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EFFICIENCY TESTS OF A FLUIDIZED-BED INCINERATOR BURNING WOOD WASTE WITH HEAT RECOVERY - CHAPLEAU LUMBER COMPANY LTD, CHAPLEAU, ONTARIO - DECEMBER 6 AND 7, 1977

F. D. Friedrich and F. L. Wigglesworth
CANADIAN COMBUSTION RESEARCH LABORATORY

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EFFICIENCY TESTS OF A FLUIDIZED-BED INCINERATOR BURNING WOOD WASTE WITH HEAT RECOVERY CHAPLEAU LUMBER COMPANY LTD, CHAPLEAU, ONTARIO DECEMBER 6 AND 7, 1977

by

F. D. Friedrich* and F. L. Wigglesworth**

ABSTRACT

Two 4-h efficiency tests were carried out on a wood waste incinerator equipped with waste heat boilers generating low pressure steam. The incinerator is a fluidized-bed combustor built by York-Shipley Ltd.

During the tests the combustor burned approximately 3900 kg/h (8600 lb/hr) of wood waste containing 30 to 35% moisture, and generated approximately 15,900 kg/h (35,000 lb/hr) of steam with an overall efficiency of 73 to 75%.

Some difficulties were experienced with incoming fuel smothering fluidization over substantial portions of the bed. This could probably be overcome by increasing the pressure drop through the air distributor and/or the bed.

*Research Scientist and **Technologist, Canadian Combustion Research Laboratory, Energy Research Laboratories, Canada Centre for Mineral and Energy Technology, Department of Energy, Mines and Resources, Ottawa, Canada.

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INTRODUCTION

In September 1977 the Canadian Centre for Mineral and Energy Technology (CANMET) entered into an agreement with the Environmental Protection Service of Fisheries and Environ,ent Canada to share the cost of a combustion performance assessment. The work was to be carried out by the Canadian Combustion Research Laboratory (CCRL) on fluidized-bed-fired incinerator burning wood waste which generates low pressure steam by means of a pair of waste heat boilers. This equipment is located at the Chapleau Lumber Company in Chapleau, Ontario.

The boilers are not equipped with any instrumentation to indicate steam output. Some delay was experienced in obtaining and installing, on a temporary basis, water meters to measure feedwater flow. Tests were scheduled for the week beginning December 5th, 1977, but due to operating difficulties with the combustor, which will be described later, only two 4-h tests at full-load conditions were carried out. This report describes the incinerator plant, the test procedures, and the results.

DESCRIPTION OF EQUIPMENT

General

The Chapleau Lumber Company Ltd operates a large softwood sawmill, and has solved the problem of wood waste disposal by installing a fluidized-bed-fired incinerator. Since steam is required to heat drying kilns, waste heat boilers have been coupled to the incinerator exhaust. When the incinerator is operating at full capacity the steam output substantially exceeds the heating requirements and the excess is vented to atmosphere.

The steam plant layout is shown schematically in Figure 1. Bark, sawdust, and wood scraps are hogged, then dumped into an outdoor pit from which an inclined drag conveyor transports them into a large storage silo. The silo is located inside the steam plant to minimize handling difficulties with frozen fuel. At the bottom of the silo a vertical auger equipped with flail-chains discharges fuel into a horizontal screw conveyor, which feeds an inclined screw conveyor, which charges the metering bin.

