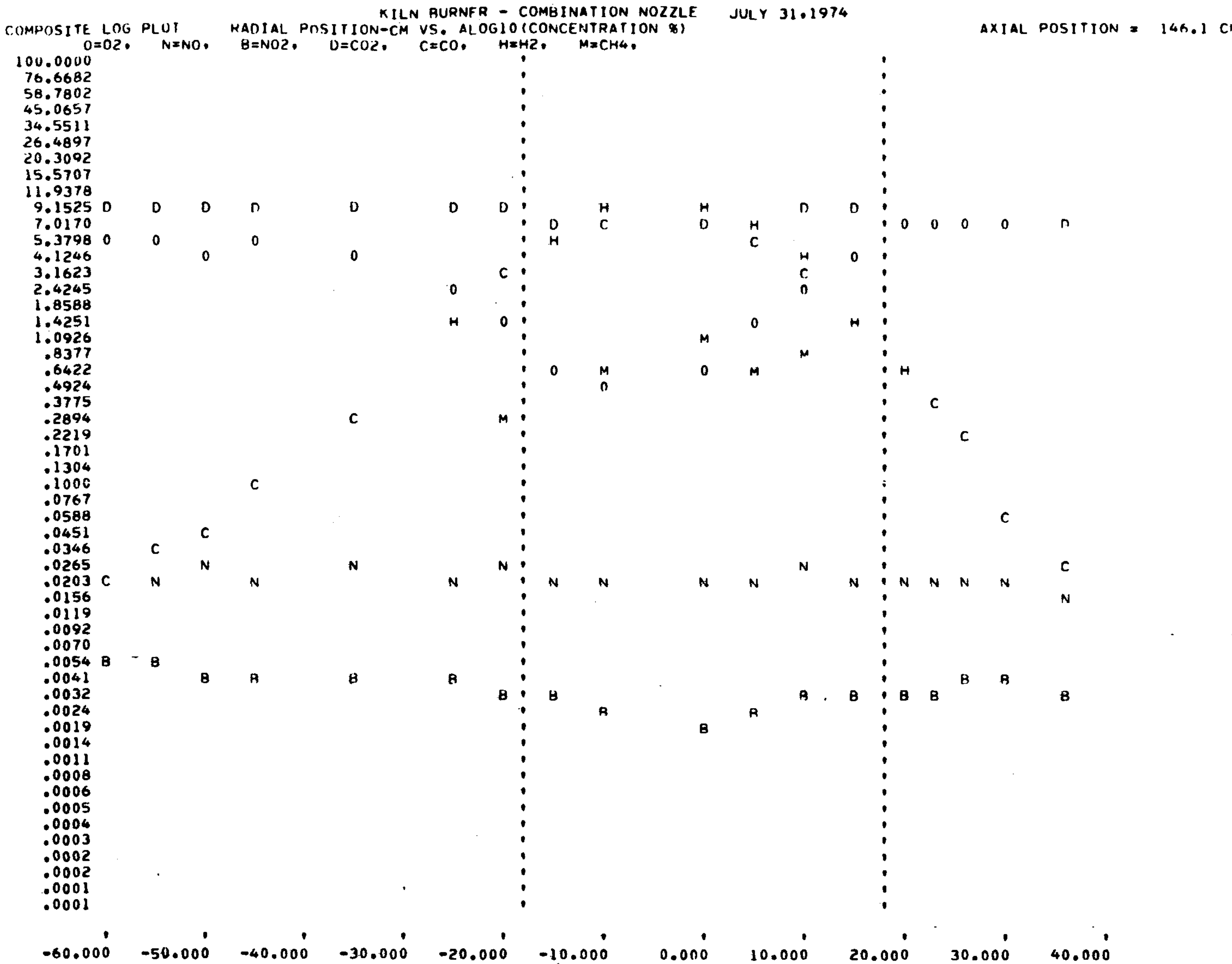

Figure 28. Combination kiln burner nozzle – radial profile of all the gases at an axial position of 146. 1 cm

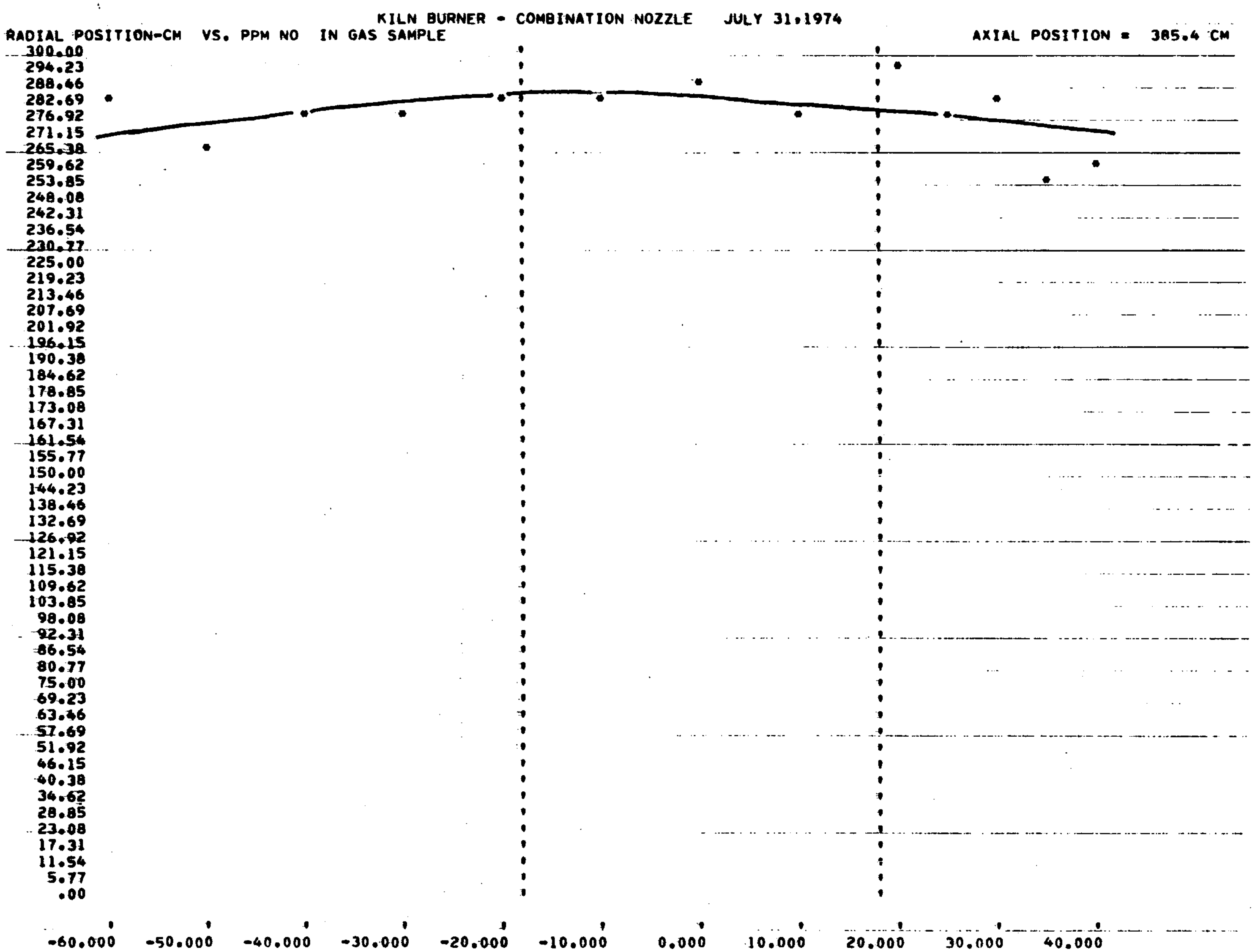

Figure 29. Combination kiln burner nozzle – radial profile of NO at an axial position of 385.4 cm

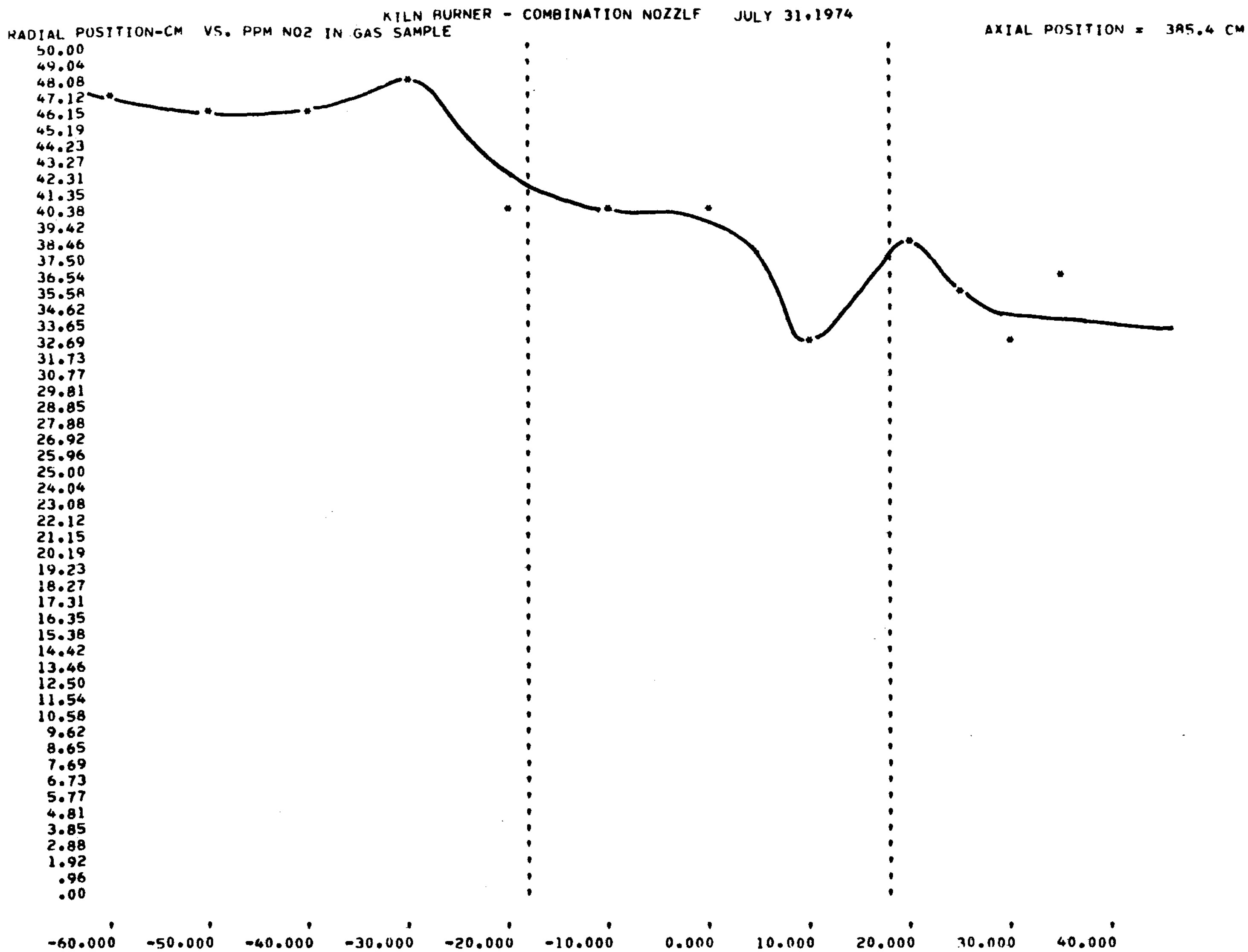

Figure 30. Combination kiln burner nozzle – radial profile of NO_2 at an axial position of 385.4 cm

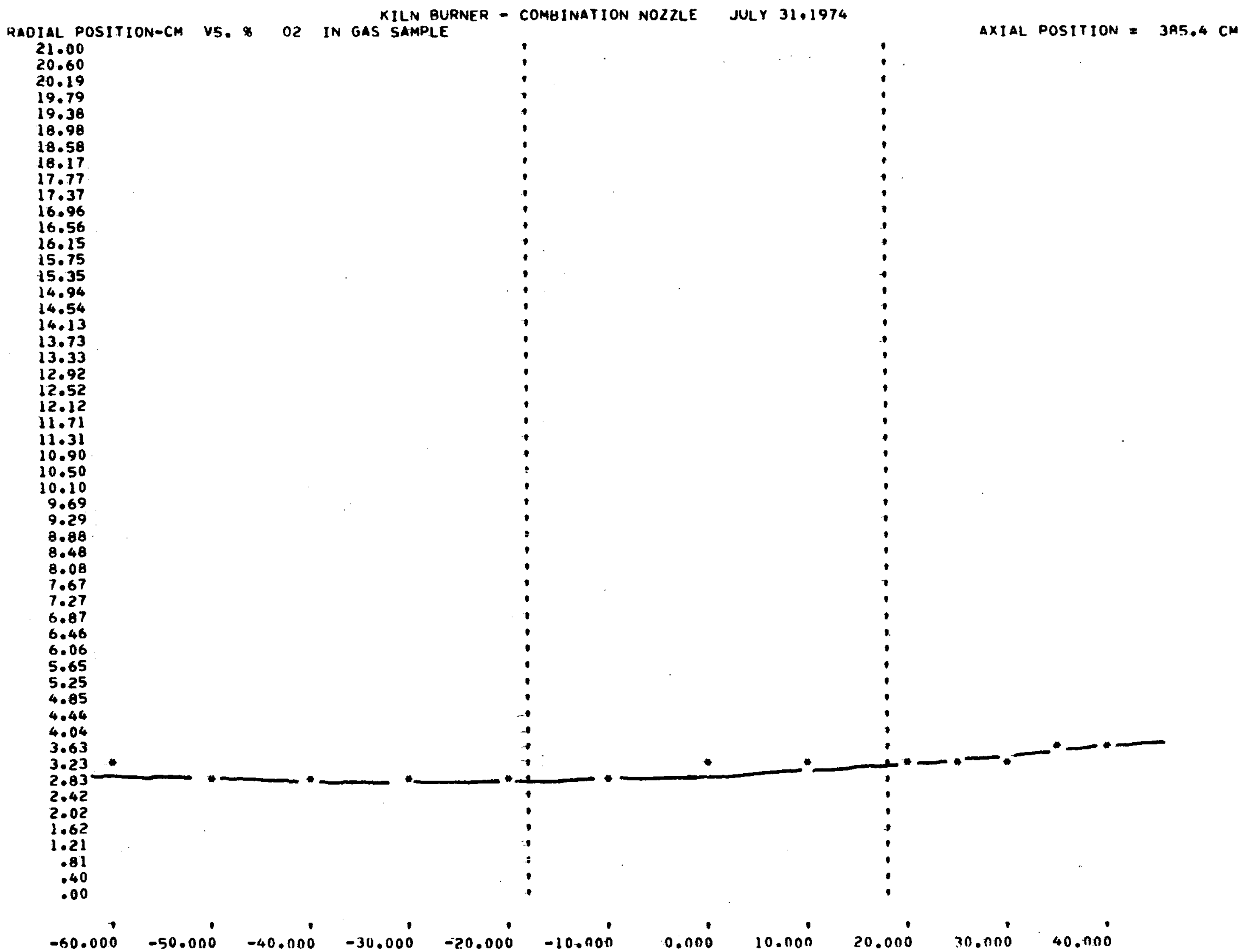

Figure 31. Combination kiln burner nozzle – radial profile of O_2 at an axial position of 385.4 cm

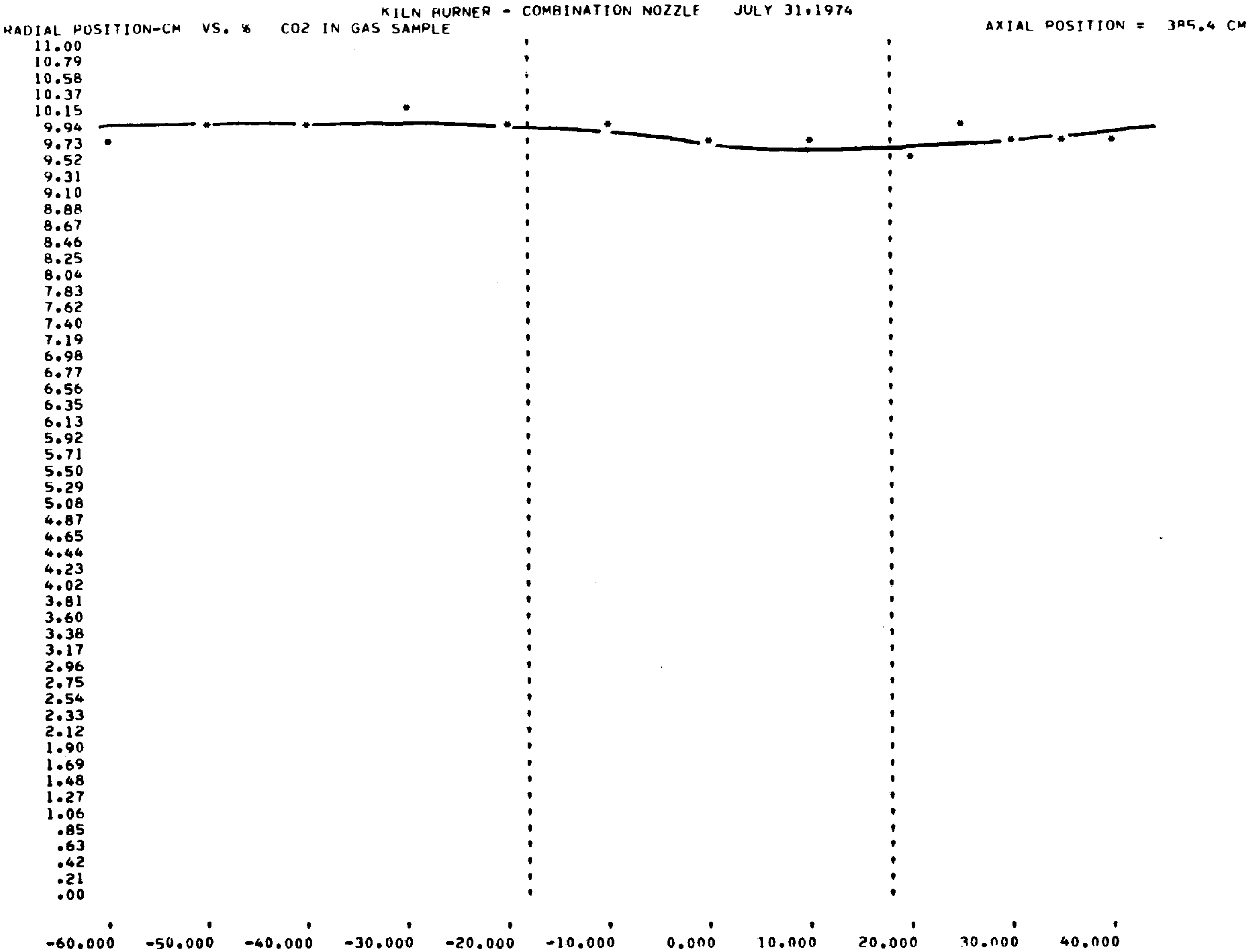

Figure 32. Combination kiln burner nozzle — radial profile of CO_2 at an axial position of 385.4 cm

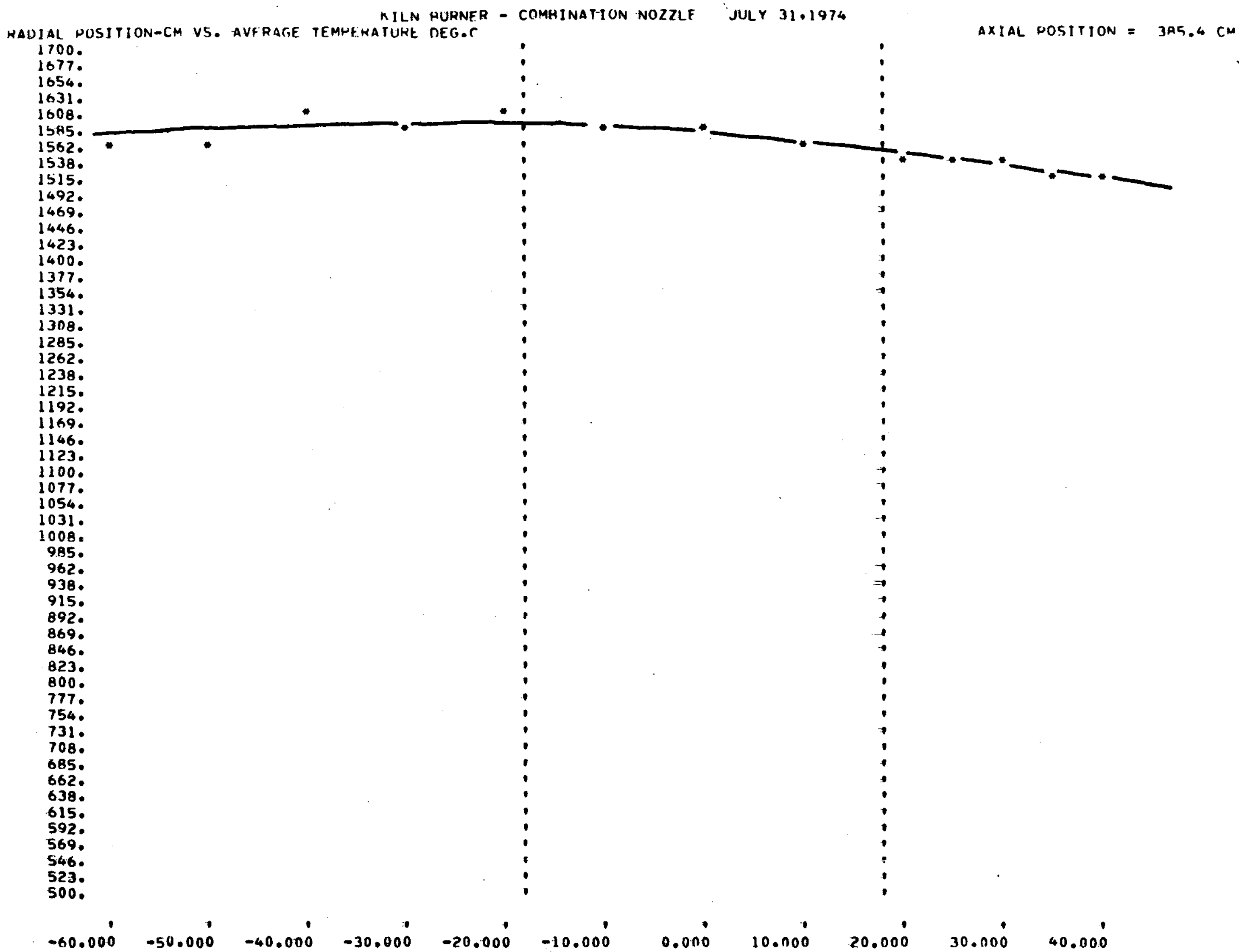

Figure 33. Combination kiln burner nozzle — radial profile of temperature at an axial position of 385. 4 cm

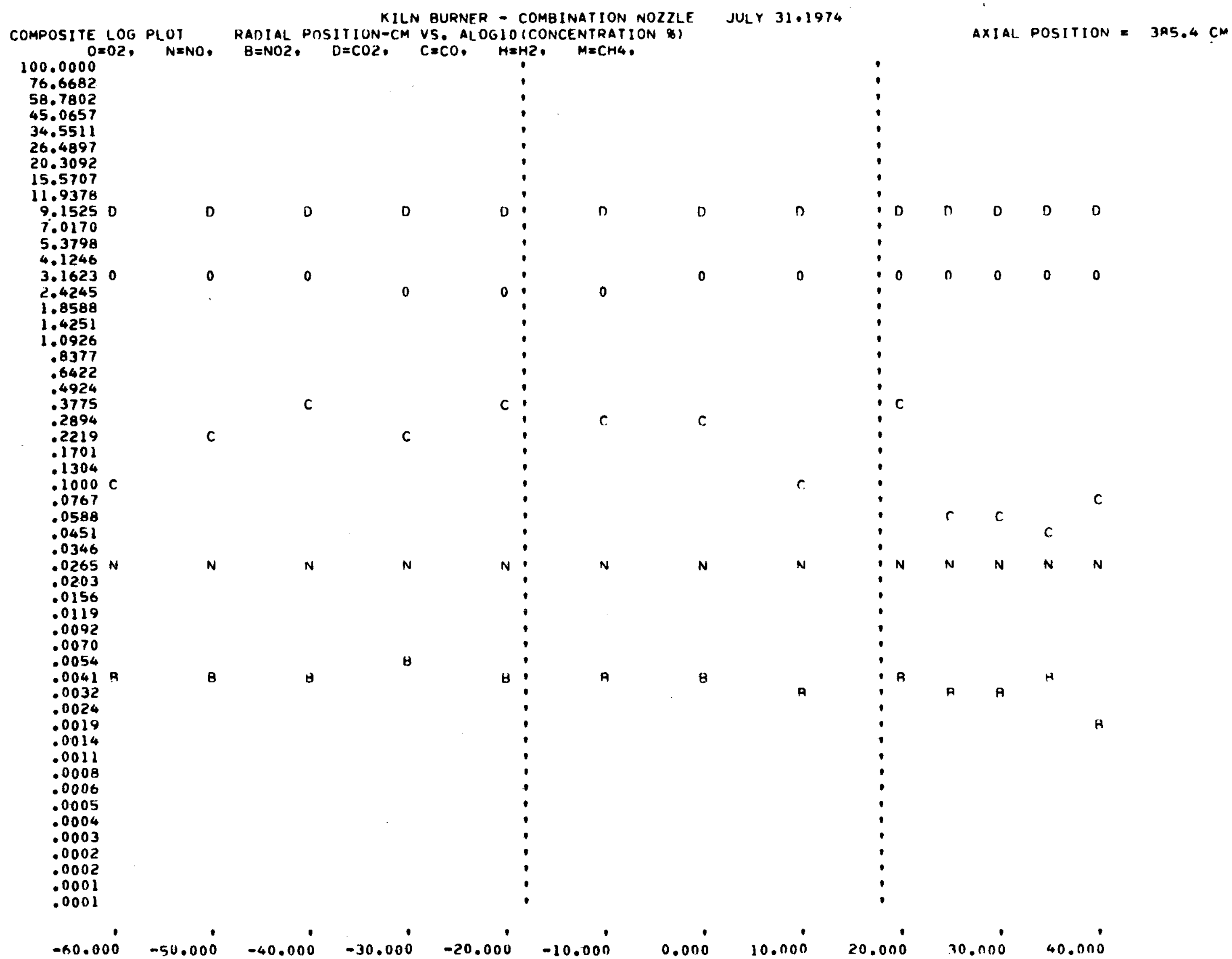

Figure 34. Combination kiln burner nozzle — radial profile of all the gases at an axial position of 385.4 cm

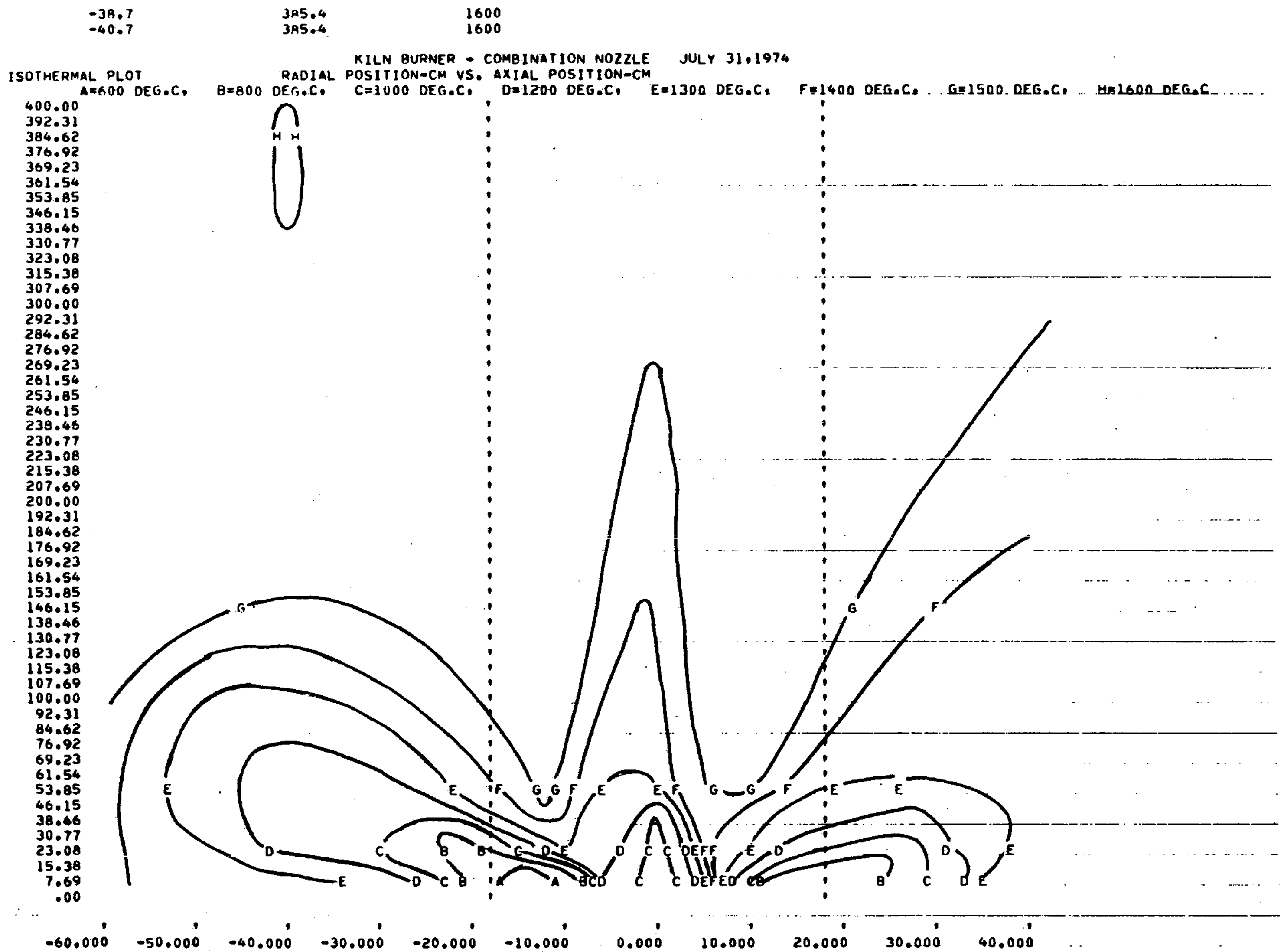

Figure 35. Combination kiln burner nozzle — isothermal plot of furnace temperature

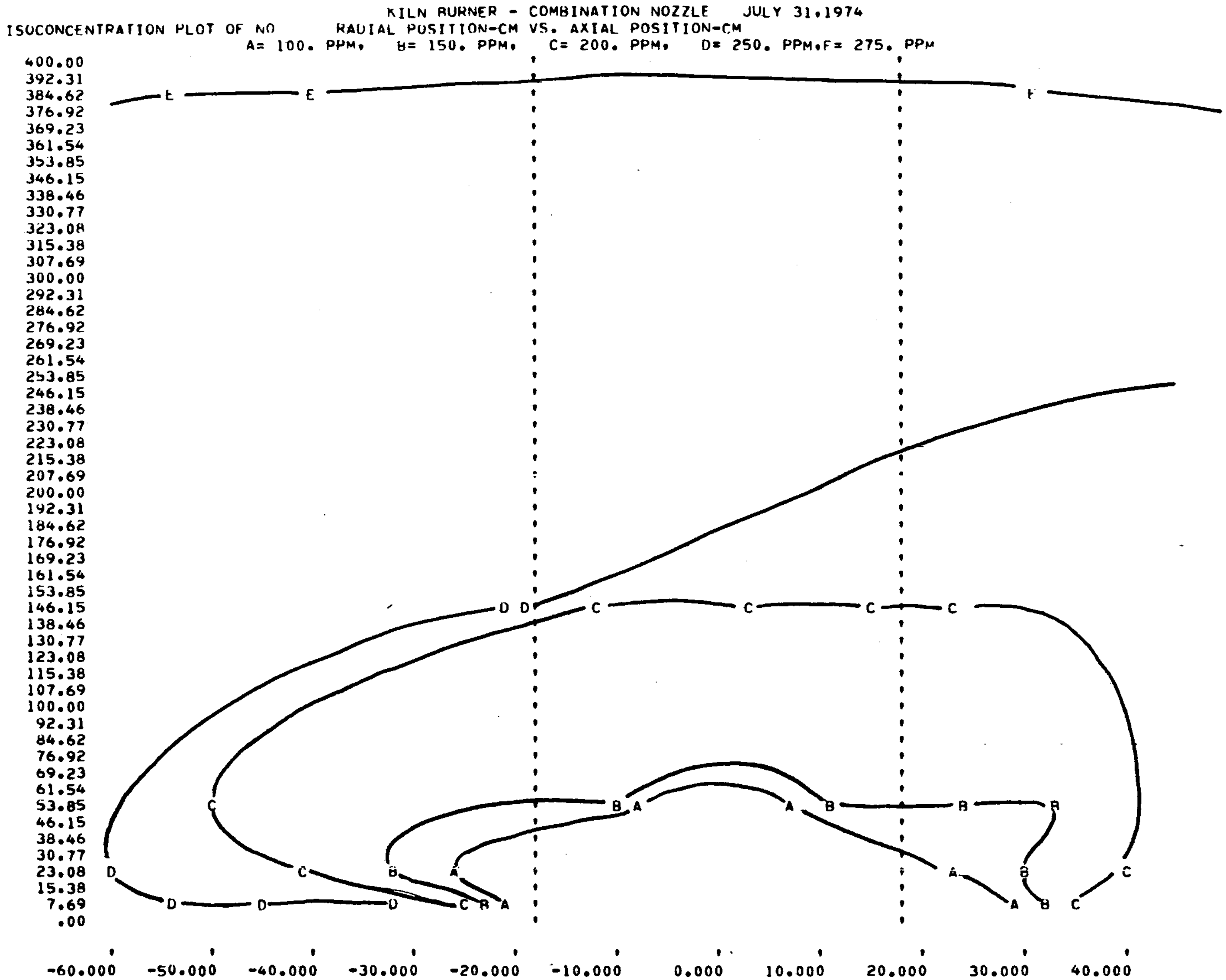

Figure 36. Combination kiln burner nozzle – isoconcentration plot of NO

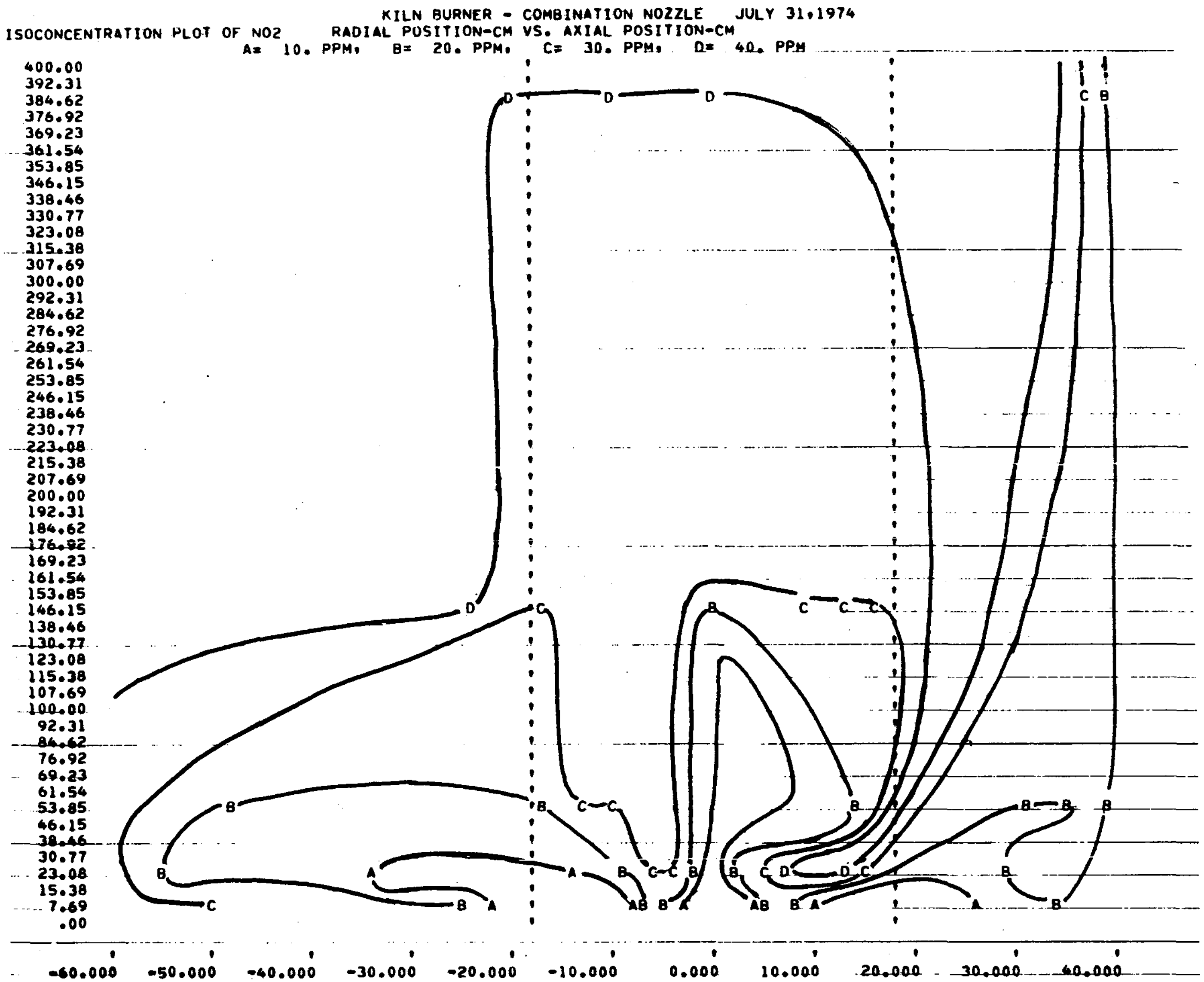

Figure 37. Combination kiln burner nozzle – isoconcentration plot of NO_2

Kiln Burner-Baseline Conditions

Table 3 lists the operating conditions at which baseline in-the-flame runs were made with the kiln burner (described in Volume I). The data obtained are shown in Table 4 and Figures 1 through 7 for an axial sampling position of 5.1 cm. Table 5 shows the results of radial sampling at an axial position of 26.0 cm. Figures 8 through 14 show plots of these data. The radial profile data at axial positions of 57.2 cm, 146.1 cm, and 385.4 cm are presented in Tables 6 to 8 and Figures 15 through 34.

The nitric oxide versus radial position plots show that the nitric oxide concentrations in the secondary recirculation zone (−60 cm to −24 cm) average about 250 ppm, as compared with a flue concentration of 265 ppm. Comparing this with the average NO concentration of 7 ppm in the burner-block region would indicate that 20.1 cm downstream of the gas injection, only a trace amount of the nitric oxide appears to be created through combustion.

The plots of nitrogen dioxide versus radial position show a pattern similar to that of nitric oxide in the secondary recirculation zone. However, in the burner-block area, there are two distinct peaks occurring at −6cm and +6 cm. The nitrogen dioxide concentrations measured in these peaks are 26 ppm and 29 ppm, respectively, as compared with a flue value of 36 ppm. The significance of these peaks will be discussed later.

The oxygen profile at the 5.1-cm axial position shows peaks at −12 cm and +20 cm, with concentrations of 20.2% and 20.4%, respectively, which represent the secondary combustion air input. A third peak occurs on the centerline of the burner with a 12.8% concentration. This peak would mainly represent the primary combustion air input.

The methane profile shows a 28.4% maximum concentration on the centerline of the burner and falls to zero at −9 cm and +6 cm in an asymmetrical pattern.

The carbon dioxide versus radial position curve shows that, in the secondary combustion air entrance zones (+12 cm to +24 cm and −9 cm to −18 cm as determined from the oxygen profile), the carbon dioxide concentrations vary from zero to 0.5%, as compared with secondary recirculation zone values of 8.0-10%. The carbon dioxide curve exhibits two peaks within the burner block (−6 cm and +6 cm). These peaks enclose a minimum which lies inside the methane core, along the centerline of the burner. This profile shows that there is a minimal amount of entrainment of secondary recirculation products into the burner-block region at the 5.1-cm axial position.

Figures 7, 14, 21, 28, and 34 show composite log plots of concentration versus radial position within the composition range of 0.0001% (1 ppm) - 100%. In these plots the interrelationships between concentration variations of oxygen, nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, hydrogen, and methane can easily be visualized.

Figures 6, 13, 20, 27, and 33 are plots of the average temperatures measured versus radial positions. In these profiles, the secondary recirculation zone shows a temperature in approximate equilibrium with the furnace walls. There is a sharp decrease in temperature in the secondary combustion air zones. Two peaks in temperature occur within the burner block at −6cm and +6 cm, with temperatures of 1216°C and 1437°C, respectively.

A correlation of the carbon dioxide, nitric oxide, temperature, and nitrogen dioxide profiles indicate that nitrogen dioxide is formed before nitric oxide in the flame (so-called "instantaneous NO_2"). The positions of the peaks (−6cm and +6 cm) inside the burner block coincide for temperature, carbon dioxide, and nitrogen dioxide. This agreement in the peak values for carbon dioxide and the temperature would indicate where the combustion is occurring. At these positions, the nitric oxide concentration is only 5% of its flue value, while nitrogen dioxide has 77% of its final concentration.

<u>Kiln Burner-NO Control Conditions</u>

The furnace conditions at which the control case in-the-flame probing was conducted are listed in Table 9. These conditions are identical to baseline operation except for 12% flue gas recirculation. This percentage of flue gas recirculation (% FGR) is determined using the relationship —

$$\%\ FGR = \frac{FGR(SCFH)}{Fuel(SCFH) + Primary\ Air(SCFH) + Secondary\ Air(SCFH)} \times 100$$

Table 9. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS–FURNACE CONDITIONS FOR IN-THE-FLAME SAMPLING WITH FLUE-GAS RECIRCULATION

```
                KILN BURNER-COMBINATION NOZZLE-POLLUTION CONTROL CONDITIONS

NUMBER OF SETS OF DATA =   6.
MINIMUM GRID VALUE OF AVERAGE TEMPERATURE =  550. DEG.C
MAXIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1550. DEG.C

POSITION OF OUTSIDE EDGES OF BURNER BLOCK
   MINIMUM POSITION = -23. CM
   MAXIMUM POSITION =  23. CM

GAS INPUT,     AXIAL  876. CF/HR        RADIAL 1830. CF/HR
WALL TEMPERATURE              1330. DEG.C
PREHEAT TEMPERATURE            460. DEG.C
FLUE GAS RECIRCULATION 12.0 %

GAS SAMPLE ANALYSIS IN THE FLUE
   NITROGEN OXIDE      120.0 PPM
   NITROGEN DIOXIDE     22.0 PPM
   OXYGEN                3.1 %
   CARBON DIOXIDE       10.1 %
   CARBON MONOXIDE     .0281 %

LIMITS FOR CONCENTRATION PLOTS
     LOWER LIMIT OF NO  =     0. PPM     UPPER LIMIT =  130. PPM
     LOWER LIMIT OF NO2 =     0. PPM     UPPER LIMIT =   35. PPM
     LOWER LIMIT OF O2  =     0. %       UPPER LIMIT =   21. %
     LOWER LIMIT OF CH4 =     0. %       UPPER LIMIT =   20. %
     LOWER LIMIT OF CO2 =     0. %       UPPER LIMIT =   11. %

ISOCONCENTRATION VALUES
   OBTAIN VALUE OF RADIAL POSITION AT NO  PPM CONCENTRATION    18.    43.    75.    90.   108.
   OBTAIN VALUE OF RADIAL POSITION AT NO2 PPM CONCENTRATION     4.     8.    14.    20.
```

The data obtained for an axial sampling position of 5. 1 cm are listed in Table 10 and plotted in Figures 38 through 45. Table 11 lists the results of radial sampling at an axial position of 26. 0 cm. Figures 46 through 53 show plots of these data. The radial profile data at axial positions of 57. 2 cm, 146. 1 cm, 290. 2 cm, and 385. 4 cm are presented in Tables 12 to 15 and Figures 54 through 83.

Flow direction analysis at the 5. 1-cm axial position shows secondary recirculation zones exist in the regions –60 cm to –30 cm and +30 cm to the furnace wall. Inside the edges of the burner block, +23 cm to –23 cm, there are three resolved peaks. The high-velocity central peak represents the axially injected gas and primary air, while the two lower velocity flanking peaks represent the secondary combustion air. These flow peaks occur at radial positions of –3 cm, –18 cm, and +20 cm, respectively.

Correlating the 5. 1-cm axial position temperature profile to the above flow analysis, a constant temperature of 1281 °C exists in the regions of recirculation (compared with a wall temperature of 1330 °C). At the peak secondary combustion air inlets, the temperature drops to 556 °C and 637 °C. In the central forward flow region, the temperature is 1211 °C. Inside the burner block area two peaks occur in the temperature at –6 cm and +3 cm, with values of 1331 °C and 1318 °C, respectively.

Figure 38, the nitric oxide versus radial position plot, shows that the nitric oxide concentrations in the secondary recirculation zone (–60 cm to –30 cm) average about 111 ppm, as compared with a flue concentration of 120 ppm. Comparing this with the average NO concentration of 15 ppm in the burner-block region would indicate that at 20. 1-cm downstream of the gas injection, only trace amounts of nitric oxide appear to be created through combustion.

The plots of nitrogen dioxide versus radial position show a pattern similar to that of nitric oxide in the secondary recirculation zone. However, in the burner-block area, there are two distinct peaks occurring at –6 cm and +3 cm. The nitrogen dioxide concentrations measured in these peaks are 24 ppm and 26 ppm, respectively, as compared with a flue value of 22 ppm.

Table 10. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS – IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 5.1 cm

KILN BURNER-COMBINATION NOZZLF-POLLUTION CONTROL CONDITIONS

AXIAL POSITION = 5.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.4	?	105.	20.	9.2	.0020	?	0.0	?	?	?	?	1287.	1293.	6.
-48.	5.0	?	110.	18.	8.9	.0018	?	0.0	?	?	?	?	1291.	1292.	1.
-39.	4.7	?	115.	19.	9.1	.0016	?	0.0	?	?	?	?	1286.	1286.	0.
-36.	5.0	?	114.	22.	8.9	.0015	?	0.0	?	?	?	?	1277.	1281.	4.
-33.	4.7	?	115.	18.	9.0	.0016	?	0.0	?	?	?	?	1277.	1279.	2.
-30.	4.9	?	110.	20.	9.1	.0015	?	0.0	?	?	?	?	1258.	1271.	13.
-27.	5.1	?	97.	16.	8.9	.0012	?	0.0	?	?	?	?	1191.	1222.	31.
-25.	6.4	?	85.	13.	8.3	.0014	?	0.0	?	?	?	?	1090.	1138.	48.
-24.	7.9	?	76.	12.	7.4	.0016	?	0.0	?	?	?	?	959.	995.	36.
-22.	12.6	?	24.	5.	4.7	.0011	?	0.0	?	?	?	?	679.	737.	58.
-18.	17.2	?	15.	2.	1.3	.0010	?	0.0	?	?	?	?	553.	556.	3.
-15.	17.1	?	14.	1.	1.3	.0011	?	0.0	?	?	?	?	604.	652.	48.
-12.	16.2	?	14.	2.	1.4	.0176	?	0.0	?	?	?	?	643.	728.	85.
-6.	15.2	78.3	10.	24.	2.7	.5900	.5	1.6	.1	.1	0.0	.0	1331.	1404.	73.
-3.	11.2	64.3	6.	10.	2.2	1.6900	2.0	16.3	.5	.7	0.0	.4	1166.	1284.	118.
0.	11.2	63.5	7.	17.	2.0	1.5200	1.8	17.6	.5	.8	0.0	.4	1126.	1211.	85.
3.	10.7	71.5	10.	26.	3.2	2.0300	2.2	8.6	.4	.4	0.0	.2	1318.	1386.	68.
6.	14.4	80.0	22.	6.	3.3	.4500	.3	.5	.0	.0	0.0	0.0	722.	770.	48.
12.	18.9	?	19.	4.	1.4	.0019	?	0.0	?	?	?	?	614.	670.	56.
18.	18.4	?	18.	9.	1.7	.0026	?	0.0	?	?	?	?	611.	690.	79.
20.	17.8	?	19.	6.	1.7	.0027	?	0.0	?	?	?	?	611.	637.	26.
24.	15.8	?	43.	8.	3.4	.0028	?	0.0	?	?	?	?	984.	1039.	55.
30.	6.2	?	100.	25.	8.4	.0038	?	0.0	?	?	?	?	1259.	1273.	14.
36.	6.7	?	98.	22.	8.0	.0035	?	0.0	?	?	?	?	1275.	1282.	7.

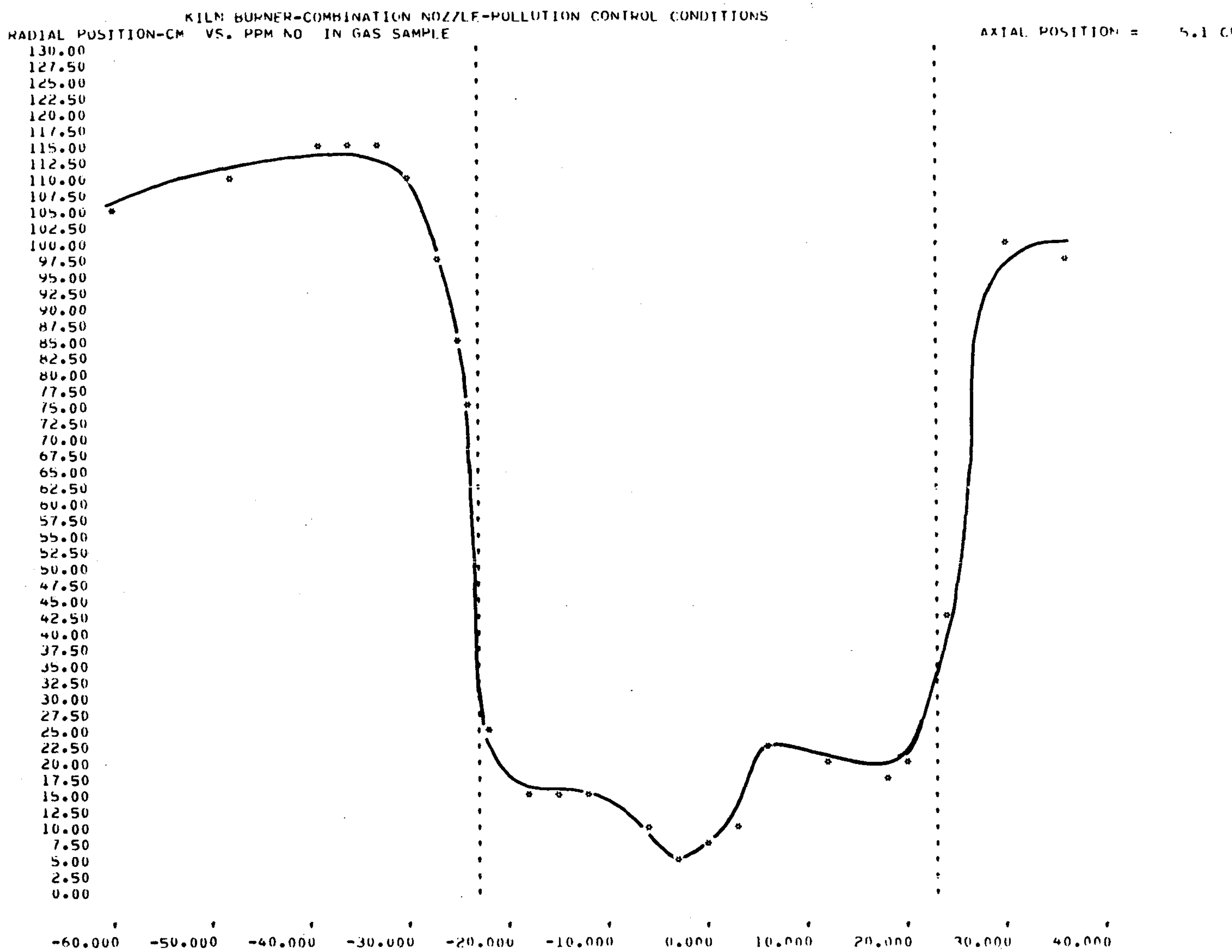

Figure 38. Combination kiln burner nozzle – pollution control conditions – radial profile of NO at an axial position of 5.1 cm

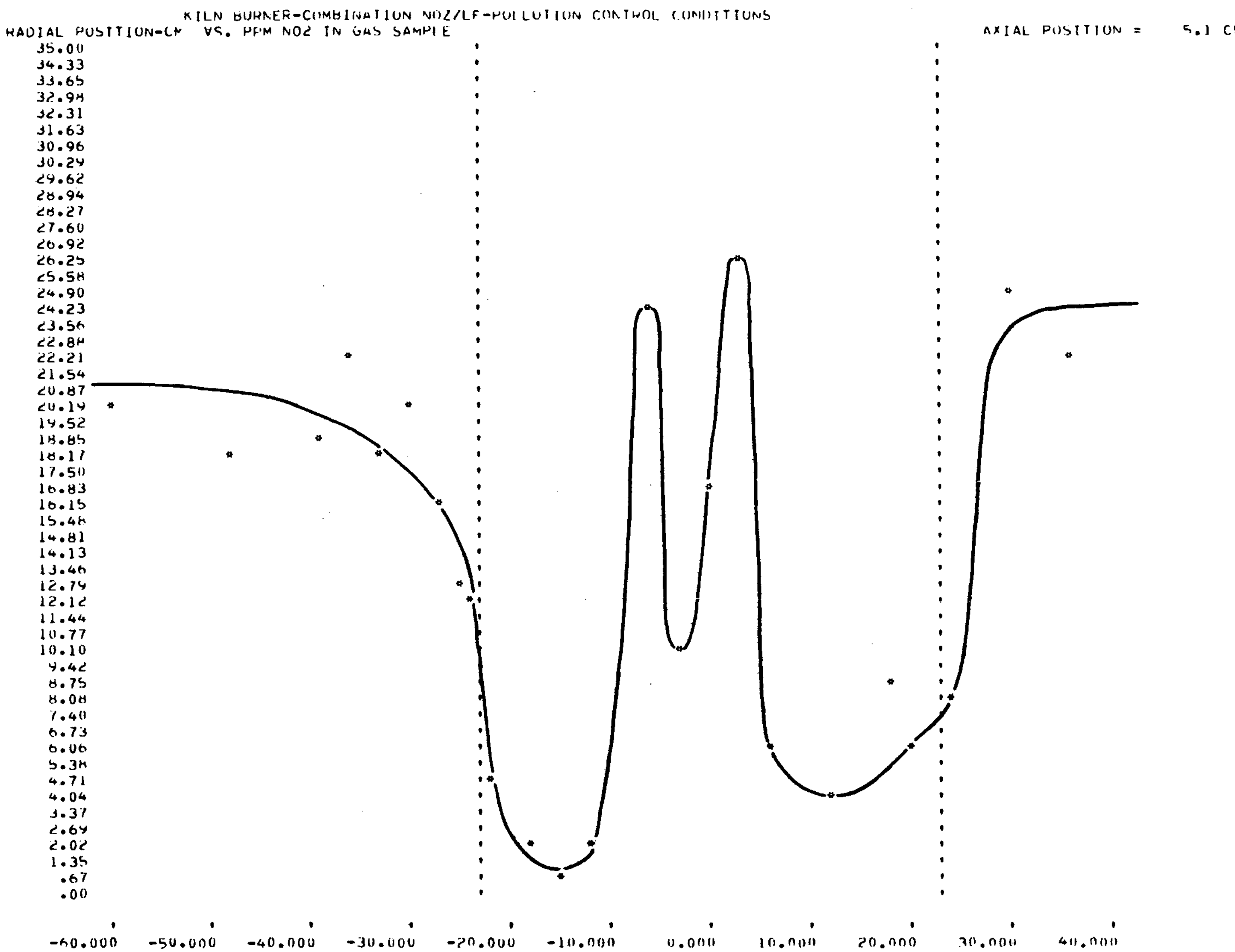

Figure 39. Combination kiln burner nozzle – pollution control conditions – radial profile of NO_2 at an axial position of 5.1 cm

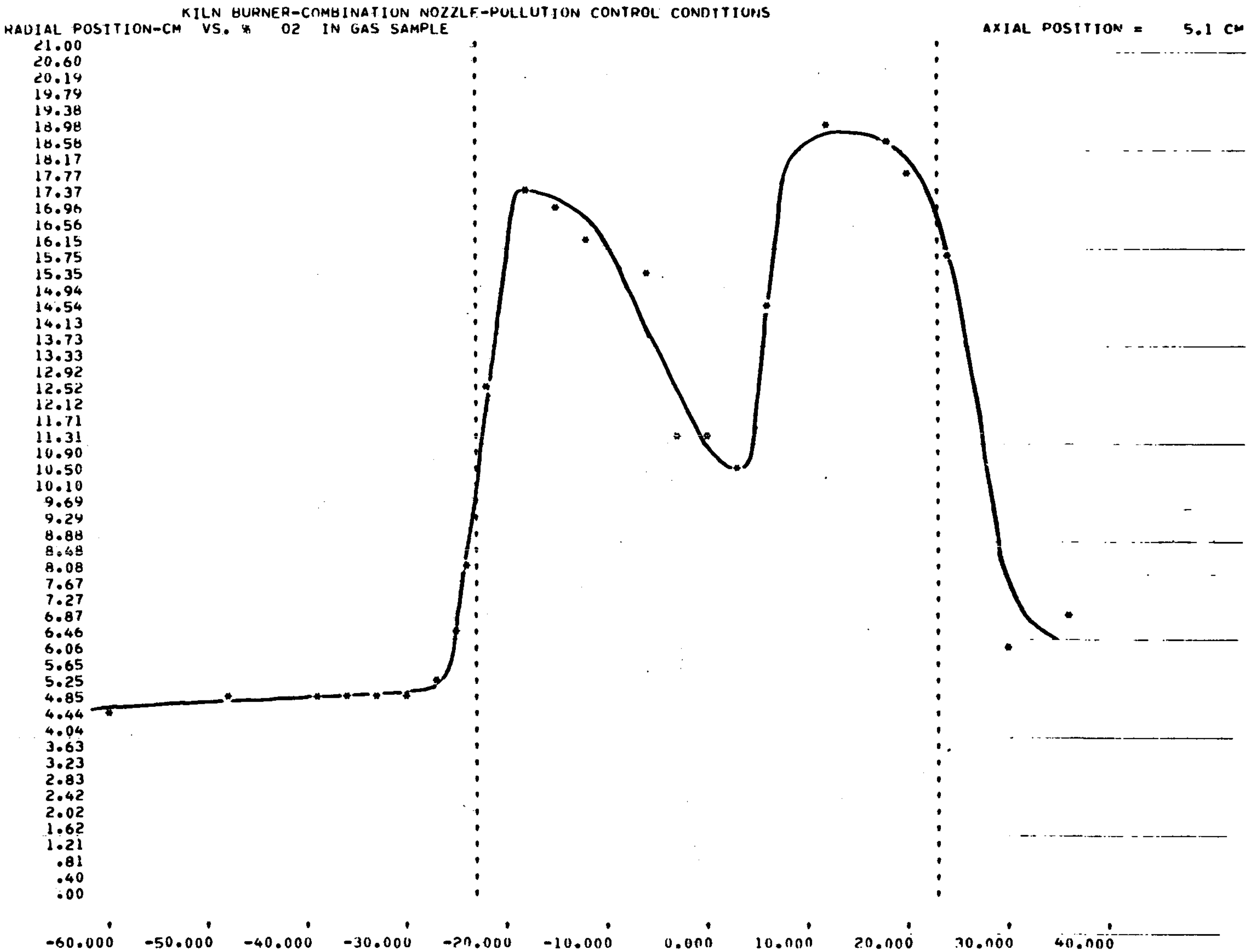

Figure 40. Combination kiln burner nozzle – pollution control conditions – radial profile of O_2 at an axial position of 5.1 cm

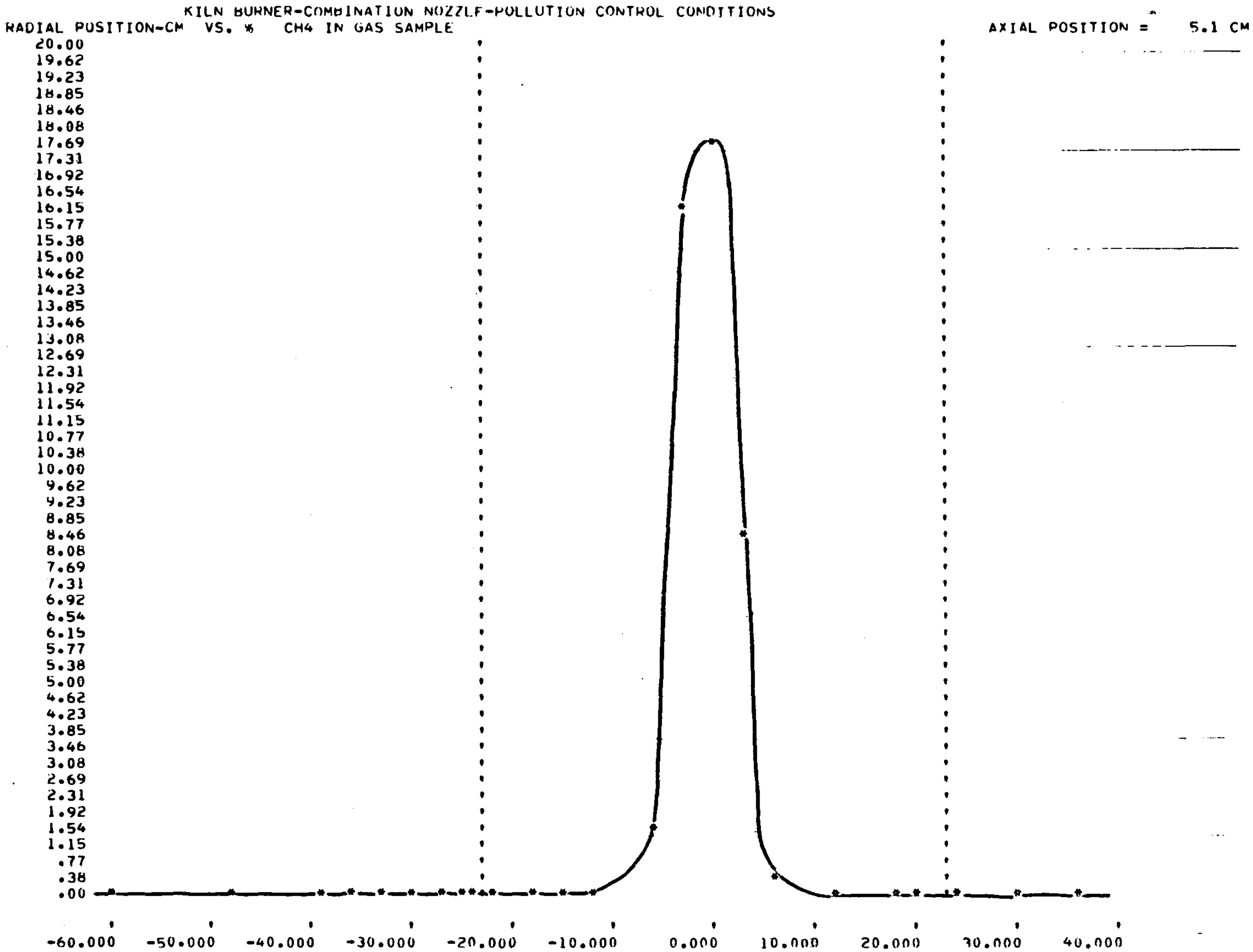

Figure 41. Combination kiln burner nozzle – pollution control conditions – radial profile of CH_4 at an axial position of 5. 1 cm

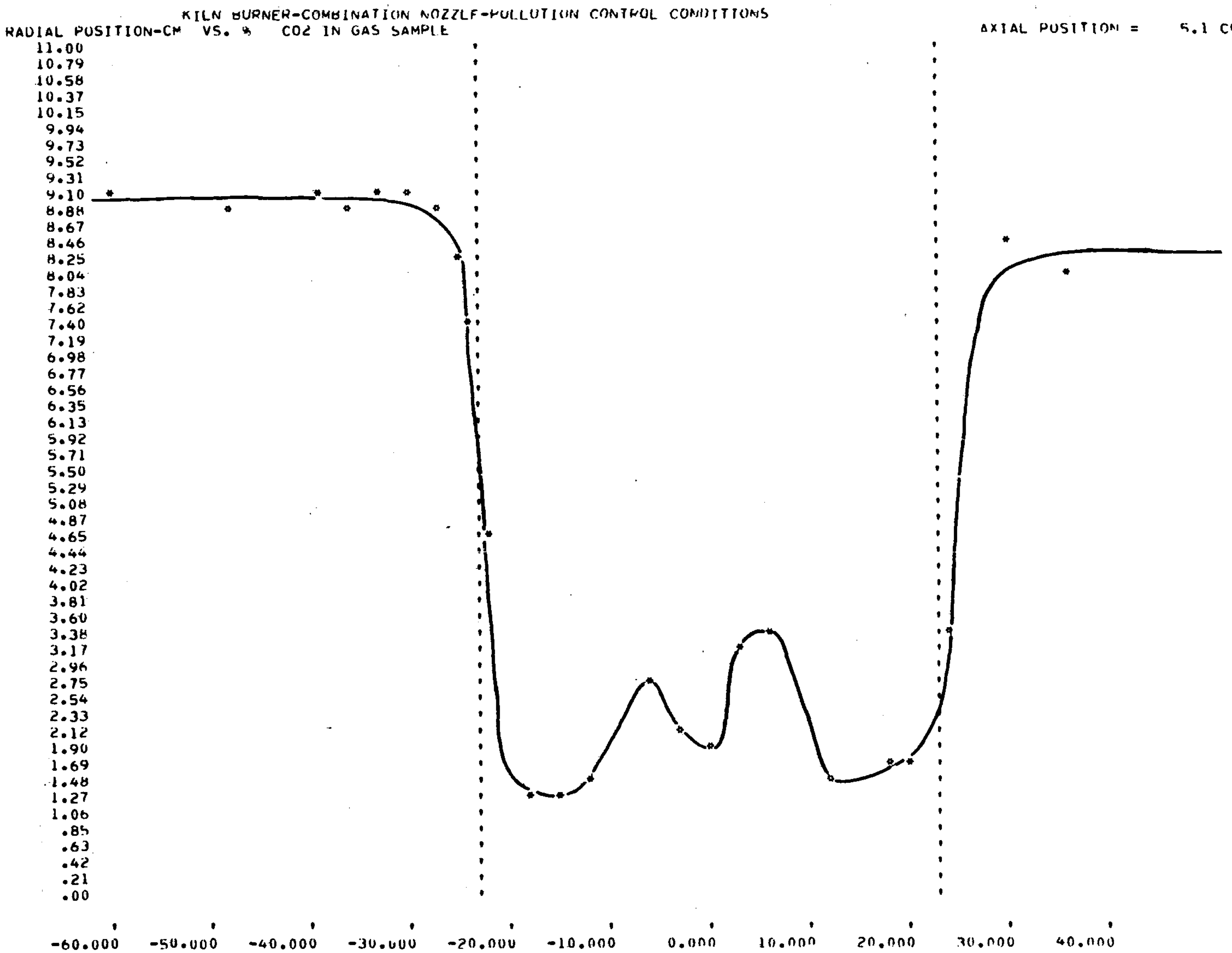

Figure 42. Combination kiln burner nozzle – pollution control conditions – radial profile of CO_2 at an axial position of 5. 1 cm

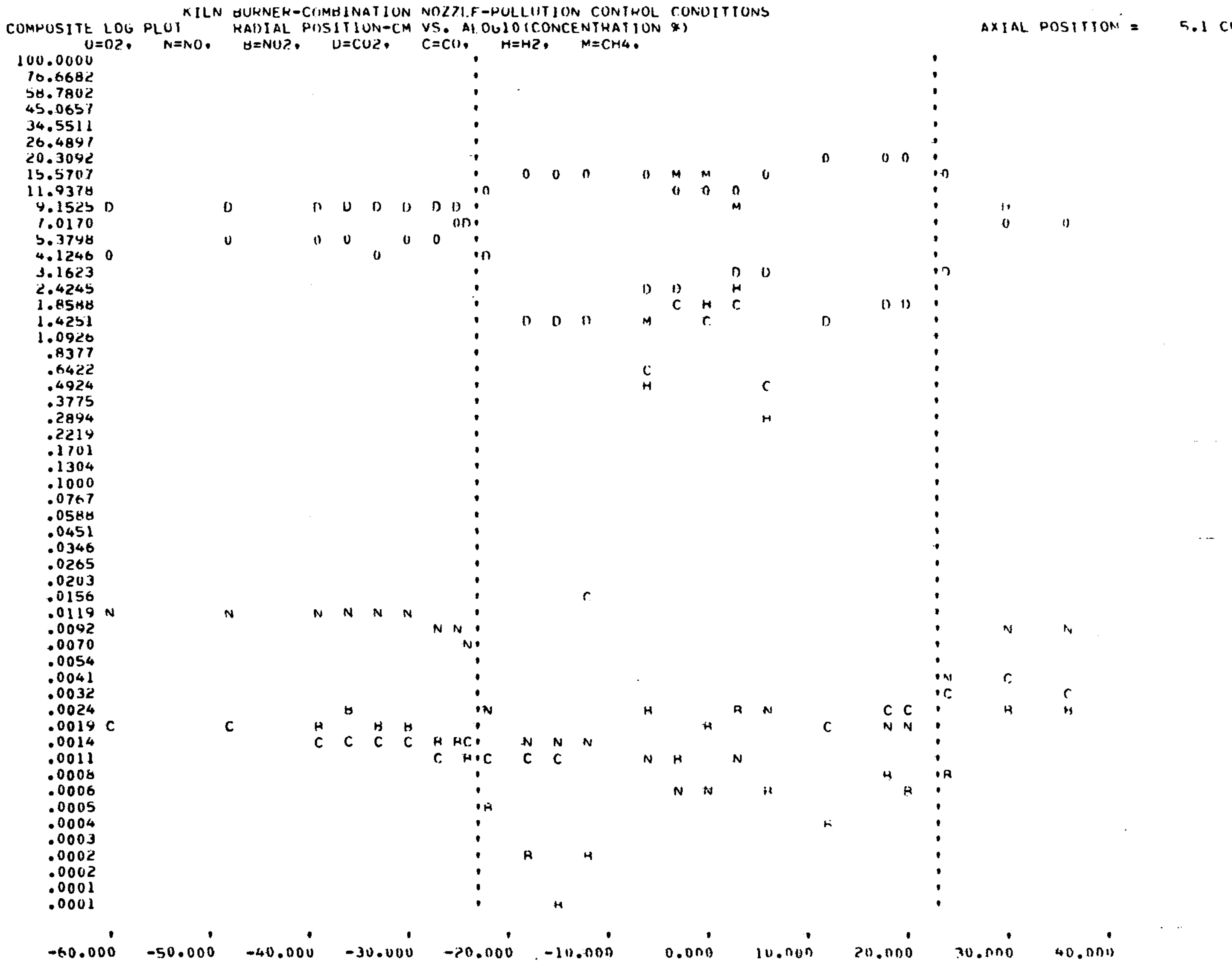

Figure 43. Combination kiln burner nozzle – pollution control conditions – radial profile of all the gases at an axial position of 5.1 cm

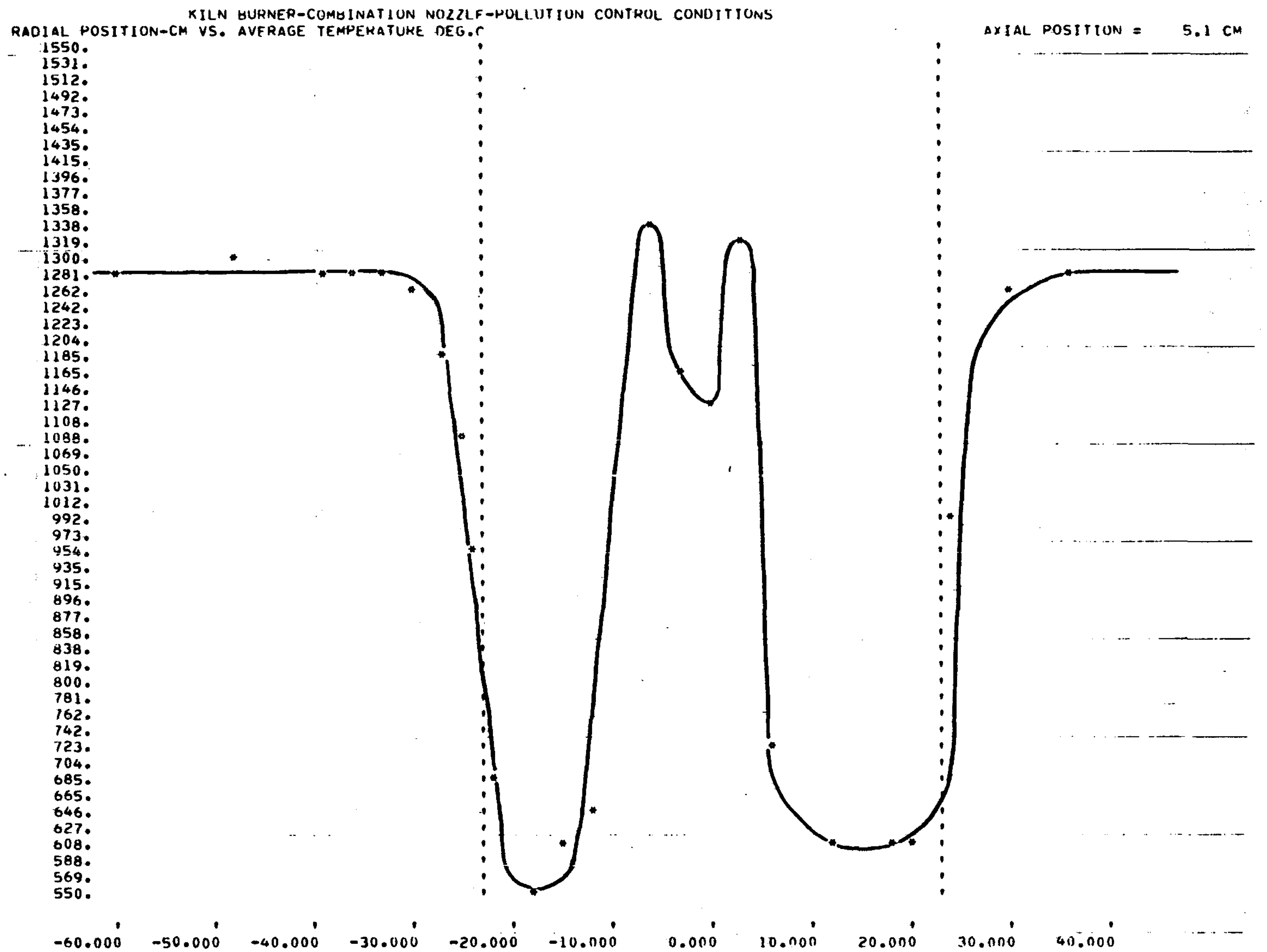

Figure 44. Combination kiln burner nozzle — pollution control conditions — radial profile of temperature at an axial position of 5. 1 cm

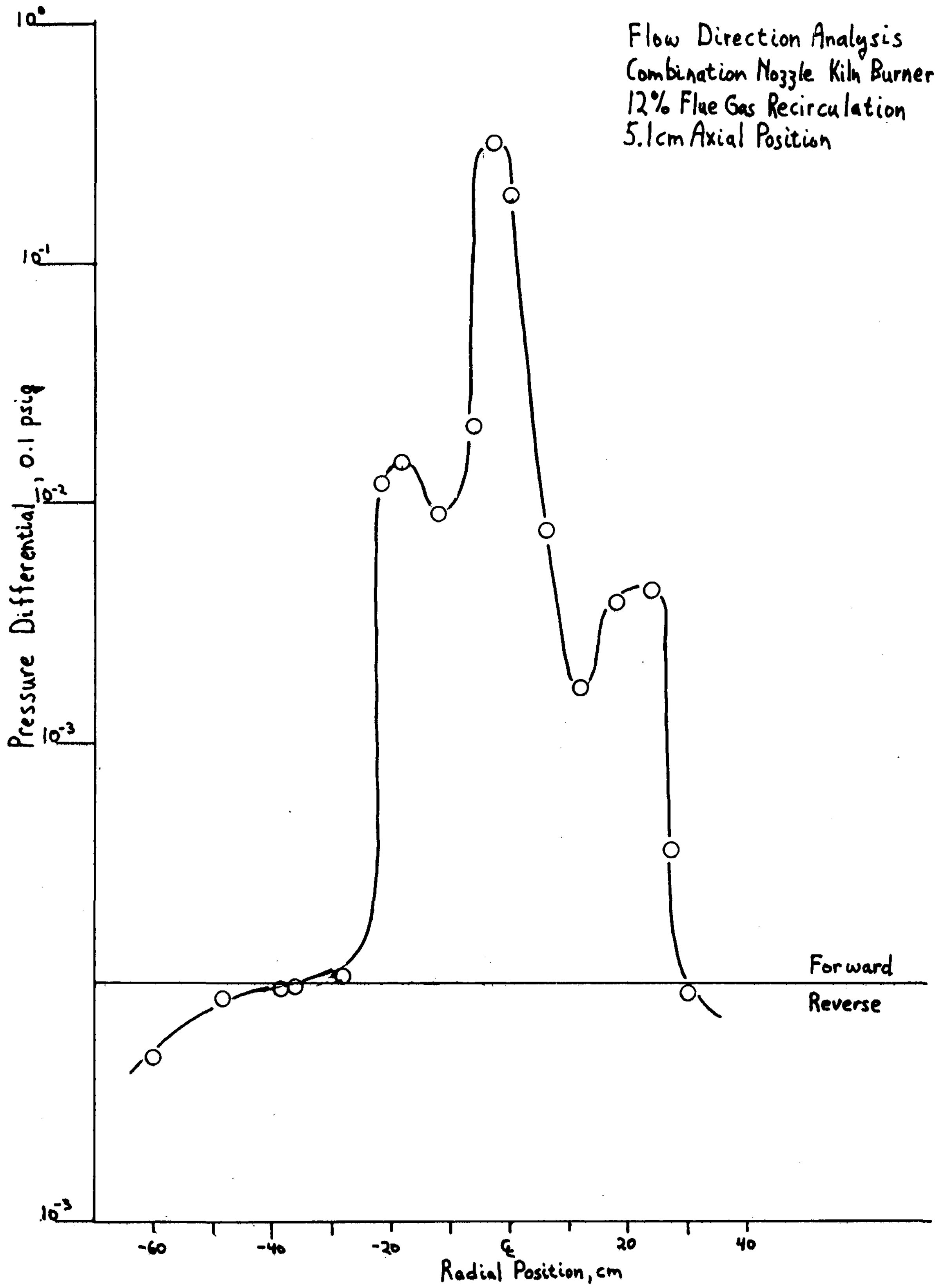

Figure 45. Combination kiln burner nozzle – pollution control conditions – radial profile of flow direction at an axial position of 5.1 cm

Table 11. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS – IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 26.0 cm

KILN BURNER-COMBINATION NOZZLE-POLLUTION CONTROL CONDITIONS

AXIAL POSITION = 26.0 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.9	?	107.	19.	8.6	.0027	?	0.0	?	?	?	?	1294.	1299.	5.
-54.	5.1	?	102.	23.	8.5	.0025	?	0.0	?	?	?	?	1288.	1299.	11.
-48.	5.0	?	103.	21.	8.5	.0026	?	0.0	?	?	?	?	1288.	1290.	2.
-42.	5.4	?	101.	22.	8.0	.0025	?	0.0	?	?	?	?	1237.	1268.	31.
-36.	7.2	?	95.	20.	7.8	.0024	?	0.0	?	?	?	?	1191.	1287.	96.
-30.	10.0	?	80.	13.	6.4	.0020	?	0.0	?	?	?	?	1032.	1160.	128.
-24.	15.2	?	45.	10.	3.2	.0018	?	0.0	?	?	?	?	807.	868.	61.
-18.	16.8	?	28.	8.	2.4	.0037	?	0.0	?	?	?	?	864.	954.	90.
-12.	14.2	80.1	26.	16.	3.6	.4700	.4	.1	.1	.0	0.0	0.0	1175.	1317.	142.
-9.	8.3	83.5	24.	35.	3.3	1.4500	1.4	.8	.1	.0	0.0	0.0	1364.	1414.	50.
-6.	5.3	68.7	16.	28.	4.3	4.3300	7.8	7.6	1.0	.3	.0	.1	1211.	1254.	43.
-3.	6.9	62.9	15.	18.	3.0	3.6300	7.1	13.8	1.1	.5	.0	.2	1143.	1190.	47.
0.	7.0	62.7	14.	16.	3.0	3.5100	7.6	13.5	1.1	.5	0.0	.4	1288.	1357.	69.
3.	5.8	69.1	18.	31.	4.0	4.0400	4.7	9.8	1.1	.4	0.0	.1	1338.	1378.	40.
6.	8.4	79.4	28.	17.	5.3	2.1600	2.0	1.5	.2	.0	0.0	0.0	1057.	1229.	172.
9.	14.3	80.7	37.	9.	3.8	.2200	0.0	.1	0.0	0.0	0.0	0.0	869.	990.	121.
12.	15.3	?	35.	5.	3.2	.0265	?	0.0	?	?	?	?	787.	880.	93.
15.	16.0	?	41.	4.	3.0	.0010	?	0.0	?	?	?	?	825.	900.	75.
18.	14.2	?	45.	7.	4.1	.0012	?	0.0	?	?	?	?	891.	1107.	216.
24.	12.2	?	74.	12.	5.5	.0013	?	0.0	?	?	?	?	1096.	1211.	115.
30.	8.5	?	87.	18.	7.2	.0017	?	0.0	?	?	?	?	1242.	1274.	32.
36.	5.2	?	93.	21.	9.2	.0023	?	0.0	?	?	?	?	1264.	1288.	24.

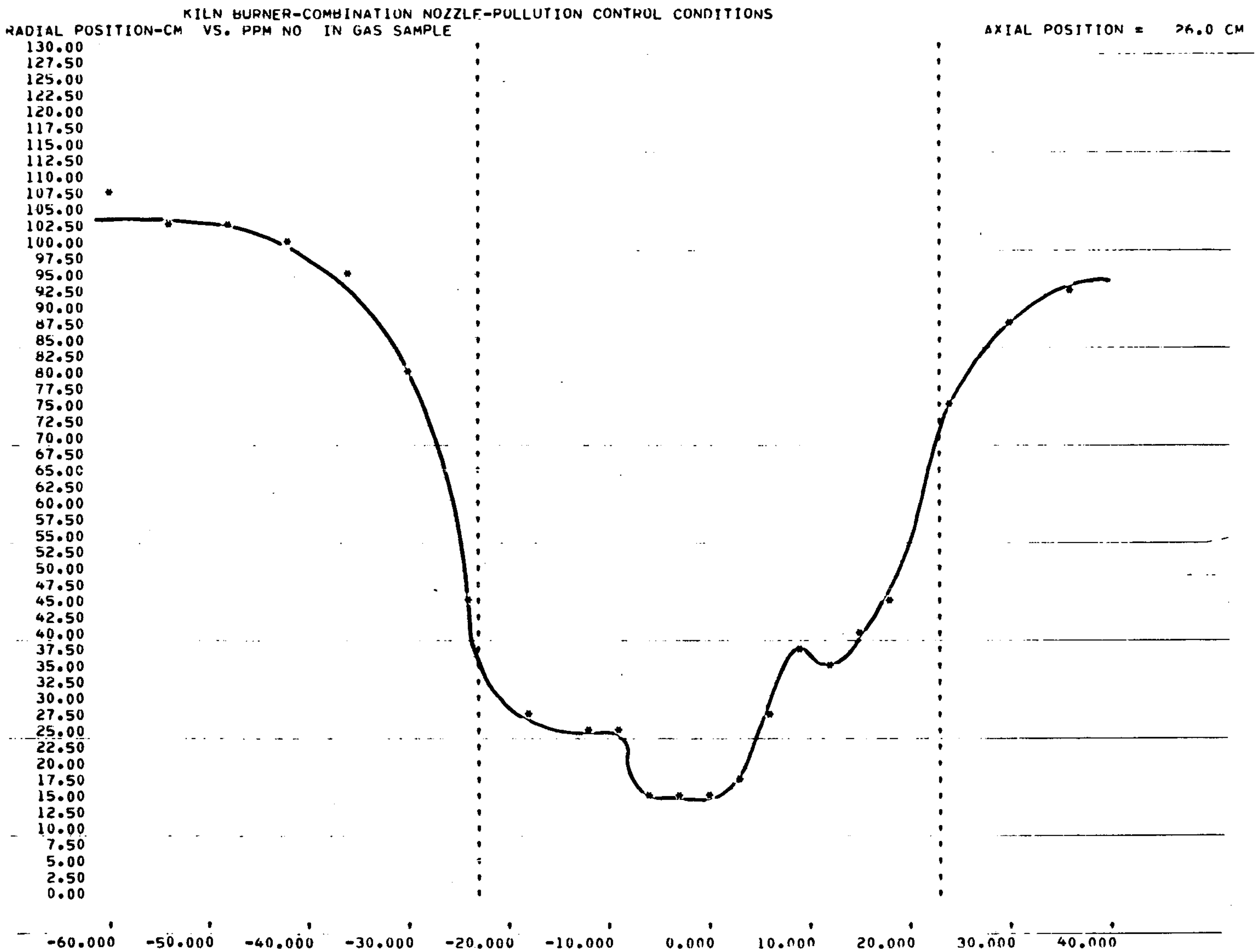

Figure 46. Combination kiln burner nozzle – pollution control conditions – radial profile of NO at an axial position of 26.0 cm

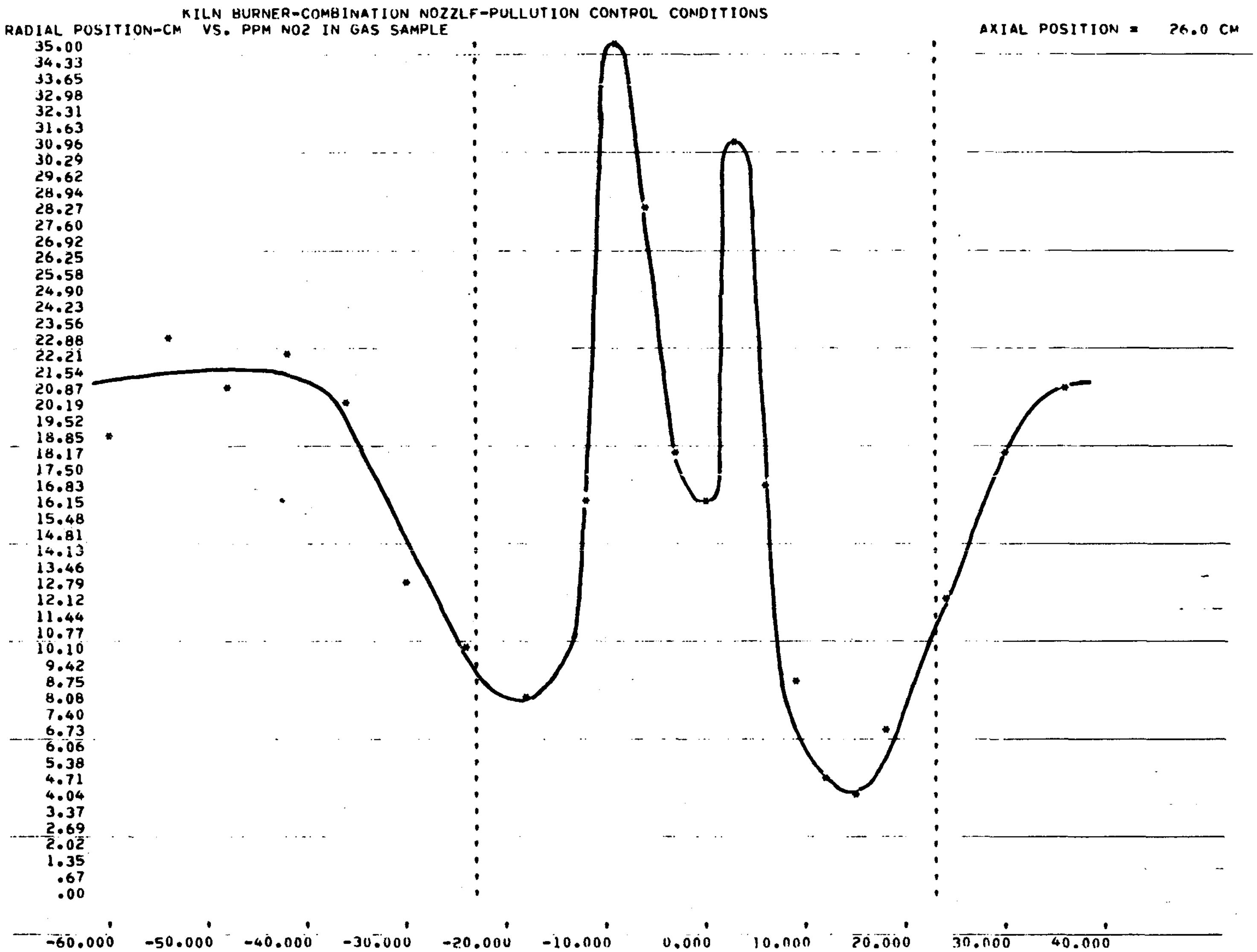

Figure 47. Combination kiln burner nozzle – pollution control conditions – radial profile of NO_2 at an axial position of 26.0 cm

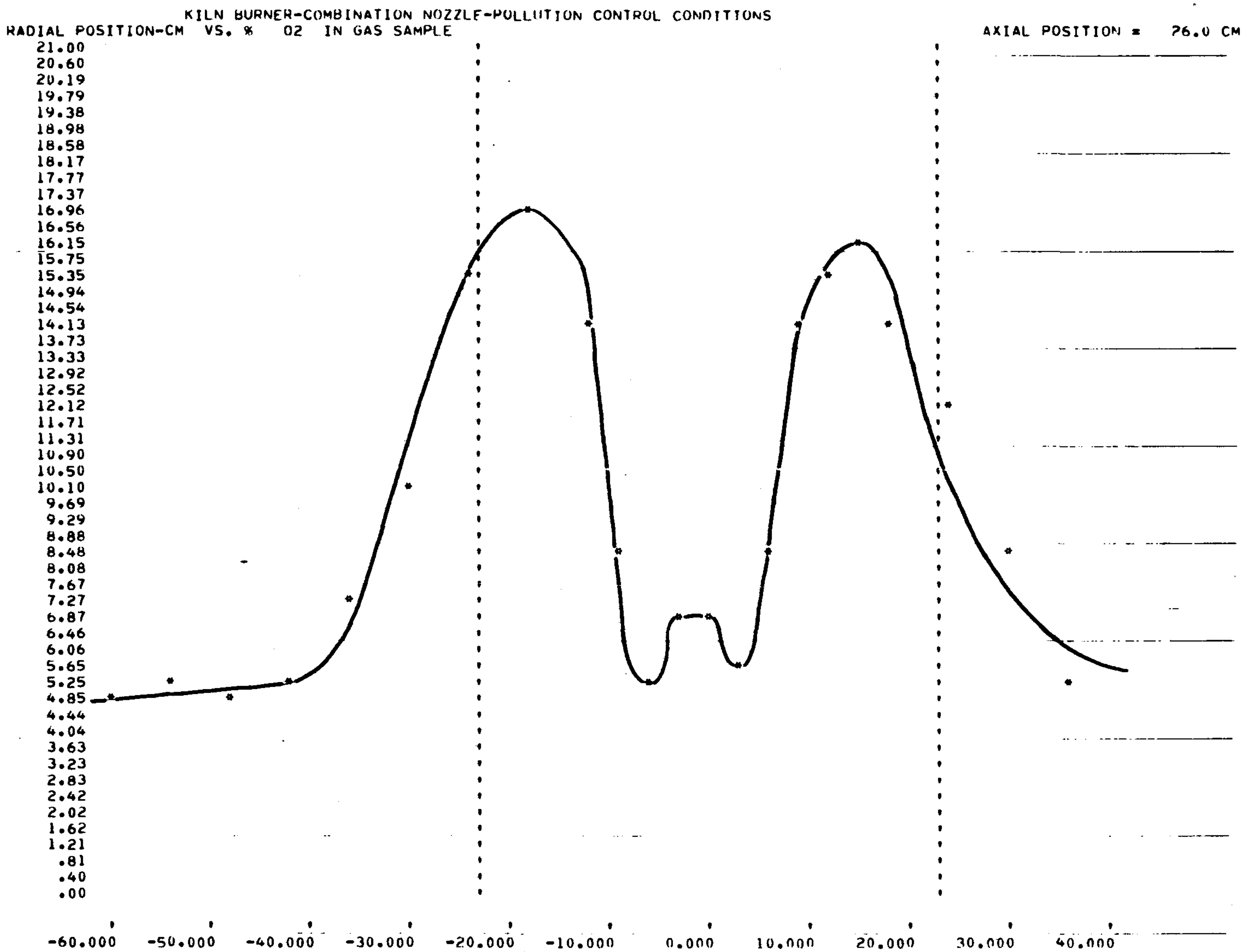

Figure 48. Combination kiln burner nozzle – pollution control conditions – radial profile of O_2 at an axial position of 26.0 cm

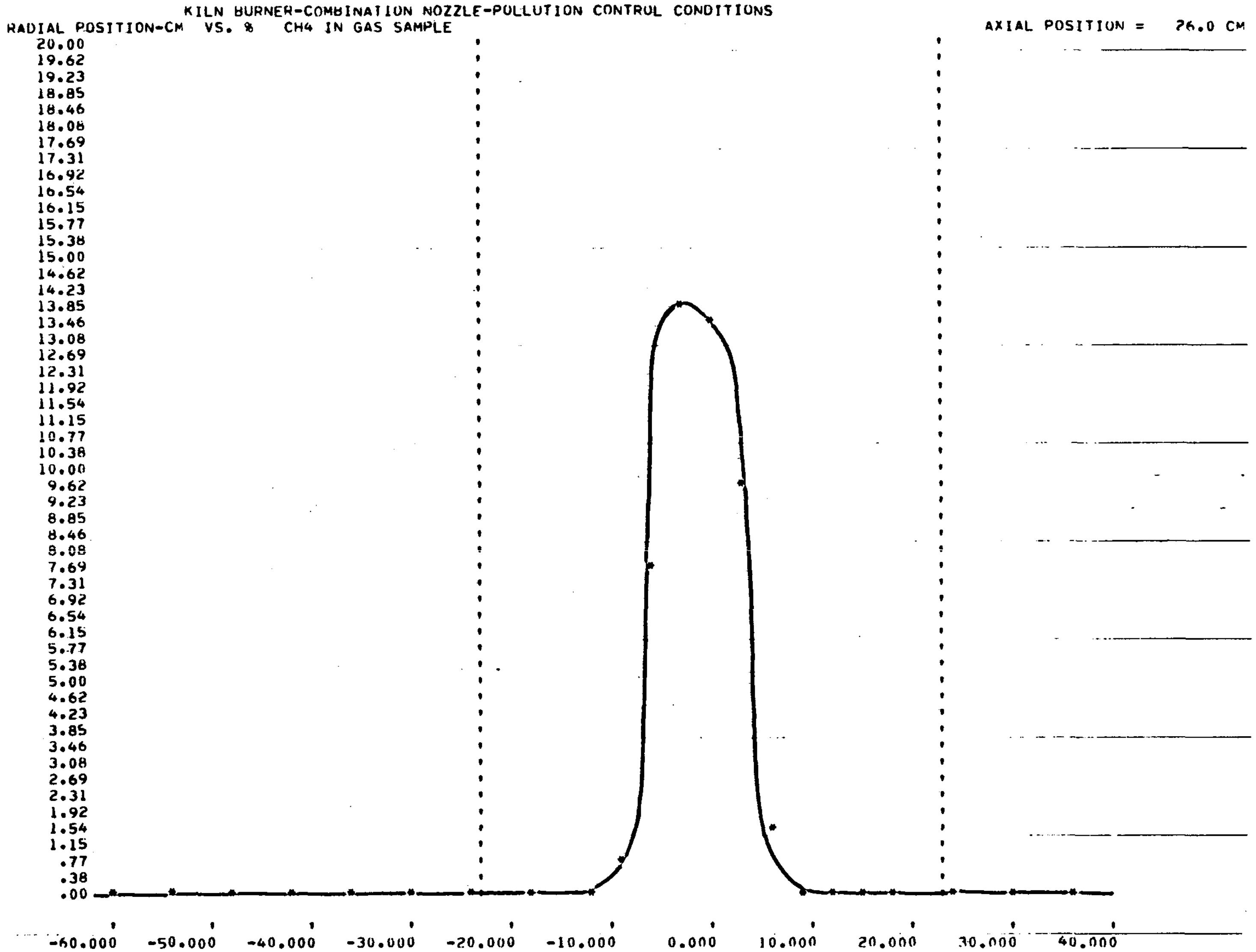

Figure 49. Combination kiln burner nozzle – pollution control conditions – radial profile of CH_4 at an axial position of 26.0 cm

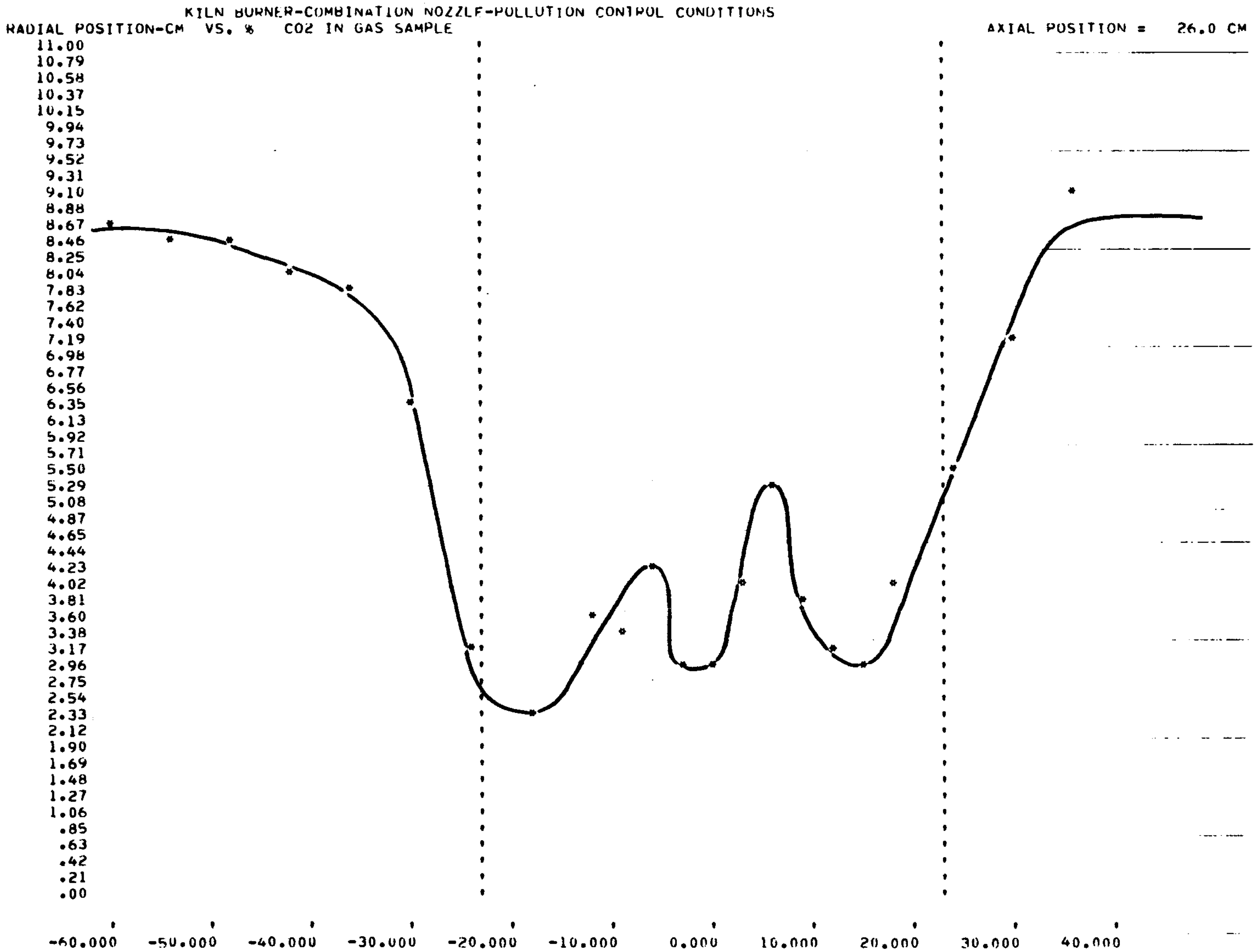

Figure 50. Combination kiln burner nozzle – pollution control conditions – radial profile of CO_2 at an axial position of 26.0 cm

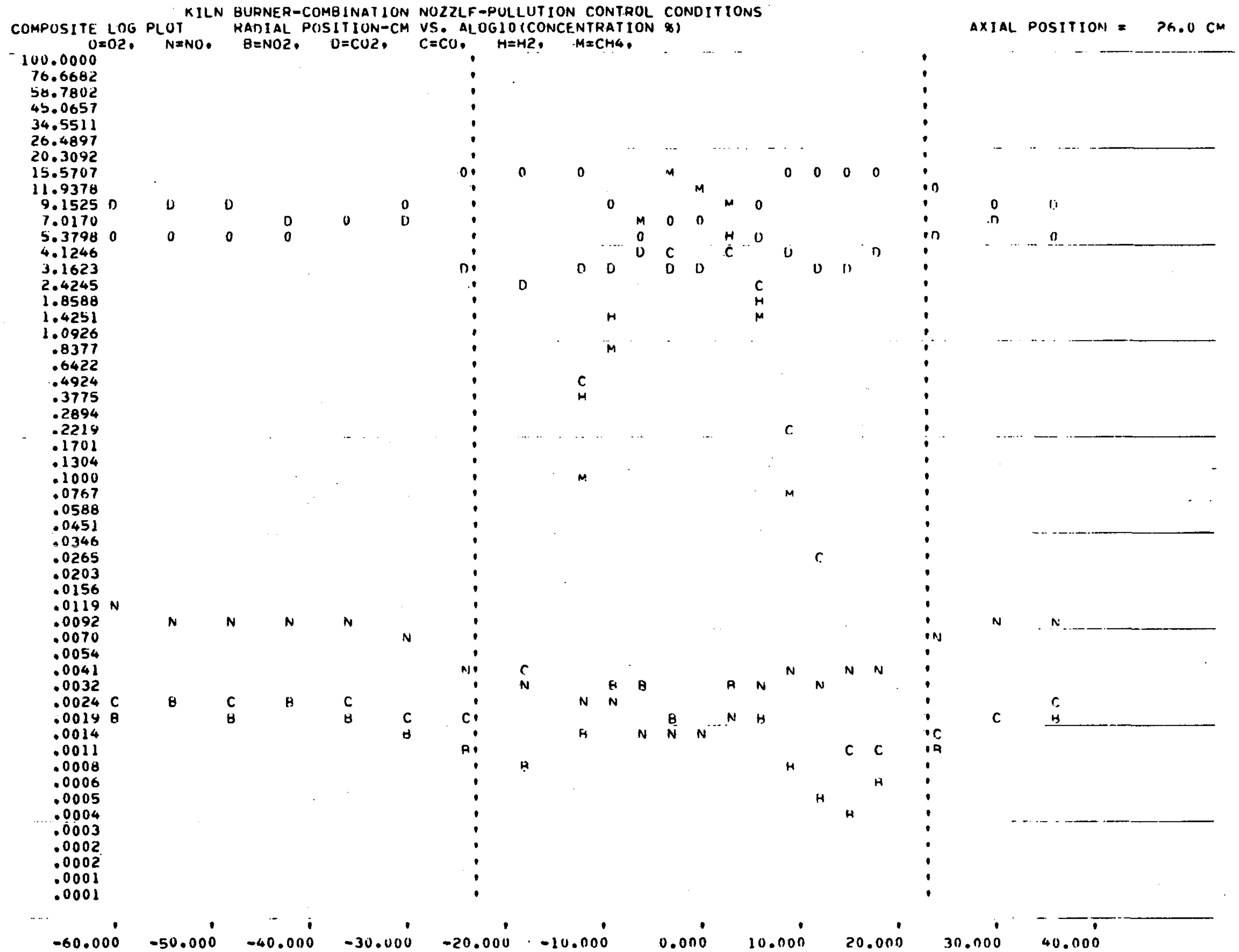

Figure 51. Combination kiln burner nozzle – pollution control conditions – radial profile of all the gases at an axial position of 26.0 cm

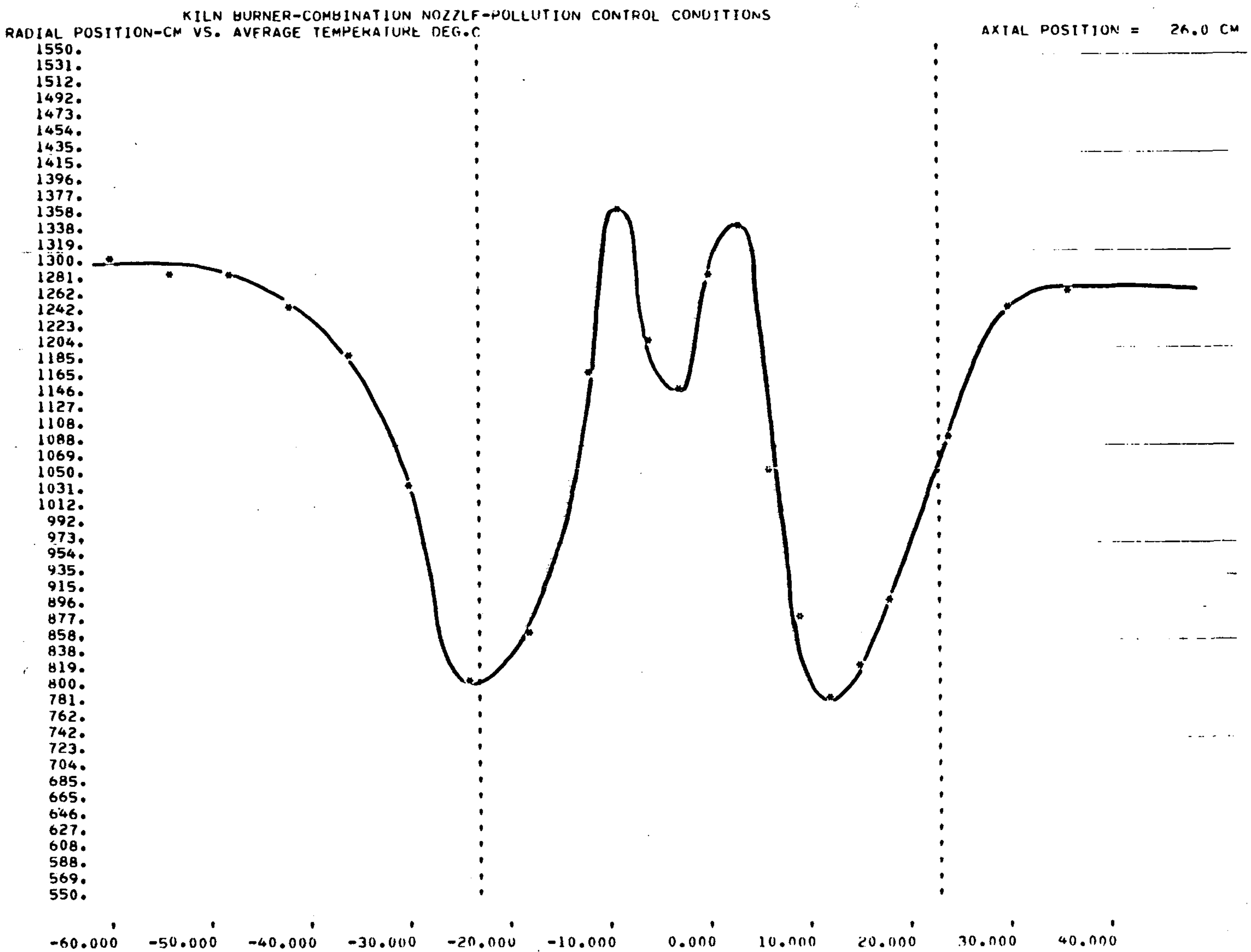

Figure 52. Combination kiln burner nozzle — pollution control conditions — radial profile of temperature at an axial position of 26. 0 cm

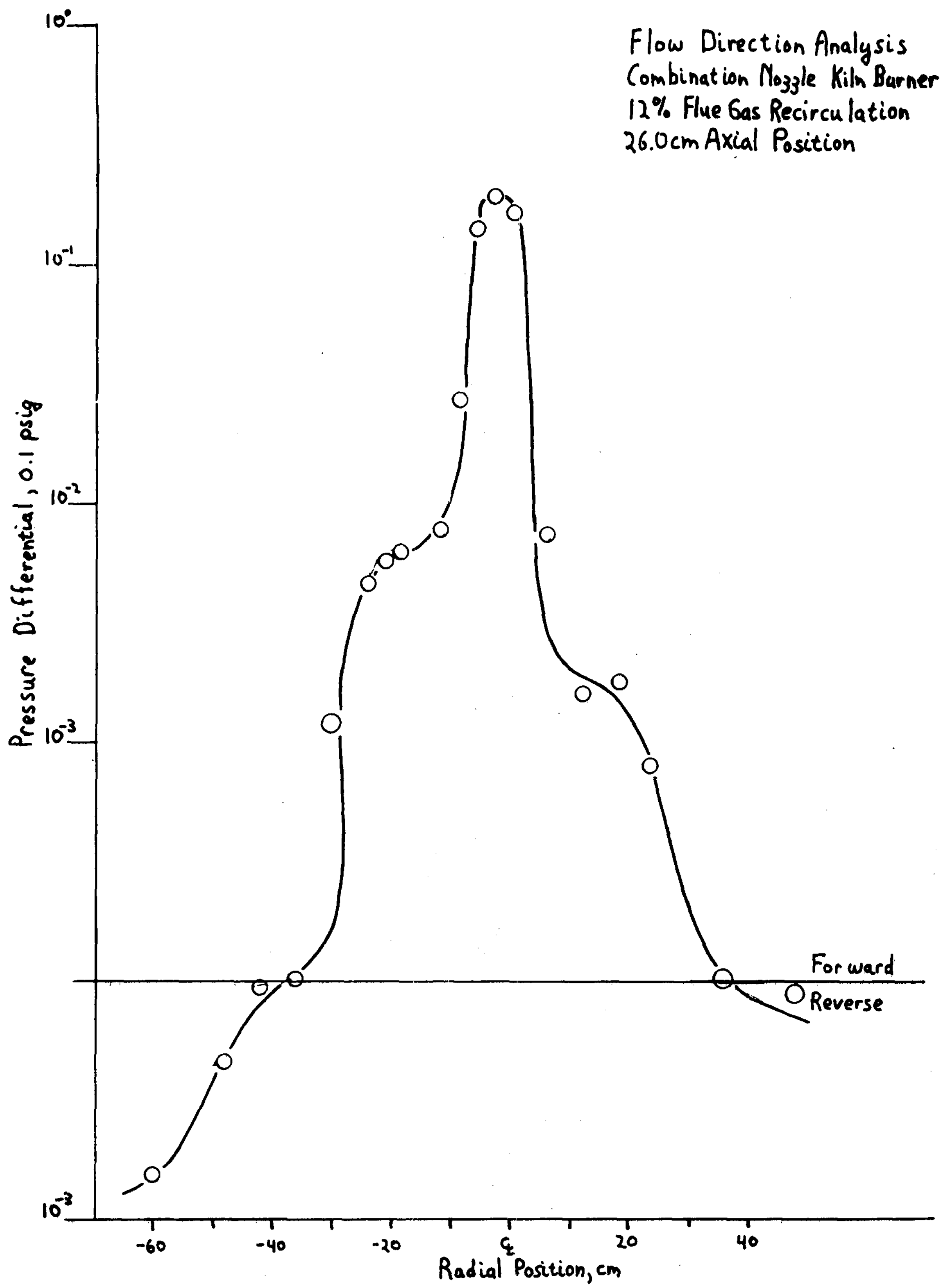

Figure 53. Combination kiln burner nozzle – pollution control conditions – radial profile of flow direction at an axial position of 26.0 cm

Table 12. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS – IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 57.2 cm

KILN BURNER-COMBINATION NOZZLE-POLLUTION CONTROL CONDITIONS

AXIAL POSITION = 57.2 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	TEMPERATURE DEG.C MAX.	TEMPERATURE DEG.C TMAX-TAVG
-60.	5.8	?	93.	19.	8.5	.0012	?	0.0	?	?	?	?	1254.	1298.	44.
-56.	5.4	?	99.	17.	8.7	.0015	?	0.0	?	?	?	?	1259.	1296.	37.
-48.	6.5	?	94.	15.	8.1	.0011	?	0.0	?	?	?	?	1231.	1279.	48.
-36.	8.3	?	69.	13.	7.0	.0013	?	0.0	?	?	?	?	1092.	1253.	161.
-24.	11.2	?	59.	10.	5.5	.0445	?	0.0	?	?	?	?	1096.	1256.	160.
-18.	8.6	80.8	48.	22.	5.7	2.4100	1.3	.2	.1	0.0	0.0	0.0	1392.	1445.	53.
-12.	4.3	78.3	33.	17.	6.1	4.0600	4.4	1.4	.5	.0	0.0	0.0	1372.	1406.	34.
-11.	3.7	75.8	30.	18.	5.9	4.7400	6.2	2.1	.6	.0	0.0	0.0	1351.	1372.	21.
-10.	3.6	76.2	27.	17.	5.9	4.8900	5.5	2.3	.6	.0	0.0	0.0	1344.	1381.	37.
-9.	2.6	73.9	23.	16.	5.4	5.6900	6.5	3.9	1.0	.1	0.0	0.0	1325.	1366.	41.
-6.	2.7	69.1	20.	18.	4.7	5.7800	9.6	5.8	1.2	.1	.0	.1	1318.	1330.	12.
-3.	3.1	68.9	22.	19.	4.6	5.4900	9.3	6.3	1.2	.2	.0	.0	1331.	1364.	33.
0.	2.9	70.1	24.	25.	5.0	5.3800	9.0	5.6	1.1	.1	.0	.0	1344.	1383.	39.
3.	4.1	74.9	26.	24.	5.7	4.1000	7.1	2.5	.6	.1	0.0	0.0	1300.	1384.	84.
6.	6.2	77.3	35.	19.	5.8	2.7800	5.6	1.2	.3	.0	0.0	0.0	1143.	12040.	10897.
9.	10.4	79.2	53.	15.	5.2	.7500	3.3	.2	.3	0.0	0.0	0.0	1010.	1100.	90.
12.	11.8	79.3	55.	7.	4.7	.3700	3.0	0.0	.0	0.0	0.0	0.0	971.	1050.	79.
18.	11.9	?	64.	9.	5.4	.0065	?	0.0	?	?	?	?	1024.	1155.	131.
24.	10.4	?	73.	11.	6.1	.0035	?	0.0	?	?	?	?	1138.	1225.	87.
30.	9.2	?	82.	16.	6.6	.0027	?	0.0	?	?	?	?	1157.	1253.	96.
40.	5.1	?	84.	20.	9.6	.0035	?	0.0	?	?	?	?	1200.	1248.	48.

Table 13. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS – IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 146.1 cm

KILN BURNER-COMBINATION NOZZLE-POLLUTION CONTROL CONDITIONS

AXIAL POSITION = 146.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	6.8	84.2	85.	21.	8.0	.0180	0.0	0.0	0.0	0.0	0.0	0.0	1344.	1403.	59.
-54.	7.0	84.0	86.	25.	8.0	.1200	0.0	0.0	0.0	0.0	0.0	0.0	1364.	1451.	87.
-48.	5.6	84.5	93.	23.	8.5	.3500	0.0	0.0	0.0	0.0	0.0	0.0	1378.	1431.	53.
-42.	5.1	84.3	92.	20.	8.5	.5800	.4	.0	0.0	0.0	0.0	0.0	1413.	1461.	48.
-36.	4.2	84.0	87.	17.	8.7	1.0900	.9	.0	0.0	0.0	0.0	0.0	1437.	1512.	75.
-30.	3.2	82.7	88.	16.	8.2	2.4300	2.3	.1	.1	0.0	0.0	0.0	1485.	1538.	53.
-24.	1.9	80.9	82.	13.	7.9	3.9300	4.2	.2	.1	0.0	0.0	0.0	1512.	1535.	23.
-18.	1.5	79.5	76.	10.	7.3	5.0000	5.3	.3	.1	0.0	0.0	0.0	1512.	1542.	30.
-12.	2.0	80.9	70.	7.	7.8	3.9600	4.1	.2	.1	0.0	0.0	0.0	1540.	1560.	20.
-6.	3.0	81.1	70.	9.	8.1	2.8500	2.2	1.7	.0	0.0	0.0	0.0	1477.	1508.	31.
0.	4.4	82.6	71.	10.	8.3	1.5800	1.4	.8	0.0	0.0	0.0	0.0	1407.	1493.	86.
6.	7.1	84.0	80.	12.	7.6	.3400	0.0	0.0	0.0	0.0	0.0	0.0	1352.	1449.	97.
12.	8.1	82.9	75.	7.	7.8	.1900	0.0	0.0	0.0	0.0	0.0	0.0	1282.	1371.	89.
18.	8.4	?	74.	6.	7.2	.0075	?	0.0	?	?	?	?	1248.	1309.	61.
24.	8.4	?	74.	8.	7.2	.0040	?	0.0	?	?	?	?	1251.	1296.	45.
30.	8.7	?	70.	11.	7.3	.0030	?	0.0	?	?	?	?	1222.	1286.	64.
40.	8.6	?	66.	15.	7.1	.0020	?	0.0	?	?	?	?	1242.	1288.	46.

Table 14. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS – IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 290. 2 cm

KILN BURNER-COMBINATION NOZZLE-POLLUTION CONTROL CONDITIONS

AXIAL POSITION = 290.2 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	TEMPERATURE DEG.C MAX.	TEMPERATURE DEG.C TMAX-TAVG
-60.	2.5	86.1	118.	20.	10.0	.3500	0.0	0.0	0.0	0.0	0.0	0.0	1494.	1530.	36.
-54.	2.5	85.7	124.	21.	10.2	.4000	0.0	0.0	0.0	0.0	0.0	0.0	1502.	1563.	61.
-48.	2.5	85.2	121.	22.	10.2	.6700	.4	0.0	0.0	0.0	0.0	0.0	1512.	1549.	37.
-42.	2.3	?	126.	21.	10.3	.7400	?	0.0	?	?	?	?	1512.	1546.	34.
-36.	2.2	85.5	130.	22.	10.2	.8200	.5	0.0	0.0	0.0	0.0	0.0	1520.	1544.	25.
-30.	2.8	85.4	124.	22.	9.5	.7700	.4	0.0	0.0	0.0	0.0	0.0	1503.	1644.	141.
-24.	2.3	85.2	121.	20.	10.2	.8200	.5	0.0	0.0	0.0	0.0	0.0	1494.	1525.	31.
-18.	2.4	85.6	117.	20.	10.1	.5500	.3	0.0	0.0	0.0	0.0	0.0	1494.	1537.	43.
-12.	2.9	85.8	113.	20.	9.9	.3700	0.0	0.0	0.0	0.0	0.0	0.0	1477.	1540.	63.
-6.	3.0	85.5	106.	21.	10.2	.2900	0.0	0.0	0.0	0.0	0.0	0.0	1461.	1538.	77.
0.	3.7	85.5	104.	27.	9.6	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1422.	1517.	95.
6.	3.6	?	99.	30.	9.7	.0380	?	0.0	?	?	?	?	1414.	1515.	101.
12.	4.0	?	97.	24.	9.5	.0846	?	0.0	?	?	?	?	1385.	1452.	67.
18.	3.9	?	97.	23.	9.9	.0620	?	0.0	?	?	?	?	1370.	1438.	68.
24.	4.0	?	95.	21.	9.8	.0092	?	0.0	?	?	?	?	1351.	1420.	69.
30.	4.1	?	88.	23.	9.6	.0080	?	0.0	?	?	?	?	1344.	1367.	23.
36.	3.6	?	94.	20.	10.0	.0050	?	0.0	?	?	?	?	1331.	1341.	10.
40.	3.7	?	97.	19.	9.9	.0040	?	0.0	?	?	?	?	1318.	1326.	8.

Table 15. COMBINATION KILN BURNER NOZZLE – POLLUTION CONTROL CONDITIONS – IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 385. 4 cm

KILN BURNER-COMBINATION NOZZLE-POLLUTION CONTROL CONDITIONS

AXIAL POSITION = 385.4 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	2.4	?	122.	20.	10.5	.0230	?	0.0	?	?	?	?	1548.	1575.	27.
-54.	2.2	?	127.	20.	10.6	.3000	?	0.0	?	?	?	?	1538.	1564.	26.
-48.	2.3	?	121.	25.	10.6	.2700	?	0.0	?	?	?	?	1548.	1573.	25.
-45.	2.4	?	122.	22.	10.5	.3100	?	0.0	?	?	?	?	1538.	1562.	24.
-39.	2.4	?	120.	22.	10.4	.2200	?	0.0	?	?	?	?	1546.	1591.	45.
-33.	2.5	?	124.	20.	10.4	.1800	?	0.0	?	?	?	?	1538.	1568.	30.
-27.	2.8	?	118.	26.	10.3	.1500	?	0.0	?	?	?	?	1530.	1556.	26.
-21.	2.9	?	114.	28.	10.3	.1200	?	0.0	?	?	?	?	1503.	1526.	23.
-15.	2.9	?	121.	26.	10.3	.1100	?	0.0	?	?	?	?	1503.	1529.	26.
-9.	3.0	?	110.	29.	10.2	.0560	?	0.0	?	?	?	?	1494.	1508.	14.
-3.	3.1	?	113.	30.	10.1	.0055	?	0.0	?	?	?	?	1494.	1515.	21.
0.	3.2	?	110.	23.	10.1	.0030	?	0.0	?	?	?	?	1486.	1509.	23.
3.	3.6	?	110.	23.	10.0	.0026	?	0.0	?	?	?	?	1469.	1499.	30.
9.	3.6	?	123.	26.	10.0	.0015	?	0.0	?	?	?	?	1469.	1489.	20.
15.	3.6	?	117.	27.	9.9	.0017	?	0.0	?	?	?	?	1465.	1495.	30.
21.	3.5	?	113.	25.	10.1	.0022	?	0.0	?	?	?	?	1461.	1493.	32.
27.	3.4	?	115.	23.	10.1	.0020	?	0.0	?	?	?	?	1448.	1477.	29.
33.	3.3	?	116.	22.	10.2	.0031	?	0.0	?	?	?	?	1445.	1470.	25.
40.	3.2	?	114.	22.	10.2	.0034	?	0.0	?	?	?	?	1440.	1470.	30.