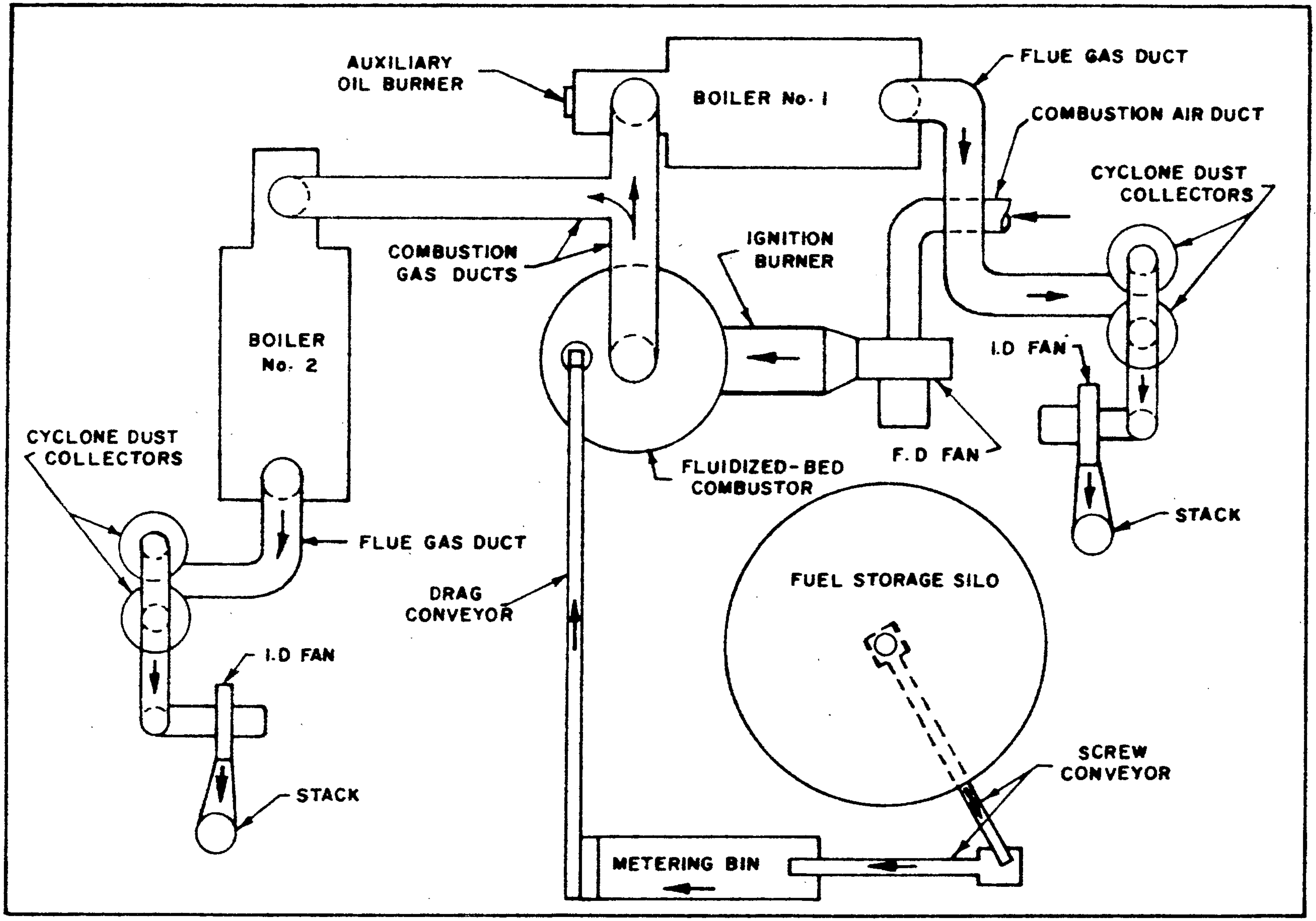

Figure 1. Schematic layout of heat recovery incinerator system for wood waste.

Control of fuel feed to the combustor is provided by a tall, narrow metering bin having at the bottom four parallel screw conveyors 30.5 cm (12-in.) diam, driven by a variable-speed DC motor. The metering bin discharges into an inclined drag conveyor which carries the wood waste to the tope of the combustor and drops it through an air-cooled opening in the combustor roof.

The combustion gases from the combustor are fed through refractory-lined ducts to two firetube boilers, each of which has its own dust collector, induced draft fan, and stack, as described in the following section.

Fluidized-bed Combustor

The combustor is a York-Shipley, Model FB140 having an outside diameter of 427 cm (14 ft) and an overall height of 815 cm (26 ft 9 in.). Its capacity rating is 38,500 kg/h (85,000 lb/hr) of flue gas at 980°C (1800°F). The combustion air distributor consists of a plenum and manifolds with 388 standpipe nozzles projecting 178 mm (7 in.) above the manifolds. The bed material normally comprises 13.6 Tonnes (15 tons) of olivine, which is a silicate of iron and magnesium having a specific gravity 3.2 to 4.4. The static bed depth is approximately 23 cm (9 in.) above the top of the air nozzles. The bed material can be drained by gravity through the spaces between the manifolds.

The first 244 cm (8 ft) of the combustion chamber above the air distributor are lined with 152 mm (6 in.) of hard, high-temperature refractory backed with 64 mm (2½ in.) of block insulation. The next section, approximately 213 cm (7 ft) is lined with 152 mm (6 in.) of the same refractory without insulation, and the top section, approximately 244 cm (8 ft), is lined with 114 mm (4½ in.) of refractory without insulation.