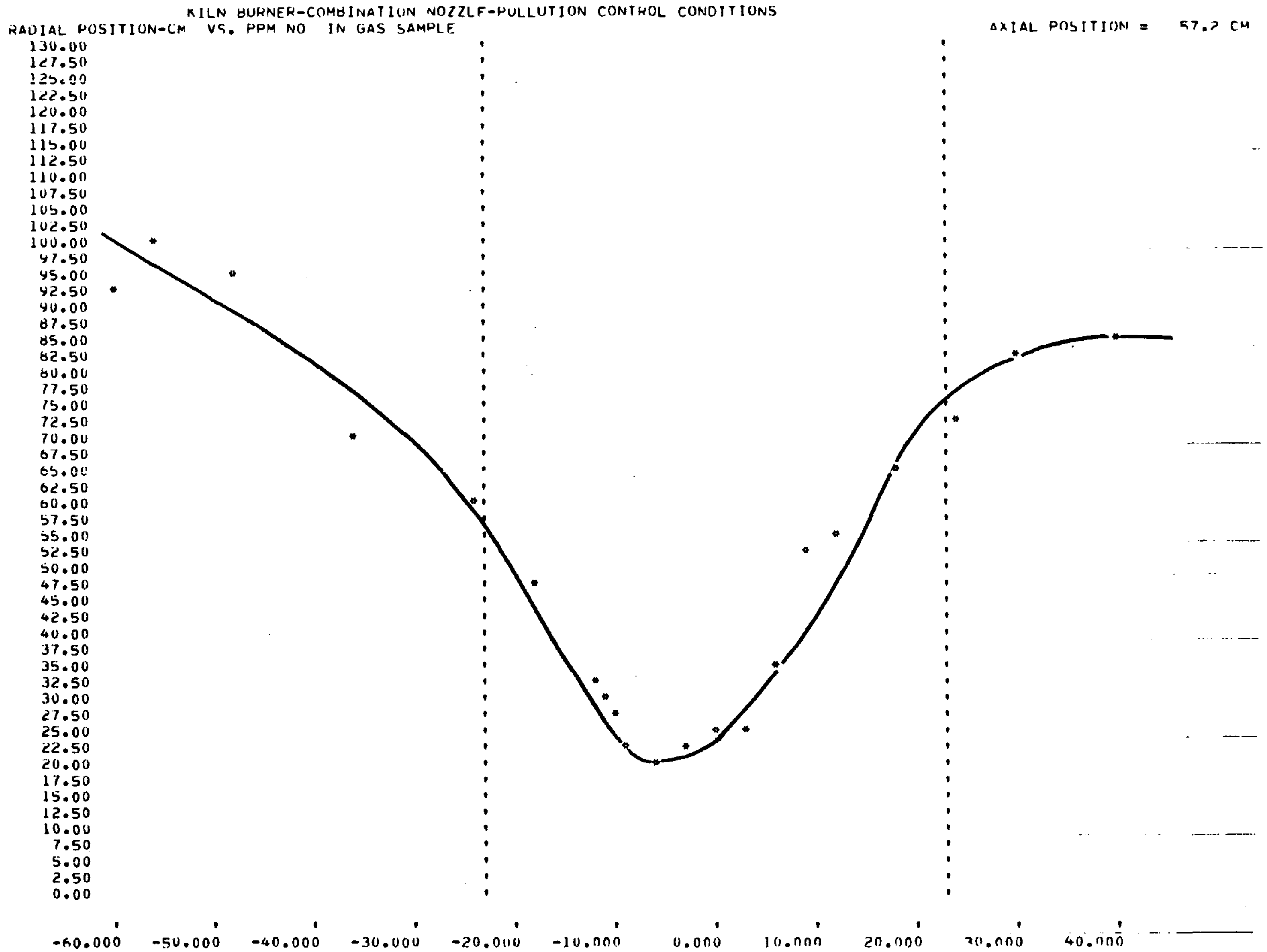

Figure 54. Combination kiln burner nozzle – pollution control conditions – radial profile of NO at an axial position of 57. 2 cm

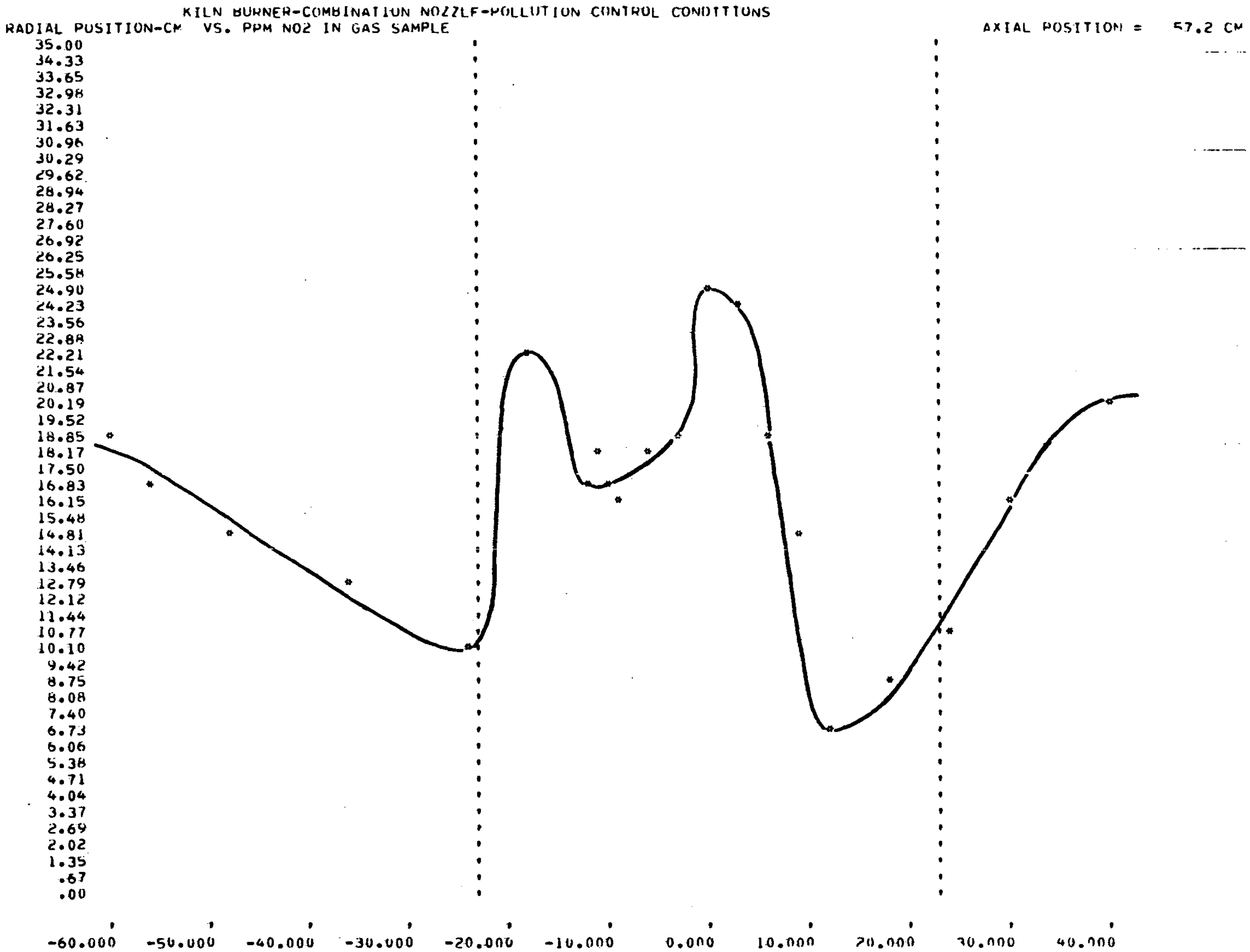

Figure 55. Combination kiln burner nozzle – pollution control conditions – radial profile of NO_2 at an axial position of 57.2 cm

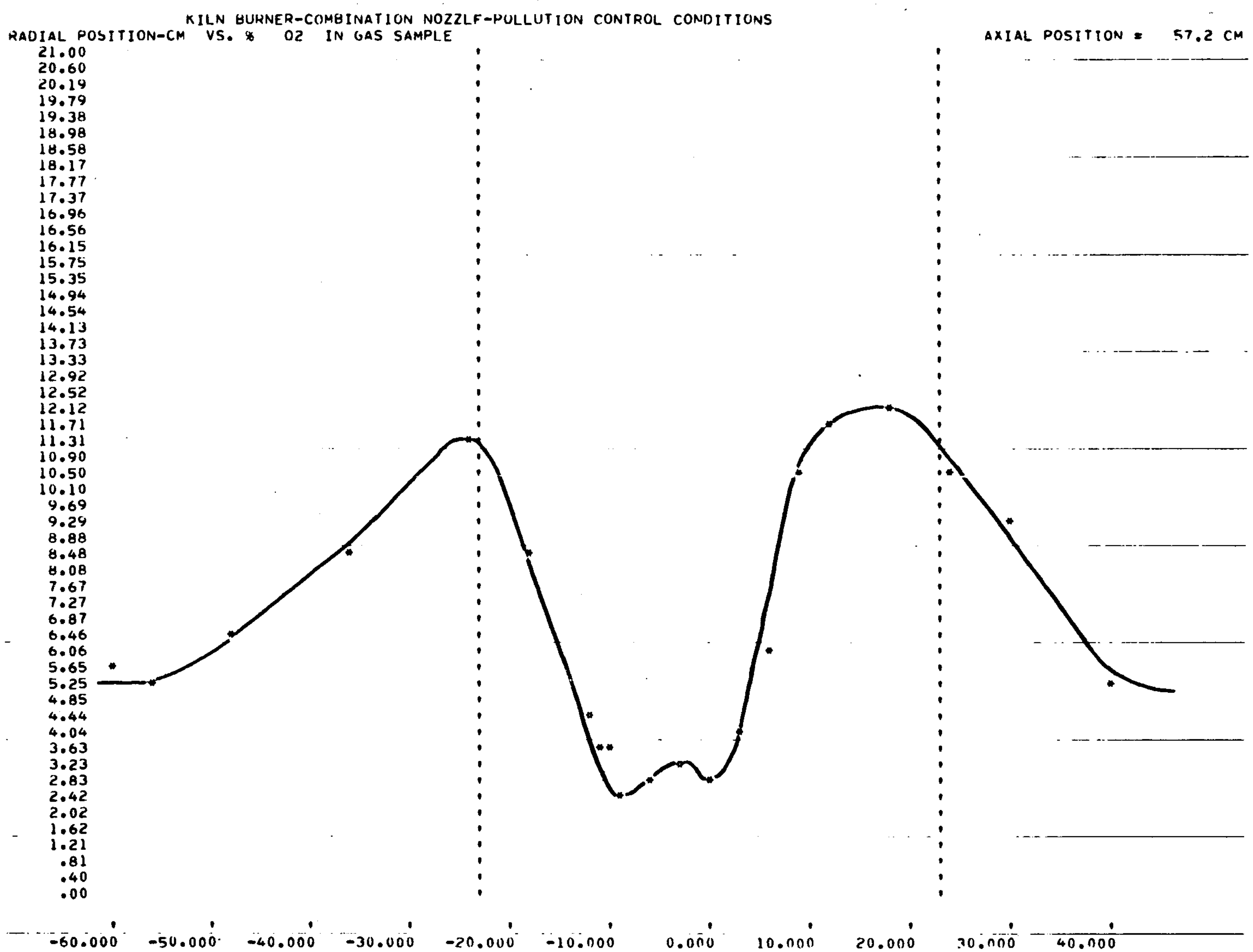

Figure 56. Combination kiln burner nozzle – pollution control conditions – radial profile of O_2 at an axial position of 57.2 cm

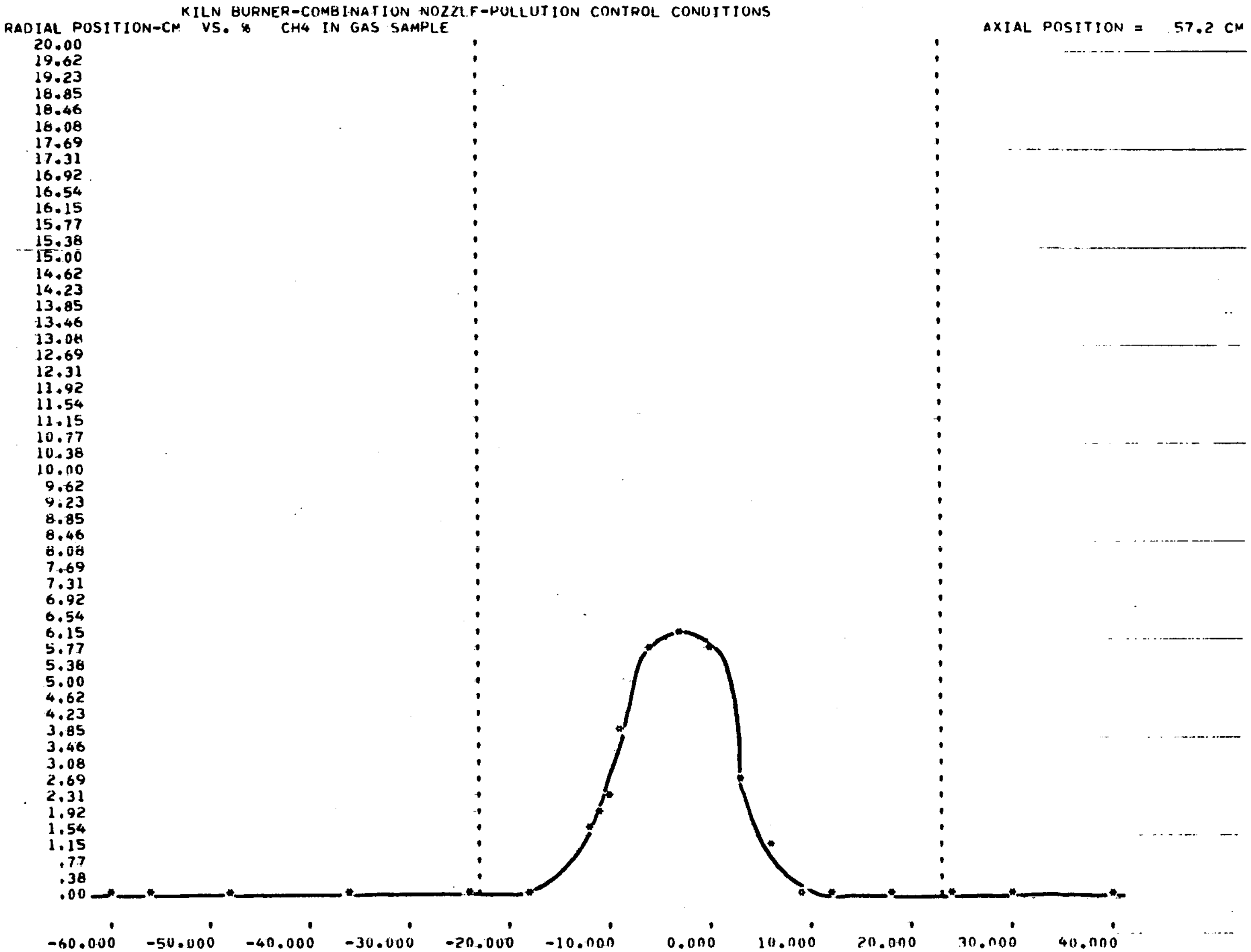

Figure 57. Combination kiln burner nozzle – pollution control conditions – radial profile of CH_4 at an axial position of 57. 2 cm

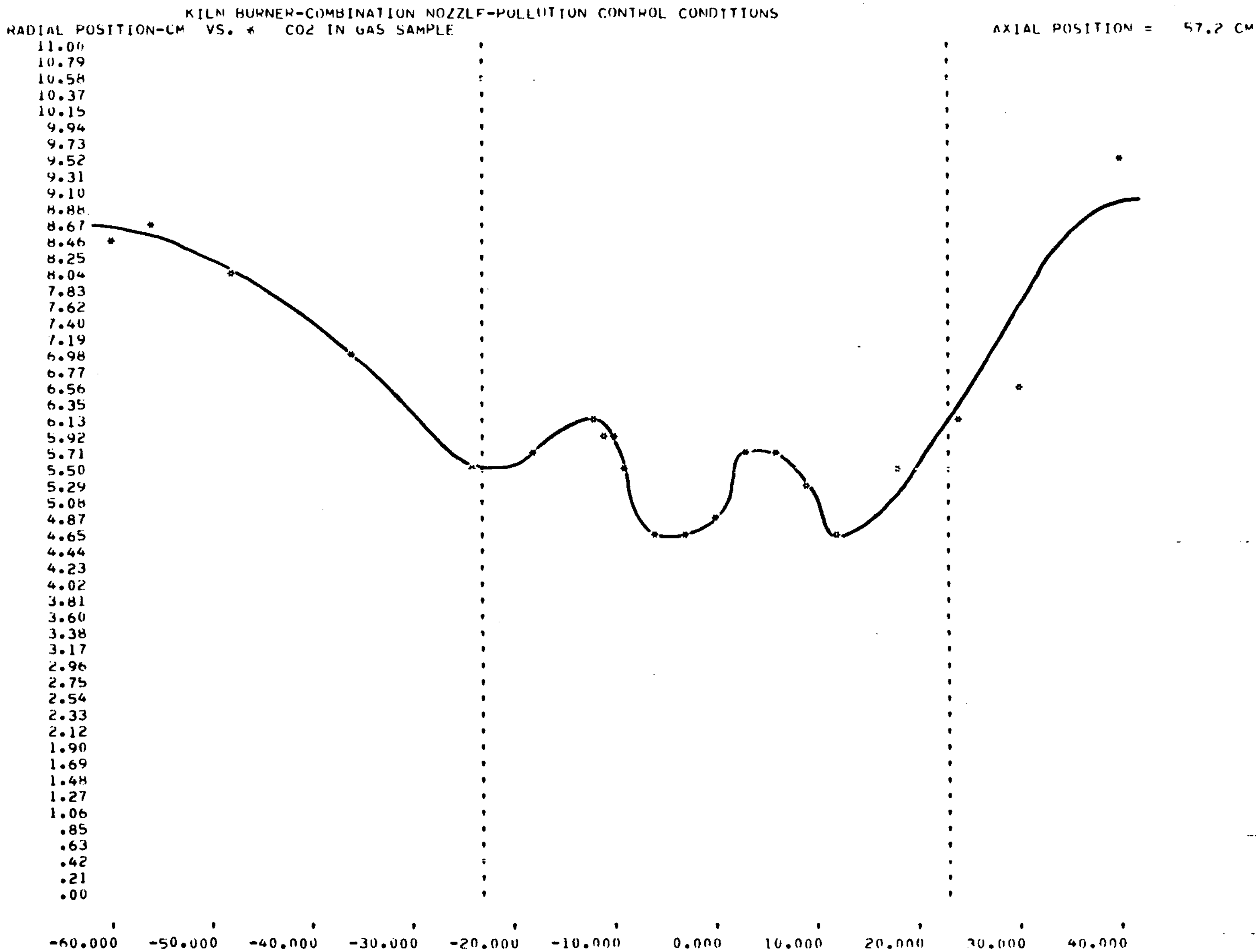

Figure 58. Combination kiln burner nozzle — pollution control conditions — radial profile of CO_2 at an axial position of 57.2 cm

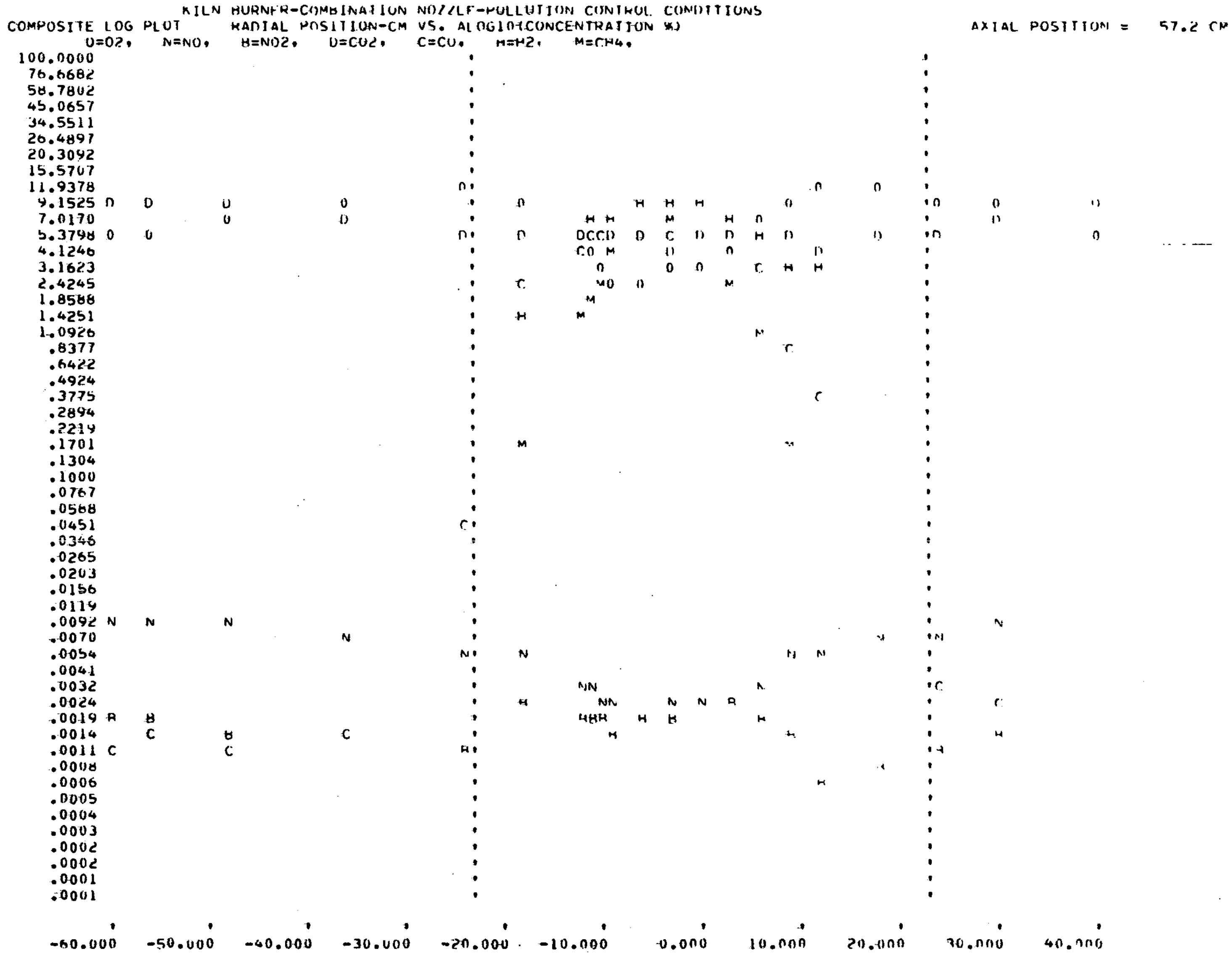

Figure 59. Combination kiln burner nozzle — pollution control conditions — radial profile of all the gases at an axial position of 57.2 cm

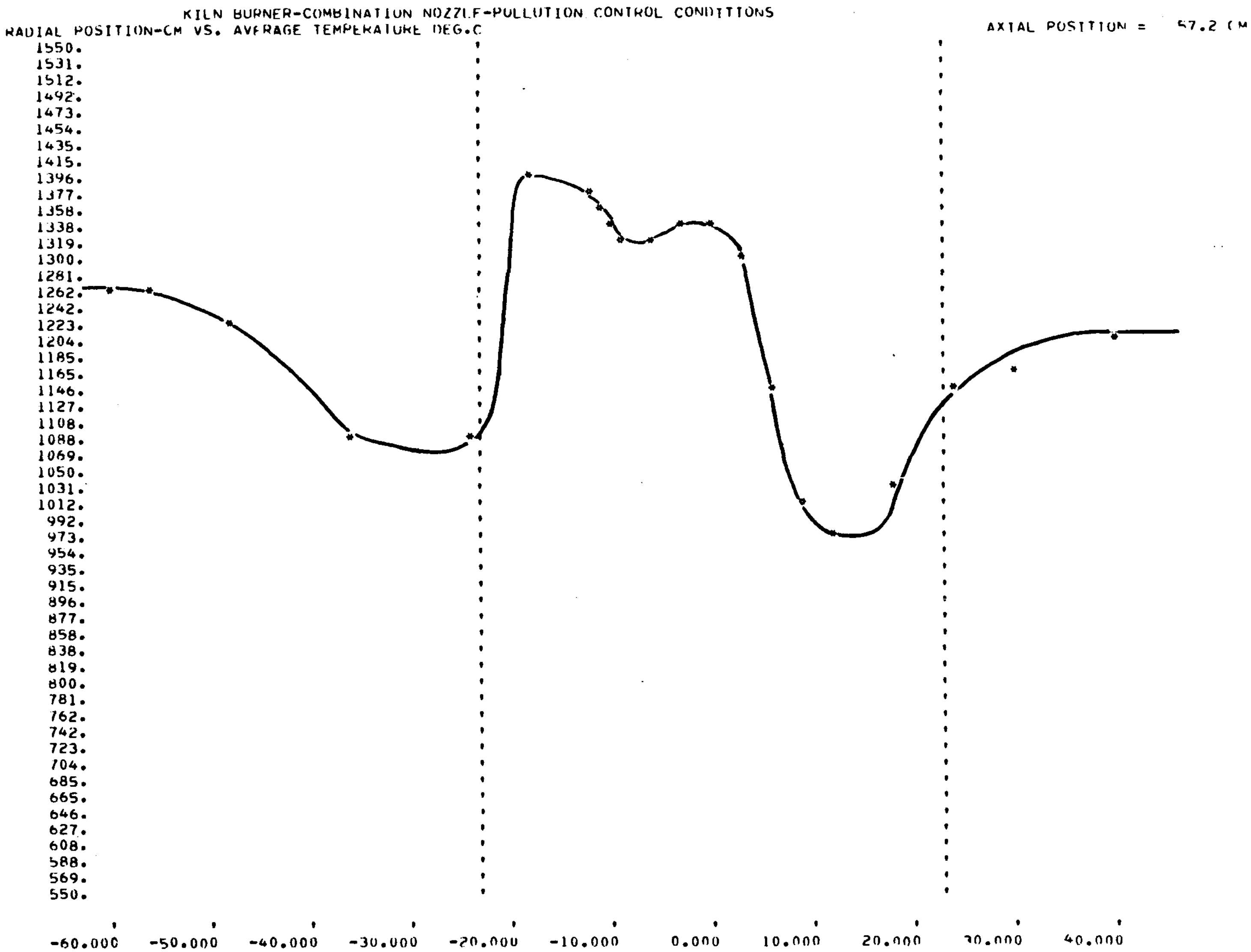

Figure 60. Combination kiln burner nozzle – pollution control conditions – radial profile of temperature at an axial position of 57. 2 cm

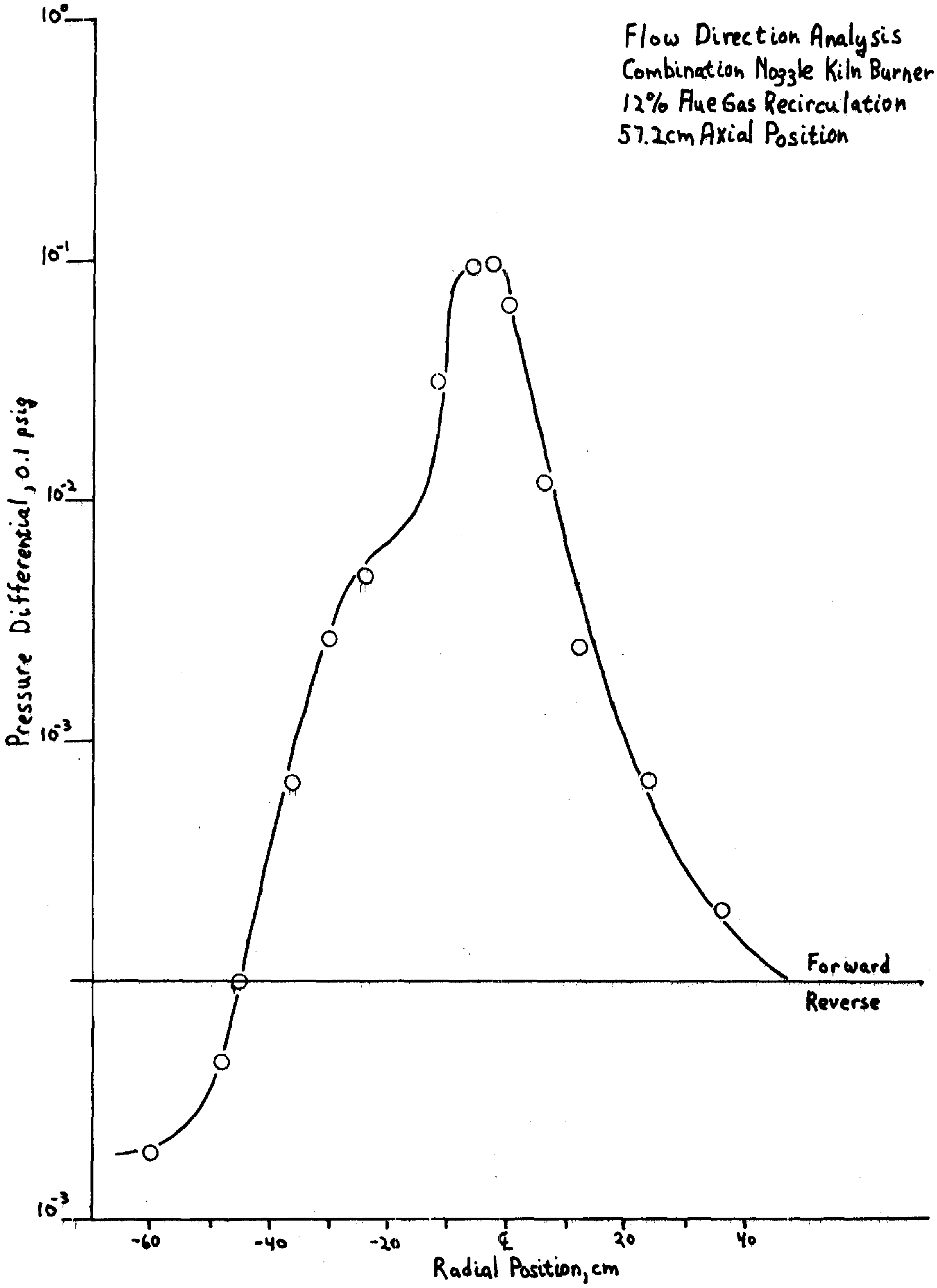

Figure 61. Combination kiln burner nozzle – pollution control conditions – radial profile of flow direction at an axial position of 57.2 cm

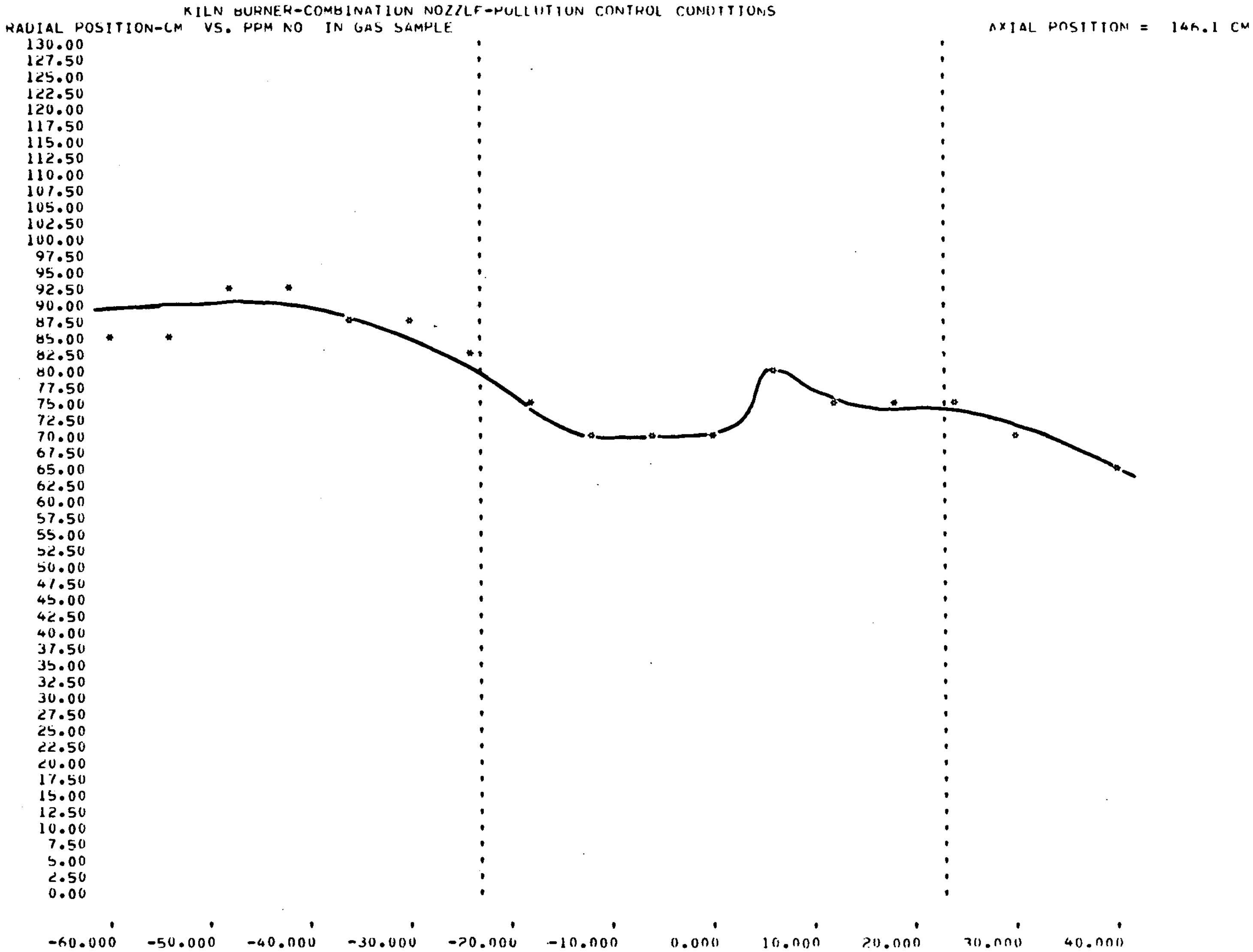

Figure 62. Combination kiln burner nozzle – pollution control conditions – radial profile of NO at an axial position of 146.1 cm

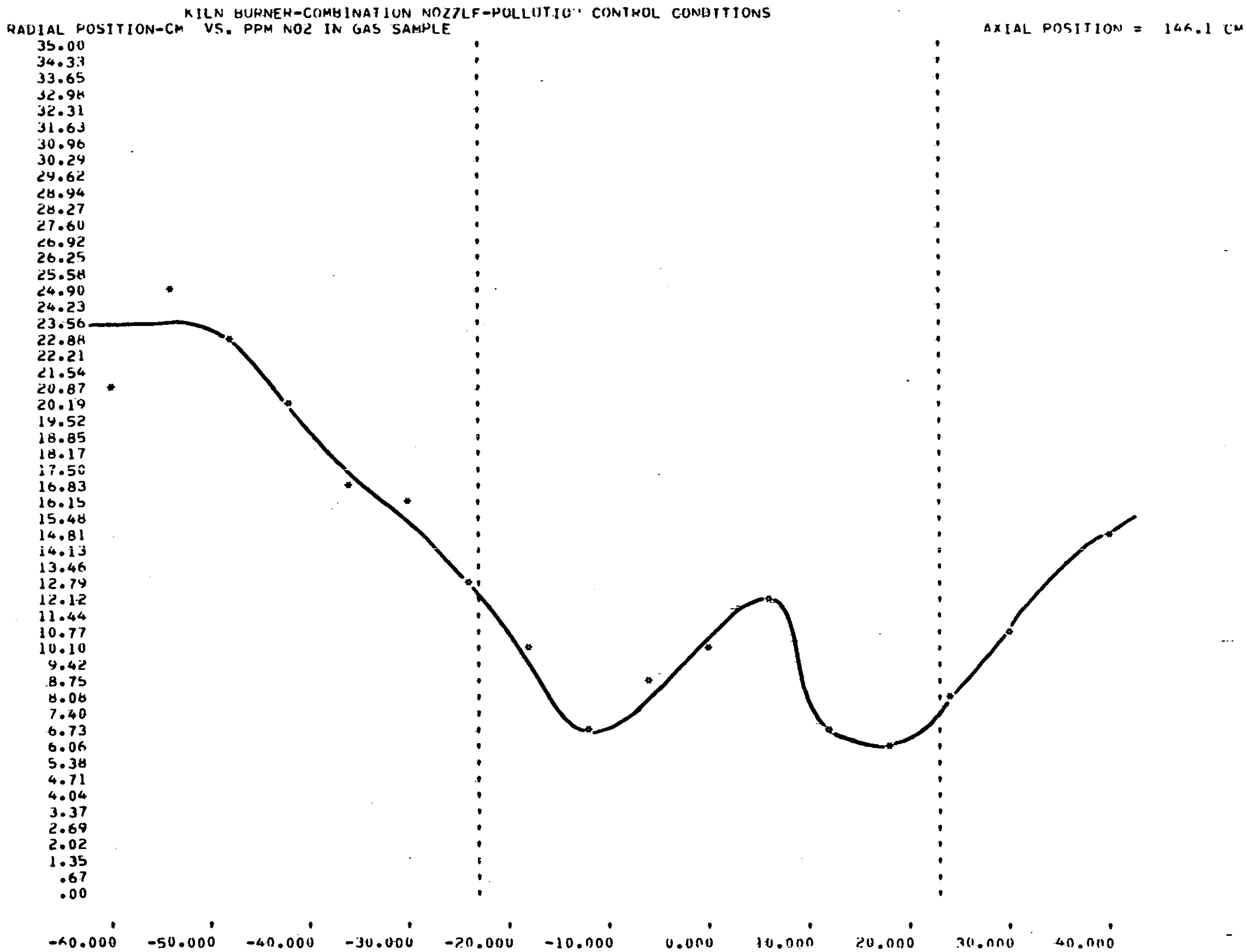

Figure 63. Combination kiln burner nozzle — pollution control conditions — radial profile of NO_2 at an axial position of 146. 1 cm

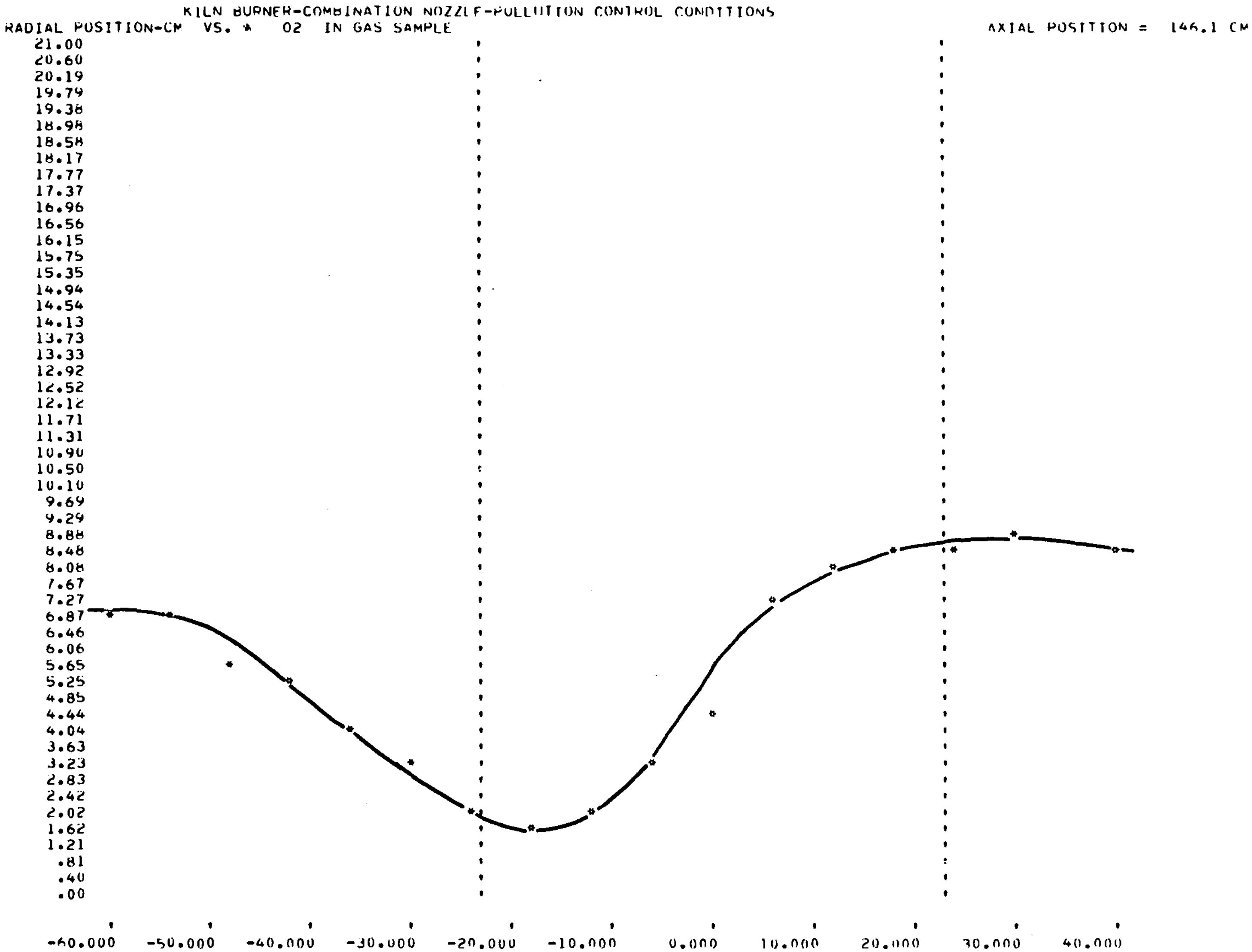

Figure 64. Combination kiln burner nozzle – pollution control conditions – radial profile of O_2 at an axial position of 146. 1 cm

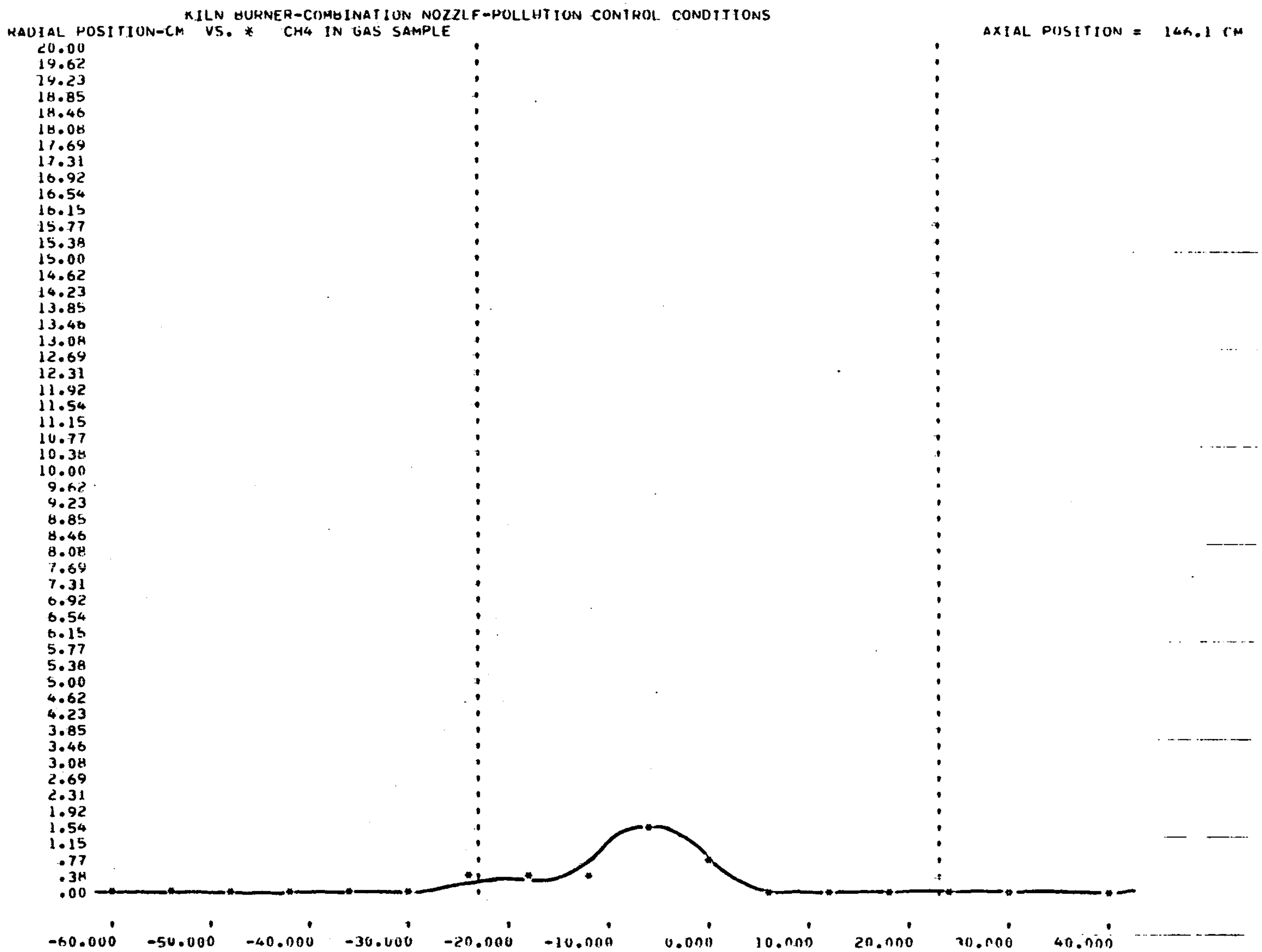

Figure 65. Combination kiln burner nozzle – pollution control conditions – radial profile of CH_4 at an axial position of 146.1 cm

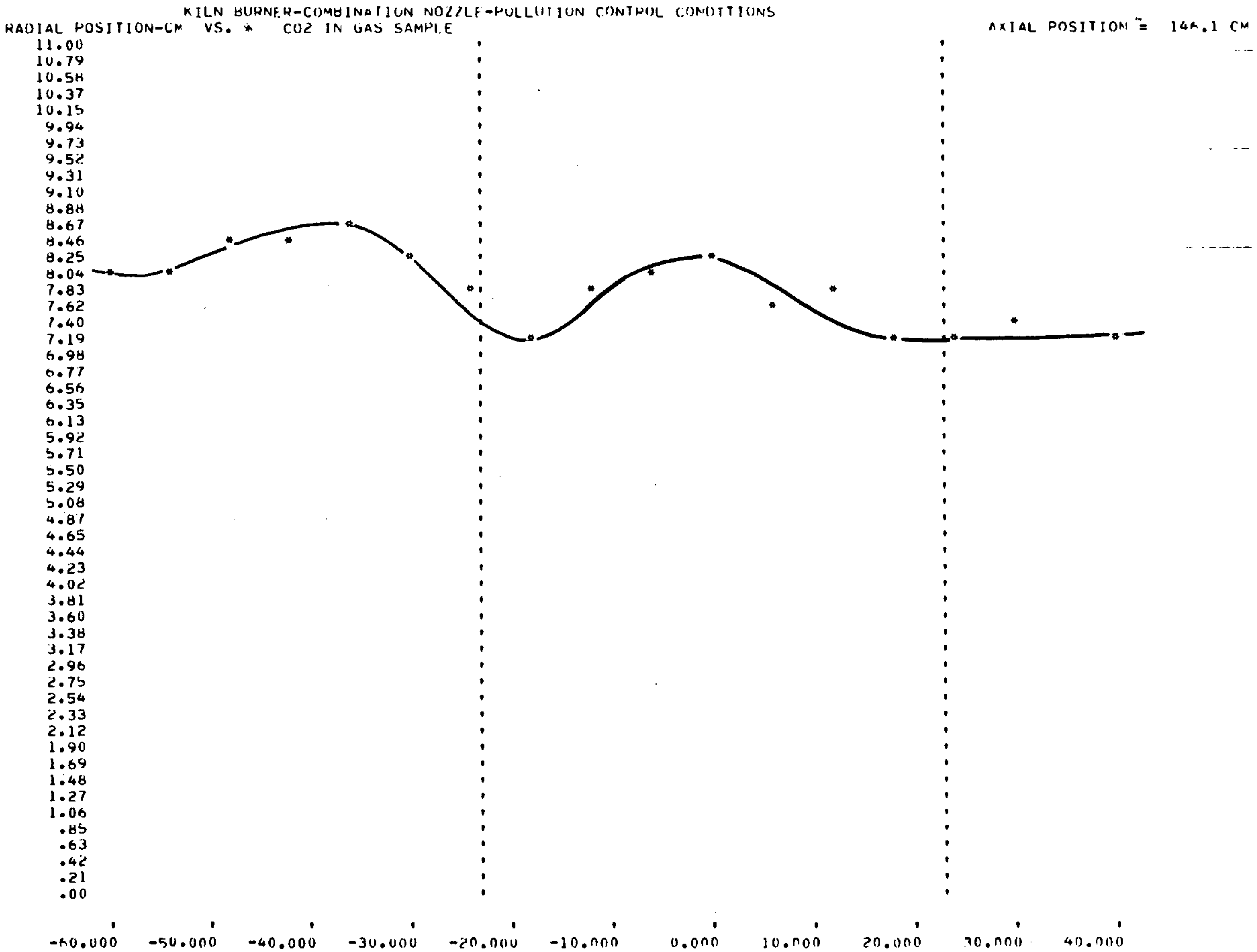

Figure 66. Combination kiln burner nozzle — pollution control conditions — radial profile of CO_2 at an axial position of 146.1 cm

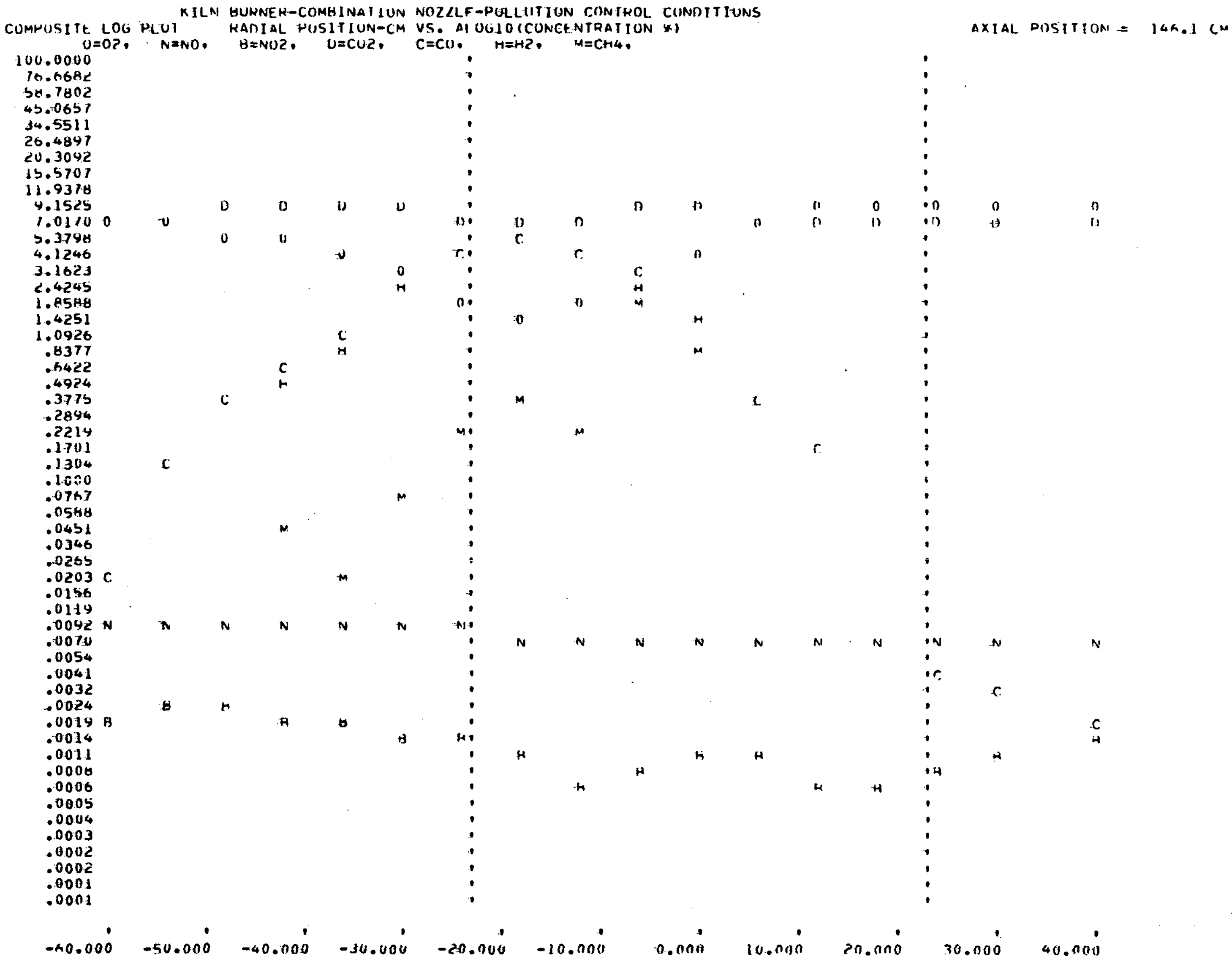

Figure 67. Combination kiln burner nozzle — pollution control conditions — radial profile of all the gases at an axial position of 146.1 cm

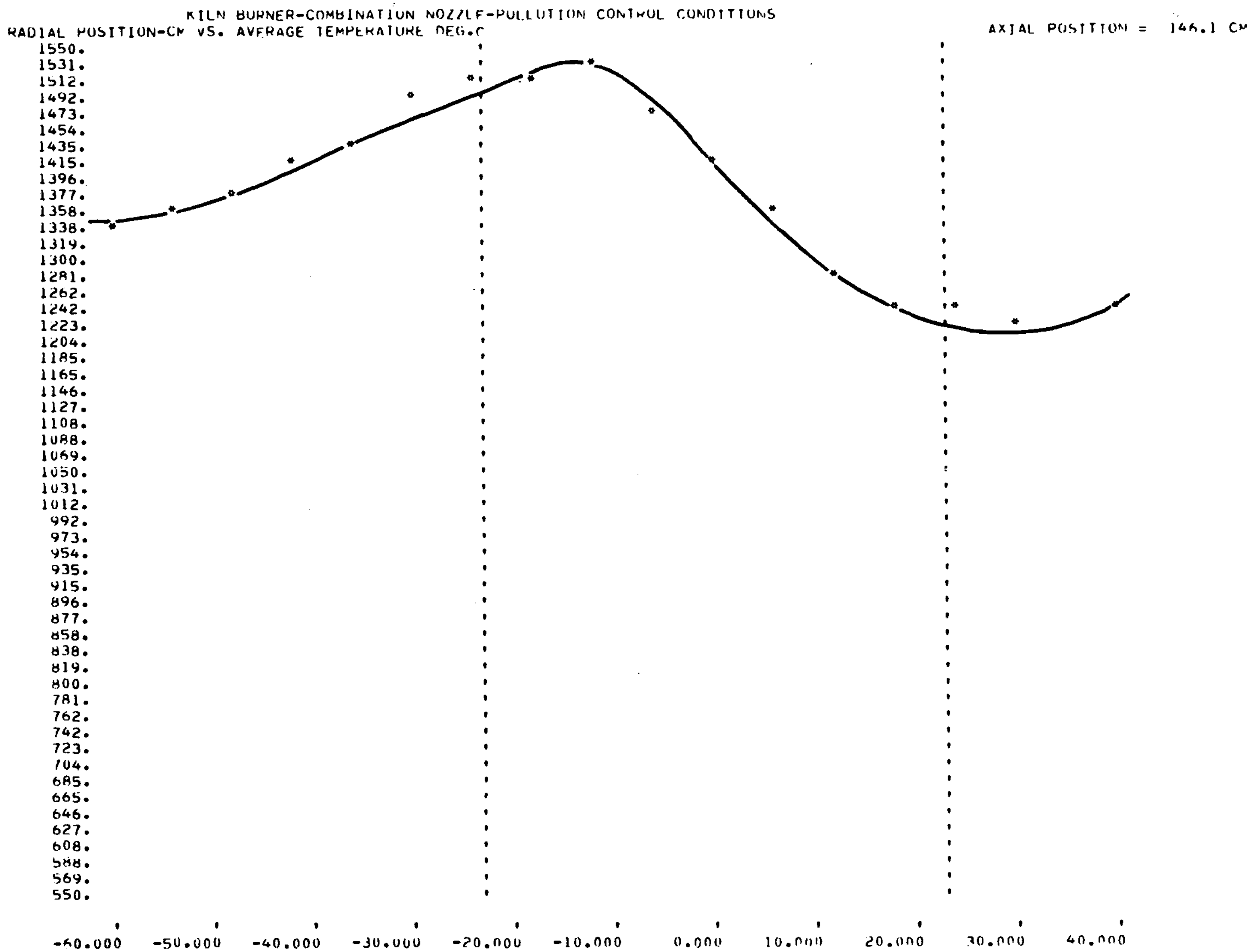

Figure 68. Combination kiln burner nozzle – pollution control conditions – radial profile of temperature at an axial position of 146. 1 cm

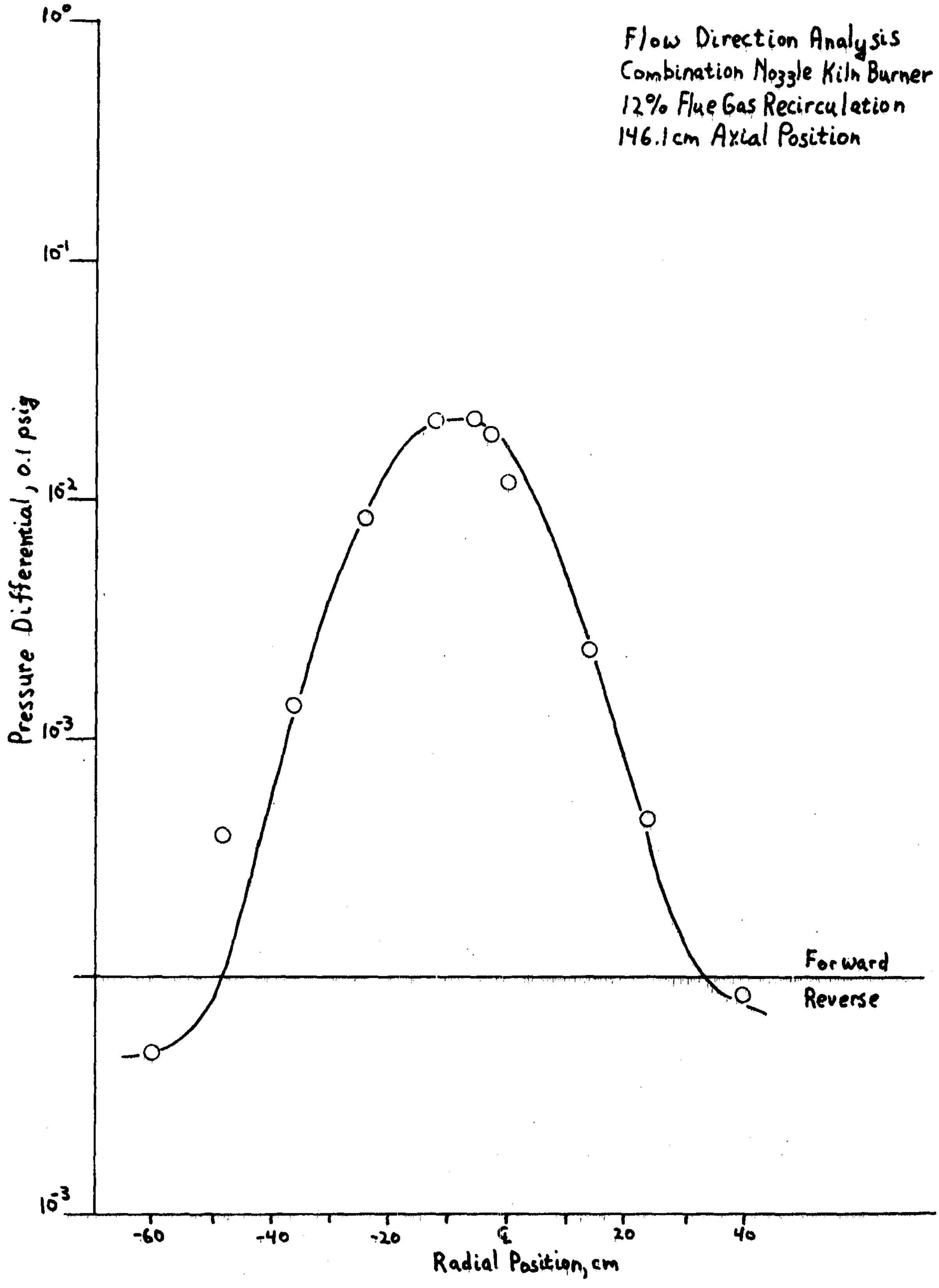

Figure 69. Combination kiln burner nozzle – pollution control conditions – radial profile of flow direction at an axial position of 146. 1 cm

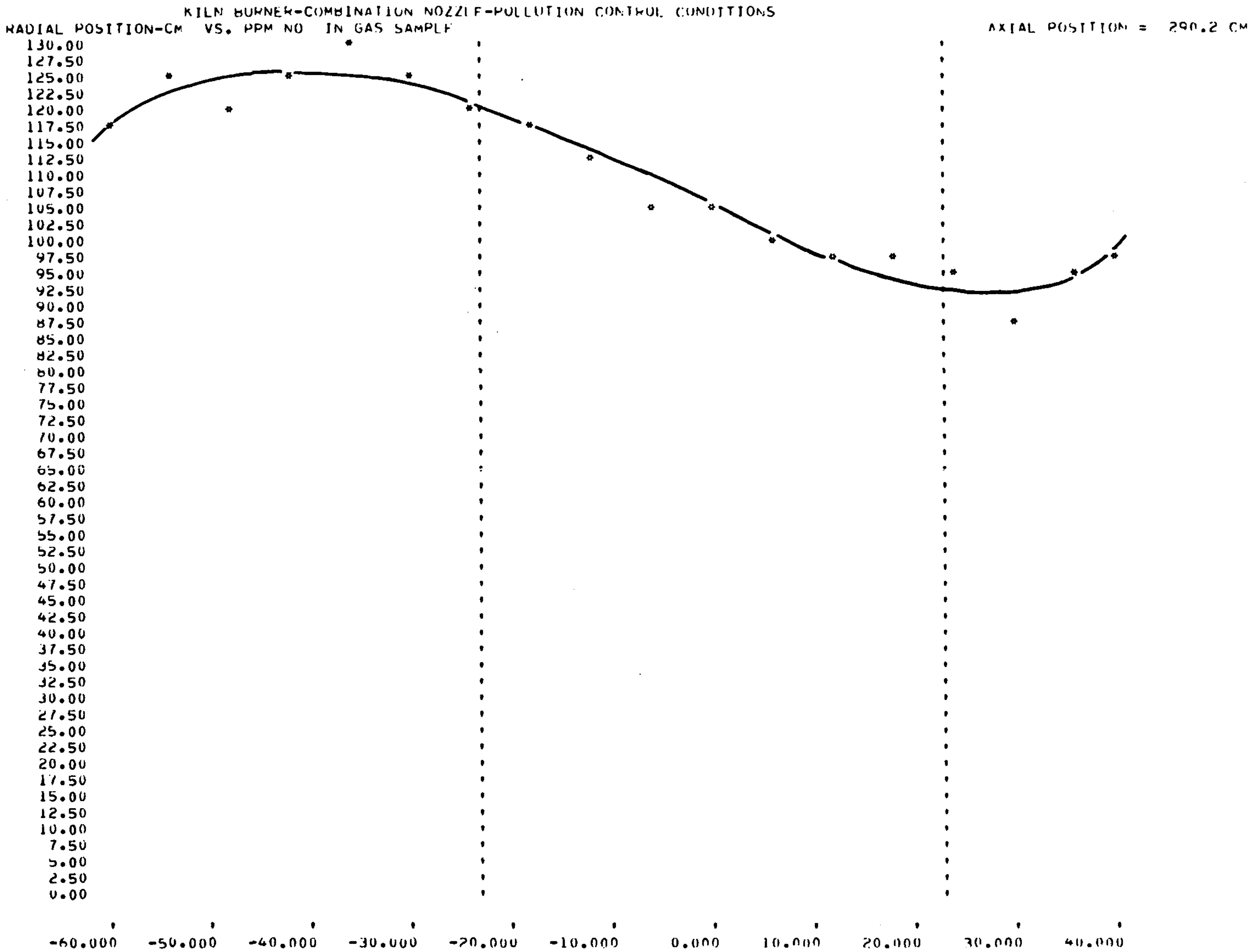

Figure 70. Combination kiln burner nozzle — pollution control conditions — radial profile of NO at an axial position of 290.2 cm

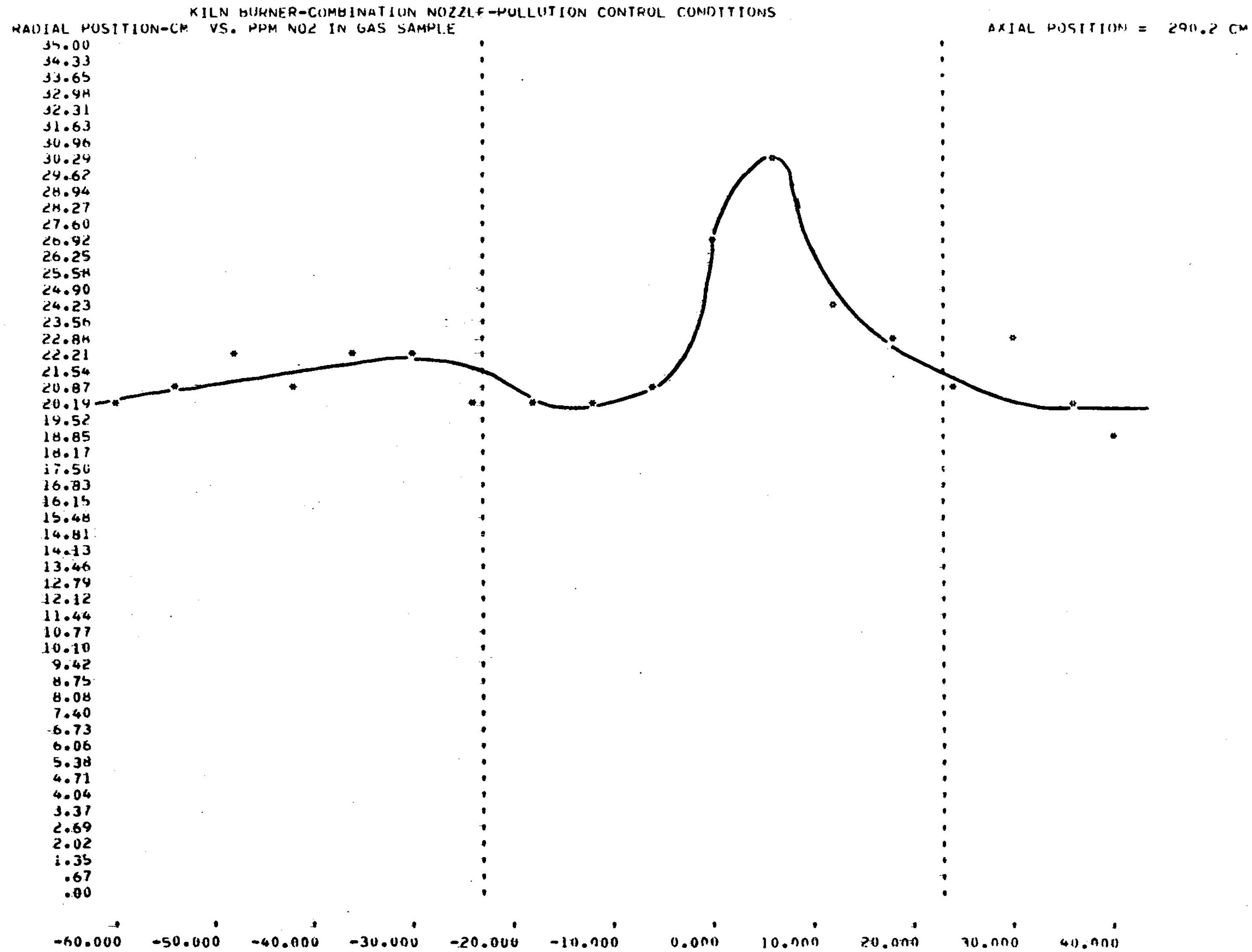

Figure 71. Combination kiln burner nozzle – pollution control conditions – radial profile of NO_2 at an axial position of 290. 2 cm

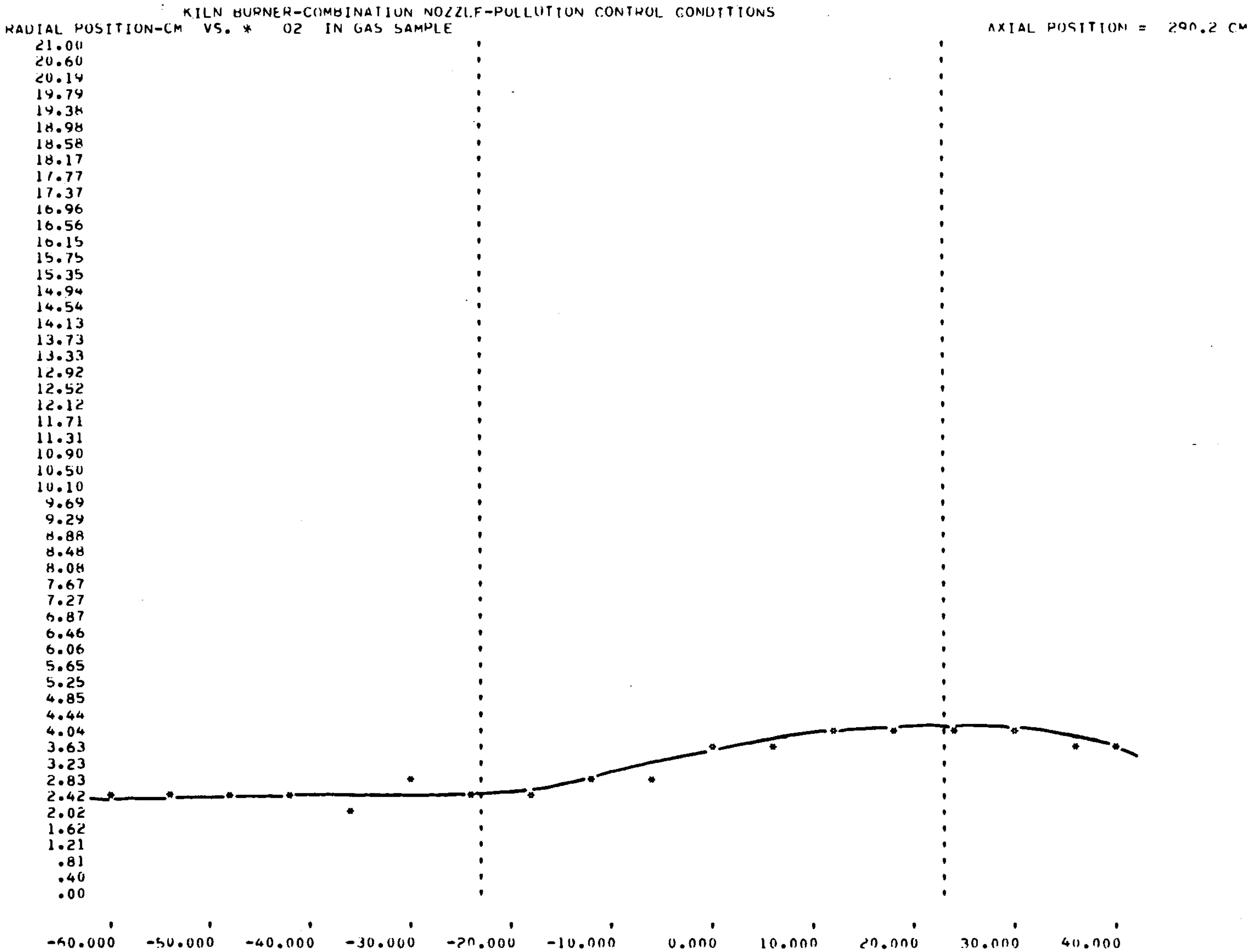

Figure 72. Combination kiln burner nozzle – pollution control conditions – radial profile of O_2 at an axial position of 290.2 cm

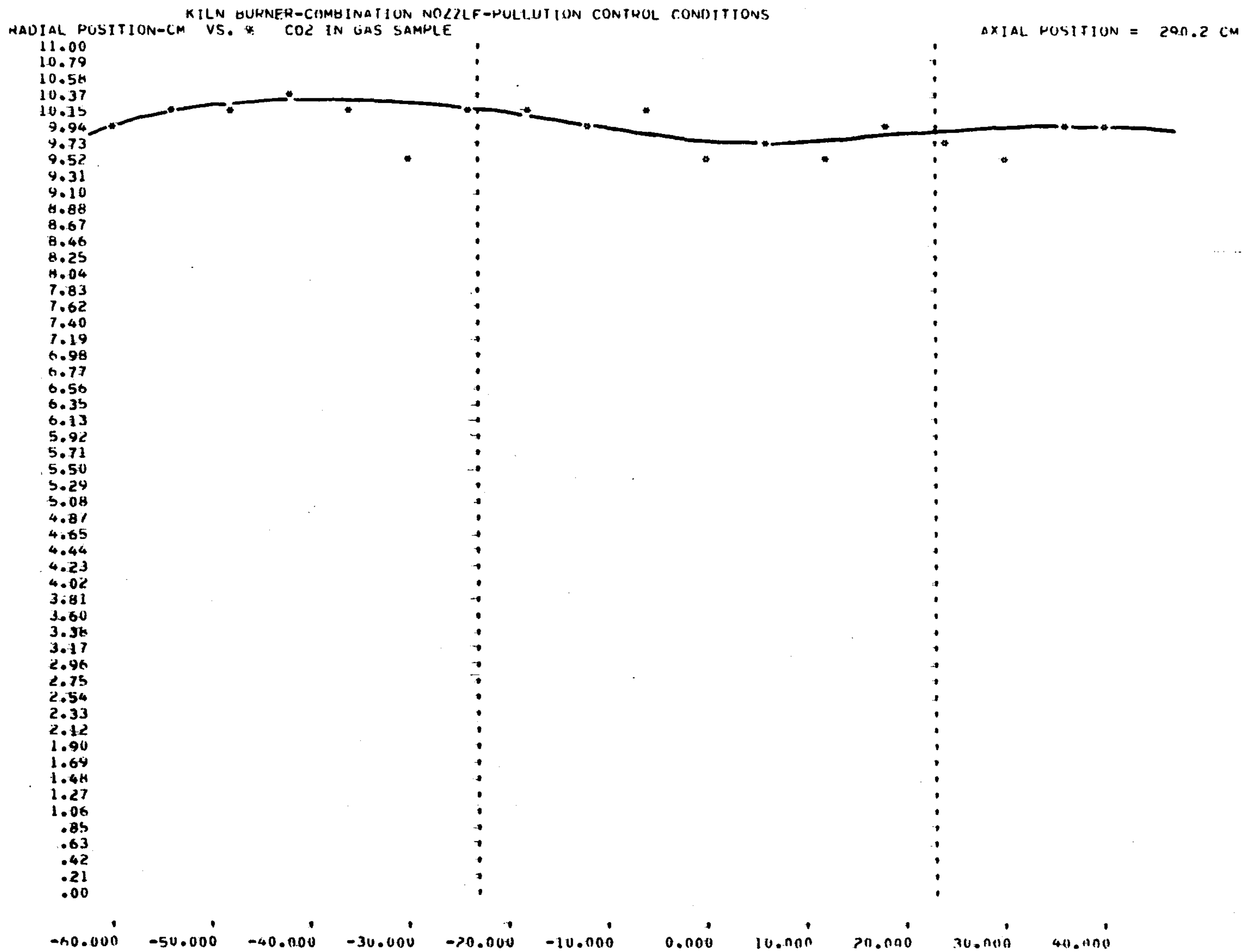

Figure 73. Combination kiln burner nozzle – pollution control conditions – radial profile of CO_2 at an axial position of 290. 2 cm

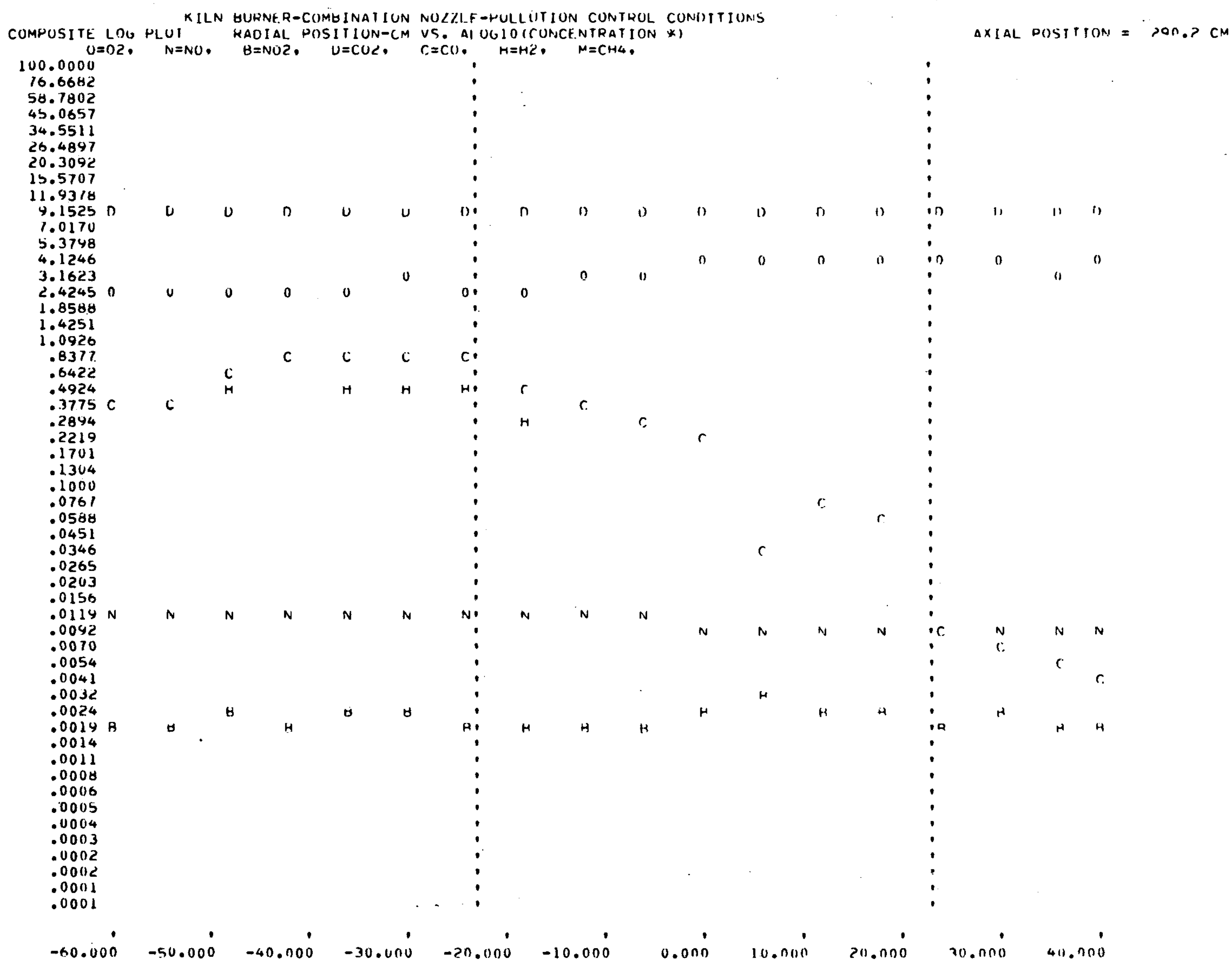

Figure 74. Combination kiln burner nozzle – pollution control conditions – radial profile of all the gases at an axial position of 290.2 cm

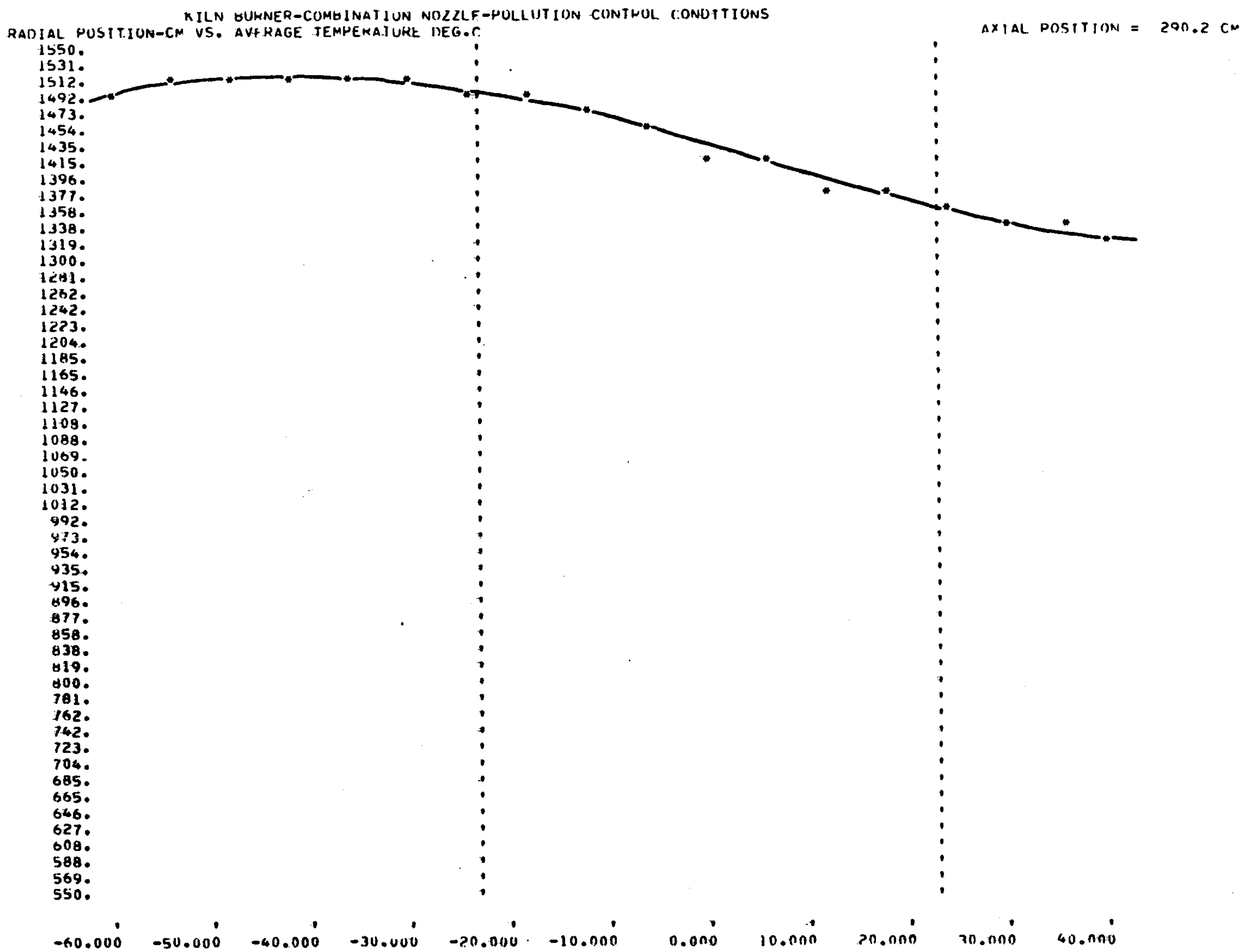

Figure 75. Combination kiln burner nozzle — pollution control conditions — radial profile of temperature at an axial position of 290. 2 cm

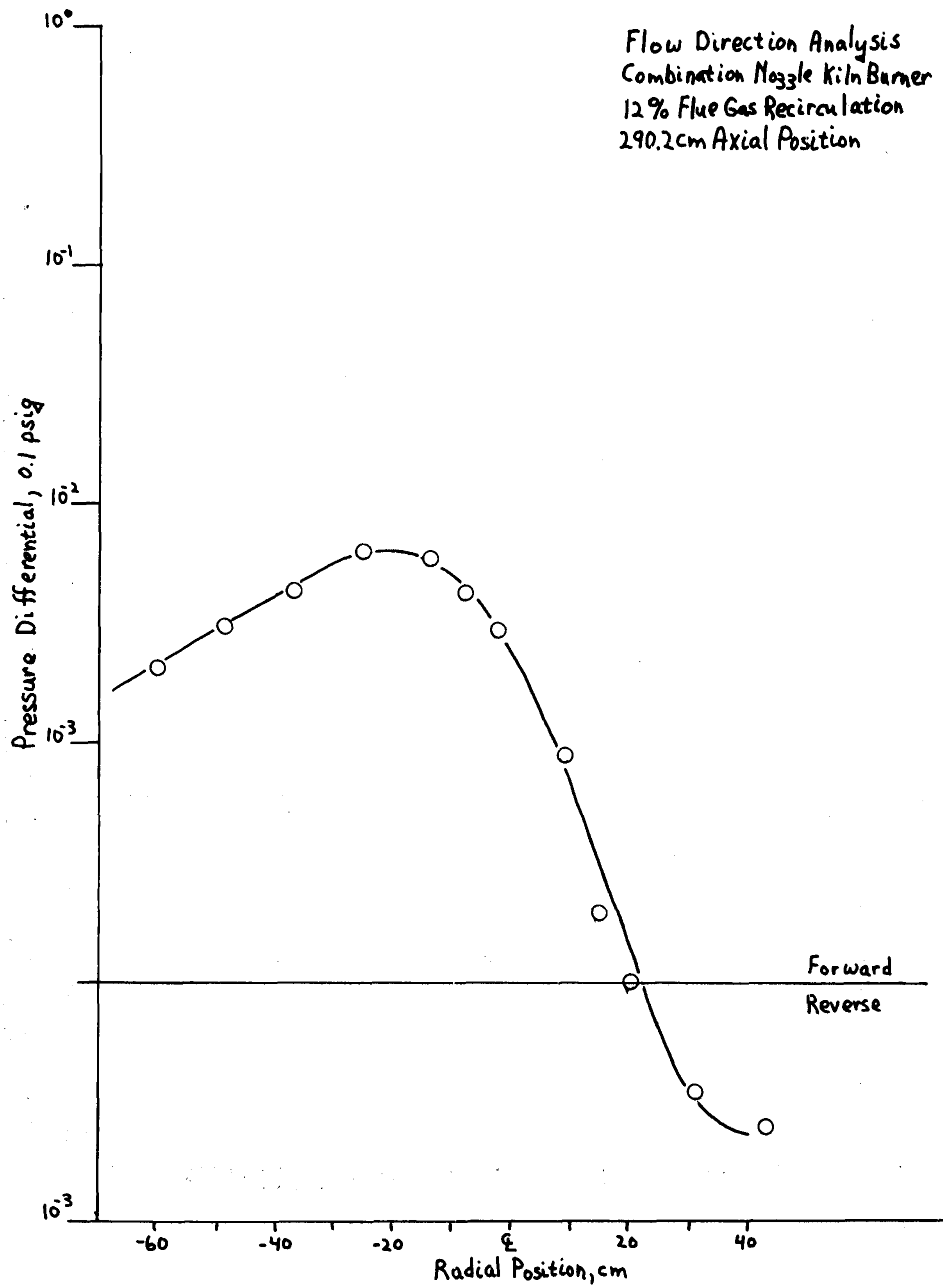

Figure 76. Combination kiln burner nozzle — pollution control conditions — radial profile of flow direction at an axial position of 290. 2 cm

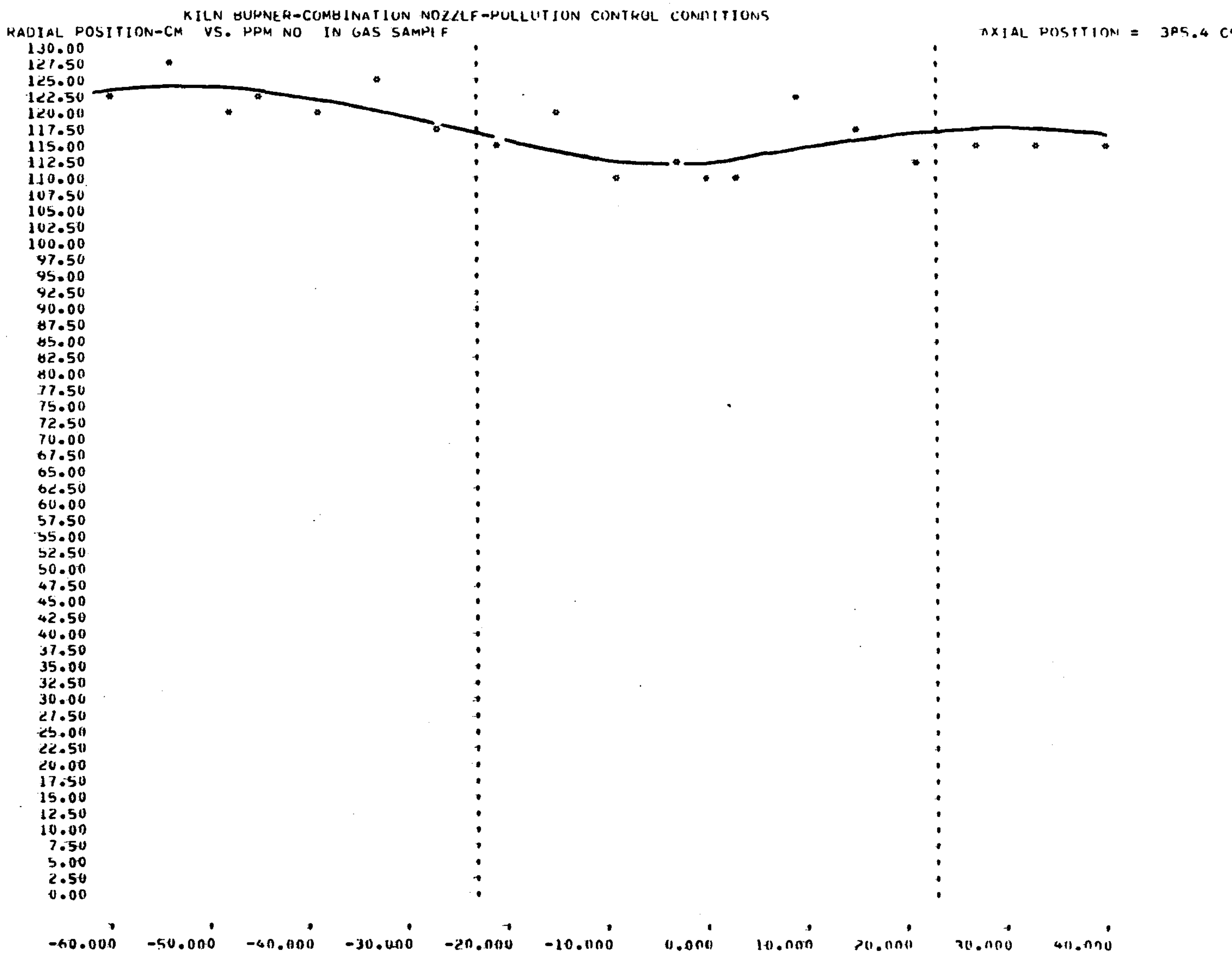

Figure 77. Combination kiln burner nozzle – pollution control conditions – radial profile of NO at an axial position of 385.4 cm

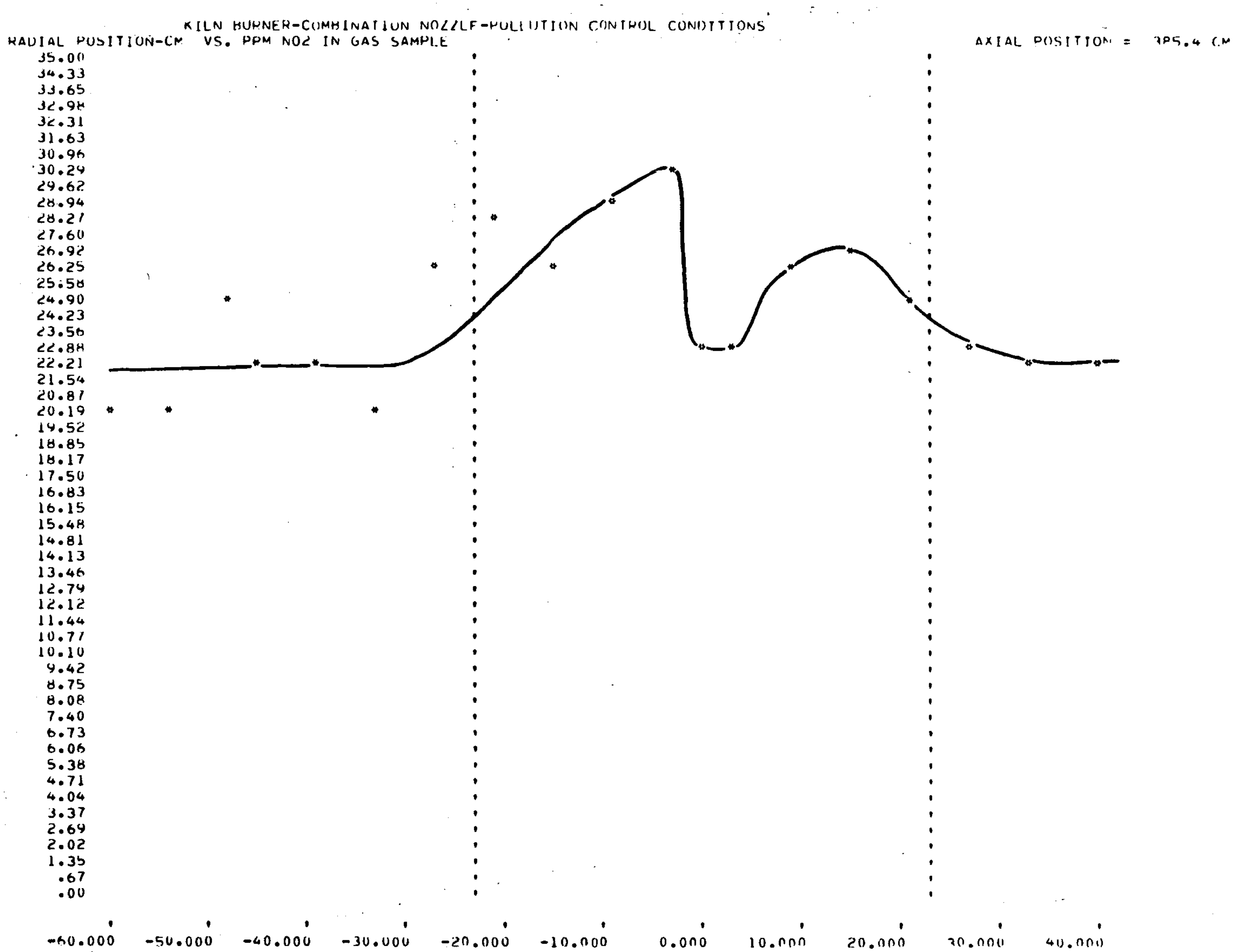

Figure 78. Combination kiln burner nozzle — pollution control conditions — radial profile of NO_2 at an axial position of 385. 4 cm

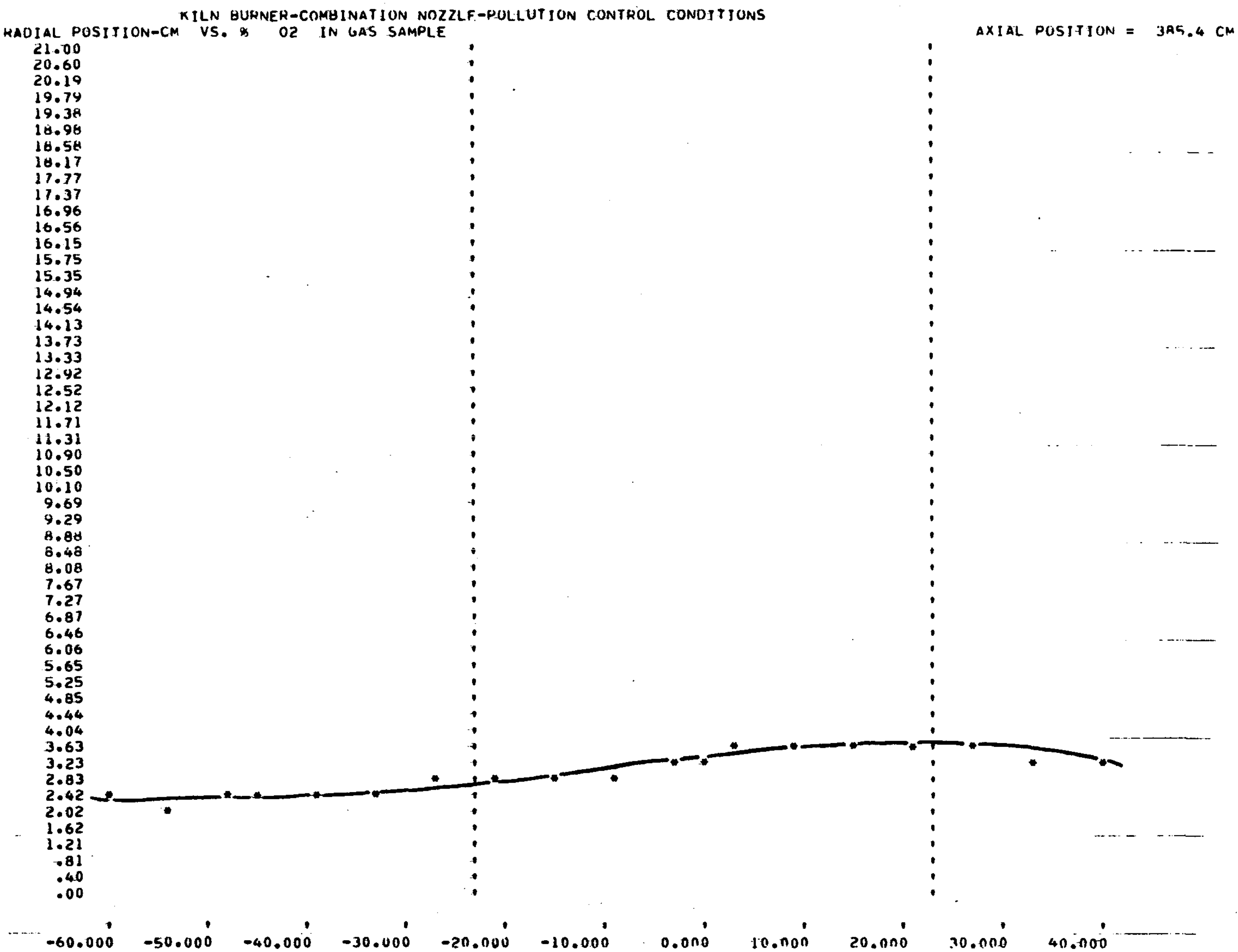

Figure 79. Combination kiln burner nozzle – pollution control conditions – radial profile of O_2 at an axial position of 385.4 cm

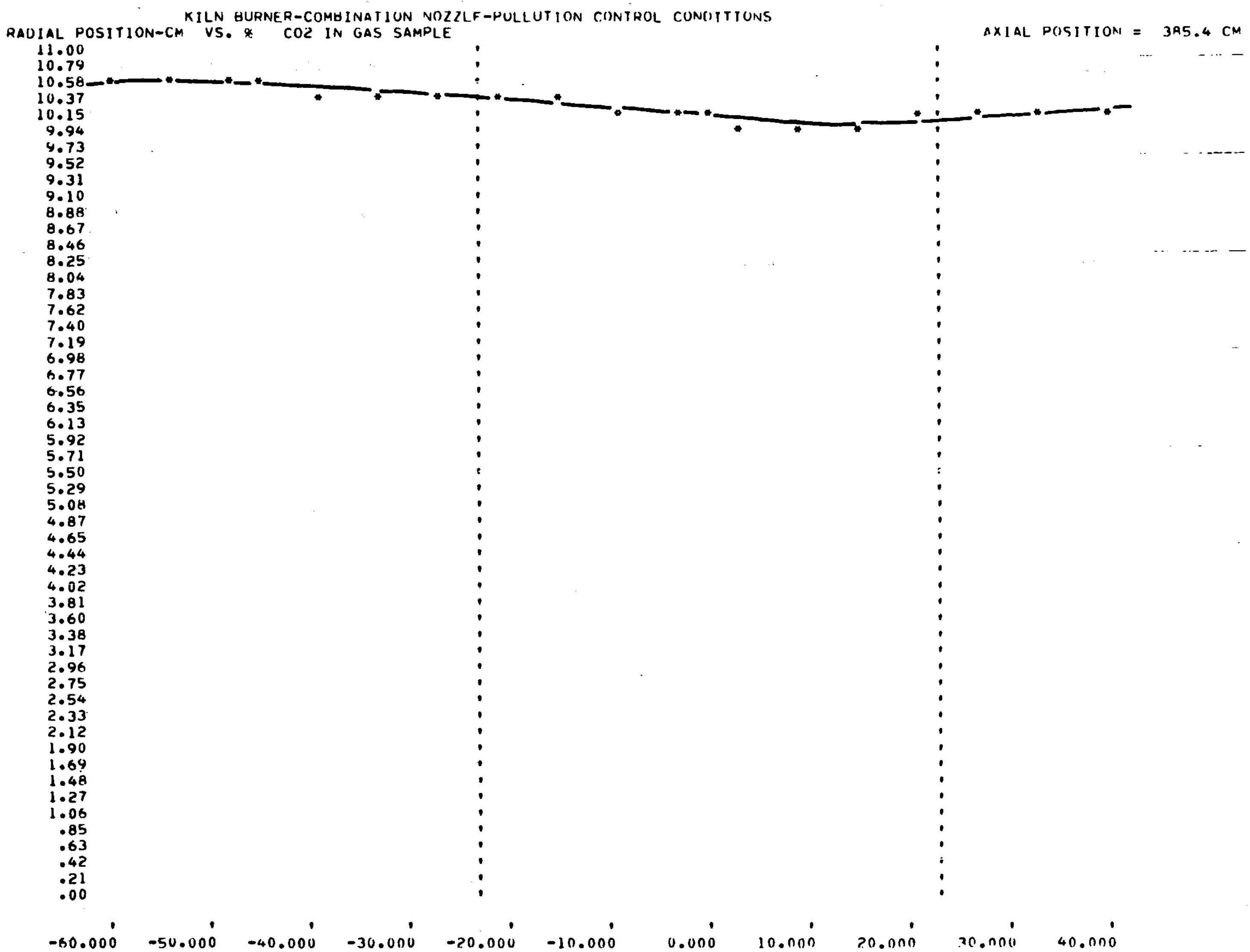

Figure 80. Combination kiln burner nozzle – pollution control conditions – radial profile of CO_2 at an axial position of 385.4 cm

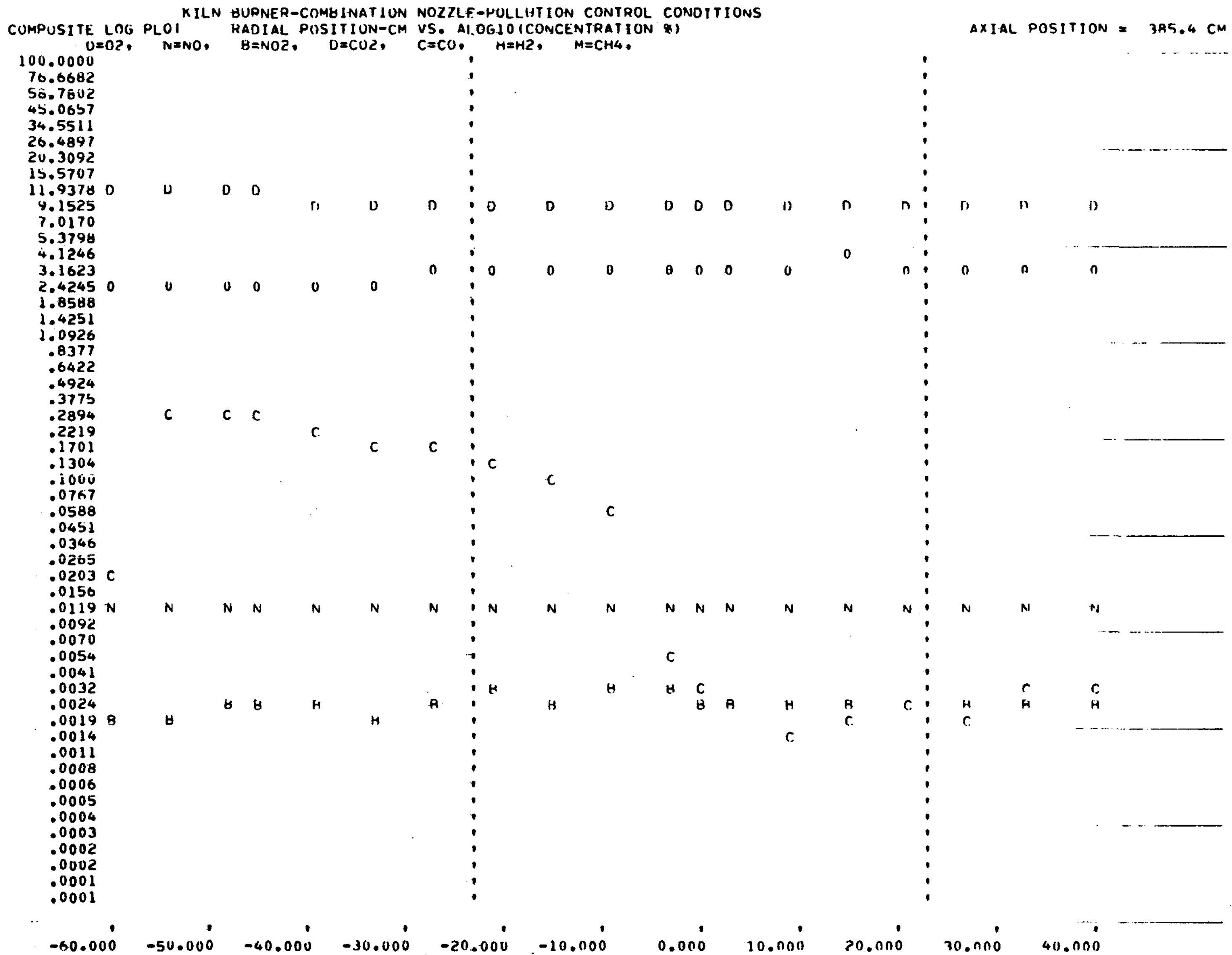

Figure 81. Combination kiln burner nozzle – pollution control conditions – radial profile of all the gases at an axial position of 385.4 cm

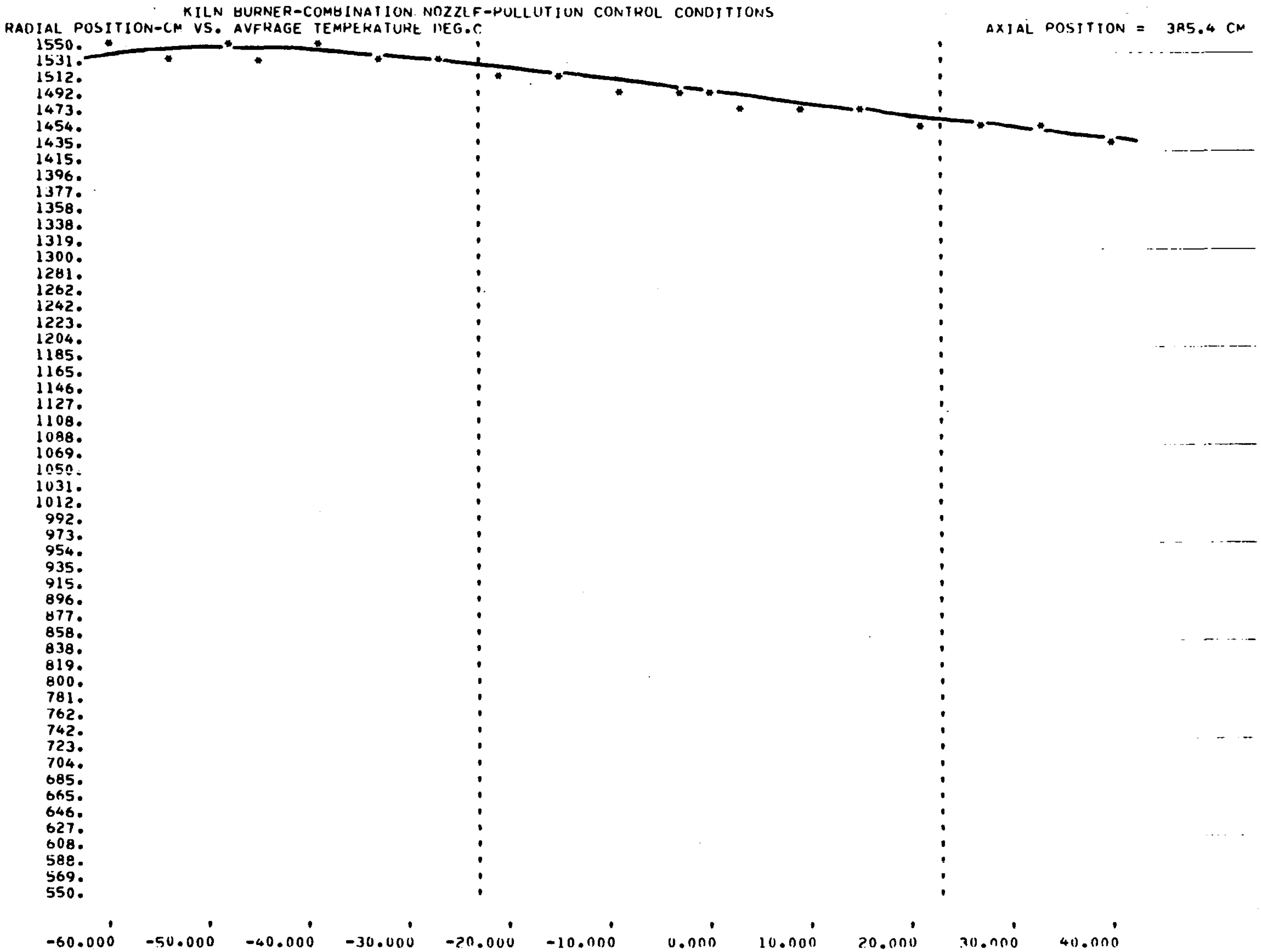

Figure 82. Combination kiln burner nozzle – pollution control conditions – radial profile of temperature at an axial position of 385.4 cm

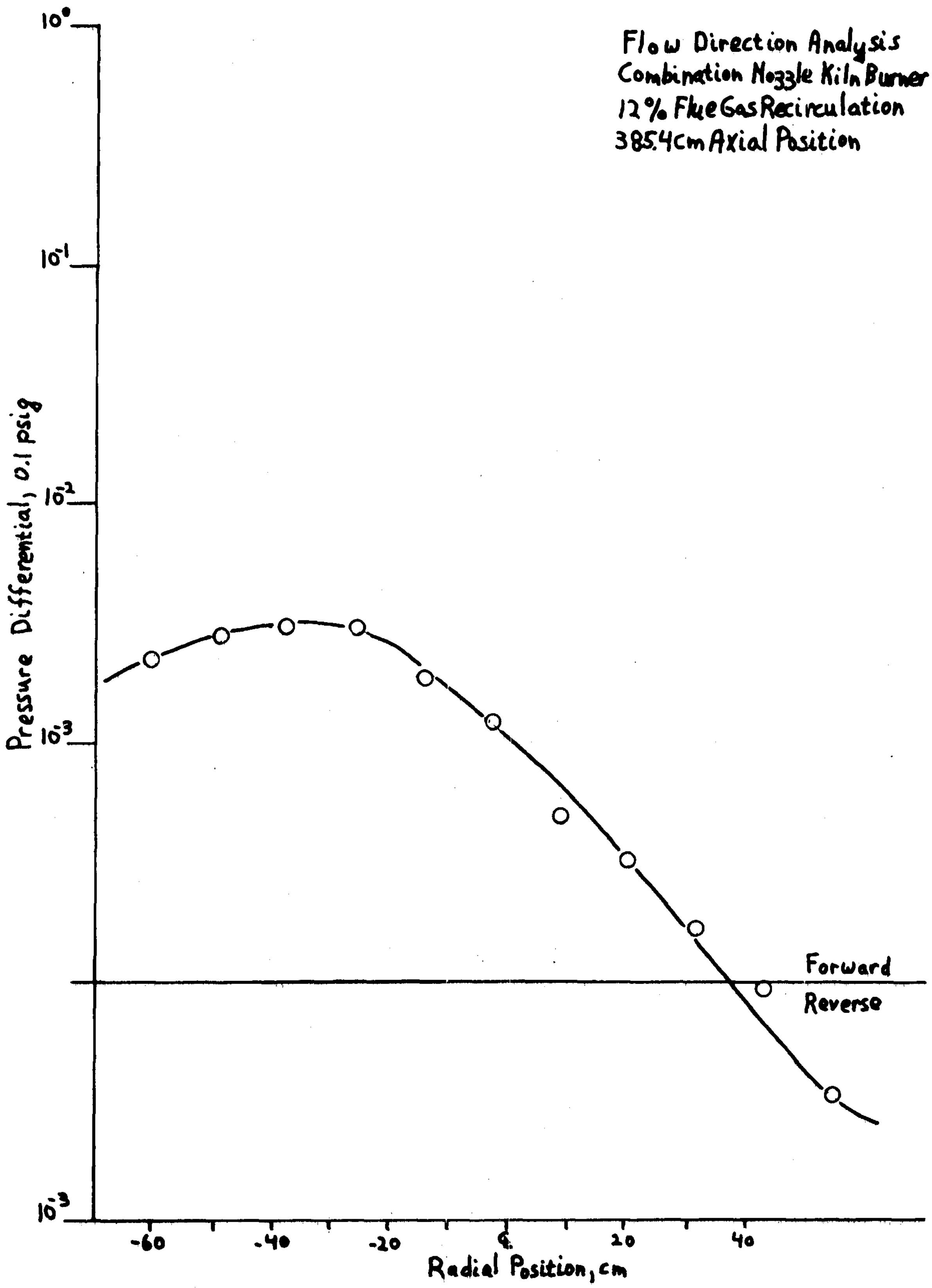

Figure 83. Combination kiln burner nozzle – pollution control conditions – radial profile of flow direction at an axial position of 385. 4 cm

The oxygen profile at the 5.1-cm axial position shows peaks at −18 cm and +12 cm, with concentrations of 17.2% and 18.9%, respectively, which respresent the primary combustion air input.

The methane profile shows a 17.6% maximum concentration on the centerline of the burner and falls to zero at −12 cm and +12 cm, in an asymmetrical pattern.

The carbon dioxide versus radial position curve shows a variation in the level of concentration from 1.3% to 1.7% in the central region of the secondary combustion air entrance zones (+20 cm to +12 cm and −12 cm to −18 cm, as determined from the oxygen profile). Although these concentrations are considerably lower than the secondary recirculation zone values of approximately 9%, they are higher than the measured concentration of carbon dioxide in the secondary combustion air entrance zones, for the kiln burner operating without flue-gas recirculation. This occurs because of the difference in composition of the secondary combustion air with and without flue-gas products. Without flue-gas recirculation, the air contains no detectable levels of carbon dioxide, while for 12% recirculation, it contains approximately 1.2% carbon dioxide. Other concentrations in the combustion air plus flue gas included 18.9% O_2, 10 ppm NO, and 1 ppm NO_2. Comparing these concentrations for the fluid entering through the secondary combustion air zones with the analyzed component concentrations shows that there is a minimal amount of entrainment of secondary recirculation products into the burner-block region at the 5.1-cm axial position.

A correlation of the carbon dioxide, nitric dioxide, temperature, and nitrogen dioxide profiles indicates that nitrogen dioxide is formed before nitric oxide in the flame (so-called "instantaneous NO_2"). This same conclusion was reached for similar operating conditions of the kiln burner without flue-gas recirculation. The positions of the peaks (−6 cm and +3 cm) inside the burner block coincide for temperature, carbon dioxide, and nitrogen dioxide. This agreement in the peak values for carbon dioxide and the temperature would indicate where the combustion is occurring. At these positions, the nitric oxide concentration is only 8% of its flue value, while nitrogen dioxide has 113% of its final concentration.

Figures 43, 51, 59, 67, 74, and 81 show composite log plots of concentration versus radial position within the composition range of 0.0001% (1 ppm)-100%. In these plots the interrelationships between concentration variations of oxygen, nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, hydrogen, and methane can easily be visualized.

Figures 45, 53, 61, 69, 76, and 83 show flow direction versus radial position. These profiles show the positions of primary and secondary forward flow, of recirculation zones (reverse flow), and of shear and boundary layers.

Figures 44, 52, 60, 68, 75, and 82 are plots of the average temperatures measured versus radial positions.

Data Correlation of Isoplots for the Kiln Burner

Figures 35, 36, and 37 are isothermal and isoconcentration plots of the data presented for the kiln burner operating under standard industrial conditions. Similar profiles are presented in Figures 84, 85, and 86 under pollution-control operating conditions.

A comparison of the isothermal plots (Figures 35 and 84) reveals the baseline flame has a higher initial combustion intensity than the control conditions. At the 57.2-cm axial position, baseline operation produces a 1500°C temperature at the burner block projections compared with a 1300°C temperature for pollution-control operation.

The isoconcentration NO plots reveal that the secondary recirculation zones at the burner wall contain concentration levels similar to those found in the flue. Comparing Figures 36 and 85 substantiates the slower rate of NO formation for the pollution-control operating conditions than for standard operating conditions. The NO_2 concentration has a larger value relative to the flue concentration for the lower temperature fuel rich region of the pollution control case than that for standard operating conditions. This may aid in determining the kinetic formation scheme of NO and NO_2.

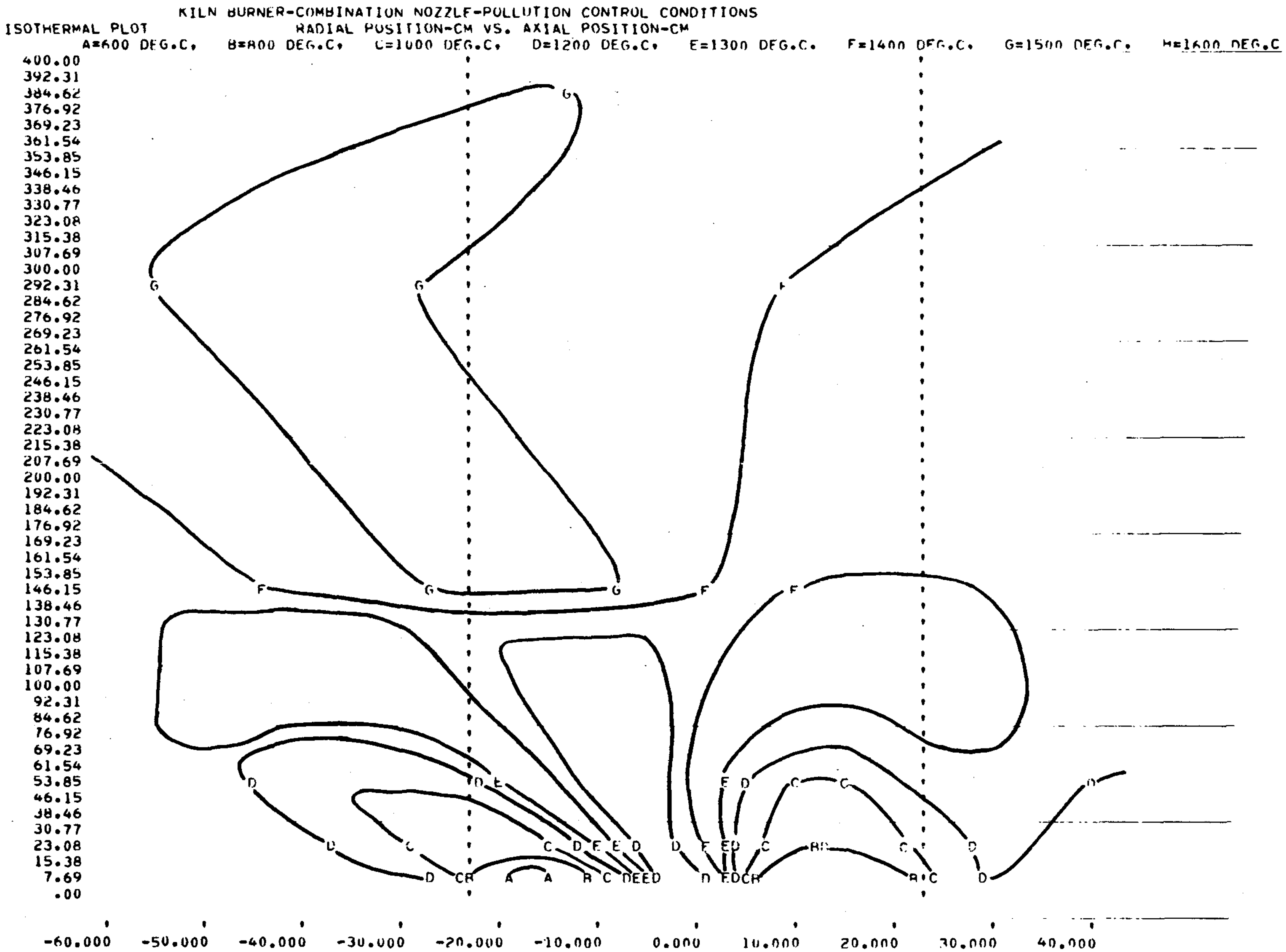

Figure 84. Combination kiln burner nozzle – pollution control conditions – isothermal plot of furnace temperature

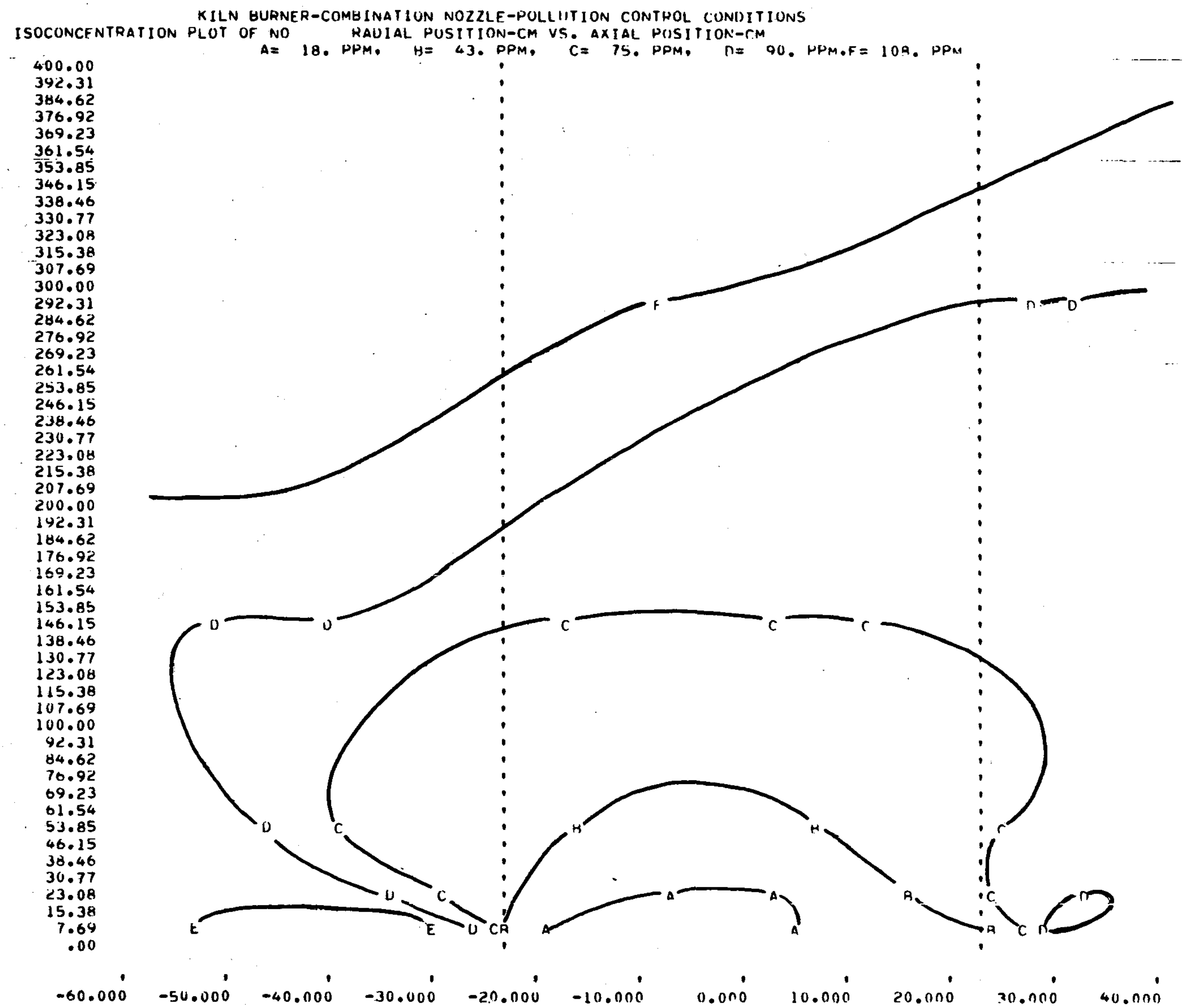

Figure 85. Combination kiln burner nozzle — pollution control conditions — isoconcentration plot of NO

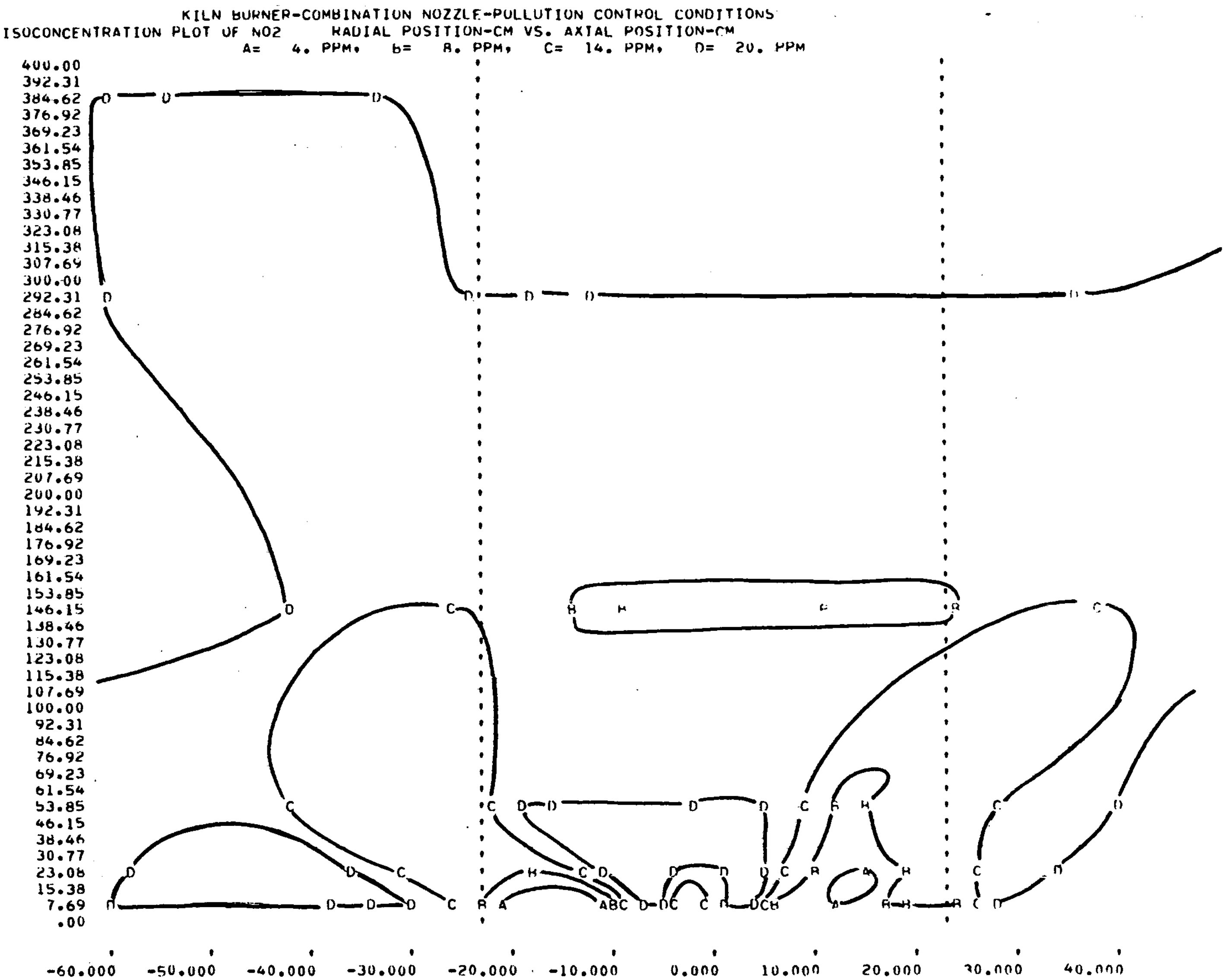

Figure 86. Combination kiln burner nozzle – pollution control conditions – isoconcentration plot of NO_2

BAFFLE BURNER

All in-the-flame experimental work conducted on the intermediate flame length baffle burner was done with a 4-degree quarl angle burner block. In-the-flame probings of two flames were made; base-line data were collected with the operating conditions of the burner identical to those used in industry. Control-case data were gathered from a flame in which the NO emission level had been reduced by a factor of two as a result of increasing the gas velocity by a factor of 16. For the base-line operating conditions, the gas velocity was 38 ft/s, compared with a control case gas velocity of 611 ft/s. The secondary combustion air velocity at the baffle in both cases was 251 ft/s. The difference in flame length was 165 cm, with the base-line flame being 146 cm long and the control-case flame having a length of 311 cm.

Both flames displayed a directional flow profile typical of Type I flames. Considering that the air ports in the baffles were rotated 15 degrees relative to the centerline of the burner, resulting in a combustion-air velocity component in the tangential direction, coupled with the fuel-to-air velocity ratio, a Type II flow profile was expected. Flow profiles were examined for the control-case operating conditions using 8- and 15-degree quarl angle burner blocks. A type II flow profile was measured only for the 15-degree quarl angle burner block, which is the same angle as the baffle ports.

Table 16 lists the furnace conditions at which the base-line, in-the-flame probing data were collected. The data obtained for an axial sampling position of 5. 1 cm are listed in Table 17 and plotted in Figures 87 through 94. Table 18 lists the results of radial sampling at an axial position of 26 cm. Figures 95 through 102 show plots of the data. The radial-profile data at axial positions of 57. 2 cm, 146. 1 cm, and 385. 4 cm are presented in Tables 19 through 21 and Figures 103 through 123.

Intermediate Flame Length Baffle Burner - Standard Gas Nozzle

The first group of in-the-flame profiles, presented in Figures 87 through 123 were collected under burner operating conditions recommended by the manufacturer. The visual flame length was 146 cm with a 38 ft/s gas velocity.

Table 16. FURNACE CONDITIONS FOR IN-THE-FLAME SAMPLING
(Intermediate Flame Length Baffle Burner — Standard Gas Nozzle)

```
                    INTERMEDIATE BAFFLE BURNER - STANDARD NOZZLE

NUMBER OF SETS OF DATA =   5.
MINIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1300. DEG.C
MAXIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1800. DEG.C

POSITION OF OUTSIDE EDGES OF BURNER BLOCK
   MINIMUM POSITION = -14. CM
   MAXIMUM POSITION =  14. CM

GAS INPUT,     AXIAL 3012. CF/HR        RADIAL    0. CF/HR
WALL TEMPERATURE              1430. DEG.C
PREHEAT TEMPERATURE            460. DEG.C
FLUE GAS RECIRCULATION  0.0 %

GAS SAMPLE ANALYSIS IN THE FLUE
   NITROGEN OXIDE      493.0 PPM
   NITROGEN DIOXIDE     53.0 PPM
   OXYGEN                3.9 %
   CARBON DIOXIDE        9.4 %
   CARBON MONOXIDE     .0093 %

LIMITS FOR CONCENTRATION PLOTS
     LOWER LIMIT OF NO  =    0. PPM     UPPER LIMIT =  650. PPM
     LOWER LIMIT OF NO2 =    0. PPM     UPPER LIMIT =   70. PPM
     LOWER LIMIT OF O2  =    0. %       UPPER LIMIT =   21. %
     LOWER LIMIT OF CH4 =    0. %       UPPER LIMIT =    2. %
     LOWER LIMIT OF CO2 =    0. %       UPPER LIMIT =   10. %

ISOCONCENTRATION VALUES
   OBTAIN VALUE OF RADIAL POSITION AT NO  PPM CONCENTRATION   600.  550.  500.  450.  350.
   OBTAIN VALUE OF RADIAL POSITION AT NO2 PPM CONCENTRATION    50.   40.   30.   20.
```

Table 17. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 5.1 cm (Intermediate Flame Length Baffle Burner — Standard Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - STANDARD NOZZLE

AXIAL POSITION = 5.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPFRATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.4	?	560.	44.	9.3	.0083	?	0.0	?	?	?	?	1476.	1476.	0.
-54.	4.3	?	570.	65.	9.3	.0085	?	0.0	?	?	?	?	1482.	1482.	0.
-48.	4.3	?	600.	53.	9.4	.0082	?	0.0	?	?	?	?	1484.	1484.	0.
-36.	4.3	?	595.	55.	9.4	.0077	?	0.0	?	?	?	?	1470.	1470.	0.
-24.	4.3	?	600.	55.	9.4	.0075	?	0.0	?	?	?	?	1455.	1455.	0.
-21.	4.4	?	590.	55.	9.3	.0073	?	0.0	?	?	?	?	1380.	1380.	0.
-18.	3.9	?	610.	45.	9.6	.0078	?	0.0	?	?	?	?	1370.	1370.	0.
-15.	4.0	?	630.	49.	9.5	.0452	?	0.0	?	?	?	?	1351.	1351.	0.
-12.	7.9	80.4	70.	51.	5.9	1.3000	3.1	.2	.1	0.0	0.0	0.0	1688.	1688.	0.
-9.	1.6	75.5	105.	18.	6.4	5.3000	9.2	.9	.3	0.0	0.0	0.0	1712.	1712.	0.
-6.	.6	72.2	118.	1.	5.3	7.6000	12.3	1.1	.4	0.0	0.0	0.0	1656.	1656.	0.
-3.	.5	71.5	125.	0.	4.7	9.0000	12.2	1.2	.5	0.0	0.0	0.0	1636.	1636.	0.
0.	.5	70.2	118.	0.	4.4	9.3000	13.4	1.3	.5	0.0	0.0	0.0	1613.	1613.	0.
3.	.5	72.2	130.	0.	5.0	8.7000	11.9	.9	.3	0.0	0.0	0.0	1649.	1649.	0.
6.	1.2	75.5	153.	0.	6.1	6.3000	9.7	.5	.1	0.0	0.0	0.0	1669.	1669.	0.
9.	6.1	82.5	105.	12.	6.7	1.8000	1.6	.1	0.0	0.0	0.0	0.0	1652.	1652.	0.
12.	11.4	82.3	80.	9.	5.0	.4000	0.0	0.0	0.0	0.0	0.0	0.0	1555.	1555.	0.
15.	14.2	?	43.	2.	3.8	.0478	?	0.0	?	?	?	?	1459.	1459.	0.
18.	13.1	?	180.	8.	4.3	.0146	?	0.0	?	?	?	?	1470.	1470.	0.
21.	4.1	?	485.	25.	9.4	.0088	?	0.0	?	?	?	?	1489.	1489.	0.
24.	3.3	?	550.	28.	9.8	.0093	?	0.0	?	?	?	?	1489.	1489.	0.
36.	3.3	?	530.	29.	9.8	.0089	?	0.0	?	?	?	?	1475.	1475.	0.

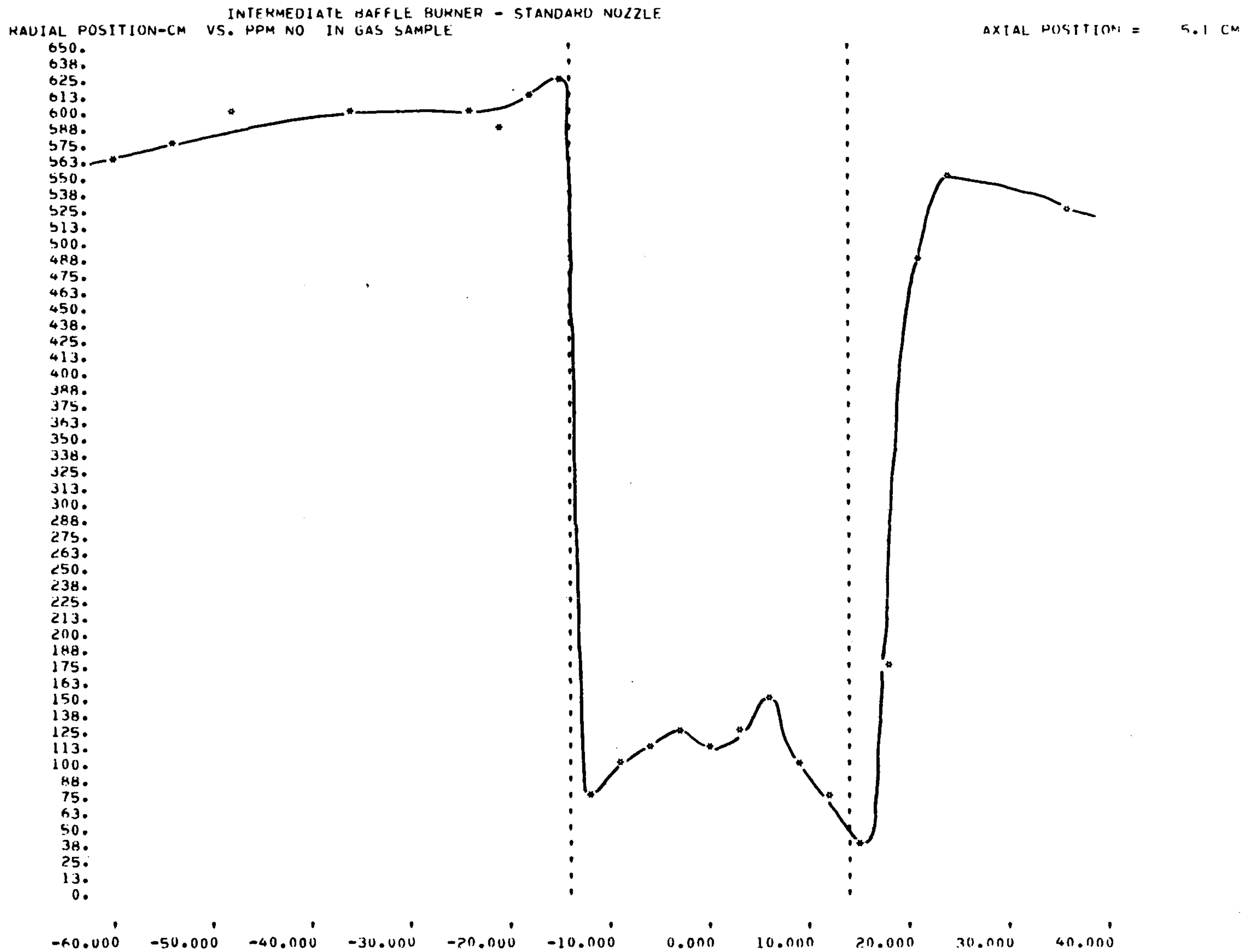

Figure 87. Radial profile of NO at an axial position of 5.1 cm (intermediate flame length baffle burner — standard gas nozzle)

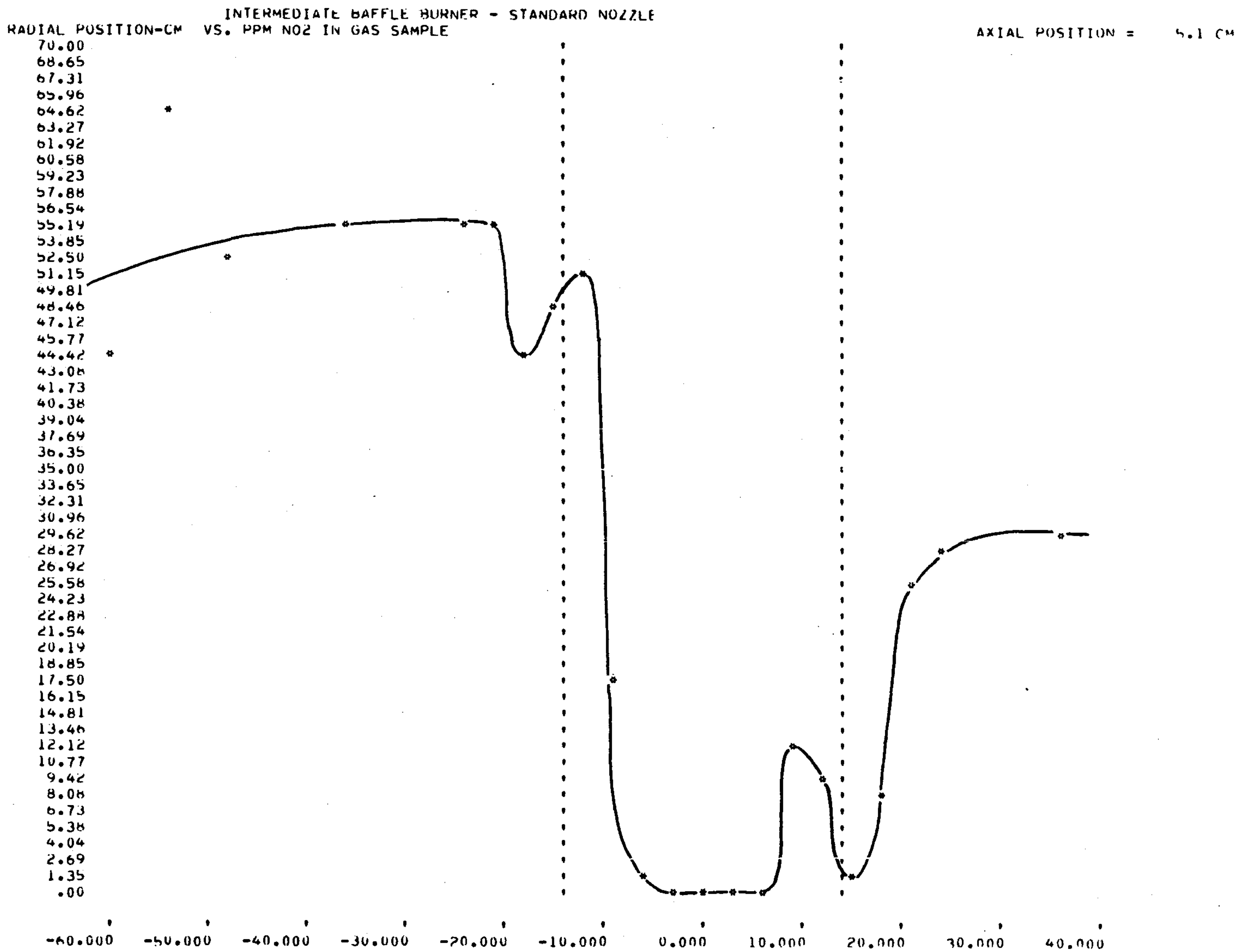

Figure 88. Radial profile of NO_2 at an axial position of 5.1 cm (intermediate flame length baffle burner – standard gas nozzle)

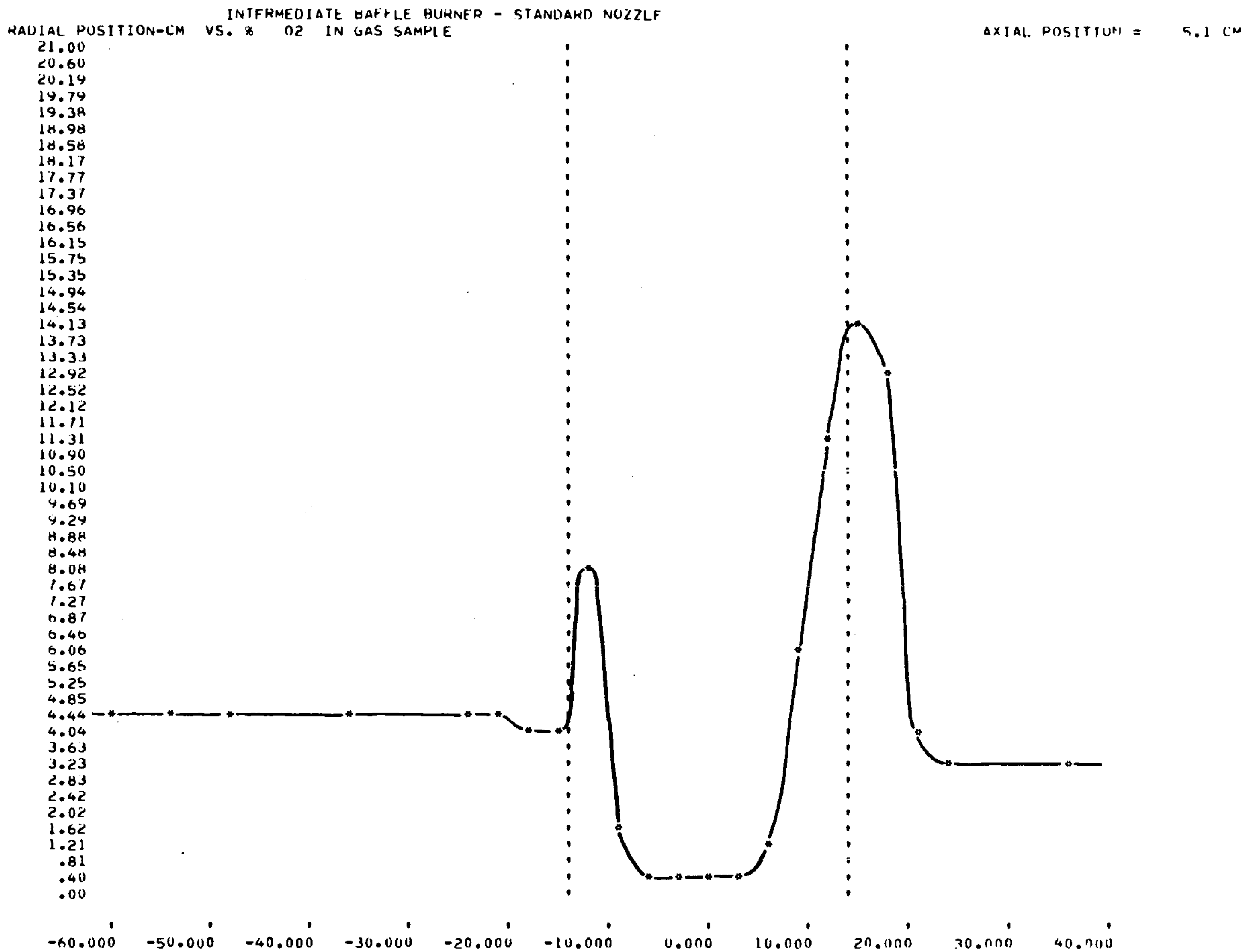

Figure 89. Radial profile of O_2 at an axial position of 5.1 cm (intermediate flame length baffle burner — standard gas nozzle)

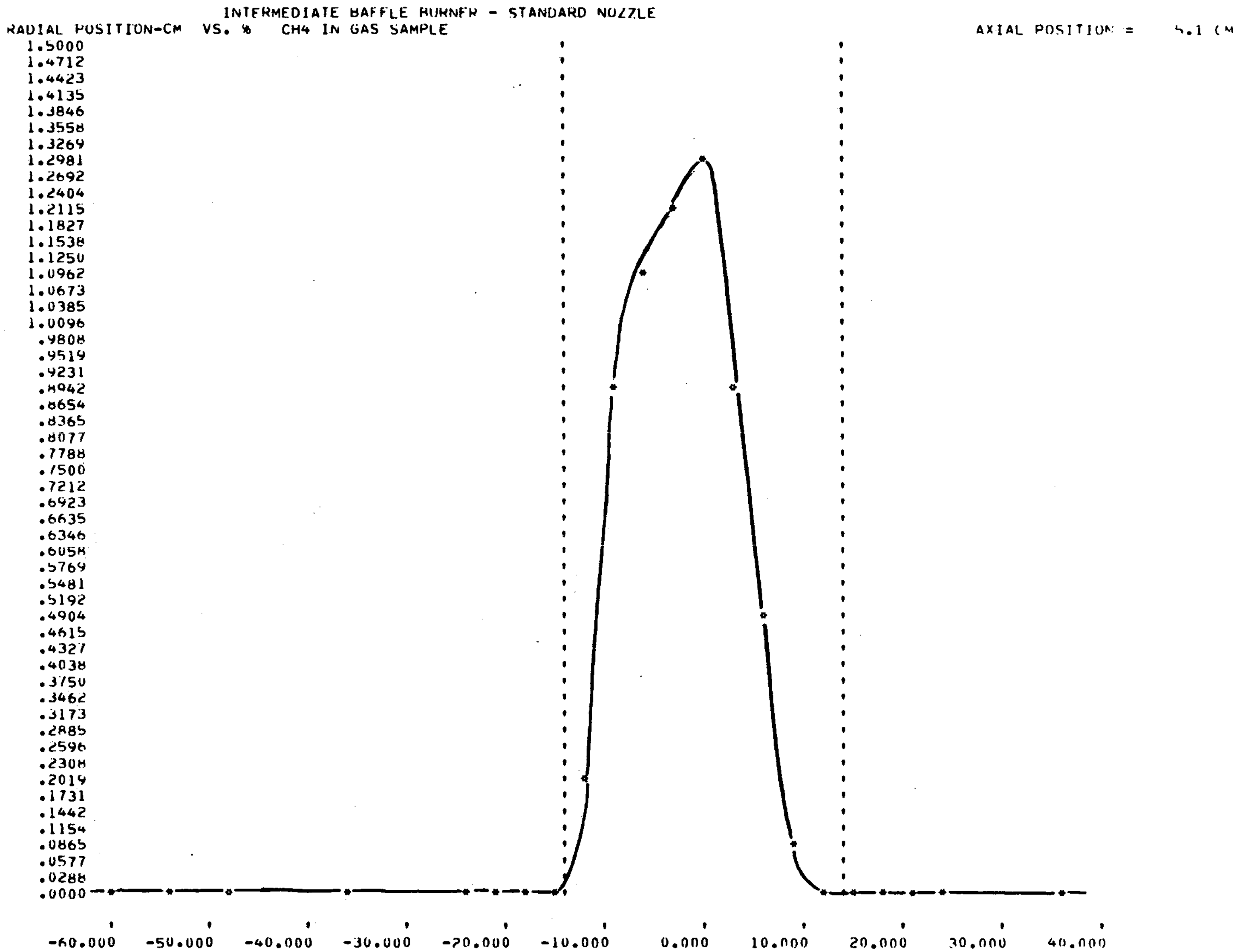

Figure 90. Radial profile of CH_4 at an axial position of 5.1 cm (intermediate flame length baffle burner – standard gas nozzle)

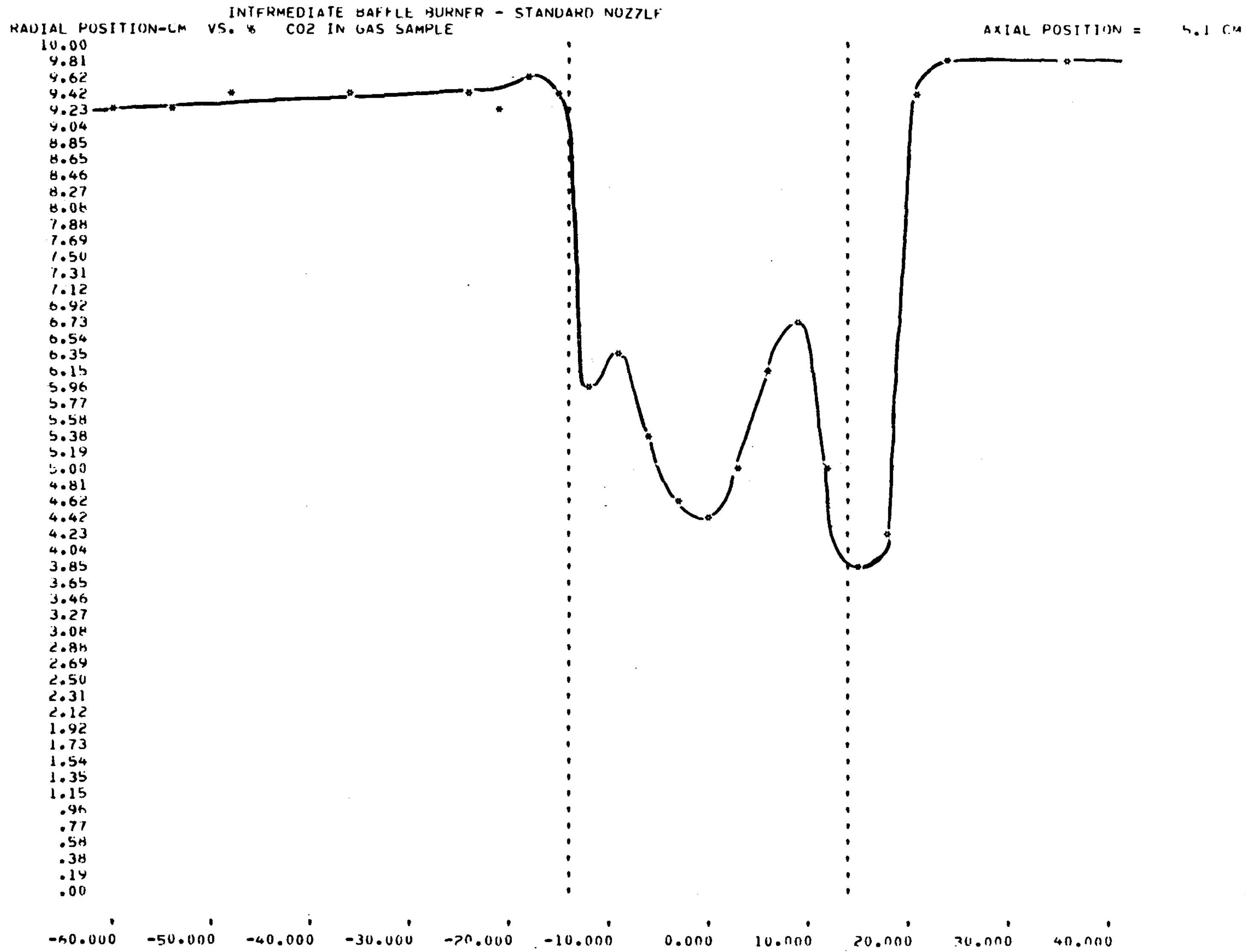

Figure 91. Radial profile of CO_2 at an axial position of 5.1 cm (intermediate flame length baffle burner – standard gas nozzle)

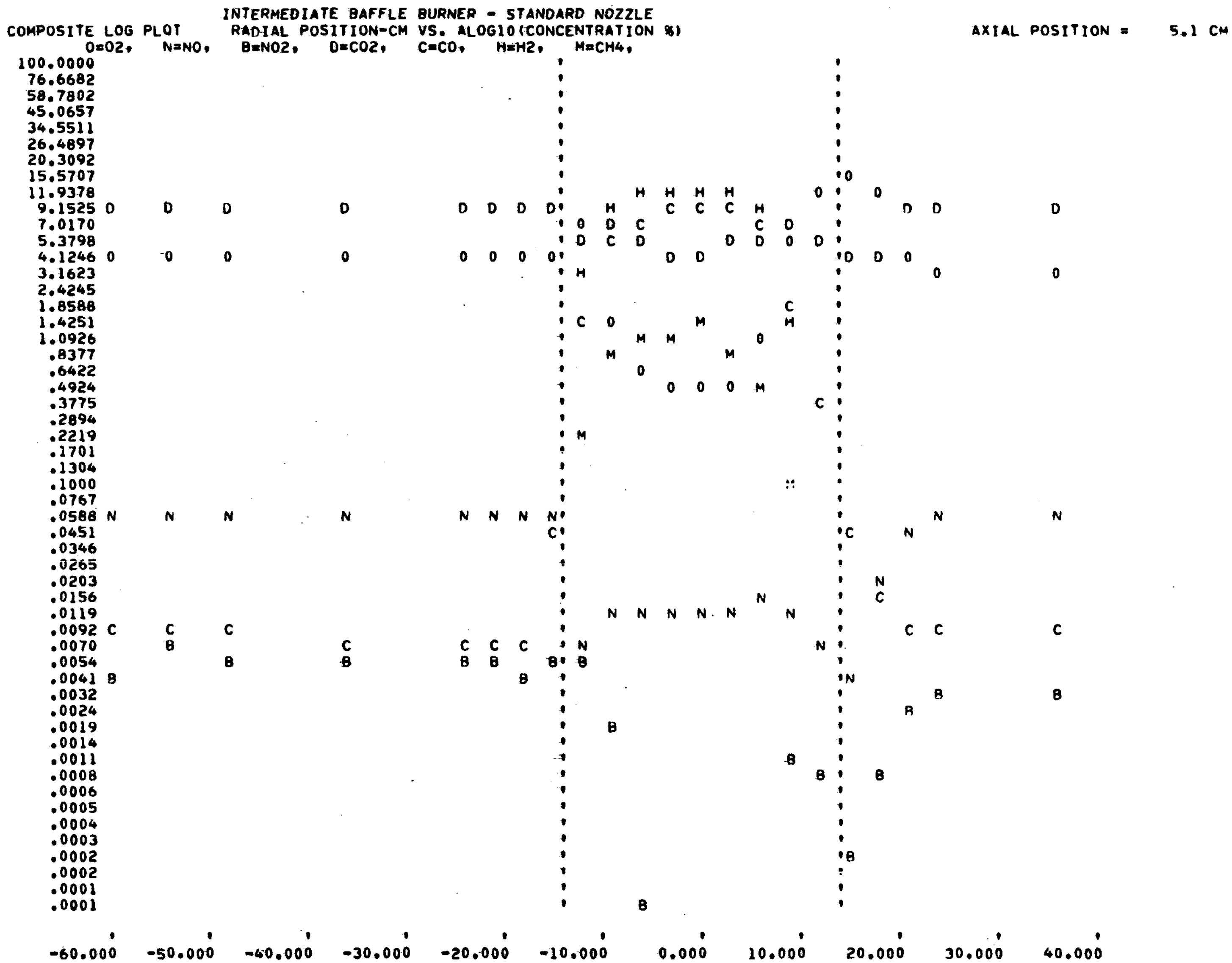

Figure 92. Radial profile of all the gases at an axial position of 5.1 cm (intermediate flame length baffle burner — standard gas nozzle)

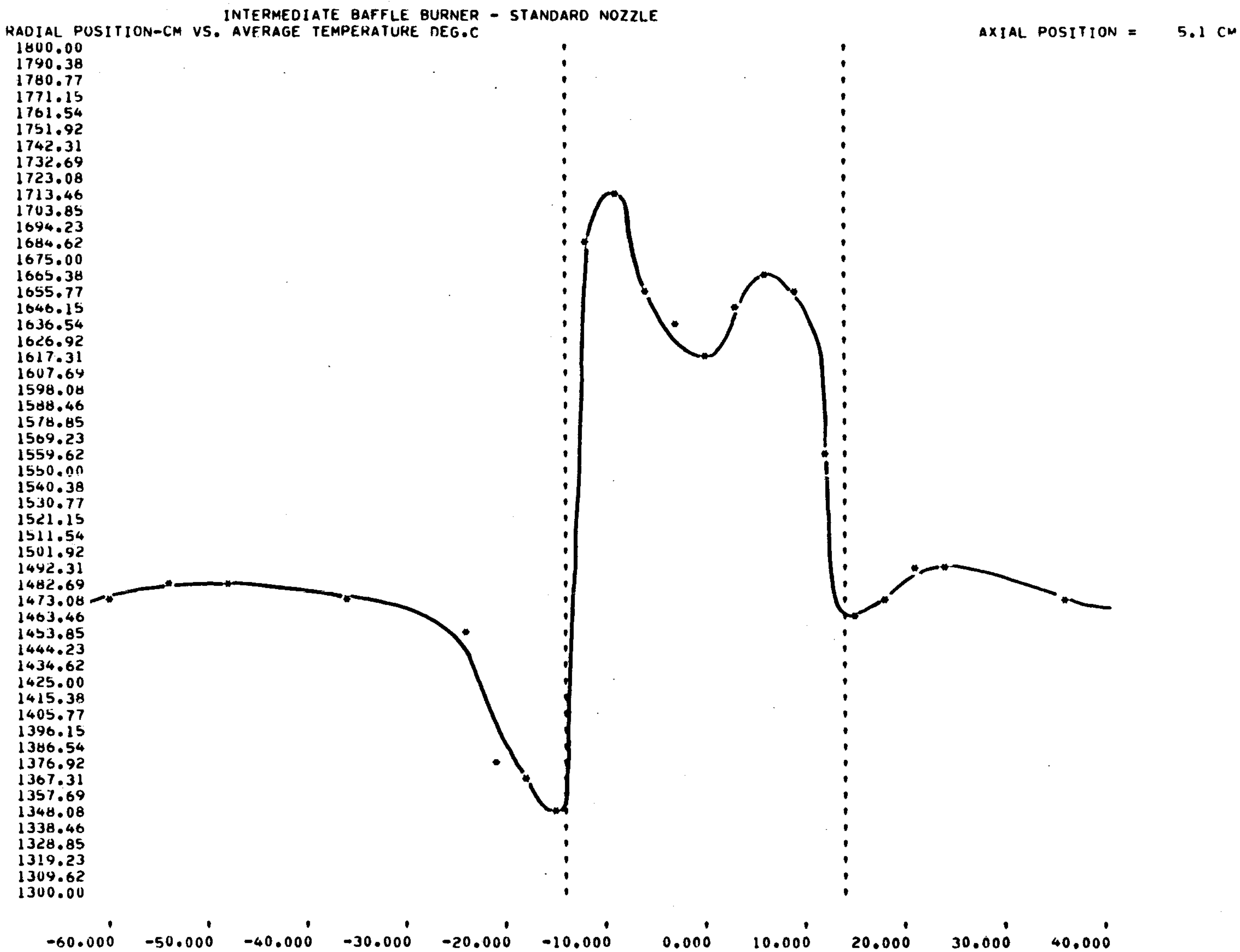

Figure 93. Radial profile of average temperature at an axial position of 5.1 cm (intermediate flame length baffle burner – standard gas nozzle)

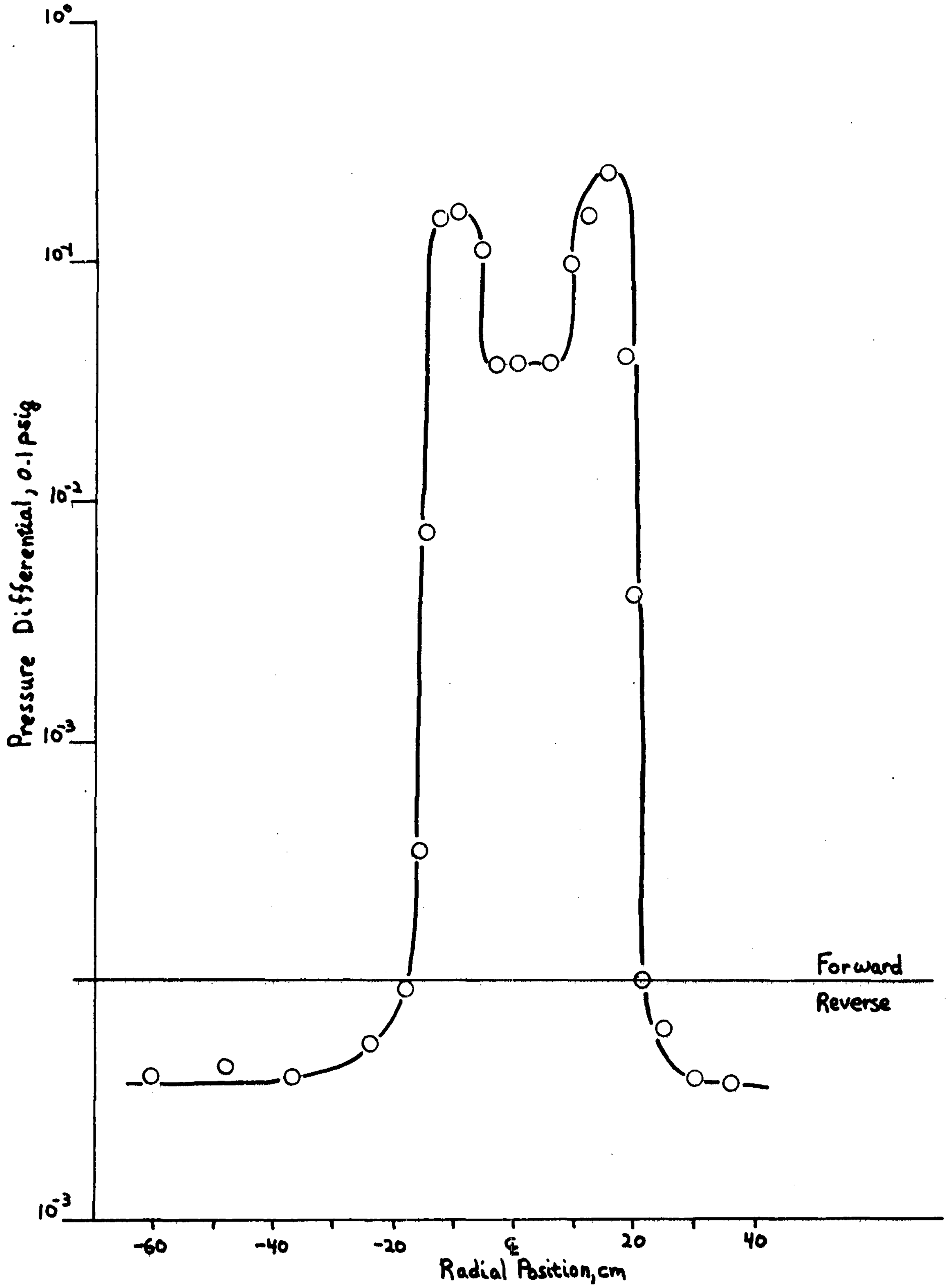

Figure 94. Radial profile of flow direction at an axial position of 5.1 cm (intermediate flame length baffle burner — standard gas nozzle)

Table 18. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 26.0 cm (Intermediate Flame Length Baffle Burner – Standard Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - STANDARD NOZZLE

AXIAL POSITION = 26.0 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.4	?	542.	54.	9.2	.0070	?	0.0	?	?	?	?	1455.	1455.	0.
-48.	4.5	?	565.	57.	9.1	.0075	?	0.0	?	?	?	?	1460.	1460.	0.
-36.	4.4	?	565.	55.	9.3	.0074	?	0.0	?	?	?	?	1440.	1440.	0.
-24.	4.4	?	530.	50.	9.3	.0086	?	0.0	?	?	?	?	1393.	1393.	0.
-21.	4.4	?	525.	48.	9.3	.0478	?	0.0	?	?	?	?	1500.	1500.	0.
-18.	4.4	?	420.	54.	9.3	.0940	?	0.0	?	?	?	?	1605.	1605.	0.
-15.	4.3	85.4	395.	51.	9.2	.3300	0.0	0.0	0.0	0.0	0.0	0.0	1632.	1632.	0.
-12.	4.0	84.3	340.	42.	8.9	1.0000	.7	0.0	0.0	0.0	0.0	0.0	1703.	1703.	0.
-9.	2.9	83.4	330.	31.	8.8	2.4000	3.1	0.0	0.0	0.0	0.0	0.0	1753.	1753.	0.
-6.	1.6	81.4	312.	13.	8.2	4.1000	4.0	0.0	0.0	0.0	0.0	0.0	1740.	1740.	0.
-3.	.8	78.7	295.	0.	7.0	6.0000	6.5	.1	0.0	0.0	0.0	0.0	1710.	1710.	0.
0.	.8	76.9	245.	0.	6.4	7.1000	8.0	.1	0.0	0.0	0.0	0.0	1679.	1679.	0.
3.	.9	77.3	225.	0.	6.2	6.8000	8.0	.1	0.0	0.0	0.0	0.0	1701.	1701.	0.
6.	2.0	79.3	198.	0.	6.7	5.3000	6.0	.1	0.0	0.0	0.0	0.0	1688.	1688.	0.
9.	5.5	82.1	150.	28.	6.7	2.5000	2.3	0.0	0.0	0.0	0.0	0.0	1640.	1640.	0.
12.	9.6	82.5	125.	20.	5.7	.7000	.4	0.0	0.0	0.0	0.0	0.0	1538.	1538.	0.
15.	11.8	82.1	145.	7.	4.9	.1000	0.0	0.0	0.0	0.0	0.0	0.0	1481.	1481.	0.
18.	11.5	82.3	195.	12.	5.3	0.0000	0.0	0.0	0.0	0.0	0.0	0.0	1461.	1461.	0.
21.	8.7	?	270.	33.	6.8	.0078	?	0.0	?	?	?	?	1430.	1430.	0.
24.	6.1	?	397.	30.	8.2	.0067	?	0.0	?	?	?	?	1434.	1434.	0.
36.	3.8	?	468.	32.	9.5	.0076	?	0.0	?	?	?	?	1444.	1444.	0.

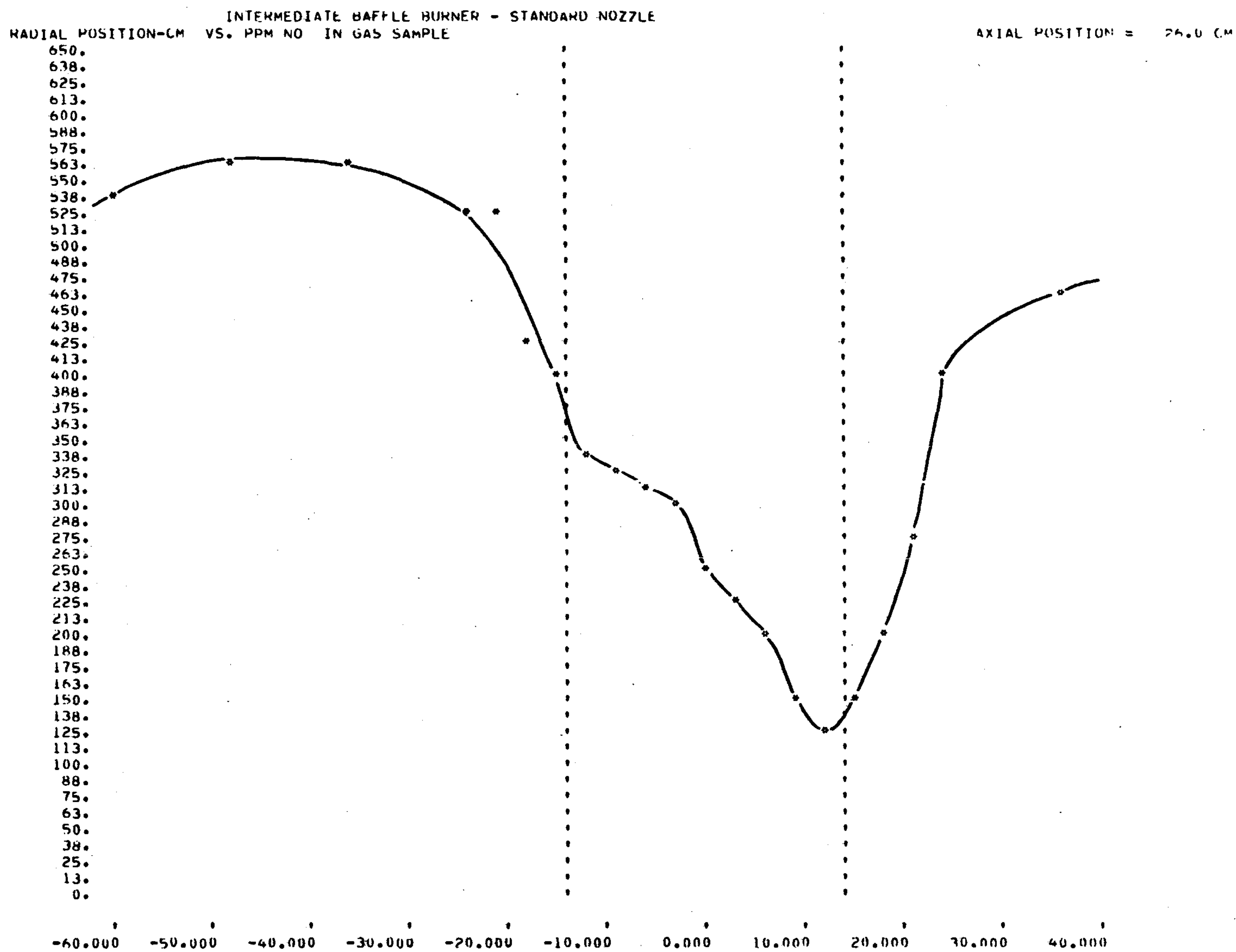

Figure 95. Radial profile of NO at an axial position of 26.0 cm (intermediate flame length baffle burner – standard gas nozzle)

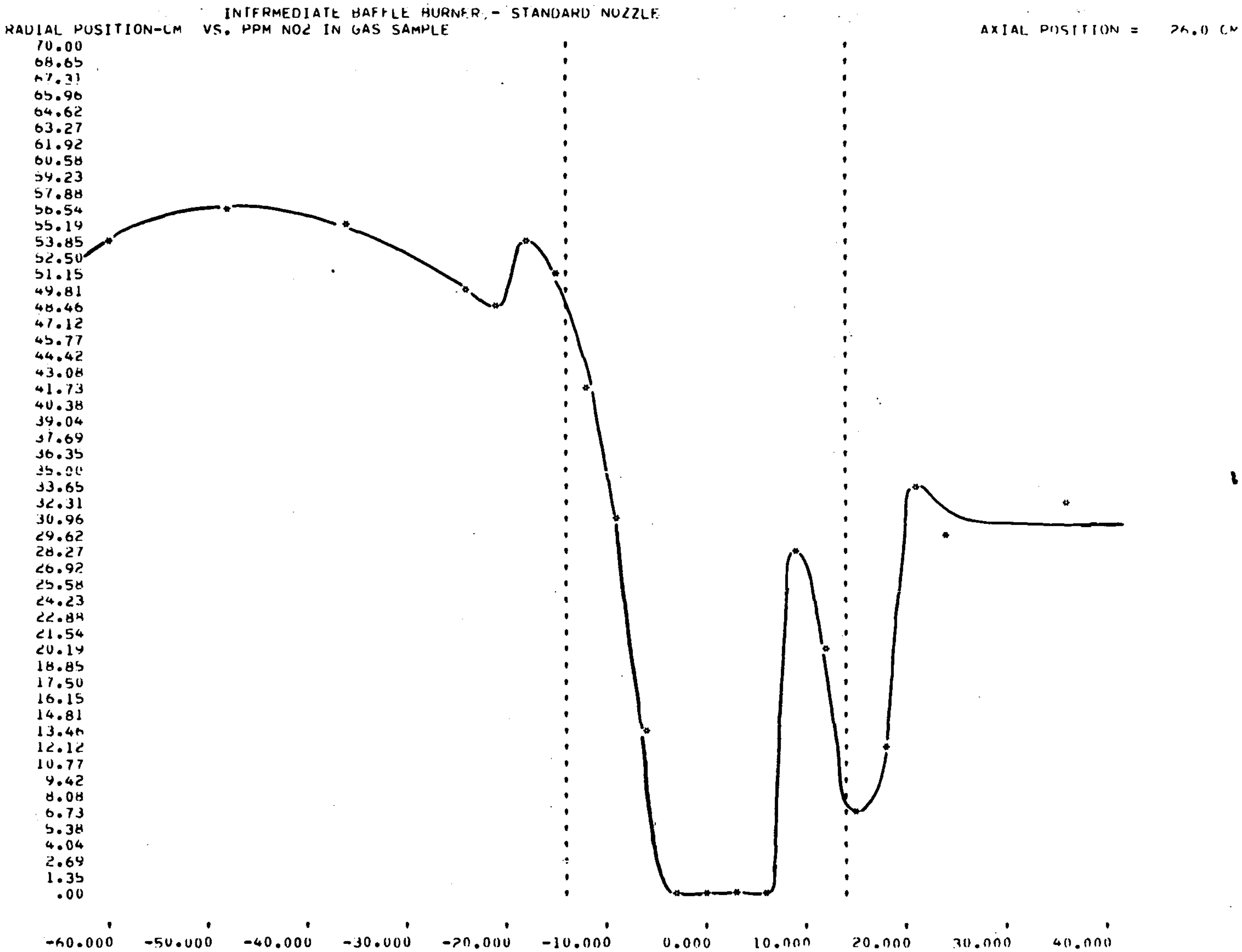

Figure 96. Radial profile of NO_2 at an axial position of 26.0 cm (intermediate flame length baffle burner – standard gas nozzle)

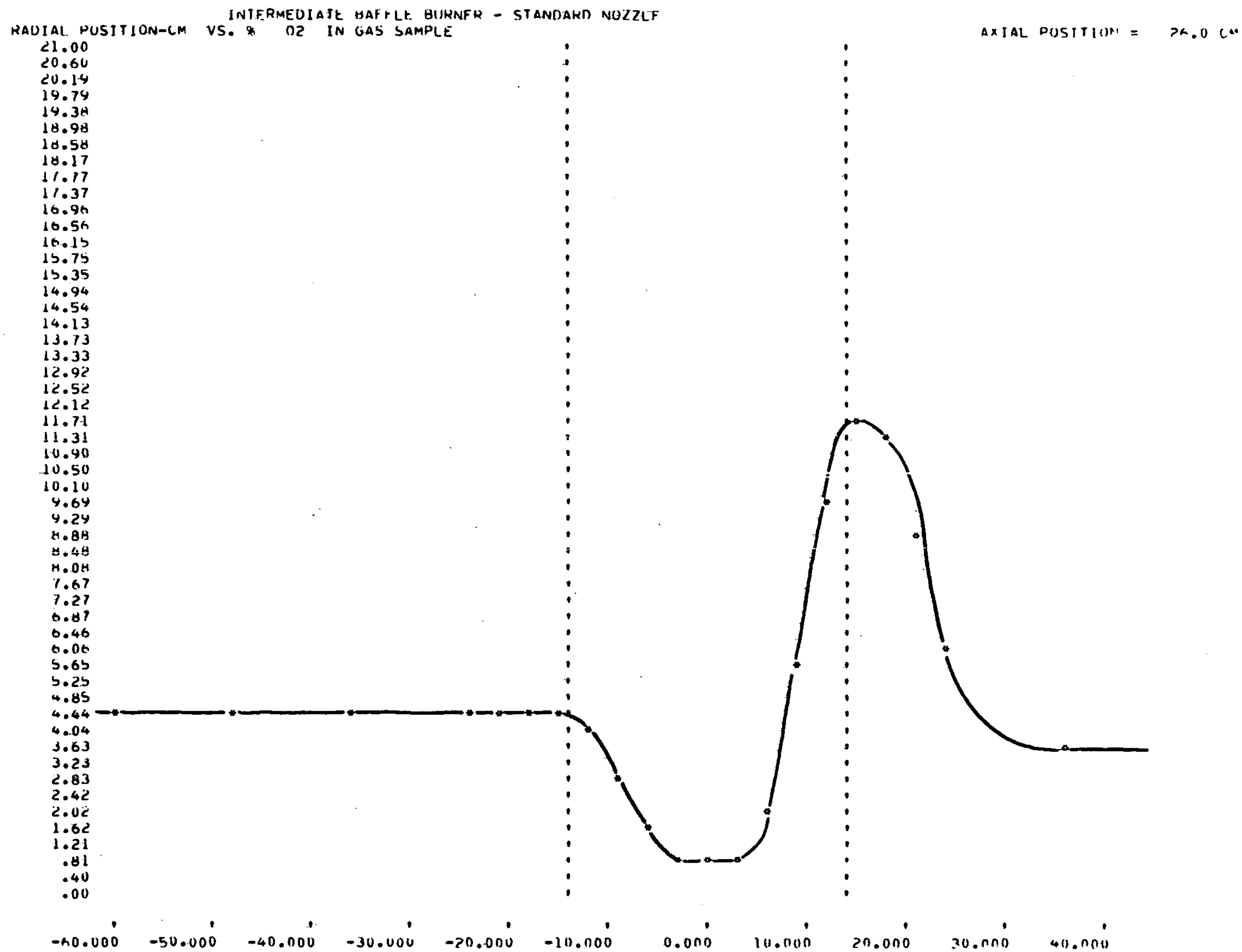

Figure 97. Radial profile of O_2 at an axial position of 26.0 cm (intermediate flame length baffle burner — standard gas nozzle)

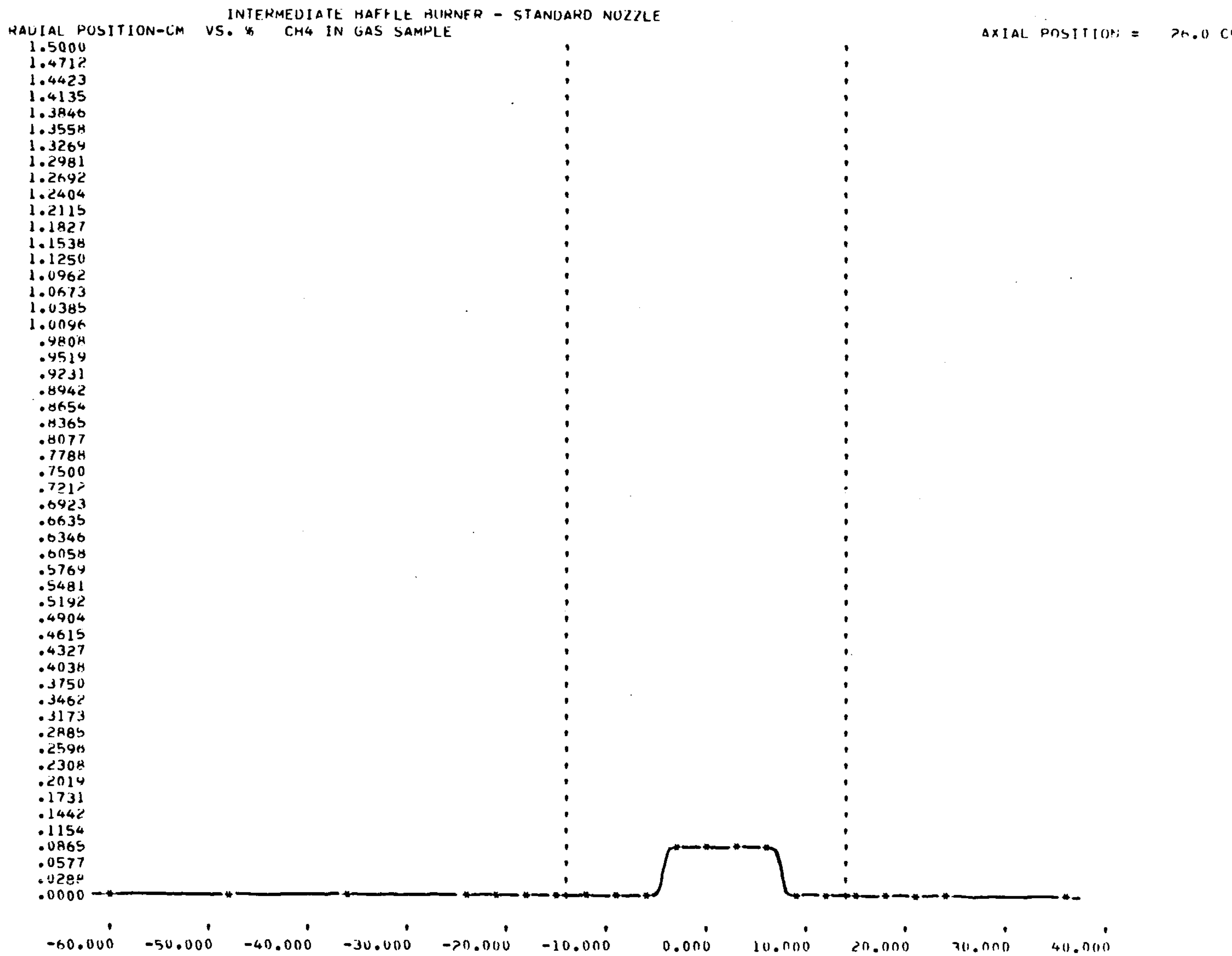

Figure 98. Radial profile of CH_4 at an axial position of 26.0 cm (intermediate flame length baffle burner — standard gas nozzle)

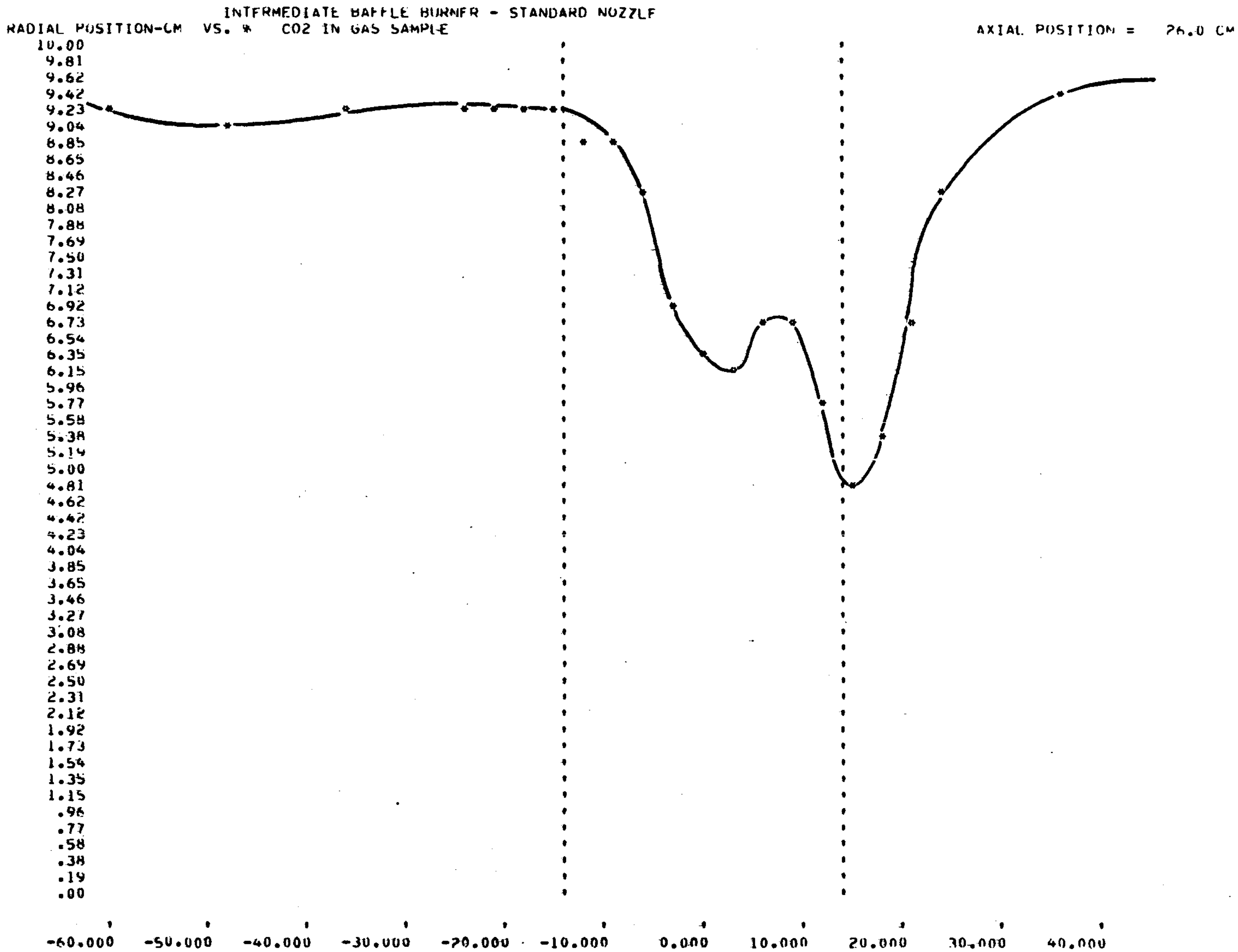

Figure 99. Radial profile of CO_2 at an axial position of 26.0 cm (intermediate flame length baffle burner — standard gas nozzle)

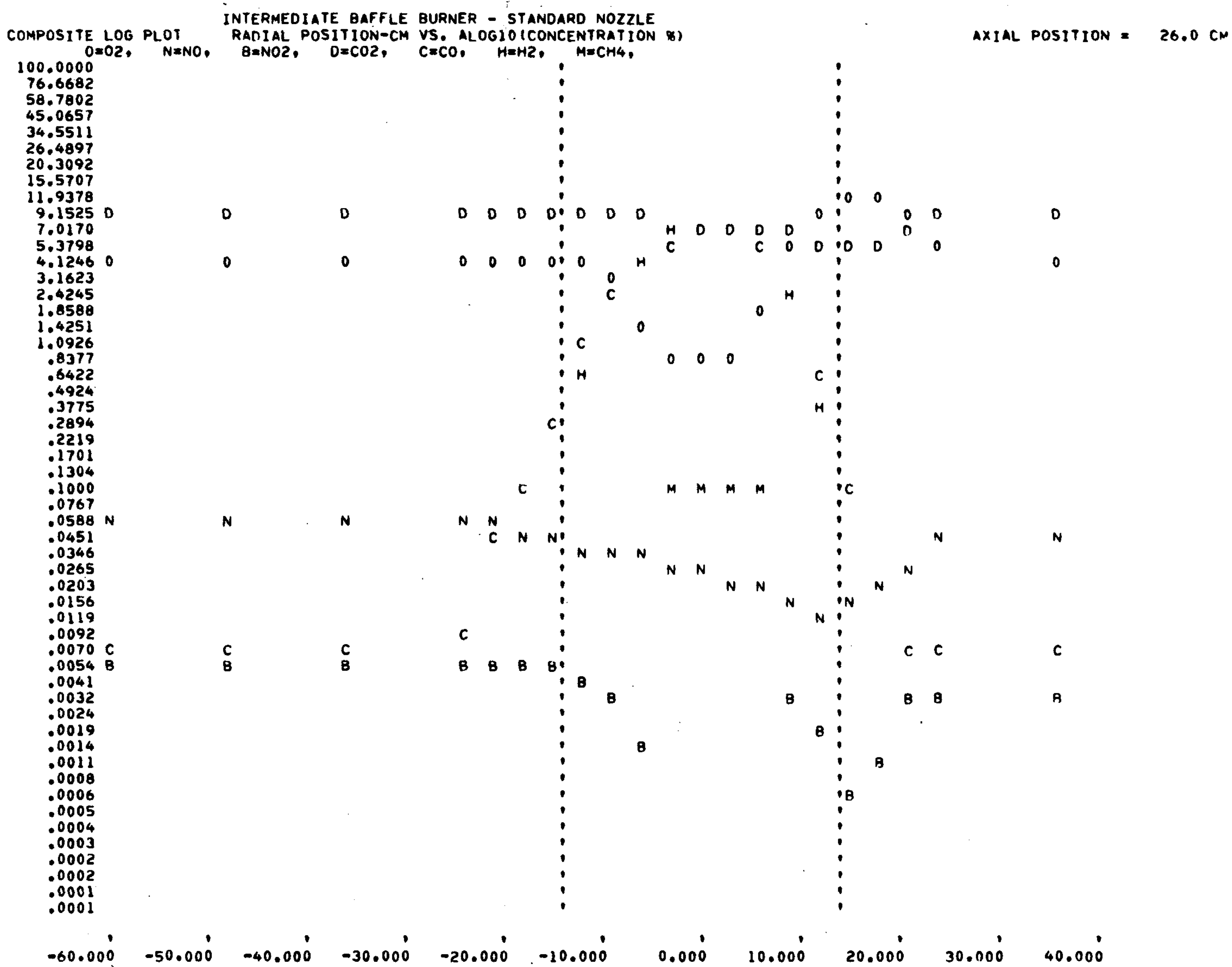

Figure 100. Radial profile of all the gases at an axial position of 26.0 cm (intermediate flame length baffle burner – standard gas nozzle)

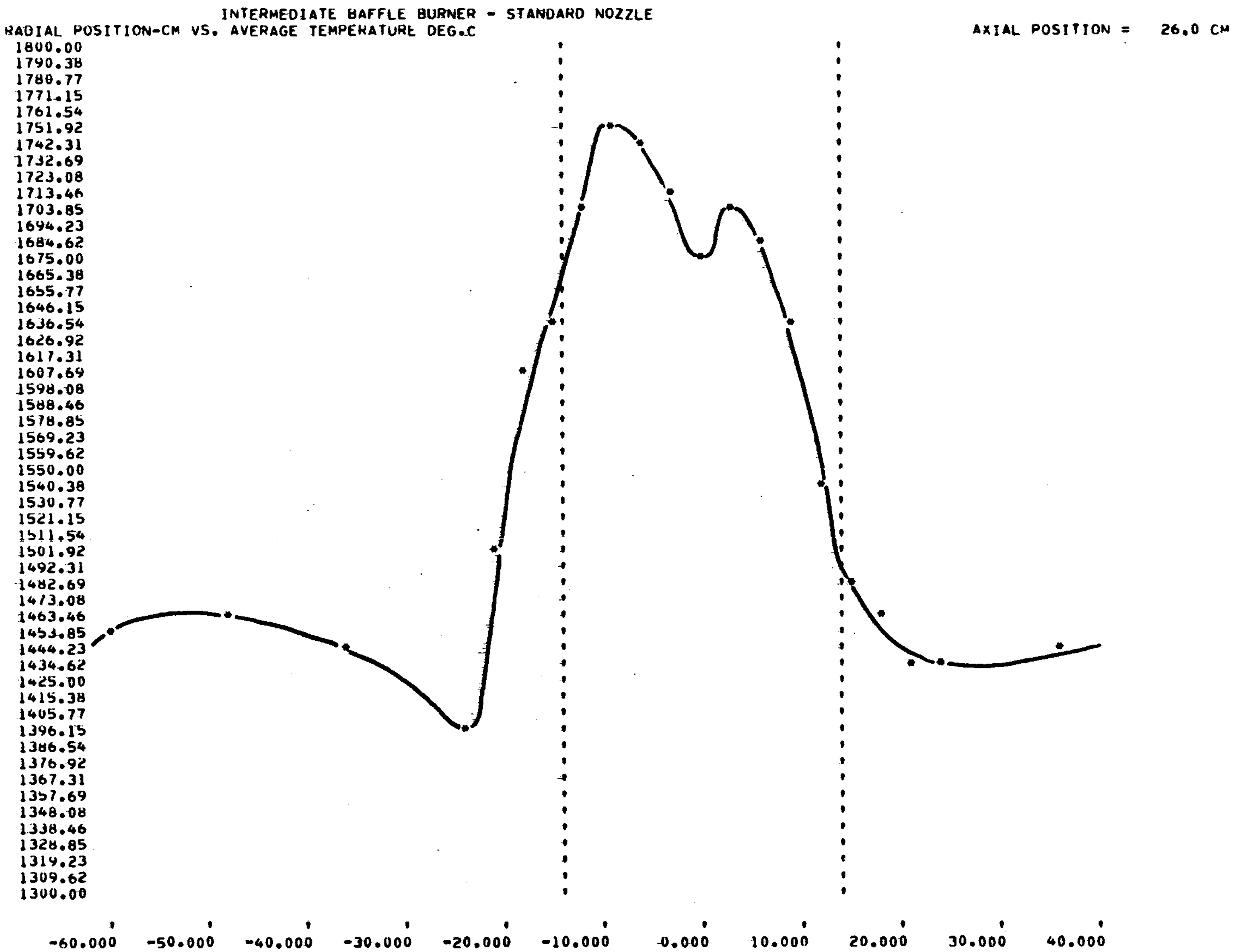

Figure 101. Radial profile of average temperature at an axial position of 26.0 cm (intermediate flame length baffle burner — standard gas nozzle)

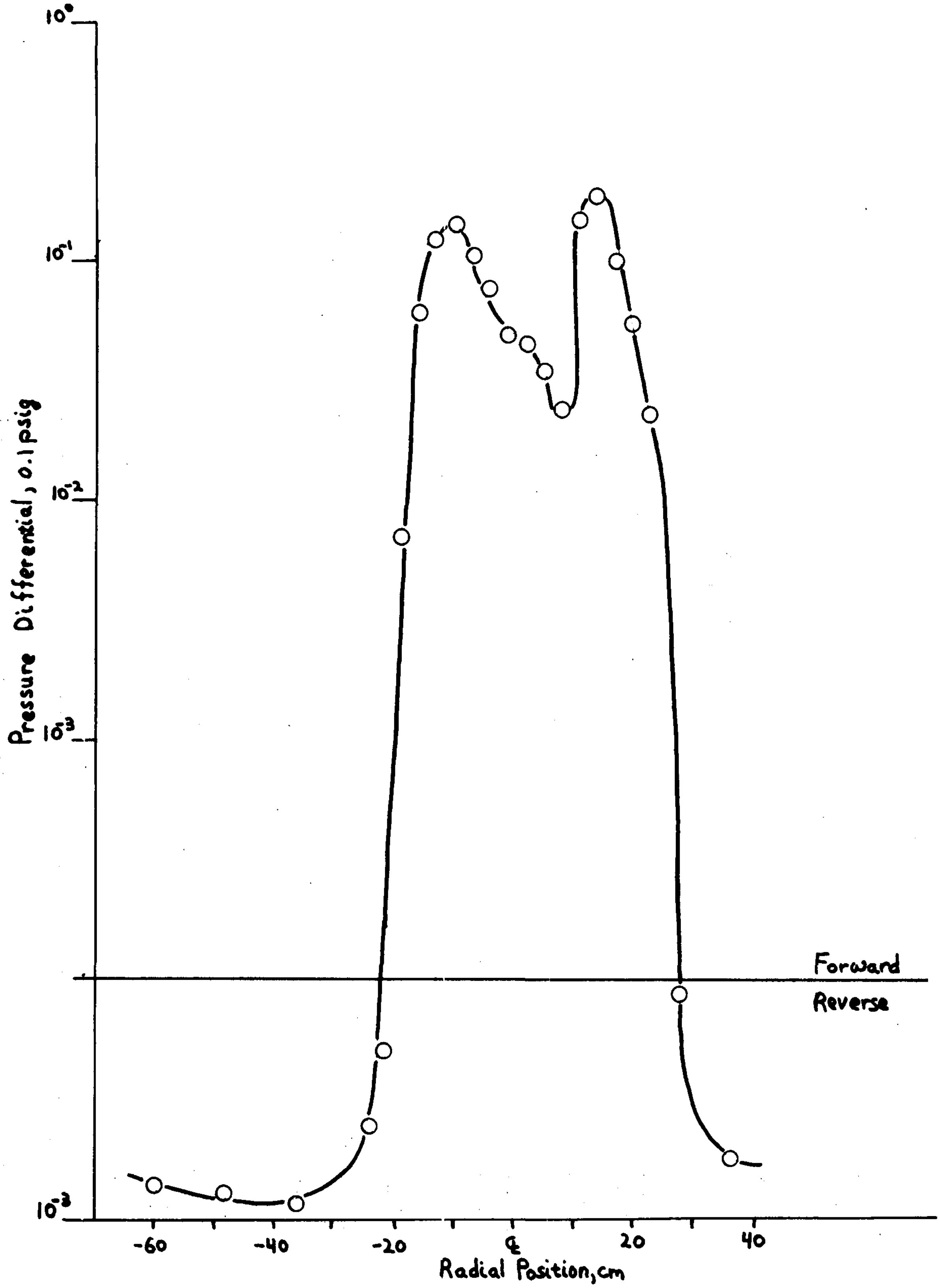

Figure 102. Radial profile of flow direction at an axial position of 26.0 cm (intermediate flame length baffle burner – standard gas nozzle)

Table 19. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 57.2 cm (Intermediate Flame Length Baffle Burner — Standard Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - STANDARD NOZZLE

AXIAL POSITION = 57.2 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.7	?	500.	60.	9.0	.0066	?	0.0	?	?	?	?	1494.	1494.	0.
-48.	4.4	?	512.	58.	9.2	.0080	?	0.0	?	?	?	?	1471.	1471.	0.
-36.	4.5	?	510.	61.	9.1	.0079	?	0.0	?	?	?	?	1451.	1451.	0.
-24.	4.3	?	475.	57.	9.2	.0445	?	0.0	?	?	?	?	1552.	1552.	0.
-18.	4.0	85.6	430.	56.	9.2	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1607.	1607.	0.
-12.	3.4	84.6	405.	51.	9.6	.5000	.7	0.0	0.0	0.0	0.0	0.0	1667.	1667.	0.
-6.	3.2	82.7	415.	52.	8.8	1.3000	3.3	0.0	0.0	0.0	0.0	0.0	1724.	1724.	0.
0.	2.4	82.5	375.	35.	8.1	3.4000	3.2	0.0	0.0	0.0	0.0	0.0	1745.	1745.	0.
6.	1.8	79.4	315.	24.	7.2	4.6000	6.6	0.0	0.0	0.0	0.0	0.0	1728.	1728.	0.
12.	4.5	83.6	280.	43.	7.9	1.8000	1.5	0.0	0.0	0.0	0.0	0.0	1629.	1629.	0.
18.	7.4	83.8	289.	47.	7.2	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1605.	1605.	0.
24.	7.1	?	340.	50.	8.3	.0351	?	0.0	?	?	?	?	1558.	1558.	0.
36.	4.4	?	458.	57.	9.2	.0080	?	0.0	?	?	?	?	1470.	1470.	0.

Table 20. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 146.1 cm
(Intermediate Flame Length Baffle Burner – Standard Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - STANDARD NOZZLE

AXIAL POSITION = 146.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.3	?	467.	65.	9.3	.0084	?	0.0	?	?	?	?	1487.	1487.	0.
-54.	4.4	?	475.	66.	9.2	.0087	?	0.0	?	?	?	?	1480.	1480.	0.
-48.	4.5	?	470.	65.	9.1	.0085	?	0.0	?	?	?	?	1485.	1485.	0.
-36.	4.7	?	475.	60.	9.0	.0089	?	0.0	?	?	?	?	1508.	1508.	0.
-30.	4.8	?	470.	61.	9.0	.0095	?	0.0	?	?	?	?	1513.	1513.	0.
-24.	4.9	?	450.	60.	8.9	.0138	?	0.0	?	?	?	?	1559.	1559.	0.
-18.	4.8	?	430.	56.	9.0	.0213	?	0.0	?	?	?	?	1621.	1621.	0.
-12.	4.9	?	430.	55.	8.9	.0417	?	0.0	?	?	?	?	1645.	1645.	0.
-6.	4.4	?	438.	53.	9.2	.0746	?	0.0	?	?	?	?	1673.	1673.	0.
0.	4.1	85.5	448.	54.	9.1	.3000	0.0	0.0	0.0	0.0	0.0	0.0	1679.	1679.	0.
6.	3.9	86.0	455.	44.	9.2	.3000	0.0	0.0	0.0	0.0	0.0	0.0	1663.	1663.	0.
12.	3.1	86.3	459.	48.	9.7	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1603.	1603.	0.
18.	3.0	86.4	463.	52.	9.8	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1570.	1570.	0.
24.	3.2	86.2	455.	56.	9.6	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1542.	1542.	0.
30.	3.4	?	448.	54.	9.8	.0813	?	0.0	?	?	?	?	1496.	1496.	0.
36.	3.7	?	446.	52.	9.6	.0512	?	0.0	?	?	?	?	1485.	1485.	0.

Table 21. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 385.4 cm (Intermediate Flame Length Baffle Burner – Standard Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - STANDARD NOZZLE

AXIAL POSITION = 385.4 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	TEMPERATURE DEG.C MAX.	TEMPERATURE DEG.C TMAX-TAVG
-60.	3.7	?	485.	53.	9.6	.0092	?	0.0	?	?	?	?	1443.	1443.	0.
-48.	3.8	?	490.	56.	9.5	.0096	?	0.0	?	?	?	?	1463.	1463.	0.
-36.	3.7	?	500.	52.	9.6	.0094	?	0.0	?	?	?	?	1482.	1482.	0.
-24.	3.8	?	512.	51.	9.5	.0103	?	0.0	?	?	?	?	1483.	1483.	0.
-12.	3.8	?	504.	53.	9.5	.0088	?	0.0	?	?	?	?	1496.	1496.	0.
0.	4.2	?	496.	53.	9.3	.0105	?	0.0	?	?	?	?	1501.	1501.	0.
12.	4.1	?	492.	52.	9.4	.0100	?	0.0	?	?	?	?	1484.	1484.	0.
24.	4.2	?	490.	54.	9.3	.0098	?	0.0	?	?	?	?	1465.	1465.	0.
36.	4.2	?	487.	52.	9.3	.0090	?	0.0	?	?	?	?	1447.	1447.	0.

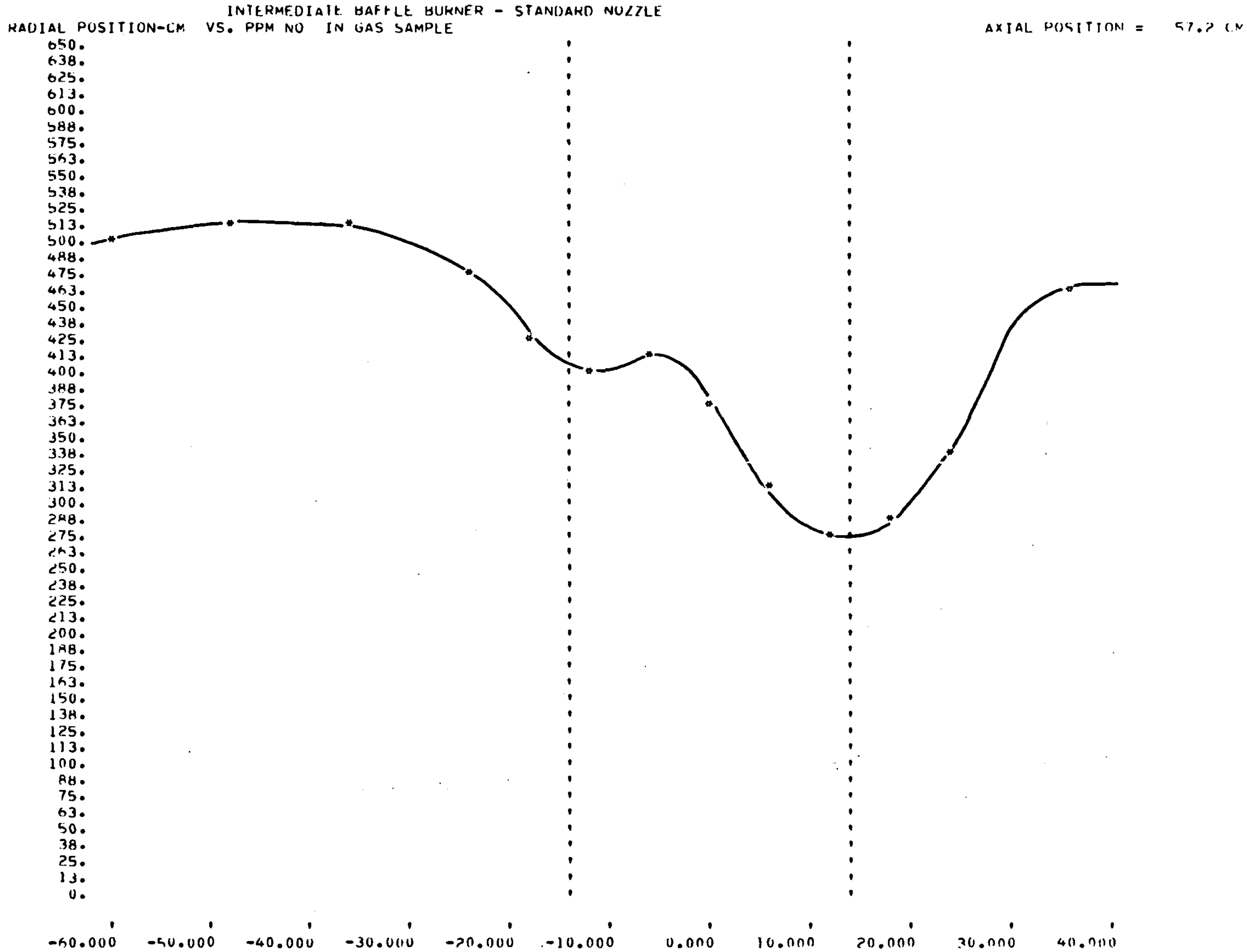

Figure 103. Radial profile of NO at an axial position of 57.2 cm (intermediate flame length baffle burner – standard gas nozzle)

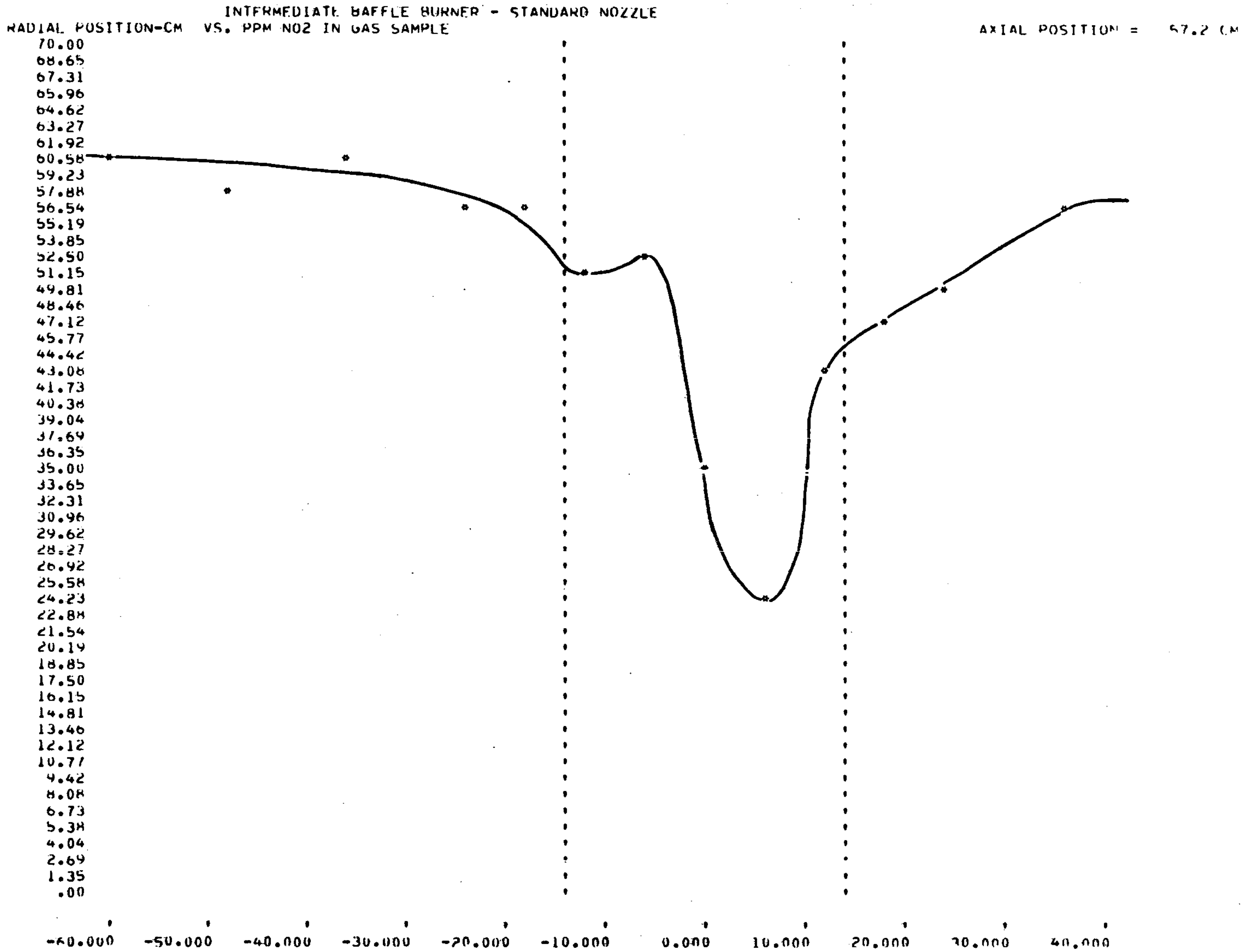

Figure 104. Radial profile of NO_2 at an axial position of 57.2 cm (intermediate flame length baffle burner — standard gas nozzle)

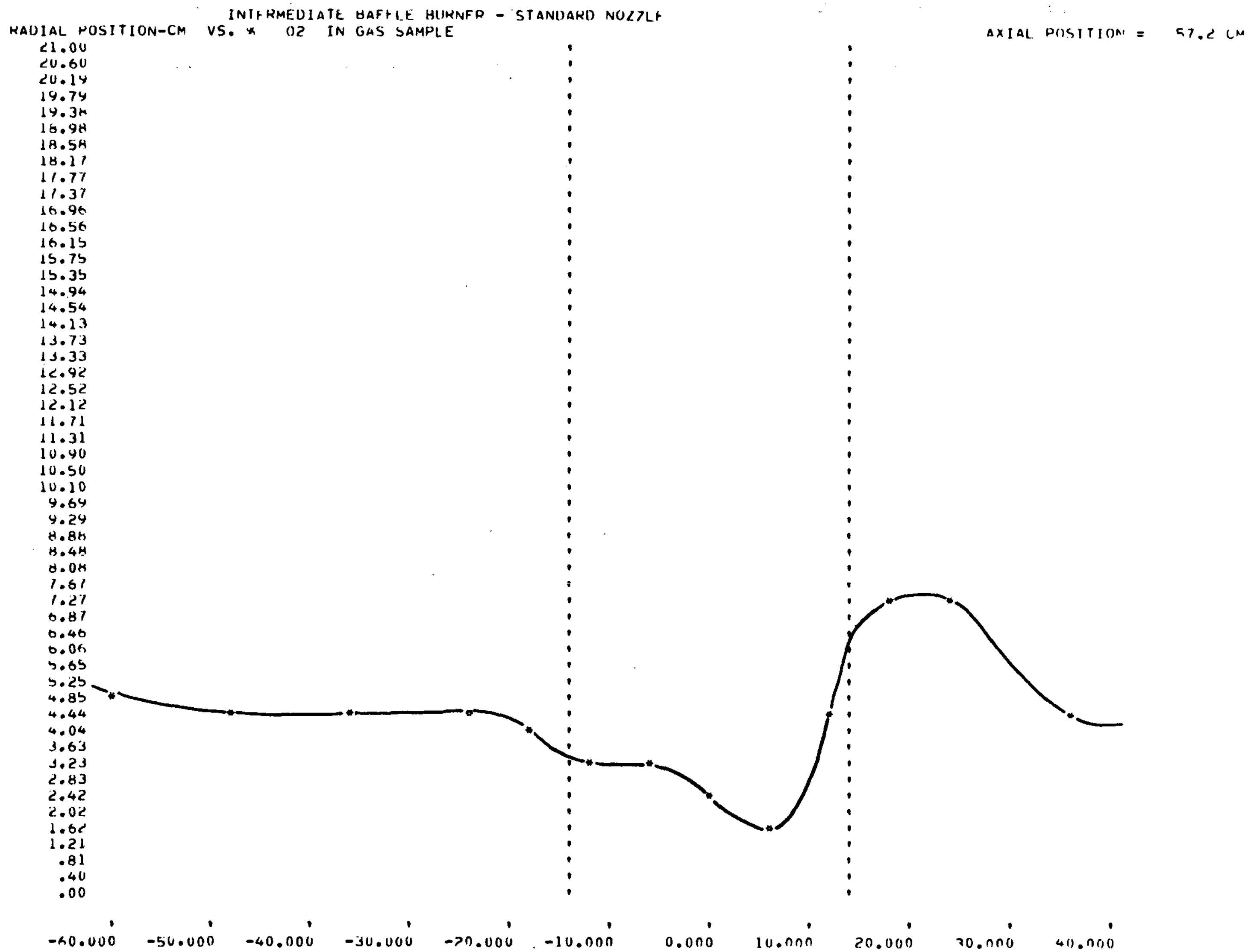

Figure 105. Radial profile of O_2 at an axial position of 57.2 cm (intermediate flame length baffle burner – standard gas nozzle)

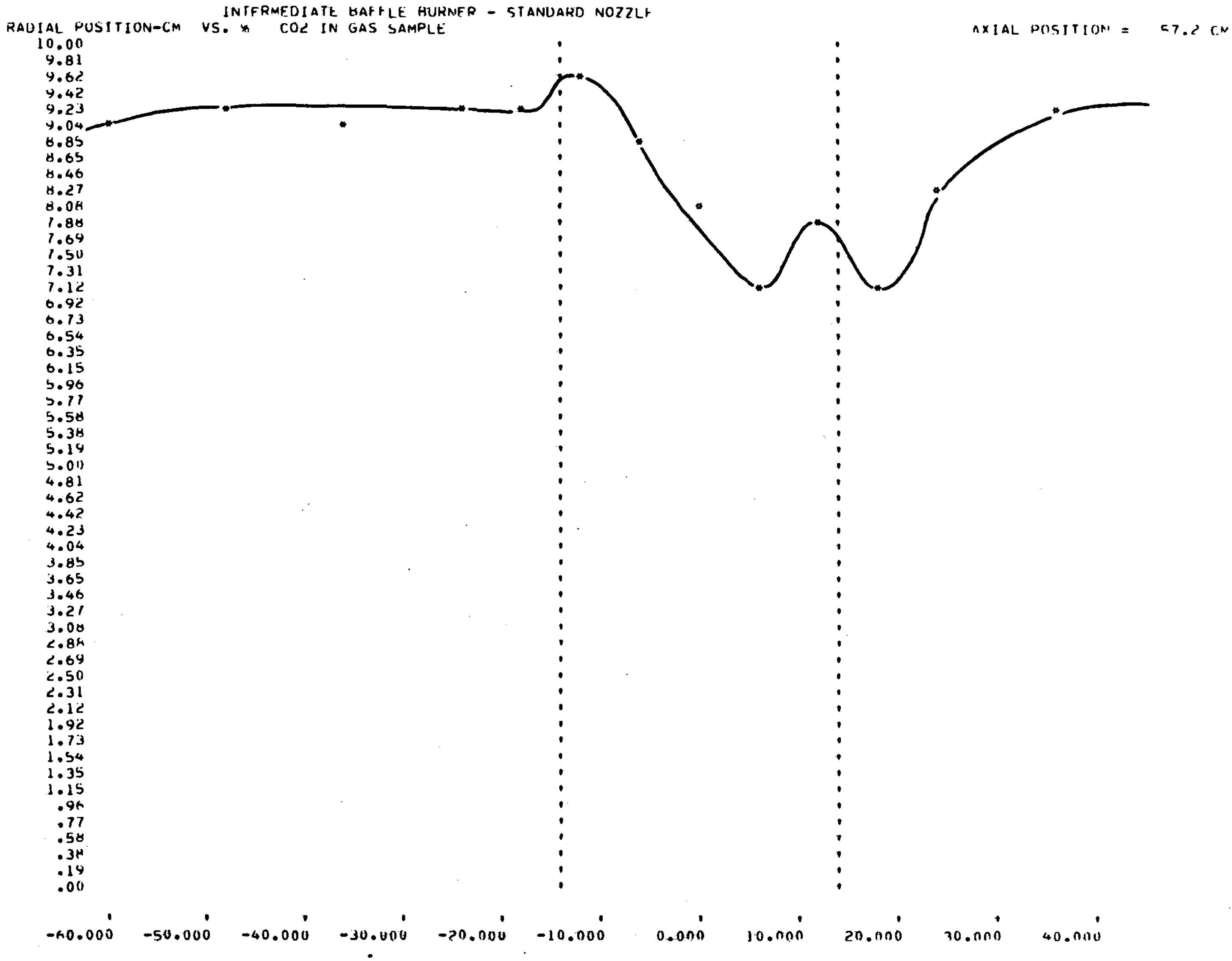

Figure 106. Radial profile of CO_2 at an axial position of 57.2 cm (intermediate flame length baffle burner – standard gas nozzle)

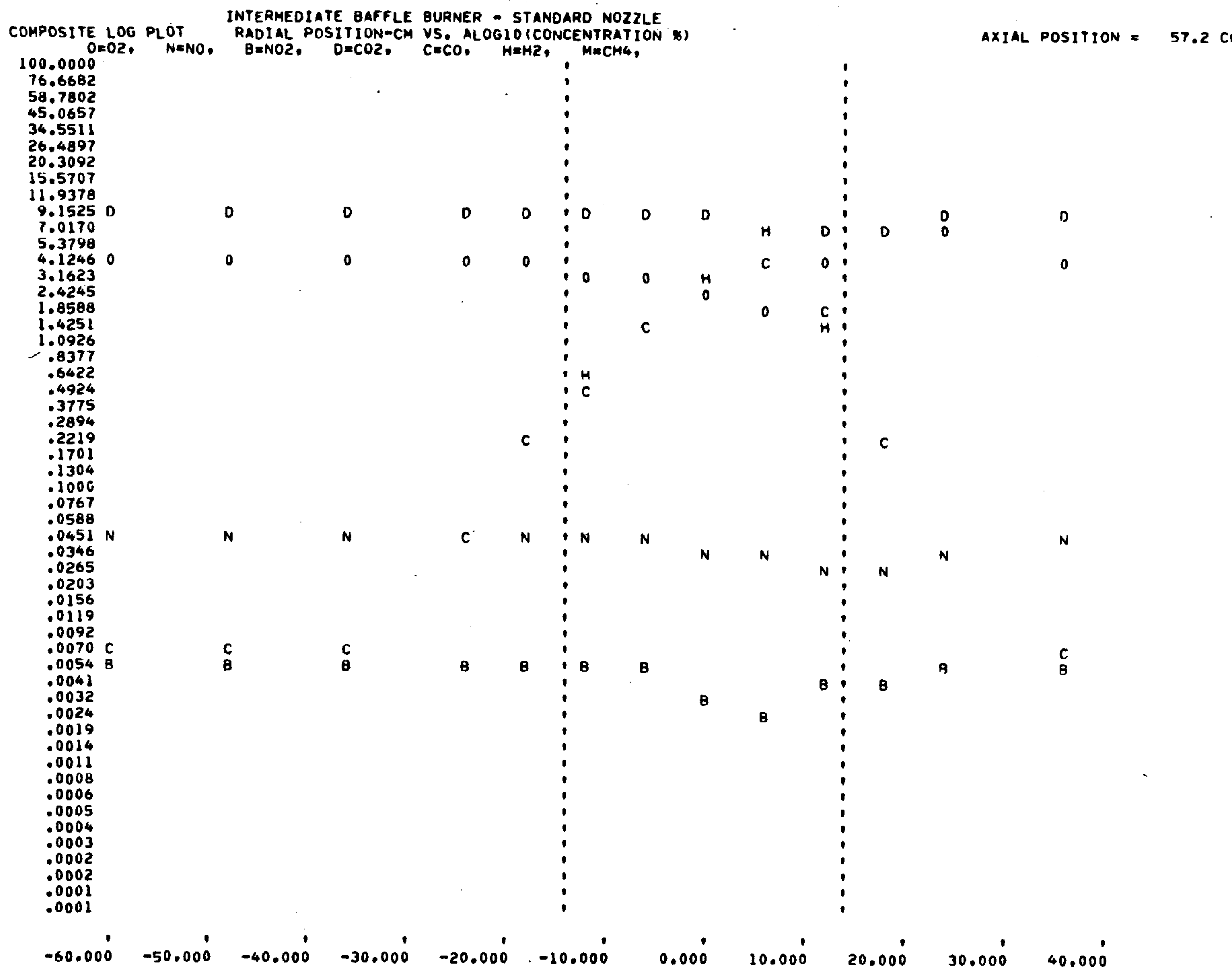

Figure 107. Radial profile of all the gases at an axial position of 57.2 cm (intermediate flame length baffle burner – standard gas nozzle)

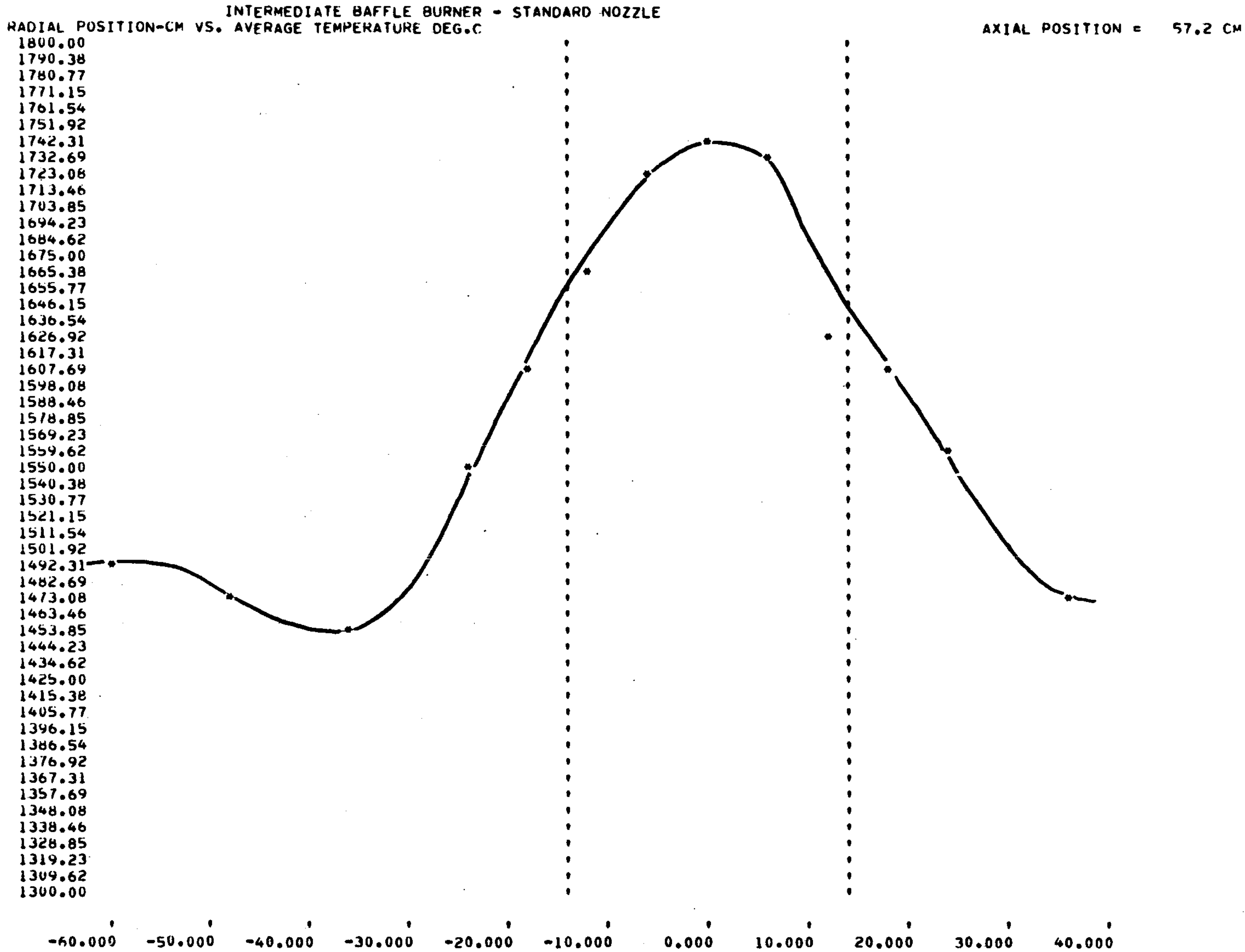

Figure 108. Radial profile of average temperature at an axial position of 57. 2 cm (intermediate flame length baffle burner — standard gas nozzle)

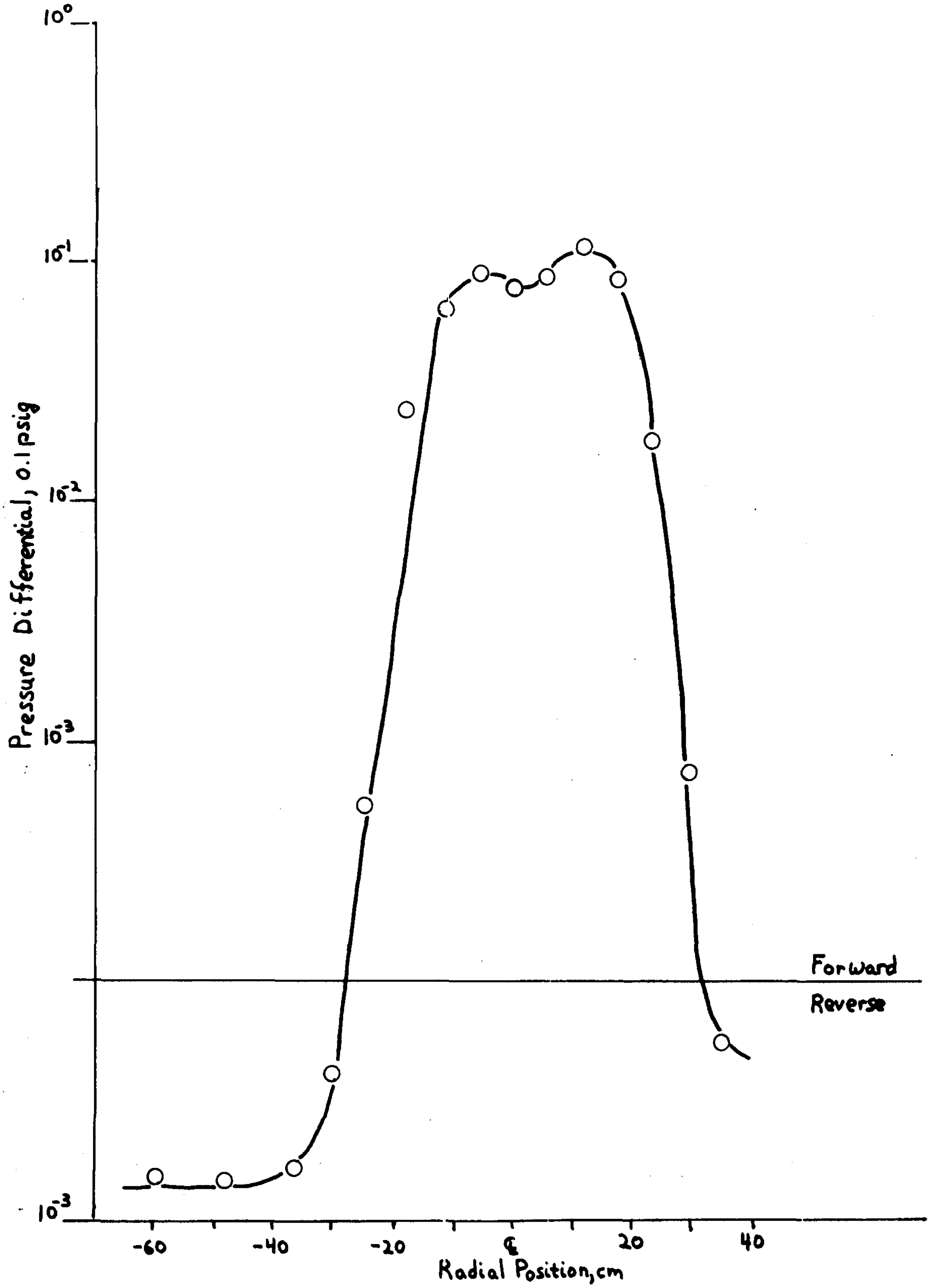

Figure 109. Radial profile of flow direction at an axial position of 57.2 cm (intermediate flame length baffle burner — standard gas nozzle)

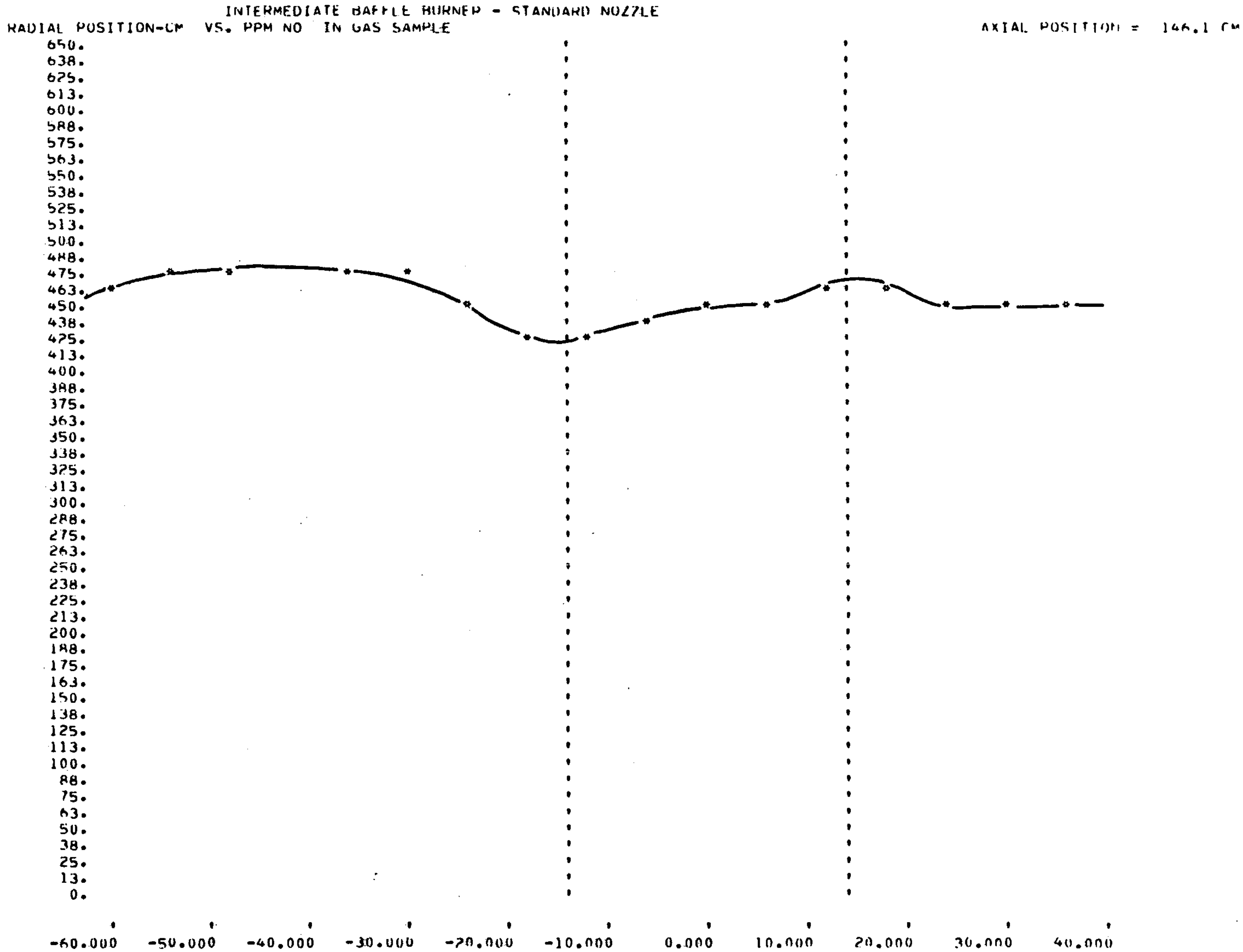

Figure 110. Radial profile of NO at an axial position of 146.1 cm (intermediate flame length baffle burner – standard gas nozzle)

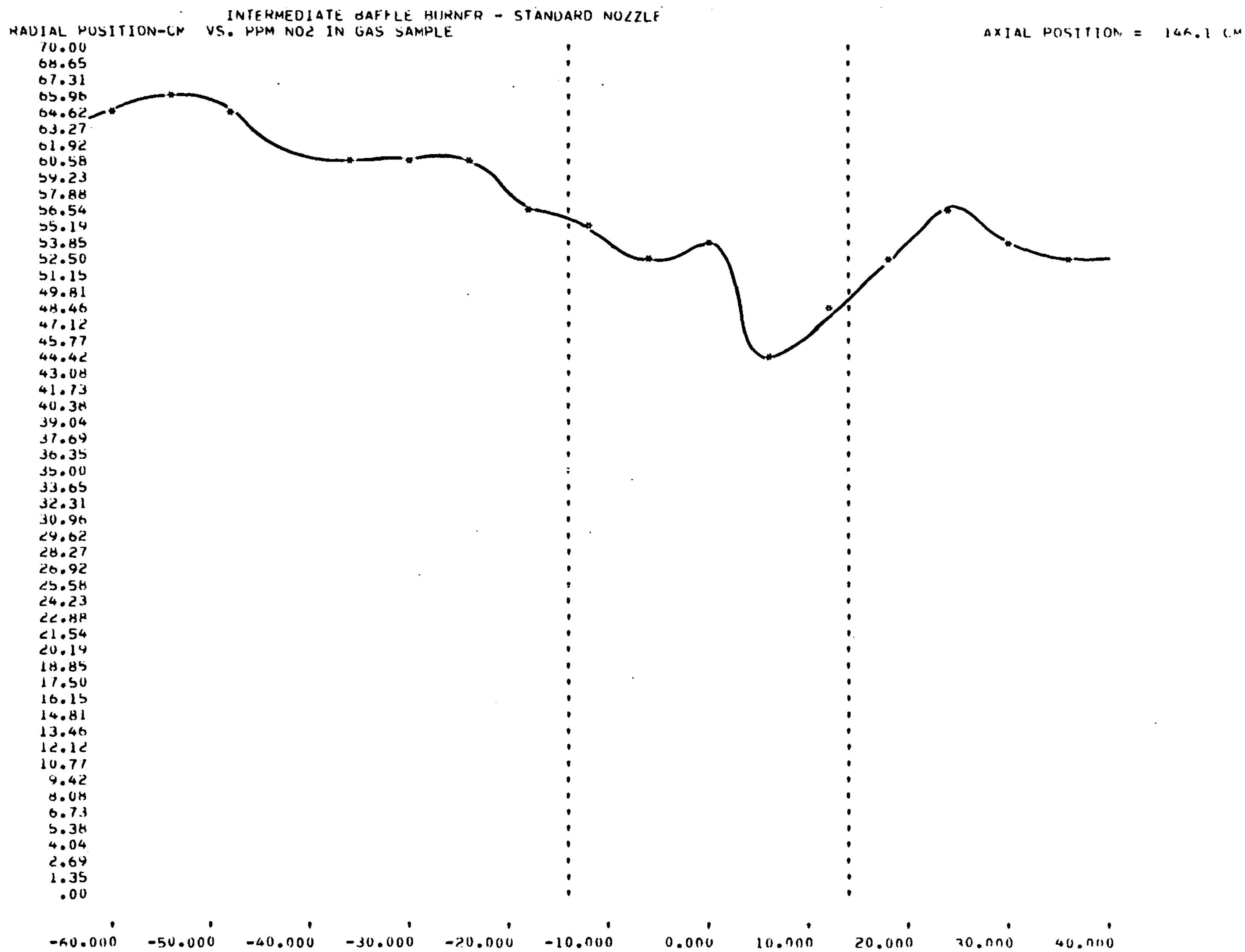

Figure 111. Radial profile of NO_2 at an axial position of 146.1 cm (intermediate flame length baffle burner — standard gas nozzle)

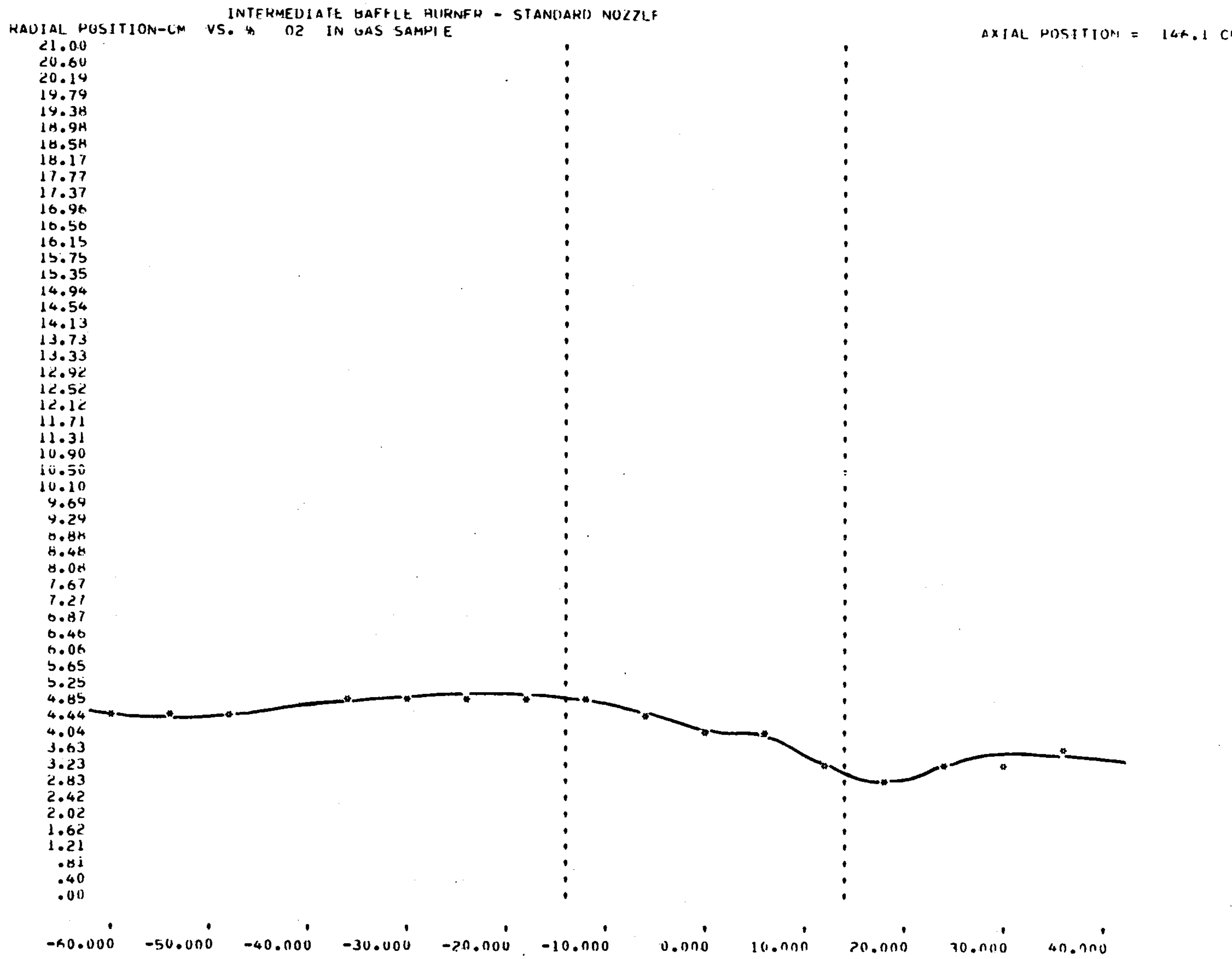

Figure 112. Radial profile of O_2 at an axial position of 146.1 cm (intermediate flame length baffle burner — standard gas nozzle)

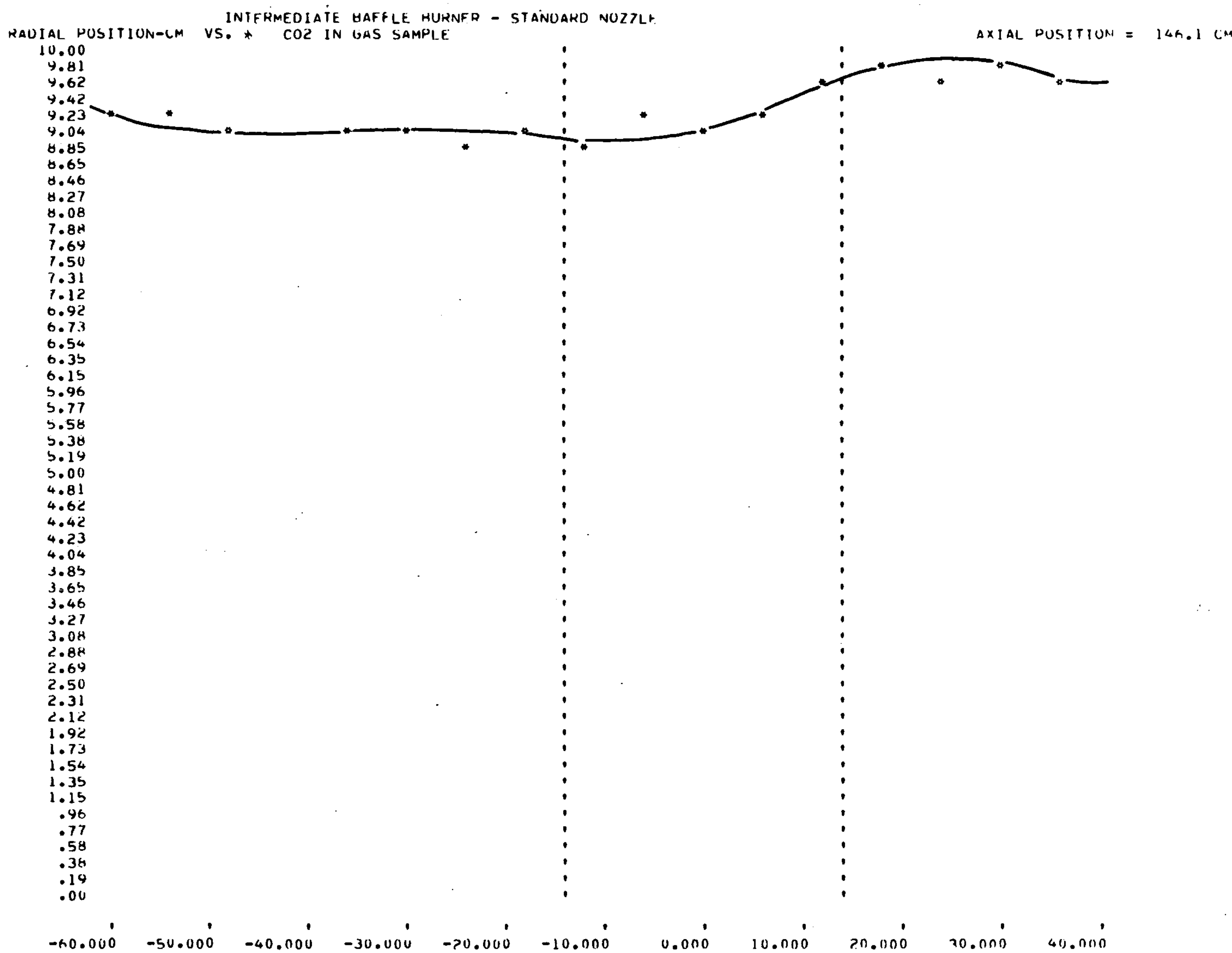

Figure 113. Radial profile of CO_2 at an axial position of 146.1 cm (intermediate flame length baffle burner — standard gas nozzle)

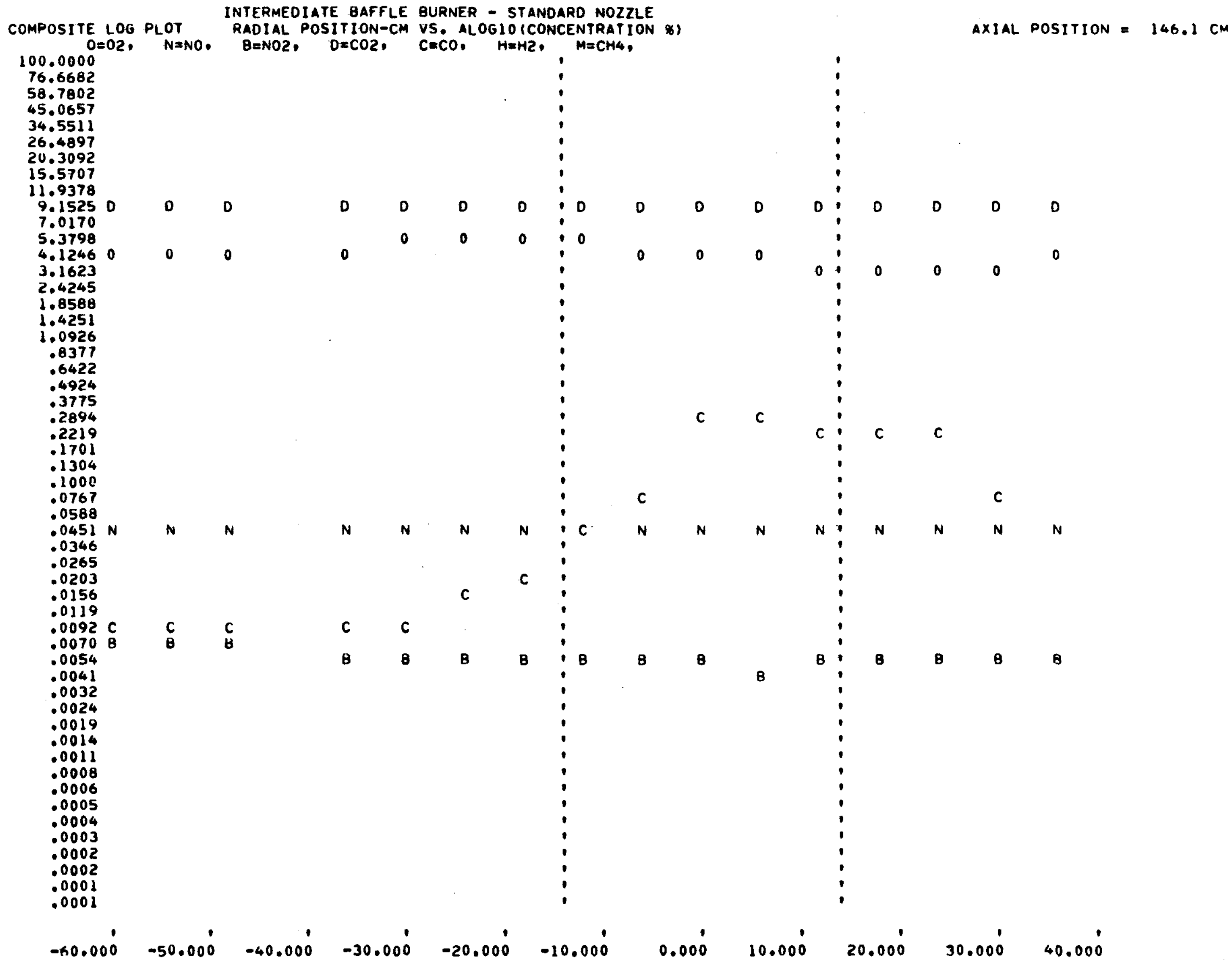

Figure 114. Radial profile of all the gases at an axial position of 146.1 cm (intermediate flame length baffle burner — standard gas nozzle)