Combustion air is supplied by a 112 kW (150 hp) blower with a rated capacity of 425 m^3/min (15,000 cfm) at 21°C (70°F). Outside air is ducted to the blower and the discharge is split into three streams. One stream enters the combustor windbox below the distributor plate through an oil-fired preheater, and this provides the means for bringing the fluidized bed to ignition temperature. The second stream feeds an air manifold girdling the combustor 244 cm (8 ft) above the distributor. Nozzles from the manifold are oriented tangentially to the combustor and provide air to support freeboard combustion. The third stream of air is ducted to the top of the combustor where it enters the freeboard co-axially around the fuel feed chute. The feed chute terminates in a simple metal splitter which helps to disperse the falling stream of fuel over the bed area. Depending on the size consist and moisture content of the fuel, a substantial portion of it burns in suspension in the freeboard space.

Waste Heat Boilers

Steam is generated from the hot combustion gases by two firetube boilers, both York-Shipley Model WHL3500, having 325 m^2 (3500 sq ft) of heating surface each. Boiler No. 1 has a rated output capacity of 21,200 MJ/h (20,085,000 Btu/hr) and is equipped with a York-Shipley burner Model FA600 for No. 2 oil, which has a maximum firing rate of 670 L/h (177 gph). The burner is operated only when the fluidized-bed combustor is out of service and steam is required for the drying kilns. Boiler No. 2 has a rated output capacity of 24,700 MJ/h (23,450,000 Btu/hr), and is not equipped with an oil burner. Both boilers have a working pressure rating for steam of 103 kPa (15 psi), but are actually operated between 35 kPa (5 psi) and 70 kPa (10 psi).

The steam line from Boiler No. 1 supplies the drying kilns and any excess steam is vented to atmosphere via a pipe through the boilerhouse roof. All the steam from Boiler No. 2 is similarly vented to atmosphere.

The flue gas from Boiler No. 1 passes through a twin cyclone dust collector, through a 112 kW (125-hp) induced draft fan and into a steel stack. Particulates from the cyclones are collected in a 205 L (45-gal) drum. For Boiler No. 2 the setup is similar, but the induced draft fan is driven by a 75 kW (100-hp) motor, and dust collector, induced draft fan and stack are located outside the boilerhouse.

Each boiler is equipped with a feedwater pumpset consisting of two pumps, connected in parallel, either one capable of supplying the needs of the boiler.

Control System

The combustor is equipped with an automatic control system that is intended to require only intermittent supervision by the operator. The key component is a Hi-Lo signal selector which controls the worm speed in the fuel metering bin. When the signal selector is in the high-fire position the forced-draft and induced draft fans take preset positions and feedrate is varied to maintain a freeboard temperature of 980°C (1800°F). When the signal selector is in the low-fire position the fans take preset positions different from the high-fire positions and feedrate is varied to maintain a bed temperature of 760°C (1400°F). Feedrate and forced draft can also be varied by manual adjustment of the controls.

To light up the combustor, the signal selector is switched to manual control. The forced-draft fan is started and the air entering the windbox is heated by bringing the oil-fired ignition burner into service. When the bed, heated by the fluidizing air, reaches the ignition temperature of wood approx 430°C (800°F) fuel feed is started at a low rate, and increased as bed temperature continues to rise. When the bed temperature reaches 980°C (1400°F) or when the freeboard temperature reaches 980°C (1800°F) the signal selector is switched to either high-fire or low-fire automatic operation, depending on the firing rate desired.

On Boiler No. 1, remote controllers operated from the panel are provided to position the main steam valve and the vent line valve. The panel also holds position controllers for the dampers controlling fluidizing air to the windbox, tangential air to the header around the freeboard, and overfire air entering with the fuel feed. Position controllers are also provided for the flue damper on each boiler.

Pressure indicators are provided on the panel for the fluidizing blower pressure, the bed differential pressure, and the flue gas pressure into each boiler. A multi-point indicator on the panel indicates temperatures at two locations in the bed, in the windbox, two locations in the freeboard, flue gas at the exit of Boiler No. 1, and flue gas entering the cyclone serving Boiler No. 1. Steam pressure gauges are provided on each boiler, but not on the control panel. Steam flow and feedwater flow are not monitored.

TEST PROCEDURE AND RESULTS

The Heat Loss Method of Efficiency Calculation

The fact that the combustor-boiler system is not equipped with means for measuring fuel input and steam output made it necessary to determine efficiency by measuring or estimating the various heat losses. These are as follows:

1. Dry flue gas loss is the sensible heat in the dry flue gas leaving the boilers. It can be calculated knowing fuel composition, excess air level, stack temperature and combustion air temperature.

2. Loss due to combustion of hydrogen is the heat required to vapourize the water formed by combustion of hydrogen in the fuel, and heat the vapour to stack temperature. It can be calculated knowing the fuel composition, stack temperature, and combustion air temperature.