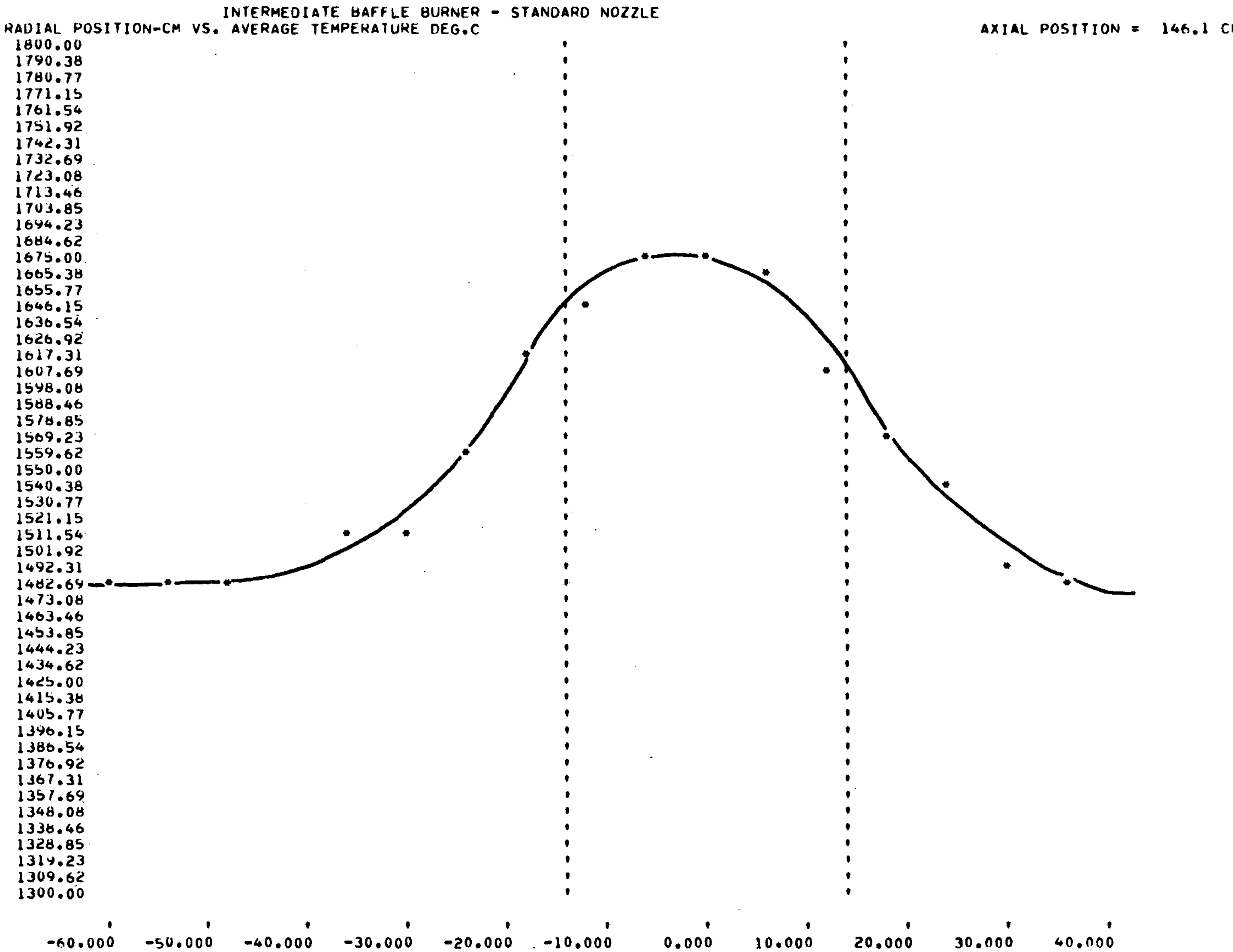

Figure 115. Radial profile of average temperature at an axial position of 146.1 cm (intermediate flame length baffle burner — standard gas nozzle)

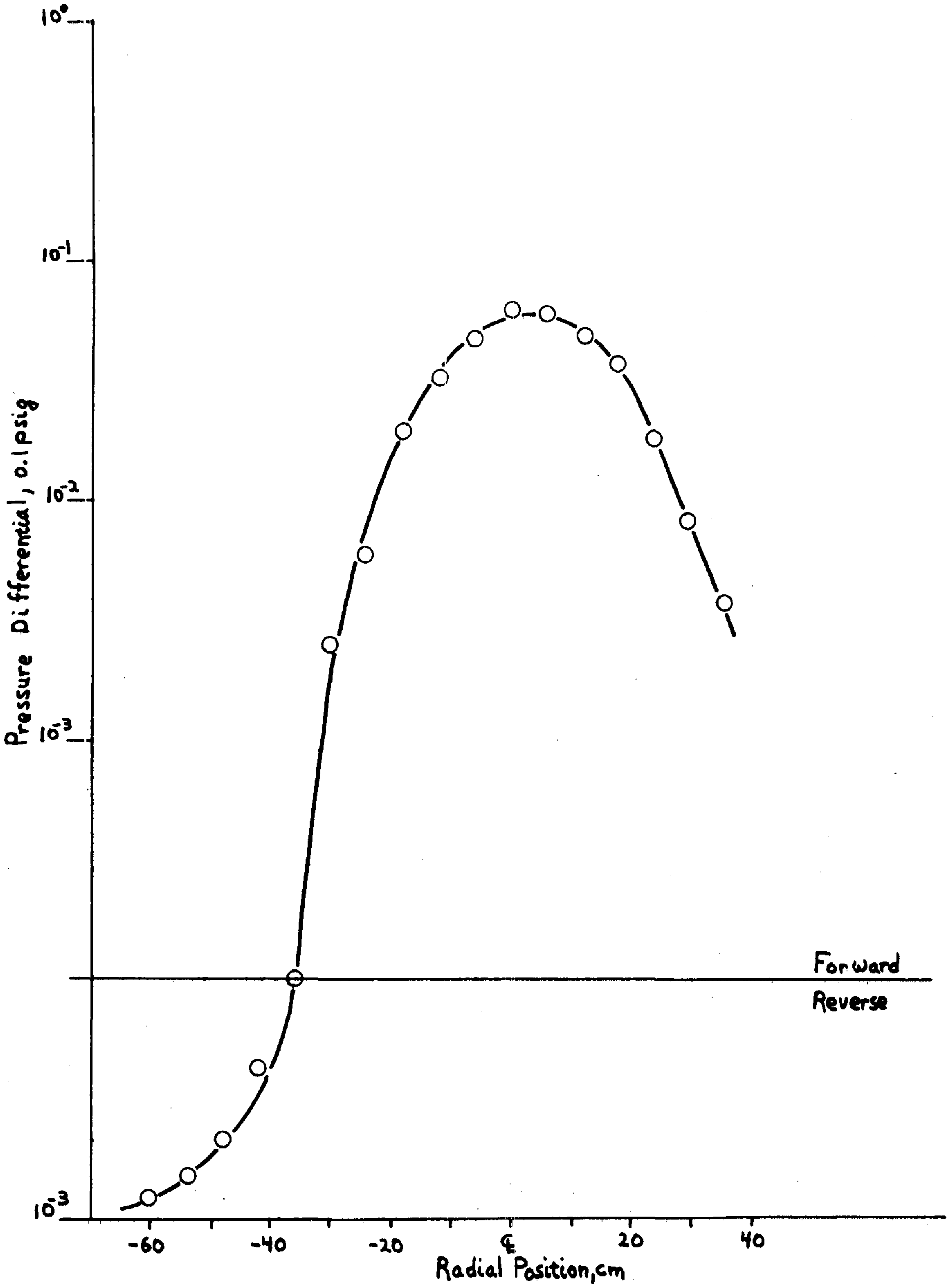

Figure 116. Radial profile of flow direction at an axial position of 146.1 cm (intermediate flame length baffle burner — standard gas nozzle)

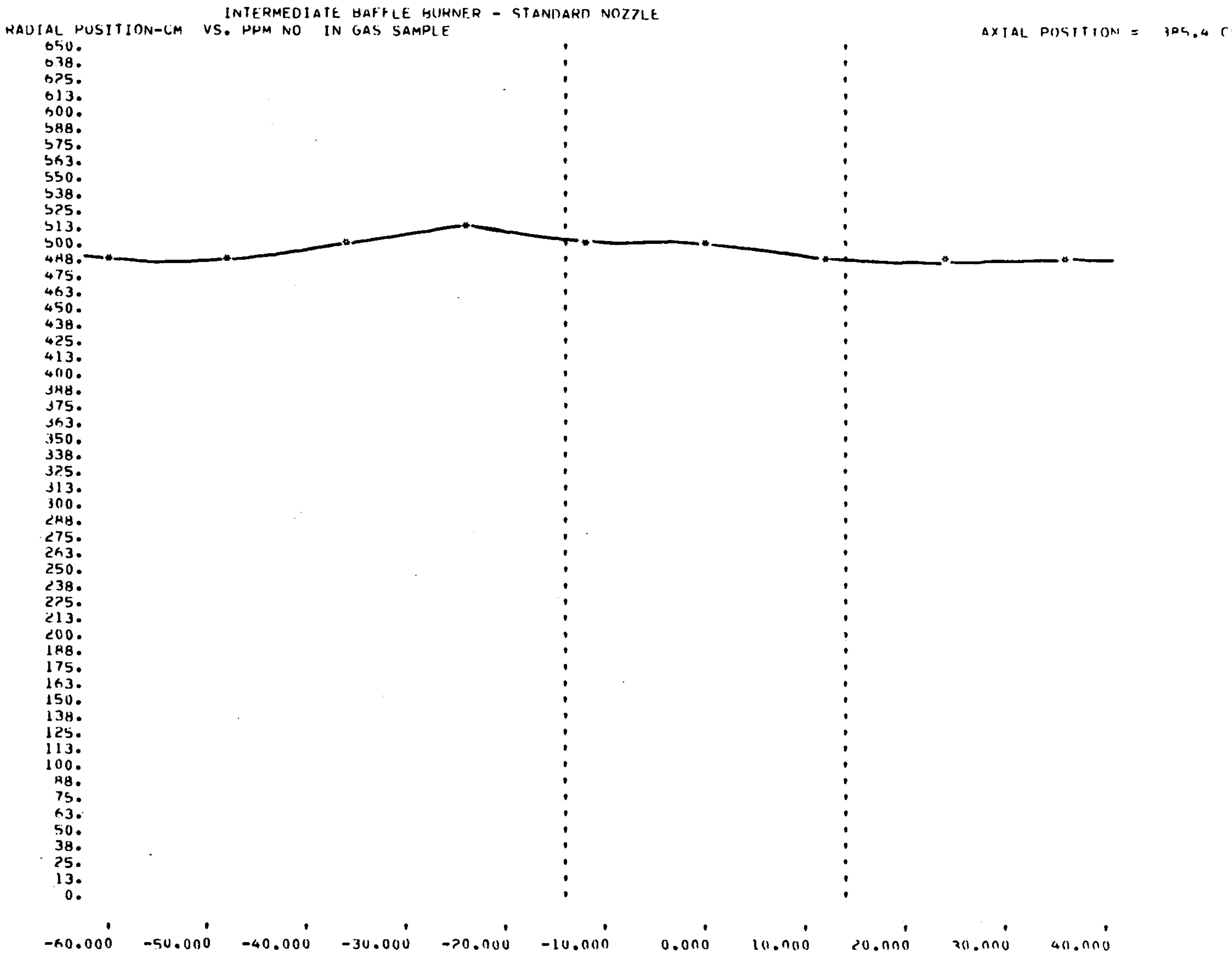

Figure 117. Radial profile of NO at an axial position of 385.4 cm (intermediate flame length baffle burner — standard gas nozzle)

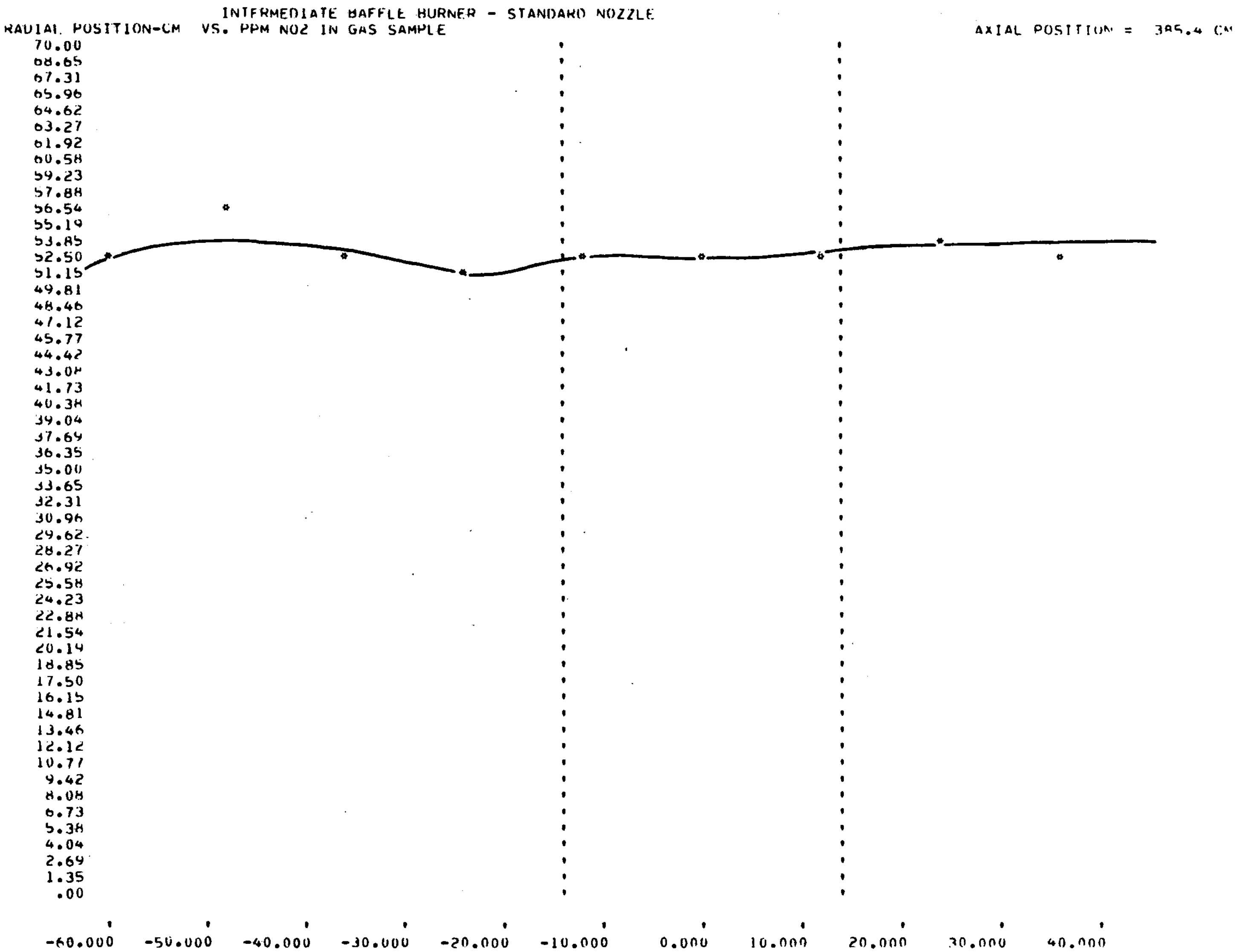

Figure 118. Radial profile of NO_2 at an axial position of 385.4 cm
(intermediate flame length baffle burner – standard gas nozzle)

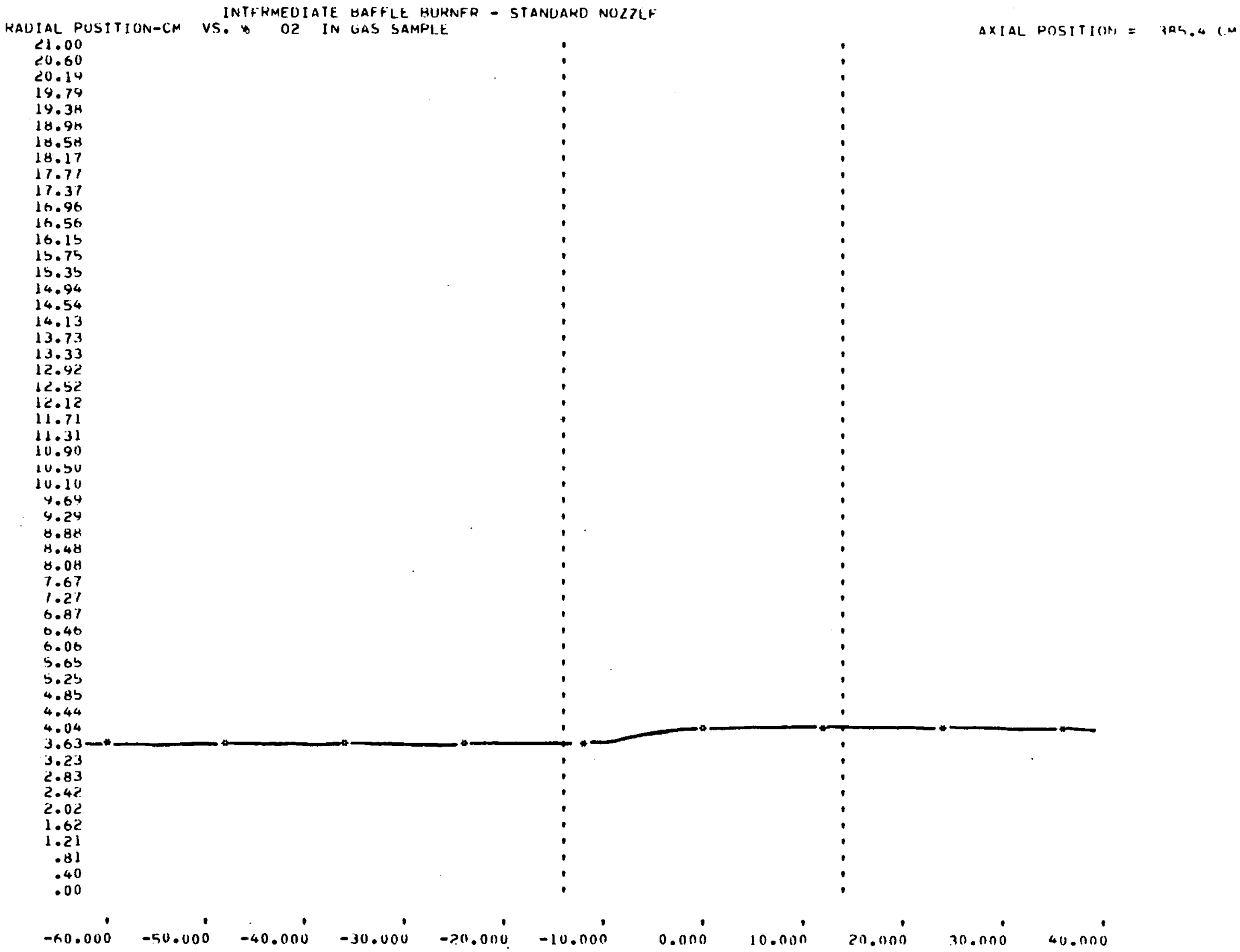

Figure 119. Radial profile of O_2 at an axial position of 385.4 cm (intermediate flame length baffle burner — standard gas nozzle)

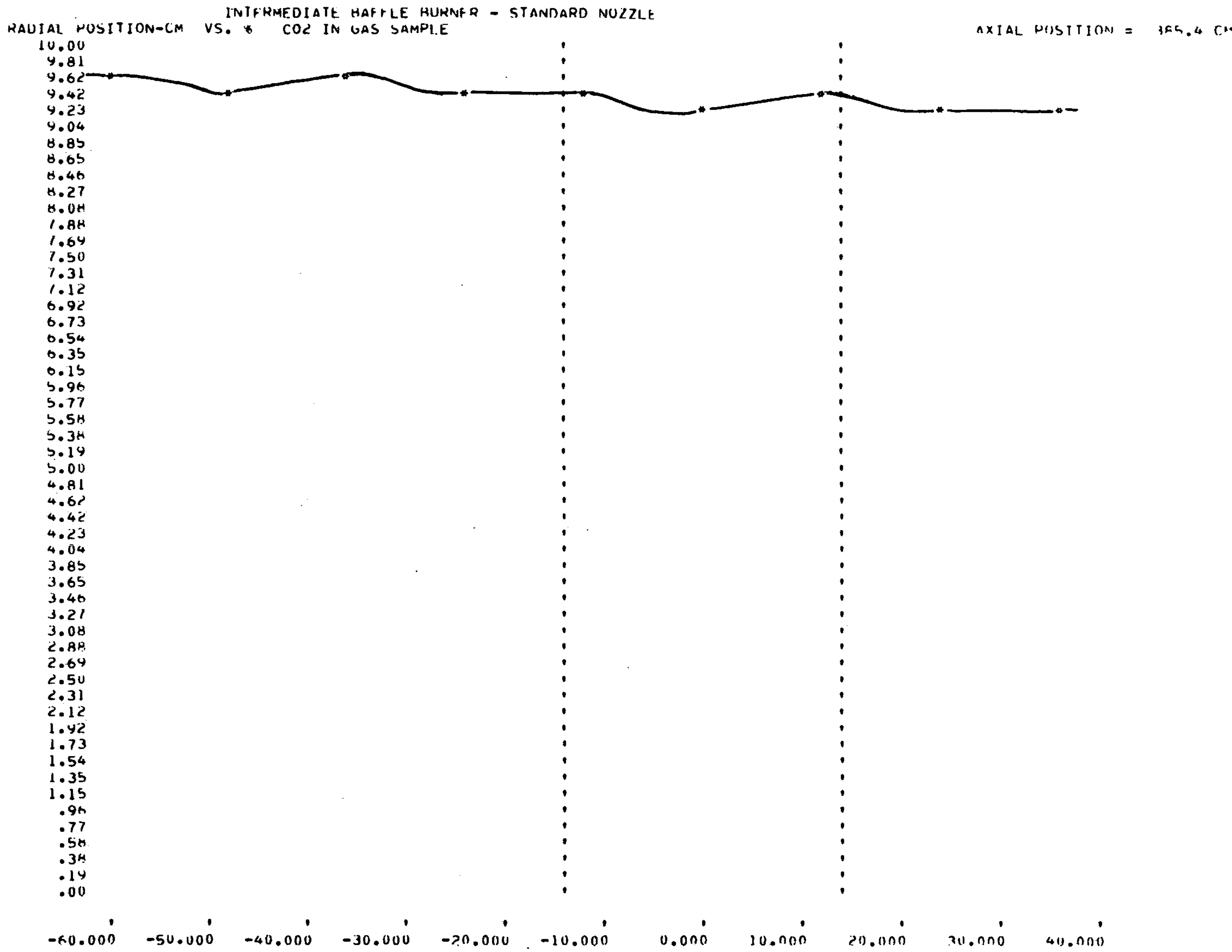

Figure 120. Radial profile of CO_2 at an axial position of 385.4 cm (intermediate flame length baffle burner – standard gas nozzle)

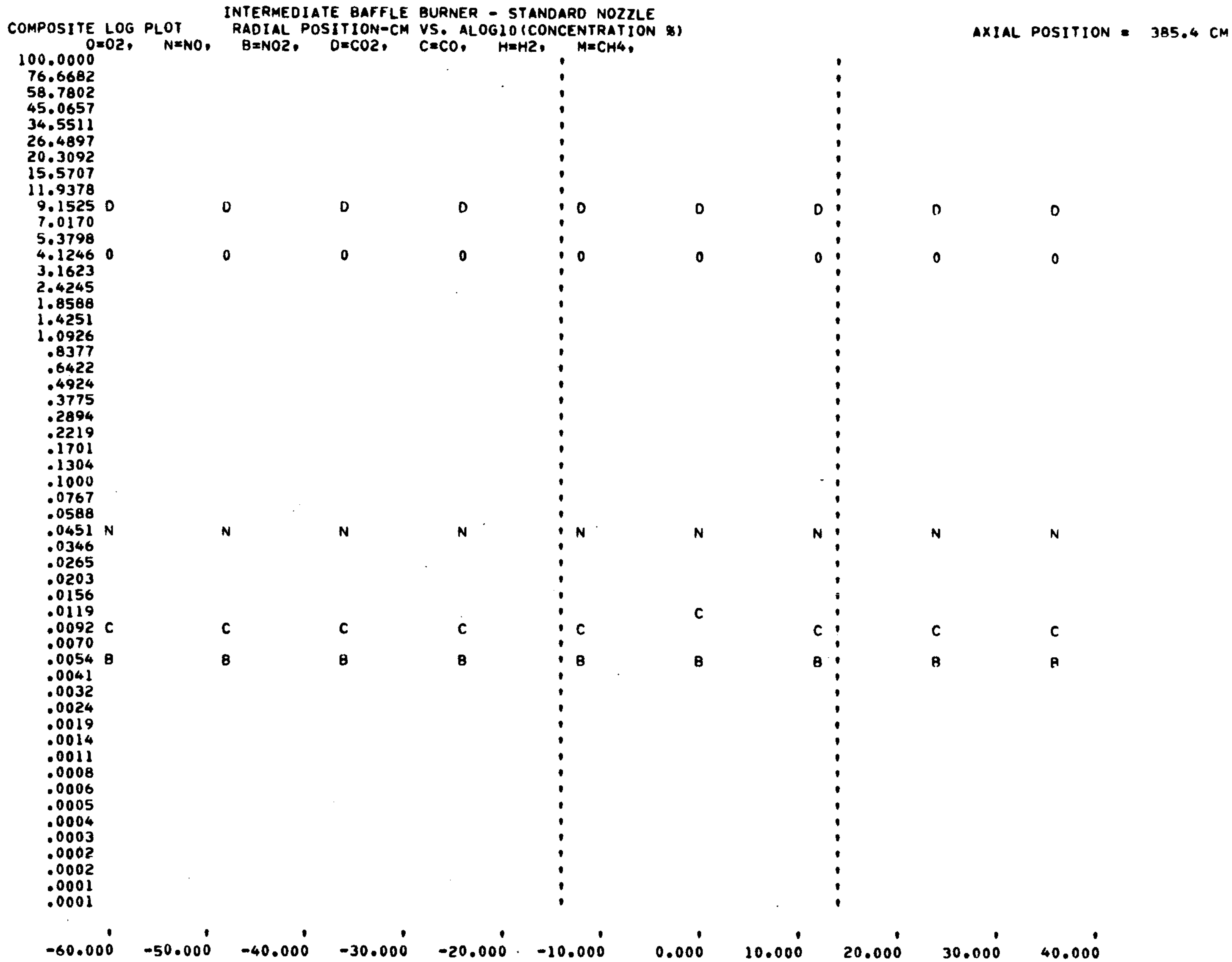

Figure 121. Radial profile of all the gases at an axial position of 385. 4 cm (intermediate flame length baffle burner — standard gas nozzle)

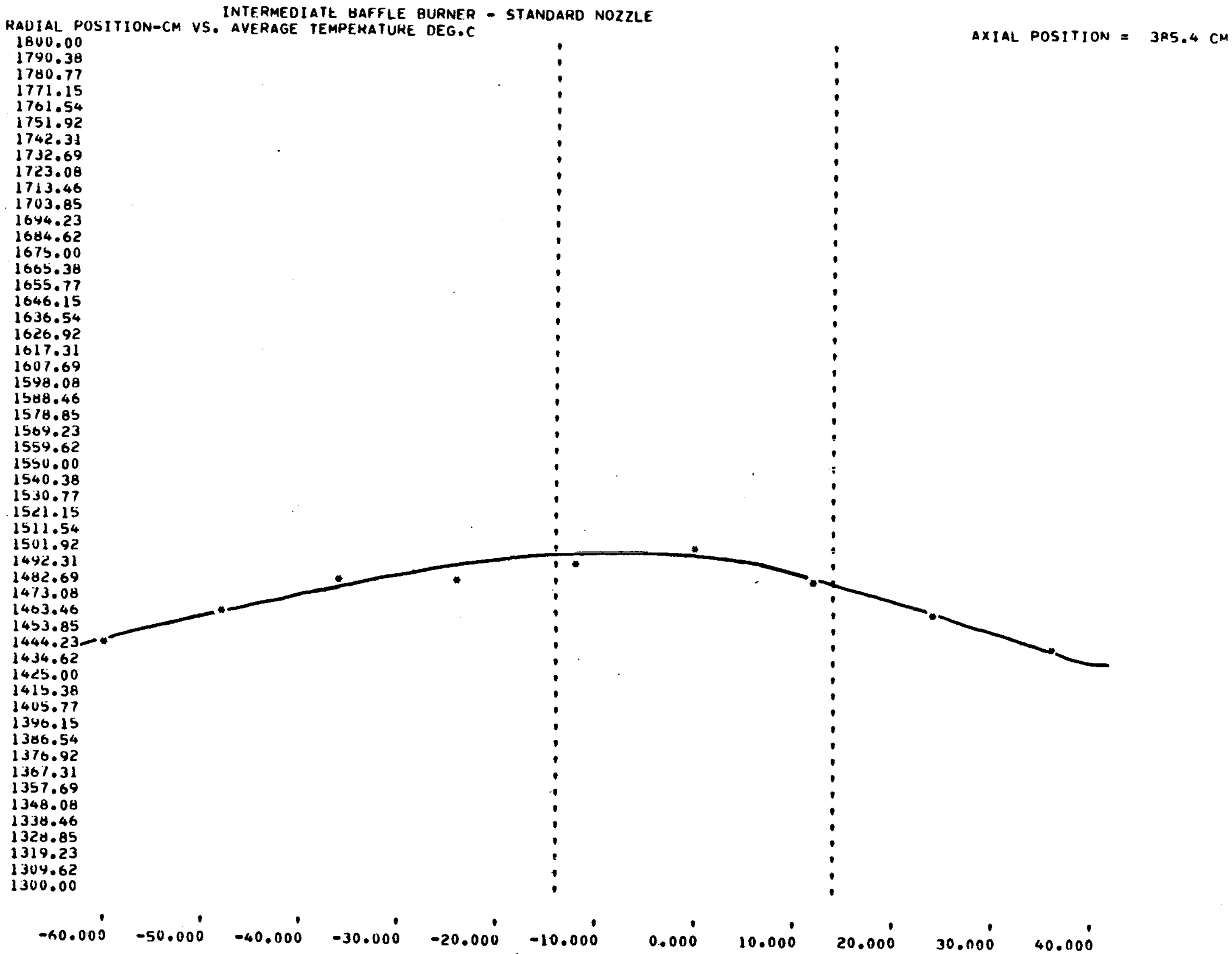

Figure 122. Radial profile of average temperature at an axial position of 385.4 cm (intermediate flame length baffle burner – standard gas nozzle)

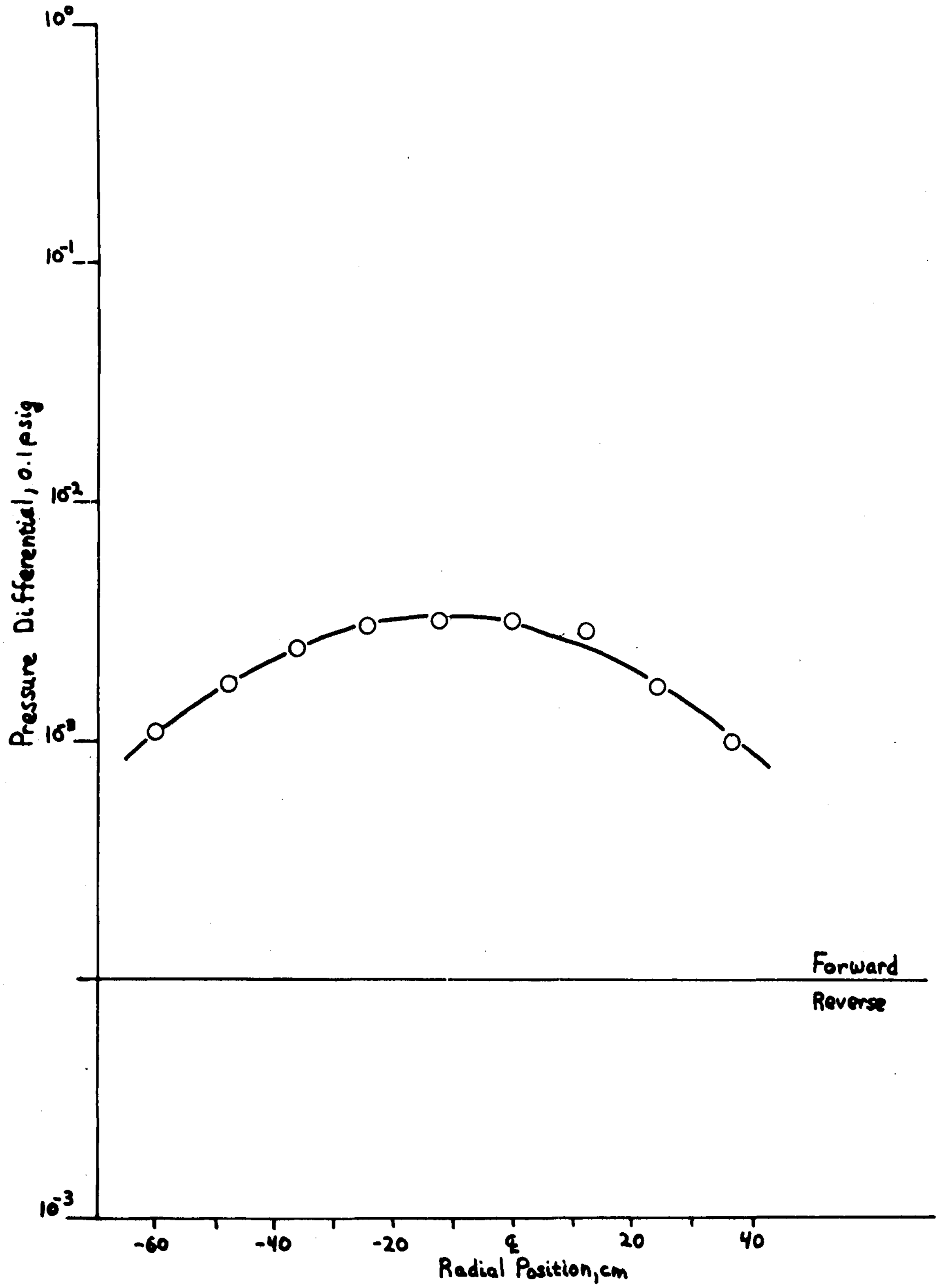

Figure 123. Radial profile of flow direction at an axial position of 385.4 cm (intermediate flame length baffle burner — standard gas nozzle)

Flow direction analysis at the 5.1-cm axial position depicts a Type I flame. Secondary recirculation zones exist in the regions −60 cm to −18 cm and +21 cm to +60 cm. Inside the edges of the burner block, −14 cm to +14 cm, there are only two resolve peaks, compared with three peaks which are normally observed in a Type I flame. Because the gas velocity is lower than that of the secondary air, the central methane core appears as a depression between the two air peaks. These flow peaks occur at −9 cm and +12 cm.

Correlating the 5.1-cm axial position temperature profile with the above flow analysis, a constant temperature of 1480°C exists in the recirculation regions (compared with a wall temperature of 1430°C). Minimum temperatures of 1351°C and 1459°C occur at −15 cm and +15 cm, respectively. Peak temperatures of 1712°C and 1669°C occur inside the burner-block area at −9 cm and +6 cm, respectively.

Figure 87, the plot of nitric oxide versus radial position, shows that the nitric oxide concentration in the secondary recirculation zone (−60 cm to −18 cm) averaged about 589 ppm, as compared with a flue concentration of 493 ppm. Comparing this with the average NO concentration of 112 ppm in the burner-block region indicates that at 20.1-cm downstream of the gas injection, only 25% of the flue concentration nitric oxide appears within the combustion zone.

The plot of nitrogen dioxide versus radial position (Figure 88) shows a strong asymmetry about the center line of the burner. Peaks occur within the burner-block region at −12 cm and +9 cm, with concentrations of 51 ppm and 12 ppm, respectively. The nitrogen dioxide concentration measured in the flue was 53 ppm.

The oxygen profile at the 5.1-cm axial position (Figure 89) shows peaks at −12 cm and +15 cm, with concentrations of 7.9% and 14.2%, respectively, which represent the secondary combustion air input. The large difference in oxygen concentration arises because of the discrete orifices in the baffle for the combustion air. Thus, the air enters the combustion chamber as six independent jets. Because each of the air ports is rotated relative to the centerline of the burner, each of these jets will rotate in a clockwise direction from the front to the rear of the furnace. It is possible to investigate along a plan at a fixed axial position and measure a large air concentration on one side of the burner centerline, while detecting almost a void of oxygen on the other side. This asymmetry will gradually disappear as the air moves down the furnace, expanding and losing velocity until, at approximately ten equivalent nozzle diameters, the flow profile becomes symmetrical.

The methane profile (Figure 90) shows a 1.3% maximum concentration on the burner centerline and falls to zero at −15 cm and +12 cm with a larger volume of methane on the left side of the burner centerline. The major combustibles present are hydrogen and carbon monoxide (Figure 92), both having their maximum concentrations on the centerline of the burner with hydrogen at a peak concentration of 13.4% and carbon monoxide at 9.3%.

The curve of carbon dioxide versus radial position (Figure 91) shows a variation in the level of concentration from 5.9% to 3.8% in the region of the secondary combustion air entrance zones (−12 cm and +12 cm to +18 cm, as determined from the oxygen profile). The average carbon dioxide concentration in the secondary recirculation zone is 9.5%. The asymmetry illustrated by this profile indicates that at the 5.1-cm axial position, a larger mass exchange has occurred between the secondary jet and secondary recirculation zone to the left of the burner centerline than to the right. Peak concentrations within the burner-block area of 6.4% and 6.7% appear at radial positions of −9 cm and +9 cm, respectively. This should give an indication as to where combustion is occurring. The maximum temperatures were measured at −9cm and +6 cm (Figure 93). However, there was only a 17°C temperature difference between the +6 cm and +9 cm radial positions. The stoichiometric ratios of fuel and air are estimated to occur at −10.4 cm and 7.5 cm.

The in-the-flame data collected at the 26-cm axial position are listed in Table 18 and illustrated in Figures 95 through 102.

Figure 95 shows the NO radial profile. The high degree of asymmetry due to the baffle still persists. Within the area of the burner block, the nitric oxide concentration averages 242 ppm, compared with 112 ppm at a 5.1-cm axial position.

The difficulty involved with trying to determine whether the NO has been formed within the burner-block area or appears there through entrainment from the secondary recirculation zone, becomes more difficult when viewing the oxygen radial profile (Figure 97) and the carbon dioxide profile (Figure 99).

The oxygen profile shows a smooth transition from the secondary recirculation zone to the fuel jet region, with no inflections due to a secondary air jet on the left side of the burner centerline. An oxygen peak of 11.8% does appear at the 15-cm radial position. At the 26-cm axial position, a 4.4% oxygen concentration in the secondary recirculation zone is typical. A minimum oxygen concentration of 0.8% is measured on the centerline of the burner. This is a slight increase over the 0.5% concentration measured at the 5.1-cm axial position.

The plot of carbon dioxide versus radial position also shows a smooth transition from the average 9.3% concentration of the secondary recirculation zone to 6.2% at 3 cm. The minimum CO_2 concentration, 4.9%, occurred at 15 cm — the position corresponding to the maximum oxygen reading. These minimums are split by a peak with a 6.7% concentration occurring between 6 cm and 9 cm.

The temperature profile (Figure 101) shows peaks of 1753° and 1701°C at −9 cm and +3 cm, respectively, with stoichiometric ratios of fuel and air occurring at −8.6 cm and +7.3 cm.

There is only a trace of methane detected, with hydrogen and carbon monoxide occurring in approximately equal concentrations at a measured maximum of 8% (Figure 100). Both concentrations are grouped about the centerline of the burner.

In-the-flame data for a 57.2-cm axial position are listed in Table 19 and presented in Figures 103 through 109. The average NO concentration within the burner-block area is 354 ppm, compared with 485 ppm outside this area. This resolves into a concentration gradient of 4.6 ppm/cm within the burner-block area from the 5.1-cm axial position to the 57.2-cm position. Conversely, the concentration gradient outside the burner-block area is −2.0 ppm/cm.

There is no longer a measurable concentration of methane. The locations of stoichiometric fuel-to-air ratios are at − 28 cm and +8.9 cm.

The in-the-flame data collected for the 146.1-cm axial position shows a general smoothing of the concentration. This data is listed in Table 20 with graphical representations in Figures 10 through 116. Combustion has been completed, with hydrogen decreasing from its maximum value of 6.6% at the 57.2-cm axial position to zero, and the carbon monoxide has decreased from 4.6% to 0.3%. The maximum measured temperature is 1679°C, with the temperature distribution being uniform about the burner centerline. The NO concentration in the burner-block area has increased to 446 ppm — only 47 ppm less than the concentration measured in the flue. The NO concentration outside the burner-block area is 467 ppm, or 26 ppm less than the flue concentration.

Figures 92, 100, 107, 114, and 121 show composite log plots of concentration versus radial position within the composition range of 0.0001% (1 ppm) to 100%. In these plots the interrelationships between concentration variations of oxygen, nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, hydrogen, and methane can easily be visualized.

Figures 94, 102, 109, 116, and 123 show flow direction versus radial position. These profiles show the positions of primary and secondary forward flow, of recirculation zones (reverse flow), and of shear and boundary layers.

Figures 93, 101, 108, 115, and 122 are plots of the average temperatures measured versus radial positions.

Intermediate Flame Length Baffle Burner - High-Momentum Gas Nozzle

From data collected during the input/output tests, we discovered that an effective and economic way to reduce NO_x emissions from the baffle burner was to increase the gas (primary jet) velocity. For these tests, the gas nozzle was changed from a 2-inch-diameter stainless steel tube to a 1/2-inch-diameter tube. The visual flame length was 311 cm, or an increase of 146 cm over the flame length observed with the standard nozzle. The furnace operating conditions for which these in-the-flame data were collected are listed in

Table 22. A complete listing of the pollution control test data is given in Tables 23 through 27 with full graphic illustrations of these data presented in Figures 124 through 161.

The profile data collected at the 5.1-cm axial position are graphically presented in Figures 124 through 131 with a detailed data listing in Table 23. The flow profile shows that the flow regions are similar to those observed for normal operating conditions. The only difference is due to the greater gas velocity. The primary jet now peaks above the maximum forward momentum air peaks. Thus, the gas jet will now be a momentum source, instead of being the momentum sink it was using the standard nozzle.

The average NO concentration in the secondary recirculation zone is 237 ppm, compared with the 254 ppm detected in the flue. The average concentration within the burner-block area is 13 ppm, with two small inflections occurring at –6 cm and +3 cm.

The profile of NO_2 versus radial position presented in Figure 125 shows two very small well resolved peaks within the burner-block area. These peaks occur at radial positions of –9 cm and +6 cm, with respective concentrations of 28 ppm and 34 ppm. At both positions, the NO_2 has a greater concentration than the NO.

The oxygen profile at the 5.1-cm axial position (Figure 126) displays peaks at –12 cm and +15 cm, with concentrations of 18.0% and 17.5%, respectively, which represent the secondary jet (combustion air) input.

The methane profile has a maximum concentration of 15% on the burner centerline and falls to zero at –12 cm and +9 cm in an asymmetrical pattern. Other combustibles present include carbon monoxide, with a maximum concentration of 5.8% at –3 cm; hydrogen, with a maximum concentration of 9.4% at –3 cm; acetylene and ethylene, with a combined maximum of 2.1% at –3 cm; and ethane at 0.3% on the centerline of the burner. The stoichiometric fuel/air ratio occurs at radial positions of –5.1 cm and +6.2 cm.

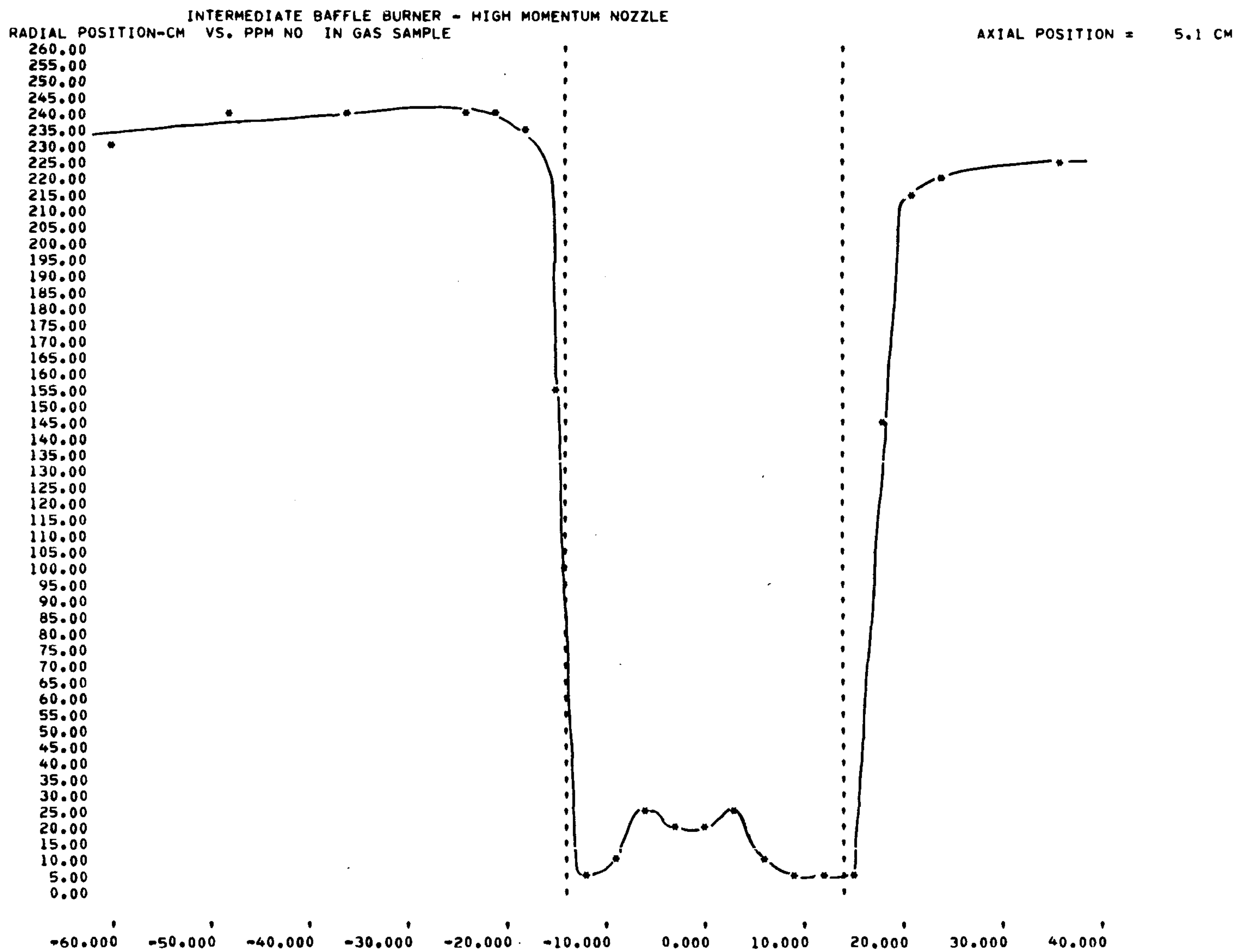

Figure 124. Radial profile of NO at an axial position of 5.1 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

Table 22. FURNACE CONDITIONS FOR IN-THE-FLAME SAMPLING
(Intermediate Flame Length Baffle Burner — High-Momentum Gas Nozzle)

```
                    INTERMEDIATE BAFFLE BURNER - HIGH MOMENTUM NOZZLE

NUMBER OF SETS OF DATA =   5.
MINIMUM GRID VALUE OF AVERAGE TEMPERATURE =  750. DEG.C
MAXIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1700. DEG.C

POSITION OF OUTSIDE EDGES OF BURNER BLOCK
   MINIMUM POSITION = -14. CM
   MAXIMUM POSITION =  14. CM

GAS INPUT,     AXIAL 3017. CF/HR        RADIAL    0. CF/HR
WALL TEMPERATURE             1380. DEG.C
PREHEAT TEMPERATURE           450. DEG.C
FLUE GAS RECIRCULATION  0.0 %

GAS SAMPLE ANALYSIS IN THE FLUE
   NITROGEN OXIDE      254.0 PPM
   NITROGEN DIOXIDE     39.0 PPM
   OXYGEN                4.1 %
   CARBON DIOXIDE        9.4 %
   CARBON MONOXIDE     .0101 %

LIMITS FOR CONCENTRATION PLOTS
     LOWER LIMIT OF NO  =     0. PPM     UPPER LIMIT =  260. PPM
     LOWER LIMIT OF NO2 =     0. PPM     UPPER LIMIT =   55. PPM
     LOWER LIMIT OF O2  =     0. %       UPPER LIMIT =   21. %
     LOWER LIMIT OF CH4 =     0. %       UPPER LIMIT =   15. %
     LOWER LIMIT OF CO2 =     1. %       UPPER LIMIT =   10. %

ISOCONCENTRATION VALUES
   OBTAIN VALUE OF RADIAL POSITION AT NO  PPM CONCENTRATION   230.  210.  190.  140.   70.
   OBTAIN VALUE OF RADIAL POSITION AT NO2 PPM CONCENTRATION    40.   30.   20.   10.
```

Table 23. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 5.1 cm
(Intermediate Flame Length Baffle Burner – High-Momentum Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - HIGH MOMENTUM NOZZLE

AXIAL POSITION = 5.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.7	?	231.	48.	9.1	.0049	?	0.0	?	?	?	?	1448.	1448.	0.
-48.	4.7	?	238.	45.	9.1	.0050	?	0.0	?	?	?	?	1340.	1340.	0.
-36.	4.4	?	238.	47.	9.2	.0051	?	0.0	?	?	?	?	1336.	1336.	0.
-24.	4.2	?	239.	46.	9.3	.0049	?	0.0	?	?	?	?	1313.	1313.	0.
-21.	4.2	?	241.	46.	9.3	.0046	?	0.0	?	?	?	?	1307.	1307.	0.
-18.	4.7	?	234.	45.	9.0	.0070	?	0.0	?	?	?	?	1269.	1269.	0.
-15.	9.0	?	156.	35.	6.6	.0226	?	0.0	?	?	?	?	1126.	1126.	0.
-12.	18.0	79.4	6.	7.	1.3	.2000	0.0	0.0	0.0	0.0	0.0	0.0	780.	780.	0.
-9.	10.7	77.9	10.	28.	3.4	2.2000	2.8	1.7	.3	.0	0.0	0.0	1205.	1205.	0.
-6.	2.5	66.1	24.	17.	3.9	5.8000	9.1	10.0	1.8	.2	0.0	0.0	1506.	1506.	0.
-3.	2.4	61.1	22.	7.	3.5	5.8000	9.4	14.7	2.1	.3	0.0	.0	1345.	1345.	0.
0.	2.9	61.2	22.	13.	3.4	5.7000	8.9	15.0	2.0	.3	0.0	.0	1286.	1286.	0.
3.	3.1	68.1	24.	20.	4.2	5.5000	7.9	9.1	1.3	.2	0.0	0.0	1482.	1482.	0.
6.	8.1	76.9	9.	34.	3.9	3.1000	3.9	2.6	.7	0.0	0.0	0.0	1462.	1462.	0.
9.	13.1	?	7.	9.	4.5	.3500	?	0.0	?	?	?	?	1108.	1108.	0.
12.	15.8	?	4.	1.	2.9	.0228	?	0.0	?	?	?	?	767.	767.	0.
15.	17.5	?	4.	1.	1.1	.0121	?	0.0	?	?	?	?	820.	820.	0.
18.	12.9	?	146.	25.	6.6	.0072	?	0.0	?	?	?	?	1143.	1143.	0.
21.	5.2	?	214.	39.	8.8	.0046	?	0.0	?	?	?	?	1253.	1253.	0.
24.	5.2	?	219.	37.	8.8	.0045	?	0.0	?	?	?	?	1343.	1343.	0.
36.	5.4	?	227.	36.	8.6	.0038	?	0.0	?	?	?	?	1355.	1355.	0.

Table 24. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 26 cm
(Intermediate Flame Length Baffle Burner — High-Momentum Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - HIGH MOMENTUM NOZZLE

AXIAL POSITION = 26.0 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	5.4	?	230.	38.	8.6	.0050	?	0.0	?	?	?	?	1368.	1368.	0.
-48.	5.6	?	229.	39.	8.5	.0046	?	0.0	?	?	?	?	1351.	1351.	0.
-36.	5.7	?	232.	41.	8.5	.0040	?	0.0	?	?	?	?	1348.	1348.	0.
-24.	7.4	?	184.	43.	7.5	.0395	?	0.0	?	?	?	?	1348.	1348.	0.
-21.	9.7	?	156.	27.	6.1	.1300	?	0.0	?	?	?	?	1349.	1349.	0.
-18.	10.5	82.4	102.	28.	5.4	.4600	.2	.1	0.0	0.0	0.0	0.0	1278.	1278.	0.
-15.	10.1	81.0	59.	47.	5.0	1.3400	1.4	.3	0.0	0.0	0.0	0.0	1333.	1333.	0.
-12.	6.6	76.6	30.	51.	4.8	3.7200	5.3	1.8	.4	0.0	0.0	0.0	1595.	1595.	0.
-9.	2.1	68.2	26.	19.	4.4	6.8600	10.8	5.6	1.5	.0	0.0	0.0	1606.	1606.	0.
-6.	1.2	64.2	25.	10.	4.1	7.2200	13.4	7.3	1.9	.0	0.0	0.0	1561.	1561.	0.
-3.	1.3	66.1	26.	10.	4.3	7.3400	11.4	7.0	2.0	.0	0.0	0.0	1606.	1606.	0.
0.	3.1	71.6	25.	28.	4.8	6.1800	8.9	3.9	.9	.0	0.0	0.0	1643.	1643.	0.
3.	9.0	78.8	19.	42.	4.3	2.5700	3.5	.9	0.0	0.0	0.0	0.0	1569.	1569.	0.
6.	15.3	79.4	24.	28.	3.1	1.0100	.5	.1	0.0	0.0	0.0	0.0	1372.	1372.	0.
9.	16.5	79.5	37.	14.	2.4	.3900	0.0	.0	0.0	0.0	0.0	0.0	1142.	1142.	0.
12.	16.2	79.9	45.	11.	2.6	.0194	0.0	0.0	0.0	0.0	0.0	0.0	1086.	1086.	0.
15.	14.9	80.7	68.	14.	3.5	.0085	0.0	0.0	0.0	0.0	0.0	0.0	1191.	1191.	0.
18.	13.4	81.4	95.	16.	4.2	.0073	0.0	0.0	0.0	0.0	0.0	0.0	1258.	1258.	0.
21.	10.7	82.6	132.	19.	5.6	.0048	0.0	0.0	0.0	0.0	0.0	0.0	1327.	1327.	0.
24.	7.6	?	173.	24.	7.4	.0045	?	0.0	?	?	?	?	1350.	1350.	0.
36.	5.1	?	201.	28.	8.8	.0056	?	0.0	?	?	?	?	1352.	1352.	0.

Table 25. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 57.2 cm
(Intermediate Flame Length Baffle Burner – High-Momentum Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - HIGH MOMENTUM NOZZLE

AXIAL POSITION = 57.2 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	5.2	?	248.	50.	8.8	.0075	?	0.0	?	?	?	?	1381.	1381.	0.
-48.	5.6	?	241.	50.	8.5	.0070	?	0.0	?	?	?	?	1365.	1365.	0.
-42.	5.9	?	241.	49.	8.4	.0129	?	0.0	?	?	?	?	1382.	1382.	0.
-36.	6.1	?	231.	47.	8.2	.0486	?	0.0	?	?	?	?	1389.	1389.	0.
-30.	6.3	84.4	199.	39.	7.9	.5000	.2	0.0	0.0	0.0	0.0	0.0	1473.	1473.	0.
-24.	6.3	83.0	151.	41.	6.6	1.7100	1.5	.1	0.0	0.0	0.0	0.0	1546.	1546.	0.
-18.	3.5	79.8	102.	41.	6.5	4.0800	5.1	.5	0.0	0.0	0.0	0.0	1692.	1692.	0.
-12.	2.0	75.4	66.	25.	5.4	6.5000	8.7	1.2	.2	0.0	0.0	0.0	1614.	1614.	0.
-6.	4.4	76.2	64.	36.	5.1	5.6200	7.1	.9	0.0	0.0	0.0	0.0	1619.	1619.	0.
0.	9.3	80.5	83.	47.	5.1	2.2300	1.9	.1	0.0	0.0	0.0	0.0	1542.	1542.	0.
6.	10.6	82.4	118.	21.	5.3	.6200	0.0	0.0	0.0	0.0	0.0	0.0	1469.	1469.	0.
12.	11.4	82.5	116.	15.	5.0	.1300	0.0	0.0	0.0	0.0	0.0	0.0	1371.	1371.	0.
18.	11.3	?	113.	6.	5.2	.0234	?	0.0	?	?	?	?	1194.	1194.	0.
21.	10.7	?	128.	28.	5.6	.0095	?	0.0	?	?	?	?	1249.	1249.	0.
24.	9.6	?	145.	28.	6.2	.0080	?	0.0	?	?	?	?	1312.	1312.	0.
30.	7.7	?	156.	36.	7.2	.0076	?	0.0	?	?	?	?	1344.	1344.	0.
36.	6.1	?	166.	47.	8.2	.0071	?	0.0	?	?	?	?	1346.	1346.	0.

Table 26. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 146.1 cm
(Intermediate Flame Length Baffle Burner — High-Momentum Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - HIGH MOMENTUM NOZZLE

AXIAL POSITION = 146.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	5.7	?	229.	50.	8.5	.0229	?	0.0	?	?	?	?	1481.	1481.	0.
-48.	5.1	?	222.	44.	8.9	.1000	?	0.0	?	?	?	?	1520.	1520.	0.
-36.	5.0	85.0	212.	42.	8.7	.3000	0.0	0.0	0.0	0.0	0.0	0.0	1590.	1590.	0.
-30.	4.7	85.1	212.	39.	8.7	.4400	0.0	0.0	0.0	0.0	0.0	0.0	1600.	1600.	0.
-24.	4.6	85.2	204.	37.	8.8	.5800	0.0	0.0	0.0	0.0	0.0	0.0	1598.	1598.	0.
-18.	4.8	85.2	194.	39.	8.7	.5600	0.0	0.0	0.0	0.0	0.0	0.0	1576.	1576.	0.
-12.	5.5	84.8	196.	41.	8.3	.3400	0.0	0.0	0.0	0.0	0.0	0.0	1526.	1526.	0.
-6.	5.8	?	188.	42.	8.5	.1000	?	0.0	?	?	?	?	1522.	1522.	0.
0.	6.5	?	179.	31.	8.1	.1300	?	0.0	?	?	?	?	1514.	1514.	0.
6.	6.5	?	175.	41.	8.2	.1300	?	0.0	?	?	?	?	1494.	1494.	0.
12.	6.4	?	181.	33.	8.1	.0800	?	0.0	?	?	?	?	1493.	1493.	0.
18.	6.7	?	162.	33.	8.0	.0400	?	0.0	?	?	?	?	1476.	1476.	0.
24.	7.1	?	158.	30.	7.6	.0427	?	0.0	?	?	?	?	1443.	1443.	0.
30.	6.9	?	159.	29.	7.9	.0140	?	0.0	?	?	?	?	1426.	1426.	0.
36.	6.6	?	158.	31.	7.9	.0093	?	0.0	?	?	?	?	1410.	1410.	0.

Table 27. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 385.4 cm (Intermediate Flame Length Baffle Burner — High-Momentum Gas Nozzle)

INTERMEDIATE BAFFLE BURNER - HIGH MOMENTUM NOZZLE

AXIAL POSITION = 385.4 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.4	?	253.	42.	9.3	.0101	0.0	0.0	?	?	?	?	1480.	1480.	0.
-48.	4.3	?	255.	39.	9.3	.0125	?	0.0	?	?	?	?	1460.	1460.	0.
-36.	4.2	?	263.	41.	9.4	.0104	?	0.0	?	?	?	?	1440.	1440.	0.
-24.	4.3	?	258.	42.	9.3	.0105	?	0.0	?	?	?	?	1420.	1420.	0.
-12.	4.3	?	258.	46.	9.2	.0094	?	0.0	?	?	?	?	1396.	1396.	0.
0.	4.4	?	251.	33.	9.2	.0091	?	0.0	?	?	?	?	1377.	1377.	0.
12.	4.2	?	249.	30.	9.4	.0093	?	0.0	?	?	?	?	1380.	1380.	0.
24.	4.1	?	248.	33.	9.4	.0095	?	0.0	?	?	?	?	1398.	1398.	0.
36.	4.0	?	246.	37.	9.4	.0088	?	0.0	?	?	?	?	1402.	1402.	0.

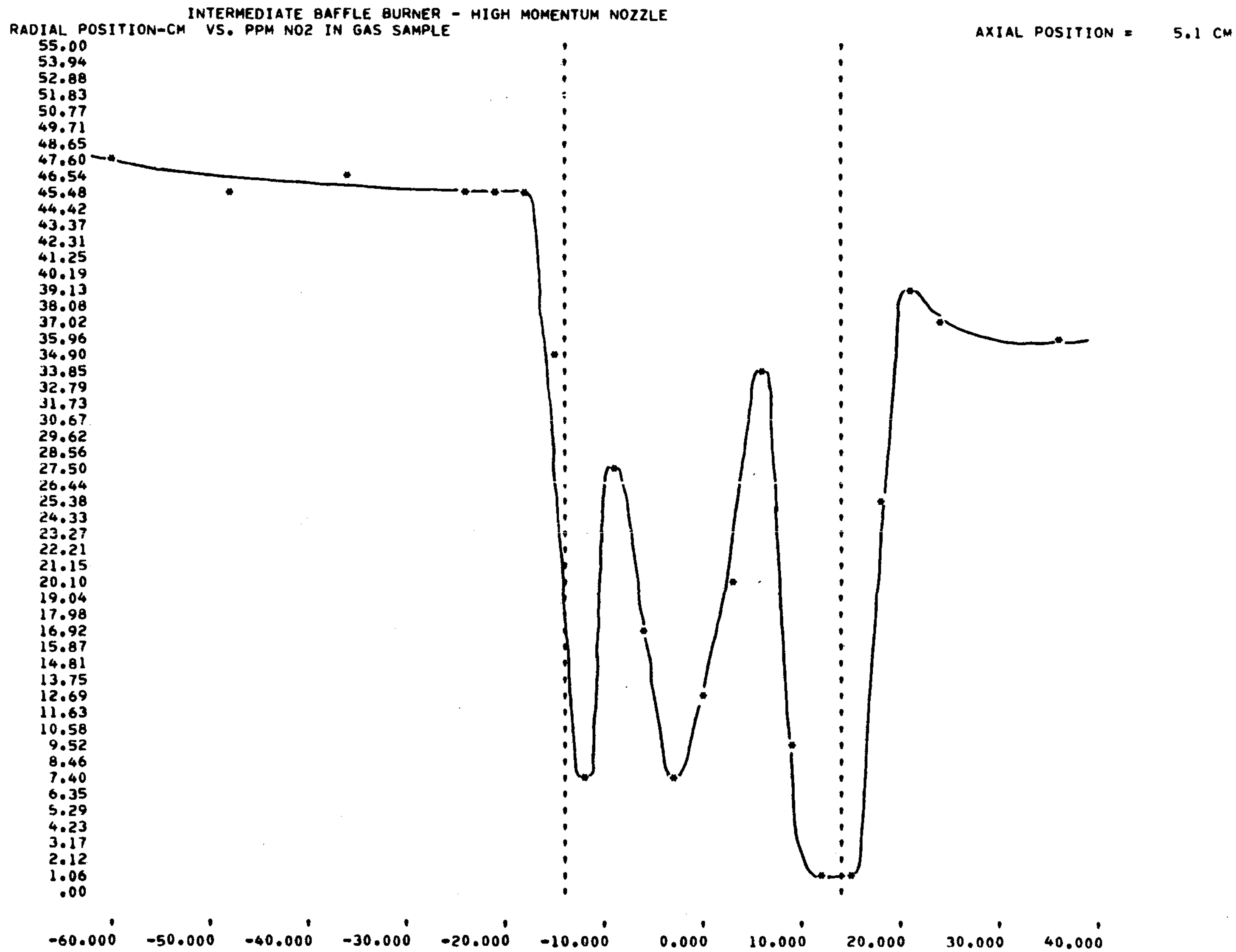

Figure 125. Radial profile of NO_2 at an axial position of 5.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

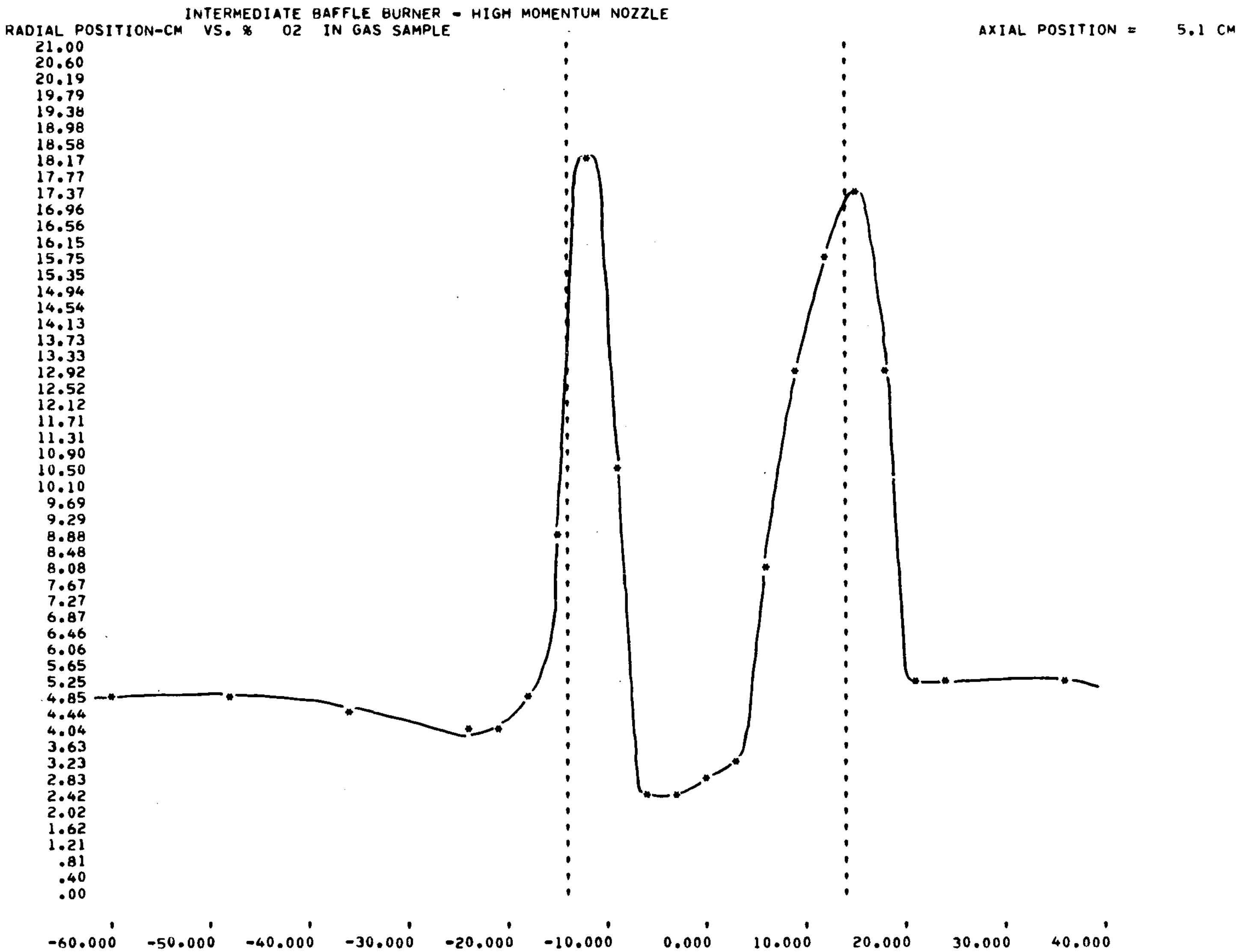

Figure 126. Radial profile of O_2 at an axial position of 5.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

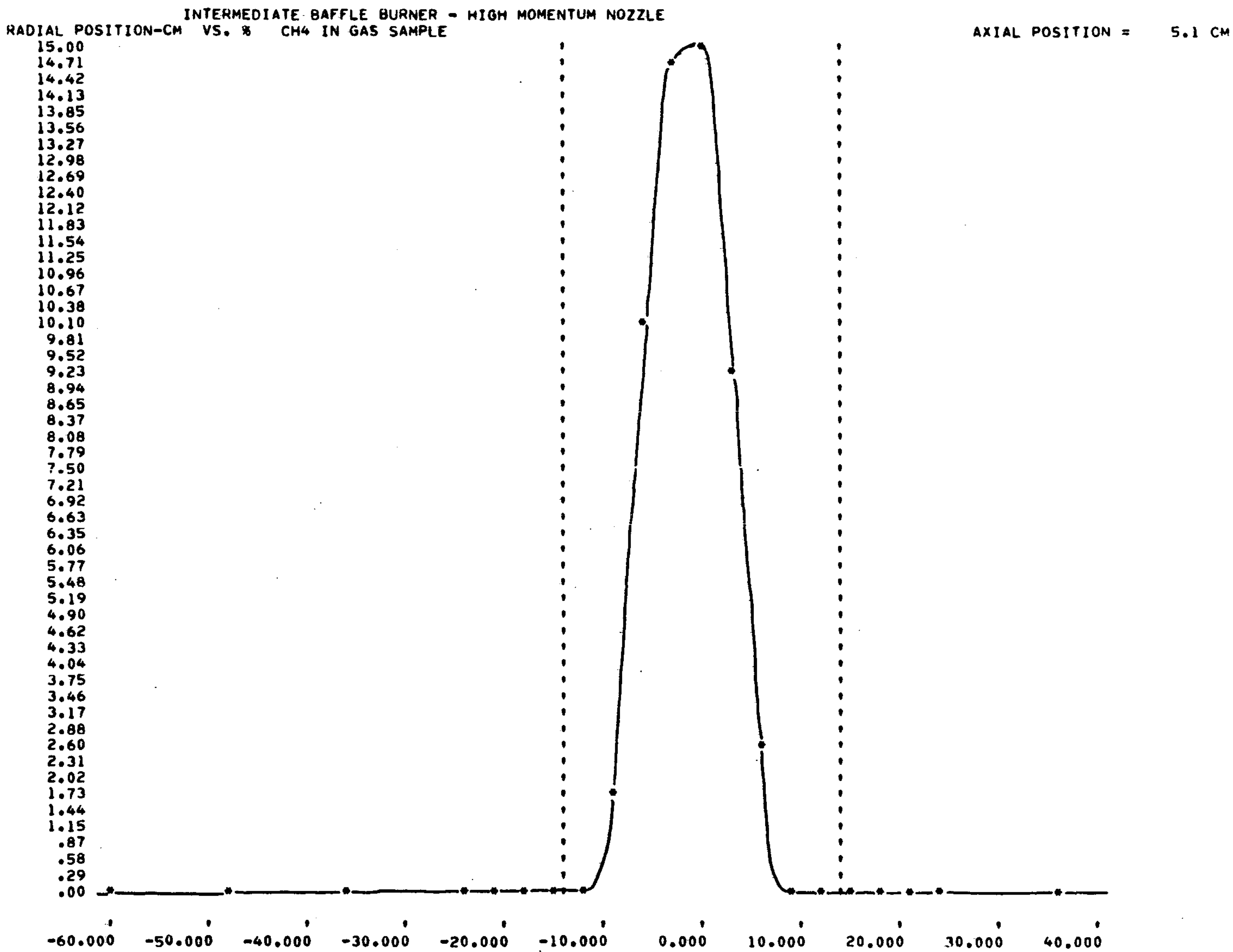

Figure 127. Radial profile of CH_4 at an axial position of 5.1 cm
(intermediate flame length baffle burner – high-momentum gas nozzle)

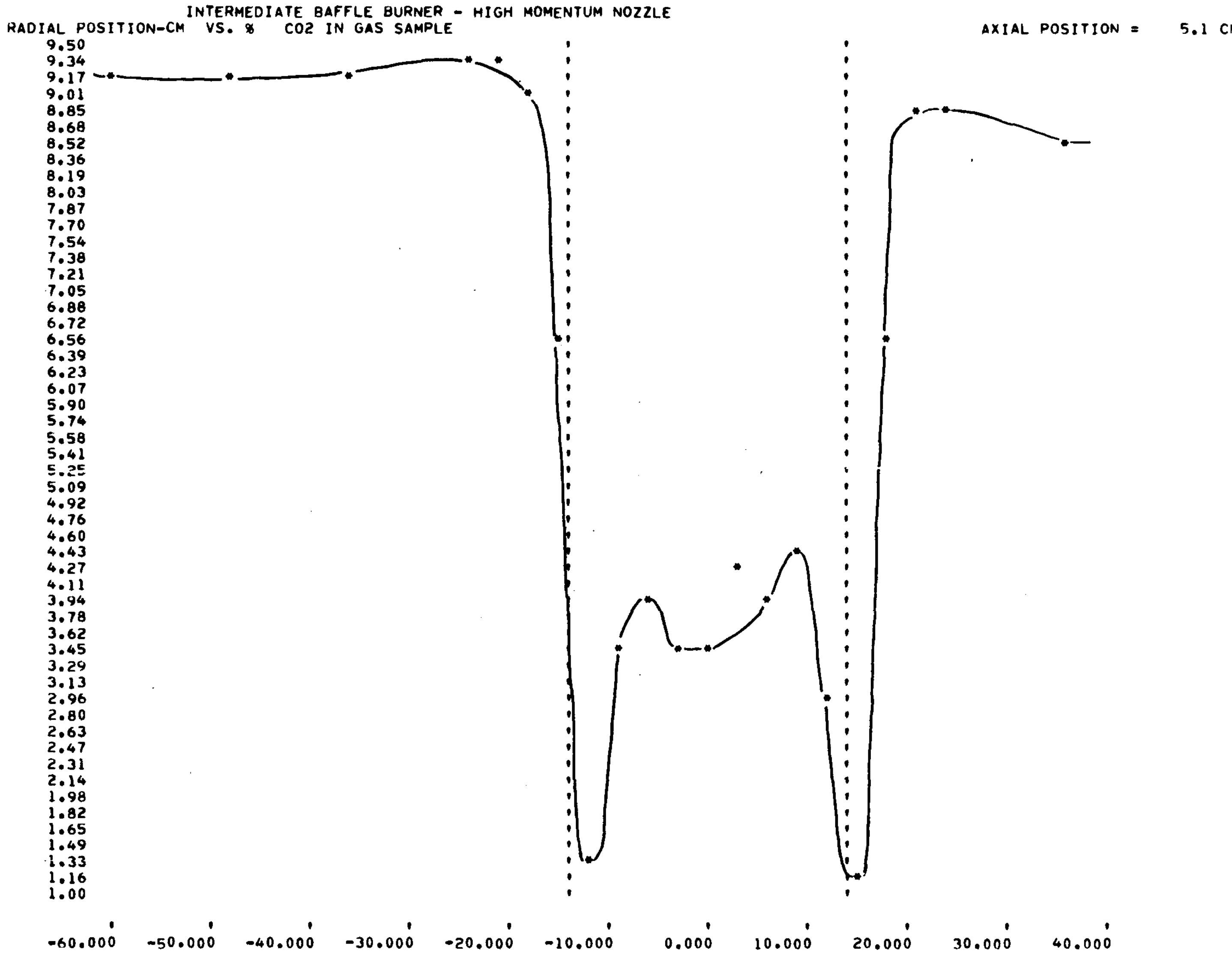

Figure 128. Radial profile of CO_2 at an axial position of 5.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

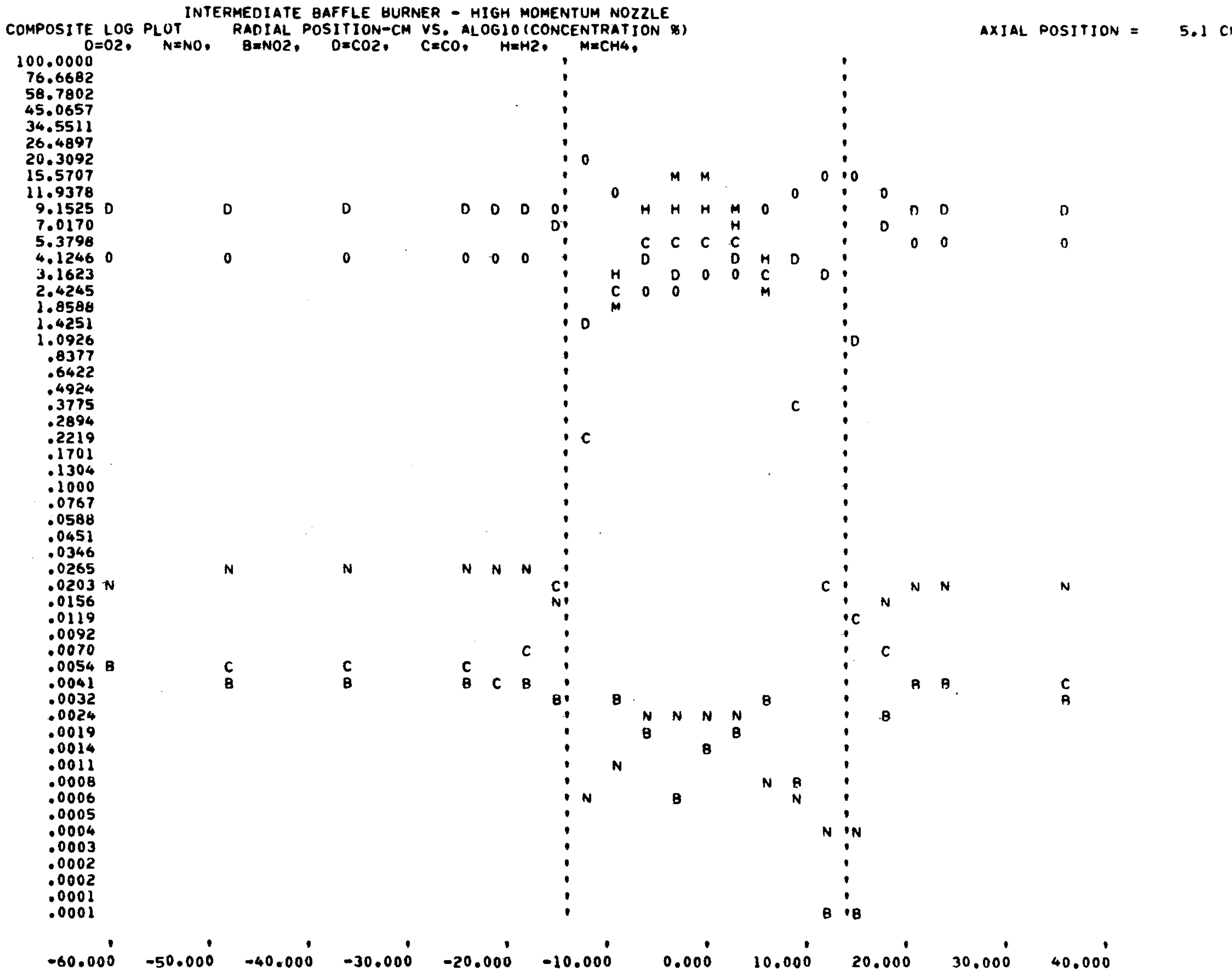

Figure 129. Radial profile of all the gases at an axial position of 5.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

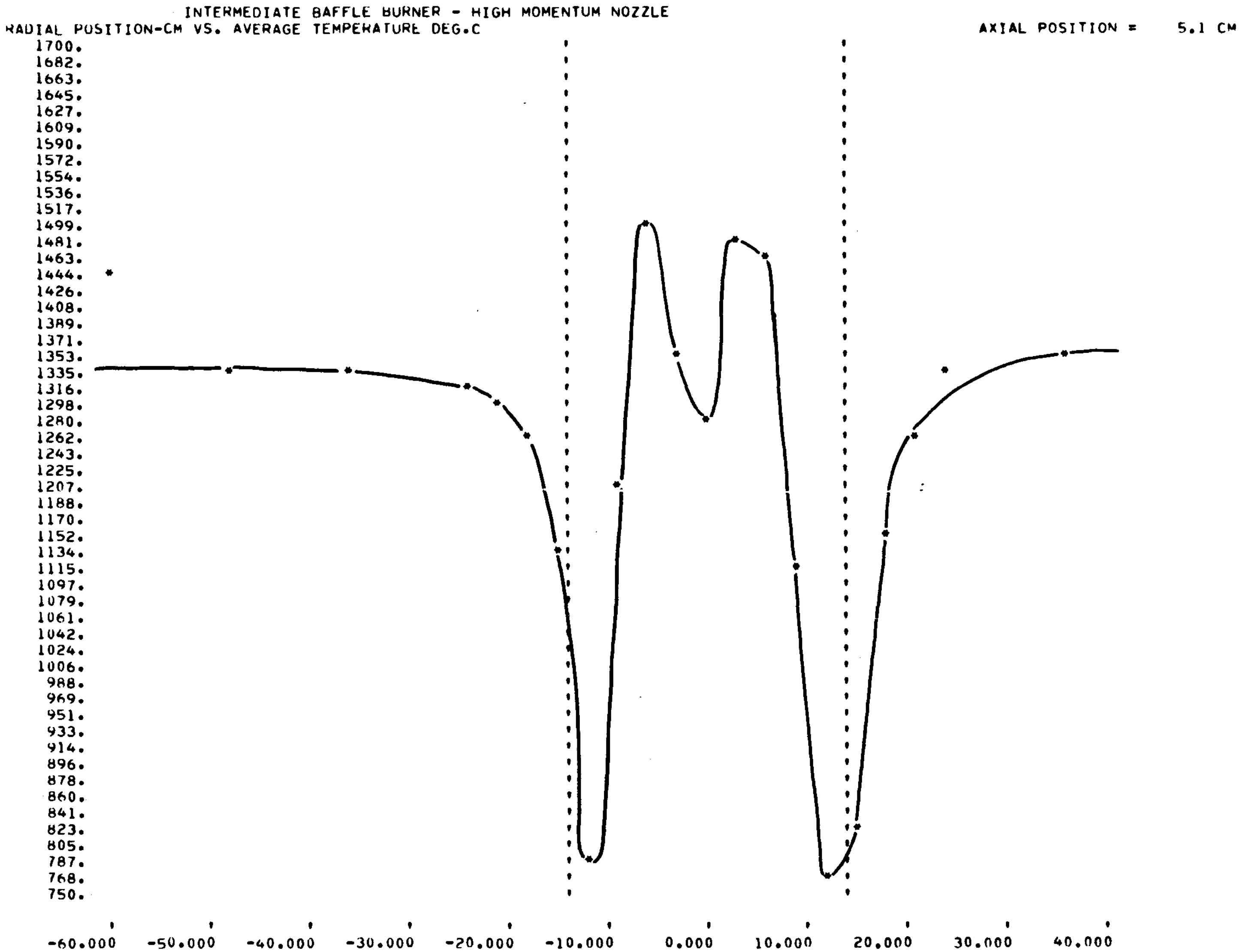

Figure 130. Radial profile of average temperature at an axial position of 5.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

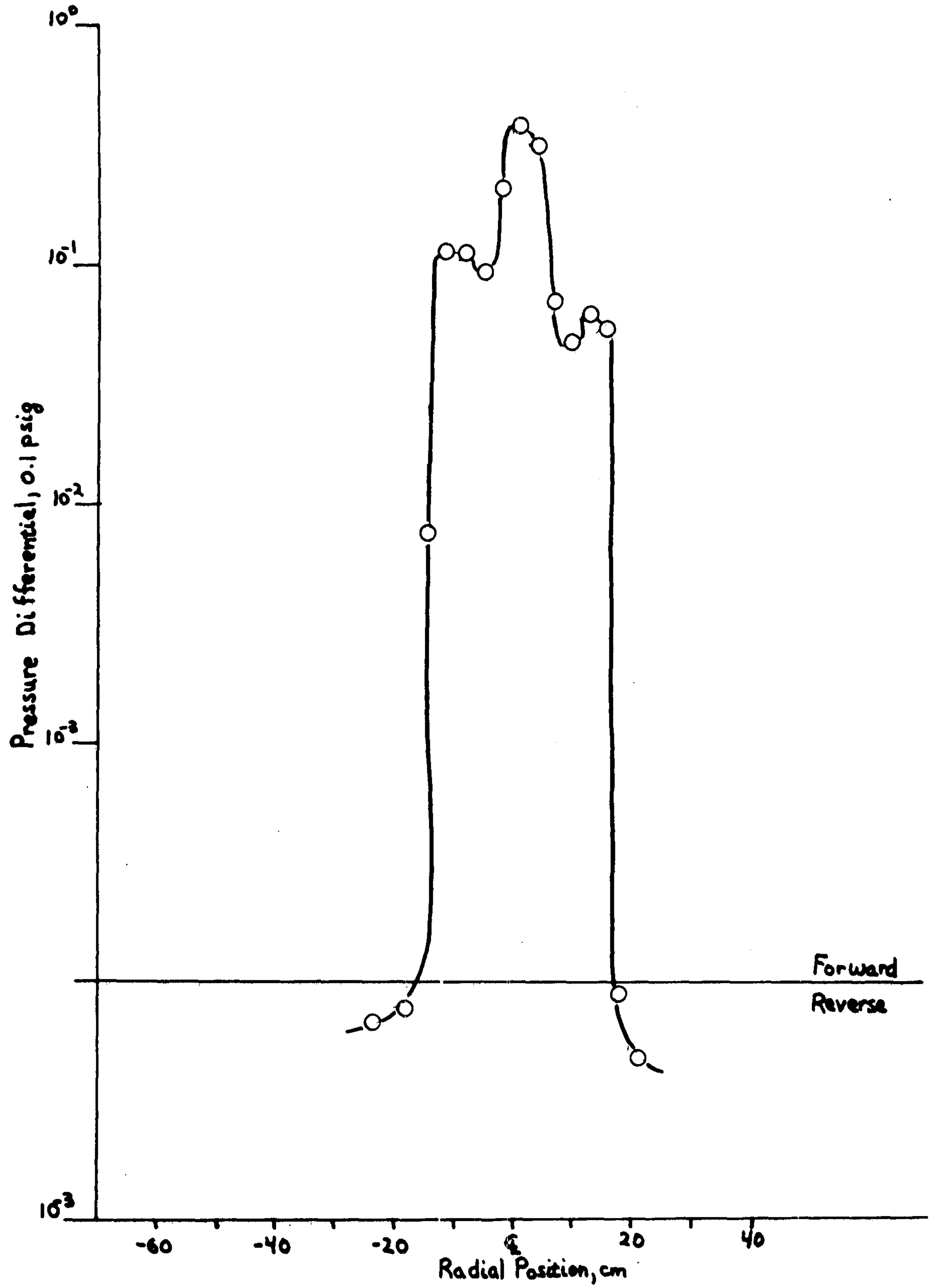

Figure 131. Radial profile of flow direction at an axial position of 5.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

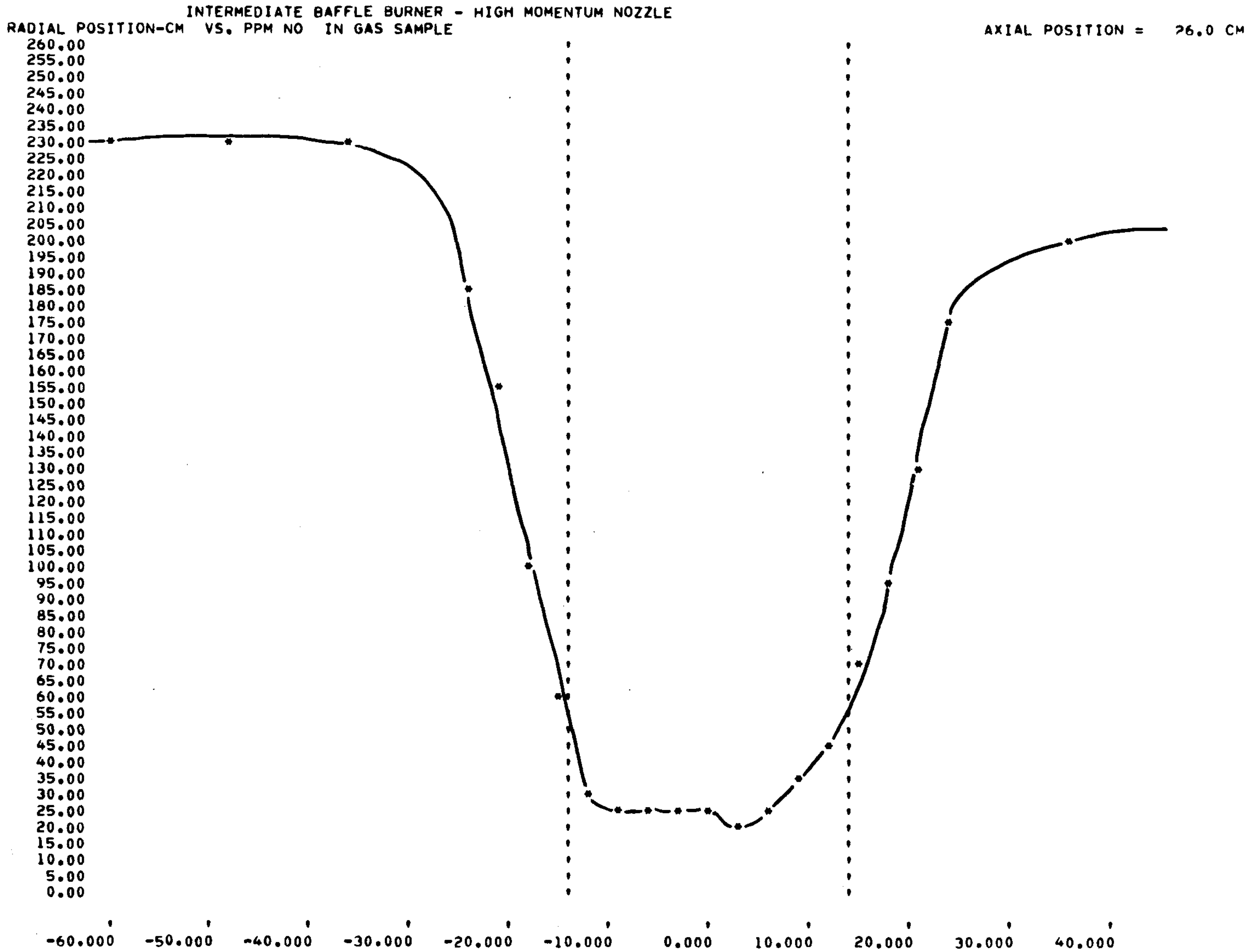

Figure 132. Radial profile of NO at an axial position of 26.0 cm (intermeidate flame length baffle burner — high-momentum gas nozzle)

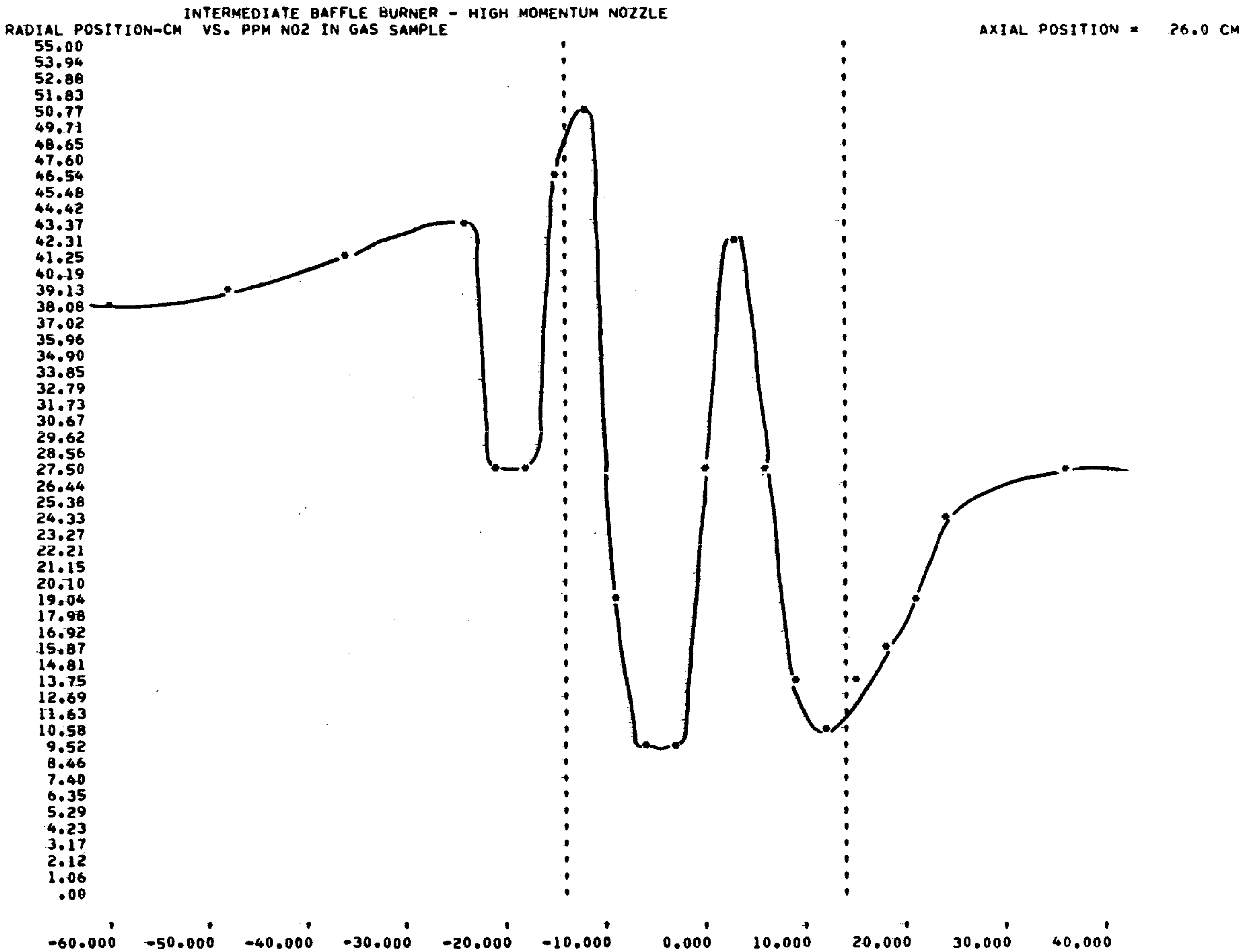

Figure 133. Radial profile of NO_2 at an axial position of 26.0 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

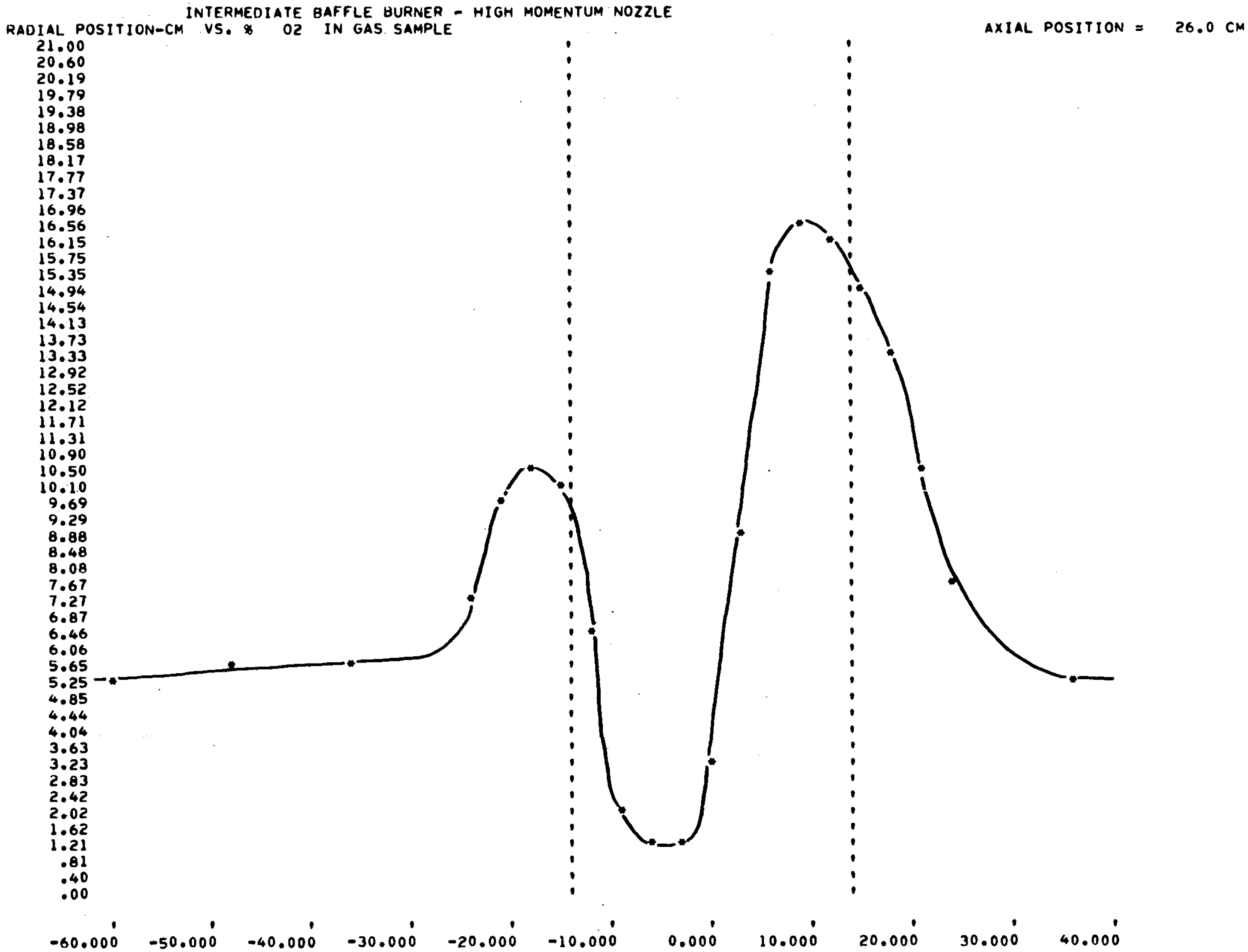

Figure 134. Radial profile of O_2 at an axial position of 26.0 cm (intermeidate flame length baffle burner — high-momentum gas nozzle)

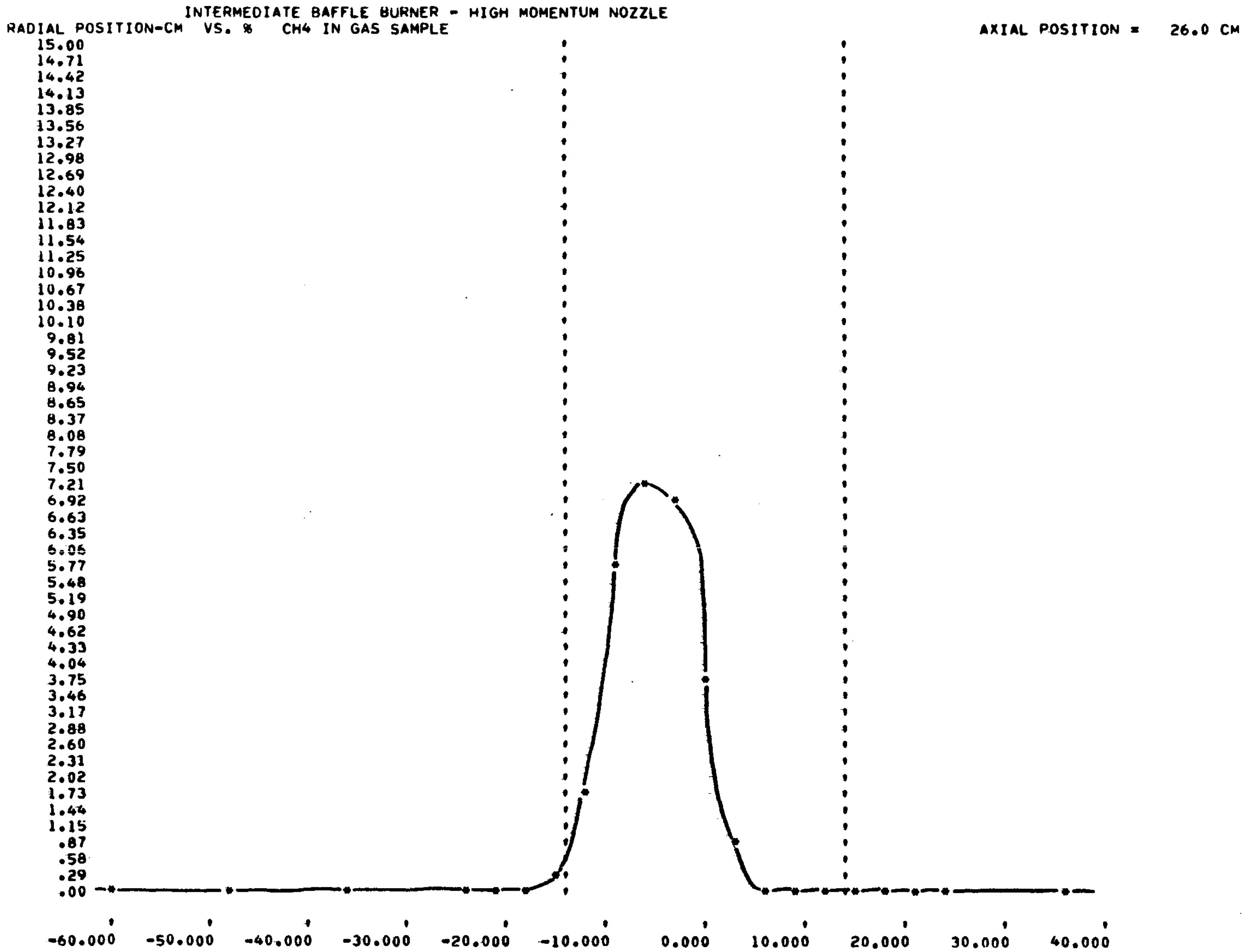

Figure 135. Radial profile of CH_4 at an axial position of 26.0 cm
(intermediate flame length baffle burner – high-momentum gas nozzle)

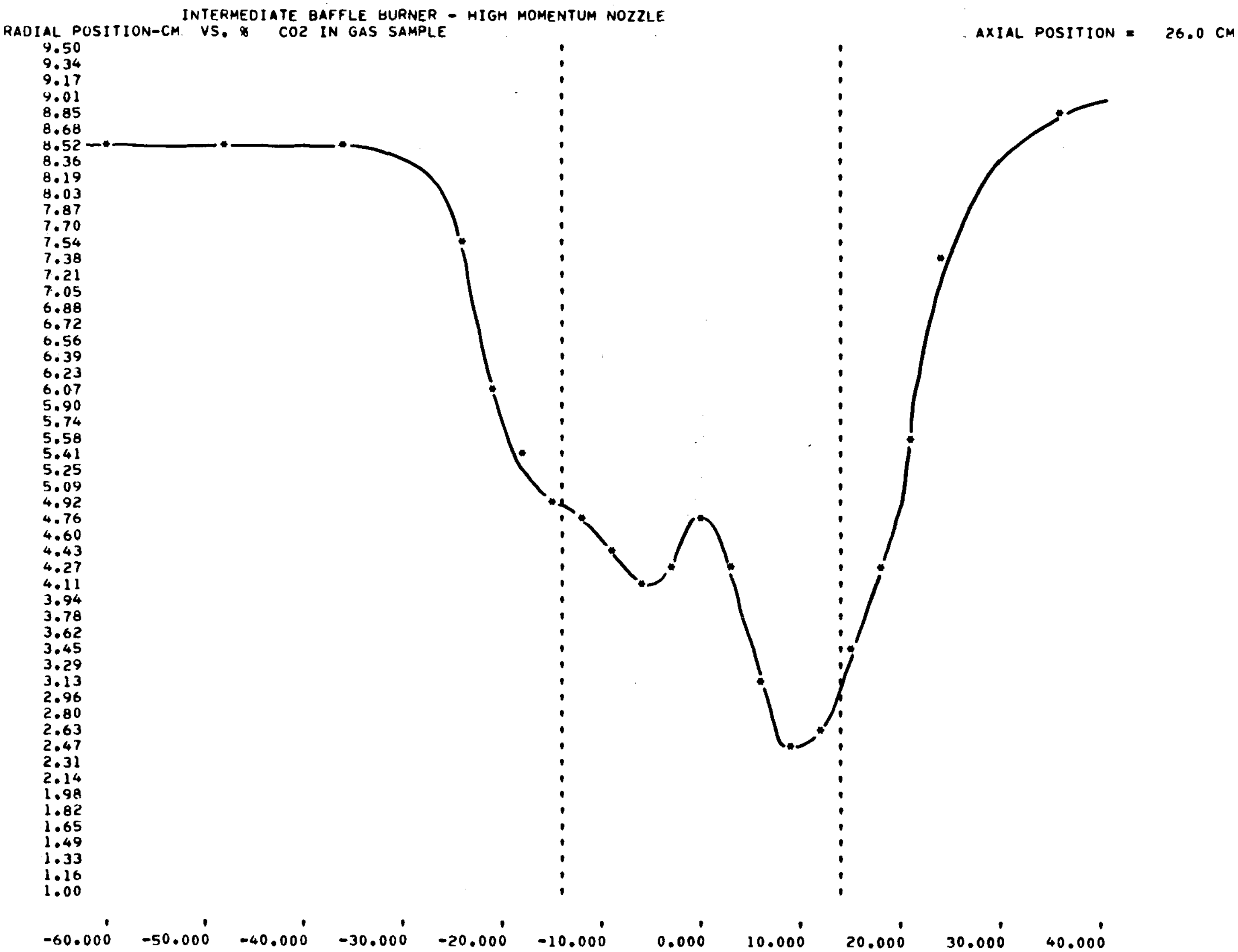

Figure 136. Radial profile of CO_2 at an axial position of 26.0 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

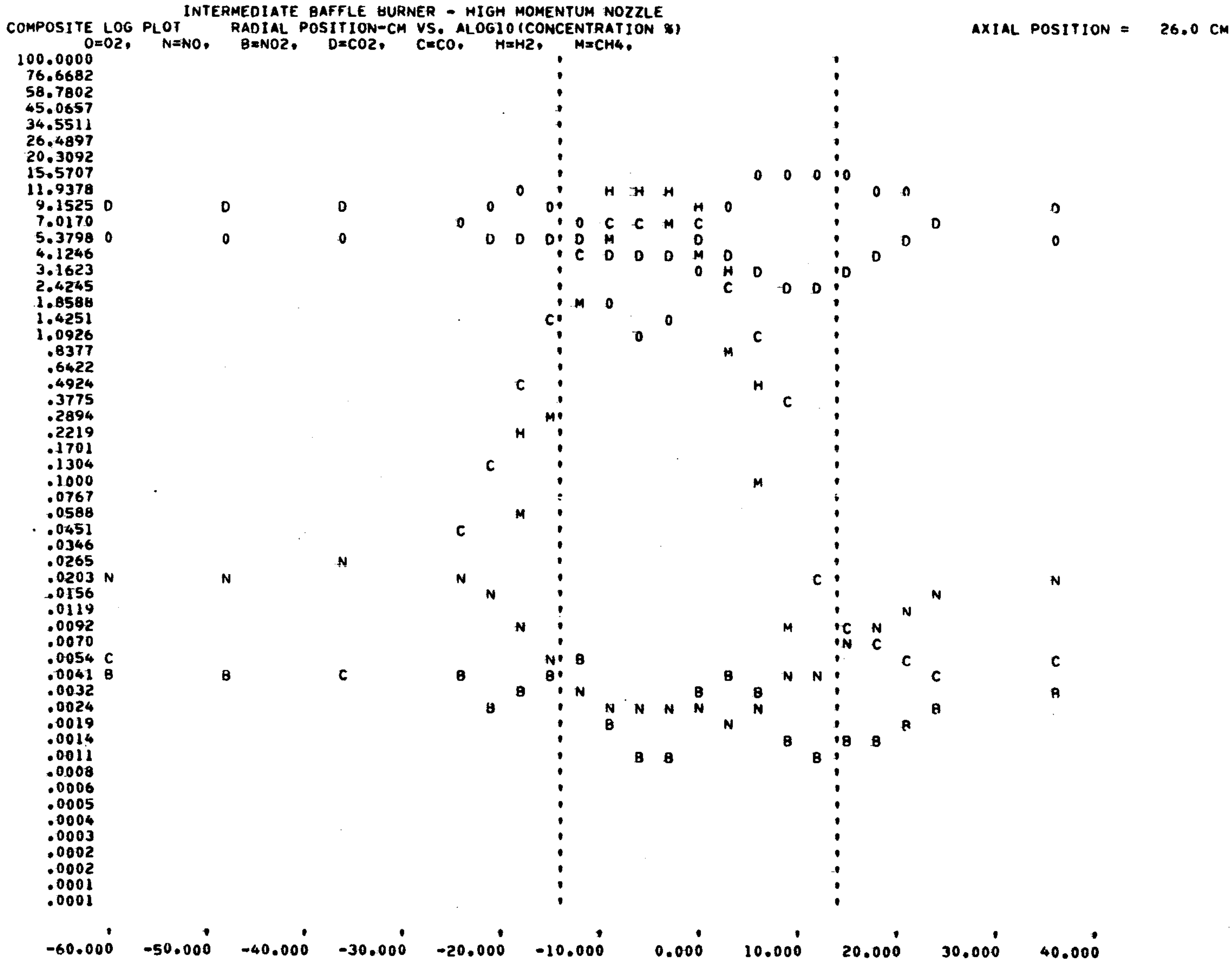

Figure 137. Radial profile of all the gases at an axial position of 26. 0 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

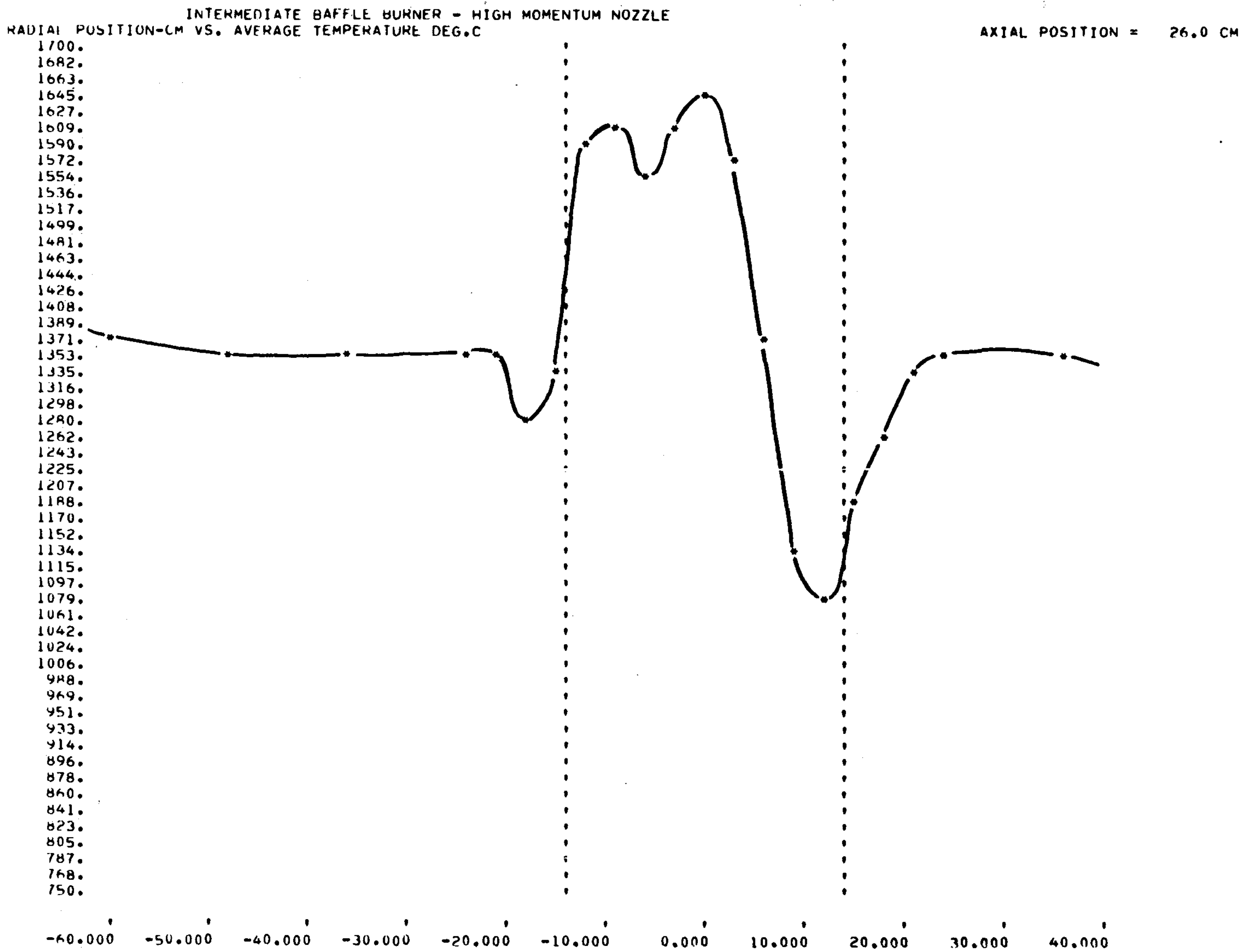

Figure 138. Radial profile of average temperature at an axial position of 26.0 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

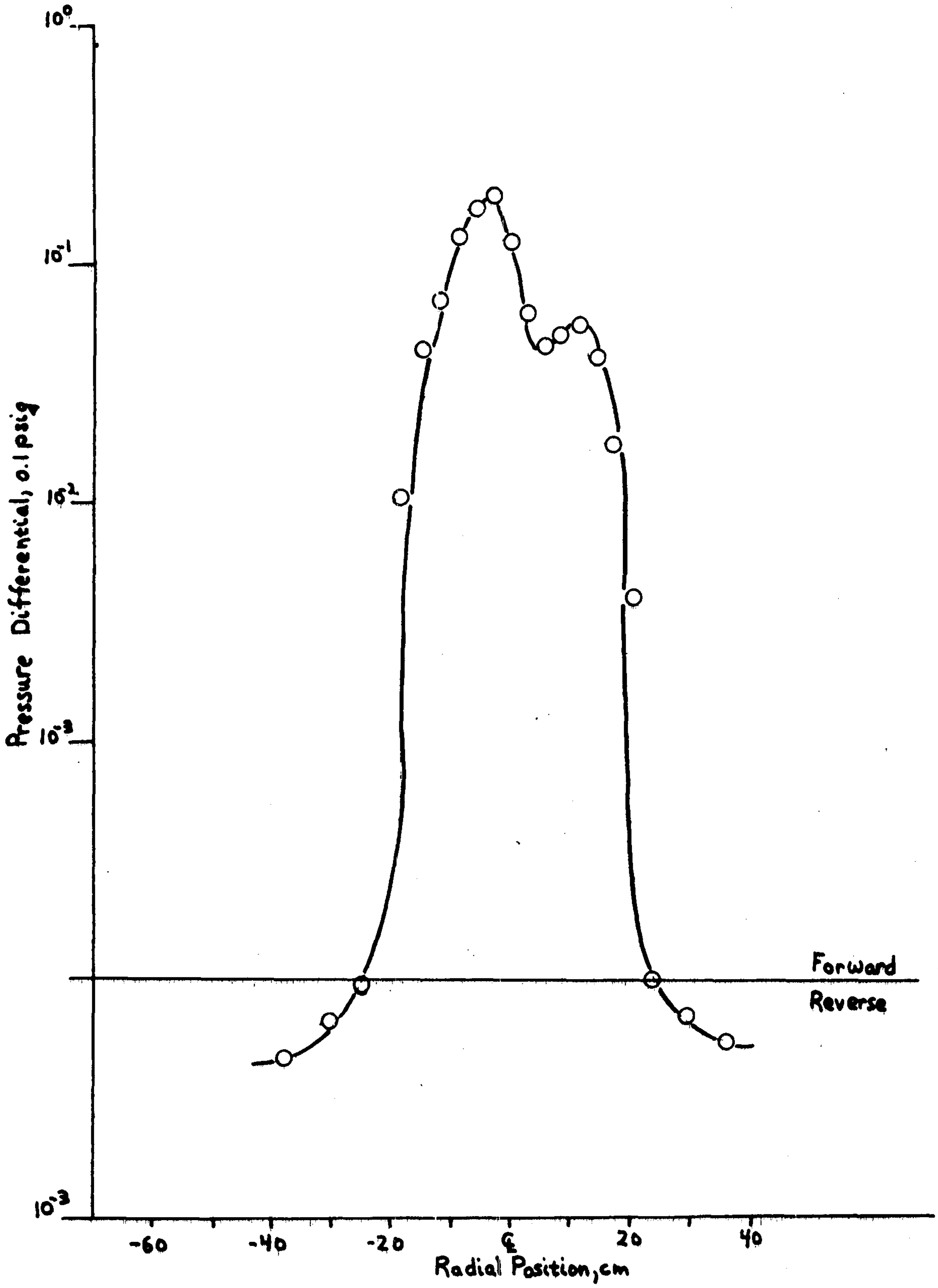

Figure 139. Radial profile of flow direction at an axial position of 26.0 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

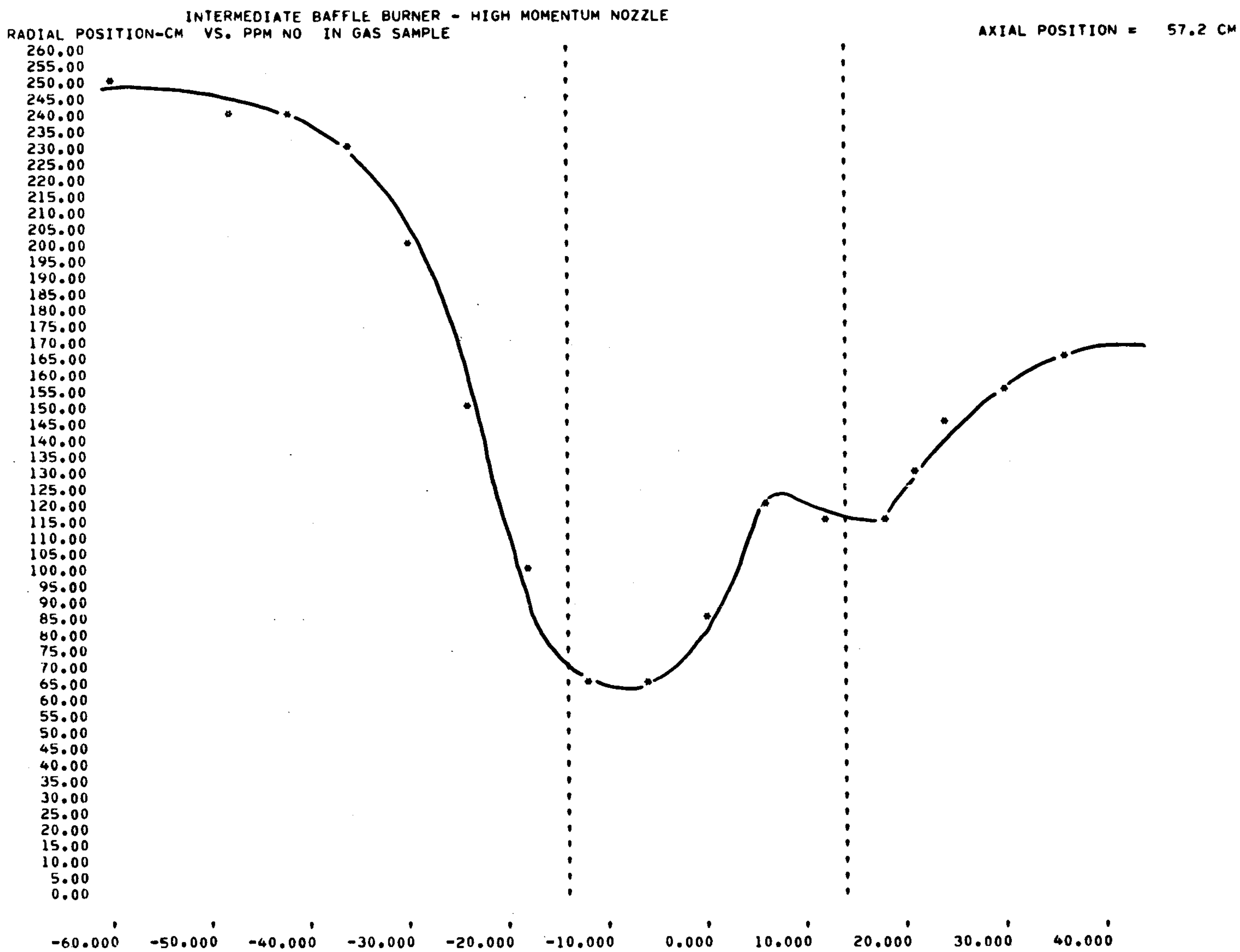

Figure 140 Radial profile of NO at an axial position of 57. 2 cm
(intermediate flame length baffle burner – high-momentum gas nozzle)

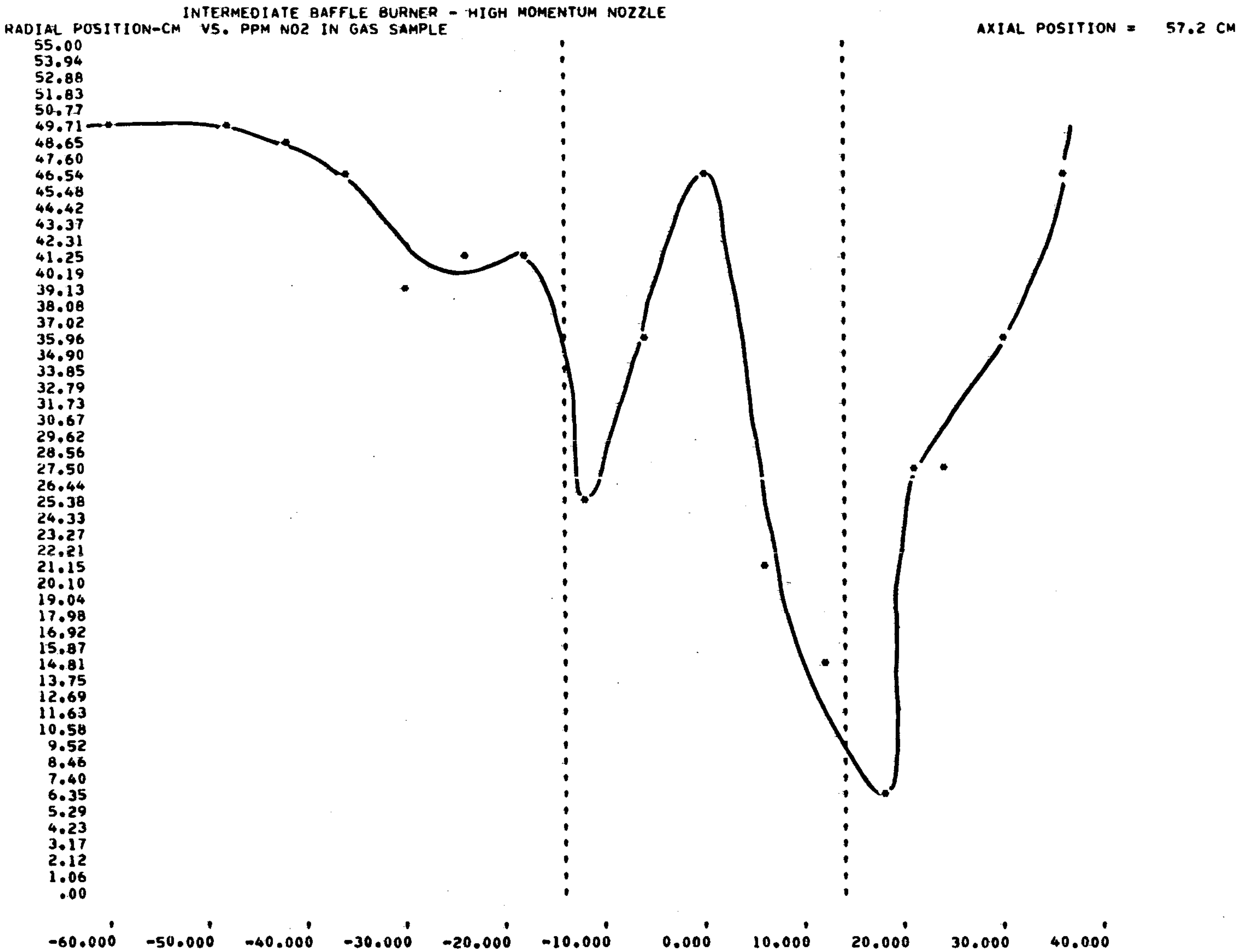

Figure 141. Radial profile of NO_2 at an axial position of 57. 2 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

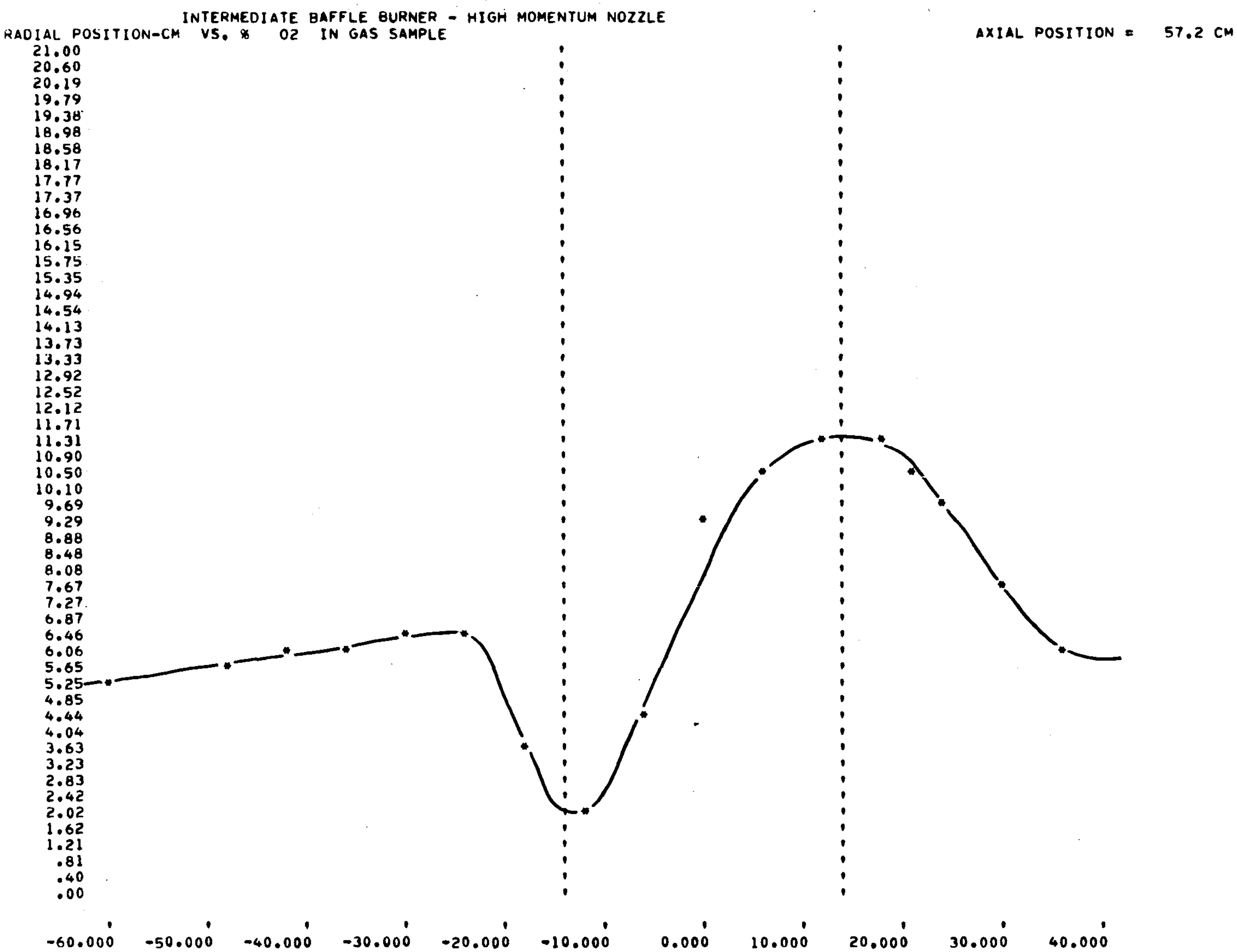

Figure 142. Radial profile of O_2 at an axial position of 57.2 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

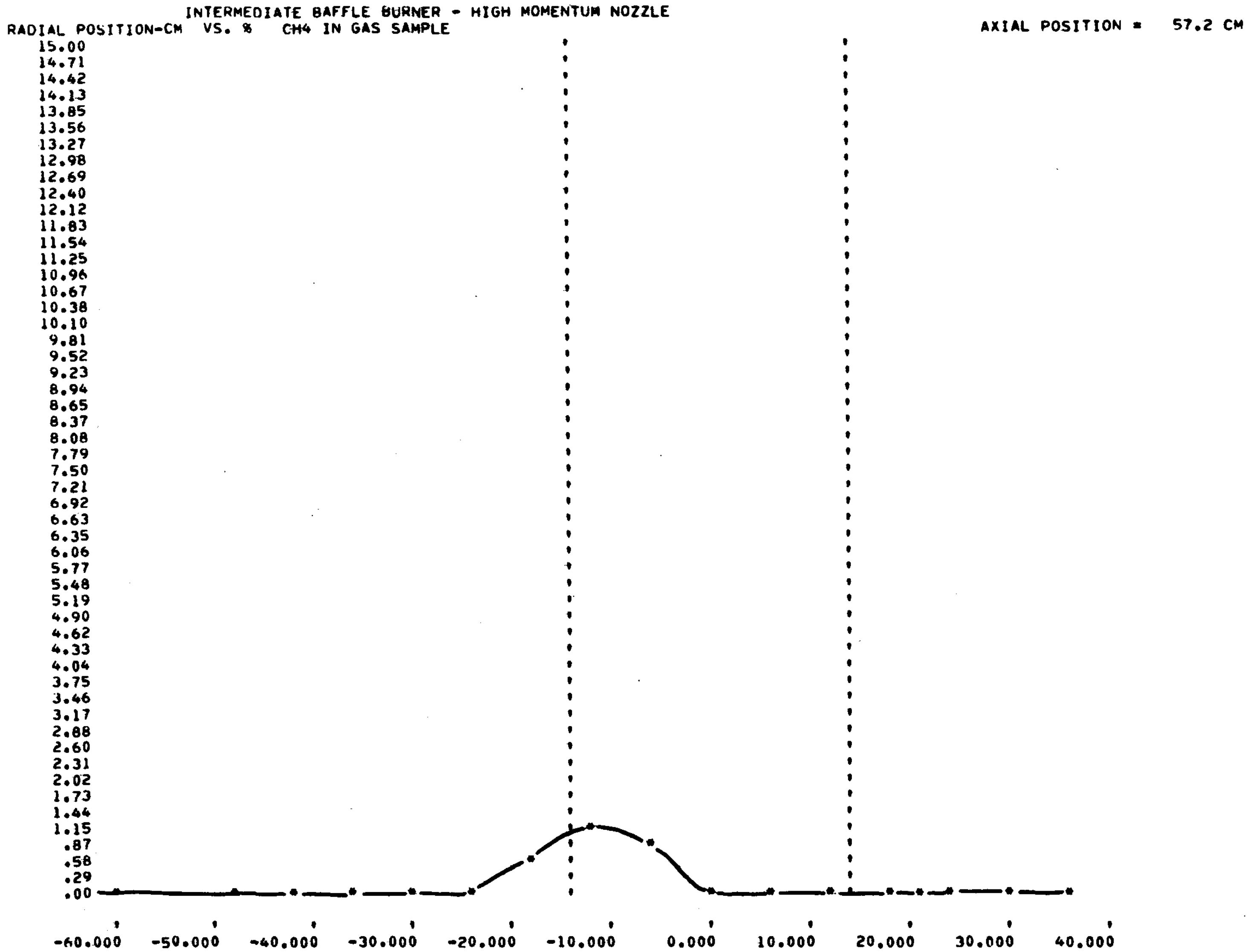

Figure 143. Radial profile of CH_4 at an axial position of 57.2 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

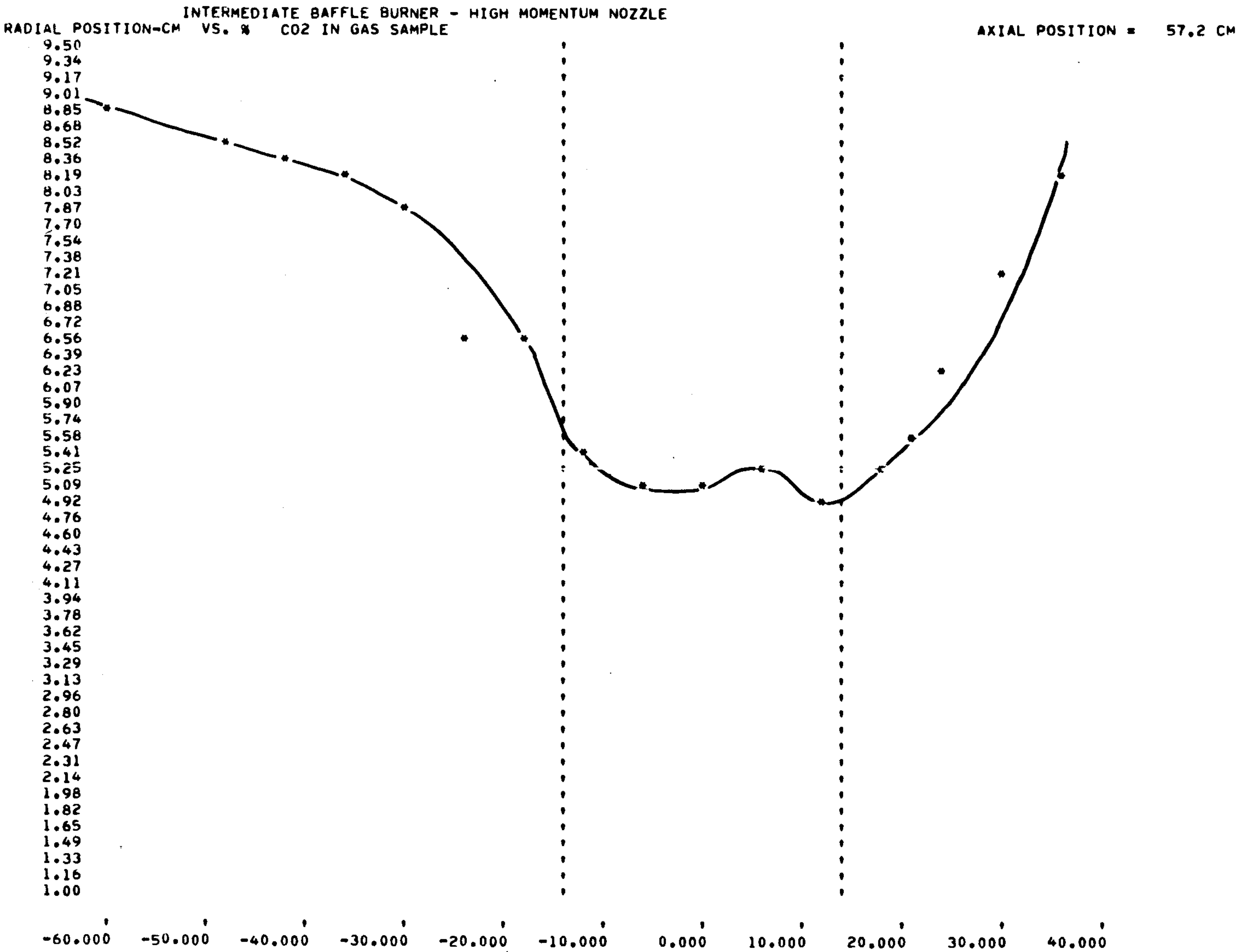

Figure 144. Radial profile of CO_2 at an axial position of 57.2 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

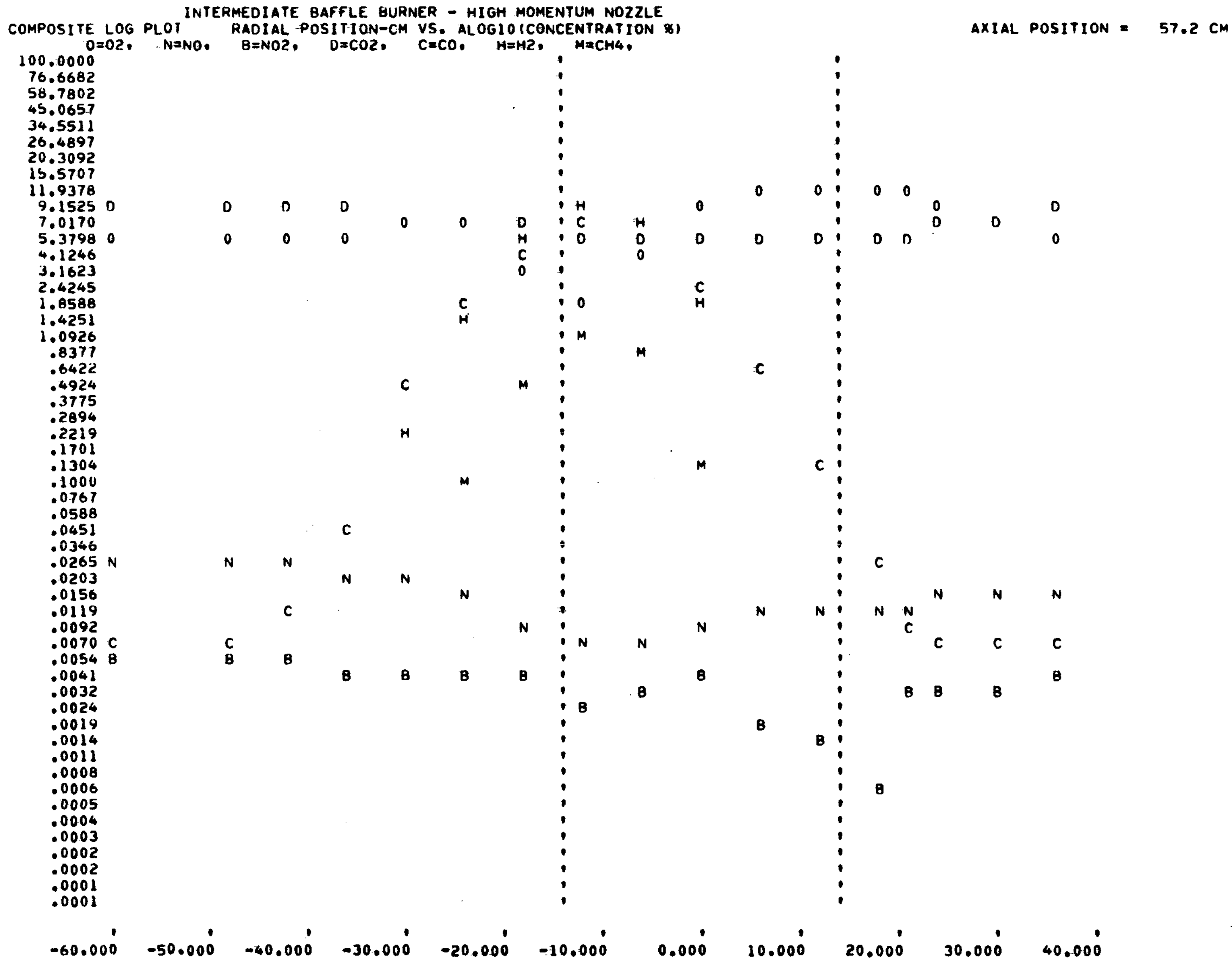

Figure 145. Radial profile of all the gases at an axial position of 57. 2 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

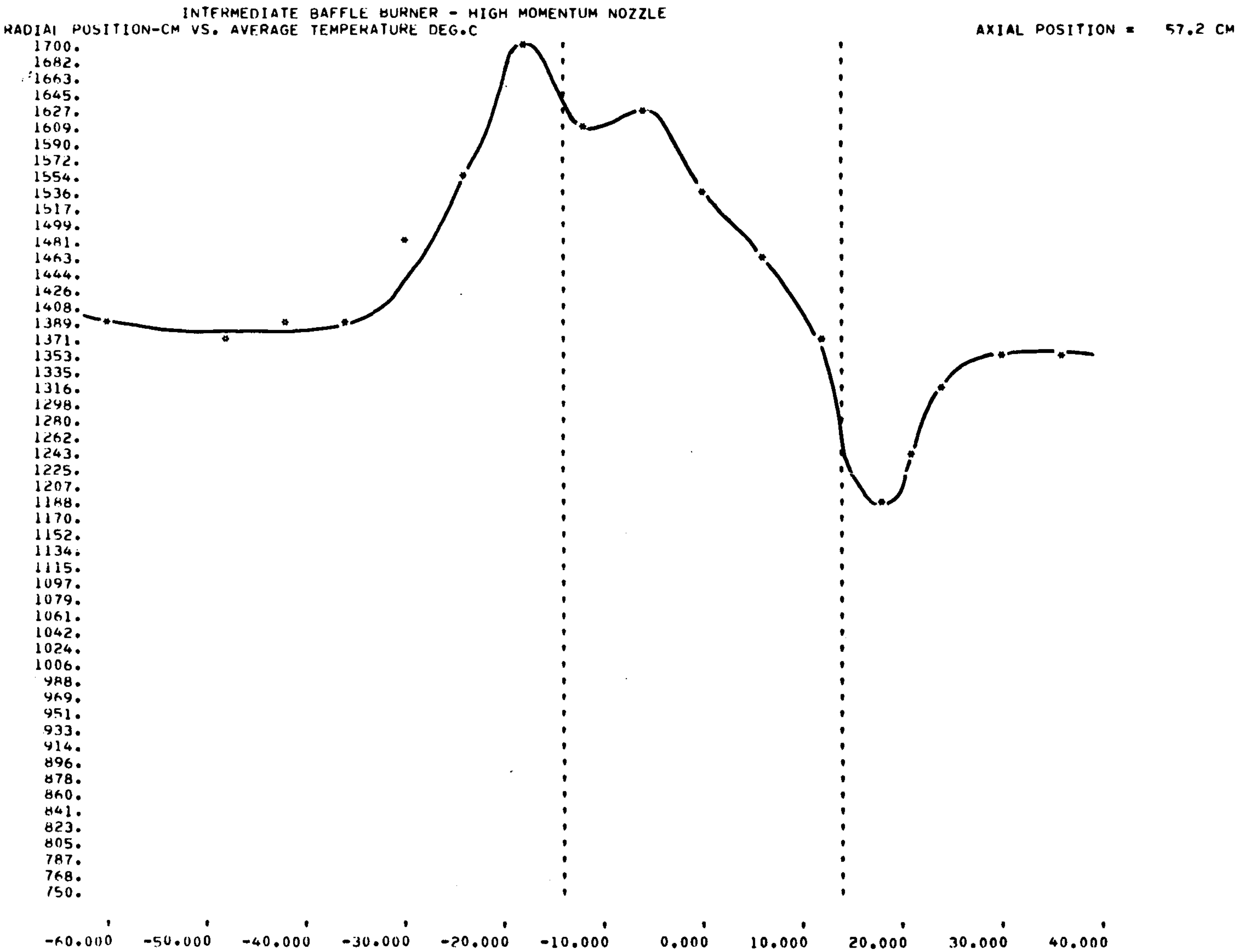

Figure 146. Radial profile of average temperature at an axial position of 57.2 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

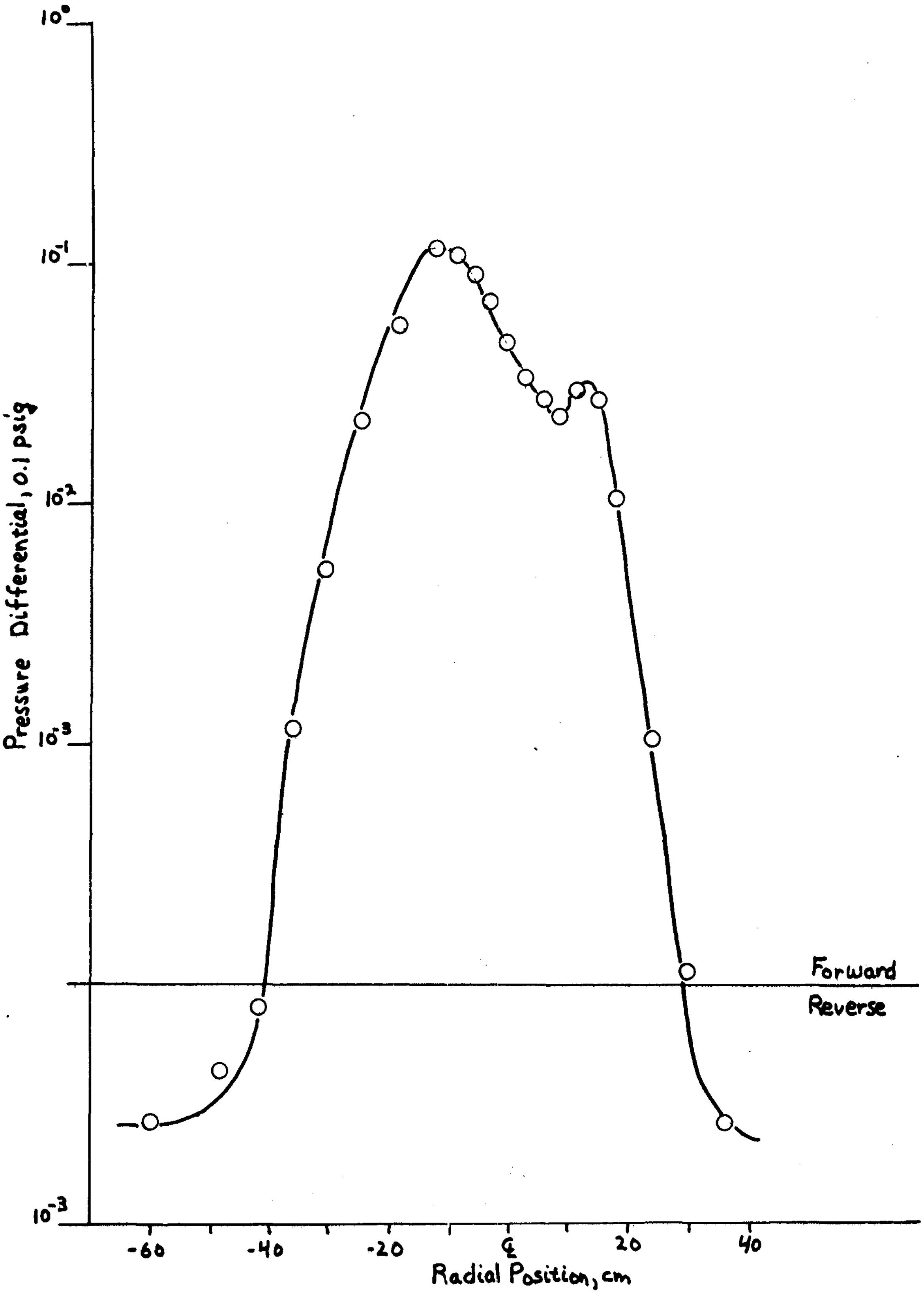

Figure 147. Radial profile of flow direction at an axial position of 57.2 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

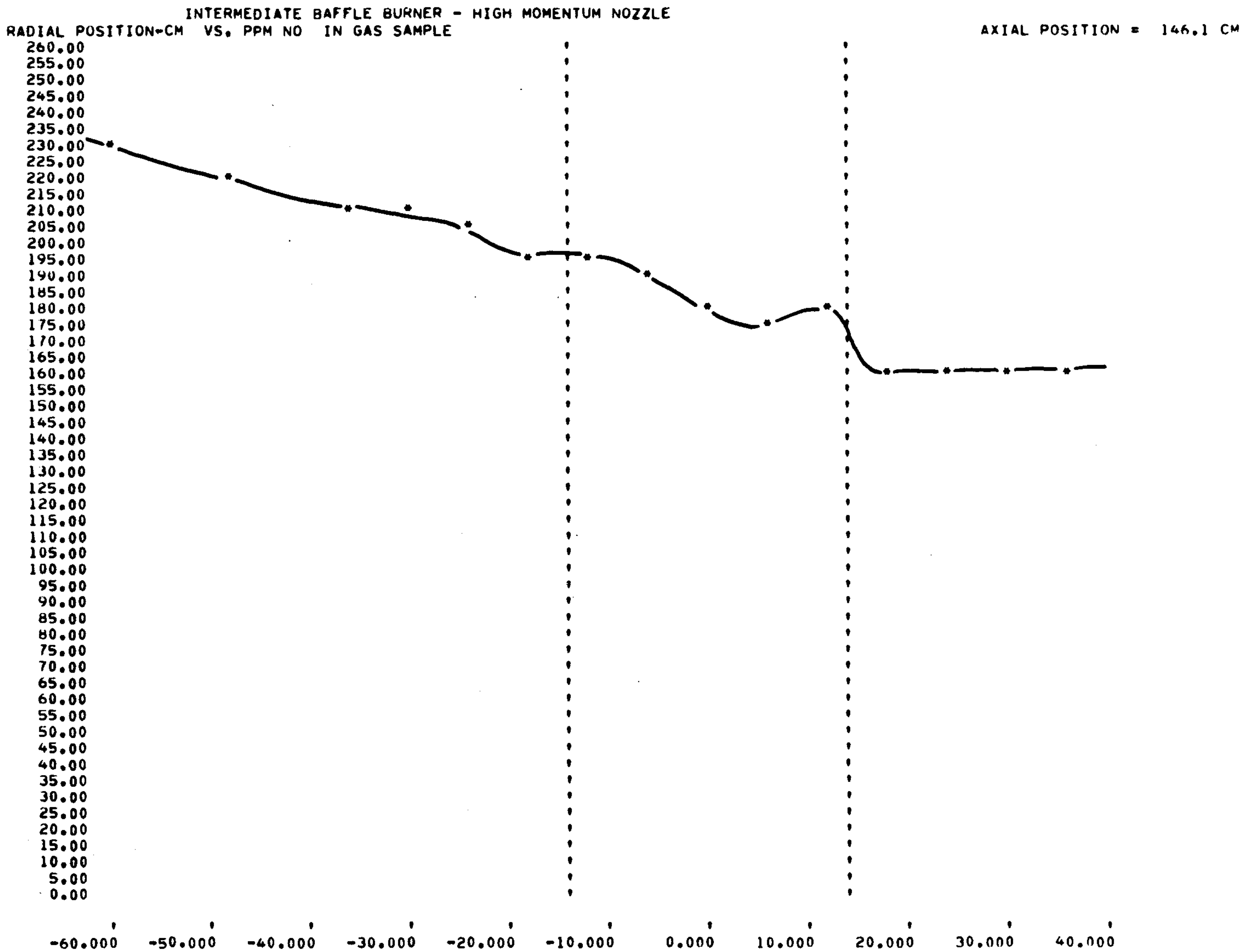

Figure 148. Radial profile of NO at an axial position of 146.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

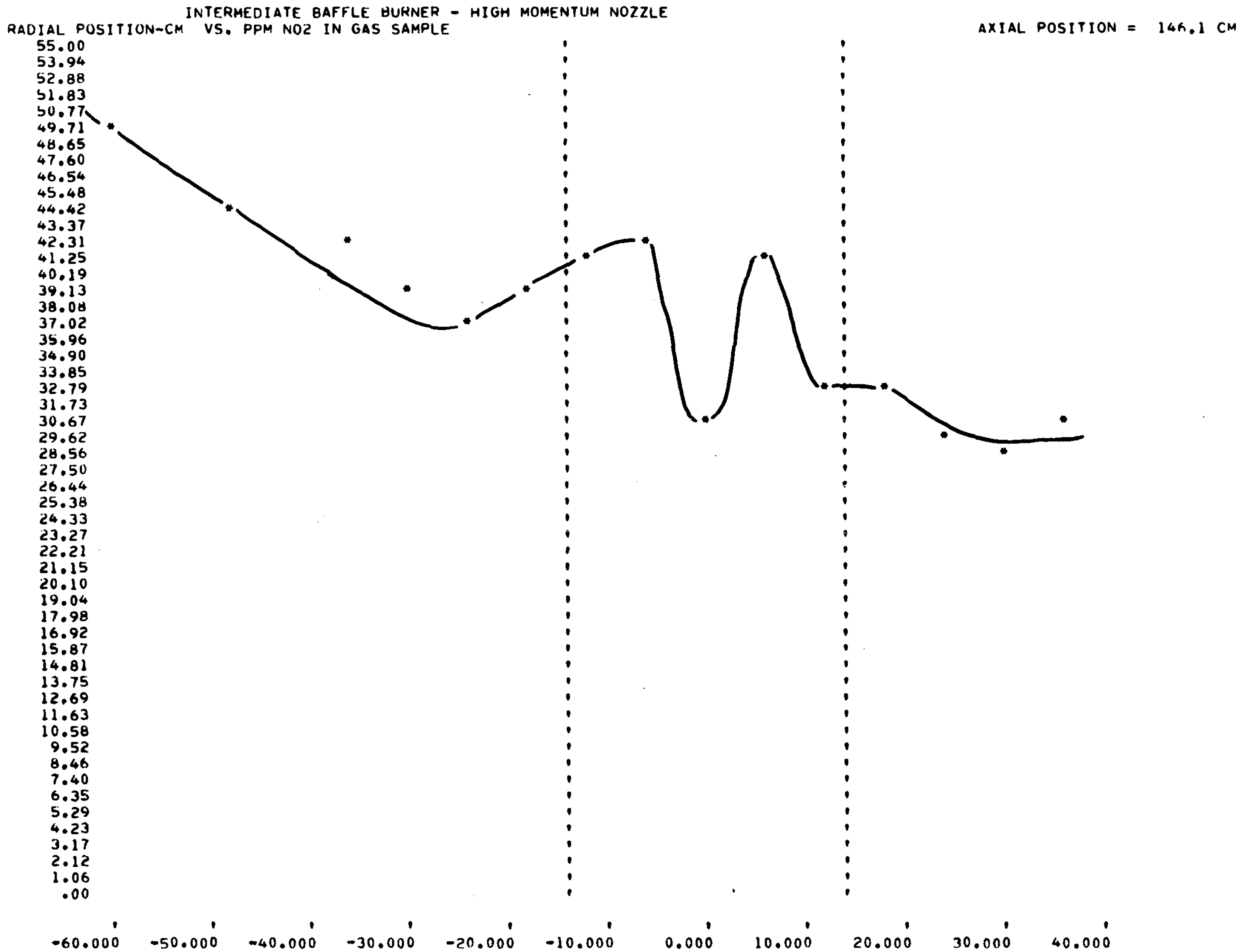

Figure 149. Radial profile of NO_2 at an axial position of 146.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

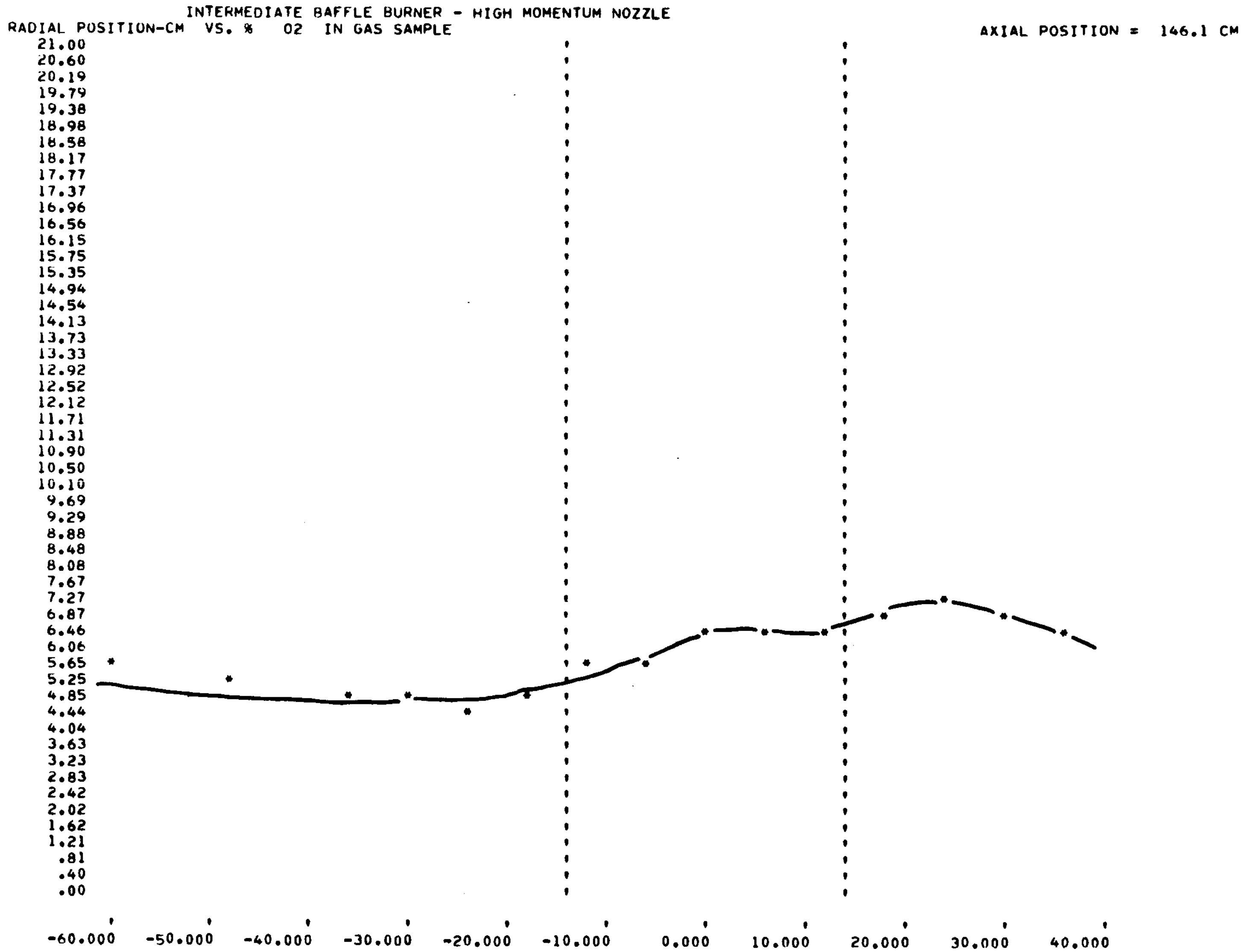

Figure 150. Radial profile of O_2 at an axial position of 146.1 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

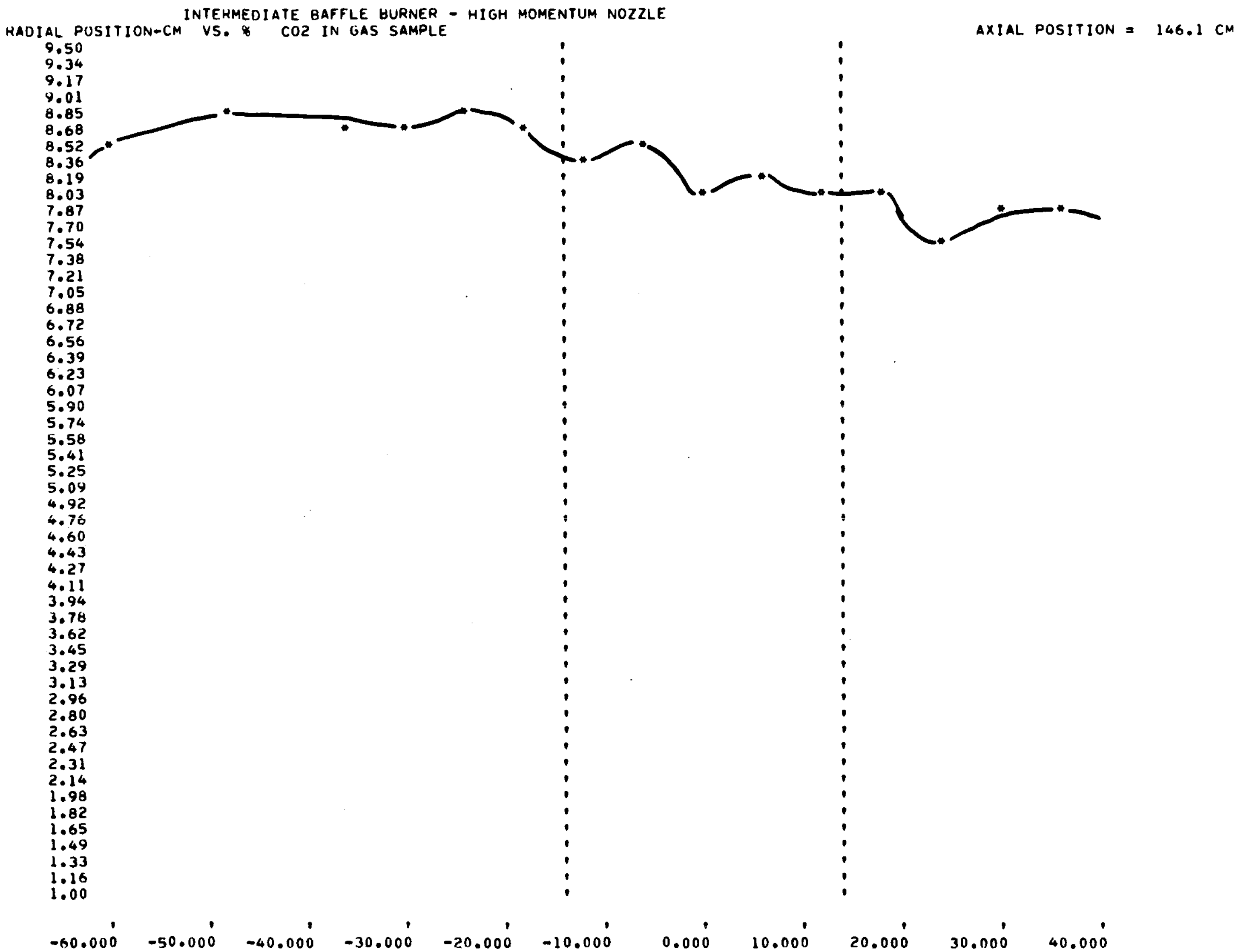

Figure 151. Radial profile of CO_2 at an axial position of 146.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

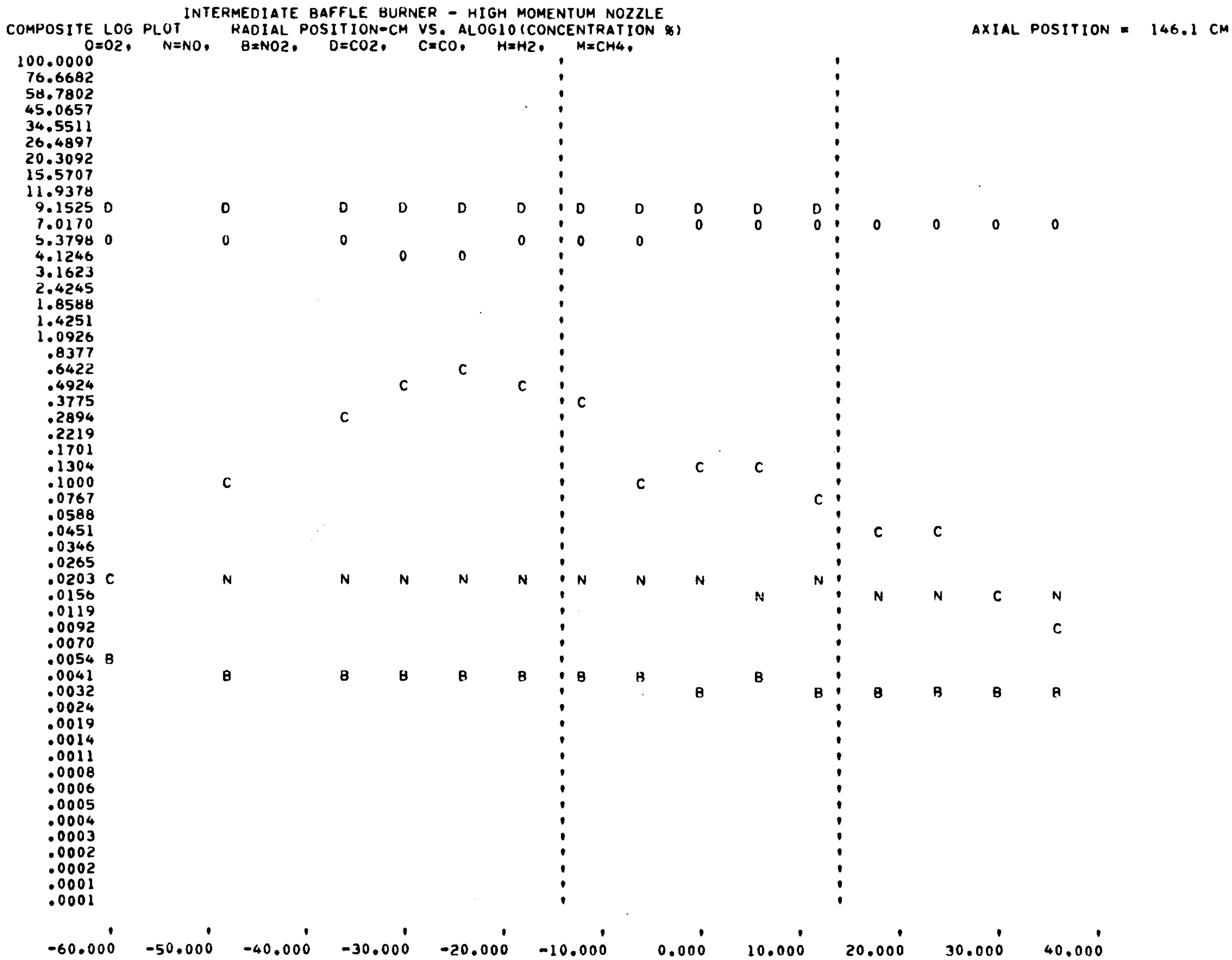

Figure 152. Radial profile of all the gases at an axial position of 146.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

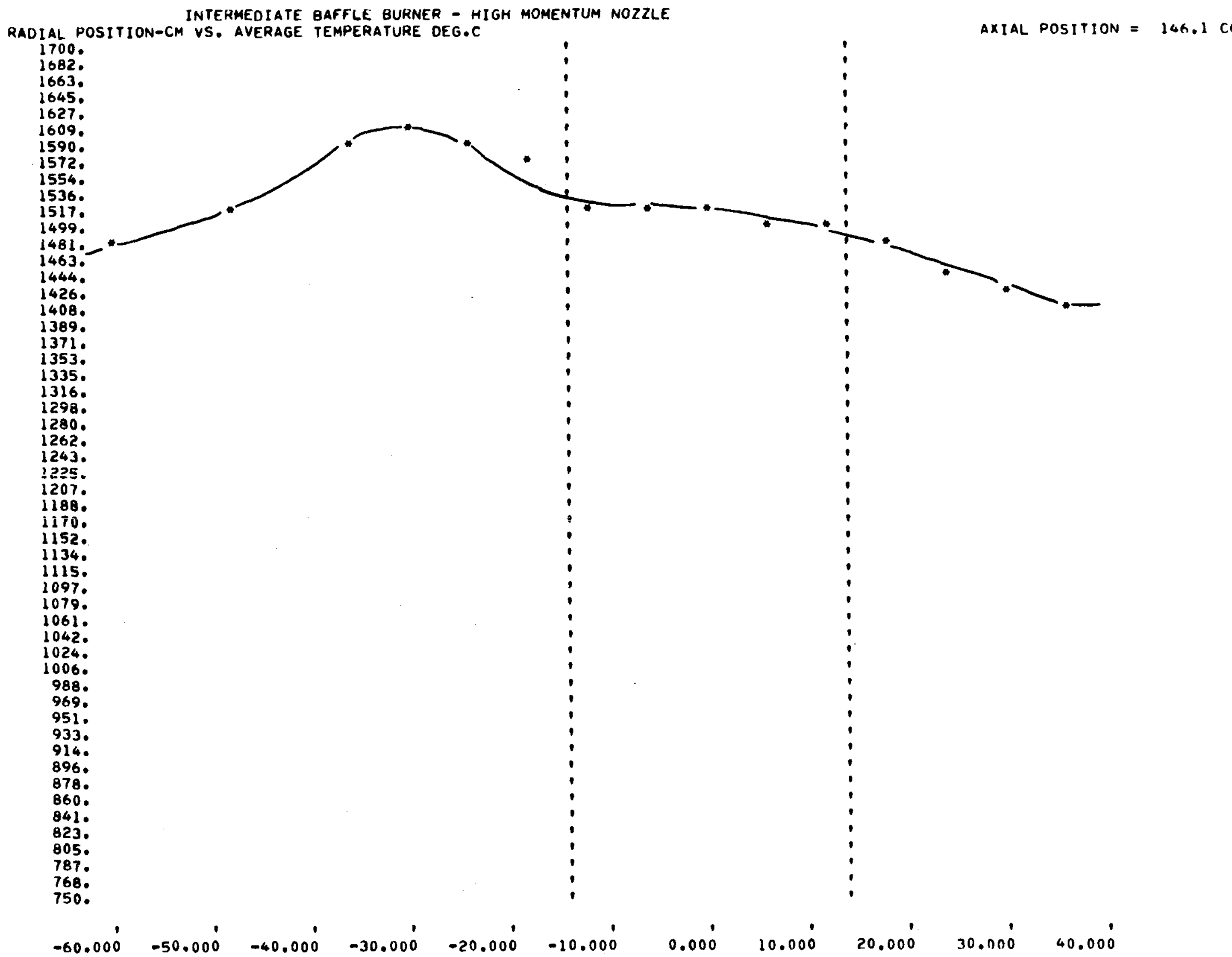

Figure 153. Radial profile of average temperature at an axial position of 146.1 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

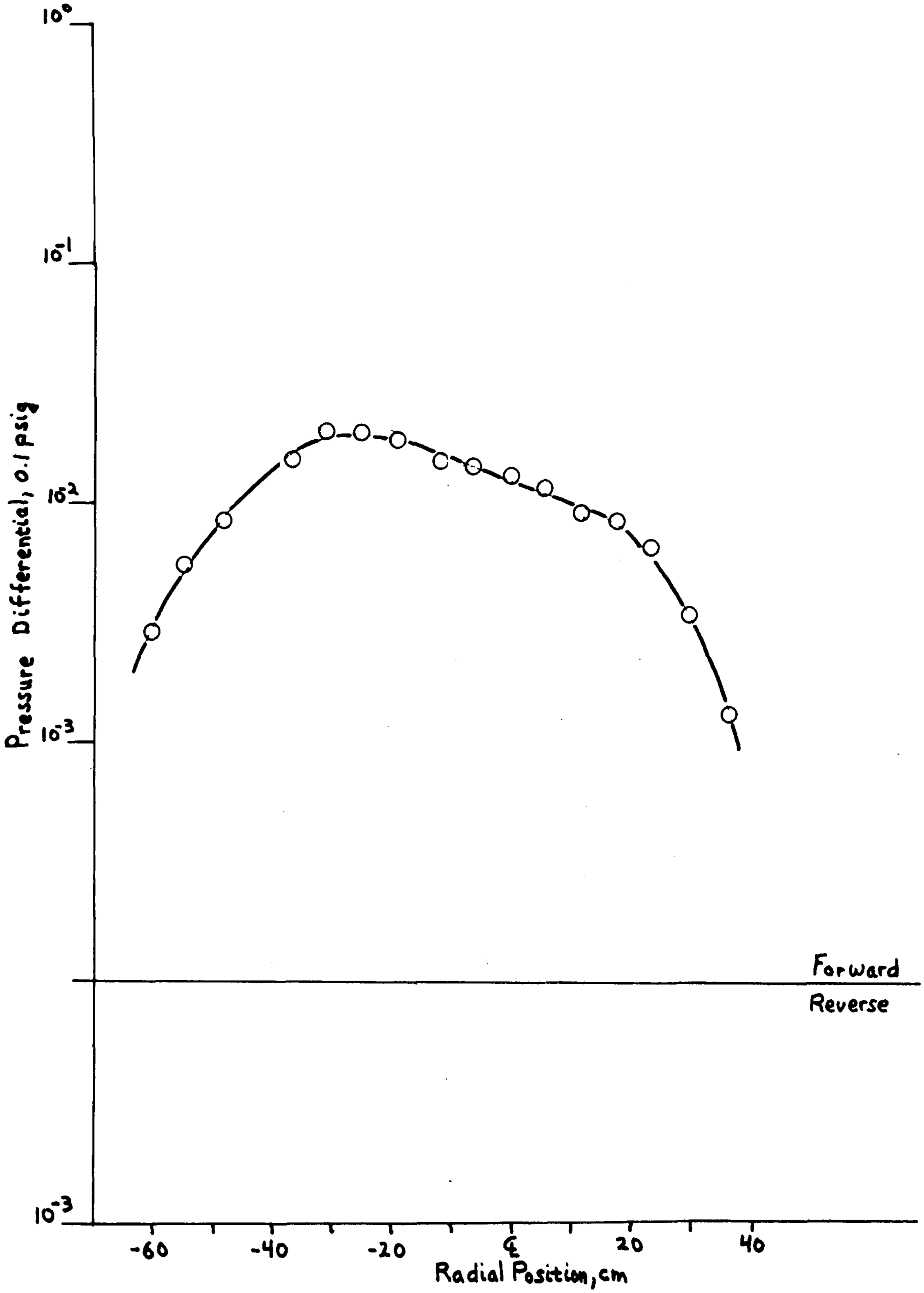

Figure 154. Radial profile of flow direction at an axial position of 146.1 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

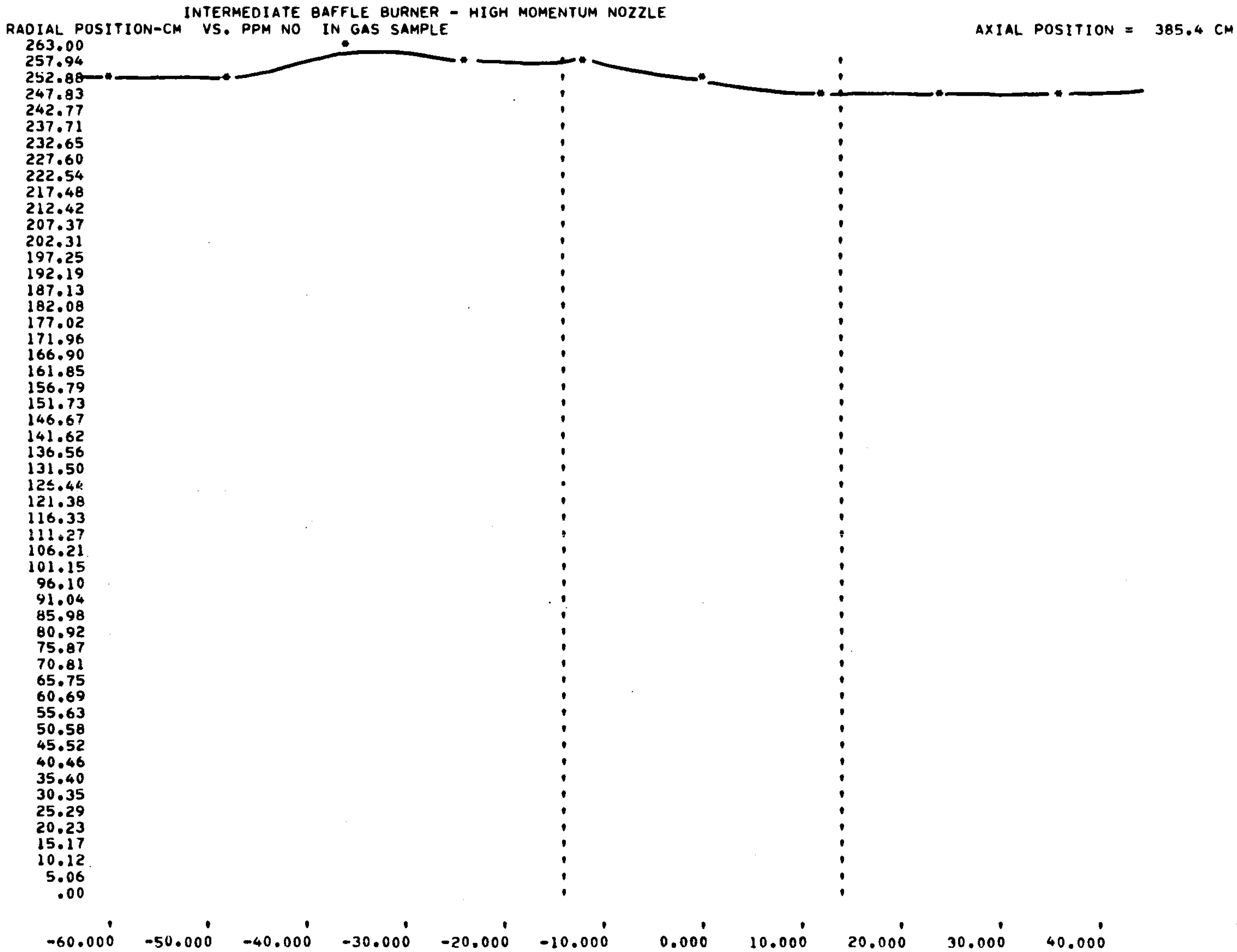

Figure 155. Radial profile of NO at an axial position of 385. 4 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

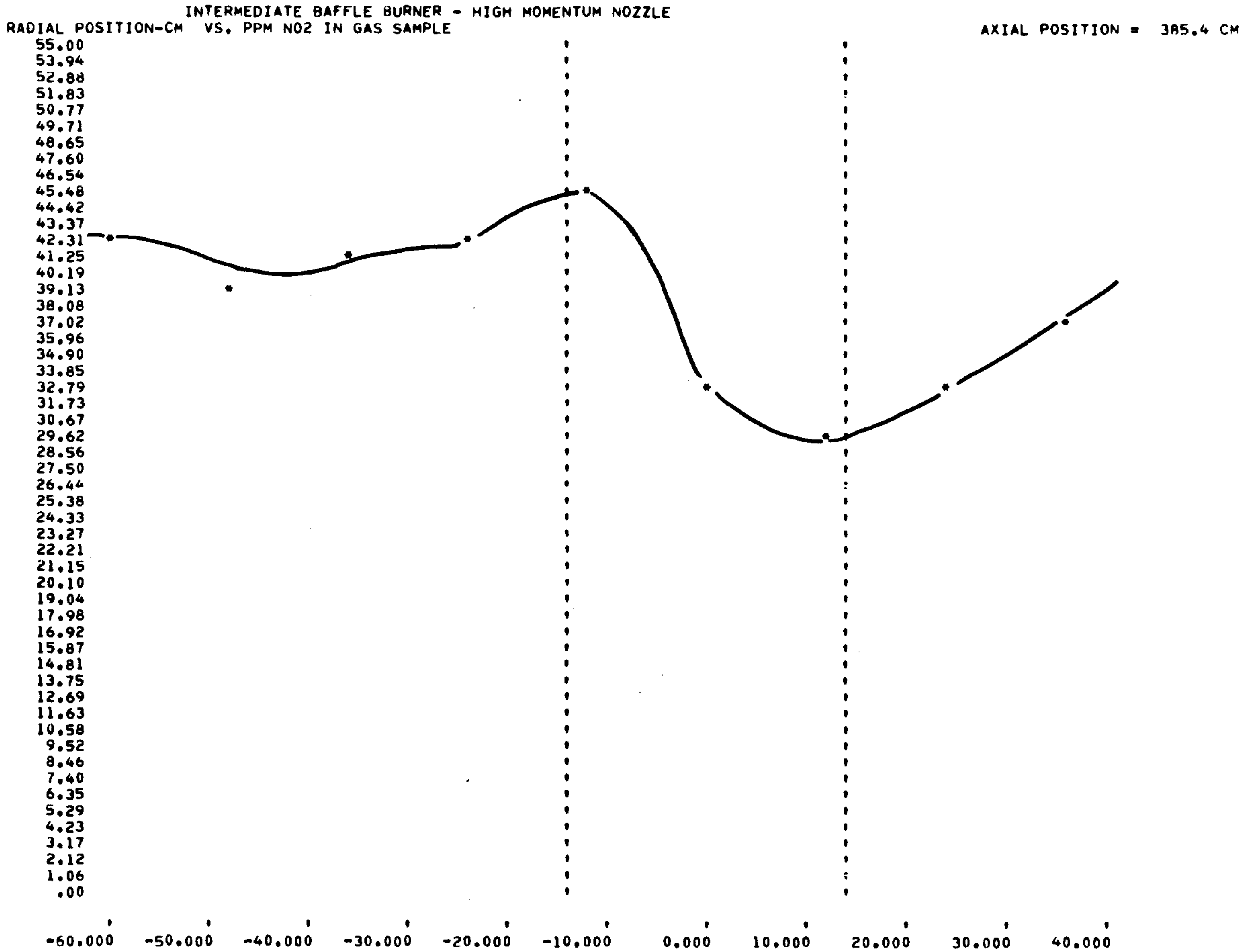

Figure 156. Radial profile of NO_2 at an axial position of 385. 4 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

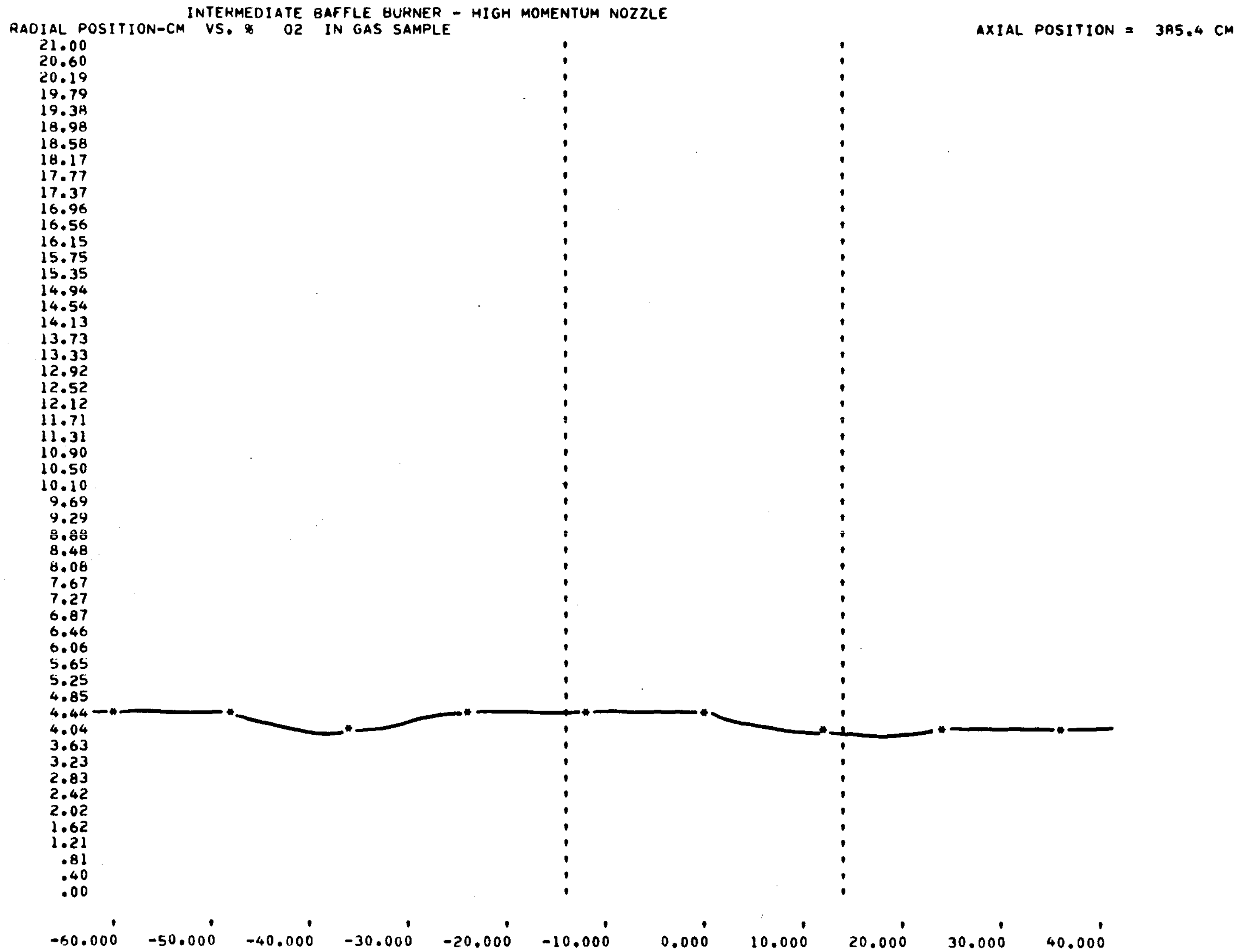

Figure 157. Radial profile of O_2 at an axial position of 385.4 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

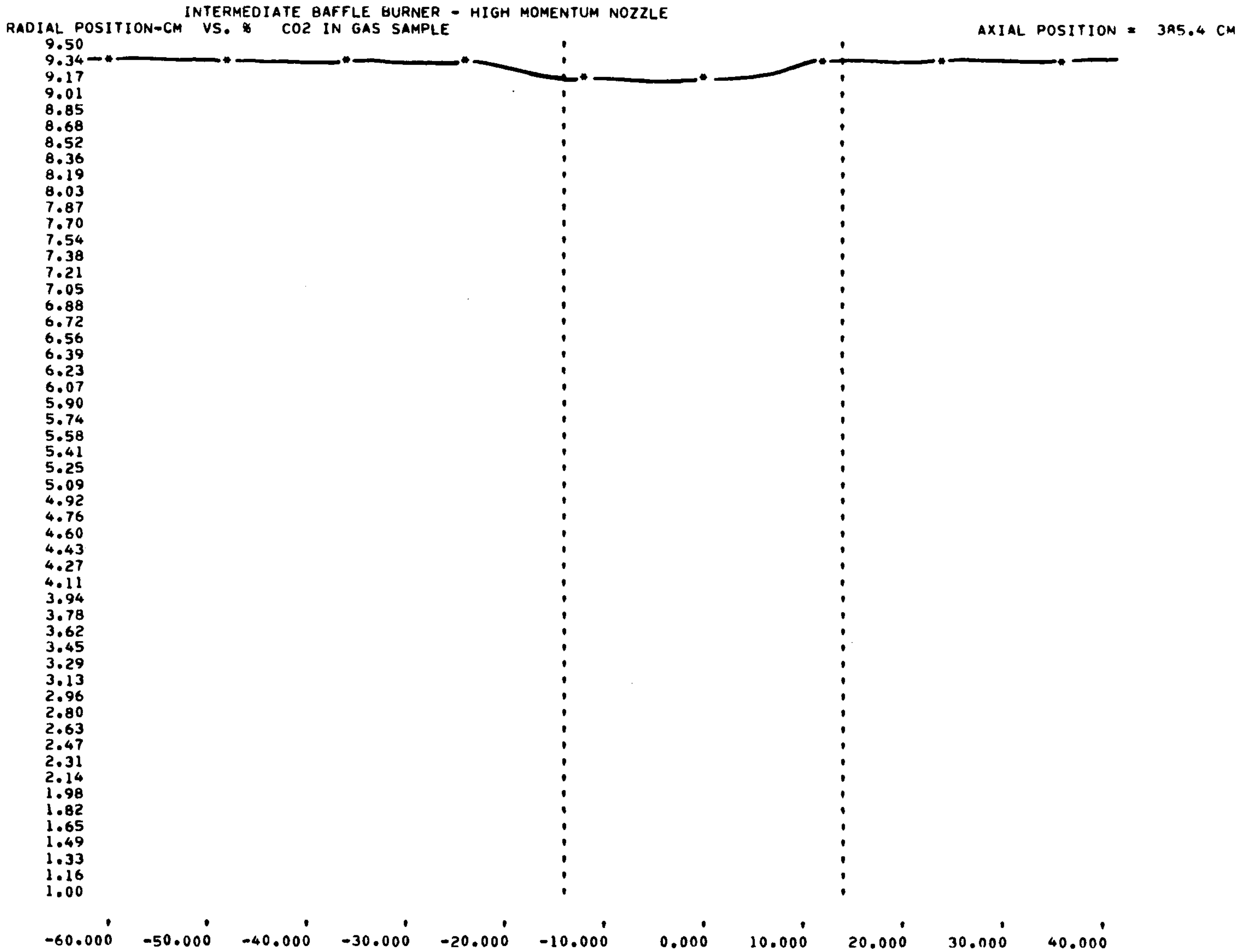

Figure 158. Radial profile of CO_2 at an axial position of 385.4 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

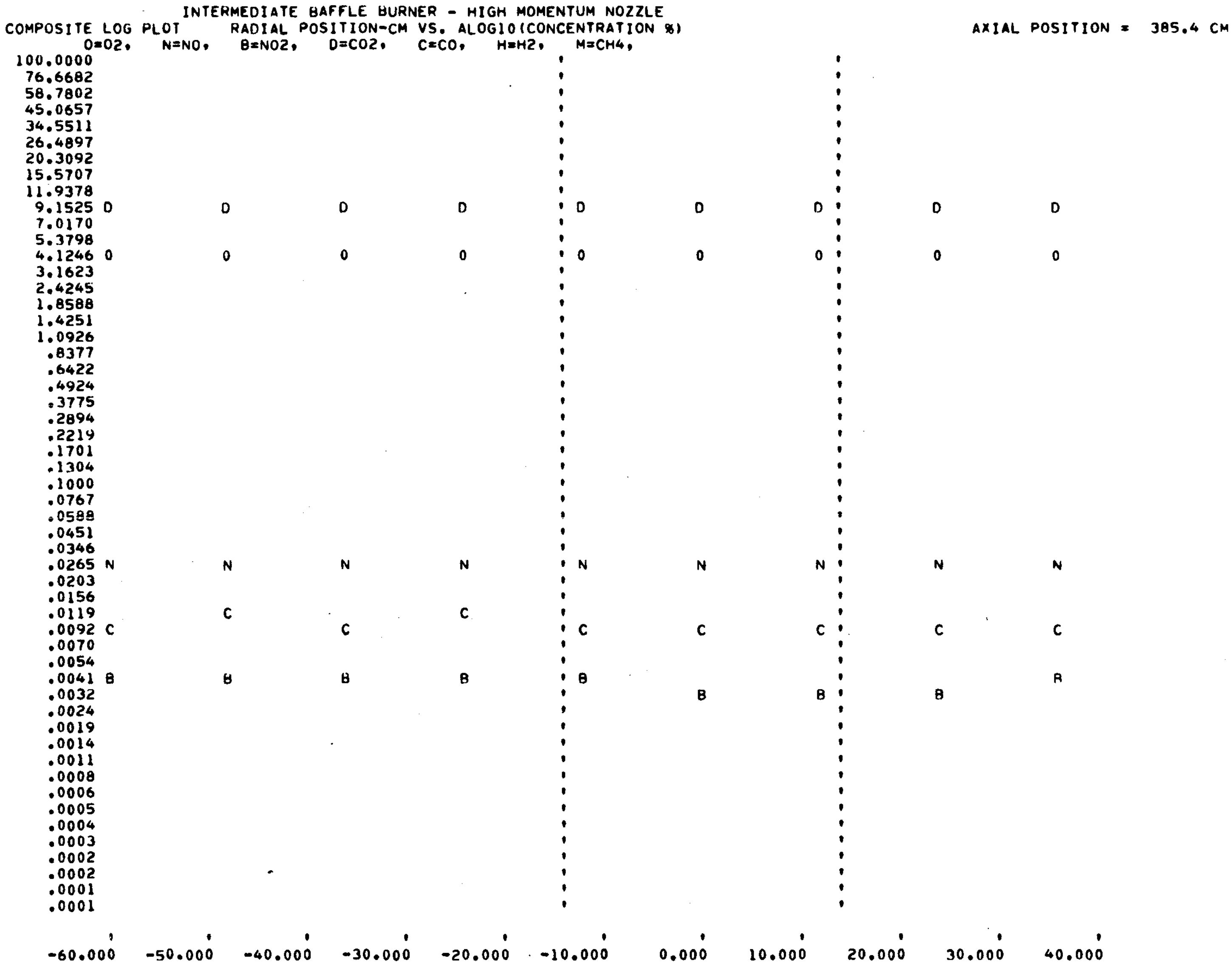

Figure 159. Radial profile of all the gases at an axial position of 385.4 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

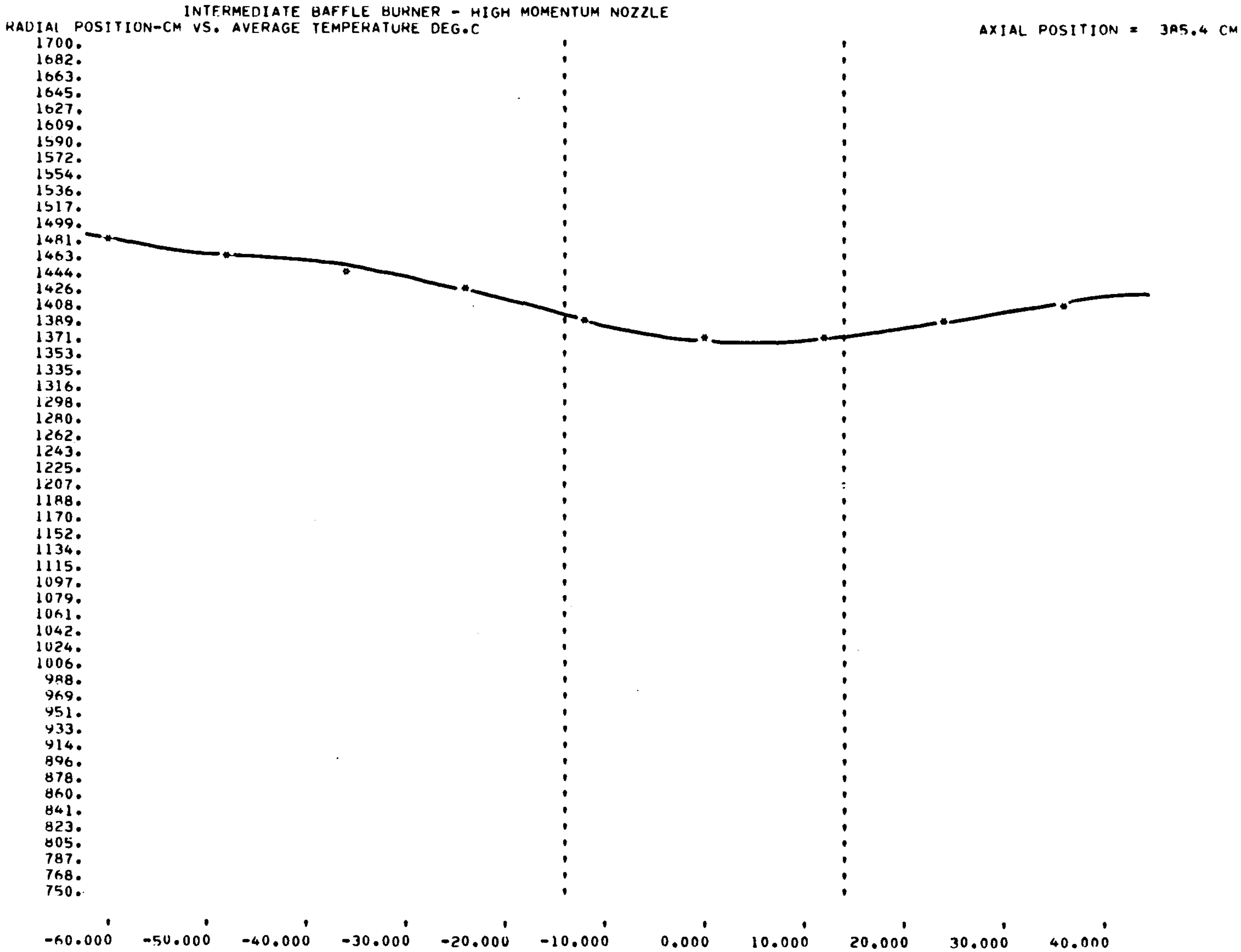

Figure 160. Radial profile of average temperature at an axial position of 385.4 cm (intermediate flame length baffle burner – high-momentum gas nozzle)

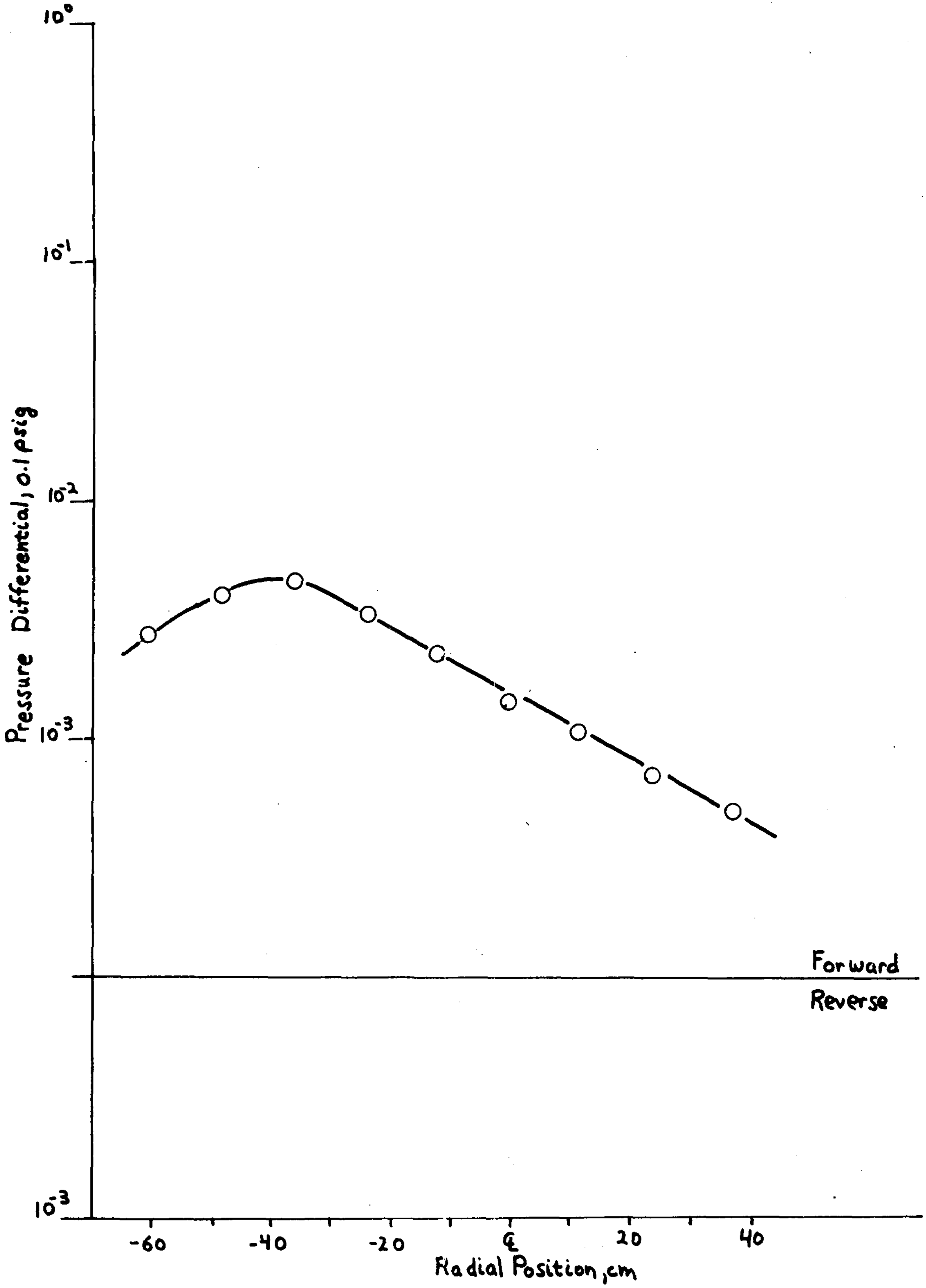

Figure 161. Radial profile of flow direction at an axial position of 385.4 cm (intermediate flame length baffle burner — high-momentum gas nozzle)

The curve of carbon dioxide versus radial position (Figure 128) shows a variation in the level of concentration from 1.3% to 1.1% in the central region of the secondary combustion air entrance zones (−12 cm and +15 cm, which correspond to the positions of maximum oxygen concentrations). Two peaks do occur within the burner-block area at −6 cm and +3 cm. Correlating the 5.1-cm axial position temperature profile (Figure 130) with the above chemical species and flow analysis reveals that a constant temperature of 1340°C exists in the region of recirculation (compared with a wall temperature of 1380°C). Minimum temperatures of 780°C and 767°C occur at −12 cm and 12 cm, respectively, which correspond to the regions of maximum oxygen concentration or the positions of peak secondary combustion air input. Inside the burner-block area, two peaks occur, at −6 cm and 3 cm, with values of 1506°C and 1482°C, respectively. These maximum temperatures correspond favorably with the positions of the stoichiometric fuel/air ratios. The largest discrepancy is to the right of the burner centerline, on the positive position side of the furnace. The temperature peak to this side of the burner may not be a narrow width profile, owing to a temperature difference of only 20°C between 3 cm and 6 cm. The reason that the region of combustion could be larger to the right of the burner centerline than to the left is that the combustion air on the right side is spinning (swirling) into the gas jet, while on the left side, it is spinning away. Thus, the increased turbulence could result in a broader region of combustion. These two temperature peaks enclosed a depression that reaches 1286°C on the centerline of the burner and corresponds to the position of maximum fuel concentration.

As was the case with the kiln burner at the burner-block exit, we measured larger concentrations of NO_2 than NO within the burner-block area. Although the peaks of temperature and CO_2 coincide (−6 cm and 3 cm) inside the burner block (which are the same positions as for the kiln burner), unlike the kiln burner, the NO_2 peaks do not coincide, but lie outside these positions at −9 cm and +6 cm. Both of these peaks occur at approximately full width half maximum of the oxygen peak. Thus, the conversion of NO to NO_2 through a reaction with either atomic oxygen or an oxygen radical is highly probable. Whether this reaction occurs within the combustion chamber or the probe is not clear. However, in all cases where we have observed this phenomenon, the fuel velocity has been greater than the air velocity. This may not be a necessary condition. When the fuel velocity is less than the air velocity (for the case we investigated), a large portion of the combustion occurred within the burner-block, and the conditions necessary for the NO-NO_2 conversion may have occurred within this region that we are not able to probe.

The data collected for the high-momentum gas nozzle baffle burner at a 26-cm axial position are listed in Table 24 and illustrated in Figures 132 through 139. The NO profile averages 19 ppm within the burner-block region. This is an average increase of only 6 ppm over the 5.1-cm axial position. The NO_2 profile still displays two maximums in the burner-block area at −12 cm and +3 cm, with concentrations of 51 ppm and 42 ppm, respectively. Three minimums occur at −20 cm, −4.5 cm, and +12 cm.

The curve for oxygen versus radial position shows maximums at 18 cm and 10 cm with respective concentrations of 10.5% and 16.5%. A minimum of 1.2% occurs at −6 cm.

The methane concentration has a maximum of 7.3% at 6 cm, with hydrogen having a 13.4% maximum at −6 cm, carbon monoxide a maximum of 7.3% at −3 cm, and acetylene-ethylene a 2% maximum at −3 cm. The stoichiometric fuel/air ratios occur at radial positions of −12.4 cm and 1.8 cm.

The temperature profile shows three minimums at −18 cm, −6 cm, and 12 cm. This correlates very well with the maximum air and fuel positions. The peak temperatures of 1606°C and 1643°C correspond to radial positions of −9 cm and 0 cm.

Data collected for the 57.2-cm axial position is tabulated in Table 25 and shown by Figures 140 through 147. The curves have become so asymmetrical that a detailed analysis is next to impossible. The flame is moving to the left side of the furnace. This is concluded from the flow-direction profile (Figure 147), and the stoichiometric fuel/air ratios which are positioned at −18.9 cm and −4.7 cm.

Figures 129, 137, 145, 152, and 159 show composite log plots of concentration versus radial position within the composition range of 0.0001% (1 ppm) to 100%. In these plots, the interrelationships between concentration variations of oxygen, nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, hydrogen, and methane can easily be visualized.

Figures 131, 139, 147, 154, and 161 show flow direction versus radial position. These profiles show the position of primary and secondary forward flow, of recirculation zones (reverse flow), and of sheared boundary layers.

Figures 130, 138, 146, 153, and 160 are plots of the average temperature measured versus radial position.

Data Correlation of Isoplots for Intermediate Flame Length Baffle Burner

Figures 162, 163, and 164 are isothermal and isoconcentration plots of the data presented earlier in this report for the intermediate flame length baffle burner operating under standard (recommended) conditions. Similar profiles are presented in Figures 165, 166, and 167 under pollution-control operating conditions.

A comparison of the isothermal plots (Figures 162 and 165) reveals that the standard nozzle produced a hotter flame than the high-momentum gas nozzle. The highest temperature isothermal line plotted is 1600°C. For the standard gas nozzle, this isotherm starts at the mouth of the burner block and extends down the furnace. The gases at the flue exit still are at a temperature above 1500°C.

For the high-momentum gas nozzle, the 1600°C isotherm does not begin until a 26-cm axial position is reaches. At the flue exit, the gases have cooled by 200°C, showing a final isotherm of 1400°C.

The graphs for NO isoconcentration versus radial position are presented in Figures 163 and 166. For both operating conditions the maximum isoconcentration curve occurs in the secondary recirculation zone by the burner wall.

The central region of the burner-block area enclosed by the first isoconcentration plot (labeled E), for both operating conditions, discloses the slower development of NO using a high-momentum gas nozzle. Under normal

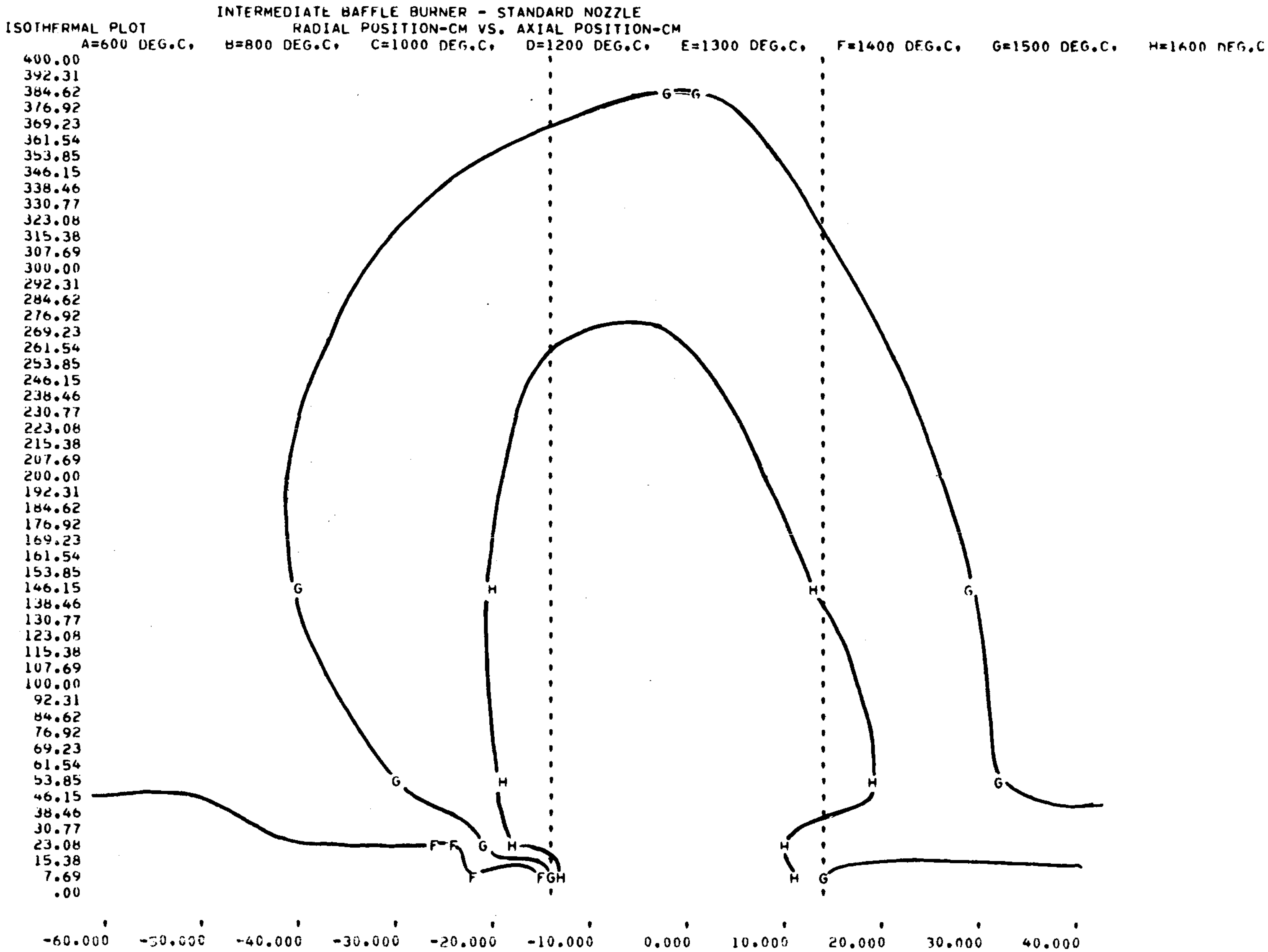

Figure 162. Isothermal plot of furnace temperature
(intermediate flame length baffle burner – standard gas nozzle)

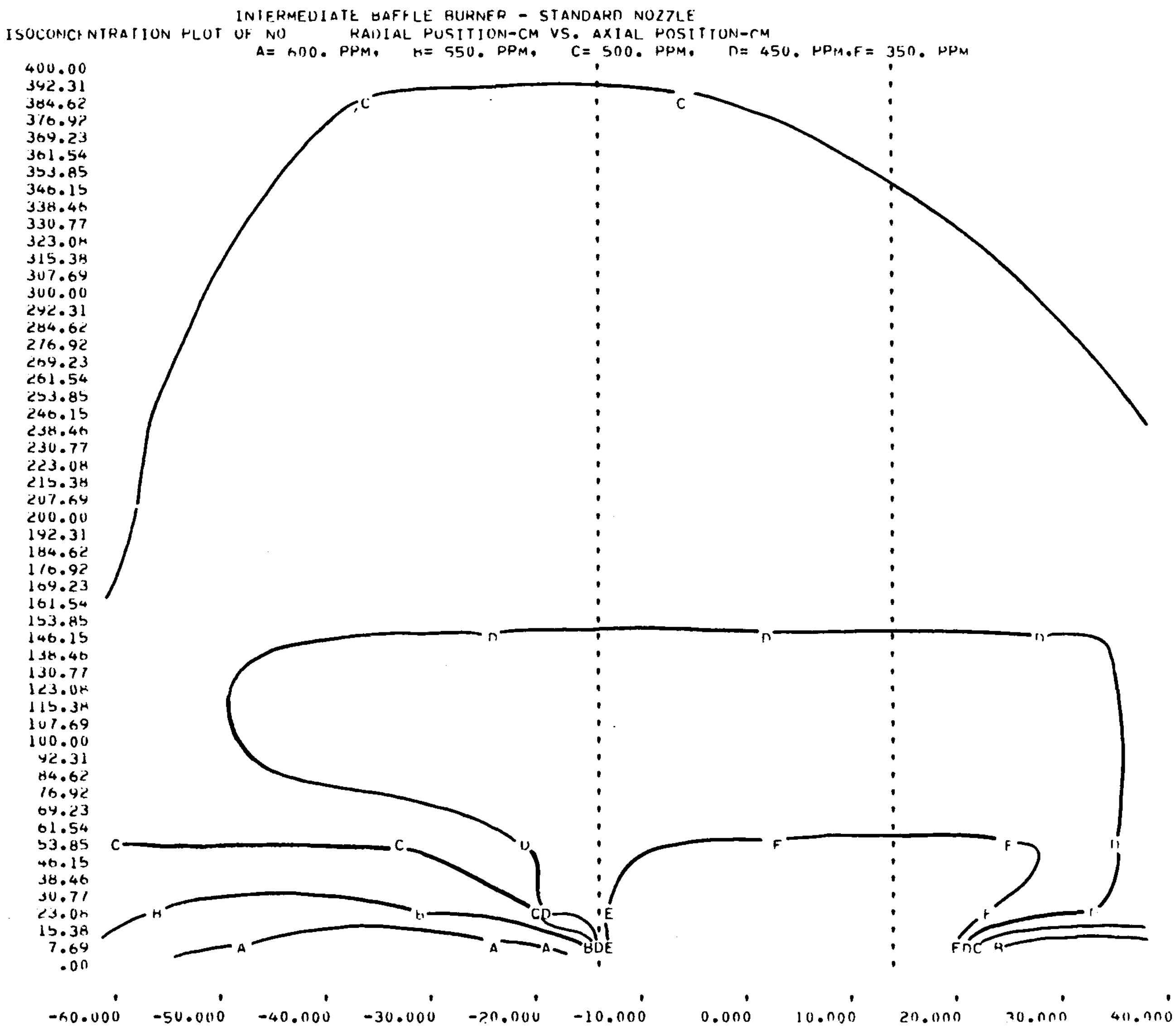

Figure 163. Isoconcentration plot of NO (intermediate flame length baffle burner — standard gas nozzle)

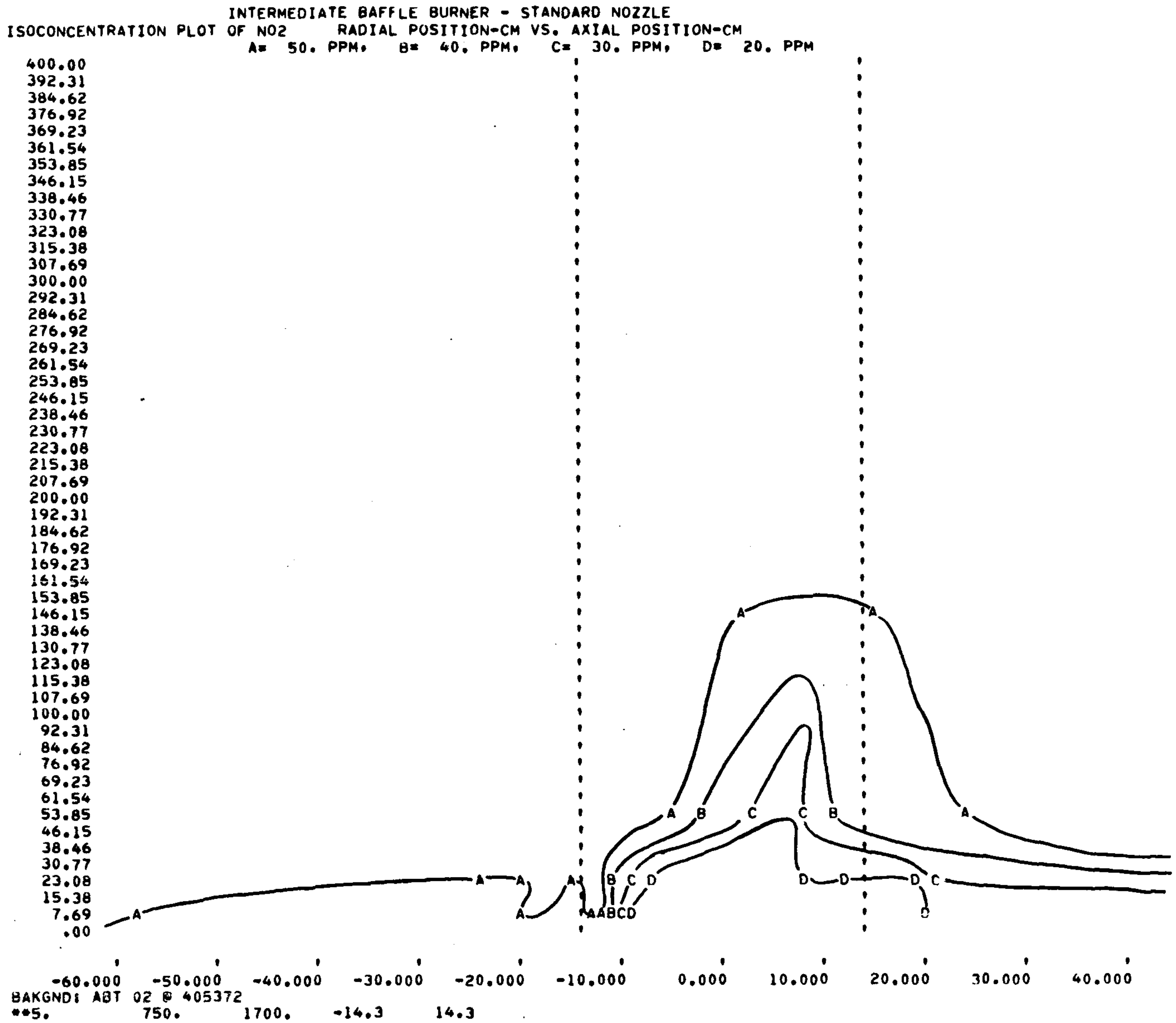

Figure 164. Isoconcentration plot of NO_2 (intermediate flame length baffle burner — standard gas nozzle)

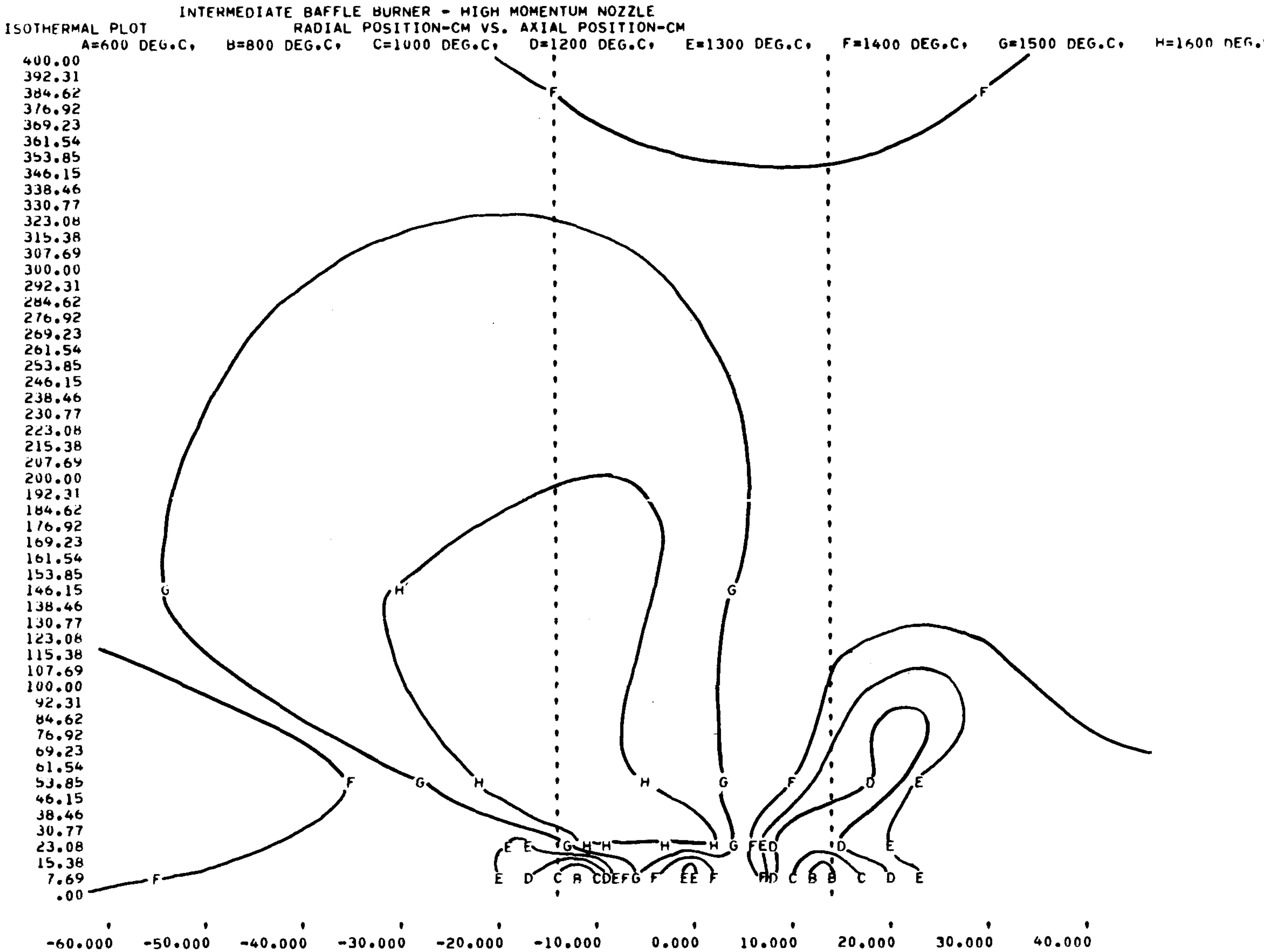

Figure 165. Isothermal plot of furnace temperature
(intermediate flame length baffle burner – high-momentum gas nozzle)

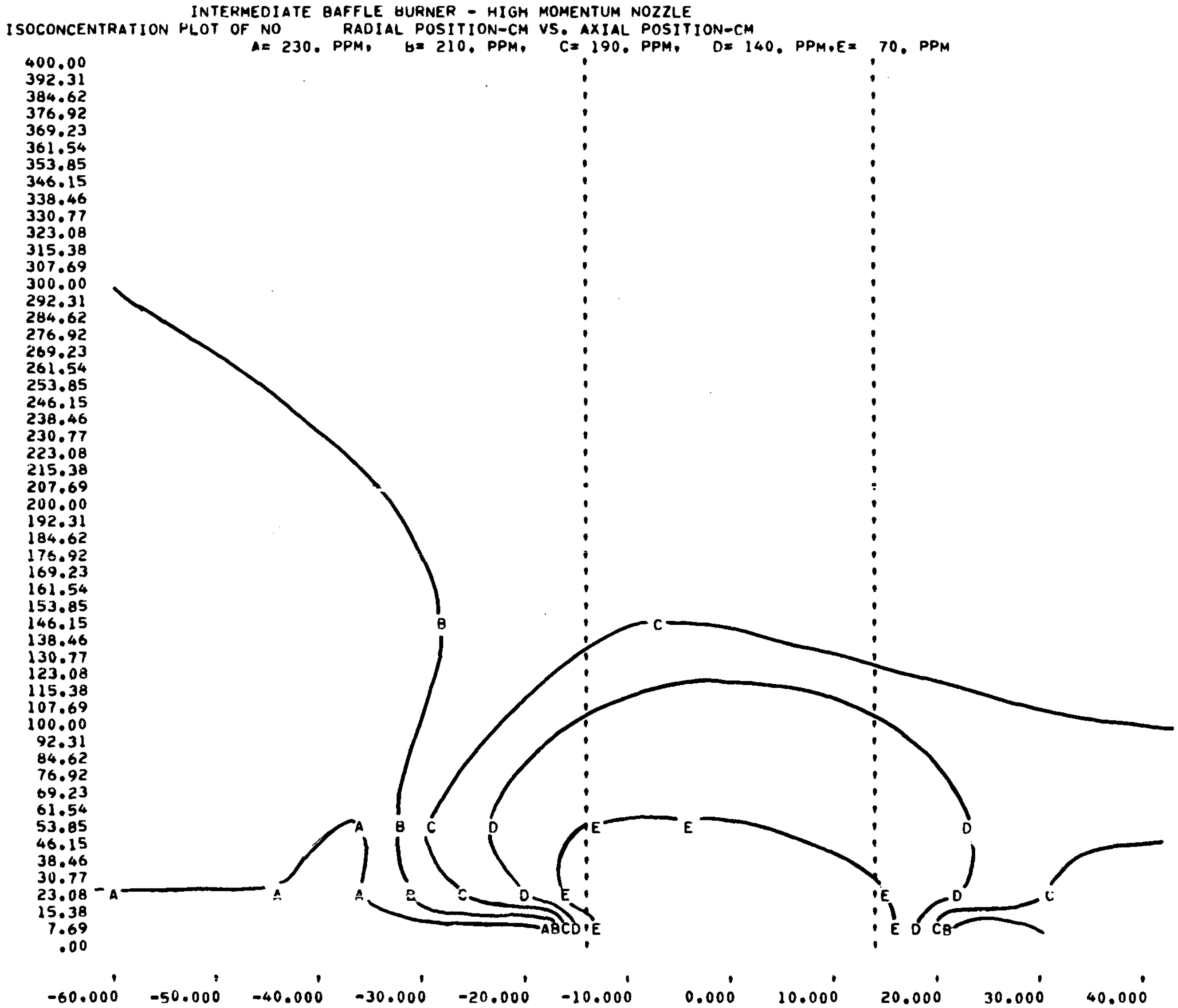

Figure 166. Isoconcentration plot of NO (intermediate flame length baffle burner – high-momentum gas nozzle)

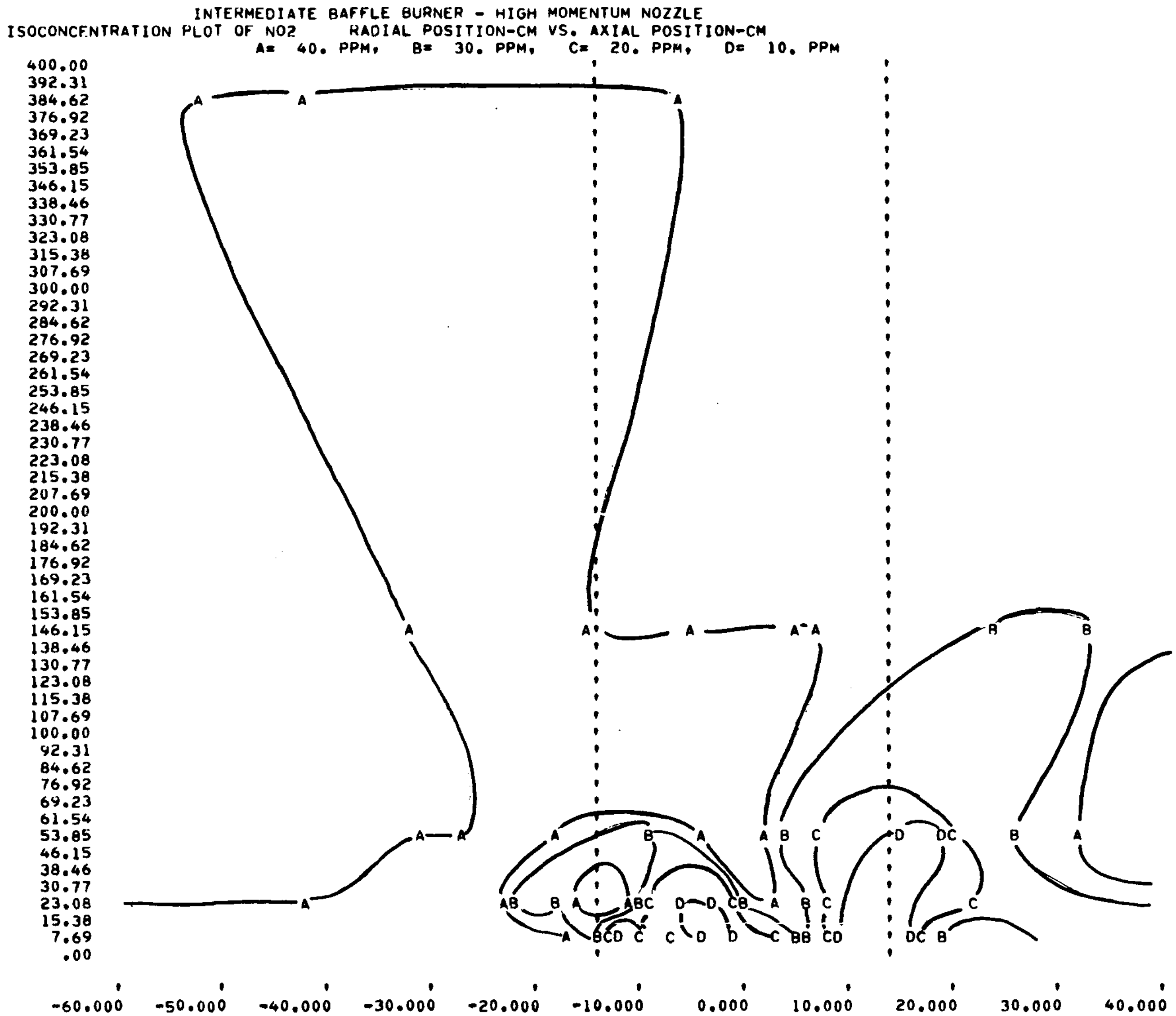

Figure 167. Isoconcentration plot of NO_2 (intermediate flame length baffle burner — high-momentum gas nozzle)

operating conditions, this curve represents 71% of the flue concentration, while under control conditions it represents only 28% of the flue NO.

Isoconcentrations profiles of NO_2 are plotted in Figures 164 and 167. These NO_2 profiles tend to follow the flow direction profiles when comparing the NO_2 isoconcentrations with pressure differentials. The flue value of NO is produced in a shorter furnace length for the standard gas nozzle than for the high-momentum nozzle.

MOVABLE VANE BOILER BURNER

In-the-flame data for the utility boiler burner was collected with the 60-degree gun fuel injector and a 30-degree quarl angle burner block. In-the-flame probings of two flames were made; base-line data were collected with the operating conditions of the burner identical to those used in older industrial boiler burners (60-degree fun nozzle, 30-degree burner-block angle, and 30-degree vane angle). Control-case data were collected from a flame in which the NO emission level had been reduced by a factor of one and three-quarters as a result of decreasing the movable-vane angle of the burner by 15 degrees. For the base-line operating conditions, the secondary air velocity was 41 ft/s (with an axial component of 32 ft/s and a 26 ft/s tangential component) compared with a control case secondary air velocity of 36 ft/s (having a 34 ft/s axial component and a 12 ft/s tangential component). The gas velocity at the nozzle in both cases was sonic. Because of wall radiation and flame transparency, it was not possible to determine flame length.

Each operating condition exhibited a distinctive directional flow profile. The base-line conditions gave rise to a Type III flow profile, while the control conditions displayed a Type II profile.

Table 28 lists the furnace conditions at which the base-line, in-the-flame data were collected. The data obtained for an axial sampling position of 5.1 cm are listed in Table 29 and are plotted in Figures 168 through 175. Table 30 lists the results of radial sampling at an axial position of 26 cm. Figures 176 through 182 show plots of the data. The radial profile data at axial positions of 46.7 cm, 146.1 cm, and 385.4 cm are presented in Tables 31 through 33 and Figures 183 through 203.

Table 28. FURNACE CONDITIONS FOR IN-THE-FLAME SAMPLING
(Movable-Vane Boiler Burner; 30-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 30 DEGREE VANE ANGLE

NUMBER OF SETS OF DATA = 5.
MINIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1200. DEG.C
MAXIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1800. DEG.C

POSITION OF OUTSIDE EDGES OF BURNER BLOCK
MINIMUM POSITION = -25. CM
MAXIMUM POSITION = 25. CM

GAS INPUT, AXIAL 0. CF/HR RADIAL 2982. CF/HR
WALL TEMPERATURE 1387. DEG.C
PREHEAT TEMPERATURE 455. DEG.C
FLUE GAS RECIRCULATION 0.0 %

GAS SAMPLE ANALYSIS IN THE FLUE

NITROGEN OXIDE	340.0 PPM
NITROGEN DIOXIDE	57.0 PPM
OXYGEN	2.6 %
CARBON DIOXIDE	10.3 %
CARBON MONOXIDE	.0054 %

LIMITS FOR CONCENTRATION PLOTS

LOWER LIMIT OF NO =	70. PPM	UPPER LIMIT =	400. PPM
LOWER LIMIT OF NO2 =	5. PPM	UPPER LIMIT =	60. PPM
LOWER LIMIT OF O2 =	0. %	UPPER LIMIT =	21. %
LOWER LIMIT OF CH4 =	0. %	UPPER LIMIT =	1. %
LOWER LIMIT OF CO2 =	0. %	UPPER LIMIT =	12. %

ISOCONCENTRATION VALUES

OBTAIN VALUE OF RADIAL POSITION AT NO PPM CONCENTRATION	300.	250.	200.	150.	100.
OBTAIN VALUE OF RADIAL POSITION AT NO2 PPM CONCENTRATION	50.	40.	30.	20.	

Table 29. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 5.1 cm
(Movable-Vane Boiler Burner; 30-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 30 DEGREE VANF ANGLE

AXIAL POSITION = 5.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	2.1	?	357.	60.	10.7	.0097	?	0.0	?	?	?	?	1450.	1450.	0.
-48.	2.1	?	355.	54.	10.7	.0089	?	0.0	?	?	?	?	1458.	1458.	0.
-36.	2.1	?	345.	49.	10.7	.0086	?	0.0	?	?	?	?	1453.	1453.	0.
-24.	1.9	80.8	196.	25.	7.6	4.8000	1.3	.2	.1	0.0	0.0	0.0	1709.	1709.	0.
-21.	3.4	81.3	207.	28.	8.0	3.6000	2.4	0.0	0.0	0.0	0.0	0.0	1796.	1796.	0.
-18.	2.9	80.9	215.	35.	8.8	3.0000	3.7	0.0	0.0	0.0	0.0	0.0	1700.	1700.	0.
-15.	1.4	80.1	217.	36.	8.4	4.9000	4.2	0.0	0.0	0.0	0.0	0.0	1678.	1678.	0.
-12.	1.0	79.1	225.	37.	7.9	5.1000	6.2	0.0	0.0	0.0	0.0	0.0	1655.	1655.	0.
-6.	.6	77.2	192.	43.	7.1	1.0000	4.6	.1	0.0	0.0	0.0	0.0	1642.	1642.	0.
0.	1.2	80.4	187.	47.	7.6	5.9000	4.1	0.0	0.0	0.0	0.0	0.0	1667.	1667.	0.
6.	6.3	82.5	144.	52.	7.1	2.3000	1.3	0.0	0.0	0.0	0.0	0.0	1645.	1645.	0.
12.	13.3	80.7	80.	35.	4.7	.4000	0.0	0.0	0.0	0.0	0.0	0.0	1533.	1533.	0.
15.	13.5	80.8	78.	33.	4.7	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1456.	1456.	0.
18.	13.7	80.1	75.	31.	4.6	0.0000	0.0	0.0	0.0	0.0	0.0	0.0	1378.	1378.	0.
21.	8.4	80.6	89.	34.	6.8	2.1000	1.2	0.0	0.0	0.0	0.0	0.0	1350.	1350.	0.
24.	2.3	81.8	100.	37.	7.6	4.4000	2.8	.1	0.0	0.0	0.0	0.0	1364.	1364.	0.
36.	1.4	86.4	250.	45.	11.2	.1000	0.0	0.0	0.0	0.0	0.0	0.0	1563.	1563.	0.
48.	1.9	?	285.	52.	10.8	.0157	?	0.0	?	?	?	?	1520.	1520.	0.
60.	2.1	?	324.	53.	10.7	.0140	?	0.0	?	?	?	?	1452.	1452.	0.

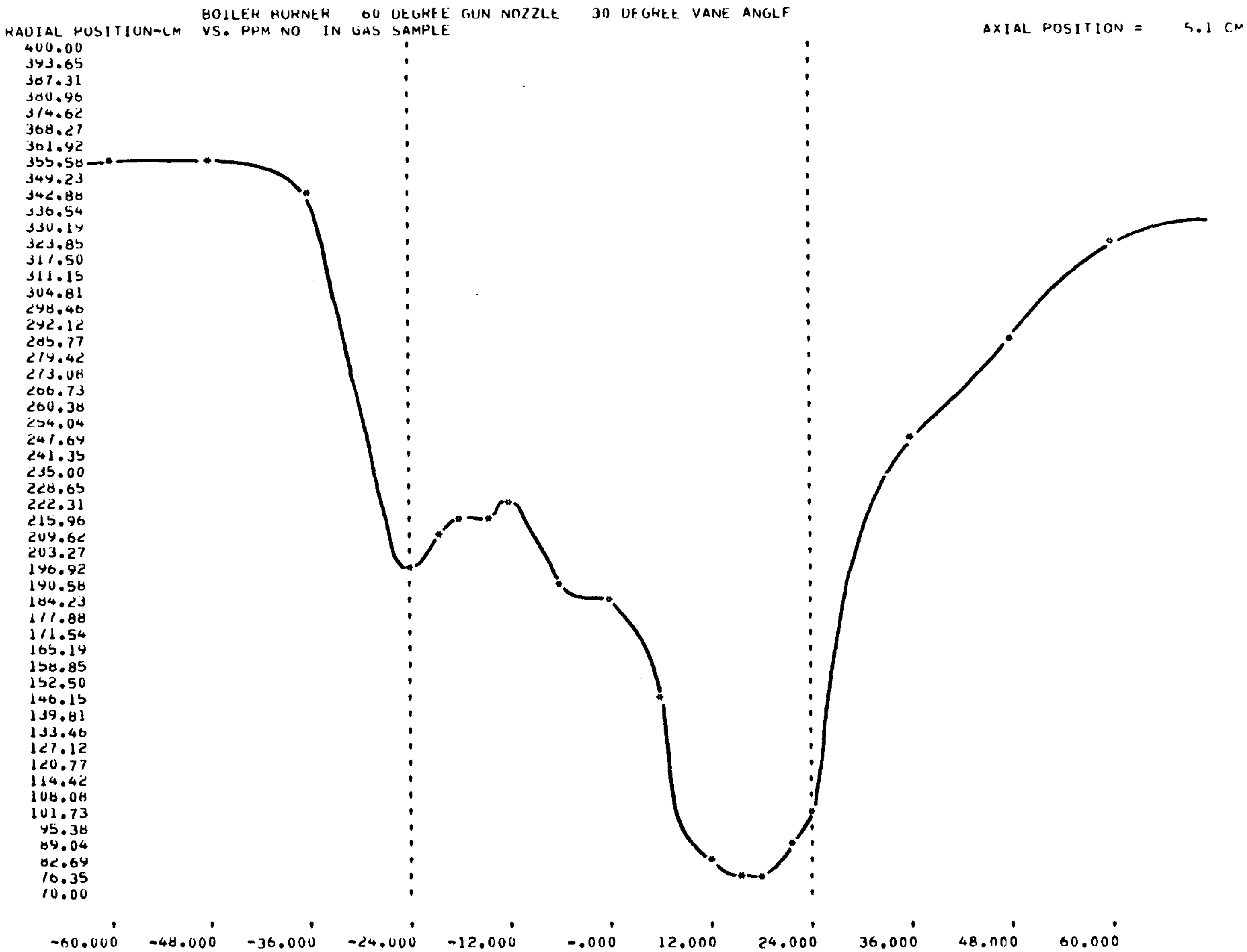

Figure 168. Radial profile of NO at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

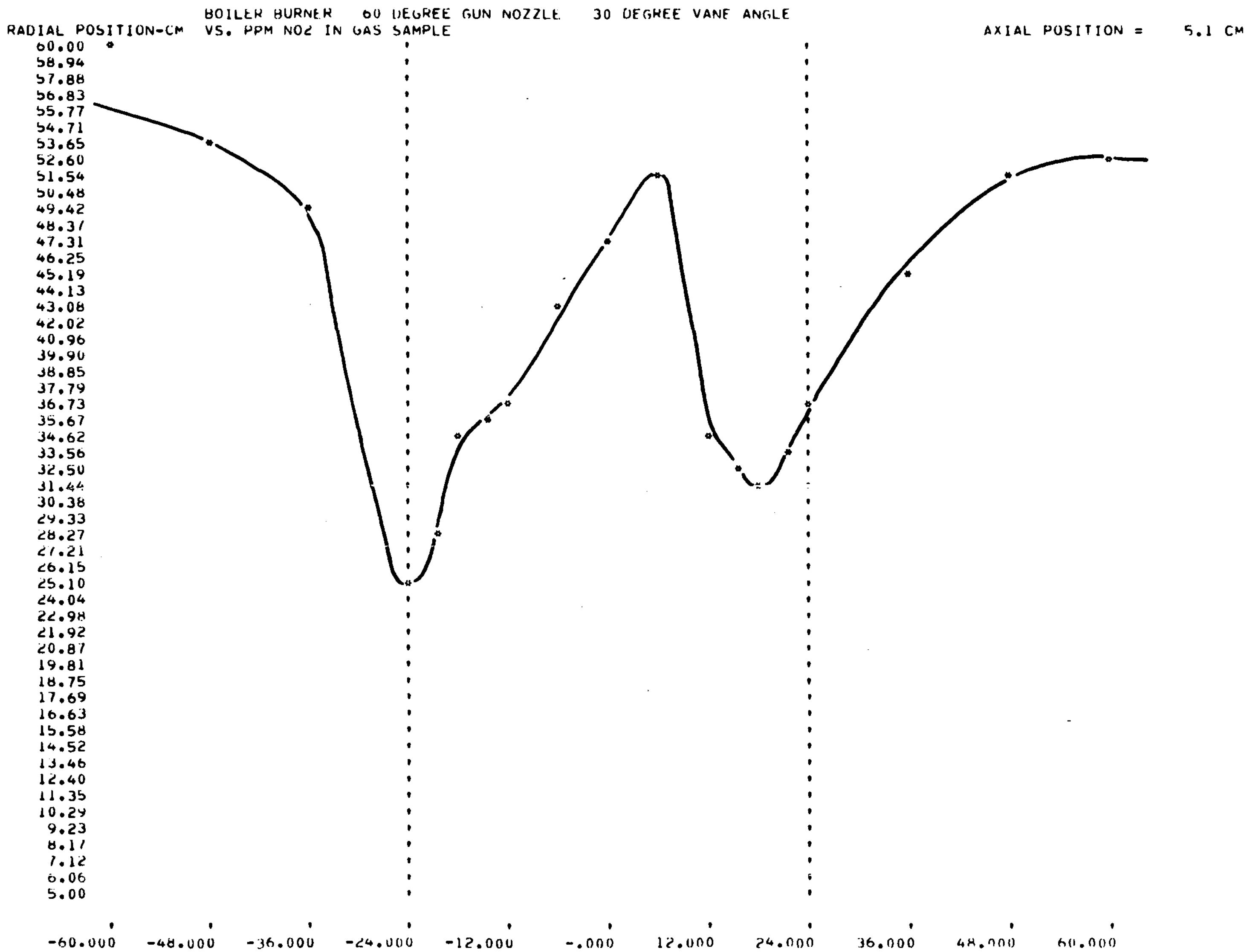

Figure 169. Radial profile of NO_2 at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

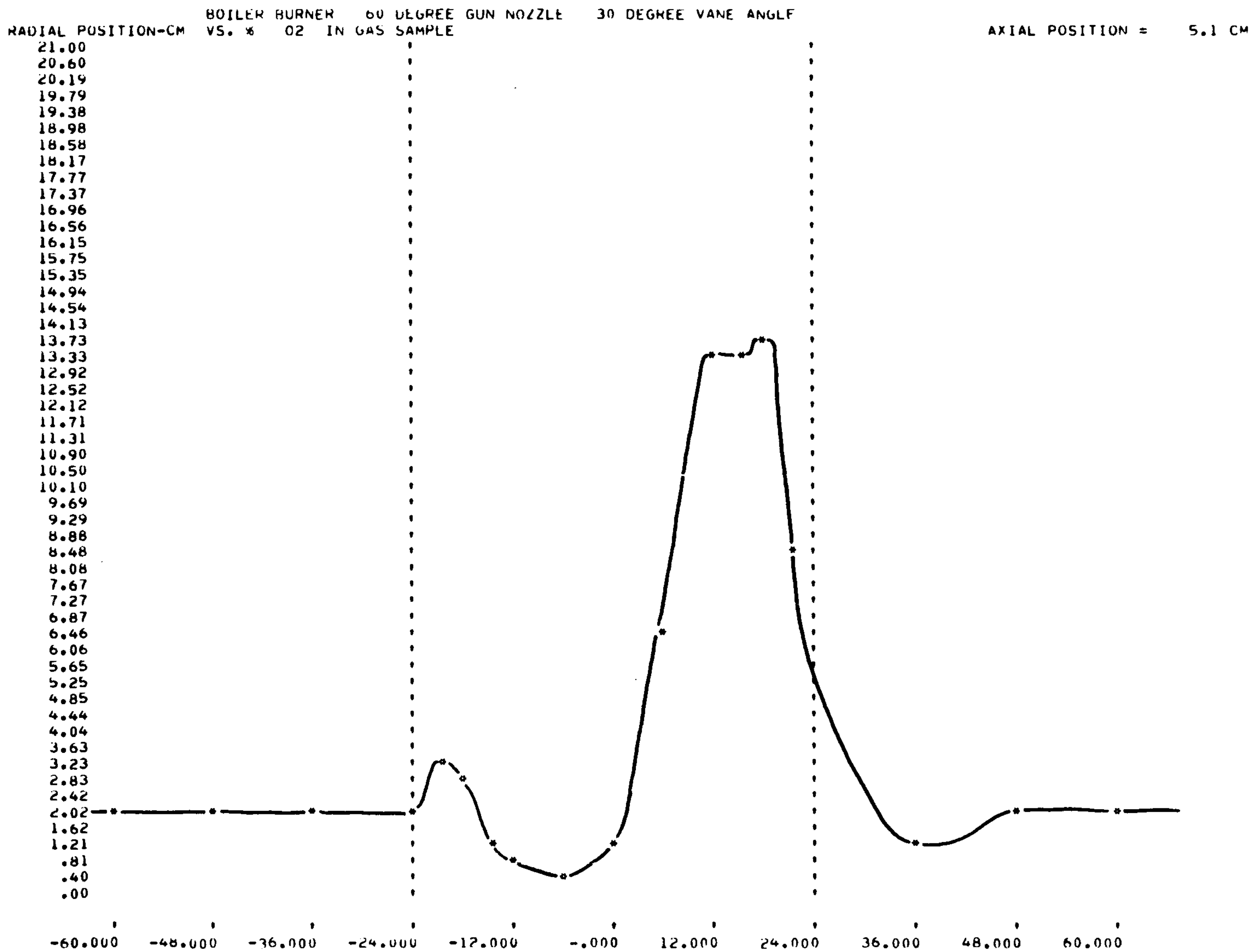

Figure 170. Radial profile of O_2 at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

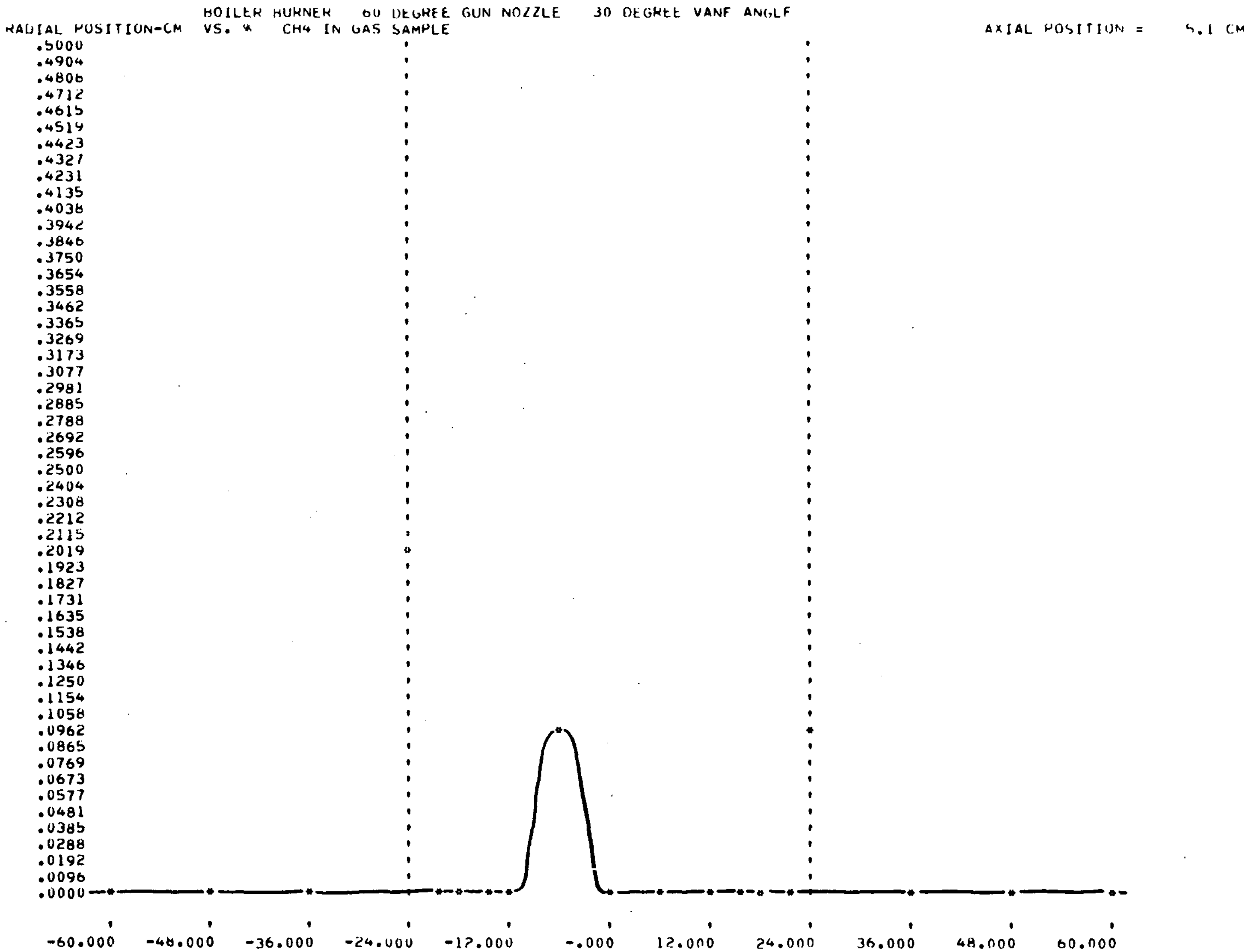

Figure 171. Radial profile of CH_4 at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

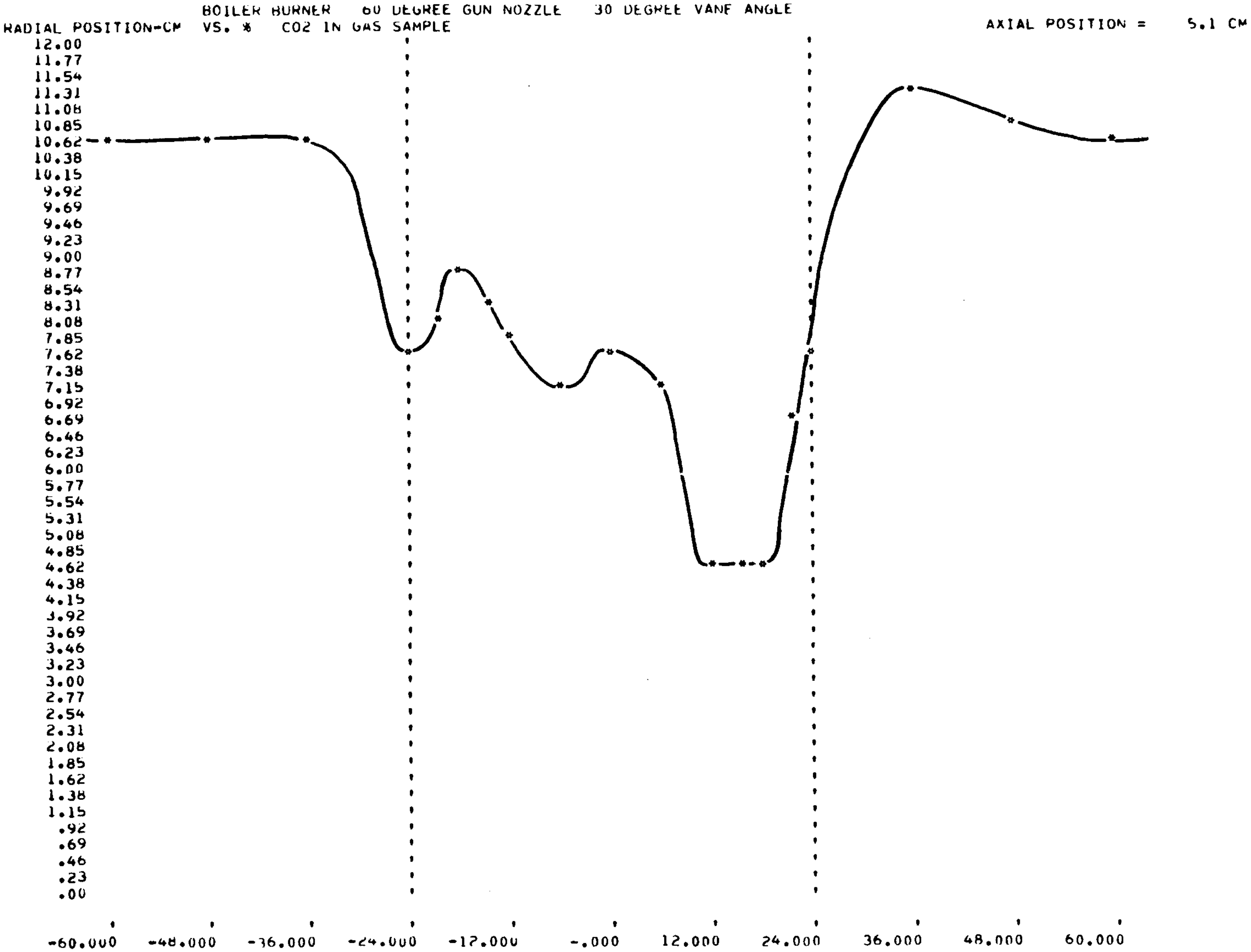

Figure 172. Radial profile of CO_2 at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

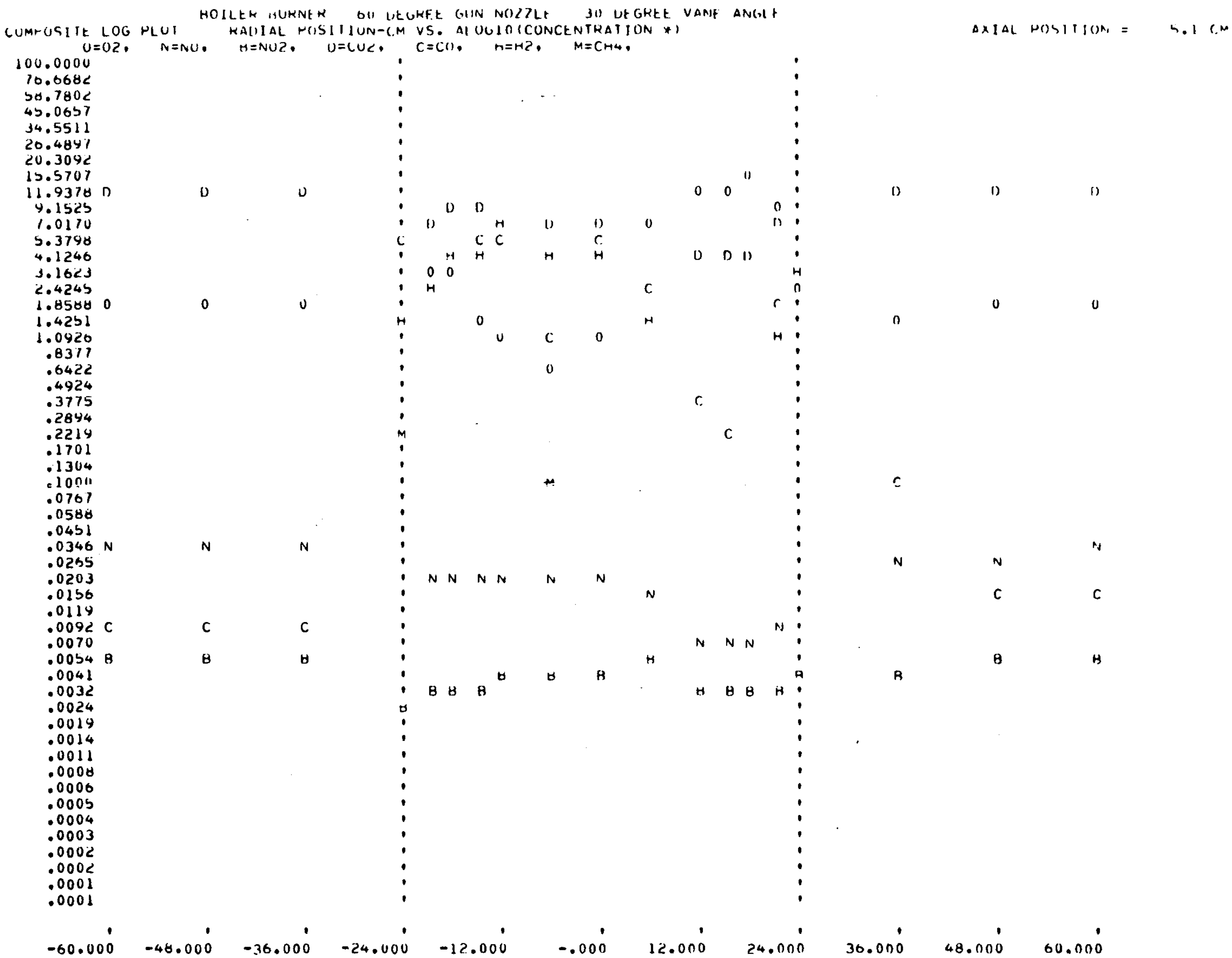

Figure 173. Radial profile of all the gases at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

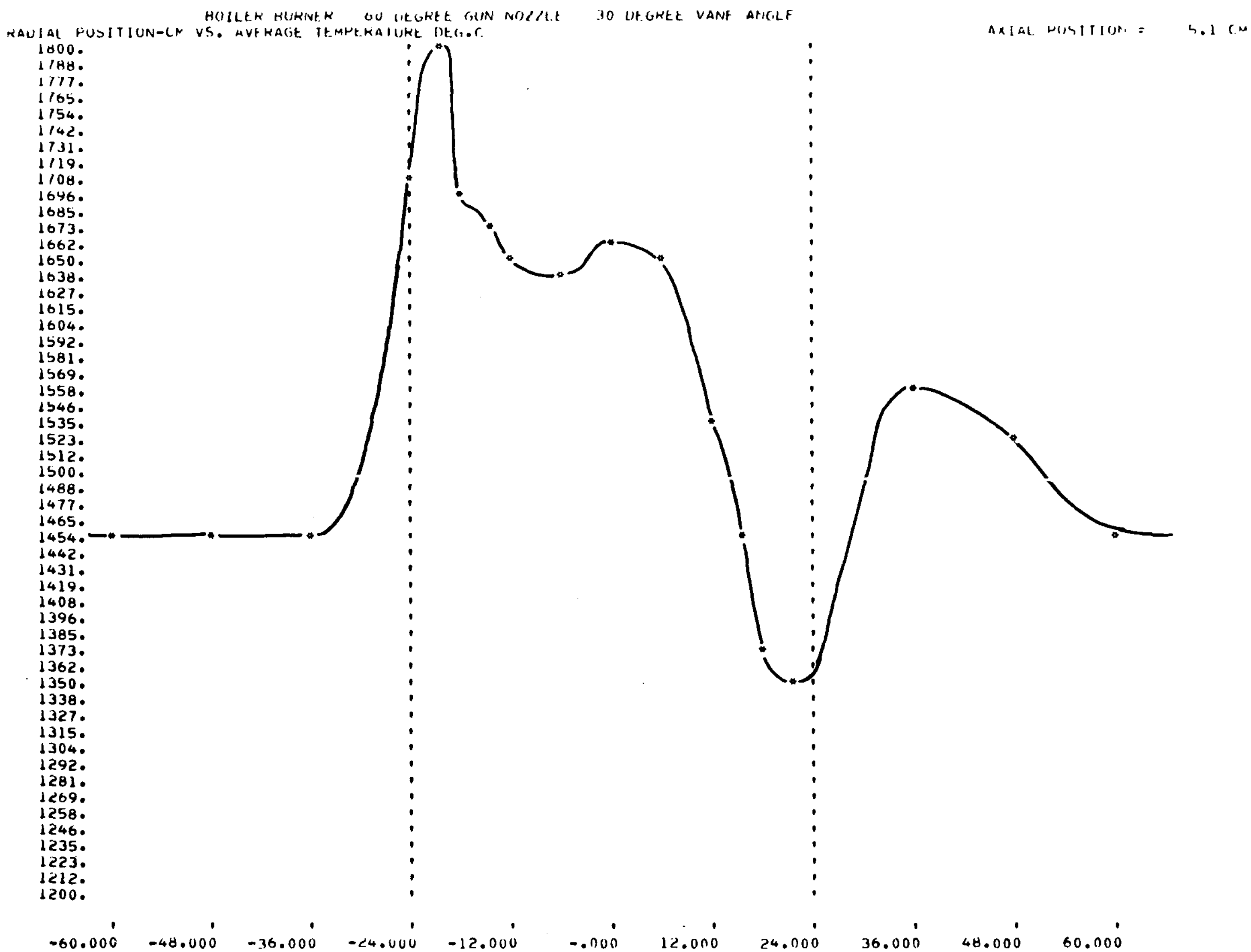

Figure 174. Radial profile of average temperature at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

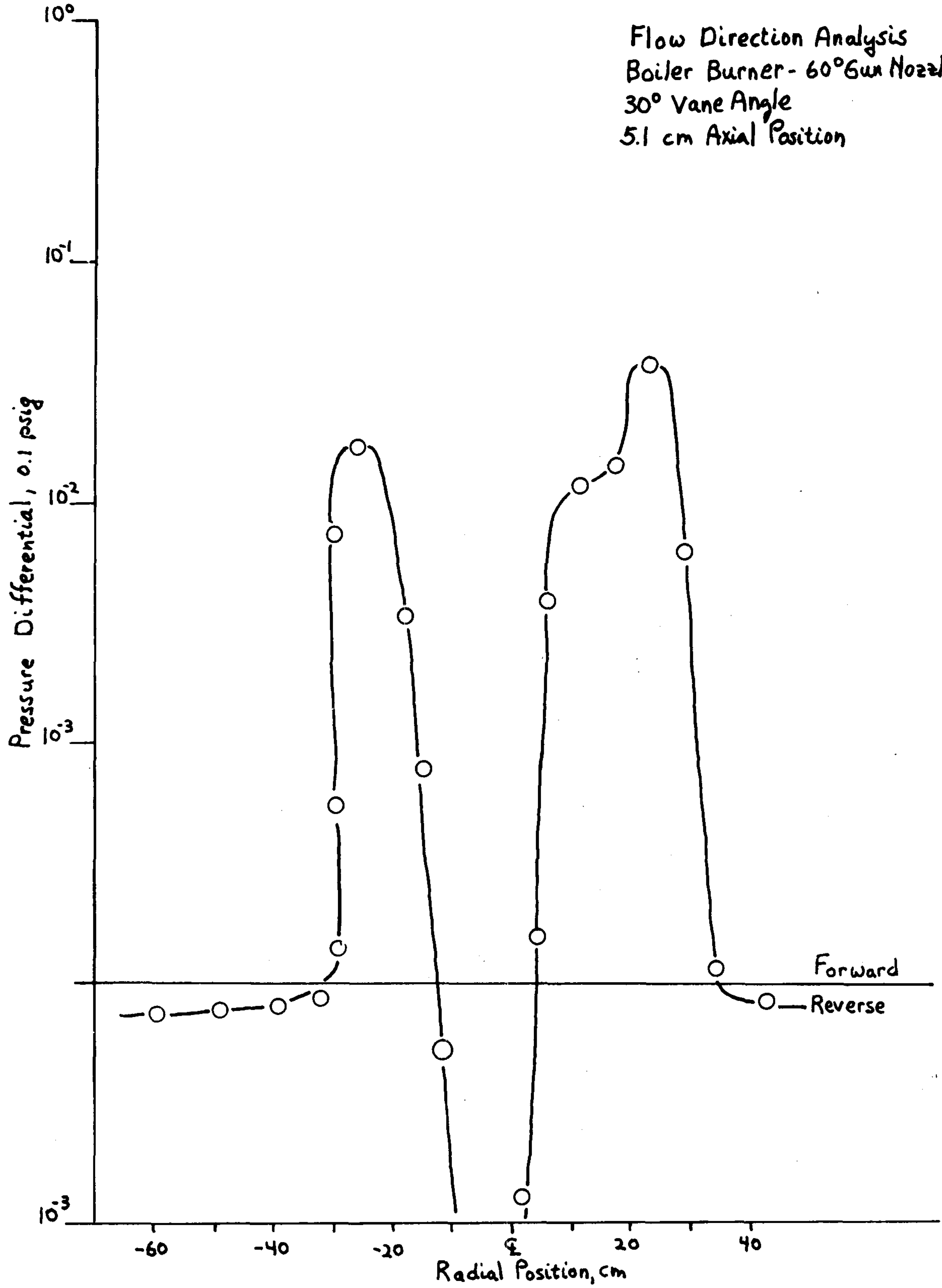

Figure 175. Radial profile of flow direction at an axial position of 5.1 cm (movable-vane boiler burner; 30-degree vane angle)

Table 30. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 26.0 cm
(Movable-Vane Boiler Burner; 30-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 30 DEGREE VANE ANGLE

AXIAL POSITION = 26.0 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	1.9	?	397.	55.	10.7	.0223	?	0.0	?	?	?	?	1422.	1422.	0.
-48.	1.5	?	385.	45.	11.0	.0371	?	0.0	?	?	?	?	1431.	1431.	0.
-36.	.9	86.8	370.	47.	10.7	.6300	0.0	0.0	0.0	0.0	0.0	0.0	1461.	1461.	0.
-24.	.4	83.8	264.	40.	9.5	3.5000	2.0	0.0	0.0	0.0	0.0	0.0	1560.	1560.	0.
-18.	.2	81.2	252.	38.	8.4	4.6000	3.7	0.0	0.0	0.0	0.0	0.0	1580.	1580.	0.
-12.	.2	79.2	210.	39.	8.6	5.5000	6.6	0.0	0.0	0.0	0.0	0.0	1554.	1554.	0.
-6.	.2	78.6	255.	43.	8.2	5.6000	6.6	0.0	0.0	0.0	0.0	0.0	1551.	1551.	0.
0.	.6	78.8	253.	38.	8.3	5.0000	6.8	0.0	0.0	0.0	0.0	0.0	1612.	1612.	0.
6.	1.0	82.4	245.	35.	9.7	1.1000	4.2	0.0	0.0	0.0	0.0	0.0	1622.	1622.	0.
12.	2.5	85.2	290.	20.	9.8	1.1000	.5	0.0	0.0	0.0	0.0	0.0	1583.	1583.	0.
18.	3.2	85.3	240.	10.	9.4	.9000	.3	0.0	0.0	0.0	0.0	0.0	1534.	1534.	0.
24.	4.3	85.8	205.	7.	8.8	.7000	0.0	0.0	0.0	0.0	0.0	0.0	1483.	1483.	0.
36.	1.0	84.6	228.	18.	9.8	2.4000	1.0	0.0	0.0	0.0	0.0	0.0	1613.	1613.	0.
48.	1.3	?	250.	24.	10.8	.4000	?	0.0	?	?	?	?	1558.	1558.	0.
60.	1.8	?	284.	32.	10.8	.0311	?	0.0	?	?	?	?	1404.	1404.	0.

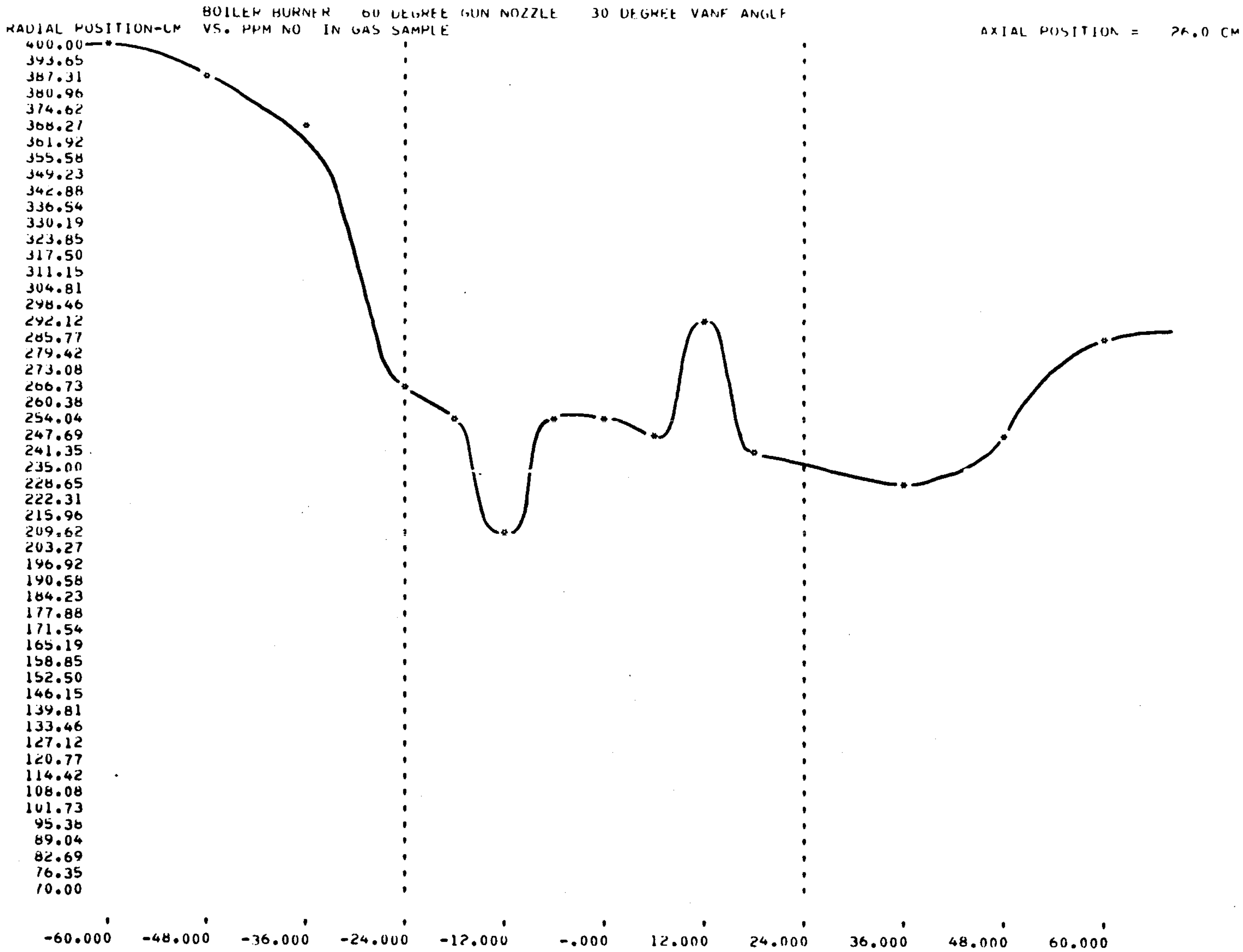

Figure 176. Radial profile of NO at an axial position of 26.0 cm (movable-vane boiler burner; 30-degree vane angle)

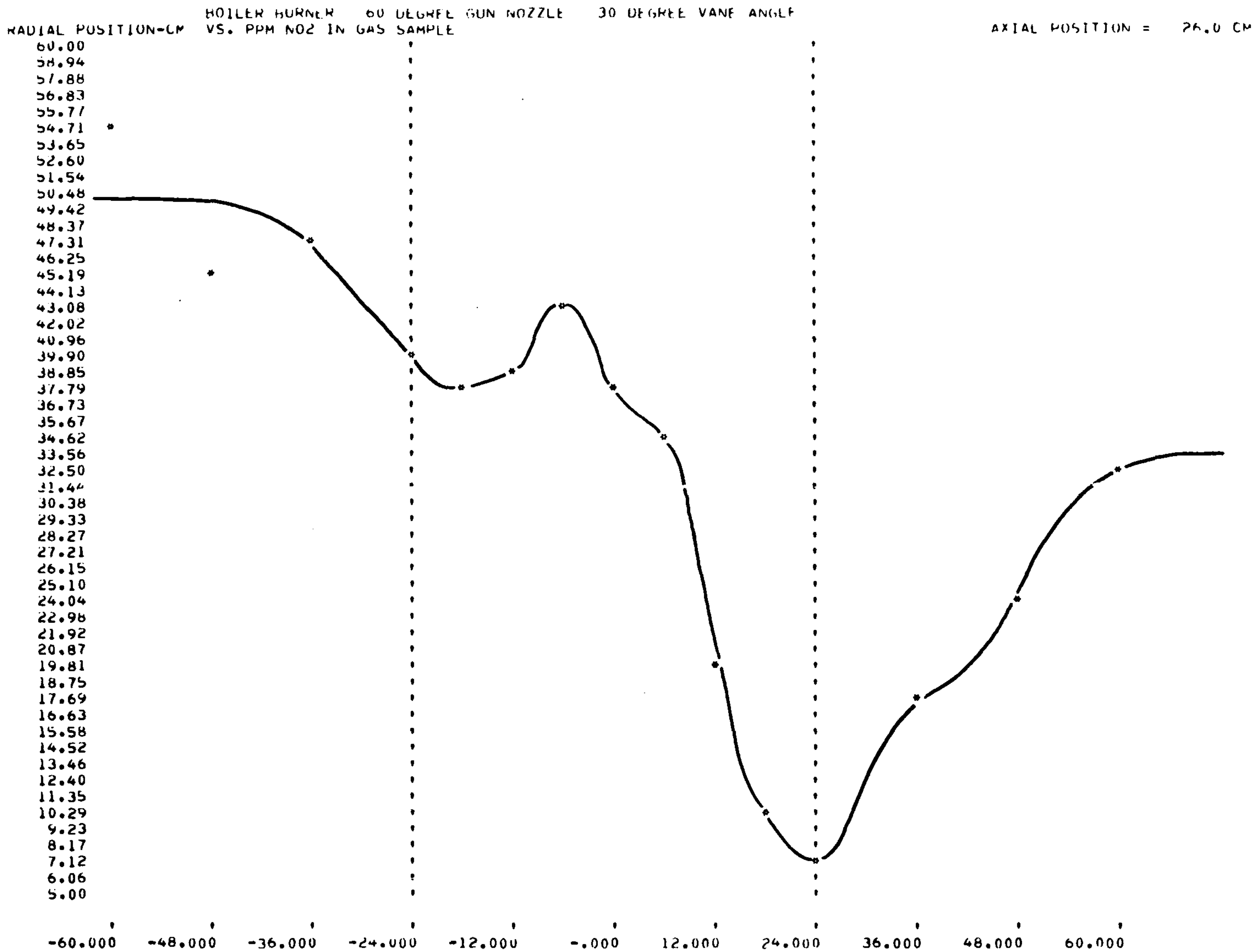

Figure 177. Radial profile of NO_2 at an axial position of 26.0 cm (movable-vane boiler burner; 30-degree vane angle)

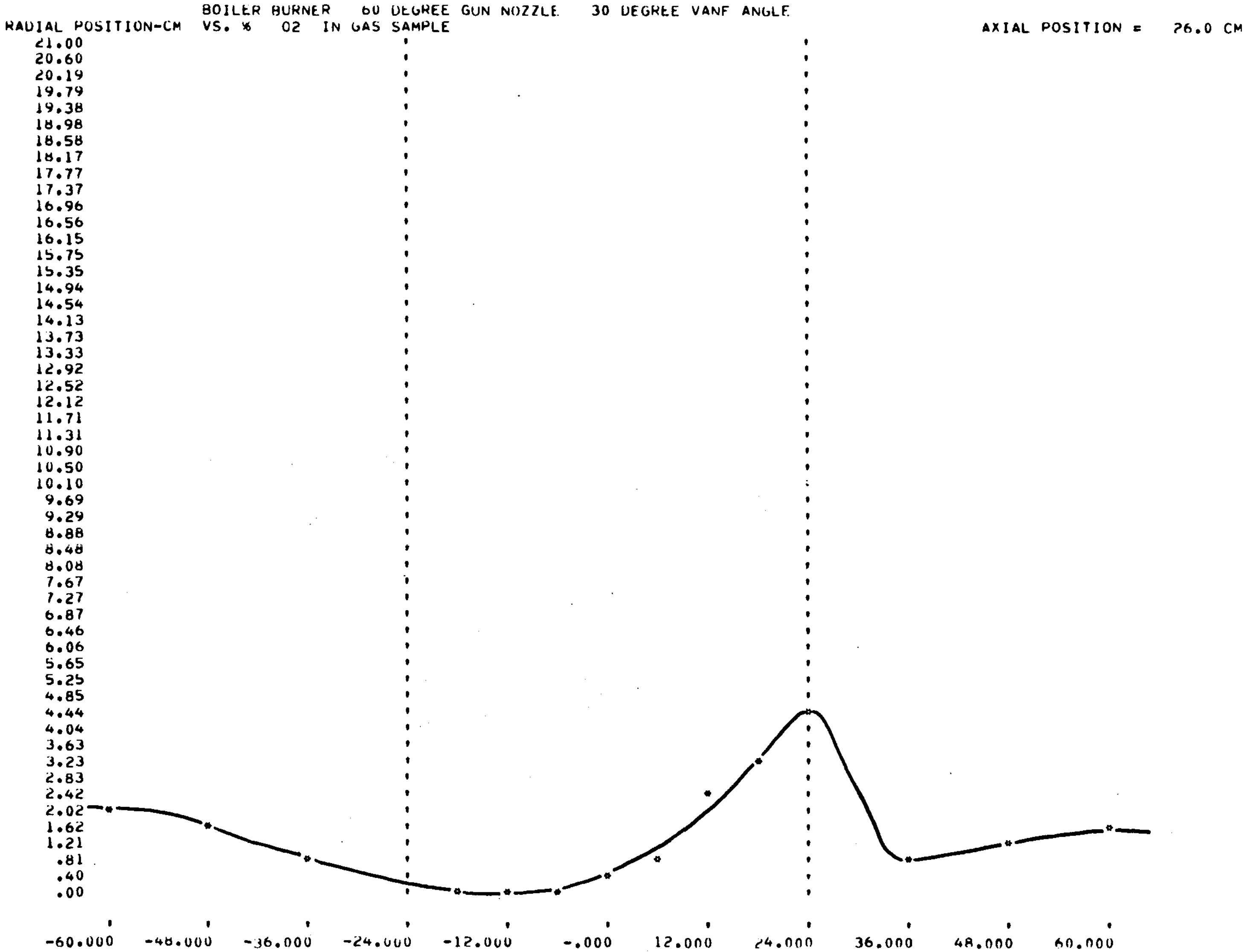

Figure 178. Radial profile of O_2 at an axial position of 26.0 cm (movable-vane boiler burner; 30-degree vane angle)

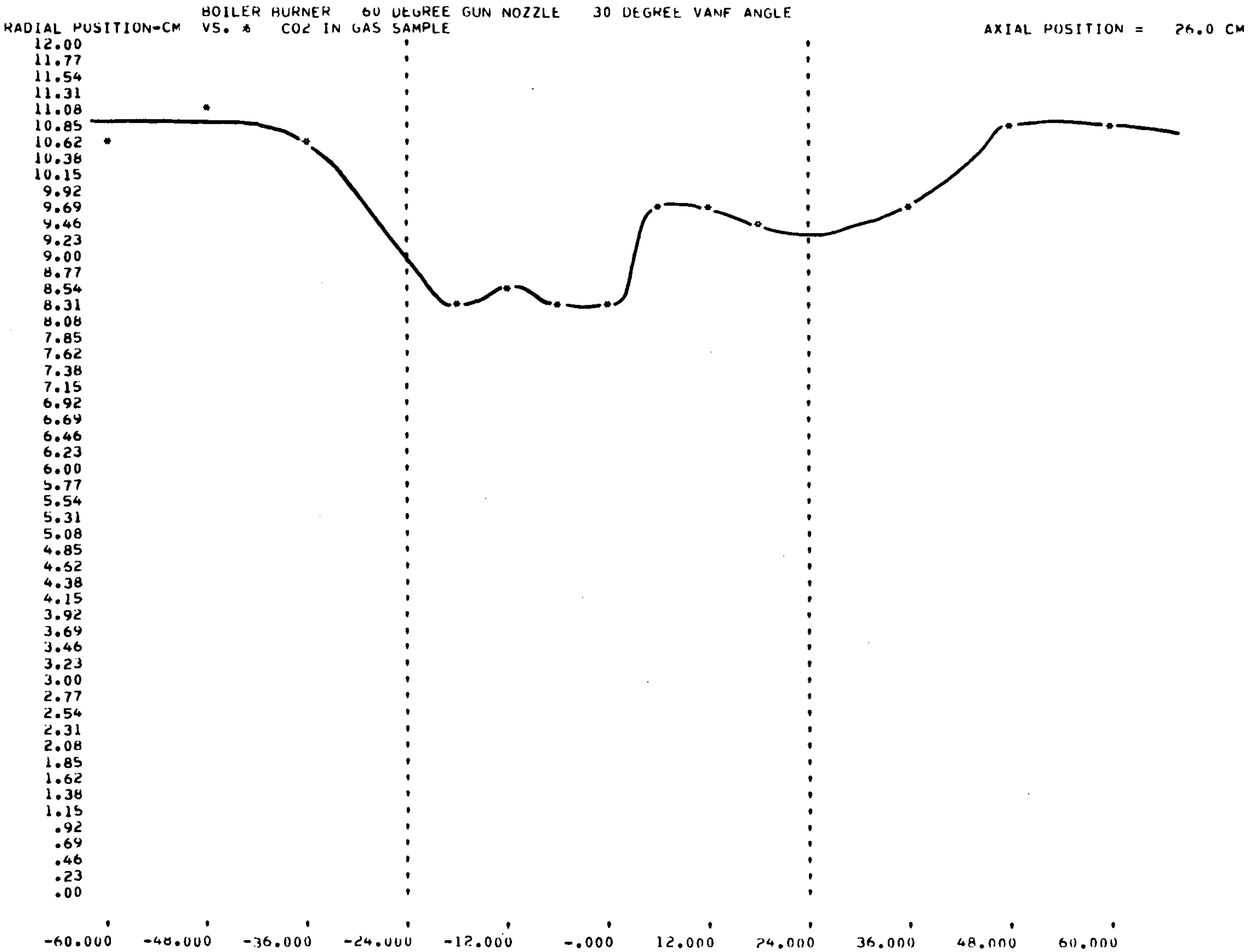

Figure 179. Radial profile of CO_2 at an axial position of 26.0 cm (movable-vane boiler burner; 30-degree vane angle)

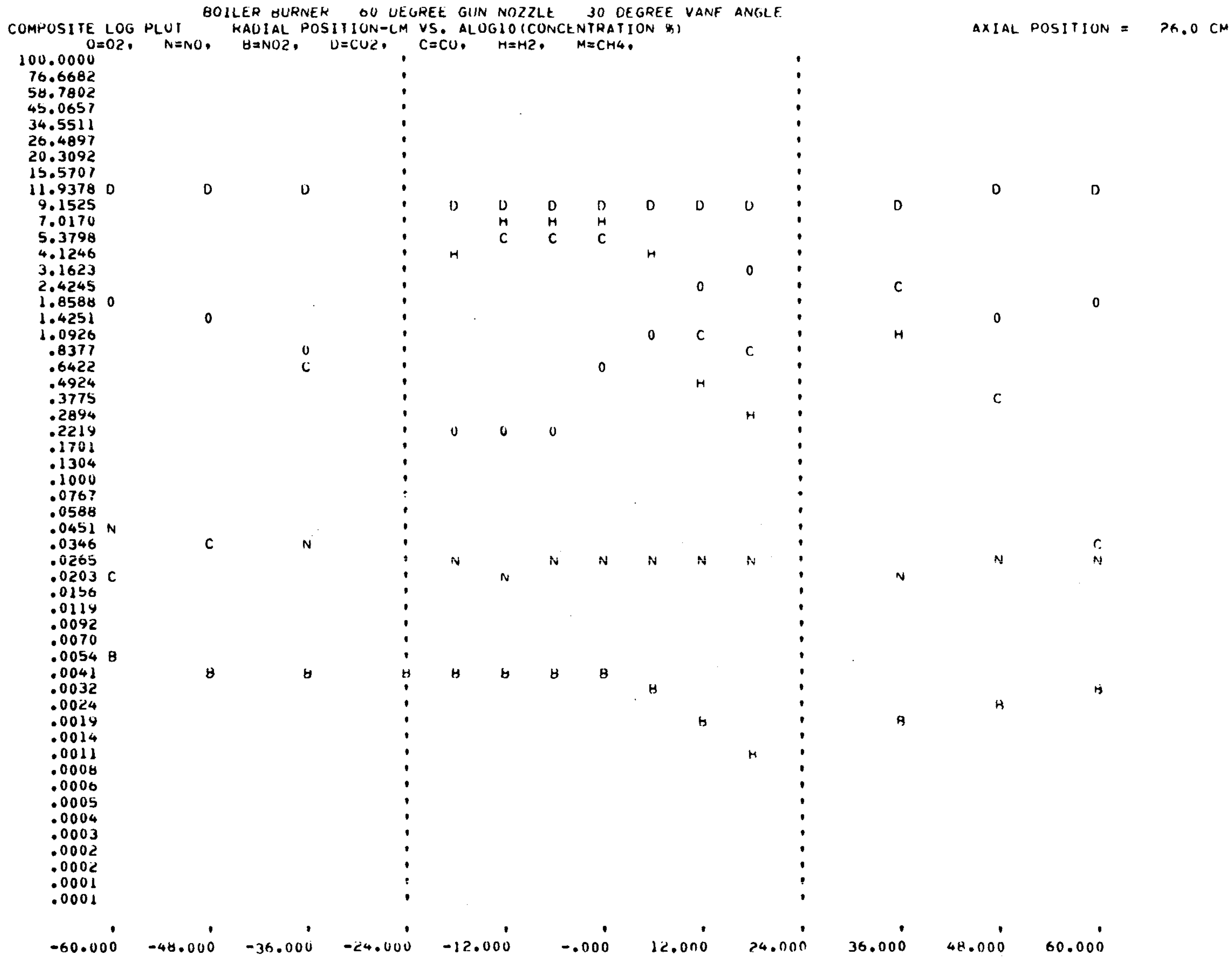

Figure 180. Radial profile of all the gases at an axial position of 26.0 cm (movable-vane boiler burner; 30-degree vane angle)

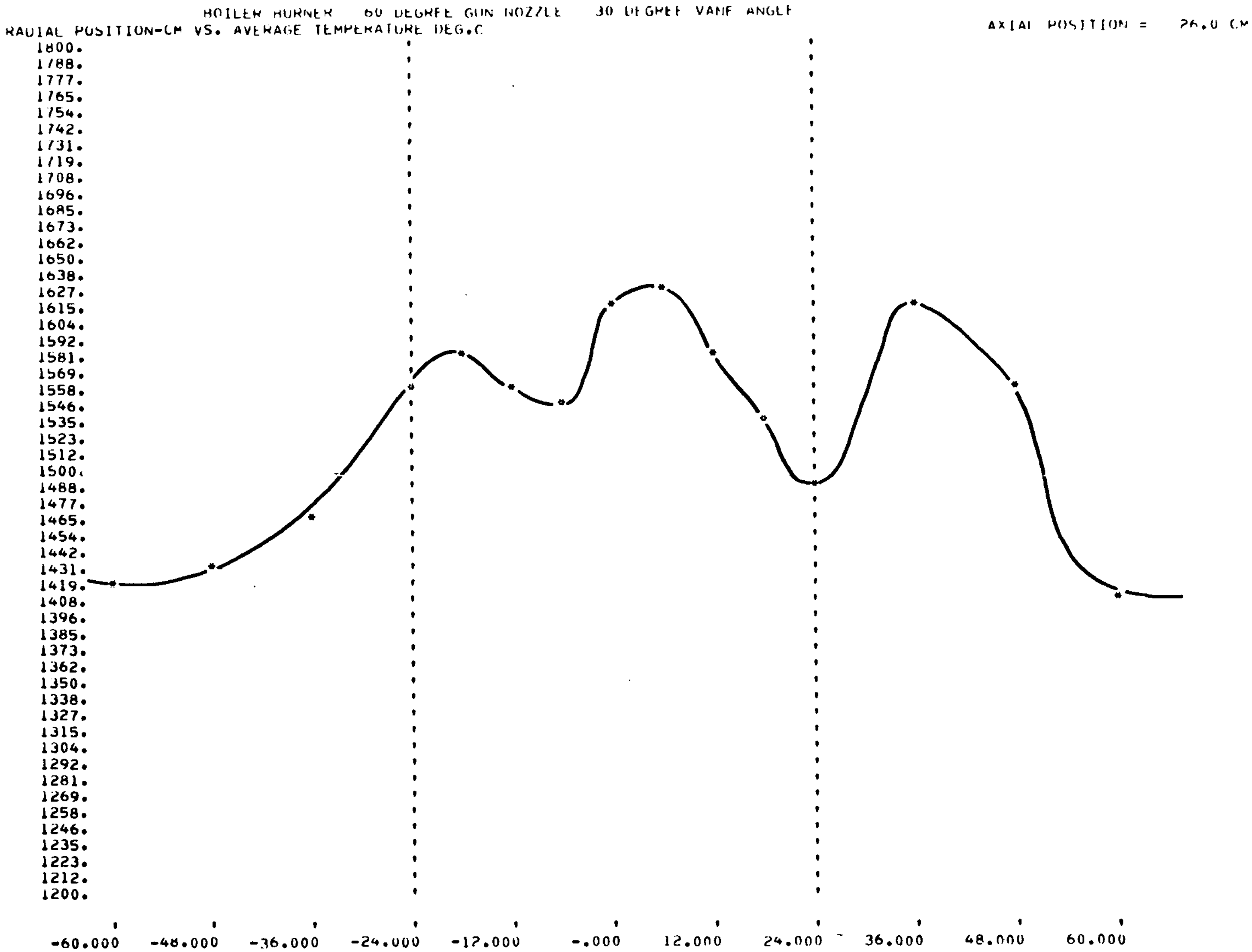

Figure 181. Radial profile of average temperature at an axial position of 26. 0 cm (movable-vane boiler burner; 30-degree vane angle)

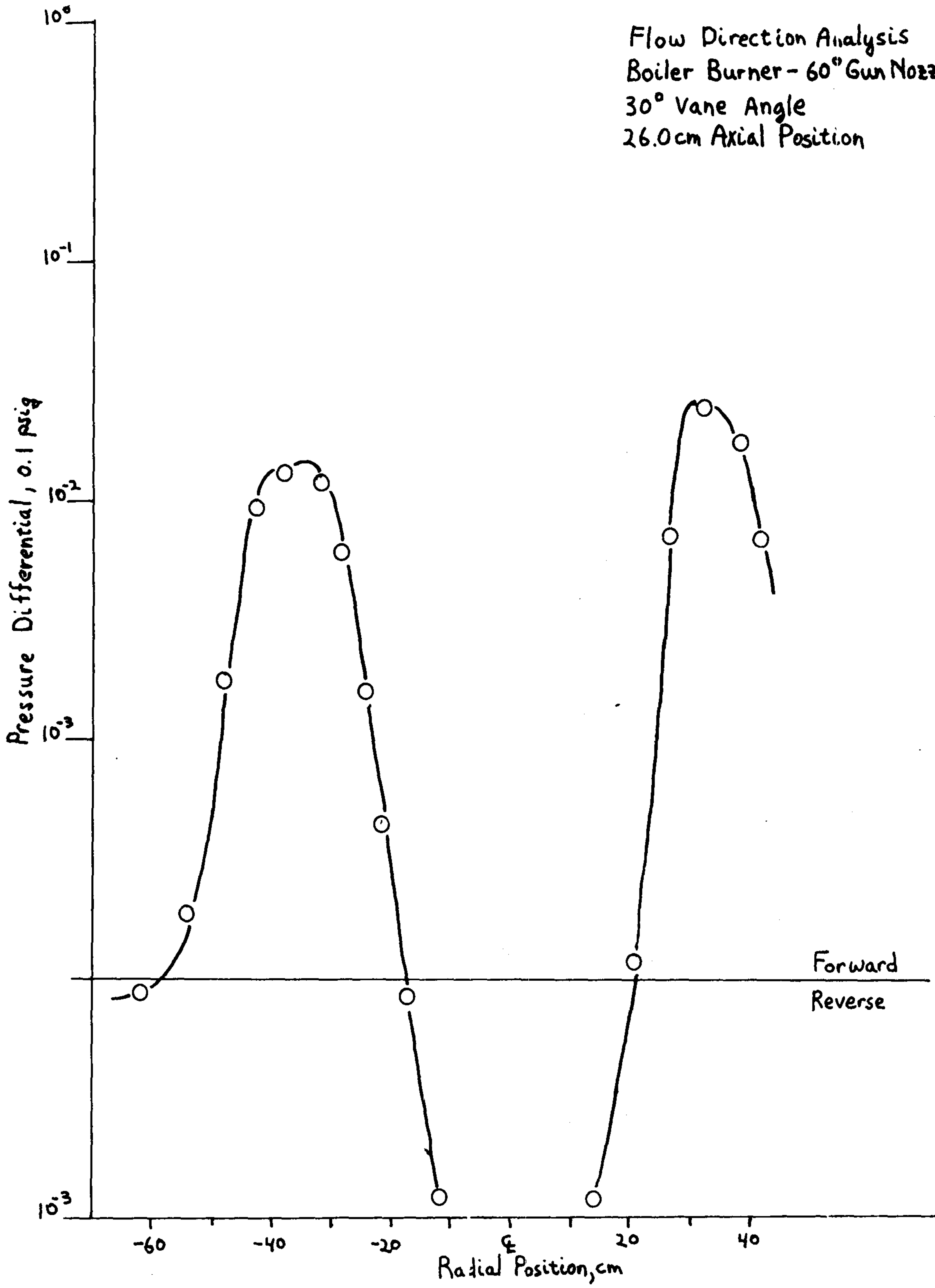

Figure 182. Radial profile of flow direction at an axial position of 26.0 cm (movable-vane boiler burner; 30-degree vane angle)

Table 31. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 46.7 cm
(Movable-Vane Boiler Burner; 30-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 30 DEGREE VANE ANGLE

AXIAL POSITION = 46.7 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	2.7	?	330.	38.	10.3	.0172	?	0.0	?	?	?	?	1420.	1420.	0.
-48.	3.0	?	324.	41.	10.1	.0221	?	0.0	?	?	?	?	1431.	1431.	0.
-36.	2.8	?	339.	36.	10.2	.0560	?	0.0	?	?	?	?	1442.	1442.	0.
-24.	1.7	86.4	346.	34.	10.8	.2100	0.0	0.0	0.0	0.0	0.0	0.0	1451.	1451.	0.
-18.	1.5	85.8	320.	28.	10.9	1.0000	.4	0.0	0.0	0.0	0.0	0.0	1459.	1459.	0.
-12.	.9	85.5	318.	24.	10.8	1.6000	.7	0.0	0.0	0.0	0.0	0.0	1437.	1437.	0.
-6.	1.1	85.7	285.	21.	10.8	1.3000	.5	0.0	0.0	0.0	0.0	0.0	1459.	1459.	0.
0.	.8	85.7	267.	18.	10.6	1.8000	.8	0.0	0.0	0.0	0.0	0.0	1466.	1466.	0.
6.	1.2	86.2	276.	20.	10.8	1.0000	.3	0.0	0.0	0.0	0.0	0.0	1478.	1478.	0.
12.	1.7	86.2	285.	28.	10.5	.6000	0.0	0.0	0.0	0.0	0.0	0.0	1500.	1500.	0.
18.	2.5	86.1	248.	31.	10.3	.3000	0.0	0.0	0.0	0.0	0.0	0.0	1508.	1508.	0.
24.	3.6	?	213.	30.	9.8	.0585	?	0.0	?	?	?	?	1505.	1505.	0.
36.	3.3	?	218.	33.	9.9	.0861	?	0.0	?	?	?	?	1507.	1507.	0.
48.	2.2	?	233.	36.	10.6	.0643	?	0.0	?	?	?	?	1556.	1556.	0.
60.	2.1	?	249.	40.	10.7	.0482	?	0.0	?	?	?	?	1501.	1501.	0.

Table 32. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 146.1 cm (Movable-Vane Boiler Burner; 30-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 30 DEGREE VANE ANGLE

AXIAL POSITION = 146.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	4.1	?	270.	48.	9.5	.0100	?	0.0	?	?	?	?	1414.	1414.	0.
-48.	2.6	?	324.	57.	10.3	.0190	?	0.0	?	?	?	?	1416.	1416.	0.
-36.	1.9	?	353.	54.	10.8	.0182	?	0.0	?	?	?	?	1420.	1420.	0.
-24.	1.5	?	346.	42.	11.0	.0350	?	0.0	?	?	?	?	1428.	1428.	0.
-18.	1.4	?	350.	40.	11.1	.0274	?	0.0	?	?	?	?	1431.	1431.	0.
-12.	.9	?	327.	44.	11.4	.0620	?	0.0	?	?	?	?	1432.	1432.	0.
-6.	1.3	?	324.	36.	11.1	.0461	?	0.0	?	?	?	?	1437.	1437.	0.
0.	1.1	?	305.	28.	11.2	.5840	?	0.0	?	?	?	?	1442.	1442.	0.
6.	1.3	?	317.	35.	11.1	.0710	?	0.0	?	?	?	?	1440.	1440.	0.
12.	1.3	?	330.	42.	11.1	.0784	?	0.0	?	?	?	?	1439.	1439.	0.
18.	1.1	?	322.	39.	11.2	.0846	?	0.0	?	?	?	?	1442.	1442.	0.
24.	.3	?	287.	34.	11.6	.0640	?	0.0	?	?	?	?	1444.	1444.	0.
36.	1.8	?	305.	37.	10.8	.0730	?	0.0	?	?	?	?	1456.	1456.	0.
48.	2.0	?	285.	35.	10.7	.0862	?	0.0	?	?	?	?	1467.	1467.	0.
60.	2.4	?	294.	40.	10.5	.0744	?	0.0	?	?	?	?	1472.	1472.	0.

Table 33. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 385.4 cm
(Movable-Vane Boiler Burner; 30-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 30 DEGREE VANE ANGLE

AXIAL POSITION = 385.4 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPFRATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	2.4	?	342.	41.	10.5	.0097	?	0.0	?	?	?	?	1386.	1386.	0.
-48.	2.3	?	347.	34.	10.5	.0104	?	0.0	?	?	?	?	1390.	1390.	0.
-36.	2.4	?	344.	37.	10.5	.0111	?	0.0	?	?	?	?	1390.	1390.	0.
-24.	2.5	?	356.	36.	10.4	.0117	?	0.0	?	?	?	?	1391.	1391.	0.
-12.	2.6	?	348.	34.	10.3	.0128	?	0.0	?	?	?	?	1394.	1394.	0.
0.	2.8	?	340.	31.	10.2	.0120	?	0.0	?	?	?	?	1396.	1396.	0.
12.	3.1	?	337.	32.	10.1	.0116	?	0.0	?	?	?	?	1395.	1395.	0.
24.	3.3	?	334.	34.	9.9	.0122	?	0.0	?	?	?	?	1400.	1400.	0.
36.	3.0	?	331.	36.	10.2	.0118	?	0.0	?	?	?	?	1393.	1393.	0.
48.	2.8	?	330.	38.	10.3	.0113	?	0.0	?	?	?	?	1391.	1391.	0.
60.	2.6	?	236.	39.	10.4	.0111	?	0.0	?	?	?	?	1387.	1387.	0.

Table 34. FURNACE CONDITIONS FOR IN-THE-FLAME SAMPLING
(Movable-Vane Boiler Burner; 15-Degree Vane Angle)

```
                 BOILER BURNER   60 DEGREE GUN NOZZLE   15 DEGREE VANE ANGLE

NUMBER OF SETS OF DATA =   5.
MINIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1200. DEG.C
MAXIMUM GRID VALUE OF AVERAGE TEMPERATURE = 1800. DEG.C

POSITION OF OUTSIDE EDGES OF BURNER BLOCK
   MINIMUM POSITION = -25. CM
   MAXIMUM POSITION =  25. CM

GAS INPUT,      AXIAL     0. CF/HR          RADIAL 2994. CF/HR
WALL TEMPERATURE                1426. DEG.C
PREHEAT TEMPERATURE              452. DEG.C
FLUE GAS RECIRCULATION  0.0 %

GAS SAMPLE ANALYSIS IN THE FLUE
   NITROGEN OXIDE      196.0 PPM
   NITROGEN DIOXIDE     28.0 PPM
   OXYGEN                2.7 %
   CARBON DIOXIDE       10.3 %
   CARBON MONOXIDE     .0094 %

LIMITS FOR CONCENTRATION PLOTS
     LOWER LIMIT OF NO  =     0. PPM     UPPER LIMIT =  200. PPM
     LOWER LIMIT OF NO2 =     0. PPM     UPPER LIMIT =   30. PPM
     LOWER LIMIT OF O2  =     0. %       UPPER LIMIT =   21. %
     LOWER LIMIT OF CH4 =     0. %       UPPER LIMIT =    4. %
     LOWER LIMIT OF CO2 =     0. %       UPPER LIMIT =   12. %

ISOCONCENTRATION VALUES
   OBTAIN VALUE OF RADIAL POSITION AT NO  PPM CONCENTRATION   150.   125.   100.    75.    50.
   OBTAIN VALUE OF RADIAL POSITION AT NO2 PPM CONCENTRATION    10.    15.    20.    25.
```

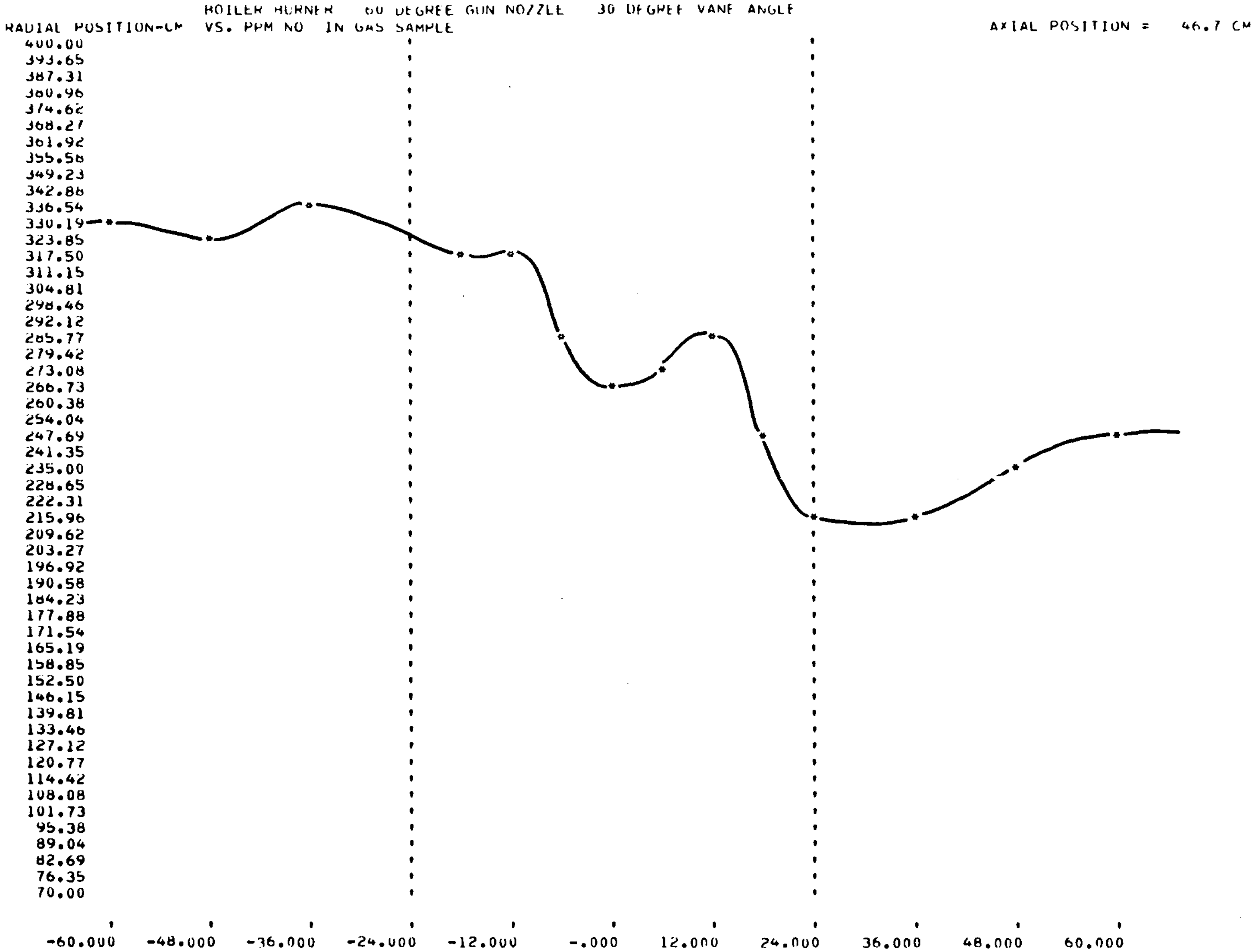

Figure 183. Radial profile of NO at an axial position of 46. 7 cm (movable-vane boiler burner; 30-degree vane angle)

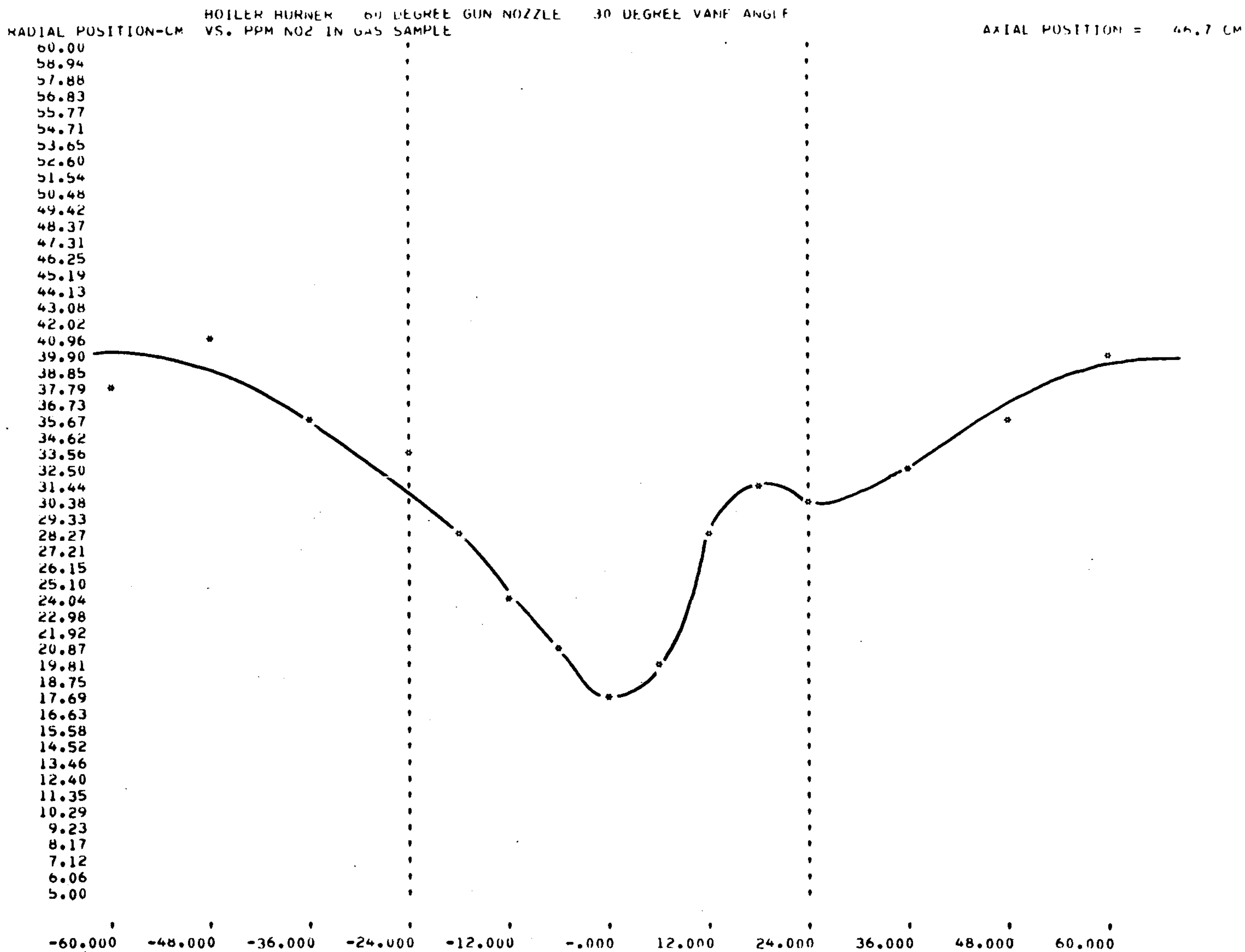

Figure 184. Radial profile of NO_2 at an axial position of 46.7 cm (movable-vane boiler burner; 30-degree vane angle)

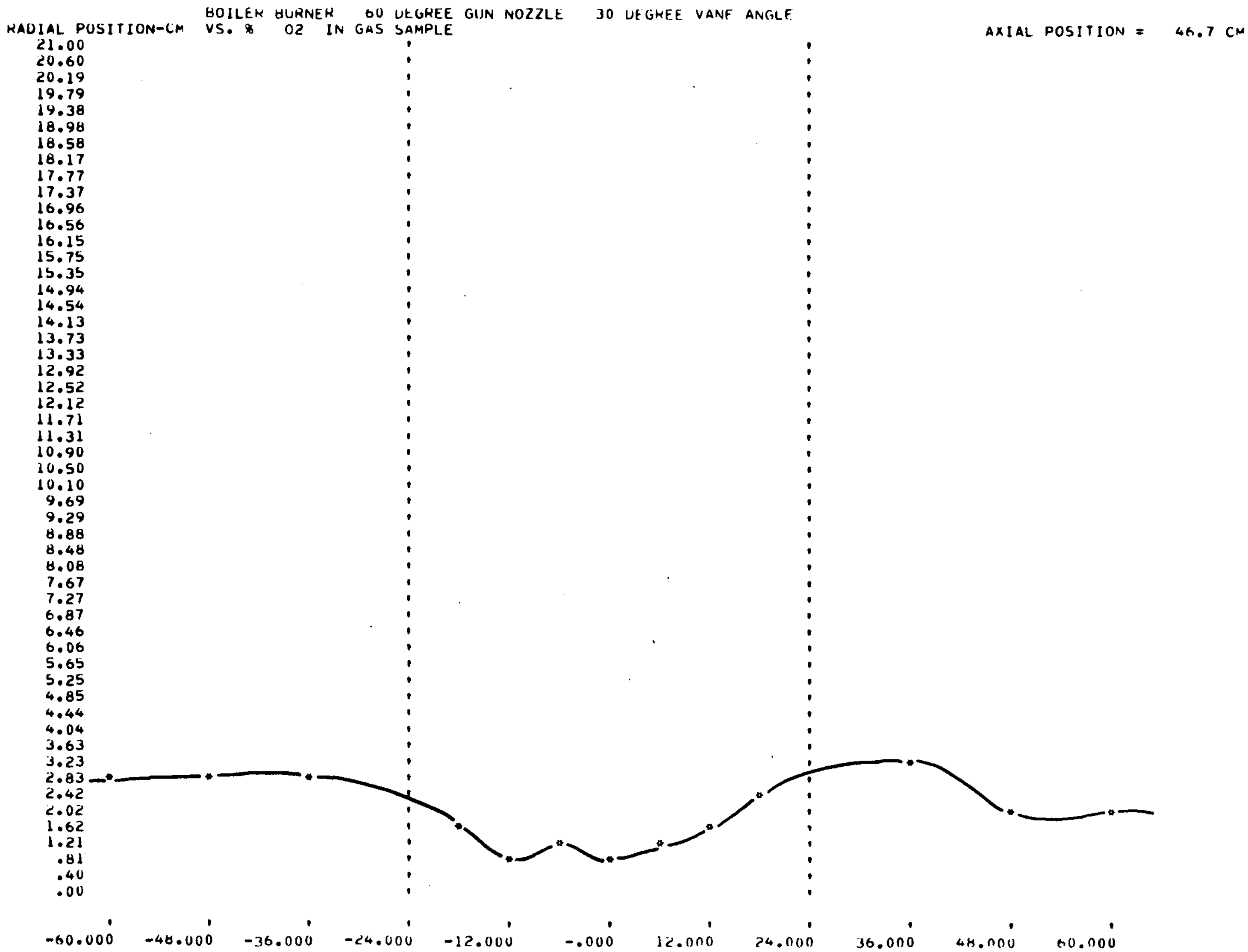

Figure 185. Radial profile of O_2 at an axial position of 46. 7 cm (movable-vane boiler burner; 30-degree vane angle)

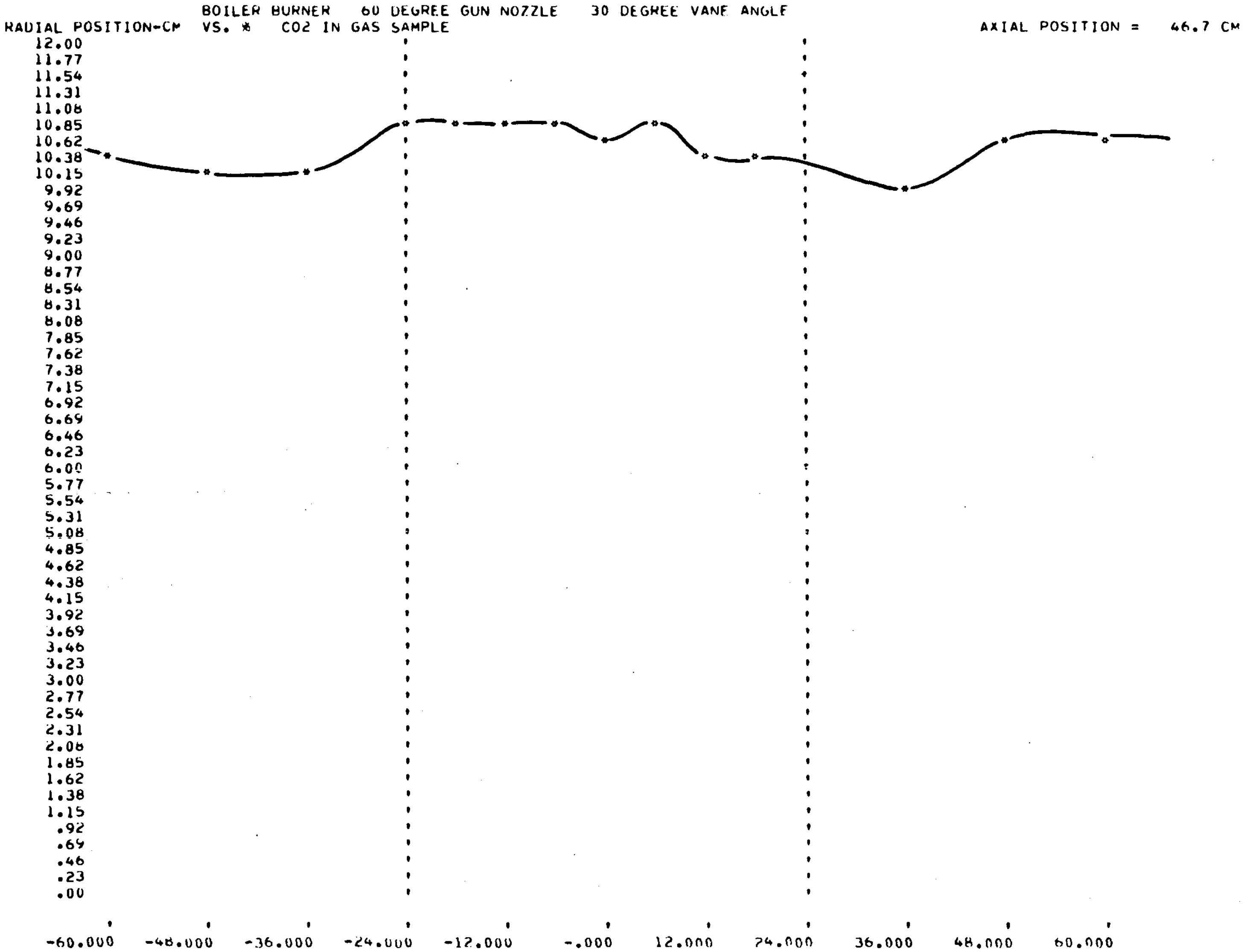

Figure 186. Radial profile of CO_2 at an axial position of 46.7 cm
(movable-vane boiler burner; 30-degree vane angle)

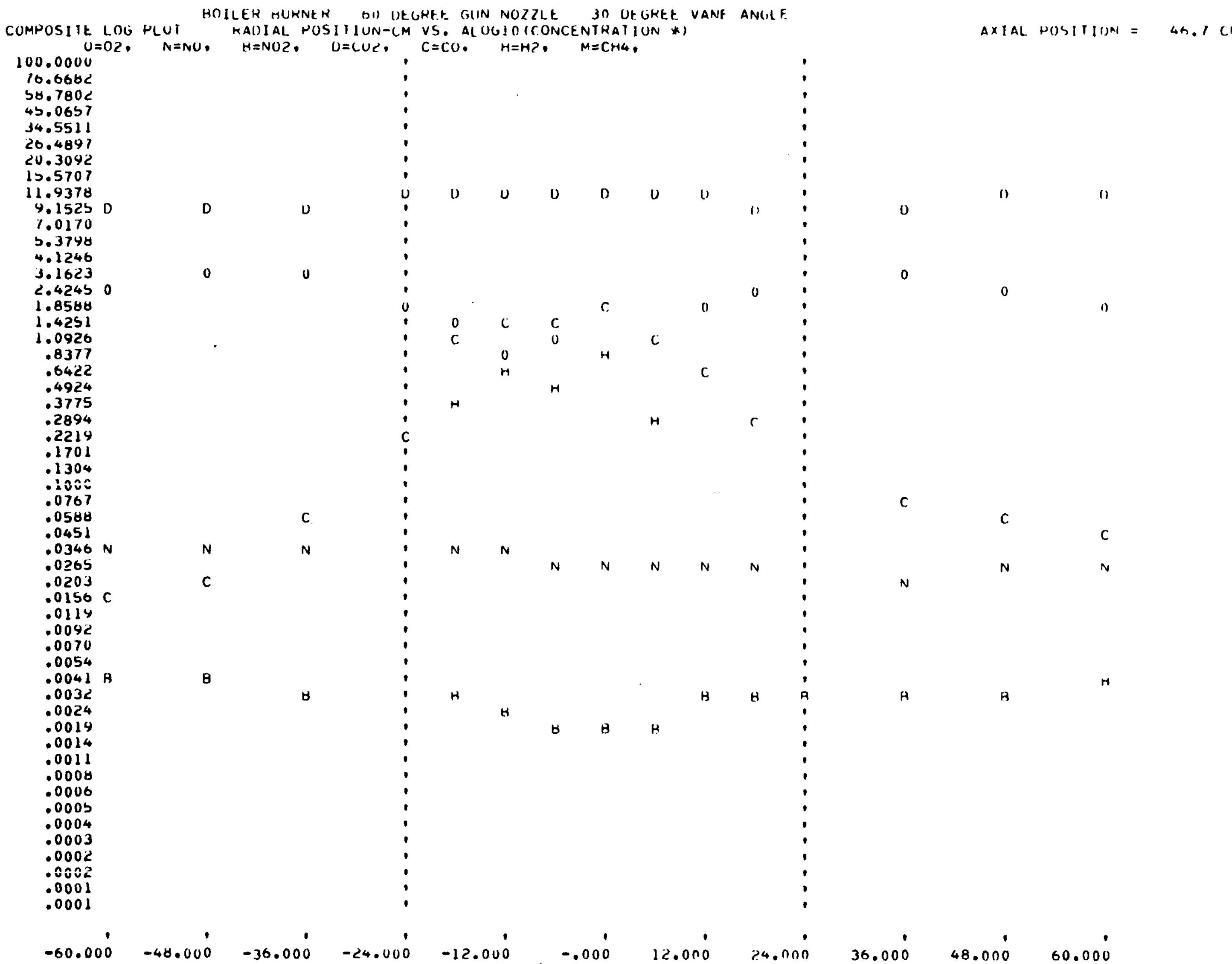

Figure 187. Radial profile of all the gases at an axial position of 46.7 cm (movable-vane boiler burner; 30-degree vane angle)

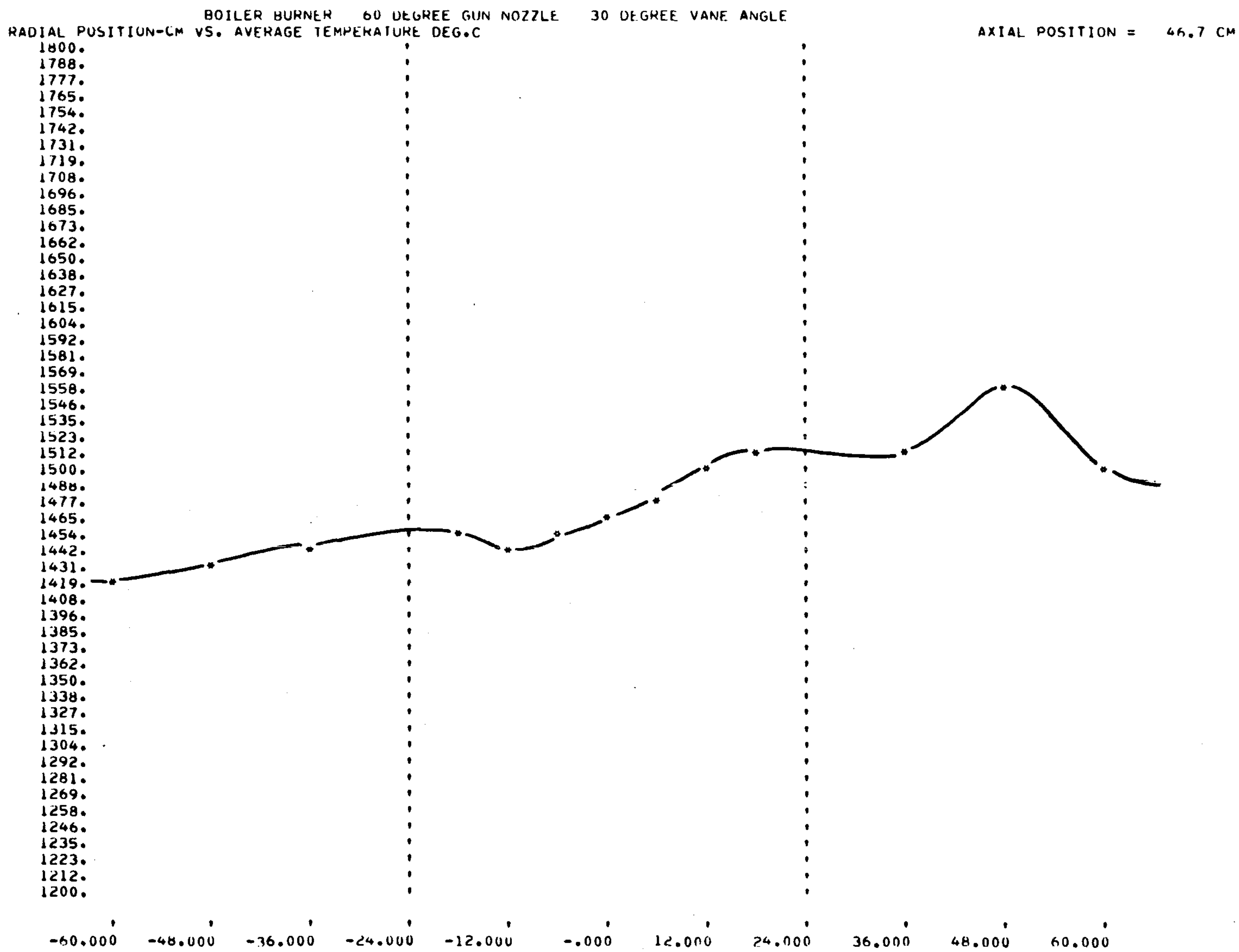

Figure 188. Radial profile of temperature at an axial position of 46. 7 cm (movable-vane boiler burner; 30-degree vane angle)

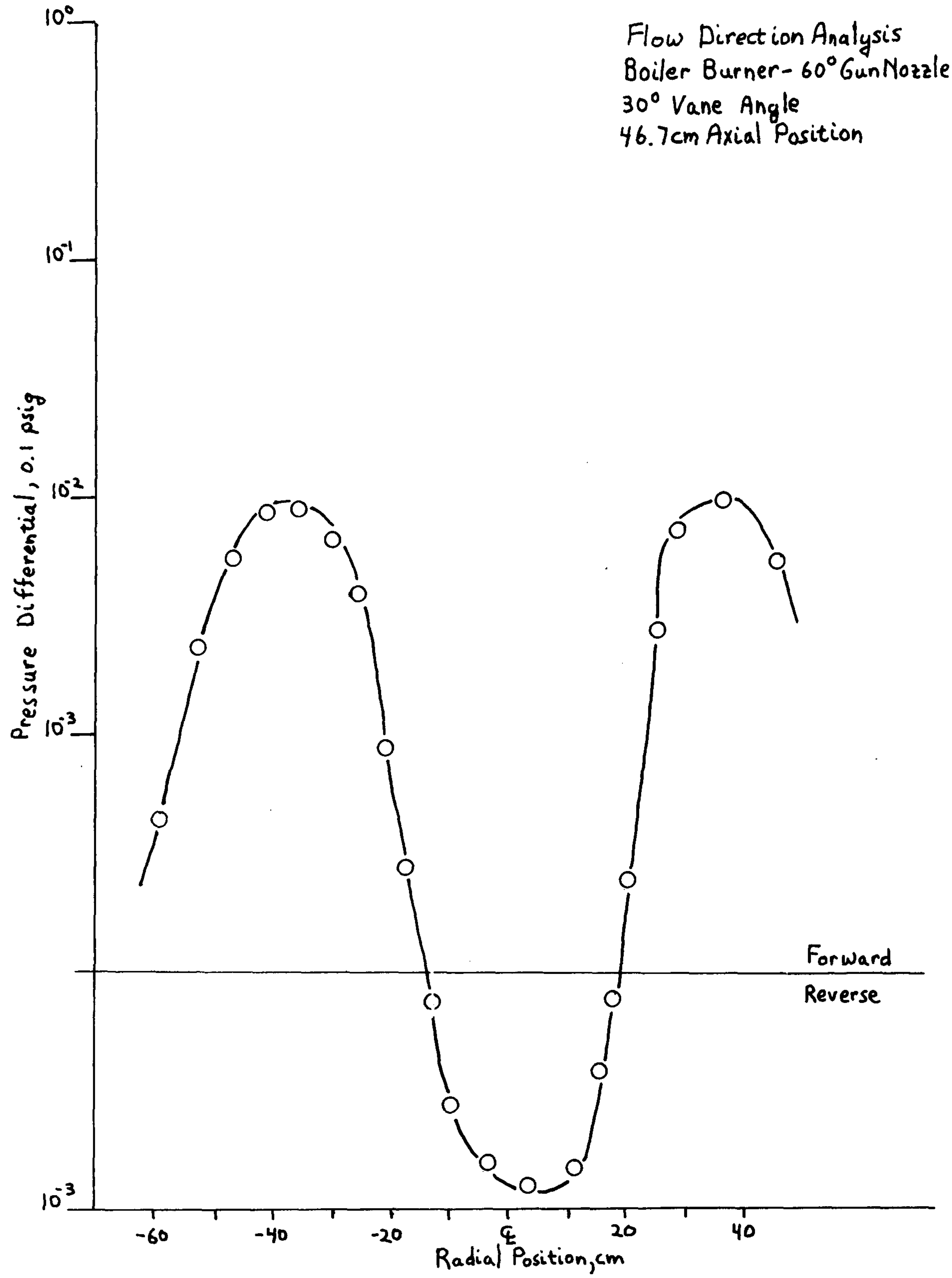

Figure 189. Radial profile of flow direction at an axial position of 46.7 cm (movable-vane boiler burner; 30-degree vane angle)

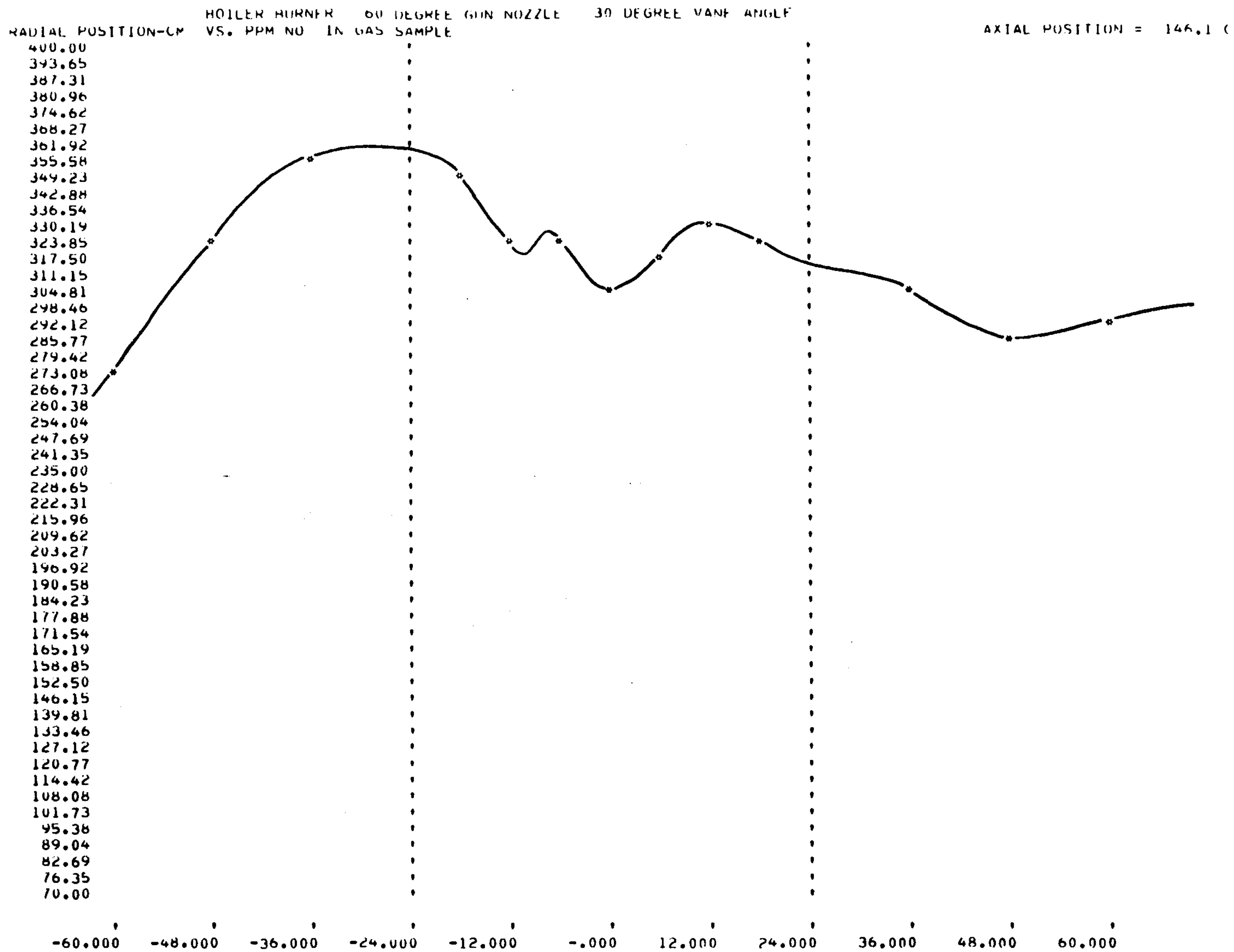

Figure 190. Radial profile of NO at an axial position of 146.1 cm (movable-vane boiler burner; 30-degree vane angle)

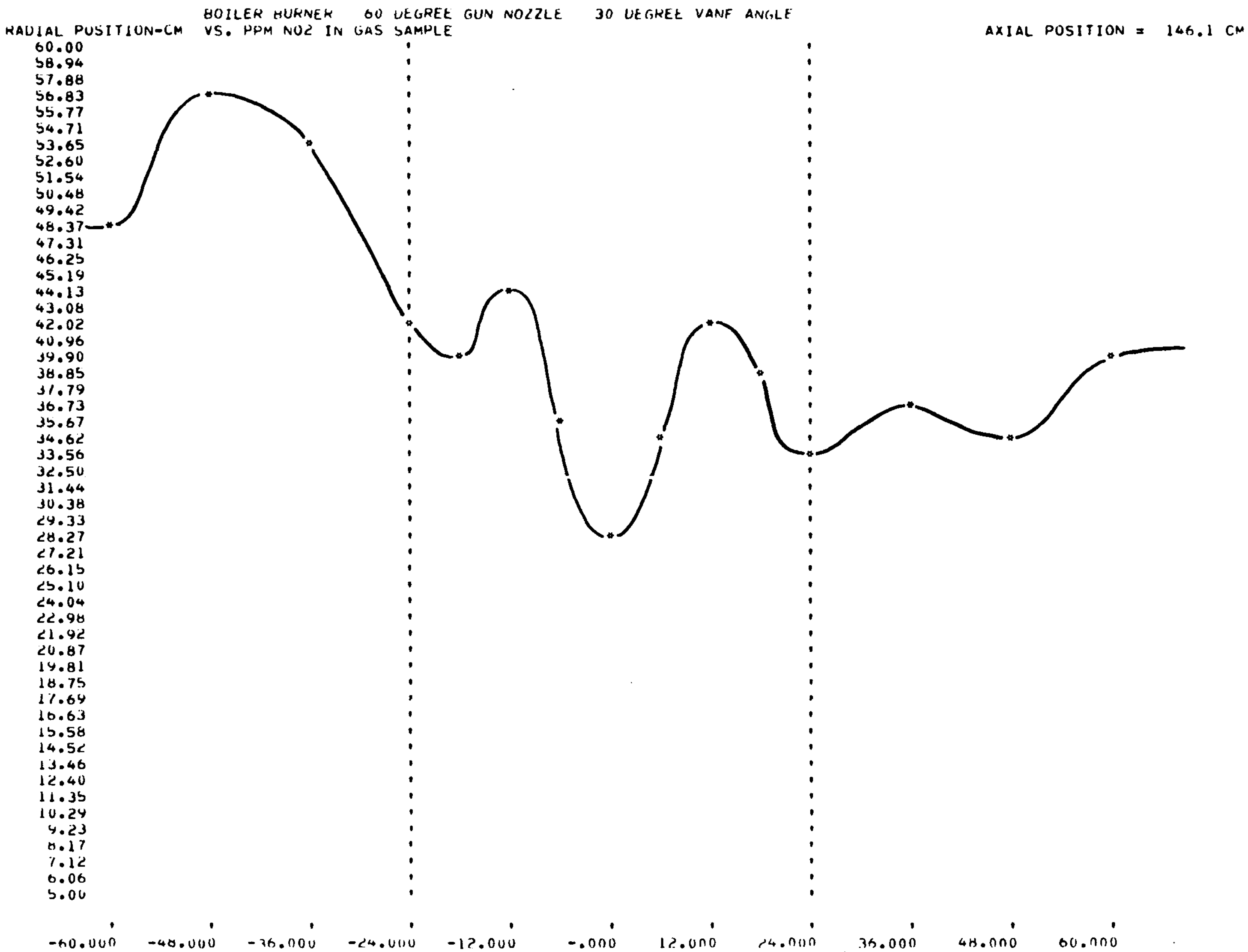

Figure 191. Radial profile of NO_2 at an axial position of 146.1 cm (movable-vane boiler burner; 30-degree vane angle)

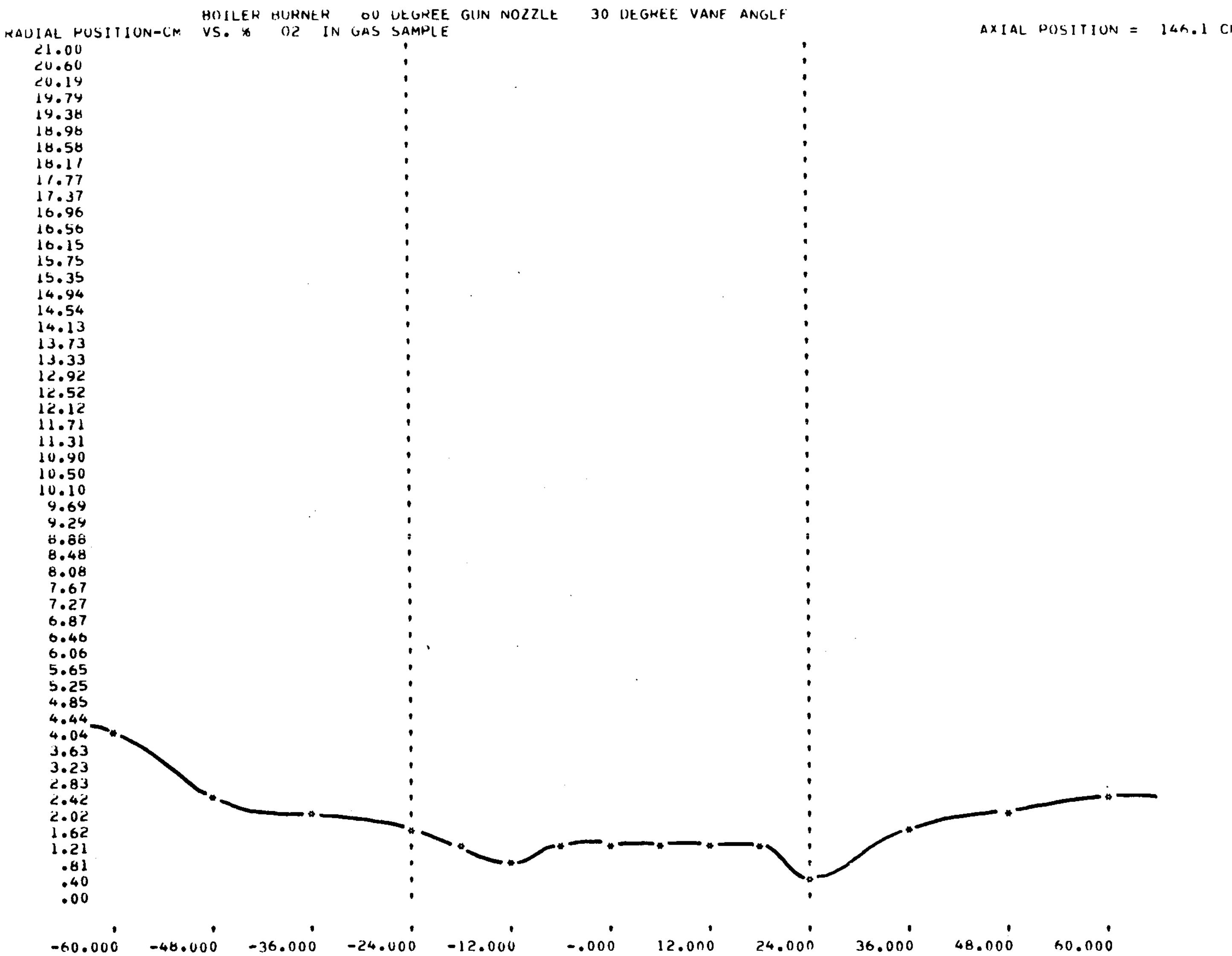

Figure 192. Radial profile of O_2 at an axial position of 146.1 cm (movable-vane boiler burner; 30-degree vane angle)

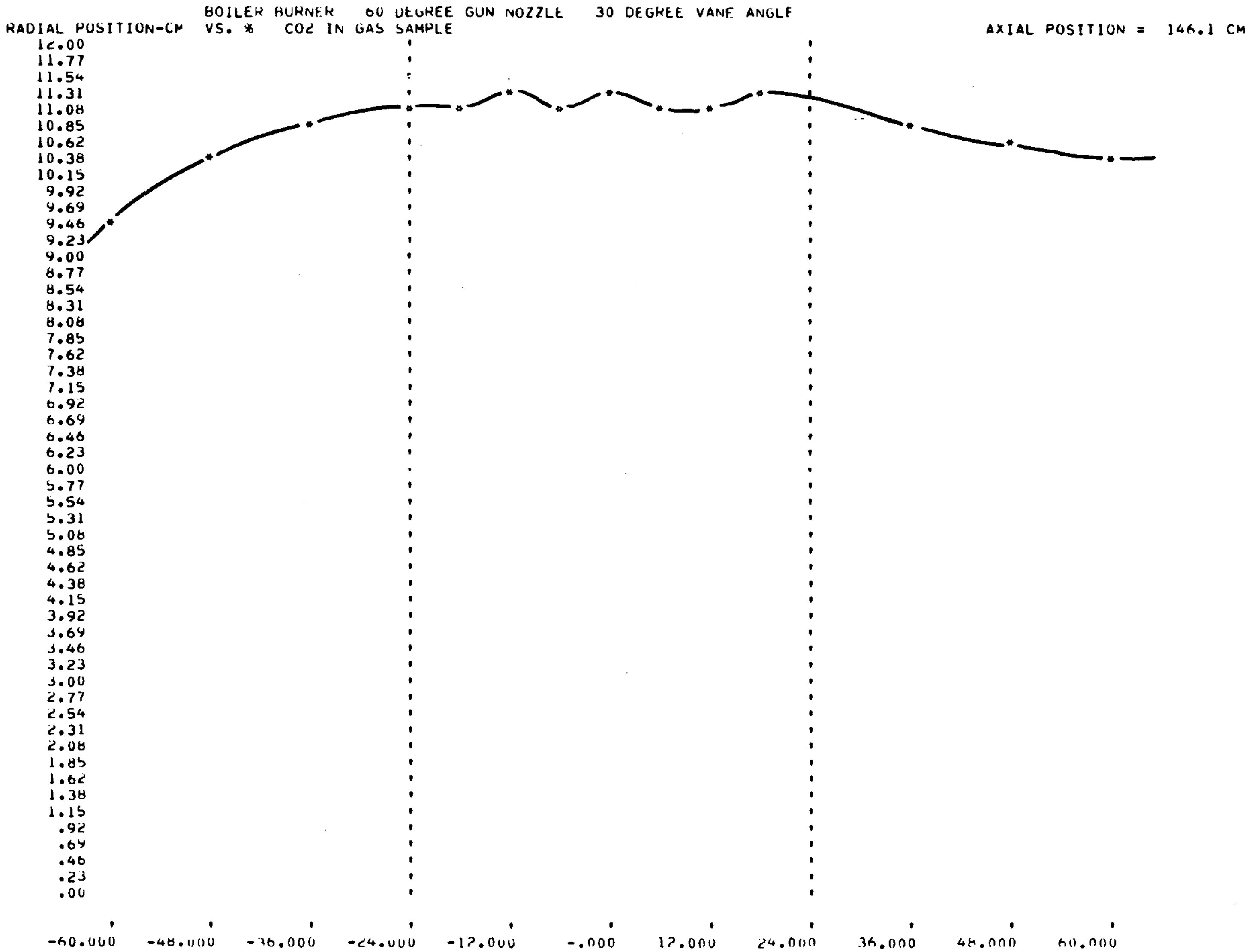

Figure 193. Radial profile of CO_2 at an axial position of 146.1 cm (movable-vane boiler burner; 30-degree vane angle)

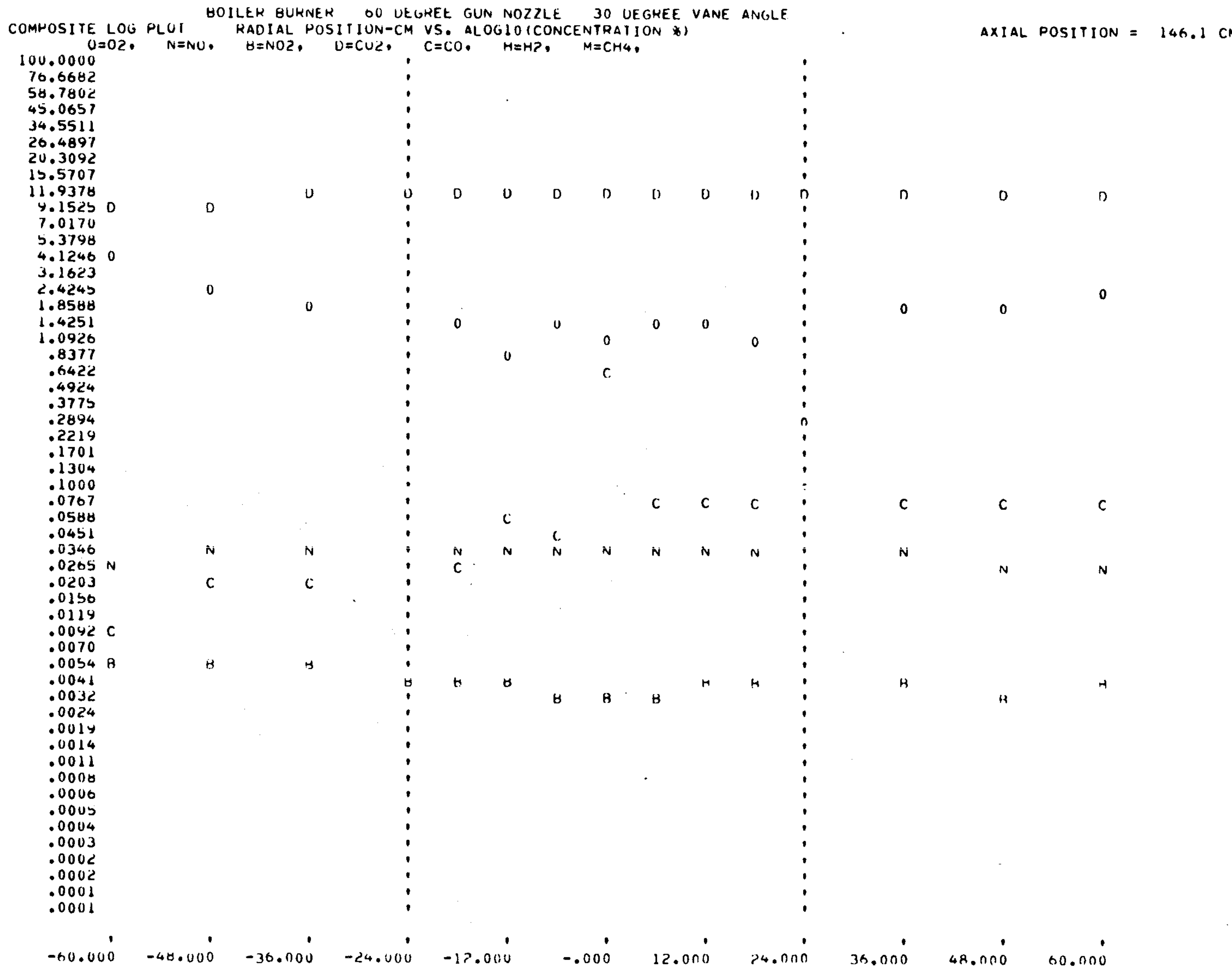

Figure 194. Radial profile of all the gases at an axial position of 146.1 cm (movable-vane boiler burner; 30-degree vane angle)

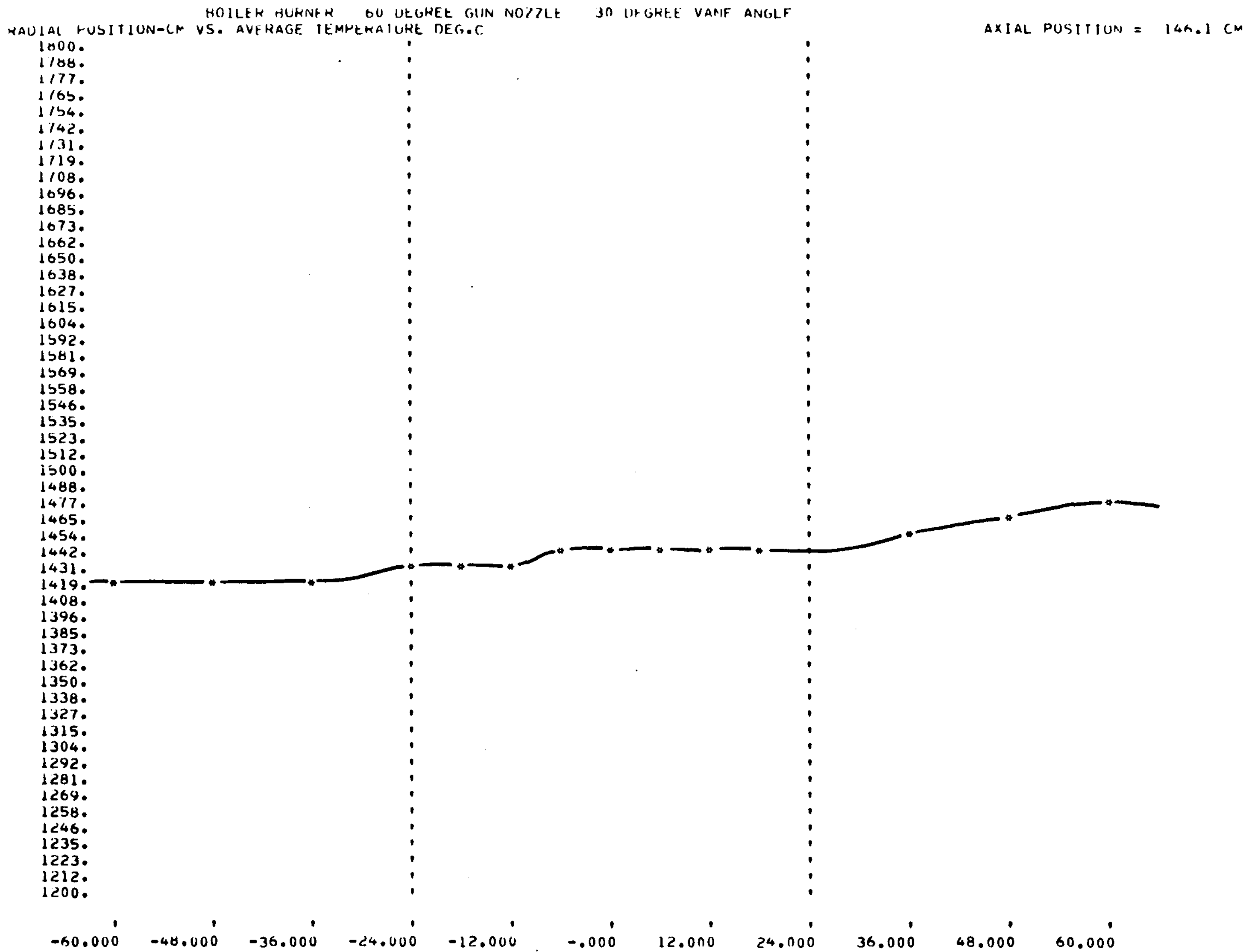

Figure 195. Radial profile of temperature at an axial position of 146.1 cm (movable-vane boiler burner; 30-degree vane angle)

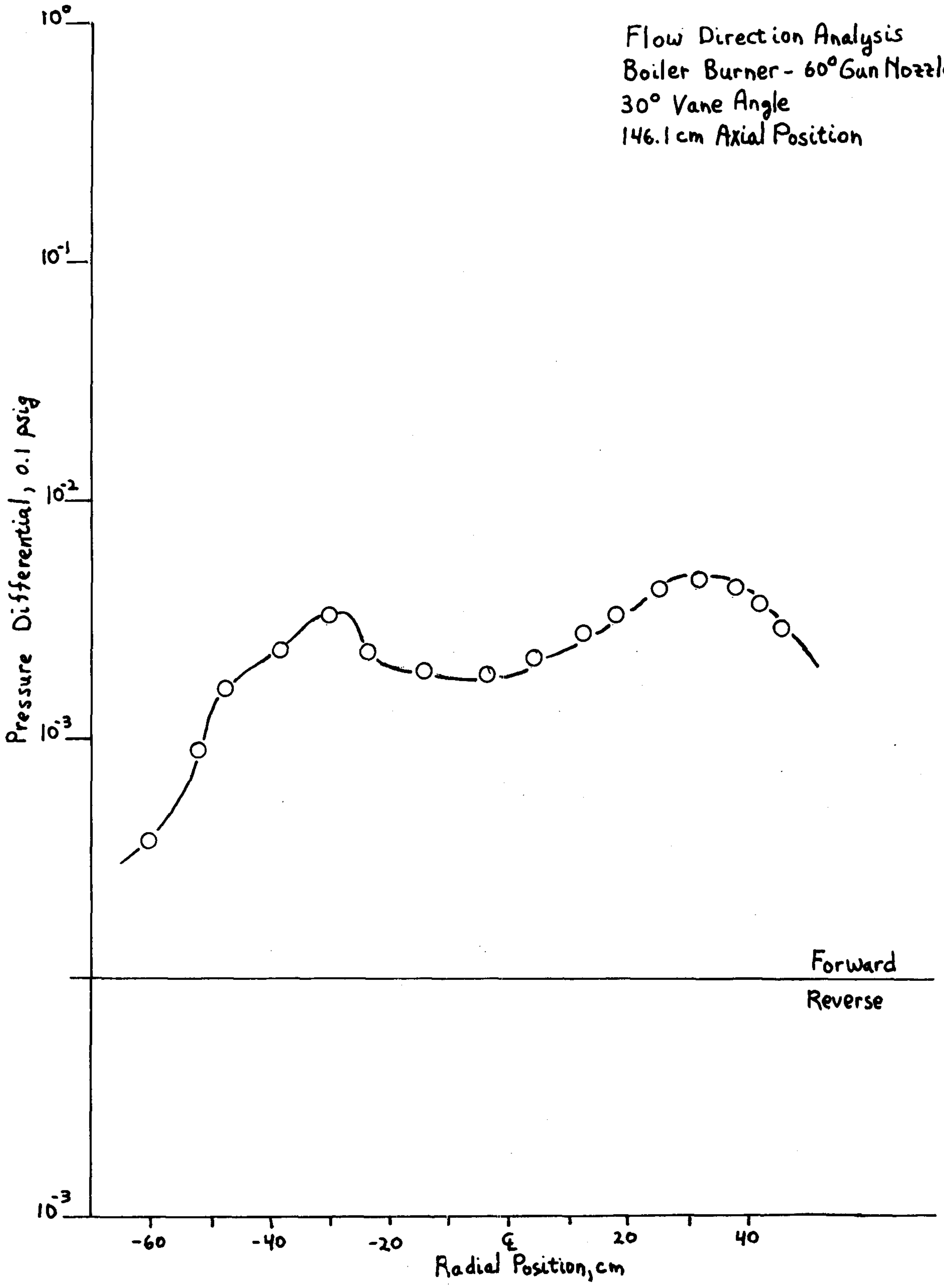

Figure 196. Radial profile of flow direction at an axial position of 146. 1 cm (movable-vane boiler burner; 30-degree vane angle)

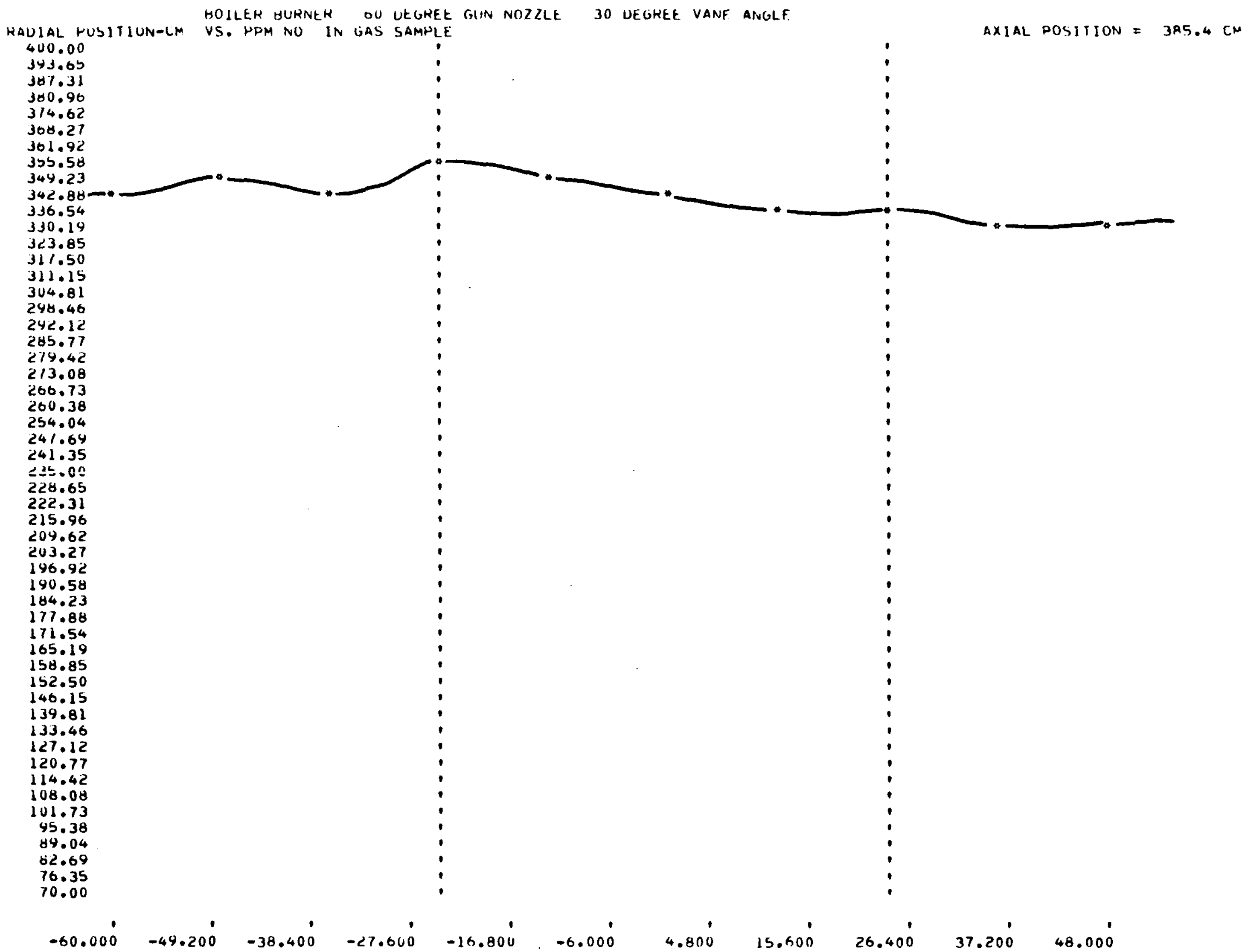

Figure 197. Radial profile of NO at an axial position of 385.4 cm (movable-vane boiler burner; 30-degree vane angle)

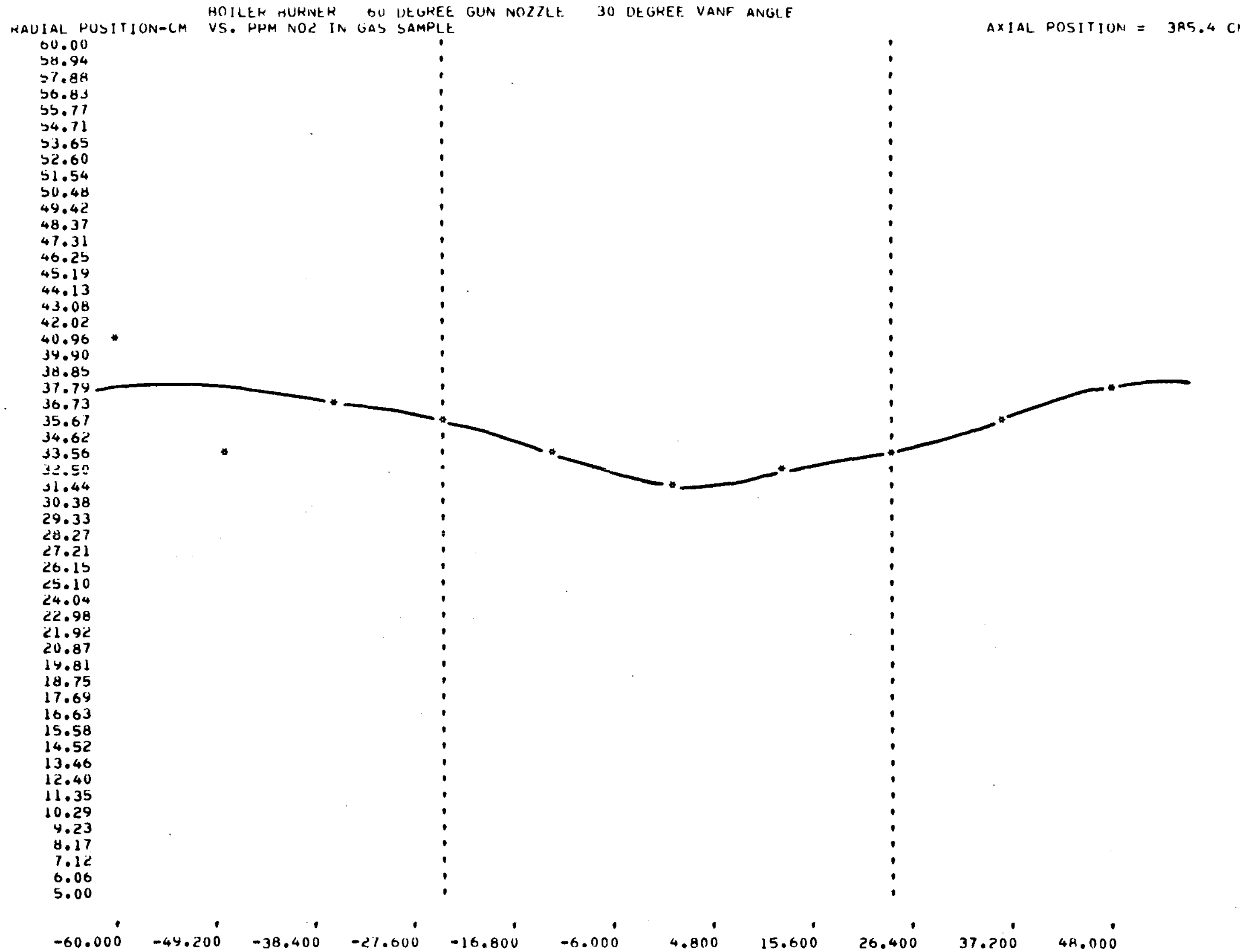

Figure 198. Radial profile of NO_2 at an axial position of 385.4 cm (movable-vane boiler burner; 30-degree vane angle)

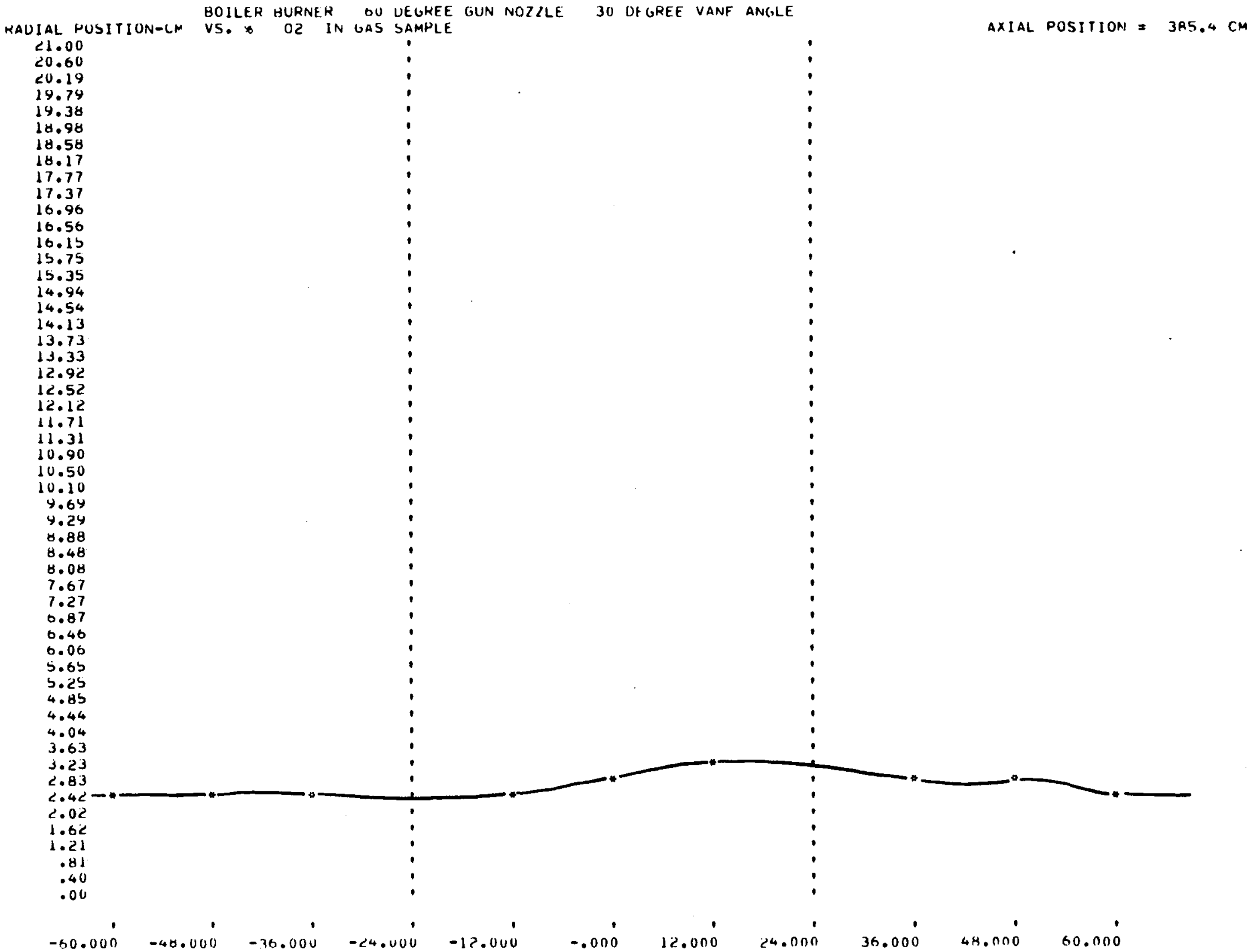

Figure 199. Radial profile of O_2 at an axial position of 385.4 cm (movable-vane boiler burner; 30-degree vane angle)

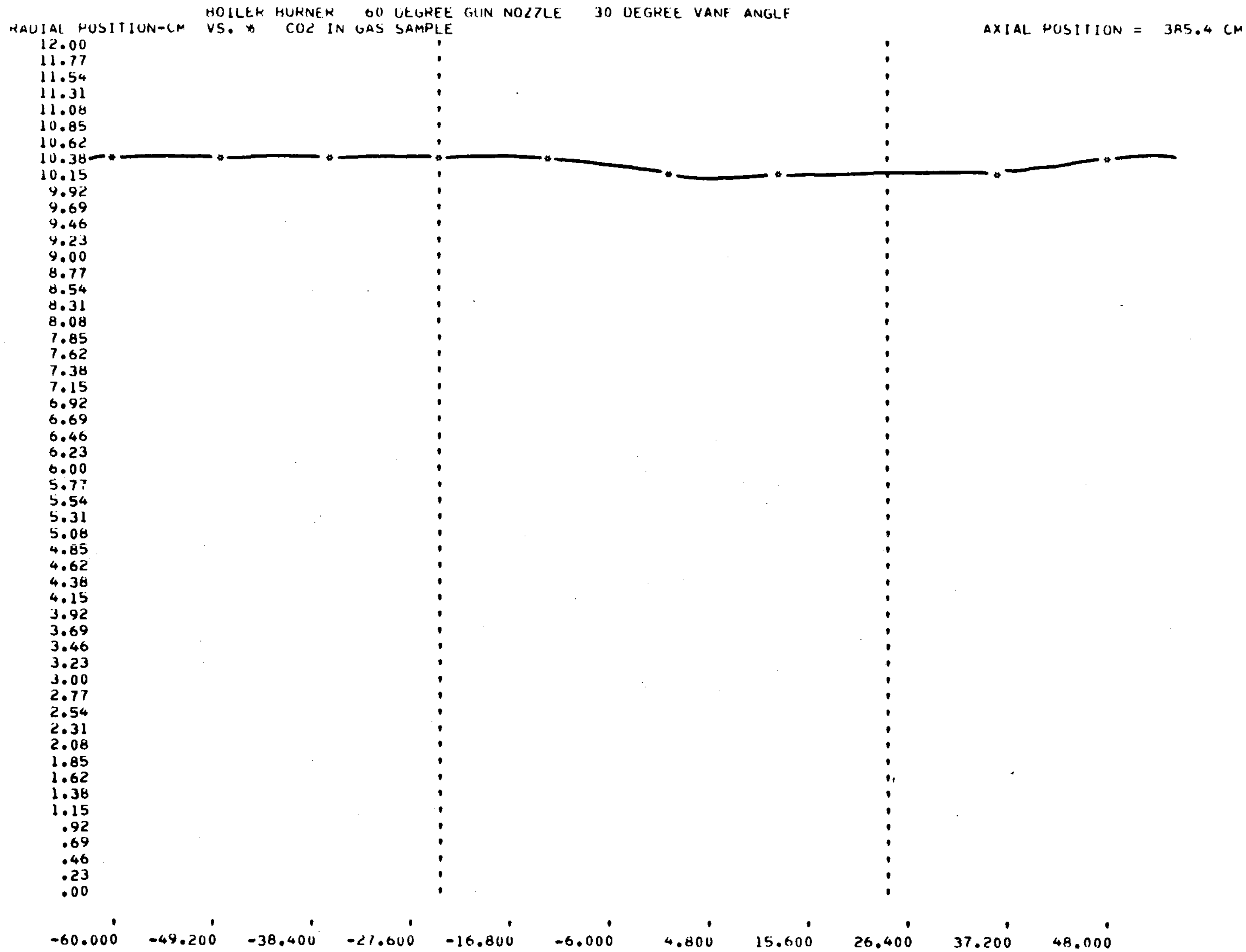

Figure 200. Radial profile of CO_2 at an axial position of 385. 4 cm
(movable-vane boiler burner; 30-degree vane angle)

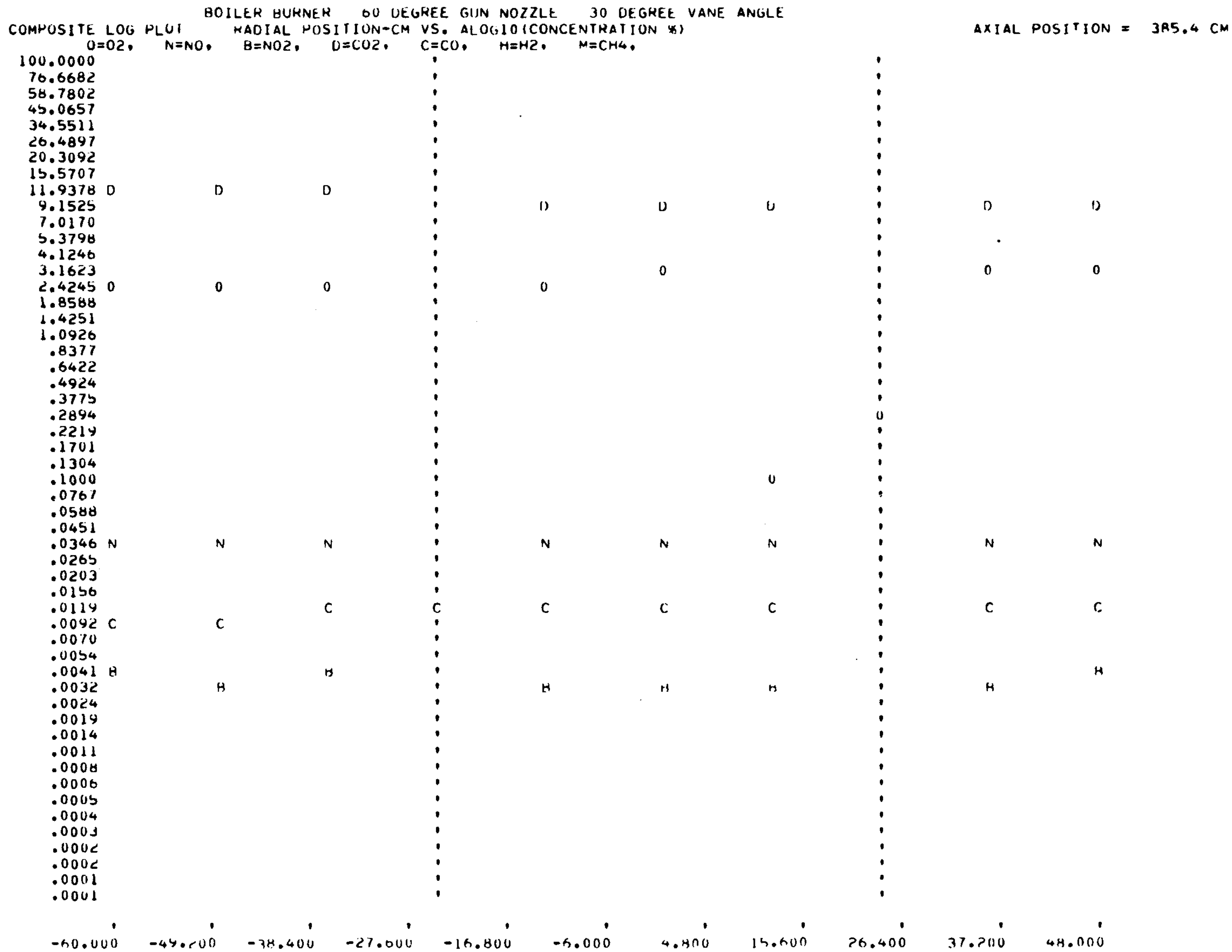

Figure 201. Radial profile of all the gases at an axial position of 385.4 cm (movable-vane boiler burner; 30-degree vane angle)

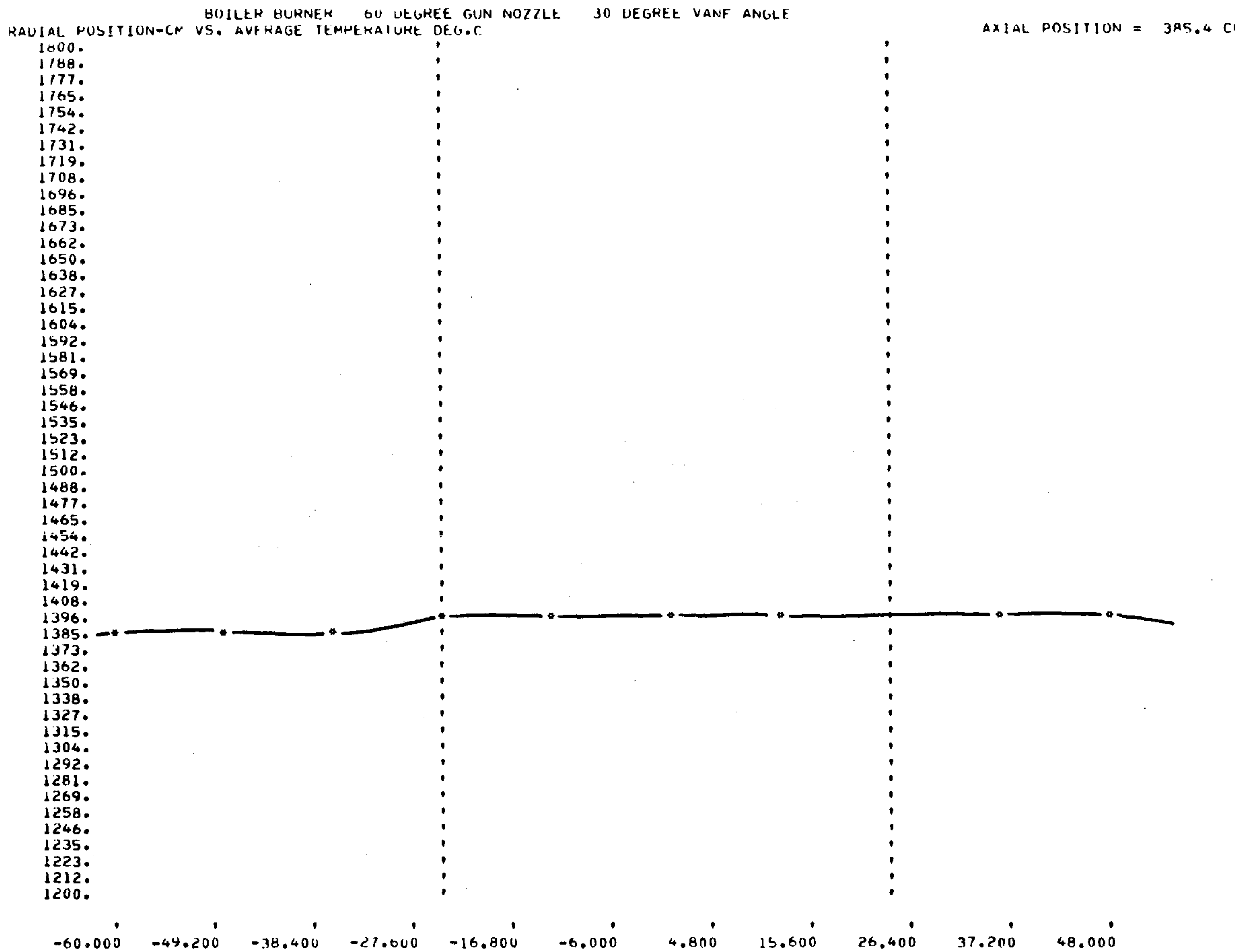

Figure 202. Radial profile of temperature at an axial position of 385. 4 cm (movable-vane boiler burner; 30-degree vane angle)

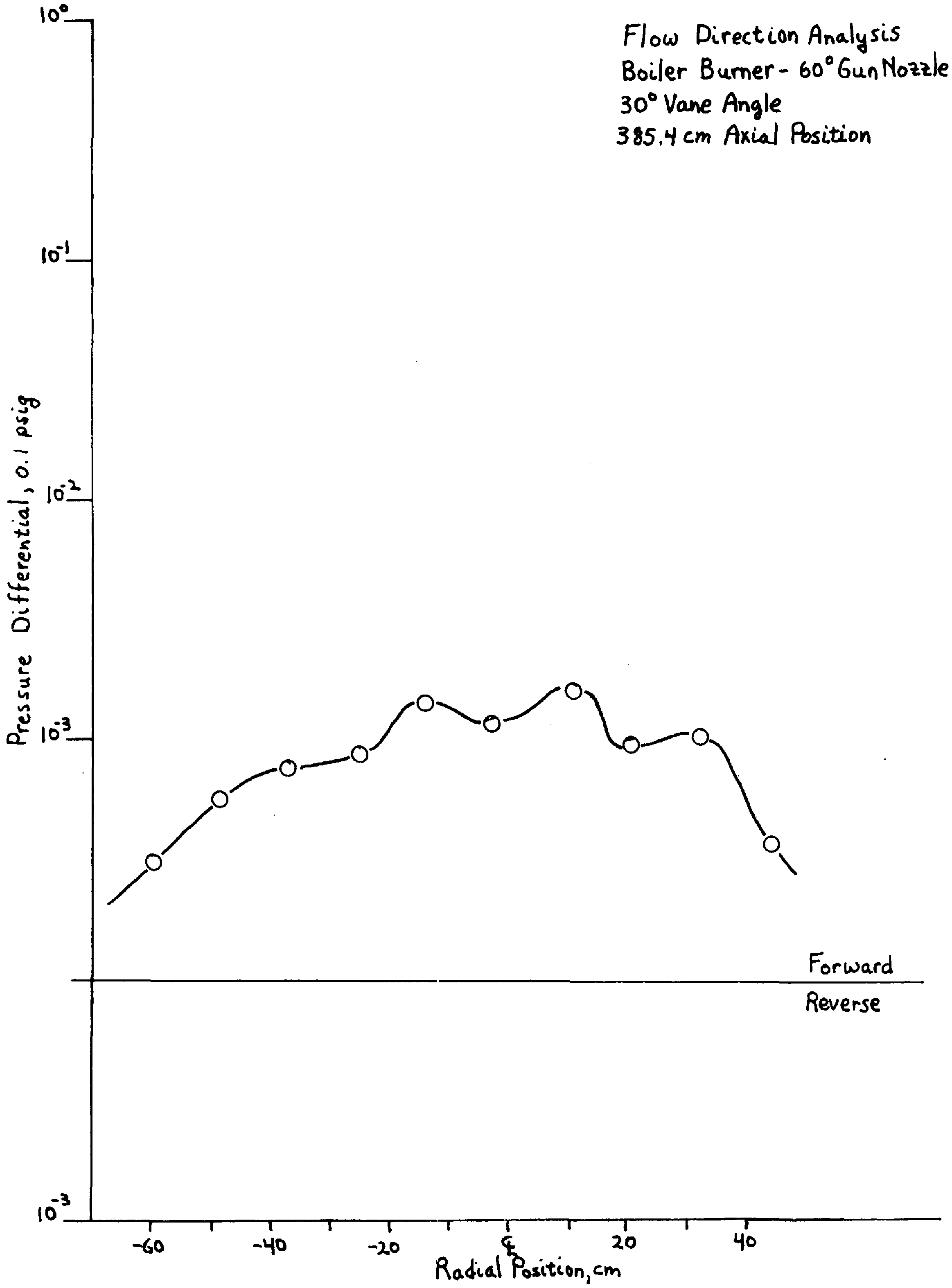

Figure 203. Radial profile of flow direction at an axial position of 385.4 cm (movable-vane boiler burner; 30-degree vane angle)

Movable-Vane Boiler Burner With 30-Degree Vane Angle

The first group of in-the-flame profiles, presented in Figures 168 through 203 were collected under burner operating conditions recommended by a utility boiler manufacturer. The gas input was 2982 SCFH with a sonic velocity.

Flow direction analyses at the 5.1-cm axial position depicts a Type III flame. Secondary recirculation zones exist in the regions –60 cm to –32 cm and 34 cm to 60 cm. Inside the edge of the burner block, two peaks occur at –24 cm and +24 cm. The primary recirculation zone occurs between –12 cm and 4 cm with its minimum at –6 cm.

Correlating the 5.1-cm axial position temperature profile with the above flow analysis, a constant temperature of 1454°C exists in the secondary recirculation zone between –60 cm and –32 cm (compared with a wall temperature of 1387°C). A peak temperature of 1796°C was measured at the –21 cm radial position, just inside the edge of the burner block (–25 cm). This position contains a gas composition whose time-averaged value is only 1% above the fuel/air stoichiometric ratio. The stoichiometric ratios of fuel and air are estimated to occur at –21 cm and –3.7 cm.

Figure 168, the plot of nitric oxide versus radial position, shows that the nitric oxide concentration in the secondary recirculation zone (–60 cm to –32 cm) averaged about 352 ppm, as compared with the flue concentration of 340 ppm. Comparing this with the average NO concentration of 140 ppm in the forward flow regions within the burner block indicates that, at 20.1 cm downstream of the gas injector, 41% of the flue concentration of nitric oxide appears within the combustion zone. The minimum concentrations of NO measured between 12 cm and 24 cm occur within the region where a large jet of secondary combustion air was detected.

The plot of nitrogen dioxide versus radial position (Figure 169) shows symmetry about the centerline of the burner. The secondary recirculation zones have concentrations on the order of 52 ppm, as compared with the flue value of 57 ppm. Minimum concentrations of nitrogen dioxide were measured at –24 cm and +18 cm, with respective levels of 25 ppm and 31 ppm. A peak occurs within the burner-block region at 6 cm, with a concentration of 52 ppm.

The oxygen profile at the 5.1-cm axial position (Figure 170) shows peaks at –21 cm and +18 cm, with concentrations of 3.4% and 13.7%, respectively, which represent the secondary combustion air input. This large difference in oxygen concentration may arise from 1) packing of the secondary combustion air to the right side of the burner; and/or 2) since the fuel is injected through small discrete orifices, the probing plane may have intersected a fuel jet to the left of the burner's centerline. Comparing the average concentrations of unburned fuels within the burner block with the left and right of the burner centerline shows 4.7% versus 1.6% CO, respectively, and 4.2% versus 0.9% hydrogen, respectively. Thus, there is experimental proof that we did intersect a fuel jet to the left of the centerline of the burner; however, this does not exclude the possibility of combustion air packing within the burner plenum.

The methane profile (Figure 171) shows peaks at –24 cm and +24 cm, with concentrations of 0.2% and 0.1%, respectively. These positions correspond with the outside edge of the burner block. The major combustibles present are hydrogen and carbon monoxide (Figure 173), both having their maximum concentrations at –6 cm, with hydrogen at a peak concentration of 7.6% and carbon monoxide at 7.0%.

The curve of carbon dioxide versus radial position (Figure 172) shows an average concentration of 10.6% in the secondary recirculation zones compared with a flue value of 10.3%. Within the burner block region, a maximum concentration of 8.8% is measured at a –18 cm radial position. The temperature measured at –18 cm was 1700°C, 96°C below the maximum temperature level at –21 cm. The minimum carbon dioxide concentration of 4.6% was detected at the 18 cm radial position. The measured temperature at this position was 1378°C, or 28°C above the minimum temperature that was detected at the 21 cm radial position.

The in-the-flame data collected at the 26-cm axial position are listed in Tables 30 and illustrated in Figures 176 through 182.

Flow direction analyses at the 26-cm axial position (Figure 182) indicates that the primary recirculation pattern still exists. The zone boundaries are [illegible] cm and 20 cm. The secondary recirculation zone occurs between –60 cm and −55 cm. Since we are probing a rotating flame, while our sampling plane is fixed, we are not analyzing the same volume of gas that was investigated at the other axial positions.

Figure 175 presents the NO concentrations versus radial position at the 26-cm axial position. The average concentration in the reverse flow region is 249 ppm, which is 73% of the level measured in the flue. The average concentration in the forward flow regions is 298 ppm.

The radial profile of NO_2 at the 26-cm axial position is shown in Figure 177. There is a distinctive minimum at the 24-cm radial position. This corresponds to the position where the peak oxygen concentration was measured. The minimum occurs just inside the forward flow zone.

Figure 178 illustrates the oxygen versus radial position for the 26-cm axial position. A slight minimum occurs at −12 cm, with a maximum at +24 cm. The minimum occurs within the primary recirculation zone and is compared with large concentrations of carbon monoxide (5.5%) and hydrogen (6.6%). The maximum appears at 24 cm, which is just inside the forward flow region. Again, the asymmetry of the fuel-air distributions, similar to the observations made from Table 29 and Figure 170 suggests a packing of the combustion air.

The carbon dioxide-versus-radial position profile is given in Figure 179. In the forward flow regions, a rather constant concentration of 10.3% has been reached. The primary recirculation zone shows a much lower average concentration of 8.9%.

The temperature profile (Figure 181) shows maximums of 1613°C and 1622°C at 36 cm and 6 cm, respectively. These locations correlate rather well with positions where the fuel/air ratio is stoichiometric. A minimum of 1483°C occurs at 24 cm, the point where the maximum air was measured.

In-the-flame data for the 46.7-cm axial position are listed in Table 31 and presented in Figures 183 through 189. The primary recirculation zone extends from −18 cm to +18 cm.

The concentrations of carbon monoxide and hydrogen have been reduced from their respective maximum of 5.6% and 6.8% at the 26-cm axial position to 1.8% and 0.8% at the 46.7-cm axial position. The maximum concentration of oxygen still occurs at the 24-cm radial position, with a percentage of 3.6. The NO concentration has an average concentration of 285 ppm in the primary recirculation zone and 281 ppm in the forward flow region.

The in-the-flame data collected for the 146.1-cm axial position show a general smoothing of the oxygen, carbon dioxide, and temperature profiles. This data is listed in Table 32 with graphic representations in Figures 190 through 196. The flow profile no longer displays a primary recirculation zone. All measured flow is in the forward direction. Combustion is completed, with only trace amounts of carbon monoxide being detected. The average concentration of NO is 316 ppm, or 24 ppm less than the flue concentration.

Figures 173, 180, 187, 194, and 201 show composite log plots of concentration versus radial position within the composition range of 0.0001% (1 ppm) to 100%. In these plots, the interrelationships between concentration variations of oxygen, nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, hydrogen, and methane can easily be visualized.

Figures 175, 182, 189, 196, and 203 show flow direction versus radial position. These profiles show the positions of the primary and secondary forward flow zones, recirculation zones (reverse flow), and of the shear and boundary layers.

Figures 174, 181, 188, 195, and 202 are plots of the average temperatures measured versus radial positions.

Movable-Vane Boiler Burner With 15-Degree Vane Angle

From data collected during the input/output tests, we discovered that an effective and economic way to reduce NO_x emissions from the boiler burner was to decrease the tangential velocity component (swirl) of the combustion air. For this trial series, the vane angle was changed from 30 degrees to 15 degrees. Because of the absence of flame luminosity, it was impossible to determine visual flame length. The furnace operating conditions for which these in-the-flame data were collected are listed in Table 34. A complete listing of the pollution-control test data is given in Tables 35 through 39, and full graphic illustrations of these data are presented in Figures 204 through 240.

Table 35. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 5.1 cm
(Movable-Vane Boiler Burner; 15-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 15 DEGREE VANE ANGLE

AXIAL POSITION = 5.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	3.4	?	144.	15.	9.9	.0061	?	0.0	?	?	?	?	1537.	1537.	0.
-54.	2.3	?	147.	19.	10.6	.0120	?	0.0	?	?	?	?	1543.	1543.	0.
-48.	2.1	?	156.	23.	10.5	.0132	?	0.0	?	?	?	?	1539.	1539.	0.
-42.	1.8	?	163.	21.	10.8	.0233	?	0.0	?	?	?	?	1537.	1537.	0.
-36.	1.7	?	156.	17.	10.9	.0476	?	0.0	?	?	?	?	1530.	1530.	0.
-30.	.4	79.1	82.	11.	7.0	5.1000	5.0	1.8	.4	0.0	0.0	0.0	1522.	1522.	0.
-24.	2.3	79.6	74.	5.	6.8	5.0000	4.4	.8	.1	0.0	0.0	0.0	1673.	1673.	0.
-21.	3.8	81.9	66.	4.	7.1	3.7000	2.7	0.0	0.0	0.0	0.0	0.0	1703.	1703.	0.
-18.	5.2	82.0	61.	7.	6.9	2.9000	2.1	0.0	0.0	0.0	0.0	0.0	1582.	1582.	0.
-15.	8.1	82.0	57.	10.	6.1	1.7000	.9	0.0	0.0	0.0	0.0	0.0	1487.	1487.	0.
-9.	14.6	80.7	25.	5.	3.7	.2000	0.0	0.0	0.0	0.0	0.0	0.0	1335.	1335.	0.
-6.	15.4	?	20.	7.	3.5	.0547	?	0.0	?	?	?	?	1328.	1328.	0.
-3.	18.9	?	14.	6.	1.2	.0589	?	0.0	?	?	?	?	1287.	1287.	0.
0.	16.3	80.1	18.	13.	2.3	.4000	0.0	.1	0.0	0.0	0.0	0.0	1364.	1364.	0.
3.	14.8	80.4	23.	17.	3.0	.5000	.4	.2	0.0	0.0	0.0	0.0	1457.	1457.	0.
6.	15.0	79.1	27.	15.	3.8	.7000	.3	.2	0.0	0.0	0.0	0.0	1499.	1499.	0.
9.	12.4	81.2	30.	16.	4.0	.9000	.5	.1	0.0	0.0	0.0	0.0	1513.	1513.	0.
15.	3.9	83.4	47.	15.	6.6	4.2000	.6	.3	0.0	0.0	0.0	0.0	1540.	1540.	0.
18.	.9	78.8	50.	15.	6.5	5.2000	7.1	.5	.1	0.0	0.0	0.0	1565.	1565.	0.
21.	.7	78.7	52.	13.	6.5	6.4000	6.0	.6	.3	0.0	0.0	0.0	1561.	1561.	0.
24.	.1	71.2	36.	5.	5.1	8.7000	9.0	3.8	1.5	0.0	0.0	0.0	1593.	1593.	0.
30.	.8	84.8	88.	9.	10.9	1.6000	.9	0.0	0.0	0.0	0.0	0.0	1550.	1550.	0.
36.	2.1	?	157.	13.	10.6	.0620	?	0.0	?	?	?	?	1505.	1505.	0.
42.	2.0	?	142.	19.	10.8	.0172	?	0.0	?	?	?	?	1505.	1505.	0.
48.	2.1	?	140.	15.	10.7	.0099	?	0.0	?	?	?	?	1497.	1497.	0.
60.	2.1	?	141.	14.	10.7	.0107	?	0.0	?	?	?	?	1485.	1485.	0.

Table 36. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 26.0 cm
(Movable-Vane Boiler Burner; 15-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 15 DEGREE VANE ANGLE

AXIAL POSITION = 26.0 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	1.1	86.9	140.	19.	10.4	.5000	0.0	0.0	0.0	0.0	0.0	0.0	1527.	1527.	0.
-54.	1.2	86.3	143.	17.	10.5	.7000	.2	0.0	0.0	0.0	0.0	0.0	1542.	1542.	0.
-48.	.8	85.1	131.	10.	9.8	2.2000	1.3	0.0	0.0	0.0	0.0	0.0	1567.	1567.	0.
-42.	.3	84.3	126.	12.	9.3	3.2000	2.0	0.0	0.0	0.0	0.0	0.0	1609.	1609.	0.
-36.	.2	81.5	106.	7.	7.6	5.6000	4.0	.1	0.0	0.0	0.0	0.0	1678.	1678.	0.
-30.	.2	80.5	78.	3.	7.1	6.4000	4.8	.1	0.0	0.0	0.0	0.0	1695.	1695.	0.
-24.	.1	82.5	110.	2.	8.0	4.5000	3.5	.5	0.0	0.0	0.0	0.0	1626.	1626.	0.
-21.	1.0	82.7	119.	1.	8.0	4.2000	2.8	.4	0.0	0.0	0.0	0.0	1598.	1598.	0.
-18.	1.7	82.6	106.	2.	7.8	3.7000	2.6	.6	0.0	0.0	0.0	0.0	1564.	1564.	0.
-15.	1.9	82.8	102.	9.	7.8	3.6000	2.4	.5	0.0	0.0	0.0	0.0	1553.	1553.	0.
-12.	5.2	82.1	69.	5.	7.3	1.6000	2.9	0.0	0.0	0.0	0.0	0.0	1548.	1548.	0.
-9.	5.9	82.6	74.	3.	8.2	1.5000	.8	0.0	0.0	0.0	0.0	0.0	1555.	1555.	0.
-6.	7.0	82.0	70.	2.	8.0	1.3000	.7	0.0	0.0	0.0	0.0	0.0	1565.	1565.	0.
-3.	5.8	81.1	72.	5.	6.7	1.8000	3.7	0.0	0.0	0.0	0.0	0.0	1573.	1573.	0.
0.	4.9	82.6	76.	10.	6.9	2.6000	2.1	0.0	0.0	0.0	0.0	0.0	1568.	1568.	0.
3.	6.1	82.5	61.	9.	6.3	2.5000	1.7	0.0	0.0	0.0	0.0	0.0	1564.	1564.	0.
6.	5.5	81.6	64.	10.	6.4	2.8000	2.8	0.0	0.0	0.0	0.0	0.0	1562.	1562.	0.
9.	4.1	79.3	68.	11.	6.4	5.9000	4.3	.1	0.0	0.0	0.0	0.0	1554.	1554.	0.
12.	3.3	80.7	72.	12.	7.0	3.8000	3.2	1.1	0.0	0.0	0.0	0.0	1550.	1550.	0.
15.	1.8	81.6	58.	13.	8.0	4.1000	3.0	.6	0.0	0.0	0.0	0.0	1540.	1540.	0.
18.	1.2	80.1	70.	15.	8.3	3.9000	5.0	.5	0.0	0.0	0.0	0.0	1543.	1543.	0.
24.	.3	82.3	76.	17.	9.1	3.6000	3.1	.4	0.0	0.0	0.0	0.0	1558.	1558.	0.
30.	.1	82.3	84.	10.	9.7	3.3000	2.1	.1	0.0	0.0	0.0	0.0	1577.	1577.	0.
36.	.3	85.2	91.	14.	10.3	1.6000	1.7	.1	0.0	0.0	0.0	0.0	1562.	1562.	0.
42.	.7	84.0	94.	19.	11.2	.4600	0.0	0.0	0.0	0.0	0.0	0.0	1541.	1541.	0.
48.	1.1	?	110.	21.	11.2	.0760	?	0.0	?	?	?	?	1528.	1528.	0.
54.	1.2	?	125.	18.	11.2	.0481	?	0.0	?	?	?	?	1520.	1520.	0.
60.	1.3	?	134.	20.	11.1	.0460	?	0.0	?	?	?	?	1513.	1513.	0.

Table 37. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 46.7 cm (Movable-Vane Boiler Burner; 15-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 15 DEGREE VANE ANGLE

AXIAL POSITION = 46.7 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	.6	85.1	135.	20.	10.1	2.0000	1.1	0.0	0.0	0.0	0.0	0.0	1493.	1493.	0.
-54.	.5	83.7	131.	19.	9.4	3.5000	1.8	0.0	0.0	0.0	0.0	0.0	1517.	1517.	0.
-48.	.5	81.8	115.	19.	8.5	5.1000	3.1	0.0	0.0	0.0	0.0	0.0	1538.	1538.	0.
-42.	.2	80.1	90.	14.	7.8	6.2000	4.2	0.0	0.0	0.0	0.0	0.0	1564.	1564.	0.
-36.	.2	79.9	94.	9.	7.5	6.8000	4.6	0.0	0.0	0.0	0.0	0.0	1553.	1553.	0.
-30.	.6	80.1	96.	14.	7.7	6.2000	4.4	0.0	0.0	0.0	0.0	0.0	1535.	1535.	0.
-24.	.8	81.6	98.	19.	8.3	5.1000	3.2	0.0	0.0	0.0	0.0	0.0	1517.	1517.	0.
-18.	1.2	82.1	101.	15.	8.5	4.6000	2.6	0.0	0.0	0.0	0.0	0.0	1503.	1503.	0.
-12.	1.8	83.5	104.	13.	9.1	2.9000	1.7	0.0	0.0	0.0	0.0	0.0	1484.	1484.	0.
-6.	2.1	84.6	107.	9.	9.3	1.9000	1.2	0.0	0.0	0.0	0.0	0.0	1477.	1477.	0.
0.	2.5	83.8	122.	11.	9.4	2.2000	1.1	0.0	0.0	0.0	0.0	0.0	1471.	1471.	0.
6.	3.8	83.0	102.	12.	8.9	2.1000	1.1	0.0	0.0	0.0	0.0	0.0	1472.	1472.	0.
12.	4.3	82.9	84.	13.	8.9	2.0000	1.1	0.0	0.0	0.0	0.0	0.0	1470.	1470.	0.
18.	4.2	82.7	106.	14.	9.2	1.9000	1.0	0.0	0.0	0.0	0.0	0.0	1465.	1465.	0.
24.	3.7	84.2	115.	15.	9.8	1.7000	.6	0.0	0.0	0.0	0.0	0.0	1471.	1471.	0.
30.	2.8	85.4	119.	14.	9.9	.5000	0.0	0.0	0.0	0.0	0.0	0.0	1468.	1468.	0.
36.	2.9	?	123.	15.	10.1	.1000	?	0.0	?	?	?	?	1459.	1459.	0.
42.	2.8	?	126.	16.	10.3	.0584	?	0.0	?	?	?	?	1457.	1457.	0.
48.	3.1	?	124.	17.	10.1	.0462	?	0.0	?	?	?	?	1452.	1452.	0.
54.	3.7	?	123.	21.	9.8	.0260	?	0.0	?	?	?	?	1449.	1449.	0.
60.	4.3	?	119.	18.	9.3	.0207	?	0.0	?	?	?	?	1444.	1444.	0.

Table 38. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 146.1 cm
(Movable-Vane Boiler Burner; 15-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 15 DEGREE VANE ANGLE

AXIAL POSITION = 146.1 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	1.7	?	188.	20.	10.8	.0324	?	0.0	?	?	?	?	1538.	1538.	0.
-54.	1.7	?	184.	22.	10.8	.0341	?	0.0	?	?	?	?	1527.	1527.	0.
-48.	1.8	?	180.	21.	10.8	.0305	?	0.0	?	?	?	?	1525.	1525.	0.
-42.	2.0	?	156.	18.	10.7	.0296	?	0.0	?	?	?	?	1517.	1517.	0.
-36.	2.1	?	164.	22.	10.6	.0282	?	0.0	?	?	?	?	1504.	1504.	0.
-30.	2.6	?	172.	19.	10.3	.0247	?	0.0	?	?	?	?	1502.	1502.	0.
-24.	3.0	?	156.	17.	10.1	.0220	?	0.0	?	?	?	?	1496.	1496.	0.
-18.	3.1	?	164.	15.	10.1	.0158	?	0.0	?	?	?	?	1494.	1494.	0.
-12.	2.8	?	156.	18.	10.2	.0201	?	0.0	?	?	?	?	1487.	1487.	0.
-6.	3.0	?	156.	20.	10.1	.0149	?	0.0	?	?	?	?	1491.	1491.	0.
0.	2.6	?	127.	25.	10.4	.0094	?	0.0	?	?	?	?	1482.	1482.	0.
6.	2.3	?	138.	24.	10.5	.0095	?	0.0	?	?	?	?	1469.	1469.	0.
12.	2.2	?	135.	20.	10.6	.0094	?	0.0	?	?	?	?	1459.	1459.	0.
18.	2.4	?	142.	23.	10.5	.0080	?	0.0	?	?	?	?	1461.	1461.	0.
24.	2.4	?	135.	26.	10.5	.0086	?	0.0	?	?	?	?	1468.	1468.	0.
30.	2.6	?	133.	30.	10.4	.0080	?	0.0	?	?	?	?	1464.	1464.	0.
36.	2.5	?	137.	32.	10.4	.0077	?	0.0	?	?	?	?	1469.	1469.	0.
42.	2.4	?	135.	31.	10.4	.0078	?	0.0	?	?	?	?	1463.	1463.	0.
48.	2.8	?	145.	28.	10.2	.0076	?	0.0	?	?	?	?	1465.	1465.	0.
54.	3.0	?	139.	24.	10.1	.0068	?	0.0	?	?	?	?	1470.	1470.	0.
60.	3.0	?	135.	26.	10.1	.0093	?	0.0	?	?	?	?	1468.	1468.	0.

Table 39. IN-THE-FLAME SAMPLING DATA AT AN AXIAL POSITION OF 385.4 cm
(Movable-Vane Boiler Burner; 15-Degree Vane Angle)

BOILER BURNER 60 DEGREE GUN NOZZLE 15 DEGREE VANE ANGLE

AXIAL POSITION = 385.4 CM

RADIAL POSITION CM	O2 %	N2 %	NO PPM	NO2 PPM	CO2 %	CO %	H2 %	CH4 %	C2H2 C2H4 %	C2H6 %	C3H6 %	C3H8 %	TEMPERATURE DEG.C AVG.	MAX.	TMAX-TAVG
-60.	2.7	?	188.	24.	10.3	.0103	?	0.0	?	?	?	?	1438.	1438.	0.
-48.	2.8	?	192.	27.	10.2	.0092	?	0.0	?	?	?	?	1443.	1443.	0.
-36.	2.6	?	194.	25.	10.3	.0095	?	0.0	?	?	?	?	1444.	1444.	0.
-24.	2.8	?	201.	25.	10.2	.0122	?	0.0	?	?	?	?	1448.	1448.	0.
-12.	2.8	?	196.	26.	10.2	.0099	?	0.0	?	?	?	?	1446.	1446.	0.
0.	2.8	?	192.	25.	10.2	.0084	?	0.0	?	?	?	?	1447.	1447.	0.
12.	2.7	?	194.	24.	10.2	.0087	?	0.0	?	?	?	?	1448.	1448.	0.
24.	2.5	?	196.	25.	10.4	.0094	?	0.0	?	?	?	?	1449.	1449.	0.
36.	2.5	?	192.	28.	10.4	.0089	?	0.0	?	?	?	?	1447.	1447.	0.
48.	2.7	?	198.	24.	10.3	.0081	?	0.0	?	?	?	?	1443.	1443.	0.
60.	2.9	?	195.	27.	10.2	.0076	?	0.0	?	?	?	?	1438.	1438.	0.

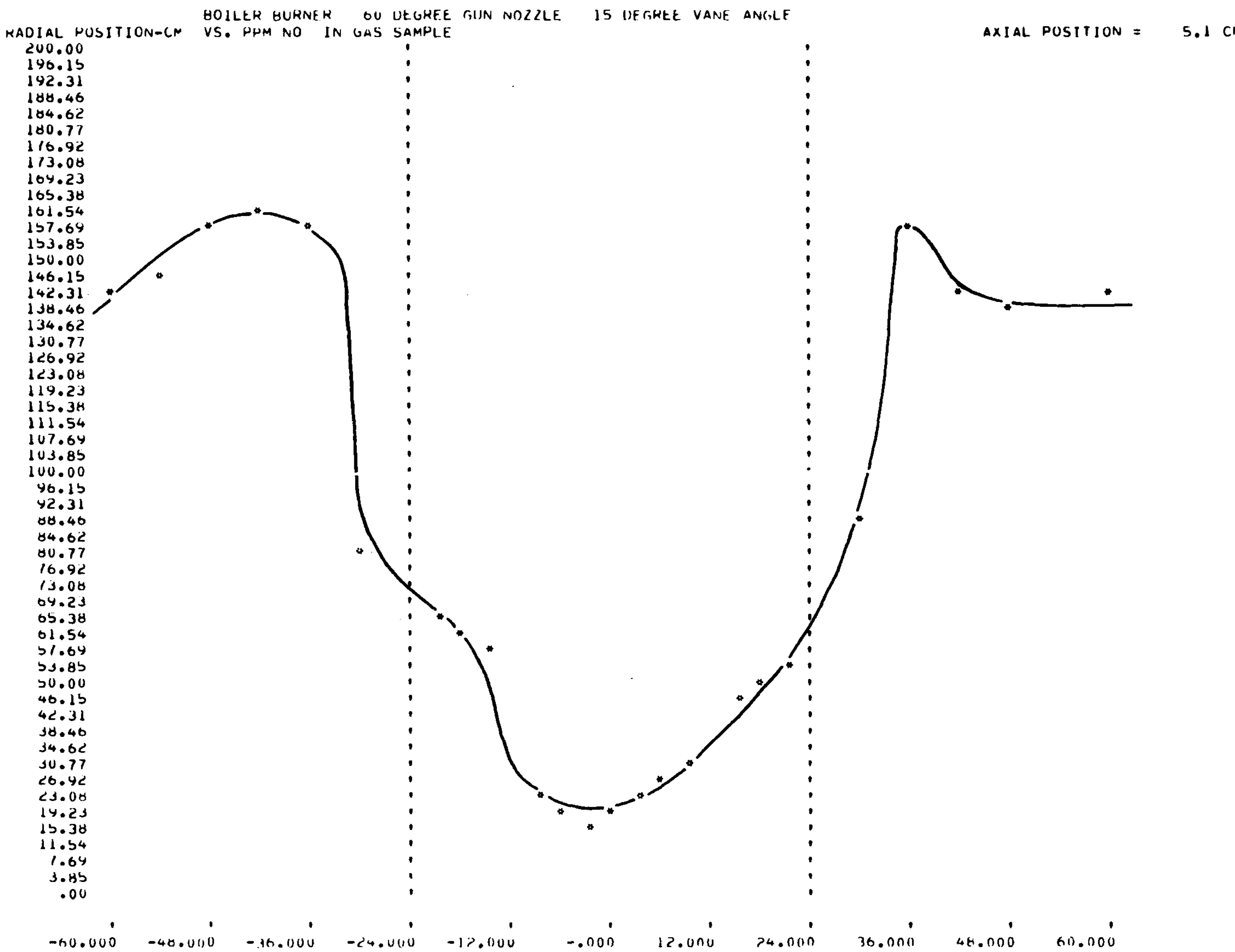

Figure 204. Radial profile of NO at an axial position of 5.1 cm
(movable-vane boiler burner; 15-degree vane angle)

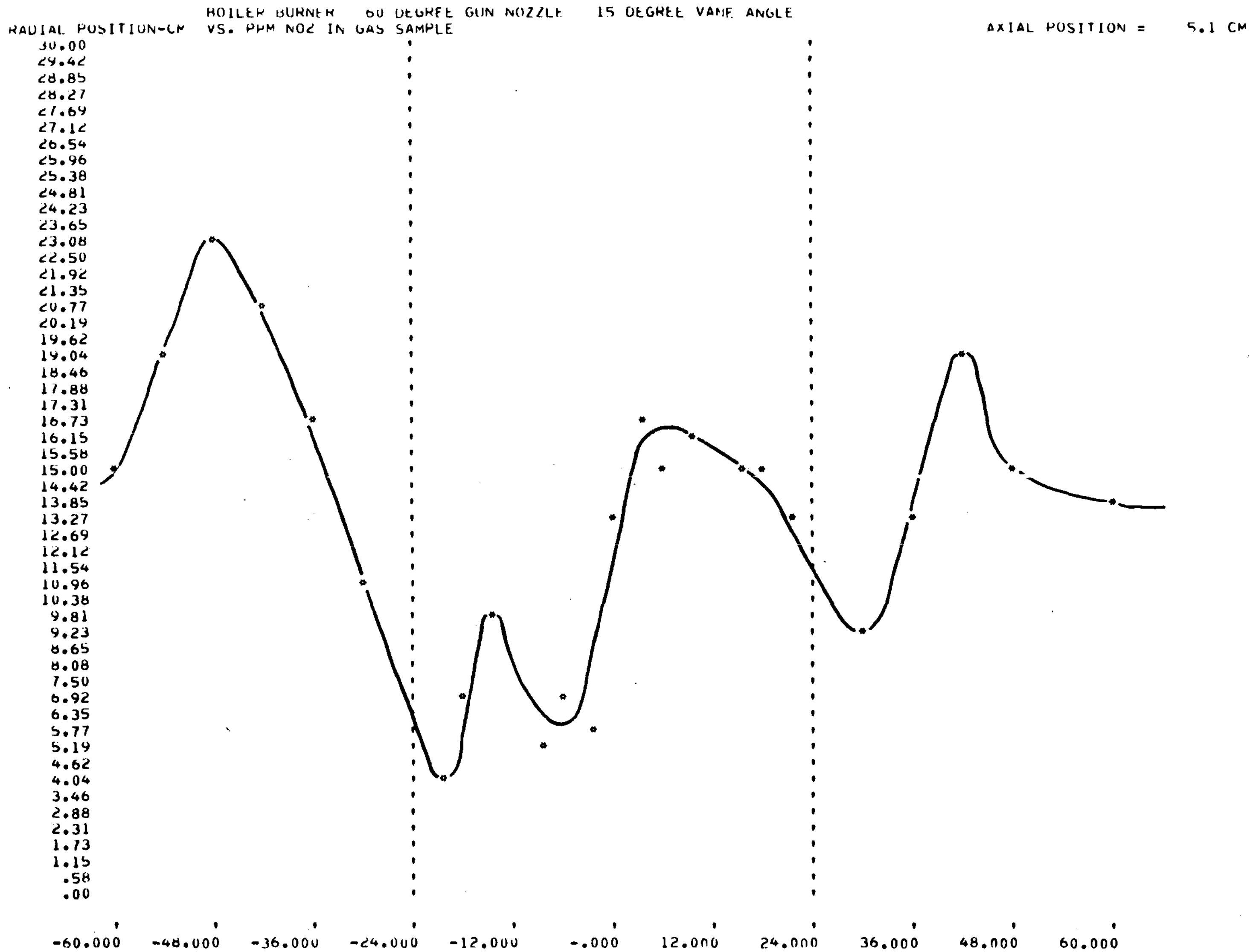

Figure 205. Radial profile of NO_2 at an axial position of 5.1 cm (movable-vane boiler burner; 15-degree vane angle)

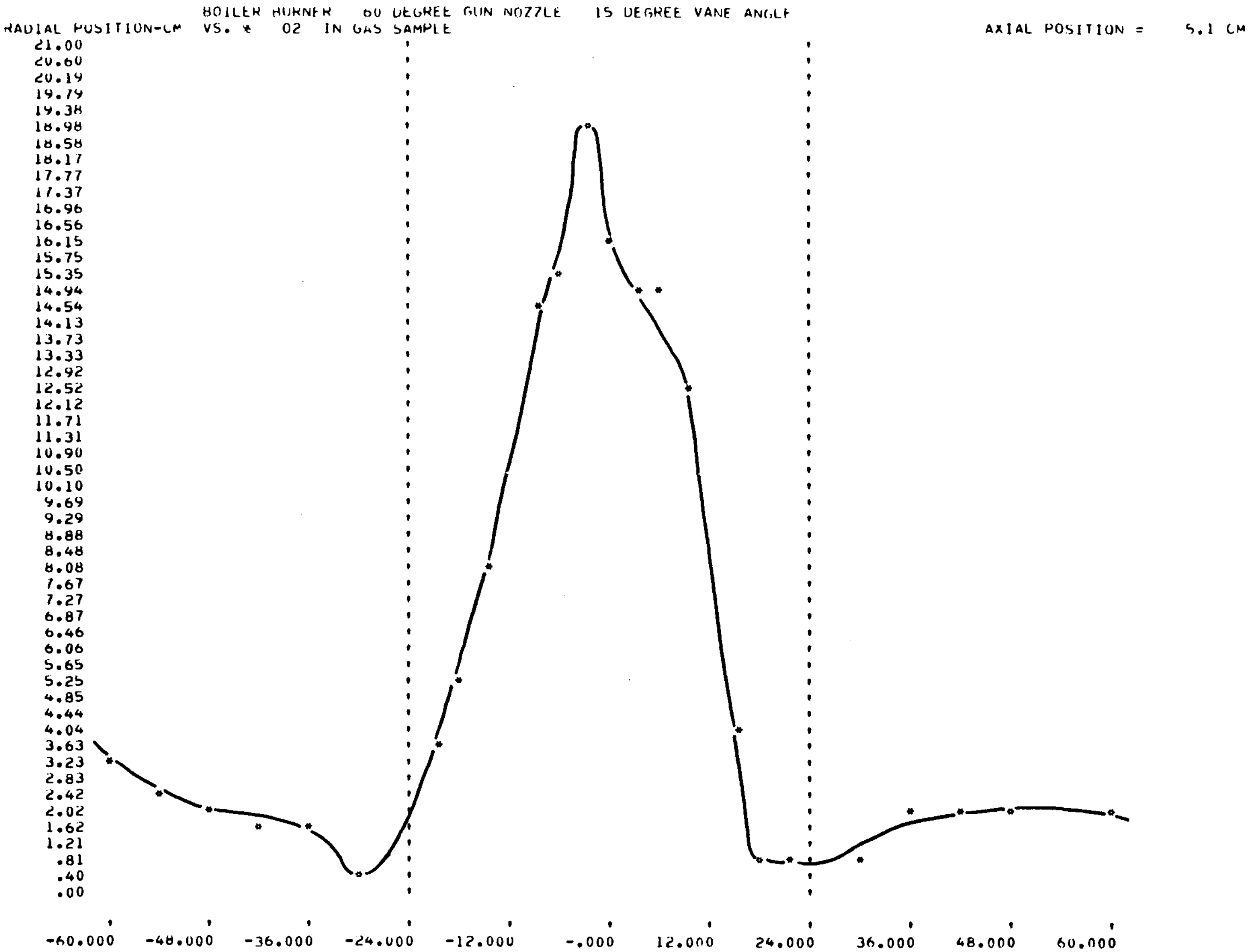

Figure 206. Radial profile of O_2 at an axial position of 5.1 cm (movable-vane boiler burner; 15-degree vane angle)

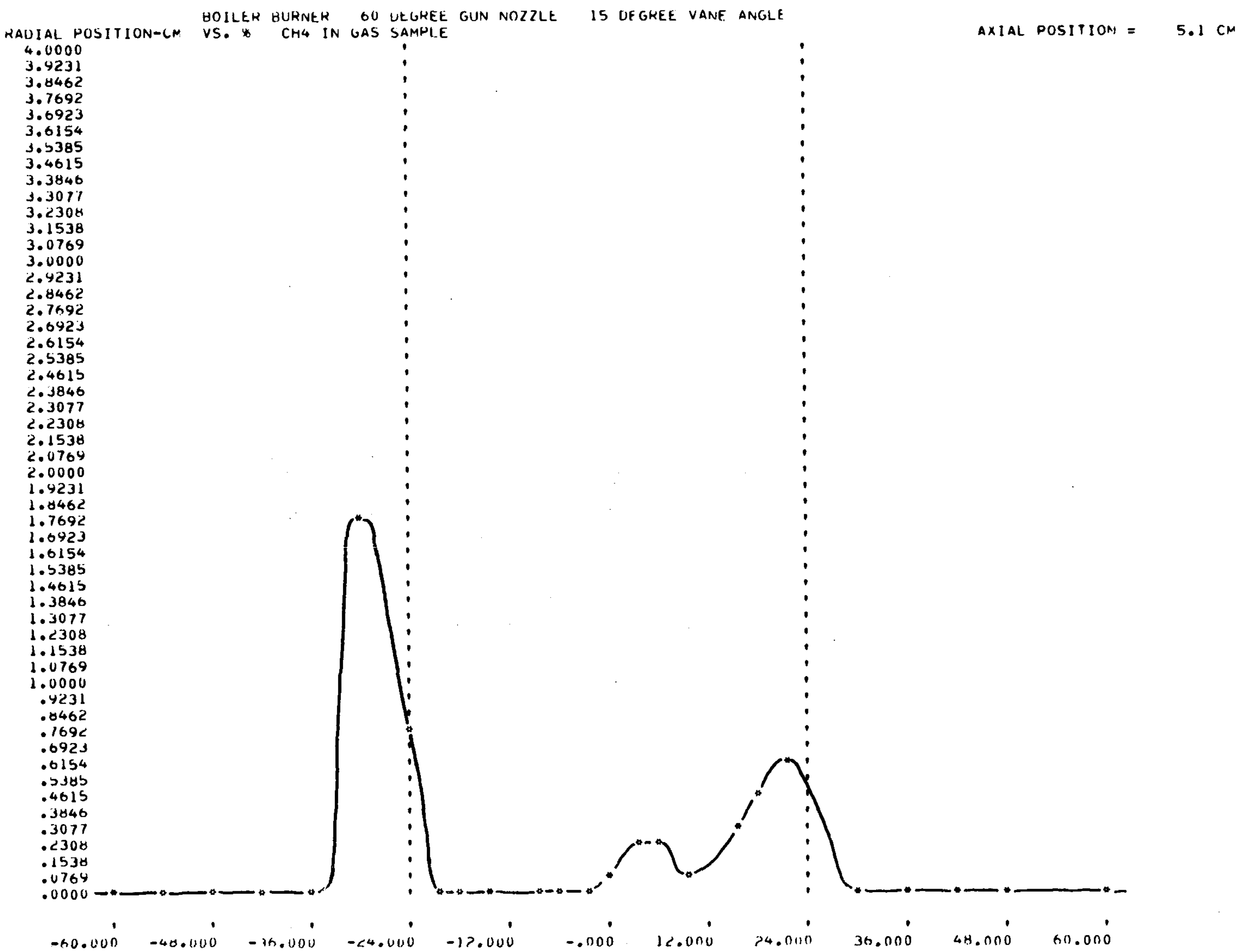

Figure 207. Radial profile of CH_4 at an axial position of 5.1 cm
(movable-vane boiler burner; 15-degree vane angle)

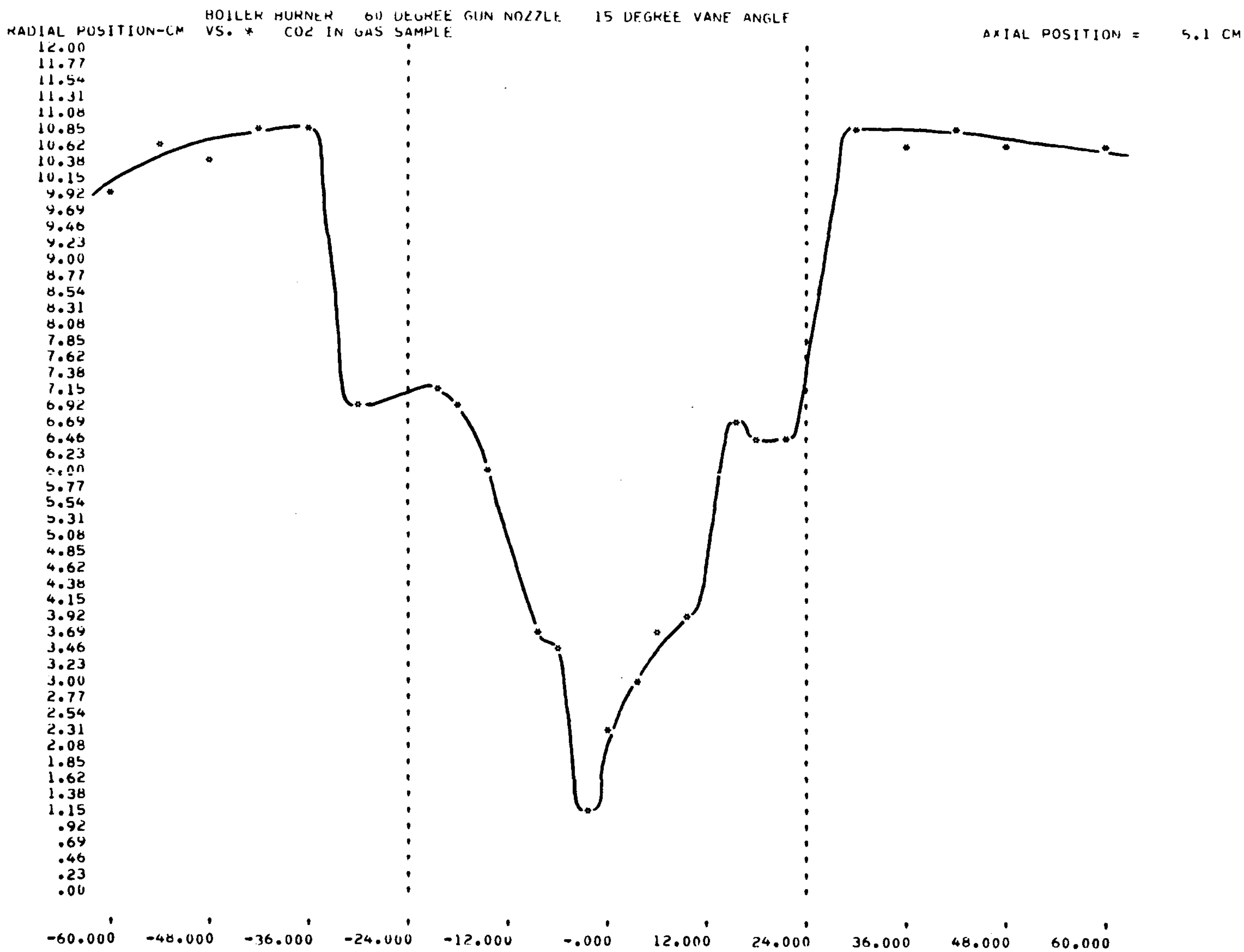

Figure 208. Radial profile of CO_2 at an axial position of 5.1 cm (movable-vane boiler burner; 15-degree vane angle)

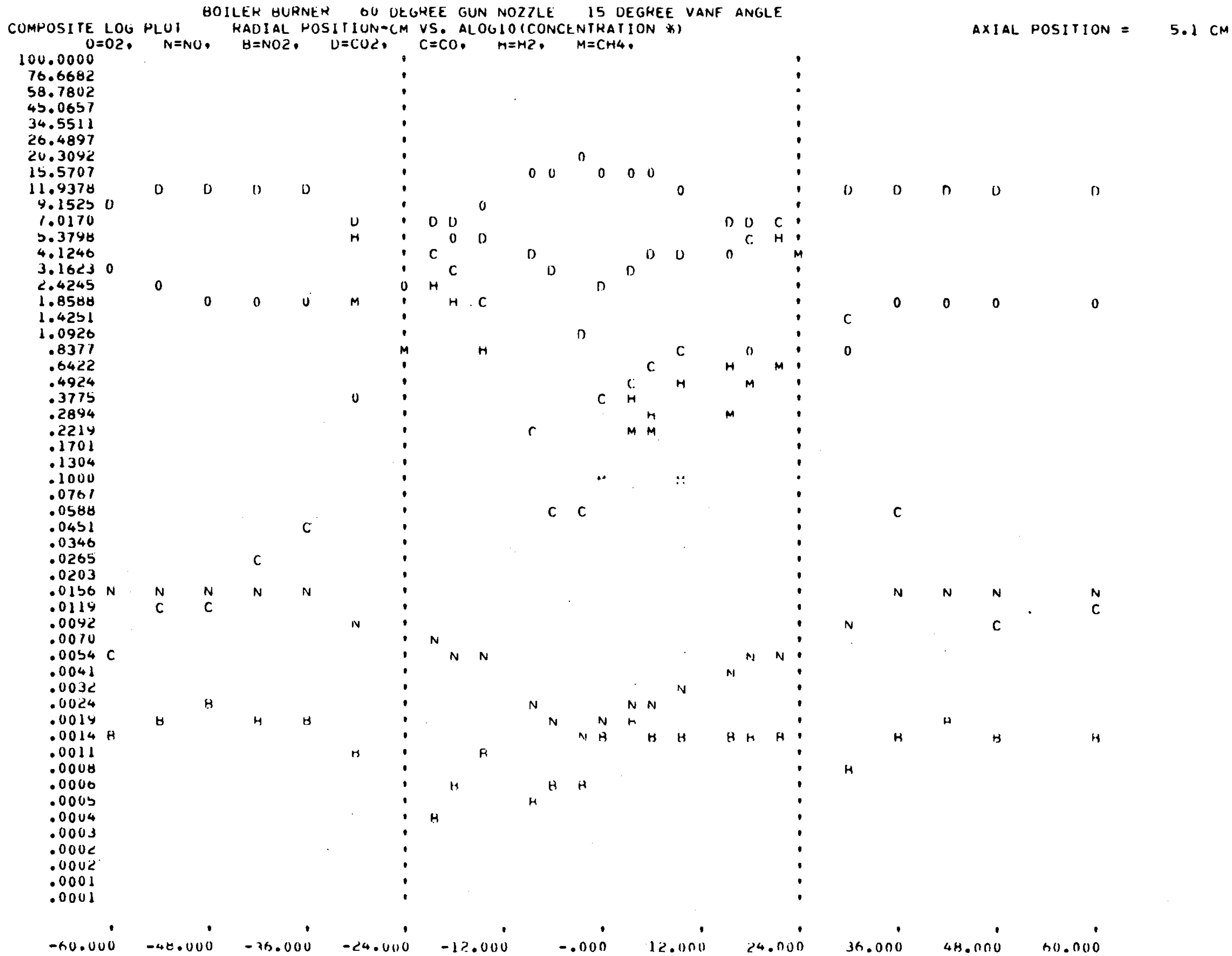

Figure 209. Radial profile of all the gases at an axial position of 5.1 cm (movable-vane boiler burner; 15-degree vane angle)

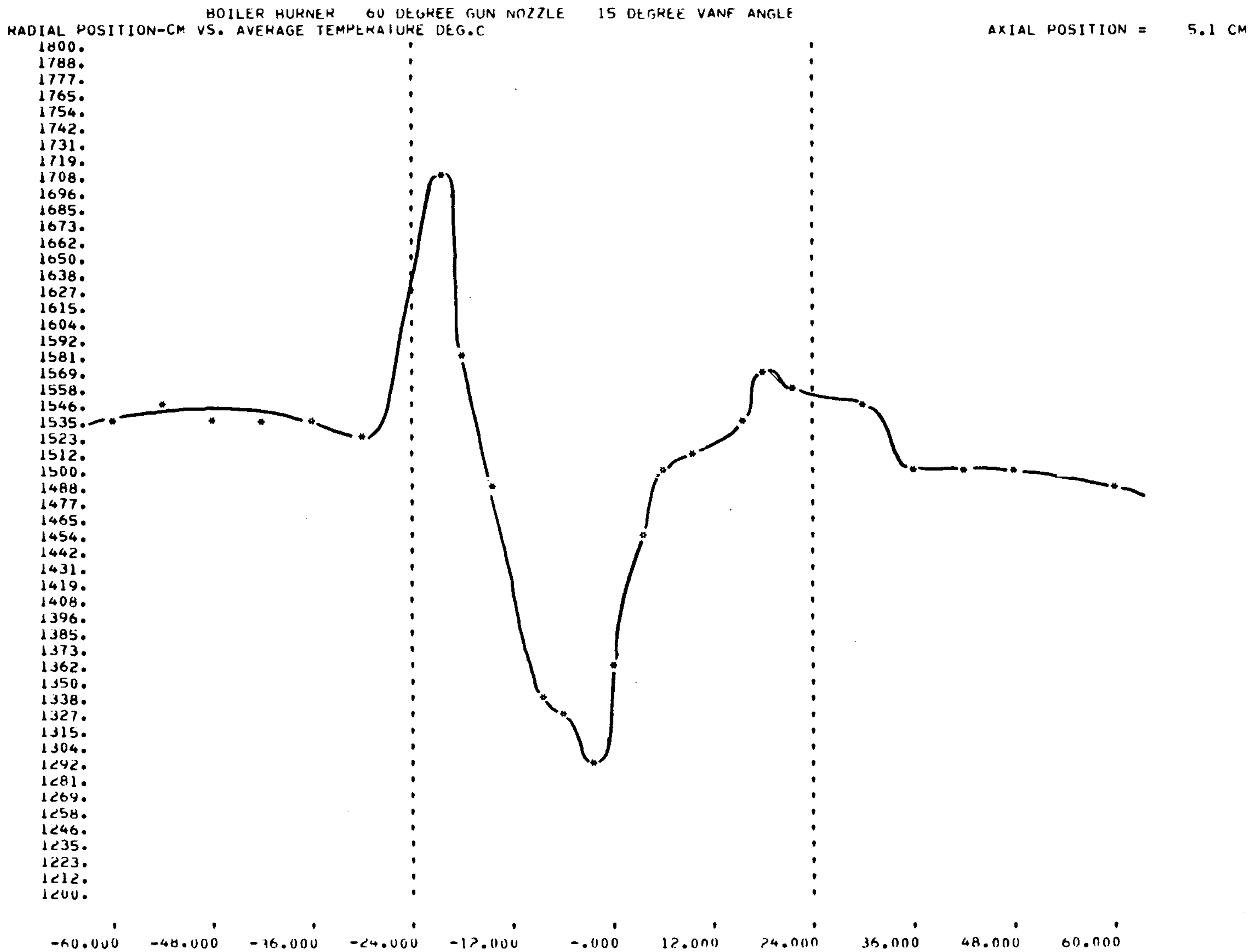

Figure 210. Radial profile of temperature at an axial position of 5.1 cm (movable-vane boiler burner; 15-degree vane angle)

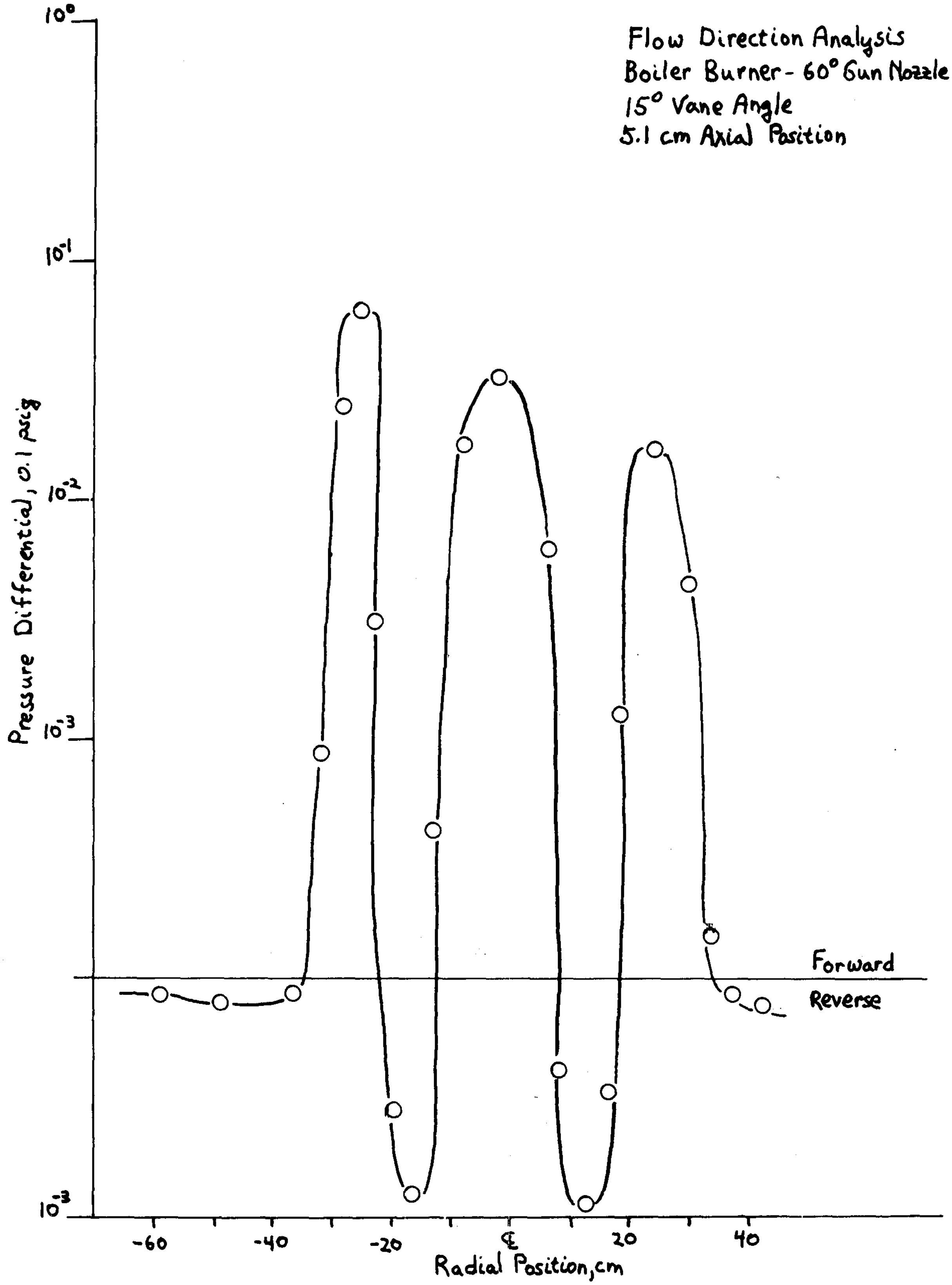

Figure 211. Radial profile of flow direction at an axial position of 5.1 cm (movable-vane boiler burner; 15-degree vane angle)

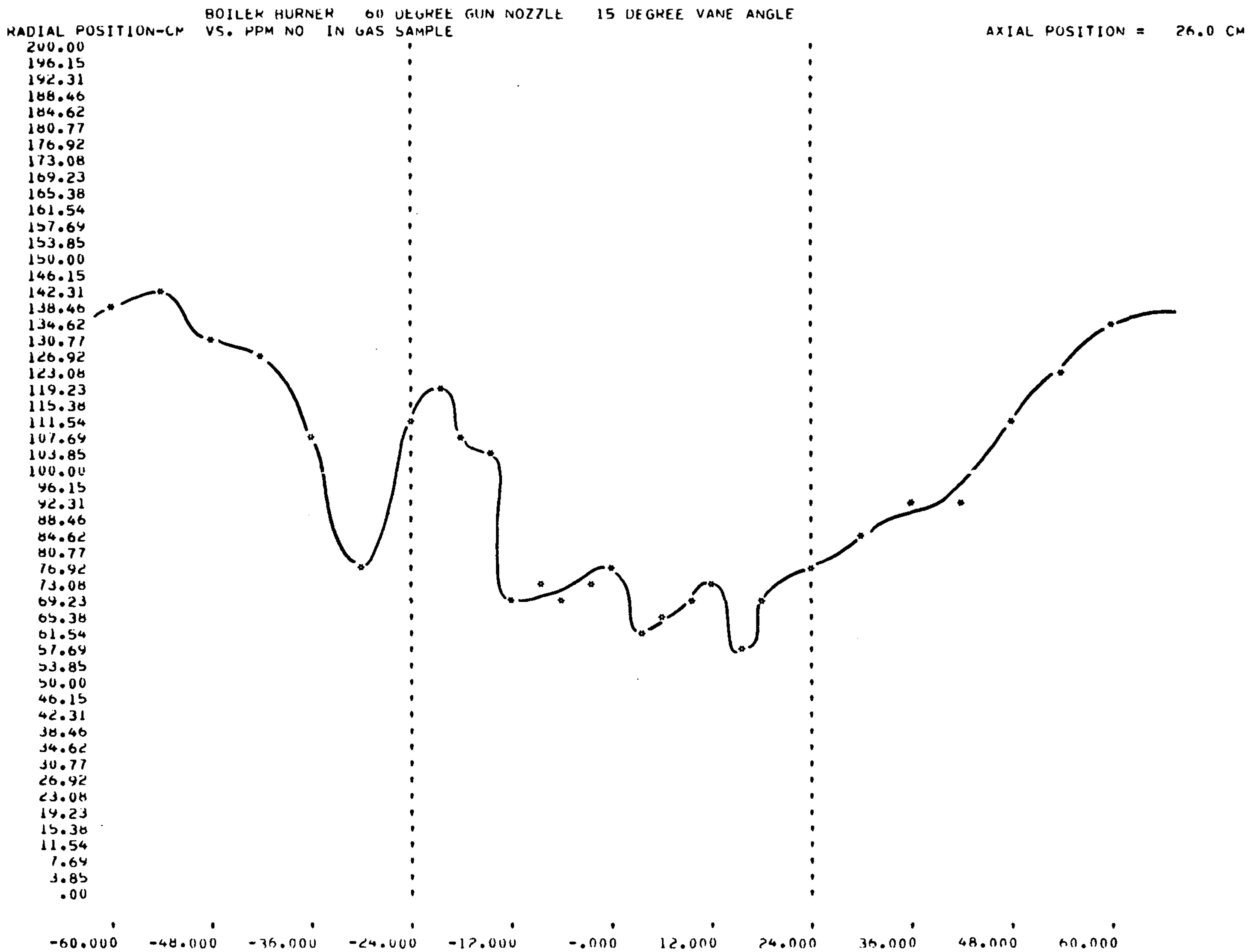

Figure 212. Radial profile of NO at an axial position of 26.0 cm
(movable-vane boiler burner; 15-degree vane angle)

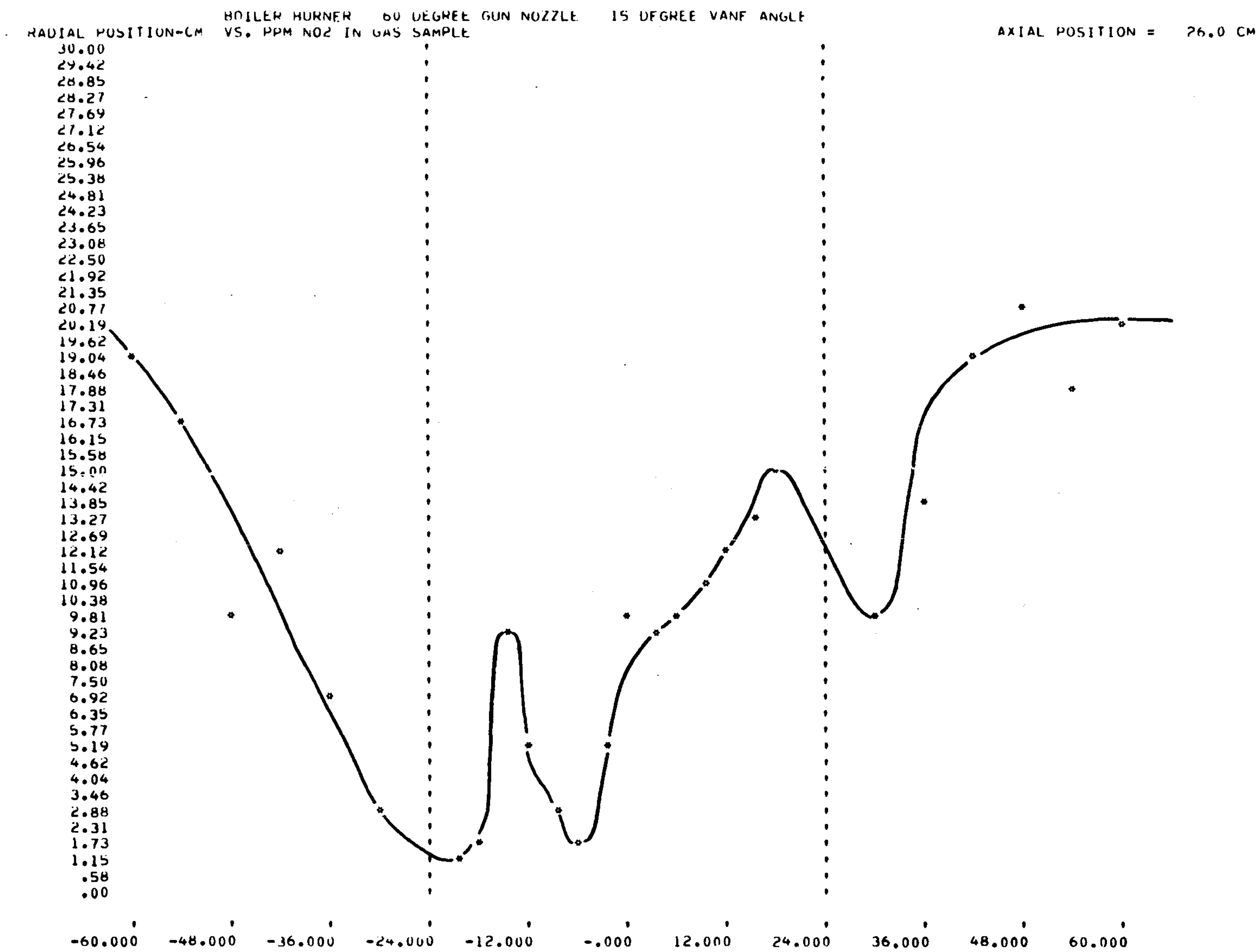

Figure 213. Radial profile of NO_2 at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

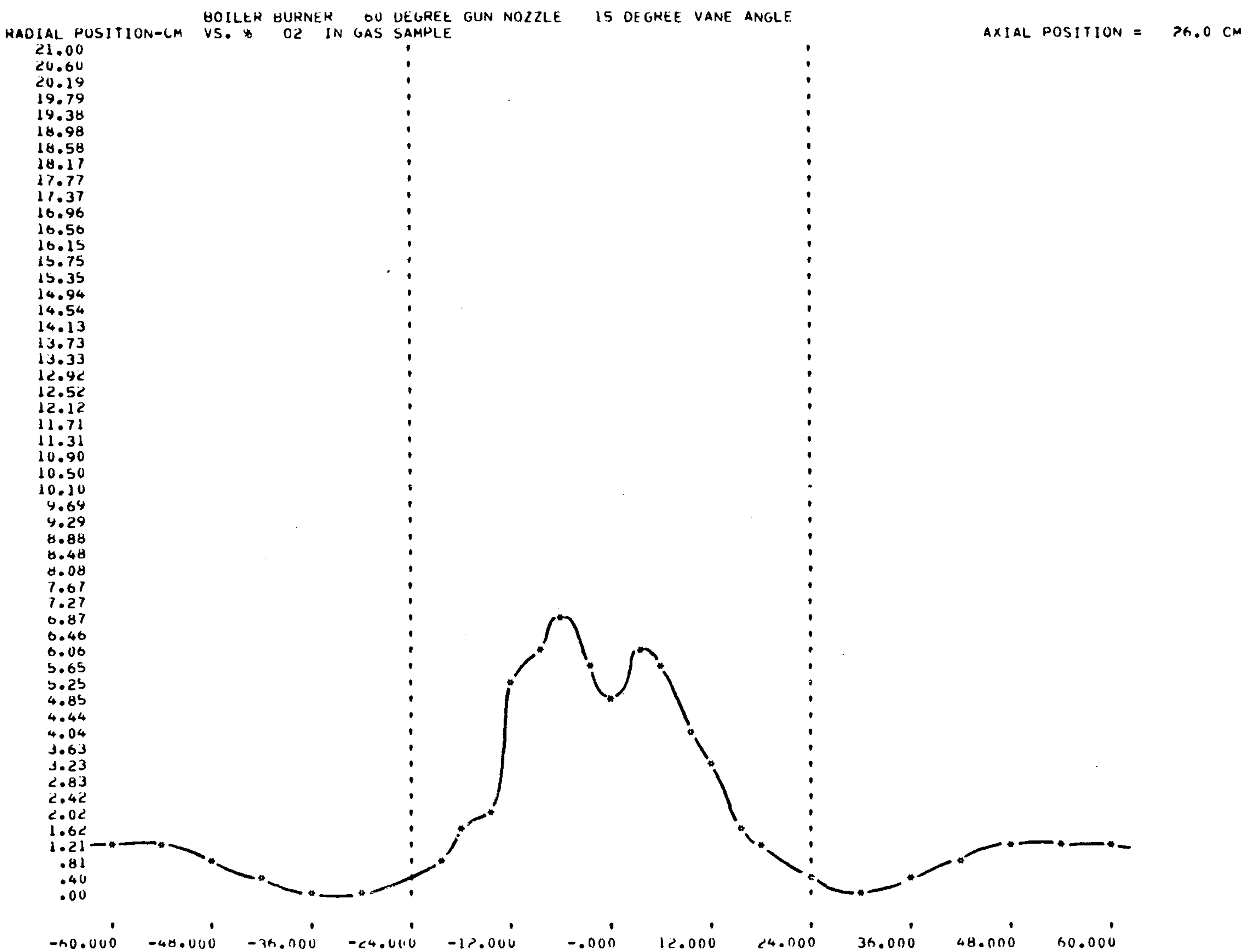

Figure 214. Radial profile of O_2 at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

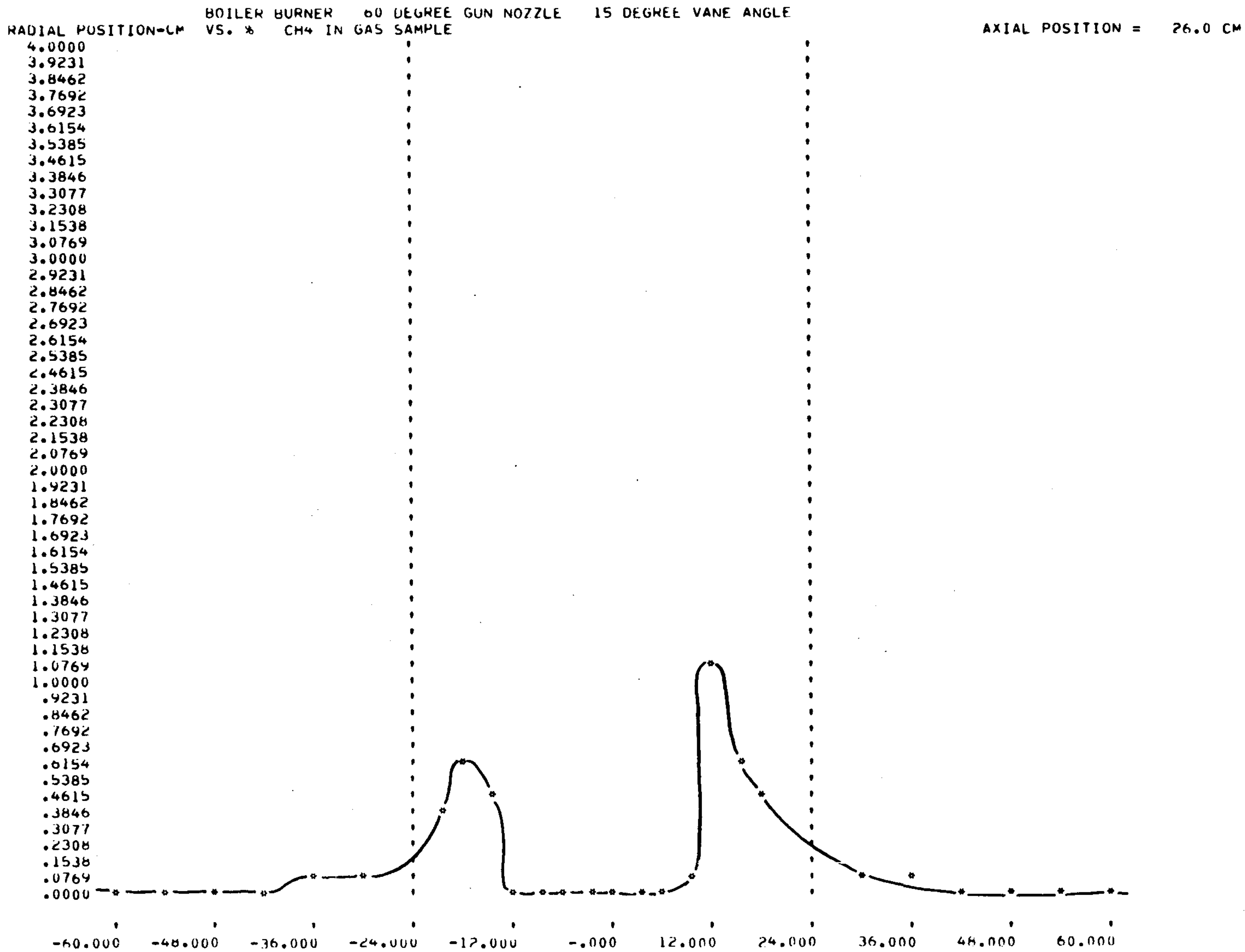

Figure 215. Radial profile of CH_4 at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

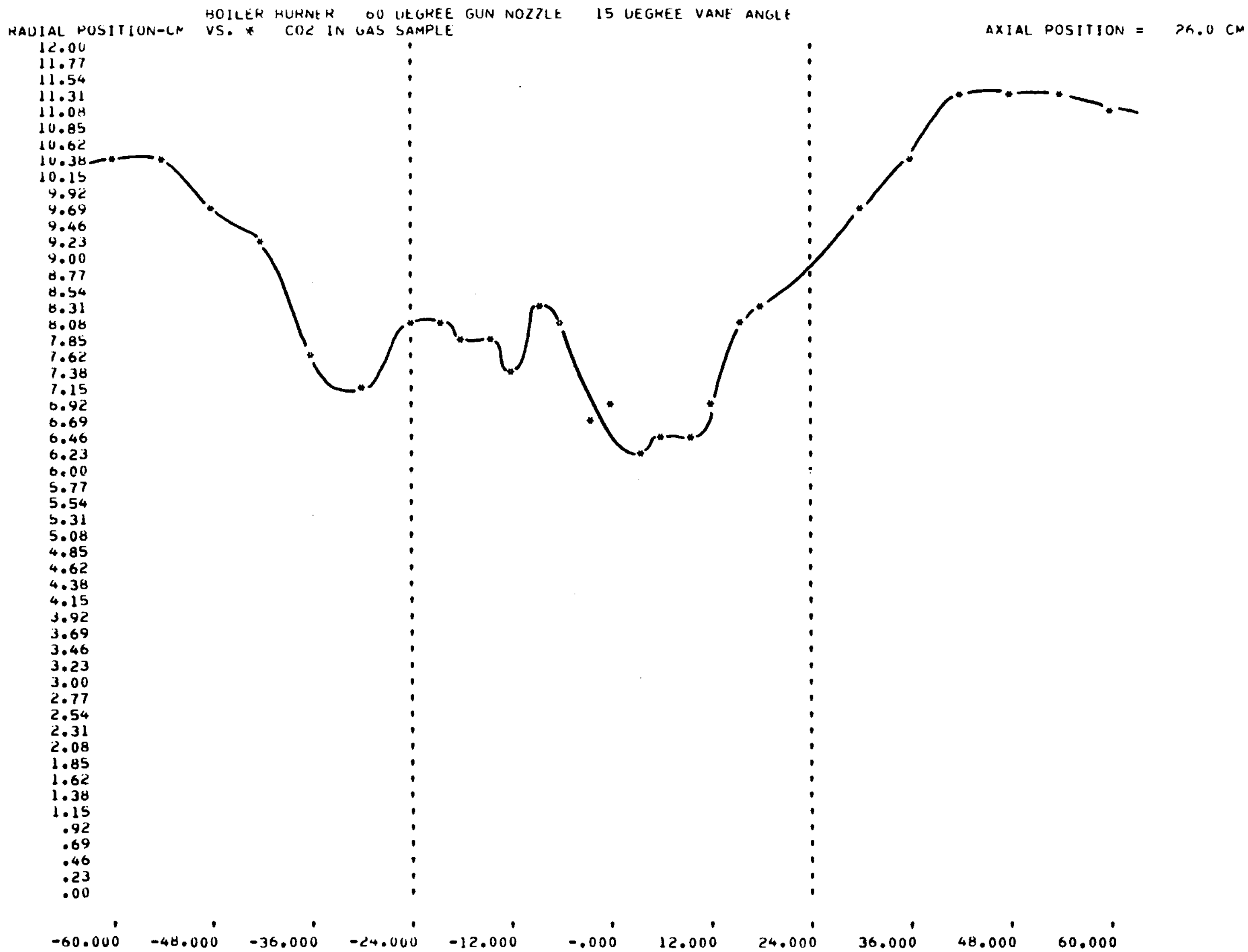

Figure 216. Radial profile of CO_2 at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

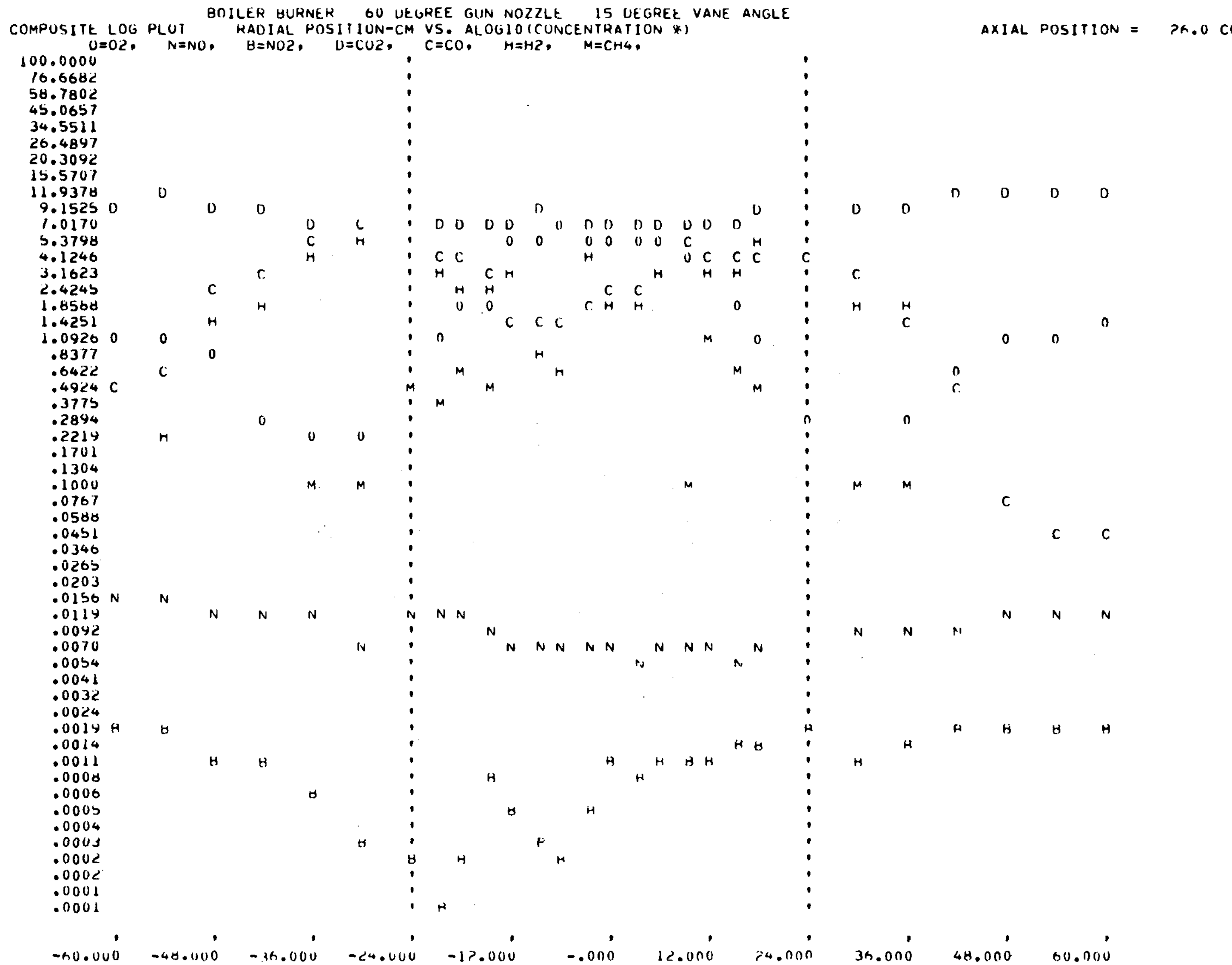

Figure 217. Radial profile of all the gases at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

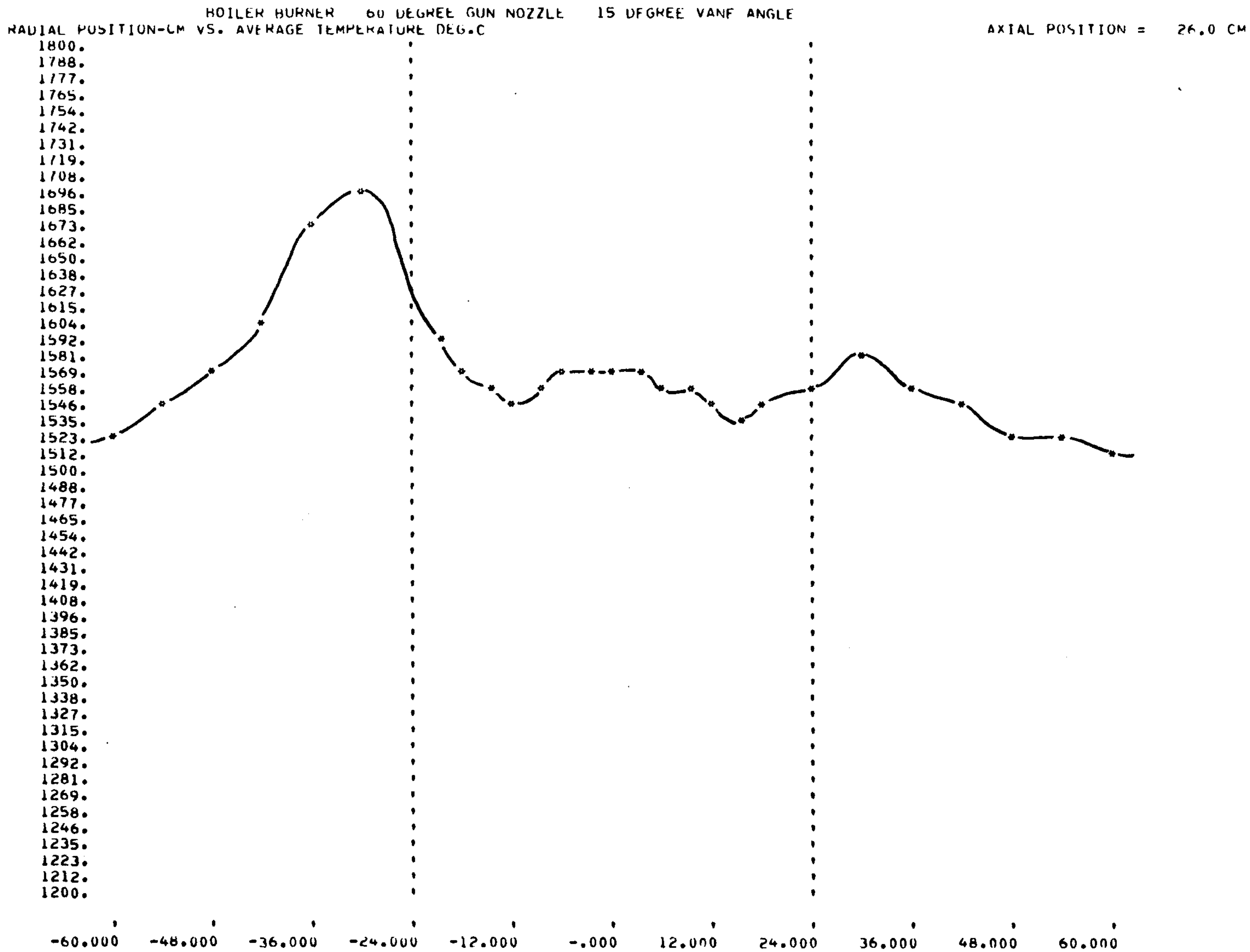

Figure 218. Radial profile of temperature at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

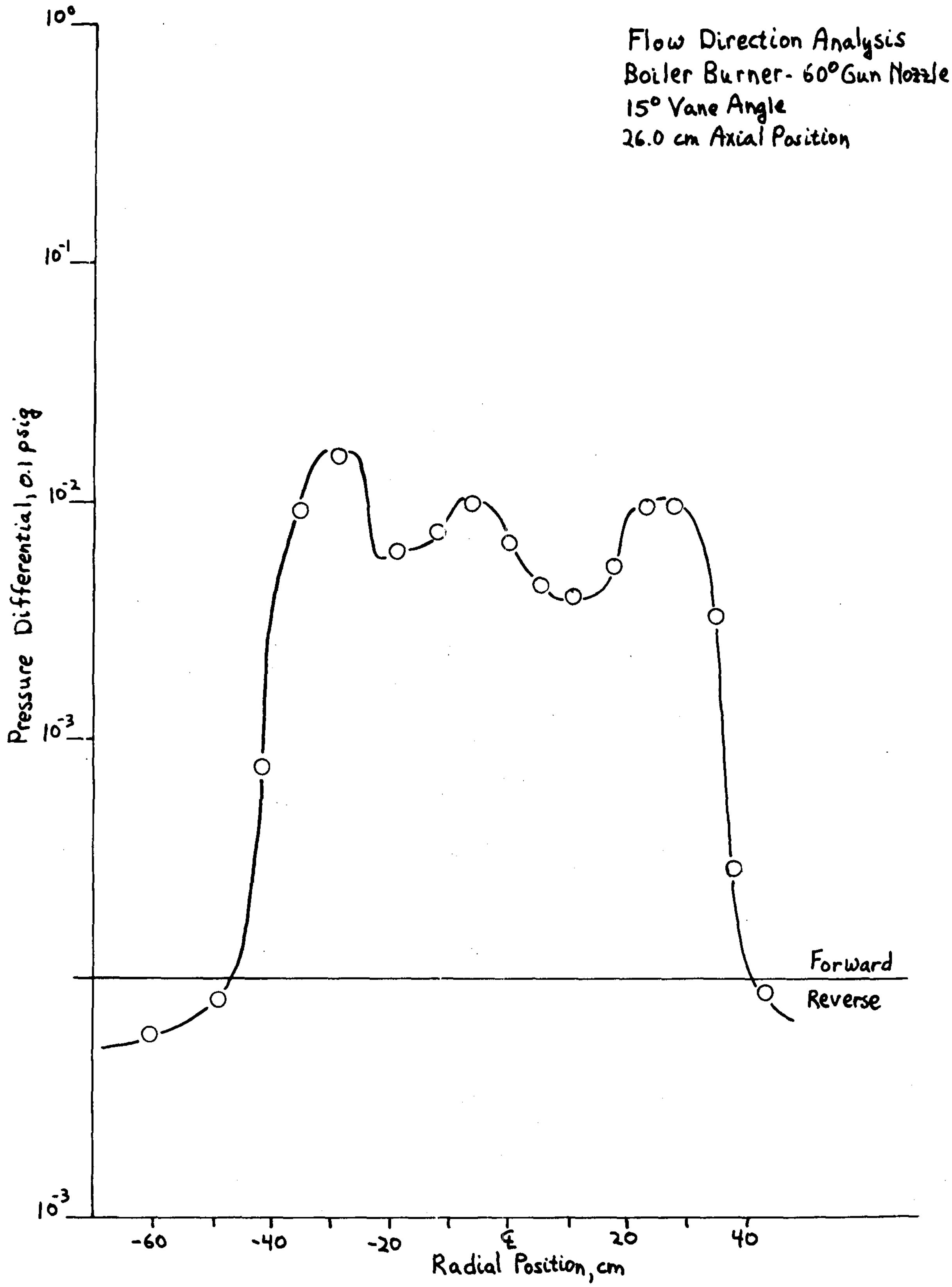

Figure 219. Radial profile of flow direction at an axial position of 26.0 cm (movable-vane boiler burner; 15-degree vane angle)

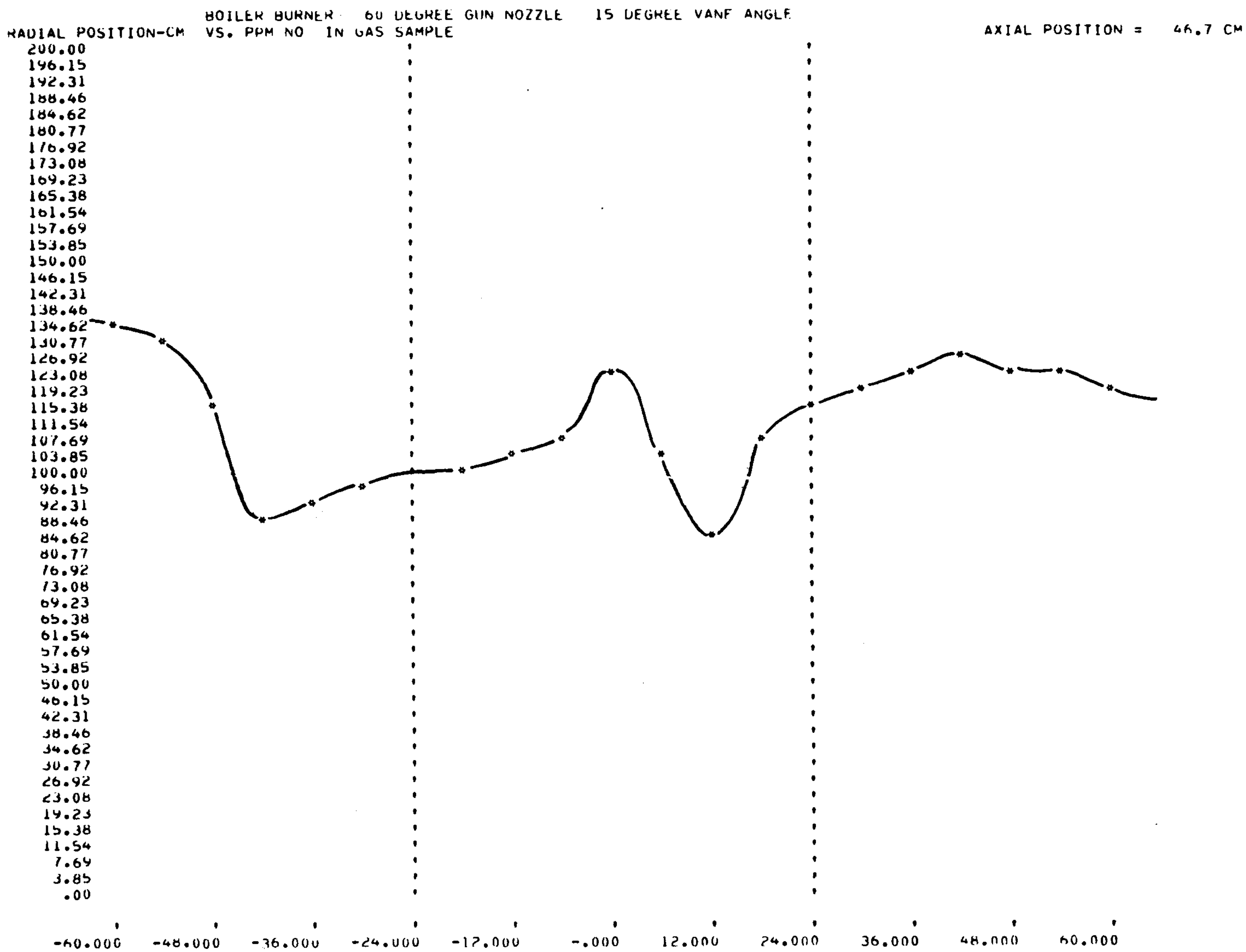

Figure 220. Radial profile of NO at an axial position of 46.7 cm
(movable-vane boiler burner; 15-degree vane angle)

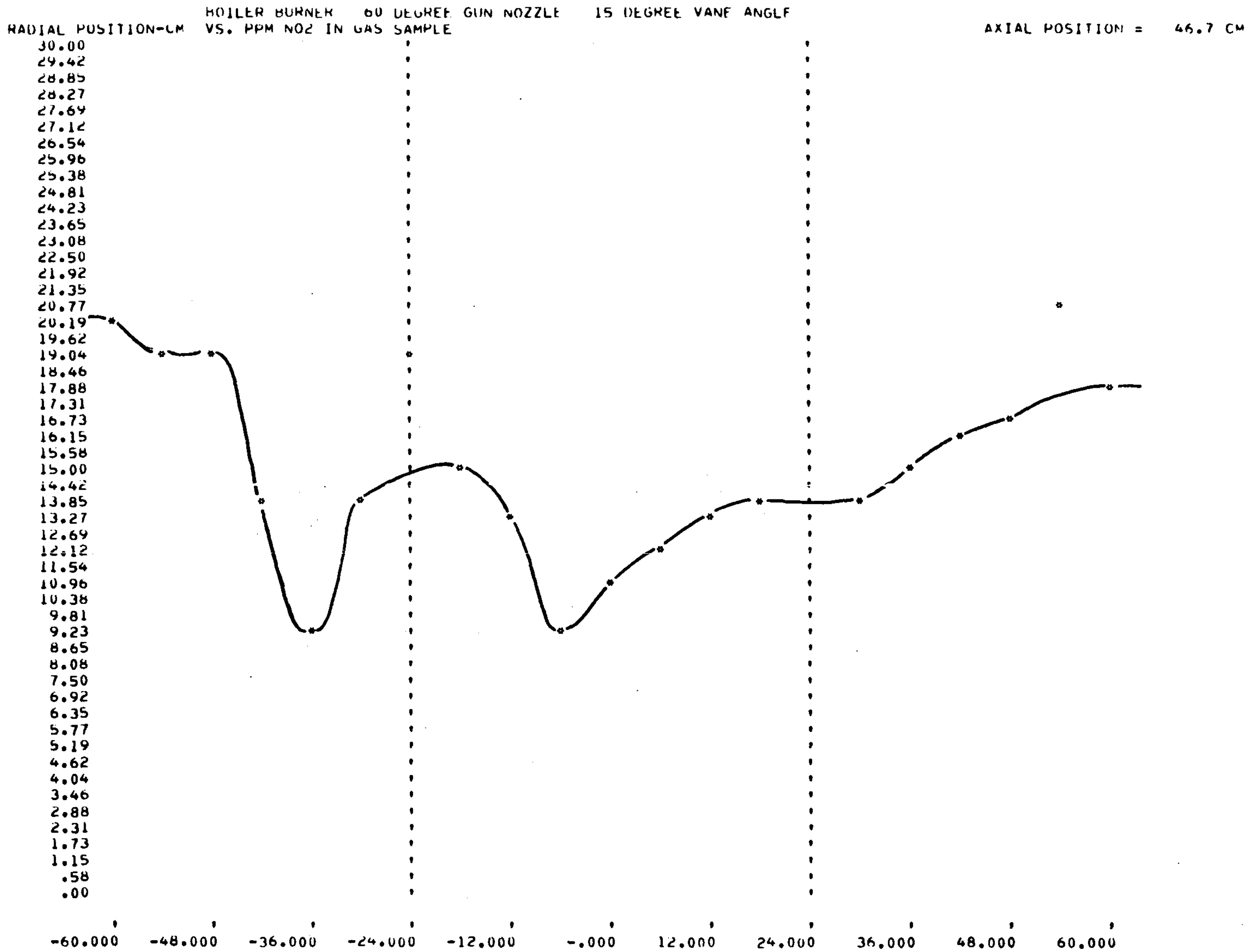

Figure 221. Radial profile of NO_2 at an axial position of 46.7 cm (movable-vane boiler burner; 15-degree vane angle)

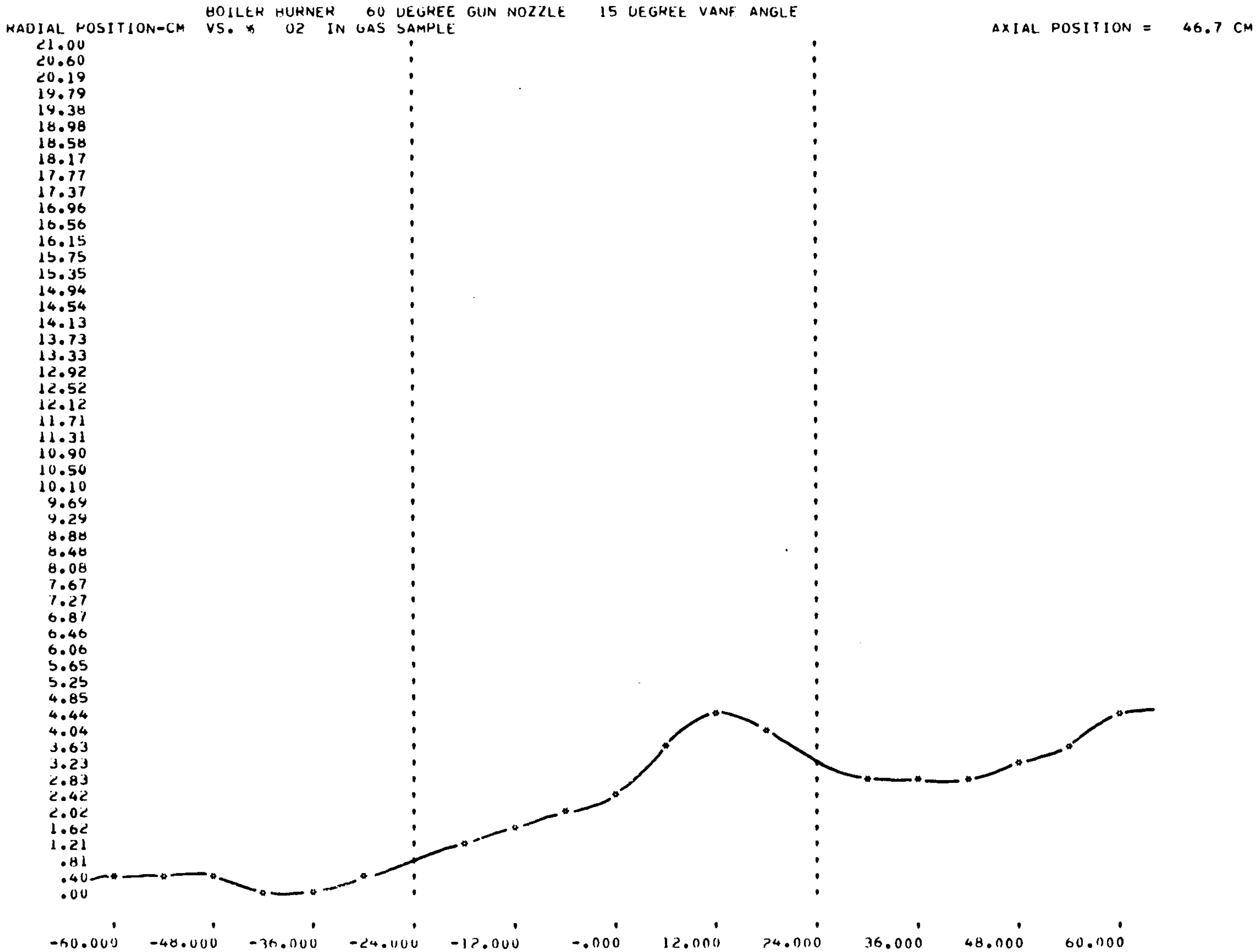

Figure 222. Radial profile of O_2 at an axial position of 46.7 cm (movable-vane boiler burner; 15-degree vane angle)

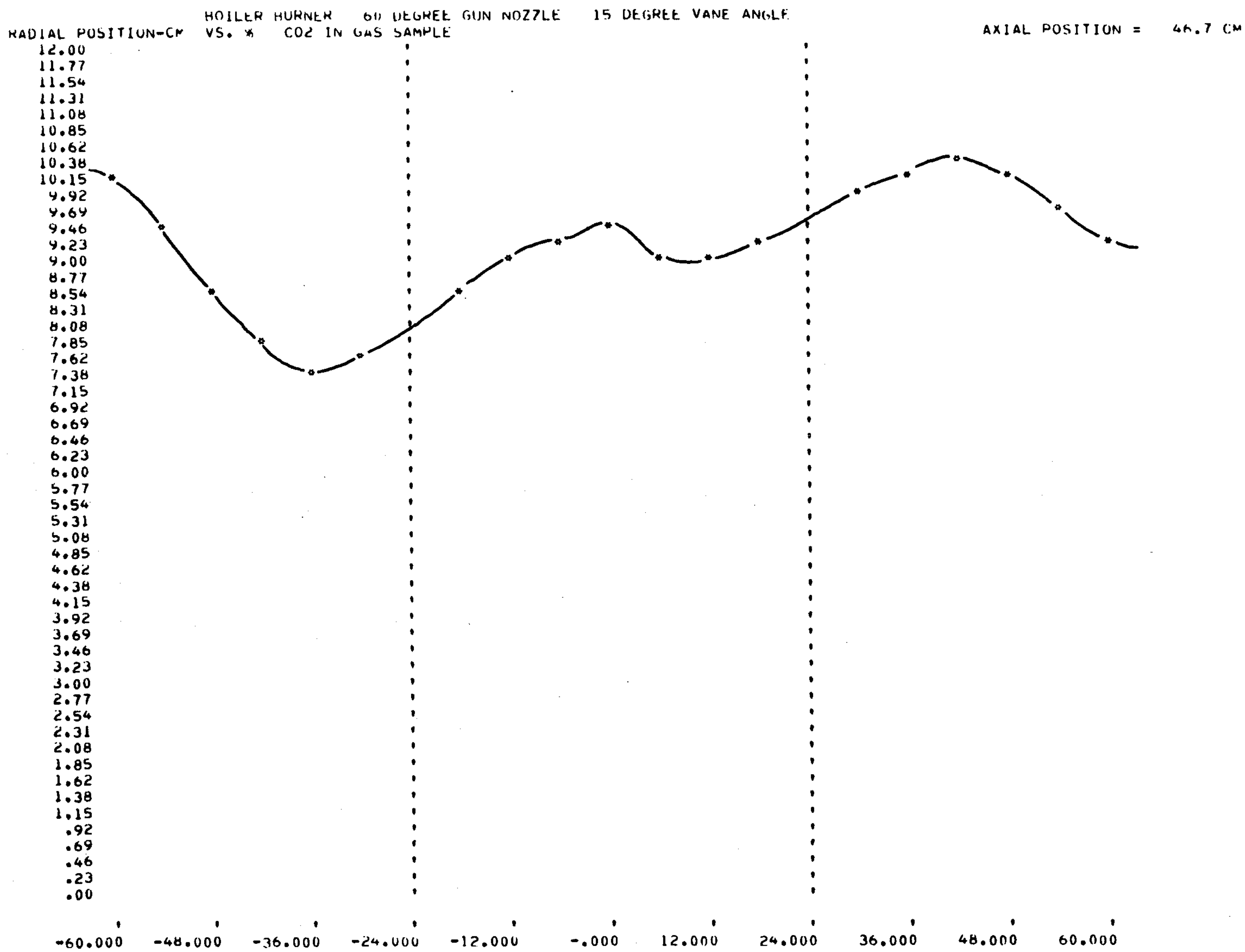

Figure 223. Radial profile of CO_2 at an axial position of 46. 7 cm (movable-vane boiler burner; 15-degree vane angle)

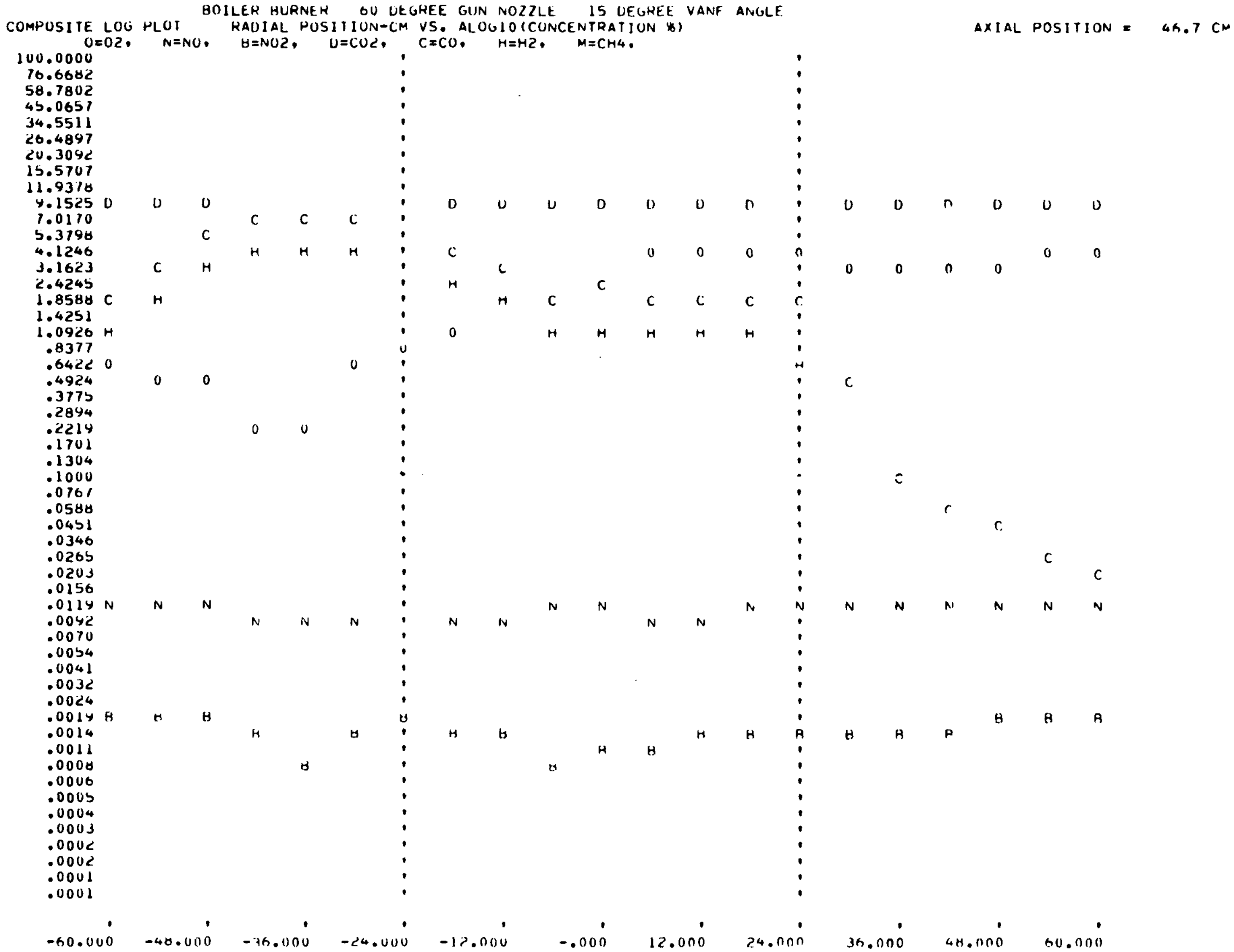

Figure 224. Radial profile of all the gases at an axial position of 46. 7 cm (movable-vane boiler burner; 15-degree vane angle)

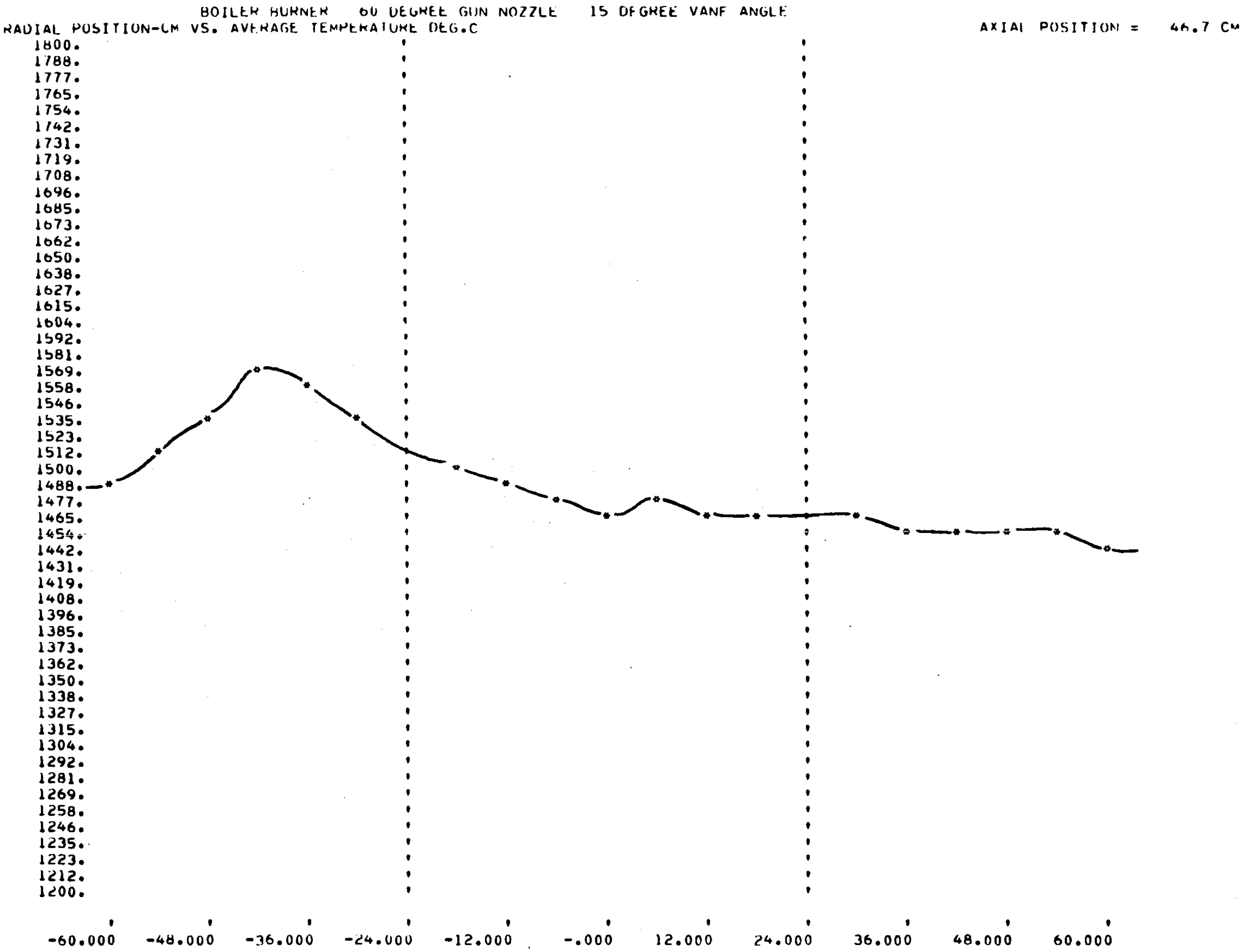

Figure 225. Radial profile of temperature at an axial position of 46.7 cm (movable-vane boiler burner; 15-degree vane angle)

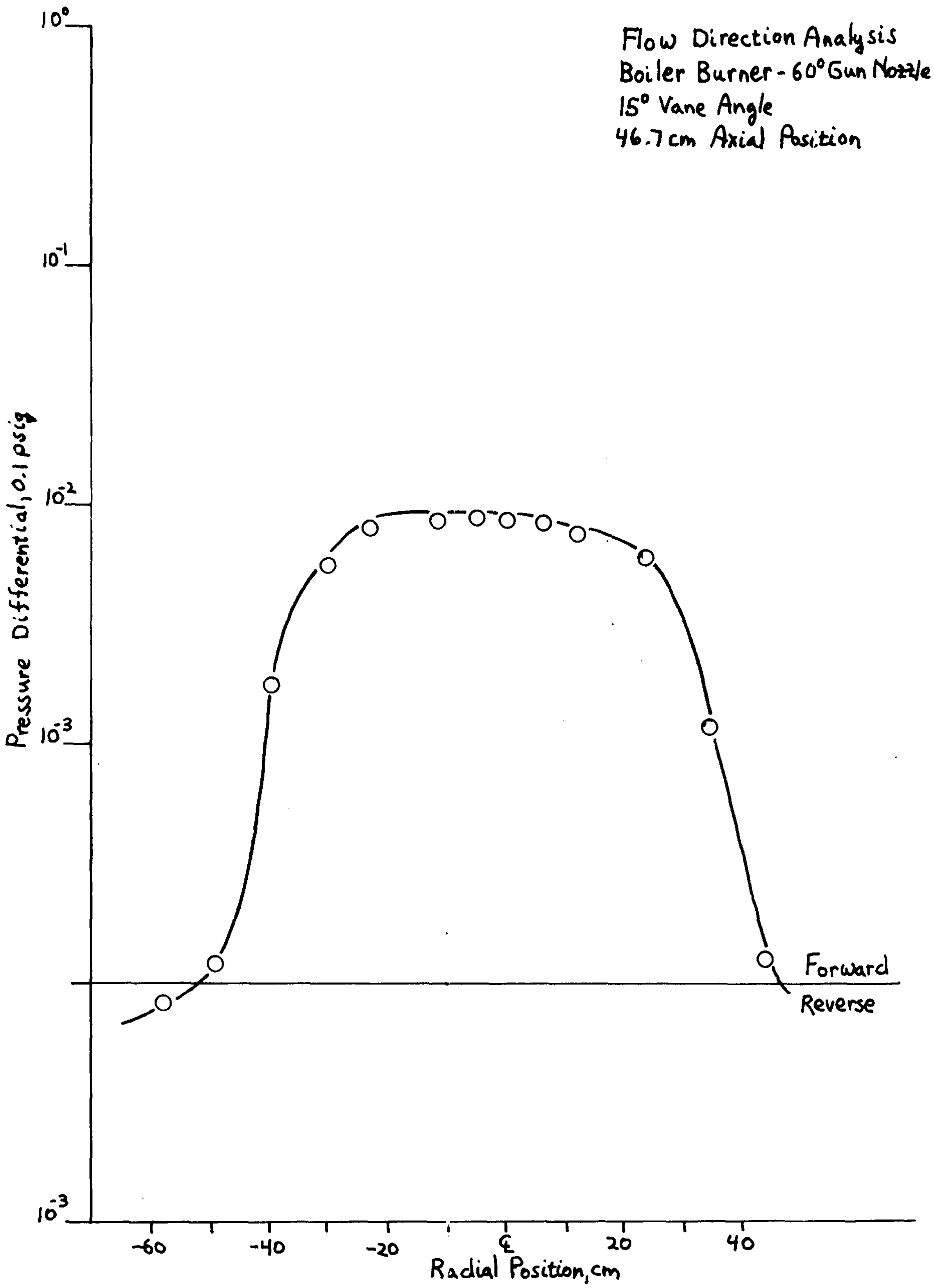

Figure 226. Radial profile of flow direction at an axial position of 46.7 cm (movable-vane boiler burner; 15-degree vane angle)

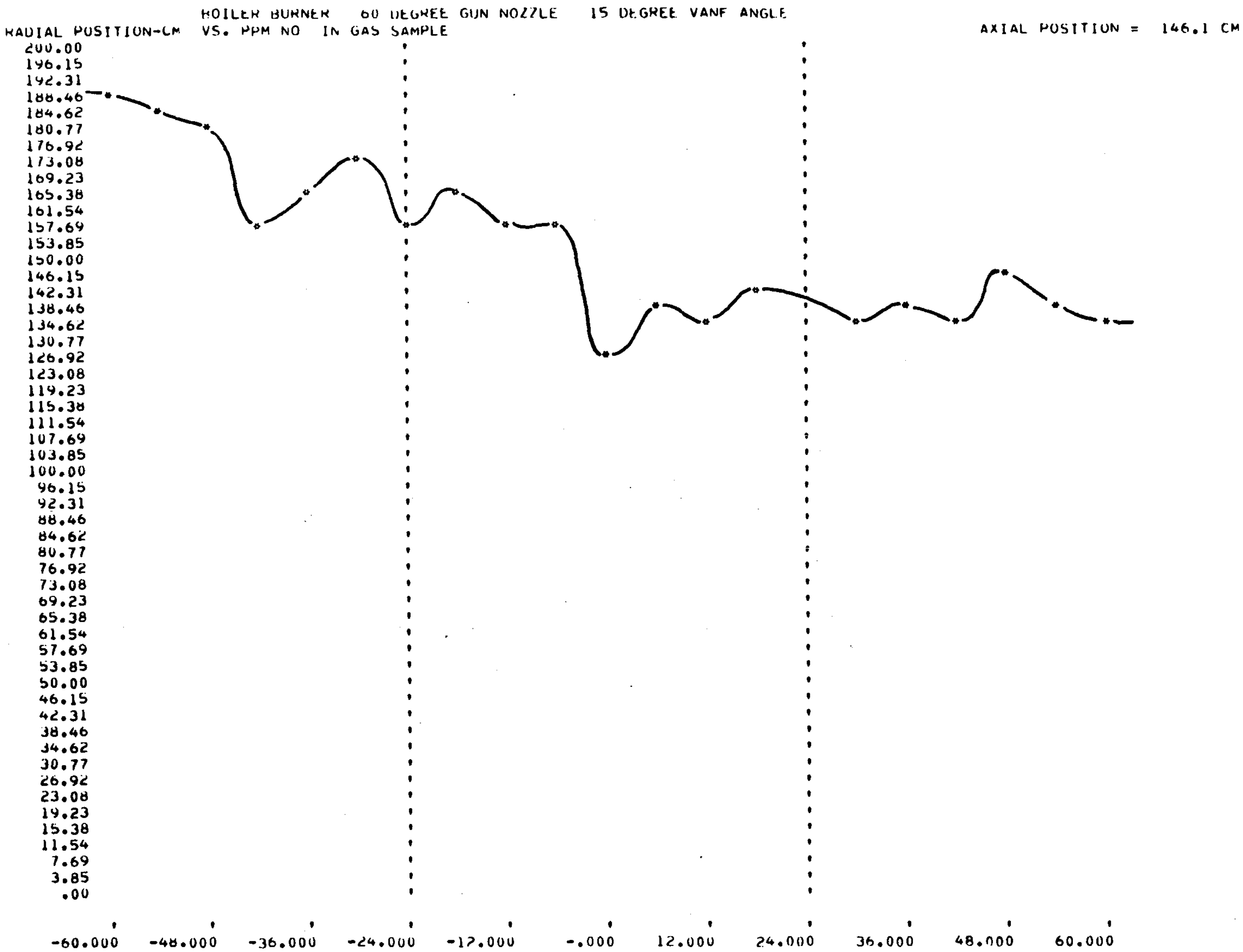

Figure 227. Radial profile of NO at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

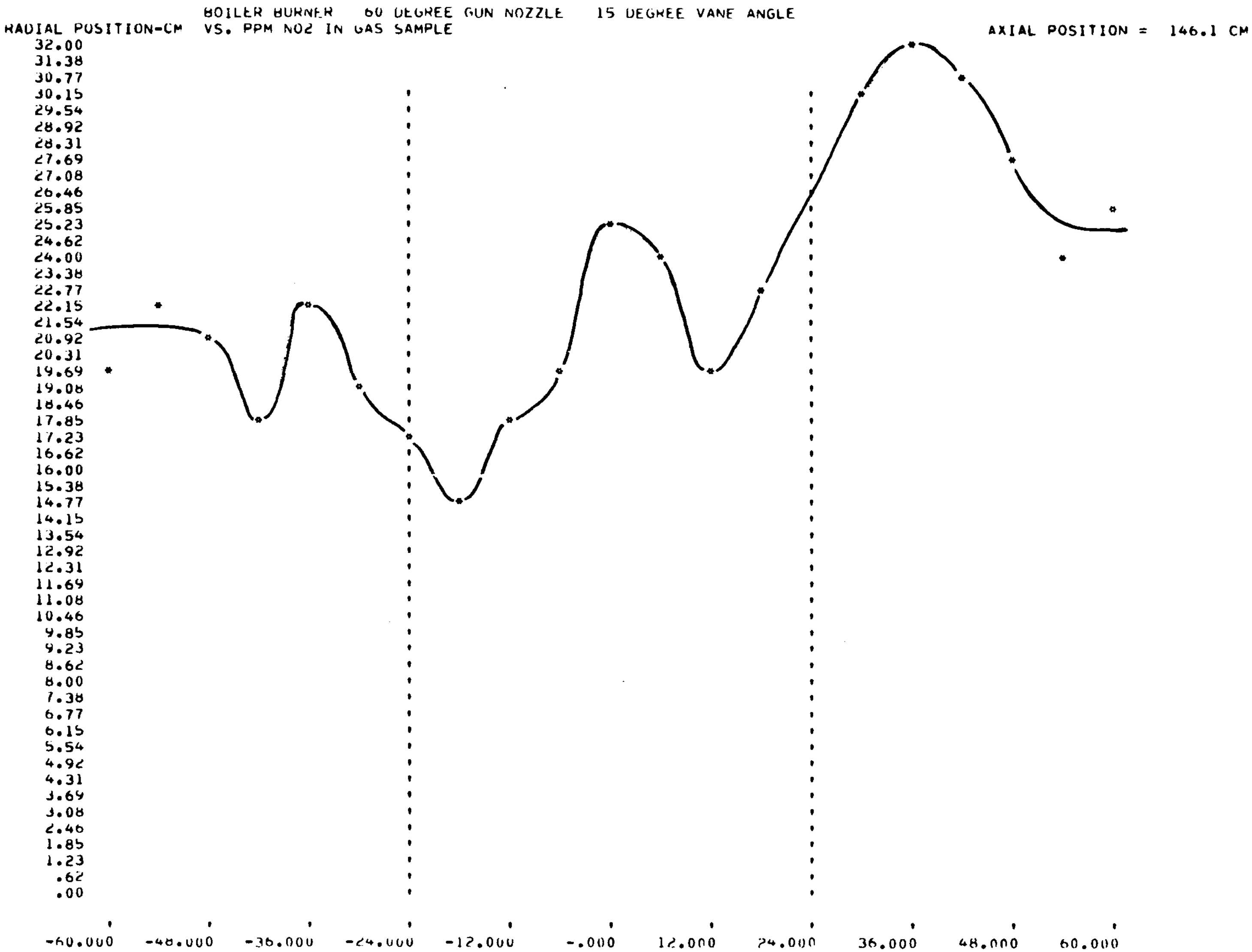

Figure 228. Radial profile of NO_2 at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

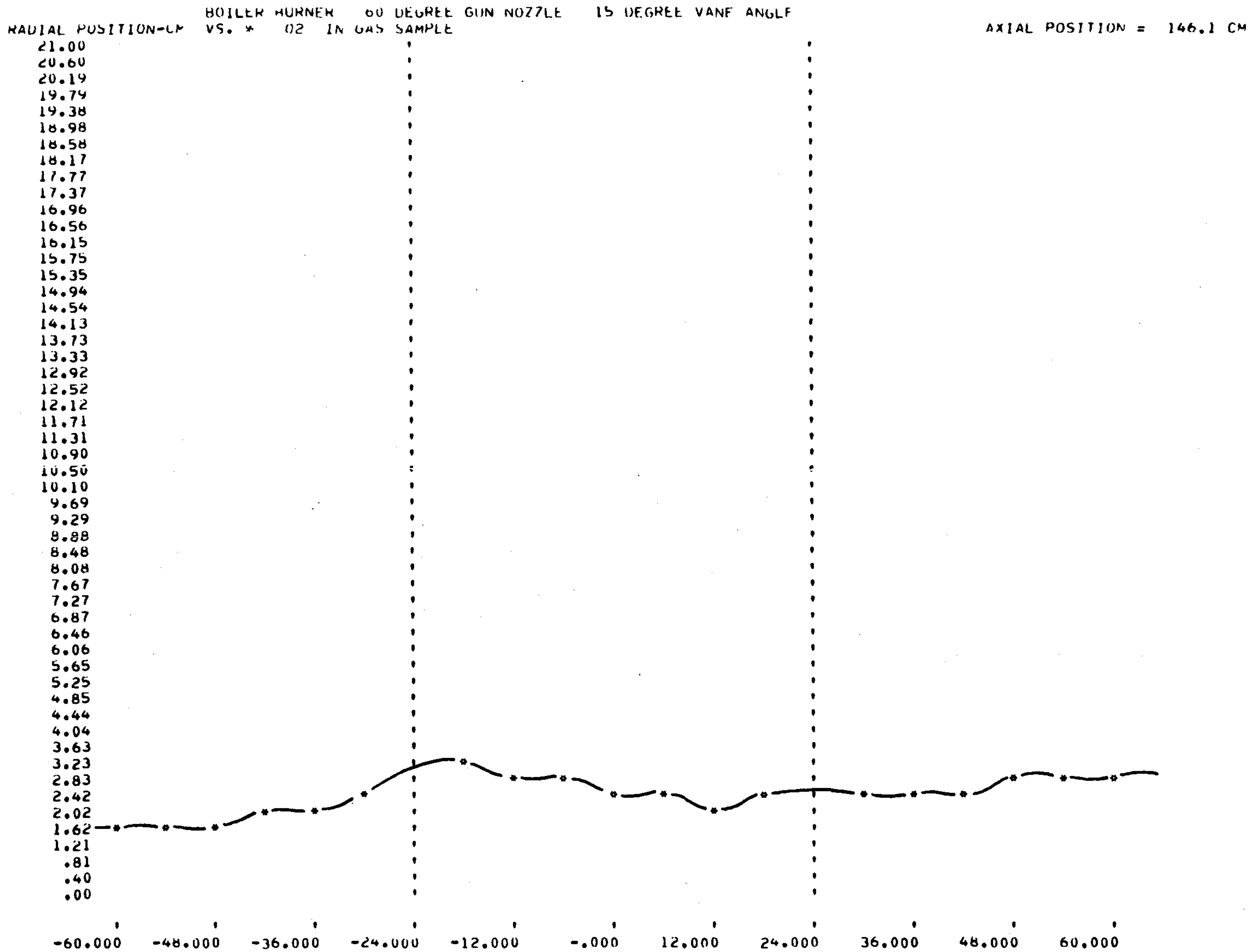

Figure 229. Radial profile of O_2 at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

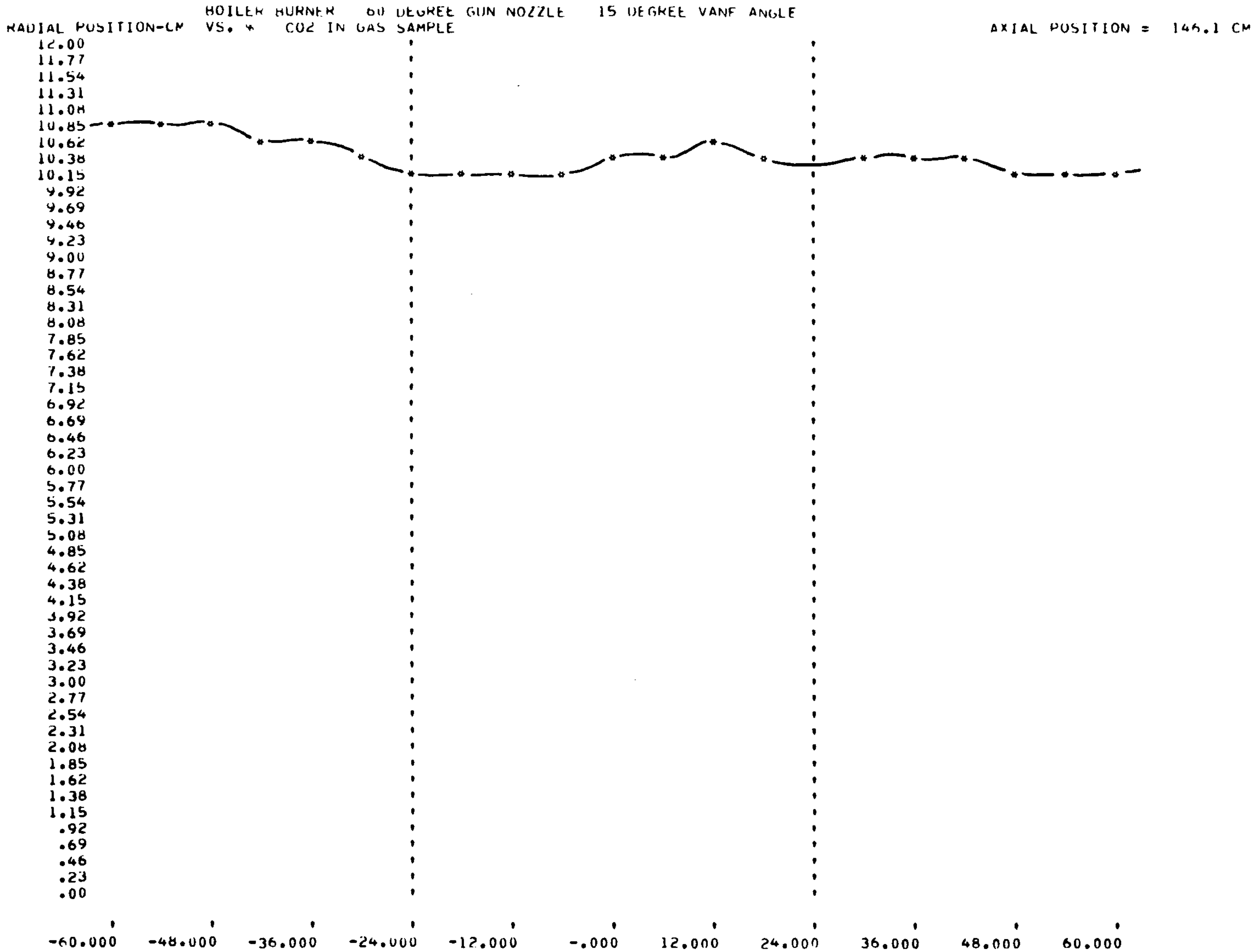

Figure 230. Radial profile of CO_2 at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

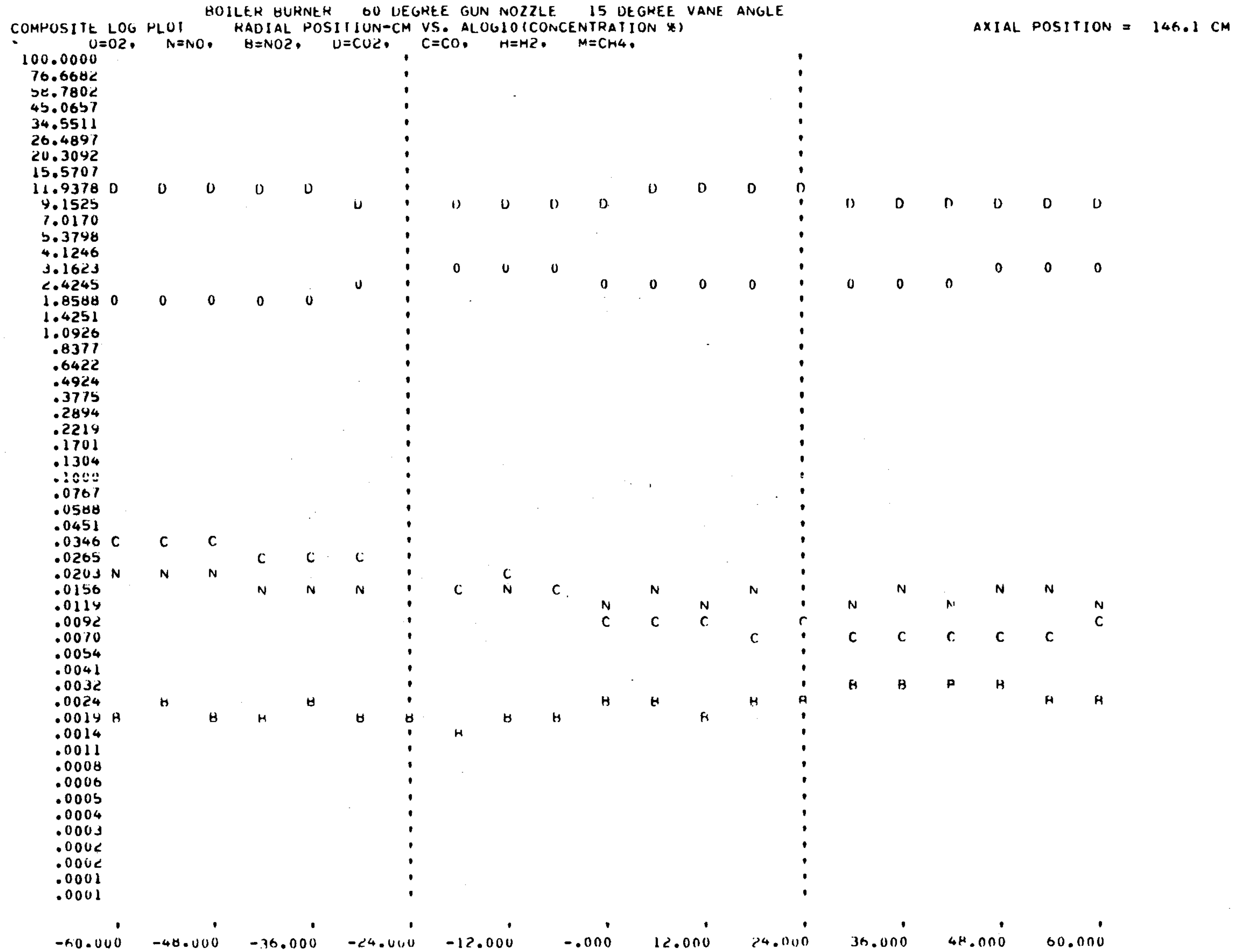

Figure 231. Radial profile of all the gases at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

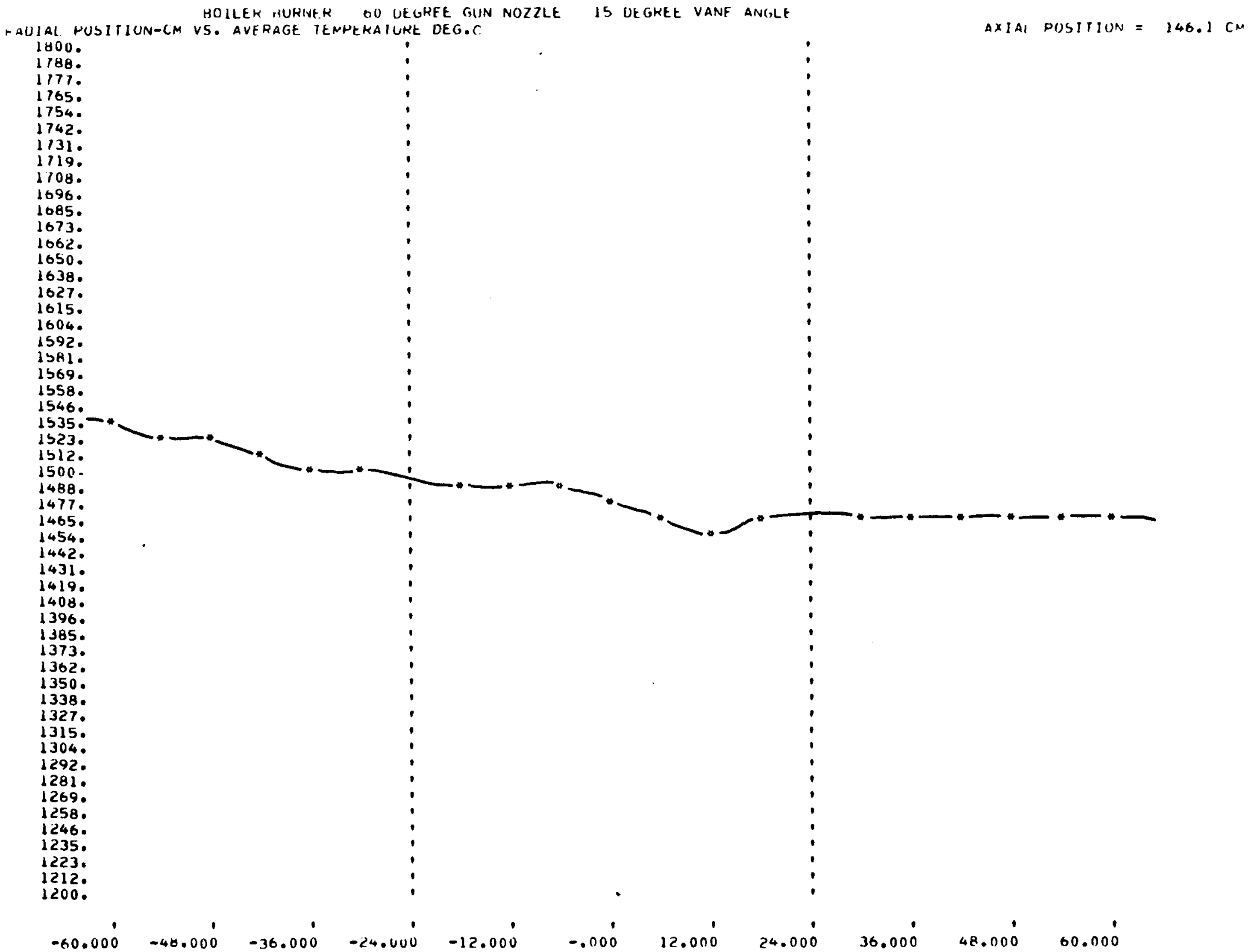

Figure 232. Radial profile of temperature at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

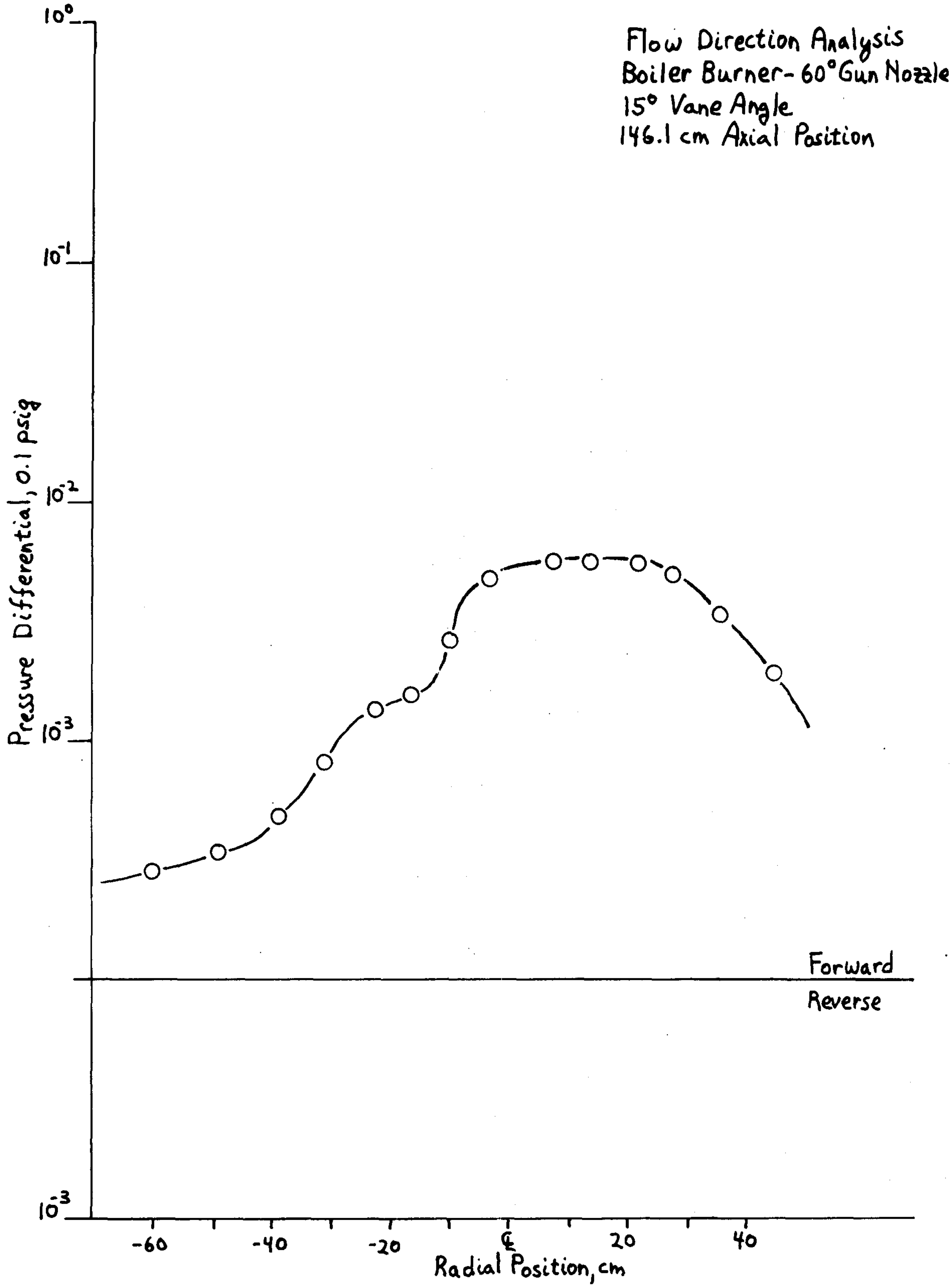

Figure 233. Radial profile of flow direction at an axial position of 146.1 cm (movable-vane boiler burner; 15-degree vane angle)

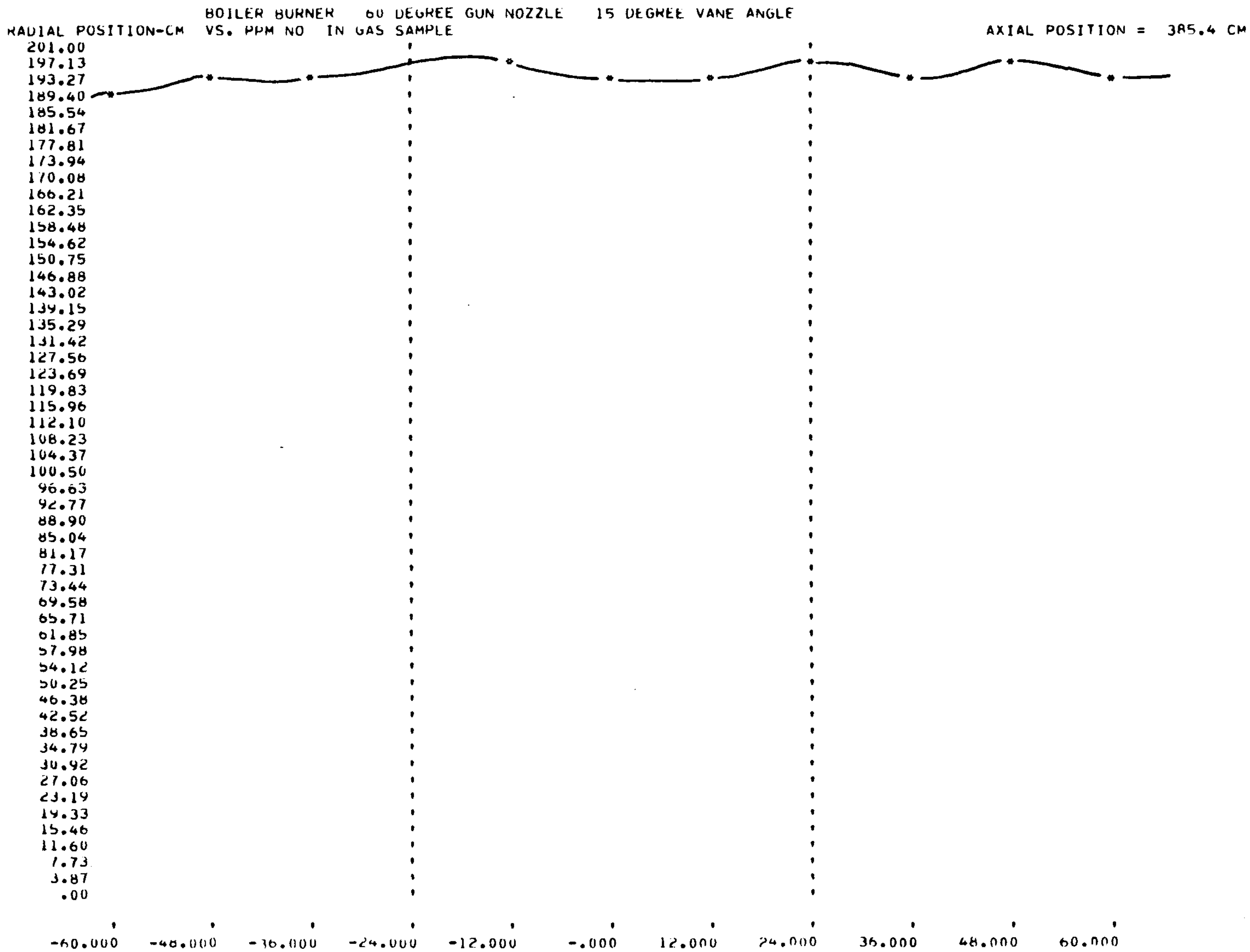

Figure 234. Radial profile of NO at an axial position of 385.4 cm (movable-vane boiler burner; 15-degree vane angle)

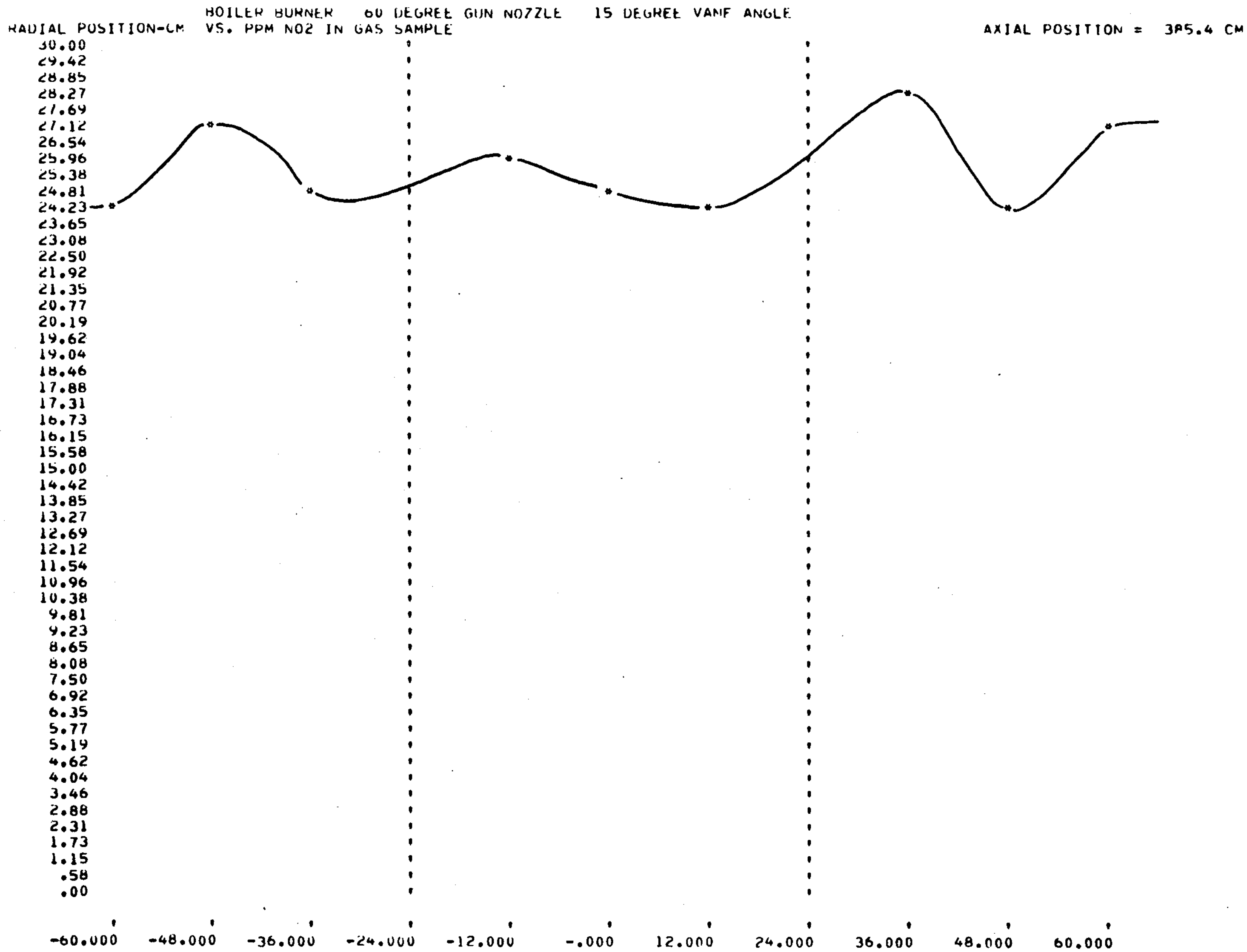

Figure 235. Radial profile of NO_2 at an axial position of 385. 4 cm (movable-vane boiler burner; 15-degree vane angle)

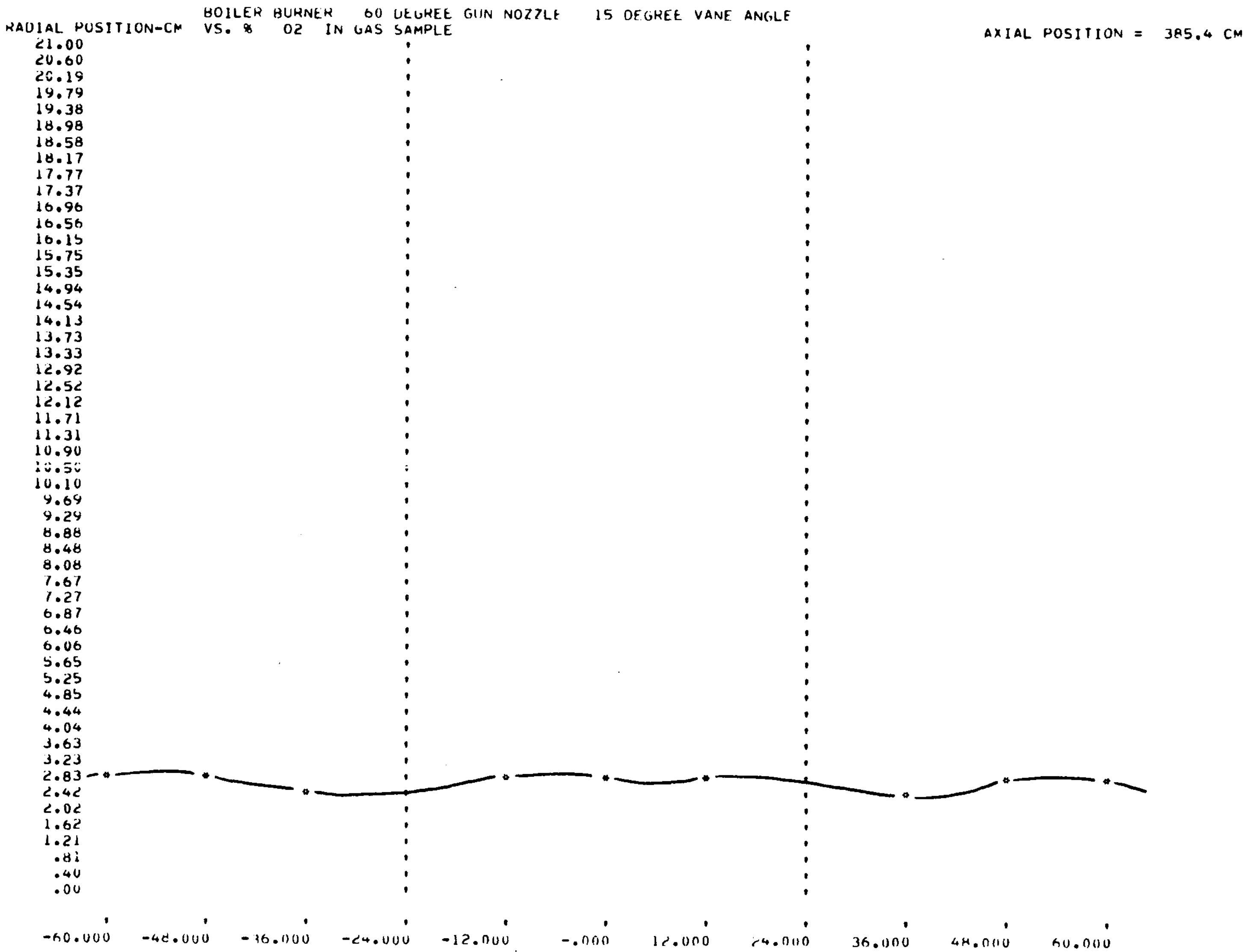

Figure 236. Radial profile of O_2 at an axial position of 385.4 cm (movable-vane boiler burner; 15-degree vane angle)

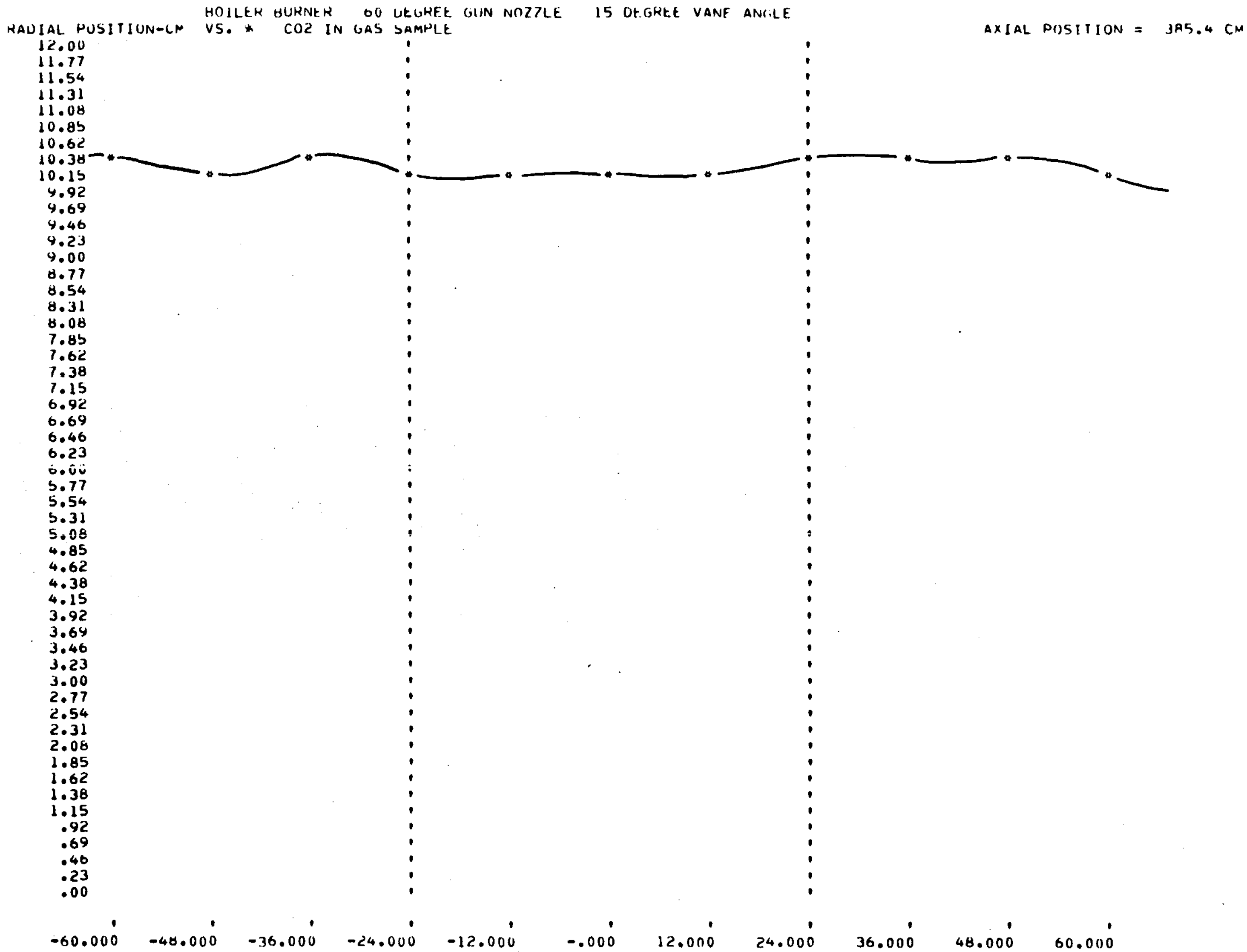

Figure 237. Radial profile of CO_2 at an axial position of 385.4 cm (movable-vane boiler burner; 15-degree vane angle)

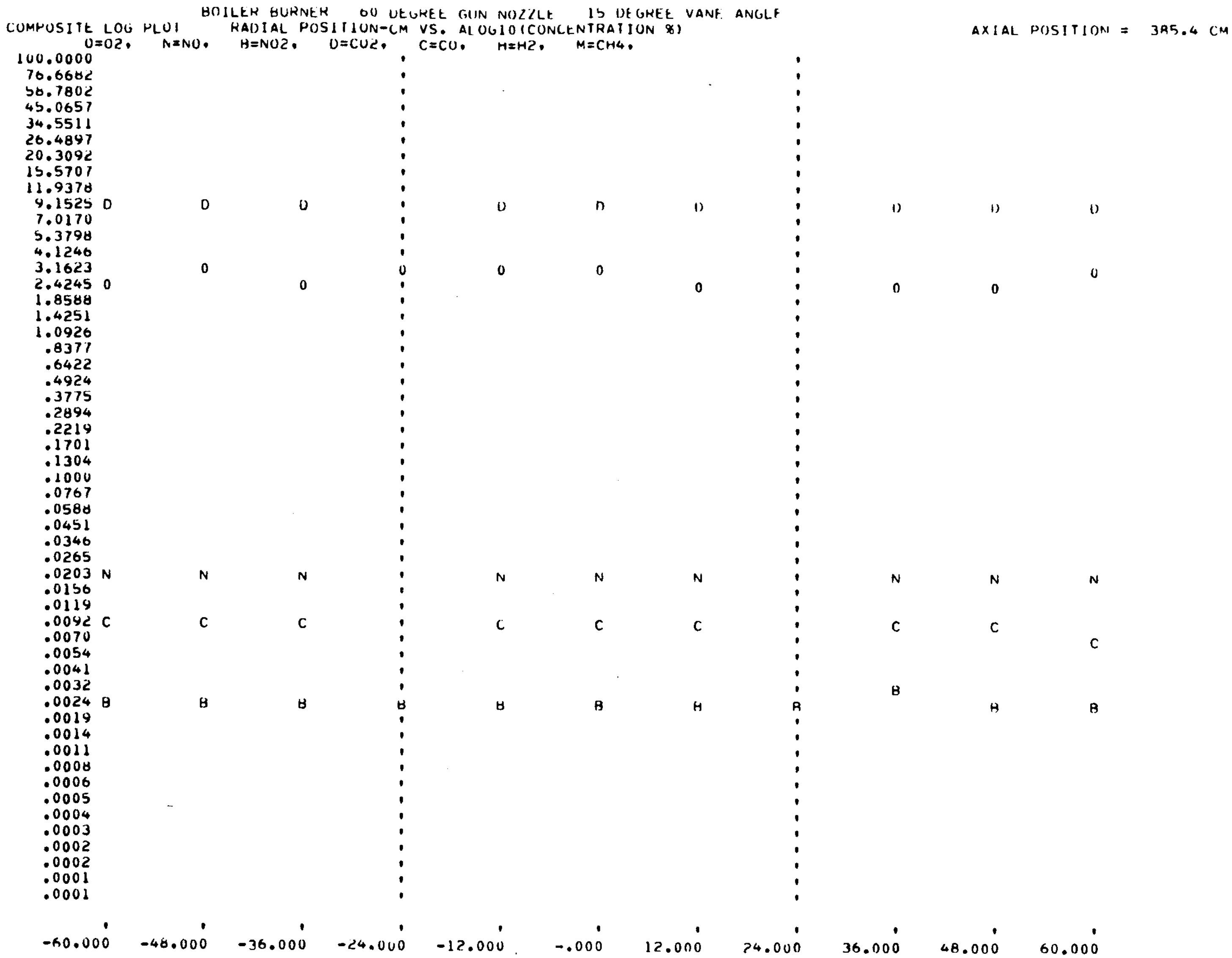

Figure 238. Radial profile of all the gases at an axial position of 385. 4 cm (movable-vane boiler burner; 15-degree vane angle)

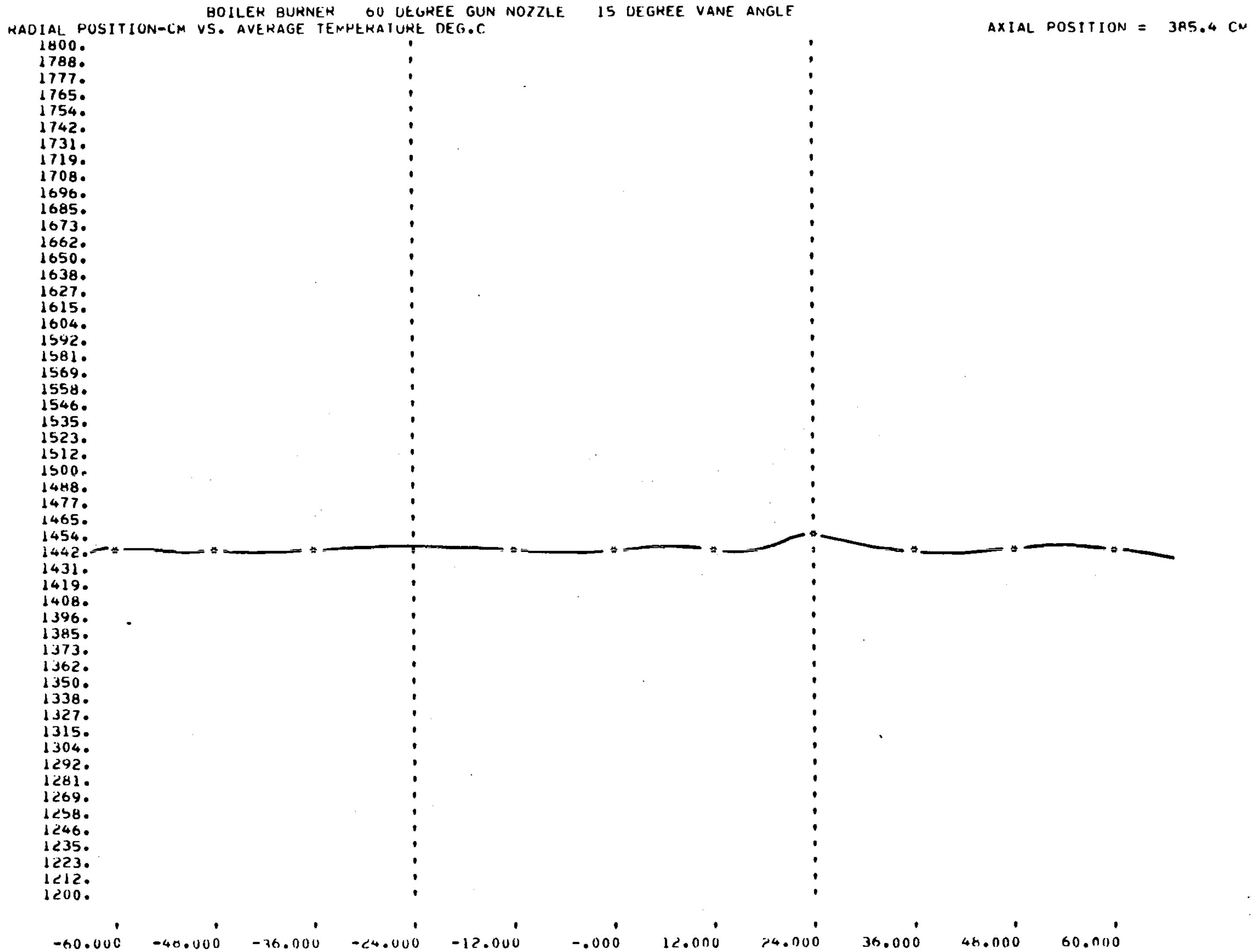

Figure 239. Radial profile of temperature at an axial position of 385. 4 cm (movable-vane boiler burner; 15-degree vane angle)

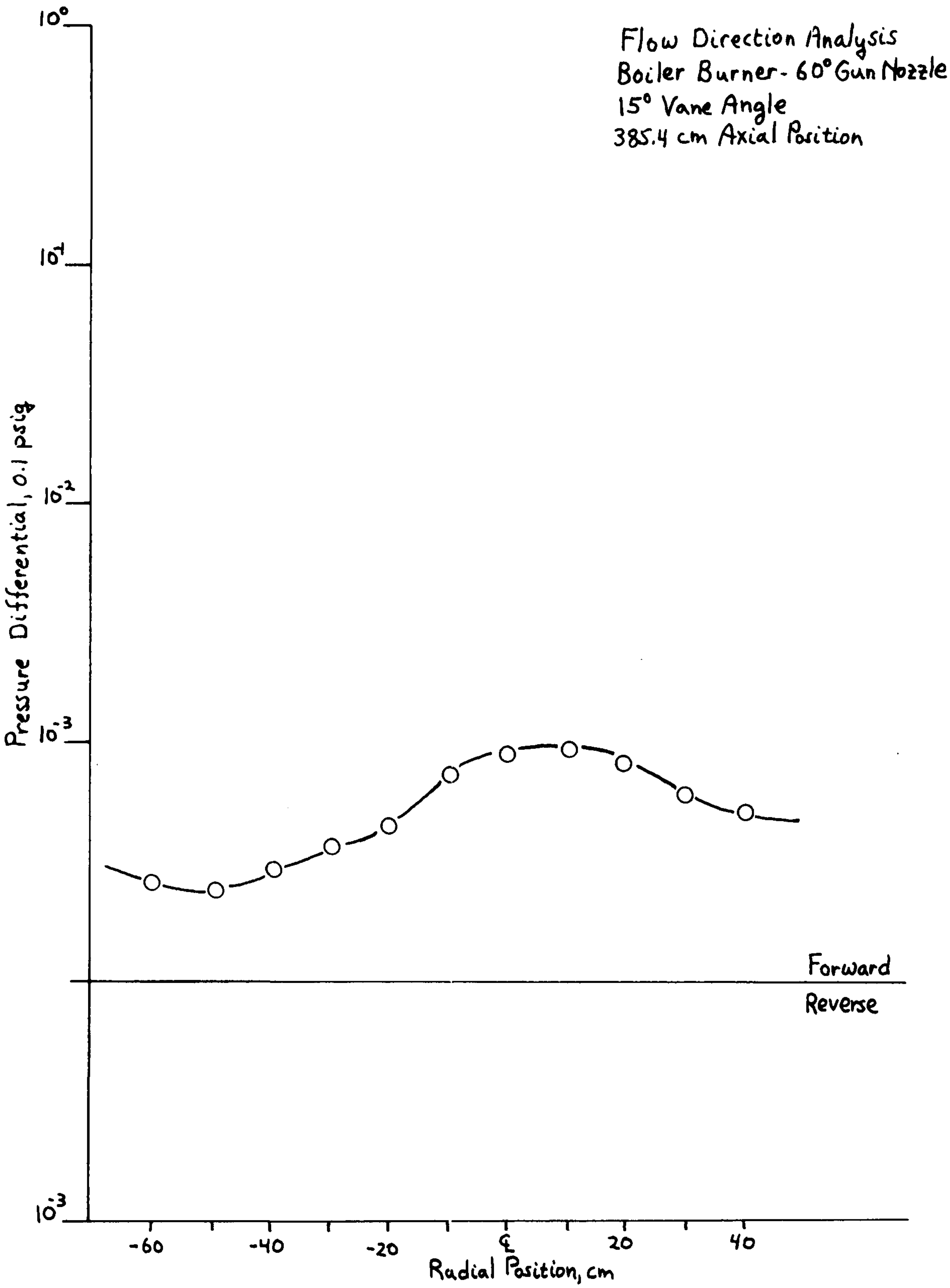

Figure 240. Radial profile of flow direction at an axial position of 385.4 cm (movable-vane boiler burner; 15-degree vane angle)

The profile data collected at the 5.1-cm axial position are graphically presented in Figures 204 through 211, with detailed data listings given in Table 35. The flow profile data show a flame Type II. The primary jet, however, is composed mainly of oxygen, indicating that the combustion does not have a large enough tangential velocity component for adherance to the burner block. The secondary jets, which appear to follow the contour of the burner block, contain large quantities of fuel.

The average NO concentration in the secondary recirculation zone is 150 ppm, compared with the 196 ppm detected in the flue. The average concentration within the burner-block area is 40 ppm with the minimum concentration of 14 ppm occurring at the same radial position (–3 cm) as the maximum oxygen concentration (18.9%).

The profile of NO_2 versus radial position is presented in Figure 205. Unlike profiles from slower mixing burners (kiln and intermediate flame length baffle) the NO_2 concentration is never larger than the NO.

The oxygen profile at the 5.1-cm position (Figure 206) shows a peak concentration of 18.9% at a –3 cm radial position. Minimum levels of oxygen were measured at –30 cm and +24 cm with respective concentrations of 0.4% and 0.1%. These minimum concentrations correspond to the location of the fuel jets, while the maximum concentration indicates a centrally located jet of combustion air, which has not attached to the burner block. Other combustibles present include carbon monoxide, with maximum concentrations of 5.1% and 8.7% at –30 cm and 24 cm, respectively; hydrogen, with maximum concentrations of 5.0% and 9.0% at –30 cm and –24 cm, respectively; and acetylene and ethylene with combined maximums of 0.4% and 1.5% at –30 cm and –24 cm, respectively. Because of the unusual arrangement of fuel and air jets, there are four radial positions at which stoichiometric fuel/air ratios occur; these are –34.8 cm, –21.4 cm, +15.4 cm, and +31.2 cm.

The curve of carbon dioxide versus radial position (Figure 208) shows the minimum concentration of 1.2% at –3 cm. The CO_2 concentration increases on both sides of this minimum until it reaches the primary recirculation zone. The carbon dioxide concentration remains rather constant at approximately 6.7% on both sides of the burner, in the regions occupied by the primary recirculation zone and the fuel jets. The concentration increases sharply to 10.6% on the boundary between the fuel jet and the secondary recirculation zone. This concentration is held rather constant throughout the secondary recirculation zone. Correlating the 5.1-cm axial position temperature profile (Figure 210) with the above chemical species and flow analyses reveals that a constant temperature of 1520°C exists in the secondary recirculation zone (compared with a wall temperature of 1426°C). A minimum temperature of 1287°C was measured at −3 cm, which corresponded to the location of the maximum oxygen concentration. There is only one highly resolved temperature peak, which occurs at −21 cm and has a magnitude of 1703°C. This maximum temperature position agrees with the location of a stoichiometric fuel/air ratio concentration.

The data collected for the movable-vane boiler burner with a 15-degree vane angle at a 26-cm axial position are listed in Table 36 and illustrated in Figures 212 through 219. The flow profile shows that the primary recirculation zones have disappeared. The forward flow region extends from −46 cm to +39 cm. This region is bounded on both sides by a secondary recirculation zone.

The NO profile at the 26-cm position (Figure 212) has an average concentration in the secondary recirculation zone of 125 ppm compared with 150 ppm in the secondary recirculation zone at the 5.1-cm axial position and 176 ppm detected in the flue. The average concentration within the forward flow zone is 79 ppm compared with 40 ppm at the 5.1-cm axial position.

The NO_2 profile (Figure 213) shows two peaks in the burner block area at −15 cm and +24 cm, with respective concentrations of 9 ppm and 17 ppm.

The curve for oxygen versus radial position (Figure 214) shows two peaks occurring at −6 cm and +3 cm, with concentrations of 7% and 6.1%, respectively. A minimum oxygen concentration of 0.1% was detected at −24 cm and +30 cm, while the locations of the maximum unburned fuel are at −30 cm and +18 cm.

The temperature profile (Figure 218) shows only one highly resolved peak, which occurs at −30 cm and corresponds to a temperature of 1695°C.

Data collected for the 46.7-cm axial position are tabulated in Table 37 and graphically presented in Figures 220 through 226. The number of locations at which stoichiometric fuel/air ratios occur has decreased from four to one. This ratio occurs at −9.1 cm for the 46.7-cm axial position. The large concentrations of the combustibles all occur to the left of the burner. Thus, although the flow profile shows only a slight asymmetry to the left side of the furnace, the gas analyses indicate that nearly all the remaining combustion will occur on the left side of the furnace.

Figures 209, 217, 224, 231, and 238 show composite log plots of concentration versus radial position within the composition range of 0.0001% (1 ppm) to 100%. In these plots, the interrelationships between concentration variations of oxygen, nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, hydrogen, and methane can easily be visualized.

Figures 210, 218, 225, 232, and 239 are plots of the average temperature measured versus radial position.

Figures 211, 219, 220, 223, and 240 show flow direction versus radial position. These profiles show the positions of the primary and secondary forward flows, of the recirculation zones (reverse flow), and of the sheared boundary layers.

<u>Data Correlation of Isoplots for the Movable-Vane Boiler Burner</u>

Figures 241, 242, and 243 are isothermal and isoconcentration plots of the data presented earlier in this report for the movable-vane boiler burner operating under standard (recommended) conditions. Similar profiles are presented in Figures 244, 245, and 246 under pollution-control operating conditions.

A comparison of the isothermal plots (Figures 241 and 244) reveals that the 30-degree vane angle produces a hotter flame than the 15-degree vane angle. These plots indicate that the 15-degree vane angle produces a larger flame than the 30-degree vane angle.

The graphs for NO isoconcentration versus radial position are presented in Figures 242 and 245. In both operating conditions, the maximum

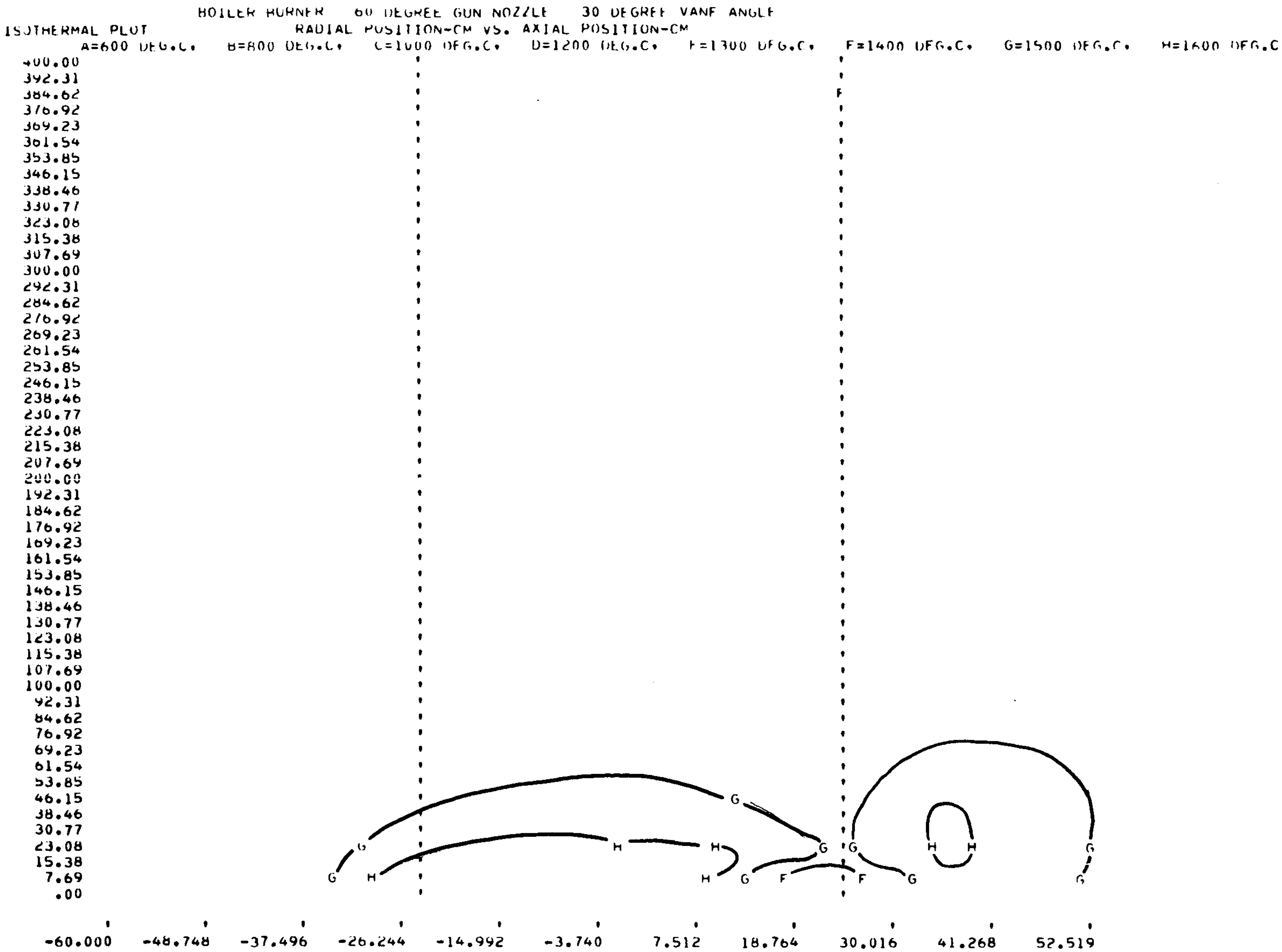

Figure 241. Isothermal plot of furnace temperature (movable-vane boiler burner; 30-degree vane angle)

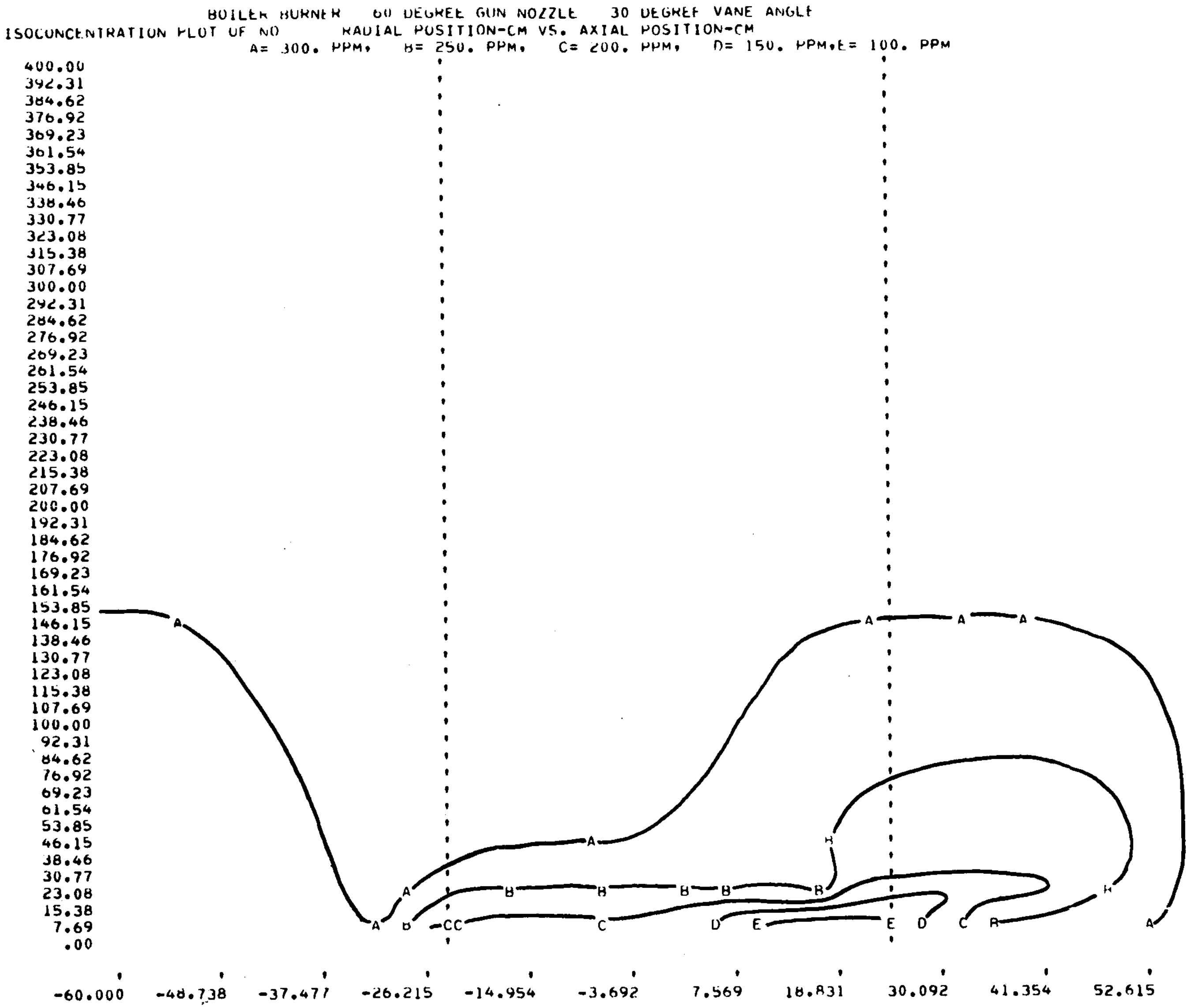

Figure 242. Isoconcentration plot of NO
(movable-vane boiler burner; 30-degree vane angle)

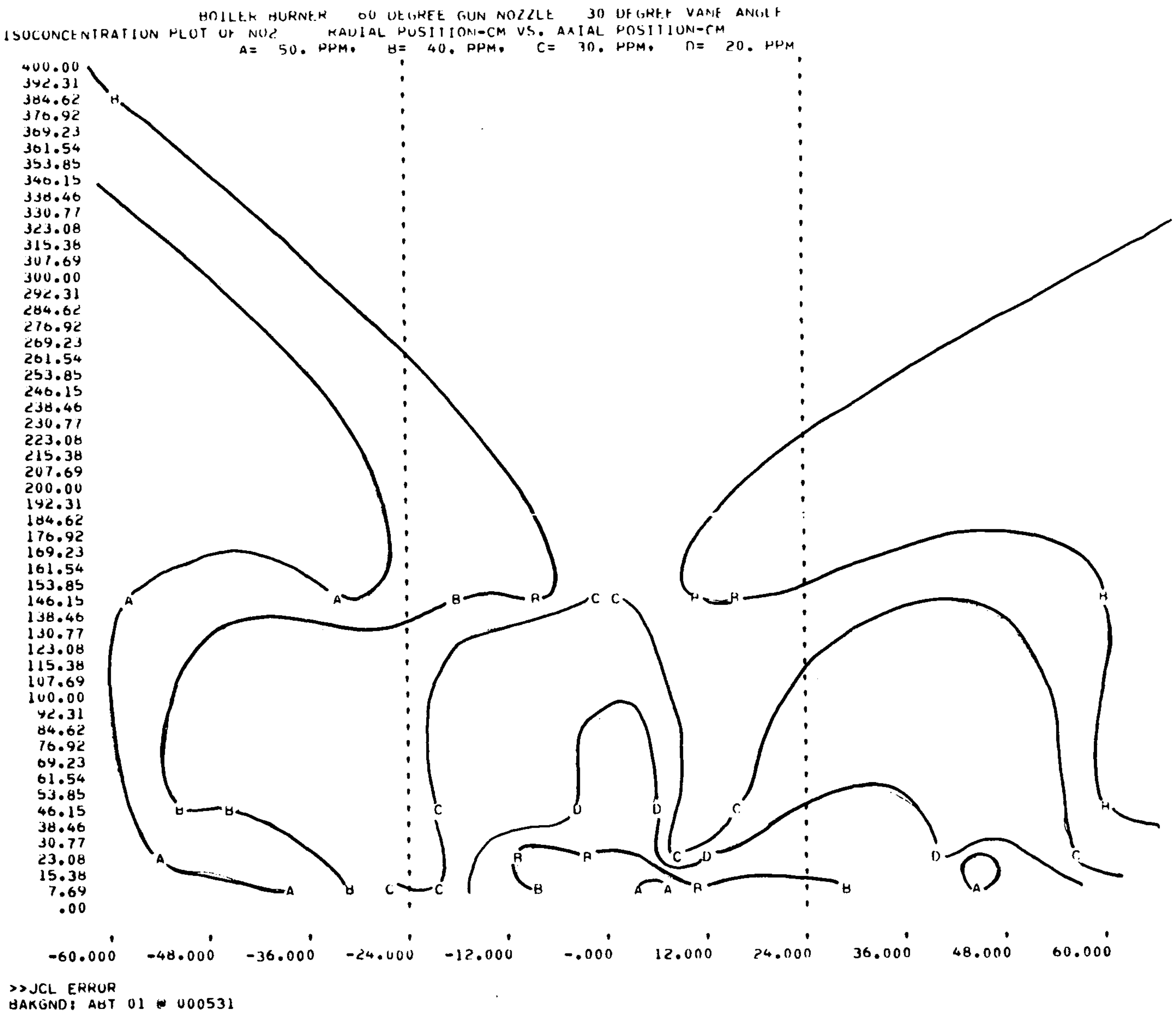

Figure 243. Isoconcentration plot of NO_2
(movable-vane boiler burner; 30-degree vane angle)

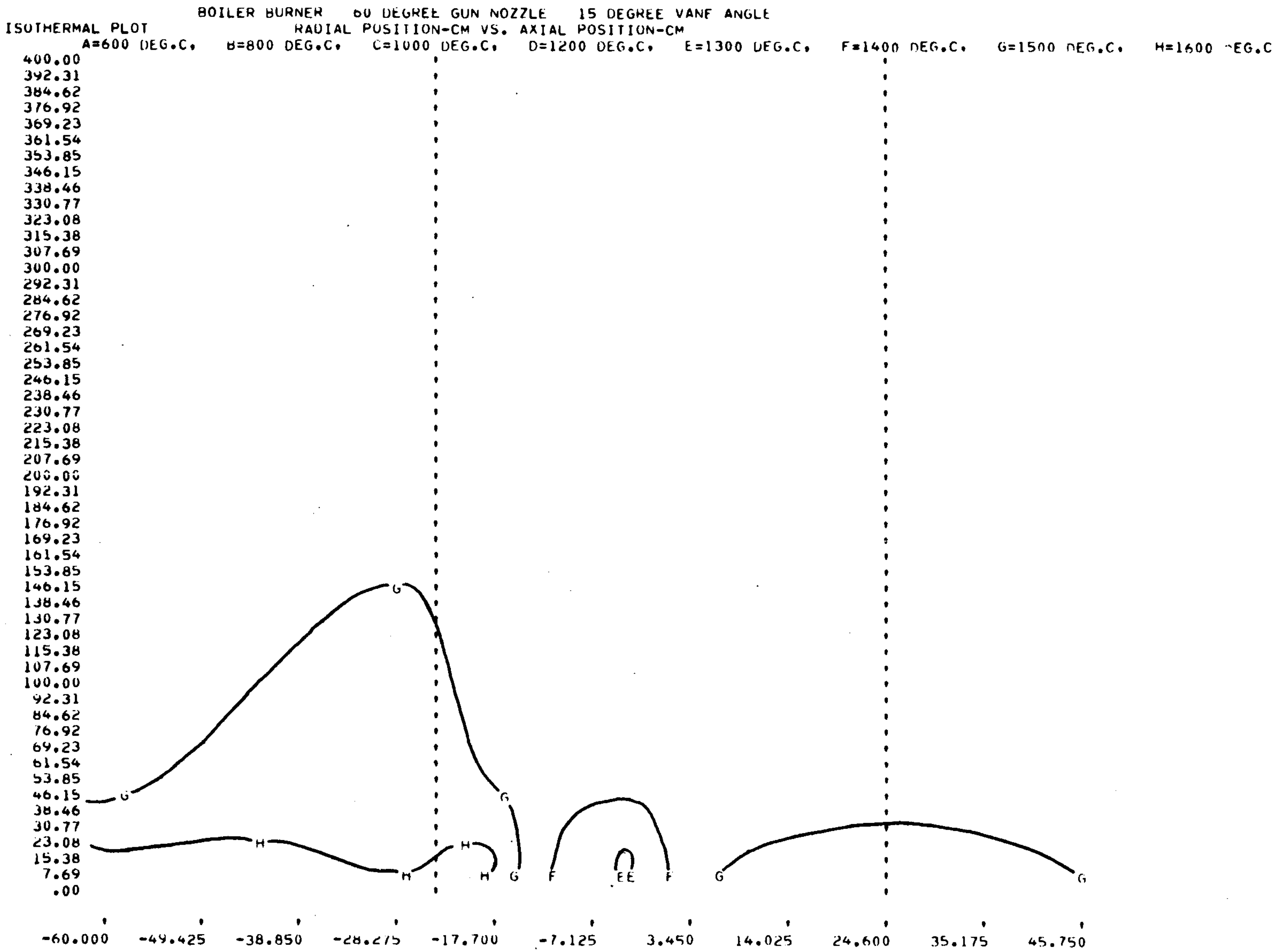

Figure 244. Isothermal plot of furnace temperature
(movable-vane boiler burner; 15-degree vane angle)

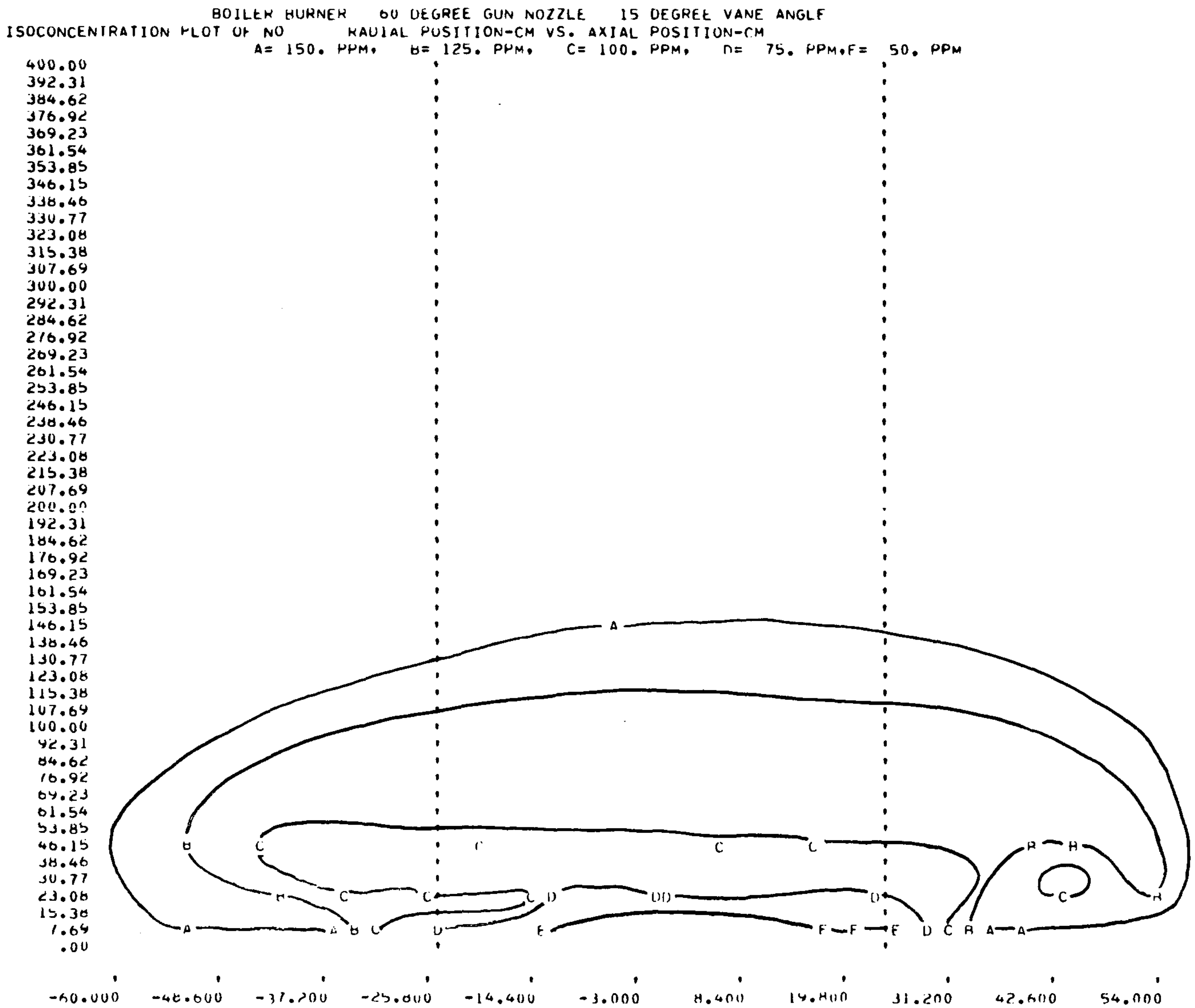

Figure 245. Isoconcentration plot of NO
(movable-vane boiler burner; 15-degree vane angle)

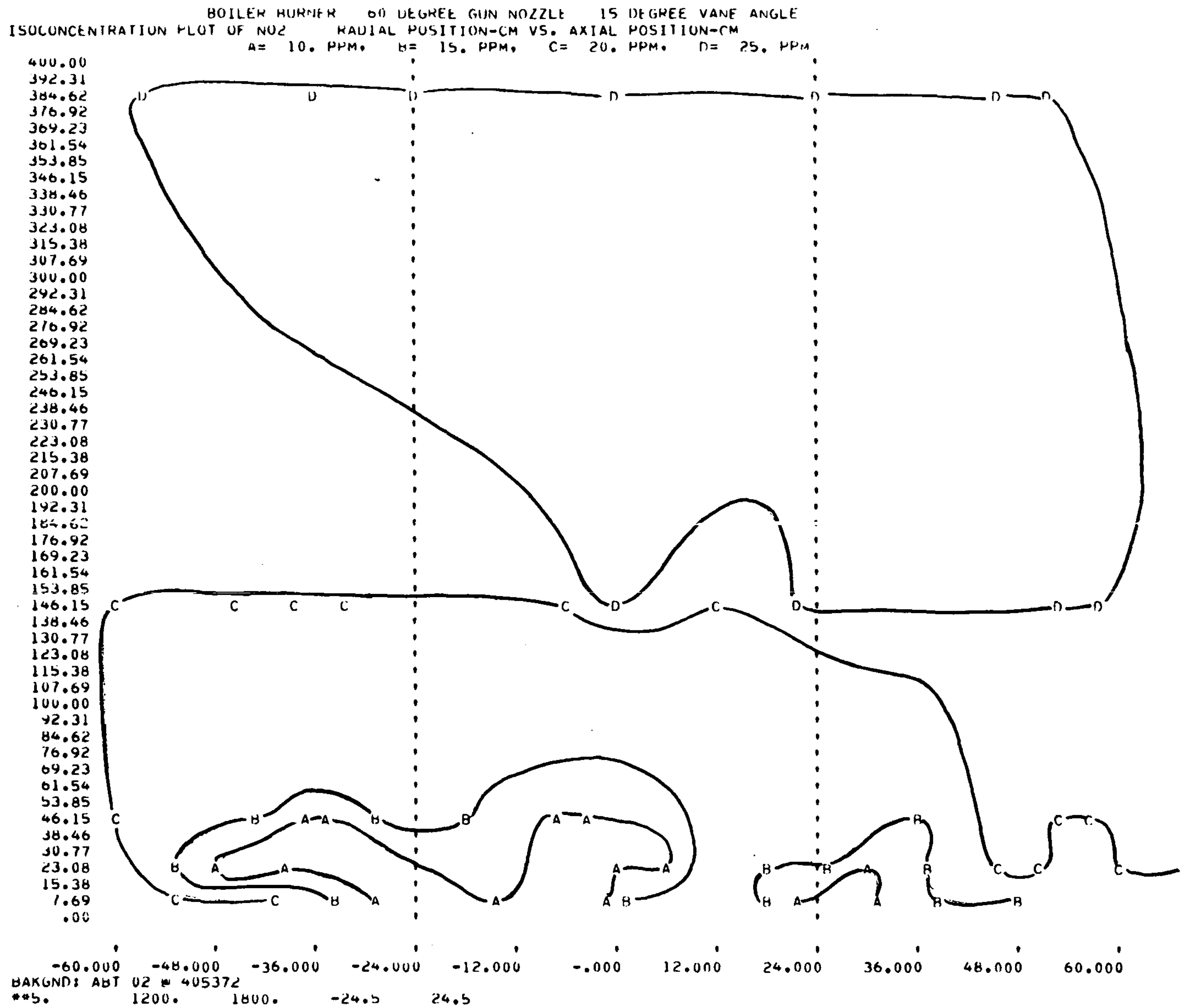

Figure 246. Isoconcentration plot of NO_2
(movable-vane boiler burner; 15-degree vane angle)

isoconcentration curve occurs in the secondary recirculation zone by the burner wall and in the forward flow zone beyond 70 cm of the burner wall. A comparison of the figures indicates that the NO developes slower when a 15-degree vane angle is used.

Isoconcentration profiles of NO_2 are plotted in Figures 243 and 246. The NO_2 profile for the 15-degree vane angle setting shows an increase in the concentration level from the burner wall to the furnace flue. In contrast, for the 30-degree vane angle, the NO_2 concentration at the exit of the burner block is equal to the level in the flue. Within the burner-block region, NO_2 concentration decreases as a function of axial position, up to 40 cm, and then the NO_2 level increases until it reaches the flue value.

APPENDIX. RAW INPUT/OUTPUT DATA

The following is a tabular listing of the raw input/output data collected during this program. Graphs of normalized NO versus excess oxygen for the test conditions listed in the table heading can be found in Volume I of this report.

Table 40. DATA FOR COMBINATION KILN BURNER NOZZLE (Gas Input, 2700 SCFH — 810 SCFH Axial and 1890 SCFH Radial; 3.2% Primary Air; 1330°C Wall Temperature)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
22	66	11	1.4	11.0	425	70
22	73	13	2.4	10.4	57	81
22	80	20	3.9	9.5	21	96
22	81	22	4.9	9.0	15	102
252	96	6	1.4	10.5	(0.9%)	102
252	112	9	2.2	10.3	(0.4%)	123
252	130	14	3.2	10.0	(0.2%)	150
252	145	19	4.4	9.4	500	178
460	250	25	3.3	9.9	314	289
460	235	23	2.6	10.4	588	263
460	350	33	5.9	8.5	215	467
460	290	29	4.1	9.5	380	351

Table 41. DATA FOR COMBINATION KILN BURNER NOZZLE
(Gas Input 2700 SCFH – 810 SCFH Axial and 1890 SCFH Radial;
3.5% Primary Air; 1150°C Wall Temperature; 12% Flue Gas Recirculation)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
460	78	18	2.45	10.4	36	87
460	72	10	1.31	11.1	183	76
460	68	7	0.9	11.4	222	71
460	80	15	2.76	10.2	13	90
242	39	7 (9)	2.7	10.1	11	44
242	41	8 (9)	4.0	9.4	10	49
242	38	9 (11)	1.4	10.9	76	40
22	16	4	1.8	10.6	253	17
22	20	4	4.7	8.9	9	25
22	18	4	3.9	9.4	20	22
22	20	6	5.7	8.3	2	27

Table 42. COMBINATION NOZZLE KILN BURNER (Gas Input 2733 CFH – 879 CFH Axial and 1854 CFH Radial; 3.2% Primary Air, Wall Temperature 1257°C (Air Cooling); and 12% Flue Gas Recirculation)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
463	110	12	2.13	10.4	516	120
463	90	7	0.9	10.9	(0.5%)	94
463	140	20	4.1	9.2	103	169
235	45	20	5.1	8.6	51	57
235	37	9	2.6	10.2	320	41
235	40	4	3.0	9.8	177	46
235	40	10	4.2	9.2	86	49
22	25	7	3.2	9.7	203	29
22	21	7	2.1	10.5	453	23
22	25	8	4.7	8.9	78	31
22	30	7	5.1	8.7	69	38

Table 43. DATA FOR COMBINATION KILN BURNER NOZZLE
(Gas Input, 2700 SCFH – 810 SCFH Axial and 1890 SCFH Radial;
3.5% Primary Air; 1130°C Wall Temperature)

Combustion Air	Flue Analysis					Normalized
Temperature, °C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
465	156	28	1.63	10.9	64	168
465	168	11	2.76	10.2	45	190
465	197	23	4.42	9.4	6	242
465	215	34	5.30	8.8	3	277
254	100	15	6.00	8.4	18	134
254	95	15	4.8	9.1	41	119
254	79	6	2.9	10.3	62	89
254	79	9	2.7	10.3	63	89
254	73	8	1.9	10.9	74	79
254	64	5	1.0	11.4	(0.6%)	68
22	39	2	0.9	11.4	(0.62%)	42
22	41	5	3.0	10.2	74	47
22	39	3	1.8	10.9	565	43
22	41	7	4.0	9.6	29	49
22	41	8	5.3	8.9	15	53

Table 44. COMBINATION NOZZLE KILN BURNER (Gas Input 2706 CFH — 876 CFH Axial and 1830 CFH Radial; 6.0% Primary Air and a 1310°C Wall Temperature [Air Cooling])

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
22	58	14	3.7	9.8	68	68
22	64	16	4.8	9.1	44	80
22	50	7	1.4	10.4	(1.0%)	55
22	52	3	0.45	10.3	(1.6%)	53
22	60	11	2.5	10.4	29	67
220	105	18	4.33	9.3	59	129
220	115	22	5.25	8.9	37	148
220	92	18	3.28	10.0	112	106
220	80	15	2.29	10.5	612	88
220	73	10	1.42	10.9	(0.18%)	78
438	145	8	1.24	11.2	220	154
438	185	28	2.57	10.4	291	206
438	275	33	4.89	9.1	96	348
438	280	37	5.64	8.7	86	368
438	210	28	3.45	9.8	190	245

Table 45. COMBINATION NOZZLE KILN BURNER (Gas Input 2700 SCFH; 30% Axial and 70% Radial; Water Cooling of Furnace Sidewalls; 1150°C Wall Temperature; 6.2% Primary Air)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
466	190	24	3.2	10.0	17	219
466	220	25	4.7	9.1	10	275
466	130	10	0.5	11.4	2000	133
466	170	18	2.0	10.7	64	185
466	190	21	2.6	10.3	30	213
272	140	19	5.2	8.9	2	180
272	130	18	4.4	9.3	13	160
272	110	17	3.1	10.0	26	126
272	80	8	1.5	11.0	72	86
272	75	3	0.8	11.4	(0.15%)	78
22	43	7	1.4	11.0	168	46
22	56	9	2.9	10.2	31	64
22	58	15	3.4	9.9	25	68
22	67	17	4.6	9.2	18	83
22	70	16	5.2	8.8	12	90

Table 46. COMBINATION NOZZLE KILN BURNER (Gas Input 2773 CFH – 873 CFH Axial and 1900 CFH Radial; 3.5% Primary Air; 1330°C Wall Temperature (Air Cooling); and the Gas Nozzle in the Exit Position)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	60	14	4.34	9.4	171	73
22	62	10	5.1	8.9	91	79
22	45	4	1.3	10.6	(0.55%)	48
22	50	8	2.5	10.2	(0.2%)	56
22	55	10	3.1	10.0	(0.17%)	63
220	100	15	2.1	10.6	489	110
220	90	11	1.3	11.0	(0.25%)	95
220	143	23	4.7	9.2	115	179
220	120	21	3.4	9.9	445	140
220	143	29	5.75	8.7	76	189
445	370	50	5.18	8.9	111	474
445	330	47	4.0	9.5	196	396
445	310	35	3.26	10.0	331	358
445	290	31	2.62	10.1	(0.6%)	325
445	245	22	1.86	10.1	(1.2%)	266

Table 47. COMBINATION NOZZLE KILN BURNER (Gas Input 2691 CFH — 368 CFH Axial and 2323 CFH Radial; 3.5% Primary Air, and 1345°C Wall Temperature [Air Cooling])

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
457	360	47	5.8	8.6	89	483
457	250	27	2.6	10.3	472	280
457	330	36	4.6	9.2	215	411
457	170	11	1.3	10.9	(0.35%)	181
247	165	30	5.6	8.7	94	259
247	128	21	2.1	10.7	212	140
247	158	25	3.5	9.9	118	188
247	115	14	1.3	11.0	(0.15%)	121
22	85	18	3.4	10.0	49	99
22	95	22	4.6	9.3	31	117
22	90	20	5.8	8.5	25	122
22	88	18	2.5	10.4	114	96
22	82	17	1.7	10.9	230	88

Table 48. COMBINATION NOZZLE KILN BURNER (Gas Input 2734 CFH – 411 CFH Axial and 2323 CFH Radial; 6.6% Primary Air, and a 1345°C Wall Temperature [Air Cooling])

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	65	14	3.2	10.0	64	75
22	55	6	2.5	10.4	179	63
22	70	15	4.4	9.3	40	85
22	49	4	0.7	11.3	(0.15%)	50
22	54	8	1.5	11.1	321	58
238	95	11	2.1	10.7	167	105
238	107	16	3.2	9.9	112	123
238	127	21	4.2	9.4	73	154
238	132	20	5.8	8.5	46	178
238	75	2	0.7	11.1	(0.35%)	77
466	100	3	0.2	10.6	(1.4%)	103
466	250	32	3.0	10.1		285
466	320	38	5.1	9.0		408
466	270	31	3.4	9.9		315
466	190	23	1.9	10.8		206

Table 49. COMBINATION NOZZLE KILN BURNER (Gas Input 2714 CFH – 411 CFH Axial and 2303 Radial; 3.5% Primary Air; 1320°C Wall Temperature, and the Gas Nozzle in the Exit Position)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	70	14	5.5	8.8	51	91
22	52	2	0.6	10.8	(0.8%)	53
22	58	9	1.85	10.9	365	63
22	65	11	2.7	10.3	190	71
22	70	16	4.7	9.1	98	88
237	127	20	3.9	9.6	65	151
237	80	10	1.5	10.7	(0.4%)	86
237	105	18	2.32	10.6	407	116
237	165	30	5.18	8.5	68	212
457	350	45	5.26	8.9	95	452
457	295	41	3.85	9.6	165	351
457	280	37	2.63	10.4	410	313
457	260	28	1.53	10.8	(0.5%)	278

Table 50. COMBINATION NOZZLE KILN BURNER (Gas Input 2687 CFH – 0 CFH Axial and 2687 CFH Radial; 3.2% Primary Air and a 1305°C Wall Temperature)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
22	95	13	3.1	10.0		115
22	75	6	1.4	11.2	(0.25%)	80
22	85	12	2.2	10.6		94
22	103	15	4.2	9.4		125
22	108	17	5.2	8.9		138
220	125	19	3.9	9.6	58	149
220	115	20	2.54	10.3	153	117
220	98	17	1.74	10.8	(0.15%)	106
220	145	23	4.8	9.1	76	182
220	155	26	5.8	8.5	51	205
447	270	33	3.62	9.8	103	317
447	300	37	5.5	8.7	90	392
447	290	36	4.44	9.3	119	357
447	220	18	1.89	10.9	(0.26%)	239
447	240	26	2.3	10.2	(0.28%)	265
447	190	8	0.6	10.8	(0.82%)	195

Table 51. COMBINATION NOZZLE KILN BURNER (Gas Input 2659 CFH – 0 CFH Axial and 2659 CFH Radial; 3.5% Primary Air; 1340°C Wall Temperature (Air Cooling); and the Gas Nozzle is in the Exit Position)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
459	365	55	4.5	9.3	75	460
459	390	60	5.15	9.0	64	499
459	275	50	2.53	10.4	192	316
459	320	50	3.25	10.1	132	370
459	260	40	1.9	10.8	281	282
459	165	--	0.4	11.0	(0.75%)	168
249	125	26	3.71	9.8	145	148
249	98	20	1.52	10.9	(0.12%)	104
249	115	22	2.28	10.6	311	127
249	80	11	0.9	11.0	(0.41%)	83
249	143	37	5.0	9.0	19	182
22	70	16	2.4	10.4	298	79
22	85	25	5.0	9.0	38	108
22	90	25	5.6	8.7	19	118
22	60	11	1.3	11.0	(0.12%)	64
22	50	--	0.5	10.8	(0.91%)	51

Table 52. DATA FOR COMBINATION KILN BURNER NOZZLE
(Gas Input 1900 SCFH – 570 SCFH Axial and 1330 SCFH Radial;
6.2% Primary Air; 1023°C Wall Temperature)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	21	5	2.8	10.2	88	24
22	14	1	0.6	11.5	(1.2%)	15
22	19	3	1.6	11.0	314	20
22	32	5	4.8	9.1	10	40
22	39	6	6.0	8.4	8	52
248	43	4	4.9	9.0	2	55
248	48	7	5.9	8.4	7	64
248	38	5	3.6	9.7	57	44
248	36	5	2.7	10.3	67	41
248	30	1	0.9	11.2	(0.61%)	31
456	62	8	2.0	10.8	80	68
456	50	11	0.53	11.4	378	51
456	55	9	1.6	11.1	158	59
456	78	15	3.1	10.1	18	89
456	95	14	4.5	9.2	7	117

Table 53. COMBINATION NOZZLE KILN BURNER (Gas Input 1800 CFH – 0 CHF Axial and 1800 CFH Radial; 4.2% Primary Air and a 1250°C Wall Temperature [Air Cooling])

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
460	120	16	4.0	9.6	278	144
460	72	9	1.1	10.9	(0.4%)	76
460	65	4	0.6	10.5	(1.0%)	67
460	105	15	2.9	10.2	497	119
242	80	10	4.5	9.2	35	99
242	92	13	5.15	8.9	10	117
242	47	--	0.2	11.2	(0.6%)	47
242	62	6	2.96	10.2	48	85
242	58	6	2.1	10.7	52	64
22	52	11	3.0	10.1	241	59
22	45	7	1.9	10.8	463	49
22	42	6	0.9	10.9	(0.62%)	44
22	48	12	2.5	10.4	371	55
22	60	14	4.1	9.5	42	73

Table 54. DIVERGENT NOZZLE KILN BURNER (Gas Input 2700 SCFH; 3.5% Primary Air; 1320°C Wall Temperature)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	Flue Analysis: NO_2, ppm	Flue Analysis: O_2, %	Flue Analysis: CO_2, %	Flue Analysis: CO, ppm	Normalized NO, ppm
22	72	6	1.0	11.3	370	76
22	105	20	4.9	9.3	--	133
22	95	20	4.4	9.4	4	117
22	95	10	3.1	10.2	32	109
22	80	15	2.1	10.7	10	88
22	82	8	1.1	11.4	215	87
243	205	45	3.0	10.1	75	234
243	190	25	1.4	11.2	240	202
243	190	40	2.0	10.6	50	207
243	210	40	4.0	10.2	15	252
243	210	35	5.1	8.9	11	268
477	370	30	4.8	9.3	--	464
477	350	20	3.0	10.2	12	399
477	340	10	2.3	10.5	79	374
477	320	20	1.0	11.3	5500	334

Table 55. DATA FOR DIVERGENT KILN BURNER NOZZLE
(Gas Input 2700 SCFH; 3.5% Primary Air; 1145°C Wall Temperature)

Combustion Air	Flue Analysis					Normalized
Temperature, °C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
22	65	10	3.7	9.7	15	77
22	70	12	5.7	8.4	5	92
22	52	10	2.5	10.4	10	58
22	63	15	4.8	8.9	7	79
22	45	7	0.8	11.2	105	47
250	98	10	2.9	10.2	14	111
250	115	20	4.4	9.2	2	141
250	125	20	5.2	8.8	0	161
250	90	13	2.4	10.3	17	100
250	106	9	3.7	9.7	4	125
250	75	8	1.0	11.2	169	78
456	113	20	3.1	9.9	16	129
456	135	22	4.6	9.1	5	167
456	133	14	3.9	9.6	6	159
456	90	12	1.5	10.8	53	96
456	144	21	5.1	8.9	2	184

Table 56. DATA FOR DIVERGENT KILN BURNER NOZZLE
(Gas Input 2700 SCFH; 9.5% Primary Air; 1150°C Wall Temperature)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
452	78	12	1.6	10.9	60	83
452	73	7	0.8	11.3	103	76
452	98	13	3.6	9.8	13	115
452	85	13	2.2	10.3	23	94
452	105	15	4.4	9.4	10	129
452	120	22	5.4	8.6	6	156
244	76	11	1.0	11.1	65	79
244	85	7	2.4	10.4	18	94
244	90	13	3.0	10.0	12	103
244	89	16	4.0	9.4	8	107
244	94	21	5.8	8.5	4	127
22	65	17	5.7	8.5	7	87
22	62	16	4.8	9.0	9	78
22	62	15	3.4	9.8	13	72
22	60	10	2.2	10.4	15	66
22	56	8	1.3	11.0	25	59

Table 57. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3070 SCFH; Baffle Gas Nozzle Position; 1435°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	110	19	1.9	10.8	114	120
22	108	15	3.7	9.8	54	127
22	103	10	0.5	11.3	2,000	105
22	107	18	2.3	10.3	85	118
22	104	20	4.0	9.4	48	124
22	99	16	5.2	9.0	32	127
229	168	35	5.9	8.5	21	225
229	201	30	4.7	9.1	32	250
229	205	32	2.7	10.3	78	231
229	222	32	3.6	9.7	63	261
229	193	34	5.2	8.8	38	247
229	192	23	1.5	11.0	118	205
229	190	5	0.5	11.3	14,000	194
462	450	61	4.4	9.4	92	549
462	398	41	1.3	10.9	265	422
462	335	23	0.6	11.4	1,700	344
462	498	64	2.5	10.3	173	556
462	505	66	3.2	9.8	142	581
462	415	64	5.5	8.6	77	540

Table 58. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 2005 SCFH; Baffle Gas Nozzle Position; 1420°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	78	22	3.7	9.8	20	92
22	71	18	5.7	8.6	9	94
22	68	11	2.0	10.6	22	74
22	48	3	0.5	10.6	16,000	50
22	73	20	4.4	9.3	20	89
22	70	15	2.5	10.3	29	78
232	140	25	4.3	9.3	19	170
232	135	20	5.1	8.9	13	171
232	105	2	0.7	11.4	635	108
232	117	16	2.7	10.3	35	132
232	110	10	1.5	10.9	52	118
454	297	32	4.3	9.4	33	361
454	295	50	5.2	8.9	26	377
454	233	2	0.4	11.3	5,000	238
454	255	25	2.0	10.7	51	278
454	290	37	3.8	9.6	39	344

Table 59. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3070 SCFH; Baffle Gas Nozzle Position; 1390°C Wall Temperature; 4-degree Burner-Block Angle; 15% and 30% Flue-Gas Recirculation)

Combustion Air	Flue Analysis					Normalized
Temperature, °C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
15% Flue-Gas Recirculation						
457	143	25	3.7	9.6	63	169
454	128	34	4.7	9.0	51	159
452	116	2	0.3	10.9	12,000	118
452	132	28	1.4	10.6	169	141
452	144	29	2.4	9.9	94	160
449	91	29	6.0	8.6	16	123
30% Flue-Gas Recirculation						
460	48	12	3.4	10.2	42	55
460	39	12	4.8	9.4	25	49
460	33	2	0.5	10.6	14,000	34
463	40	10	1.6	10.8	108	43
463	40	10	1.6	10.8	108	43
463	40	11	2.3	10.5	80	44

Table 60. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3070 SCFH; Baffle Gas Nozzle Position; 965°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	71	6	3.6	9.7	27	84
22	71	10	5.5	8.6	16	92
22	75	6	2.5	10.3	44	84
22	72	8	4.5	9.2	20	89
22	69	5	1.1	11.1	202	72
22	66	1	0.5	11.2	14,000	67
232	107	10	1.4	11.0	173	114
232	84	5	0.7	11.1	20,000	87
232	132	10	6.0	8.3	9	178
232	107	15	2.2	10.5	49	118
232	123	10	4.5	9.3	17	151
232	113	15	3.4	9.8	32	132
457	207	0	0.4	11.4	18,000	211
457	210	5	2.5	10.3	41	244
457	232	15	3.1	10.0	33	265
457	240	12	4.5	9.2	14	295
457	240	8	5.0	8.8	10	304
457	220	6	1.6	10.8	146	237

Table 61. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A COMBINATION GAS NOZZLE (Gas Input 2970 SCFH Radial; Baffle and Throat Gas Nozzle Positions; 1370°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	Flue Analysis: NO_2, ppm	Flue Analysis: O_2, %	Flue Analysis: CO_2, %	Flue Analysis: CO, ppm	Normalized NO, ppm
Baffle Position						
454	383	60	5.7	8.6	35	506
457	465	70	4.9	9.0	45	585
457	554	68	3.1	10.0	72	634
460	605	60	1.6	10.8	133	649
460	594	55	2.5	10.4	101	662
460	503	8	0.4	11.0	6,000	512
Throat Position						
460	211	20	1.4	10.9	74	225
460	233	40	5.6	8.6	21	306
463	229	22	3.3	9.8	28	265
463	216	28	2.9	10.0	34	245
463	162	0	0.4	11.1	16,900	165

Table 62. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A COMBINATION GAS NOZZLE (Gas Input 3101 SCFH – 1511 SCFH Axial and 1590 SCFH Radial; Baffle and Throat Gas Nozzle Positions; 1390°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	Flue Analysis: NO_2, ppm	Flue Analysis: O_2, %	Flue Analysis: CO_2, %	Flue Analysis: CO, ppm	Normalized NO, ppm
Baffle Position						
454	402	75	5.3	8.8	77	517
457	424	77	3.7	9.6	110	500
460	422	77	4.2	9.3	95	511
466	363	24	1.1	11.2	348	381
463	427	35	2.2	10.6	192	472
Throat Position						
460	185	30	5.5	8.6	30	241
460	180	29	4.1	9.4	45	216
460	140	23	2.0	10.4	182	153
463	95	2	0.8	11.4	473	99
463	173	28	3.6	9.7	47	203

Table 63. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3070 SCFH; Throat Gas Nozzle Position; 1455°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air	Flue Analysis					Normalized
Temperature, °C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
460	360	35	4.0	9.6	71	431
460	375	40	3.7	9.7	103	443
460	346	29	2.4	10.6	145	384
463	303	35	1.8	10.8	193	328
463	329	37	5.2	9.0	54	421
463	252	7	0.6	11.4	1000	259

Table 64. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A DIVERGENT GAS NOZZLE (Gas Input 3052 SCFH; Baffle and Throat Gas Nozzle Positions; 1415°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
Baffle Position						
471	278	29	3.9	9.6	71	331
471	283	39	4.9	9.0	60	356
471	298	39	5.7	8.5	51	393
468	266	23	2.5	10.4	110	297
466	160	4	0.5	10.6	16,000	164
463	205	15	1.1	11.0	685	215
Throat Position						
463	246	31	1.9	10.7	123	266
463	294	42	3.1	10.1	91	337
463	266	32	2.1	10.6	127	292
466	347	45	5.9	8.6	44	465
466	201	6	0.4	10.7	10,000	205
466	328	43	5.1	10.1	52	417
463	323	46	4.5	9.3	55	397

Table 65. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A COMBINATION GAS NOZZLE (Gas Input 3006 SCFH Axial; Baffle Gas Nozzle Position; 1420°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
454	243	37	4.3	9.3	65	295
454	239	43	5.7	8.6	45	315
460	238	39	2.8	10.2	104	269
460	250	40	3.6	9.7	84	294
460	215	21	1.1	11.2	480	226

Table 66. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3070 SCFH Axial; Baffle Gas Nozzle Position; 985°C Wall Temperature; 4-degree Burner-Block Angle)

Combustion Air	Flue Analysis					Normalized
Temperature, ^{0}C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
460	207	0	0.4	11.6	16,000	211
454	216	15	2.5	10.4	20	241
458	232	15	3.1	10.2	17	266
467	247	12	4.5	9.2	16	304
465	245	9	5.2	8.8	15	314
459	220	8	1.7	10.8	23	237
218	91	10	1.4	11.2	54	97
223	83	5	0.7	10.1	21,000	86
227	108	10	5.7	8.6	8	143
224	105	15	2.2	10.7	31	116
220	117	10	4.5	9.2	14	144
224	110	15	3.4	9.8	19	128
22	77	6	3.6	9.7	26	90
22	65	10	5.5	8.7	11	85
22	75	6	2.5	10.5	34	84
22	72	5	4.5	9.2	18	89
22	69	6	1.1	11.3	44	72
22	66	3	0.5	11.2	14,000	68

Table 67. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 2998 SCFH Axial; Baffle and Throat Gas Nozzle Positions; 1430°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Baffle						
443	492	45	5.3	8.6	29	632
455	510	42	3.8	9.5	31	604
450	510	43	4.4	9.2	21	624
445	465	38	2.3	10.4	64	515
440	410	34	1.2	11.1	157	433
444	352	2	0.5	11.0	6000	361
Throat						
449	510	57	4.3	9.2	75	620
458	408	33	1.5	10.9	136	439
450	460	48	2.9	10.2	97	522
443	497	44	3.6	9.7	82	584
448	505	56	5.2	8.8	58	646
450	305	3	0.4	11.0	8500	312

Table 68. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A DIVERGENT GAS NOZZLE (Gas Input 2998 SCFH Axial; Baffle Gas Nozzle Position; 1340°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
471	193	2	0.4	10.5	44	197
475	273	29	2.4	10.3	133	303
470	242	16	1.9	10.7	346	263
465	362	39	4.5	9.2	56	462
469	377	41	5.1	8.8	44	480
474	305	34	3.2	9.9	97	351

Table 69. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE INTERMEDIATE FLAME LENGTH PORTED BAFFLE BURNER WITH A COMBINATION GAS NOZZLE (Gas Input 2998 SCFH Axial; Baffle Gas Nozzle Position; 1310°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
460	166	17	1.3	11.0	152	176
454	193	28	2.4	10.3	89	215
463	212	32	3.1	10.0	83	243
465	243	37	4.8	9.1	65	304
460	250	37	5.5	8.6	56	325
460	170	--	0.5	11.1	4000	174

Table 70. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE HIGH-MOMENTUM SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 2049 SCFH Axial; Baffle Gas Nozzle Position; 1260°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	81	18	3.3	9.9	12	94
22	82	18	4.5	9.3	8	101
22	78	14	5.3	8.6	6	100
22	80	7	1.2	11.1	25	84
22	68	3	0.5	10.5	9,500	70
22	76	9	2.0	10.7	13	83
225	113	--	0.5	10.9	16,200	116
230	122	16	2.1	10.6	68	134
228	128	22	4.0	9.5	39	154
224	124	21	5.1	8.9	33	157
230	121	19	2.9	10.2	37	137
225	110	3	1.2	11.2	362	116
460	215	22	1.4	11.0	69	230
455	213	8	1.0	11.3	94	223
453	228	29	2.4	10.3	65	253
459	238	29	3.4	9.8	53	277
465	243	28	4.3	9.3	49	295
462	234	29	5.4	8.6	45	303

Table 71. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE
(Gas Input 1991 SCFH Axial; Baffle Gas Nozzle Position;
1330°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	78	17	1.53	11.1	115	85
22	105	25	5.43	8.8	25	137
22	60	0	0.5	10.6	130,000	63
22	100	15	2.77	10.3	60	113
22	100	25	4.20	9.5	30	122
22	95	20	3.50	10.0	30	111
224	215	40	5.87	8.5	30	290
224	210	40	4.25	9.5	40	256
224	150	35	1.35	11.2	75	160
224	185	30	3.15	10.1	100	213
224	110	0	0.34	10.2	150,000	114
454	241	10	0.32	11.6	35,000	245
454	276	15	1.02	11.4	155	290
454	388	24	2.92	10.2	55	440
454	344	18	2.0	10.7	84	373
454	401	34	4.5	9.2	28	493
454	388	37	5.5	8.7	27	505

Table 72. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input, 3093 SCFH Axial; Baffle Gas Nozzle Position; 1450°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	Flue Analysis: NO_2, ppm	Flue Analysis: O_2, %	Flue Analysis: CO_2, %	Flue Analysis: CO, ppm	Normalized NO, ppm
452	550	18	2.305	10.5	145	608
452	610	48	3.33	10.0	115	705
452	580	56	5.73	8.7	65	757
452	610	50	4.11	9.6	100	738
452	520	10	1.59	11.1	240	559
453	435	0	0.7	11.2	30,000	455
210	240	40	2.90	10.3	90	272
210	255	45	3.70	9.8	60	304
210	240	40	4.90	9.1	20	305
210	225	45	5.26	8.8	40	294
210	185	30	1.95	10.7	100	202
210	155	0	0.46	11.5	40,000	161
22	155	35	5.78	8.6	25	205
22	150	40	4.54	9.3	30	186
22	145	30	3.35	10.0	40	168
22	130	30	2.61	10.4	55	146
22	105	20	1.17	11.2	10,000	111
22	85	0	0.48	11.1	78,000	89

Table 73. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3064 SCFH Axial; Baffle Gas Nozzle Position; 1050°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air	Flue Analysis					Normalized
Temperature, °C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
420	294	23	2.82	10.3	20	332
420	295	26	3.31	9.9	15	341
420	293	20	4.90	9.1	15	368
420	272	20	5.93	8.5	10	364
420	270	16	1.28	11.1	25	286
420	247	0	0.64	11.4	20,000	255
212	112	23	0.92	11.4	75	118
212	123	18	1.67	10.9	20	133
212	130	30	2.43	10.6	20	144
212	142	22	3.42	10.0	20	165
212	142	22	4.15	9.5	20	172
212	140	22	5.64	8.7	19	183
22	82	5	2.7	10.3	14	92
22	91	5	3.9	9.6	12	108
22	92	7	5.2	8.8	9	118
22	78	5	1.8	10.9	19	84
22	59	0	0.4	10.8	11,000	60

Table 74. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE
(Gas Input 3070 SCFH Axial; Baffle Gas Nozzle Position; 1360°C Wall Temperature; 8-degree Burner-Block Angle; 15% and 25% Flue-Gas Recirculation)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
15% FGR						
460	129	27	5.4	8.7	38	167
455	137	28	4.0	9.6	52	164
467	127	26	3.2	10.0	70	146
463	111	22	1.9	10.8	137	121
460	122	24	2.5	10.4	86	136
465	108	7	0.5	11.2	6000	110
25% FGR						
454	66	24	2.3	10.6	61	73
460	69	20	3.3	9.9	46	80
467	66	25	4.0	9.3	37	79
462	59	12	1.3	10.9	122	63
458	56	13	1.0	11.3	134	59
465	59	31	6.0	8.5	11	80

Table 75. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A HIGH-VELOCITY RADIAL GAS NOZZLE (Gas Input 2955 SCFH Radial; Baffle Gas Nozzle Position; 1408°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
475	895	20	0.88	11.4	250	940
471	910	50	1.65	11.0	170	978
468	850	40	2.41	10.6	120	944
465	675	60	3.35	10.0	105	789
465	550	55	4.21	9.5	80	668
465	360	50	5.97	8.5	60	482

Table 76. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A LOW-VELOCITY RADIAL GAS NOZZLE (Gas Input 2982 SCFH Radial; Baffle Gas Nozzle Position; 1413°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
443	595	205	4.39	9.4	50	732
443	725	185	2.58	10.4	105	812
443	700	175	3.05	10.1	90	802
445	465	275	5.59	8.7	50	609
445	690	205	1.59	11.1	160	728
443	643	135	0.82	11.5	380	675

Table 77. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A DIVERGENT GAS NOZZLE (Gas Input 2992 SCFH; Baffle Gas Nozzle Position; 1420°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
471	505	55	5.52	8.7	35	659
471	530	601	3.88	9.6	45	633
471	520	70	4.87	9.1	40	643
471	520	50	2.86	10.2	60	589
471	500	40	1.92	10.8	85	544
471	390	25	0.33	11.7	280	406

Table 78. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A COMBINATION GAS NOZZLE (Gas Input 3061 SCFH Axial; Baffle Gas Nozzle Position; 1425°C Wall Temperature; 8-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
465	171	0	0.4	11.2	600	175
465	243	24	1.1	11.3	96	255
465	300	32	2.2	10.6	83	330
465	358	39	3.1	10.0	56	410
465	420	44	4.4	9.2	37	515
465	410	46	5.5	8.6	28	532

Table 79. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A STANDARD GAS NOZZLE (Gas Input 3008 SCFH Axial; Baffle Gas Nozzle Position; 1470°C Wall Temperature; 16-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
450	395	105	4.49	9.3	85	488
450	355	110	3.23	10.1	105	396
450	310	50	2.35	10.5	150	343
450	270	60	1.37	11.1	305	287
450	195	15	0.49	11.2	35,000	204
450	420	125	5.86	8.6	75	559

Table 80. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A DIVERGENT GAS NOZZLE (Gas Input 2863 SCFH; Baffle Gas Nozzle Position: 1440°C Wall Temperature; 16-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
460	165	0	0.45	10.6	75,000	172
460	364	45	2.55	10.5	110	400
460	240	35	1.52	11.1	340	257
460	380	60	3.20	10.1	90	437
460	435	75	4.28	9.5	60	531
460	440	70	5.64	8.7	50	579
460	395	70	6.88	7.9	35	555

Table 81. NORMALIZED NO CONCENTRATION AS A FUNCTION OF FLUE OXYGEN FOR THE SHORT FLAME LENGTH PORTED BAFFLE BURNER WITH A COMBINATION GAS NOZZLE (Gas Input 2953 SCFH Axial; Baffle Gas Nozzle Position; 1470°C Wall Temperature; 16-degree Burner-Block Angle)

Combustion Air	Flue Analysis					Normalized
Temperature, ^{0}C	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
450	395	70	5.47	8.8	80	515
450	360	105	3.05	10.1	135	410
450	370	110	4.27	9.5	100	451
450	345	40	2.52	10.5	170	385
450	310	60	1.20	11.2	10,000	329
450	290	30	0.82	11.3	25,000	305

Table 82. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 60-DEGREE GUN GAS NOZZLE (Gas Input 2969 SCFH; Exit Gas Nozzle Position; 30-degree Vane Rotation; 1340°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
22	65	36	3.9	9.7	45	78
22	68	25	4.6	9.3	27	84
22	64	27	4.9	9.1	23	80
22	78	22	1.8	10.9	62	84
22	83	25	2.5	10.5	47	93
244	145	26	2.4	10.5	165	162
244	140	37	3.2	10.1	83	161
244	130	42	5.1	9.0	45	166
244	125	36	4.2	9.6	55	151
244	155	21	1.4	11.1	438	165
457	345	40	2.8	10.2	41	390
457	275	12	0.8	11.3	6000	289
457	370	44	3.5	9.8	25	433
457	365	44	5.9	8.4	20	484
457	335	36	2.0	10.7	57	365
457	395	42	4.8	9.0	26	496

Table 83. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 60-DEGREE GUN GAS NOZZLE (Gas Input 2969 SCFH; Exit Gas Nozzle Position; 30-degree Vane Rotation; 1330°C Wall Temperature; 30-degree Burner-Block Angle; 15% and 25% Flue-Gas Recirculation)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
15% Flue-Gas Recirculation						
465	118	22	3.3	10.0	40	137
465	121	21	2.6	10.6	47	135
465	105	16	1.5	11.1	83	112
465	97	1	0.3	12.0	5000	98
465	89	20	5.2	9.0	21	114
25% Flue-Gas Recirculation						
465	31	10	4.4	9.5	20	38
465	28	11	3.4	10.2	25	33
465	28	10	2.3	10.8	34	31
465	26	8	1.4	11.2	39	28
465	24	7	0.7	11.8	364	25

Table 84. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 60-DEGREE GUN GAS NOZZLE (Gas Input 3004 SCFH; Throat, Exit, and Deflector Gas Nozzle Positions; 30-degree Vane Rotation; 1350°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	NO, ppm
Deflector Position						
458	280	44	4.8	9.1	45	354
458	260	41	3.5	9.8	72	306
458	225	33	2.5	10.4	115	252
458	200	32	2.0	10.8	170	218
458	160	0	0.8	11.5	12,500	169
458	320	47	6.2	8.2	40	429
Throat Position						
475	335	24	1.4	11.0	55	390
475	354	38	5.8	8.5	20	389
475	345	29	2.7	10.3	23	433
475	380	29	3.3	9.9	21	484
475	400	36	4.7	9.1	19	365
475	270	--	0.8	11.3	7000	496

Table 85. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A A COMPOSITE LIST OF GAS NOZZLES (Gas Input 3000 SCFH; Throat Gas Nozzle Position; 30-degree Vane Rotation; 1360°C Wall Temperature; 30-degree Burner-Block Angle; 460°C Secondary Air Preheat Temperature)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Low-Momentum Axial Nozzle						
457	470	39	4.2	9.3	26	569
457	455	42	5.6	8.5	23	569
457	415	28	2.2	10.6	31	457
457	410	26	1.8	10.8	36	444
457	335	4	0.8	11.4	6100	347
Divergent Nozzle						
465	370	34	2.2	10.6	150	407
465	410	50	5.8	8.4	83	547
465	420	47	4.4	9.2	107	515
465	400	38	3.2	9.9	126	460
465	215	5	0.9	11.1	7400	224
High-Momentum Axial Nozzle						
453	340	40	5.7	8.5	43	449
453	280	36	4.2	9.3	73	339
453	260	34	2.7	10.2	112	293
453	270	34	3.0	10.0	99	308
453	195	2	0.9	11.4	5800	203
453	215	28	1.4	11.0	326	229

Table 86. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 60-DEGREE GUN GAS NOZZLE (Gas Input 2994 SCFH; Exit, Throat, and Deflector Gas Nozzle Positions; 15-degree Vane Rotation; 1355°C Wall Temperature; 30-degree Burner-Block Angle; 457°C Secondary Air Preheat Temperature)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position						
453	240	40	6.0	8.4	49	324
453	245	35	5.0	9.0	59	310
453	173	30	2.8	10.2	84	195
453	215	33	4.0	9.5	75	257
453	158	20	2.0	10.7	130	173
453	177	15	1.5	11.0	310	189
Throat Position						
462	250	30	4.9	9.0	50	314
462	155	35	2.5	10.4	77	173
462	170	30	3.1	10.1	70	195
462	180	25	1.6	10.9	145	194
462	285	45	5.7	8.6	43	376
Deflector Position						
456	170	25	1.1	11.3	376	179
456	180	30	2.4	10.4	194	200
456	192	35	3.7	9.8	105	227
456	187	40	5.8	8.5	62	250
456	184	30	3.0	10.1	155	210

Table 87. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 60-DEGREE GUN GAS NOZZLE (Gas Input 2976 SCFH; Exit, Throat, and Deflector Gas Nozzle Positions; 45-degree Vane Rotation; 1348°C Wall Temperature; 30-degree Burner-Block Angle; 463°C Secondary Air Preheat Temperature)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
Exit Position						
469	335	34	1.5	10.9	257	358
469	395	46	2.6	10.3	189	442
469	435	51	3.7	9.7	95	515
469	450	50	4.3	9.3	74	549
469	400	55	5.7	8.4	60	526
Throat Position						
456	320	50	6.0	8.3	4	427
456	350	51	3.8	9.7	233	415
456	350	46	4.1	9.4	195	424
456	320	42	2.5	10.3	325	355
456	275	10	1.4	11.1	3000	293
Deflector Position						
463	205	30	1.8	10.8	217	222
463	235	35	2.4	10.3	126	260
463	275	40	3.6	9.8	98	323
463	290	36	4.3	9.3	78	354
463	295	44	5.2	8.8	64	379

Table 88. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A COMPOSITE LISTING OF GAS NOZZLES (Gas Input 3011 SCFH; Throat Gas Nozzle Position; 45-degree Vane Rotation; 1346°C Wall Temperature; 30-degree Burner-Block Angle; 456°C Secondary Air Preheat Temperature)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Low-Momentum Axial Nozzle						
454	370	40	1.6	11.0	97	398
454	300	40	0.9	11.4	152	312
454	440	60	4.5	9.2	43	541
454	435	55	3.8	9.6	50	515
454	405	50	2.5	10.4	55	452
454	410	60	5.8	8.5	40	547
Divergent Nozzle						
456	510	45	2.7	10.3	58	575
456	440	50	5.8	8.5	36	585
456	480	50	4.8	9.0	40	602
456	520	55	3.5	9.8	52	607
456	420	35	1.8	10.8	63	454
456	360	30	0.9	11.4	195	375
High-Momentum Axial Nozzle						
453	600	55	3.5	9.8	45	701
453	515	45	1.6	10.9	87	554
453	565	50	2.2	10.6	66	624
453	525	60	5.9	8.4	29	704
453	445	40	0.9	11.3	368	463

Table 89. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 60-DEGREE GUN GAS NOZZLE (Gas Input 2897 SCFH; Exit, Throat, and Deflector Gas Nozzle Positions; 60-degree Vane Rotation; 1382°C Wall Temperature; 30-degree Burner-Block Angle; 461°C Secondary Air Preheat Temperature)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position						
457	212	29	2.0	10.7	220	231
457	295	40	5.2	8.9	43	376
457	265	36	3.7	9.7	69	305
457	229	31	2.5	10.3	91	256
457	220	18	0.9	11.4	2500	231
Throat Position						
460	240	30	1.4	11.0	324	257
460	275	38	6.4	8.1	33	425
460	290	39	5.0	9.0	39	390
460	270	36	3.3	9.9	65	316
460	280	37	4.0	9.5	59	344
Deflector Position						
464	175	22	1.3	11.1	145	193
464	225	34	2.4	10.4	67	250
464	265	38	3.3	9.9	55	306
464	290	42	4.4	9.3	43	357
464	310	41	5.8	8.5	34	412
464	120	3	0.8	11.4	12,000	126

Table 90. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A COMPOSITE LISTING OF GAS NOZZLES (Gas Input 2883 SCFH; Throat Gas Nozzle Position; 60-degree Vane Rotation; 1376°C Wall Temperature; 30-degree Burner-Block Angle; 456°C Secondary Air Preheat Temperature)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Low-Momentum Axial Nozzle						
452	305	43	5.0	8.9	17	386
452	310	46	4.0	9.5	25	371
452	300	35	3.1	10.1	29	344
452	280	31	2.2	10.5	36	308
452	240	27	1.1	11.3	157	252
Divergent Nozzle						
458	390	40	6.0	8.4	30	527
458	460	43	4.7	9.1	39	572
458	480	44	2.9	10.3	51	545
458	455	38	1.5	11.0	70	487
458	390	34	0.6	11.6	445	401
High-Momentum Axial Nozzle						
452	170	12	1.5	11.0	396	182
452	205	34	2.7	10.3	218	231
452	225	35	3.7	9.7	140	249
452	242	42	4.3	9.3	112	294
452	270	44	5.8	8.5	85	359

Table 91. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 30-DEGREE RING GAS NOZZLE (Gas Input 2884 SCFH; Exit, Throat and Deflector Nozzle Positions; 30-degree Vane Rotation; 1357°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
Exit Position						
470	110	18	1.9	10.8	185	119
470	175	50	3.9	9.5	97	209
470	195	50	5.4	8.7	62	254
470	180	50	4.4	9.3	76	221
470	90	15	1.0	11.4	10,000	95
Throat Position						
454	175	70	1.8	10.9	135	189
454	197	63	2.4	10.4	89	219
454	212	85	3.5	9.9	76	247
454	233	67	4.6	9.2	54	289
454	240	65	5.1	8.9	46	306
Deflector Position						
466	142	28	4.7	9.1	80	177
466	125	45	3.4	9.9	122	146
466	95	22	2.6	10.4	239	106
466	70	22	1.6	11.0	500	75
466	35	0	0.6	11.5	6500	37

Table 92. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 30-DEGREE RING GAS NOZZLE (Gas Input 2938 SCFH; Exit and Deflector Nozzle Positions; 15-degree Vane Rotation; 1388°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
Deflector Position						
466	110	35	1.9	10.9	254	119
466	72	10	0.8	11.5	1000	75
466	143	52	3.0	10.1	124	163
466	200	45	4.6	9.1	84	247
466	230	50	5.4	8.7	61	299
Exit Position						
460	130	30	2.7	10.3	87	145
460	155	30	3.9	9.6	70	181
460	175	35	4.6	9.2	58	214
460	185	30	5.8	8.5	45	244
460	120	20	1.7	10.9	138	130
460	110	20	0.8	11.4	279	115

Table 93. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 30-DEGREE RING GAS NOZZLE (Gas Input 2909 SCFH; Exit and Deflector Nozzle Positions; 15-degree Vane Rotation; 1359°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position						
446	70	10	1.1	11.3	1000	74
446	65	5	0.9	11.4	2500	68
446	95	30	3.3	10.0	63	109
446	90	20	2.6	10.4	91	100
446	125	25	4.7	9.1	46	154
Deflector Position						
453	204	40	5.7	8.6	62	270
453	150	35	4.1	9.5	104	180
453	114	15	1.8	11.0	1000	123
453	90	0	0.7	11.6	19,000	92
453	132	25	3.0	10.1	215	150

Table 94. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 30-DEGREE RING GAS NOZZLE (Gas Input 2894 SCFH; Exit and Deflector Nozzle Positions; 60-degree Vane Rotation; 1370°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, ^0C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position						
459	65	10	1.8	10.9	238	70
459	90	18	2.9	10.2	102	102
459	104	21	3.6	9.8	72	123
459	121	29	4.2	9.5	54	148
459	154	34	5.1	8.9	44	196
459	57	7	0.8	11.2	3000	60
Deflector Position						
463	115	24	2.5	10.4	90	128
463	160	30	3.5	9.8	70	187
463	181	34	4.6	9.2	50	237
463	255	40	5.7	8.5	39	335
463	101	19	1.5	11.0	403	108
463	81	17	0.7	11.4	4000	84

Table 95. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 30-DEGREE GUN GAS NOZZLE (Gas Input 3054 SCFH; Exit and Deflector Nozzle Positions; 30-degree Vane Rotation; 1390°C Wall Temperature; 30-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
Exit Position						
455	250	30	2.8	10.2	91	281
455	210	35	2.0	10.7	121	227
455	290	60	4.0	9.5	75	345
455	310	55	4.9	9.0	60	383
455	310	60	6.0	8.4	51	414
455	160	10	0.4	11.5	5600	166
Deflector Position						
465	185	30	4.0	9.5	144	222
465	240	35	4.9	9.0	95	304
465	255	40	5.4	8.7	70	330
465	85	10	0.9	10.8	7100	91
465	135	20	2.7	10.3	406	152

Table 96. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH 30-DEGREE RING AND 60-DEGREE GUN GAS NOZZLES (Gas Input 3044 SCFH; Exit and Deflector Nozzle Positions; 30-degree Vane Rotation; 1347°C Wall Temperature; 15-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position, 60-Degree Gun						
462	180	5	1.0	11.4	27500	196
462	200	20	2.0	10.7	99	218
462	215	30	3.0	10.1	58	245
462	210	35	4.1	9.5	55	254
462	215	40	5.4	8.7	31	280
Deflector Position, 60-Degree Gun						
456	350	40	5.2	8.9	51	443
456	355	20	4.6	9.2	70	440
456	345	20	3.5	9.8	144	404
456	330	15	2.0	10.7	7500	360
456	335	20	2.3	10.5	176	369
Exit Position, 30-Degree Ring						
463	30	2	0.3	11.6	17000	32
463	85	7	3.2	10.0	86	98
463	95	17	4.2	9.5	57	115
463	90	19	5.2	8.9	70	115
463	60	5	2.0	10.7	274	65

Table 97. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH 60-DEGREE GUN AND 30-DEGREE RING GAS NOZZLES (Gas Input 3029 SCFH; Exit and Deflector Nozzle Positions; 15-degree Vane Rotation; 1390°C Wall Temperature; 15-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	Flue Analysis: NO_2, ppm	Flue Analysis: O_2, %	Flue Analysis: CO_2, %	Flue Analysis: CO, ppm	Normalized NO, ppm
Deflector Position, 60-Degree Gun						
465	480	15	0.5	11.6	486	481
465	510	50	1.5	11.0	330	546
465	530	65	2.2	10.6	210	591
465	520	65	3.3	9.9	152	601
465	485	65	4.9	9.0	96	611
Exit Position, 60-Degree Gun						
459	395	35	0.9	11.4	320	389
459	395	50	2.5	10.4	152	439
459	385	55	3.7	9.8	112	454
459	375	50	4.5	9.3	92	463
459	350	45	5.8	8.5	68	468
Exit Position, 30-Degree Ring						
470	85	8	0.8	11.5	384	90
470	139	22	1.9	10.8	241	151
470	185	36	3.0	10.1	143	211
470	200	35	3.4	9.9	126	232
470	225	45	4.5	9.2	81	277
470	235	50	5.2	8.8	75	301

Table 98. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH 30-DEGREE RING AND 60-DEGREE GUN GAS NOZZLES (Gas Input 2889 SCFH; Exit and Deflector Nozzle Positions; 45-degree Vane Rotation; 1395°C Wall Temperature; 15-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position, 30-Degree Ring						
470	315	40	5.5	8.7	73	411
470	300	35	4.6	9.2	96	372
470	245	35	3.0	10.1	165	279
470	275	35	3.5	9.8	135	322
470	175	15	1.4	11.1	500	187
Exit Position, 60-Degree Gun						
453	520	60	5.1	9.0	94	663
453	540	60	4.6	9.2	96	664
453	570	55	3.9	9.6	108	670
453	520	40	1.5	11.0	367	550
453	455	20	0.4	11.5	5000	472
Deflector Position, 60-Degree Gun						
455	460	60	4.7	9.1	106	566
455	450	50	3.6	9.8	138	527
455	385	45	2.4	10.5	215	424
455	350	30	1.7	11.0	385	389
455	485	65	5.1	9.0	105	609

Table 99. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH 30-DEGREE RING AND 60-DEGREE GUN GAS NOZZLES (Gas Input 2896 SCFH; Exit and Deflector Nozzle Positions; 60-degree Vane Rotation; 1385°C Wall Temperature; 15-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
Exit Position, 60-Degree Gun						
455	620	70	1.0	11.3	2500	654
455	695	40	2.4	10.5	352	771
455	630	70	4.0	9.5	243	756
455	660	65	3.4	9.9	389	766
455	570	50	5.3	8.8	187	735
Deflector Position, 60-Degree Gun						
461	560	90	4.8	9.0	82	703
461	610	90	1.7	10.9	161	659
461	640	90	3.2	10.0	116	736
461	620	90	2.1	10.6	151	679
461	595	60	1.0	11.4	12,000	628
Exit Position, 30-Degree Ring						
450	495	35	4.0	9.5	192	576
450	465	45	2.7	10.3	205	523
450	355	25	1.3	11.1	301	367
450	450	50	4.9	9.0	135	567
450	450	30	5.6	8.6	108	592

Table 100. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A 30-DEGREE RING GAS NOZZLE (Gas Input 2895 SCFH; Exit Nozzle Position; 15, 30, 45, and 60-degree Vane Rotation; 1361°C Wall Temperature; 45-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis: NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	Normalized NO, ppm
30-Degree Vane Angle						
465	142	8	0.4	11.6	449	148
465	145	13	1.2	11.2	205	154
465	165	23	2.2	10.6	138	180
465	185	35	3.4	9.9	110	216
465	210	40	4.5	9.2	78	259
465	200	40	5.8	8.5	55	265
15-Degree Vane Angle						
456	132	23	2.4	10.5	77	147
456	124	21	1.4	11.0	136	132
456	114	1	0.9	11.3	151	120
456	165	25	3.0	10.1	69	172
456	175	25	4.3	9.4	53	214
45-Degree Vane Angle						
463	255	25	0.5	11.6	372	270
463	305	45	1.1	11.3	195	323
463	380	40	2.4	10.5	112	420
463	400	55	3.2	10.0	84	460
463	365	50	4.3	9.4	64	445
463	275	40	6.0	8.4	43	370
60-Degree Vane Angle						
452	185	25	1.4	11.1	46	224
452	220	30	2.4	10.5	43	278
452	280	40	3.4	9.9	40	326
452	265	45	4.1	9.5	36	338
452	240	50	5.3	8.8	34	323
452	165	15	0.3	11.7	415	186

Table 101. FLUE ANALYSIS FOR THE MOVABLE-VANE BOILER BURNER WITH A COMPOSITE LIST OF GAS NOZZLES (Gas Input 3041 SCFH; Exit Nozzle Position; 60-degree Vane Rotation; 1396°C Wall Temperature; 45-degree Burner-Block Angle)

Combustion Air Temperature, °C	Flue Analysis					Normalized NO, ppm
	NO, ppm	NO_2, ppm	O_2, %	CO_2, %	CO, ppm	
30-Degree Gun Nozzle						
462	280	15	0.7	11.4	408	293
462	340	30	1.3	11.1	267	359
462	395	50	2.1	10.6	183	432
462	465	50	3.2	10.0	120	535
462	465	50	4.5	9.2	106	574
462	445	55	5.0	9.0	81	565
Low-Momentum Axial Nozzle						
470	310	35	5.4	8.7	37	403
470	285	30	4.4	9.3	46	351
470	255	30	3.2	10.0	59	295
470	220	15	1.8	10.8	128	237
470	185	10	0.9	11.3	200	194

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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16. ABSTRACT Volume I of the report gives details of, and analyzes, trials conducted with natural gas to determine the relationship between combustion aerodynamics and pollution emission characteristics of industrial burners. Three burner types were studied (kiln, ported baffle, and movable vane boiler), based on relative gas load and estimated total industrial emissions. Experimental measurements on a pilot-scale furnace included baseline characterization of each burner and variation of primary operating parameters (air preheat, air/fuel ratio, firing rate, heat release rate, position of gas nozzle in burner block, and air swirl intensity). Additional emissions data were gathered for suspected control conditions (fuel injector design, flue gas recirculation, fuel/air momentum ratio, and burner block angle). It also describes in detail the experimental facility and sampling probes used to collect the data. Volume II discusses completely the procedure used to select the test burners. It includes detailed flame characterizations of baseline operations assembled from in-the-flame temperature, gas species, and flow direction data analysis. Similar in-the-flame studies were made for control conditions which minimized emissions for each burner type. It also includes all raw data collected from the input/output trials.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Flames	Air Pollution Control	13B	
Nitrogen Oxides	Swirling	Stationary Sources	07B	13H, 07A
Aerodynamics		Axial Injection	20D	
Natural Gas		Radial Injection	21D	
Combustion Control		Swirl	21B	
Burners		Industrial Burners	13A	

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