3. Loss due to moisture in fuel is the heat required to vapourize the moisture in the fuel and heat the vapour to stack temperature. It can be calculated knowing fuel composition, fuel temperature and stack temperature.

4. Loss due to combustible in fly ash is the heat lost by some of the fuel not being burned and thus escaping as carbon in the fly ash. It can be calculated knowing the quantity of fly ash produced, and its combustible content.

5. Radiation and convection loss from the boilers is the heat thus lost from the boiler surfaces exposed to ambient air. The loss is a constant quantity but varies as a percentage of boiler output. It can be determined from a standard chart prepared by the American Boiler Manufacturers Association, knowing actual output, rated capacity and construction of the boiler.

6. Radiation and convection loss from the combustor and flue gas ducts is the heat lost from the combustor surfaces and the extensive ductwork carrying the products of combustion to the boilers. It can be calculated knowing the surface area exposed to ambient, its emissivity, its mean temperature, its orientation, the ambient temperature, and air velocity over the exposed surfaces.

7. Unaccounted-for loss is a composite of several minor losses due to such things as moisture in the air, CO and combustible vapour in the flue gas, sensible heat in the ash and boiler blowdown. It is usually estimated.

To determine the so-called boiler heat losses one therefore needs to know boiler output, fuel composition, flue gas analysis, weight and carbon content of the fly ash, and temperature of the fuel, combustion air and stack gas. In addition, factors governing radiation and convection from the combustor and ductwork must be determined.

To measure boiler output, two integrating water meters were installed on a temporary basis, one on the feedwater line to each boiler. With no blowdown, feedwater flow equals steam flow, and steam quality was assumed to be dry and saturated. To obtain representative fuel analyses, incremental samples of wood waste were taken from the metering bin during the tests, sealed in plastic bags to avoid moisture loss, and later subjected to proximate, ultimate and calorific determinations. Oxygen, carbon dioxide and carbon monoxide in the flue gas were monitored during the tests by means of portable continuous analyzers.

No weigh scales were available to weigh the fly ash collected from each boiler during each test. However, the level of fly ash in each drum was measured at the beginning and end of each test, making it possible to calculate the volume collected. Incremental samples of fly ash were collected during the tests, and were later subjected to density and combustible determinations. This provided sufficient information to calculate the loss due to combustible in fly ash.

Flue gas temperature and combustion air temperature were measured by thermocouple and thermometer respectively. Fuel temperature was assumed to be the same as combustion air temperature.

The dimensions of the combustor and ductwork connecting it to the boilers were measured. Also, a surface pyrometer was used to take many spot measurements of surface temperature. Since much of the ductwork was inaccessible without scaffolding, a systematic mapping of surface temperature was not attempted. Because the heat loss in question is a relatively minor one, it was felt that random measurements would provide a sufficiently accurate mean temperature. Also, since both tests were run at full combustor capacity, the surface temperatures were measured only once, prior to Test No. 2.

Summary of Combustor Operation

During the week prior to the tests the bed material had been removed from the combustor and screened to eliminate oversize particles of ash, stones, etc. Subsequently the combustor was operated at full capacity to cope with the supply of wood waste generated by the sawmill. The fuel storage silo was full, making an opportunity to carry out part-load tests unlikely.

Instruments required for the tests were set up and connected on December 6th, and a 4-h full-load test (Test No. 1) was carried out that evening, between 1830 h and 2230 h. The combustor was operated in automatic high-fire mode and performed satisfactorily. The oxygen content of the flue gas was observed to fluctuate between 6 and 14% on a cycle of approximately 10 min, while CO_2 content varied correspondingly, but in the opposite direction as expected. The fluctuation appeared to originate at the metering bin. It is intermittently charged to maintain the fuel level between two sets of limit switches, and having no provision to maintain a uniform level of fuel at the discharge end, it delivers a varying quantity to the drag conveyor which feeds the combustor. Data from this test are summarized in Tables 1 and 2.

The following day, December 7th, difficulty was experienced in maintaining bed temperature in the combustor. Fluidization appeared to be erratic, quiescent piles of smouldering fuel were frequently visible in the combustor, and much of the time the ignition burner was in service to prevent the fire from going out altogether. Toward evening, conditions stabilized to the point where full firing rate was maintained but bed temperature was well below the normal level of 760°C (1400°F).

Another 4-h full-load test (Test No. 2) was carried out between 1830 h and 2330 h. Fuel feedrate was manually controlled. From time to time, as much as one-third of the bed area lost fluidization because raw fuel had piled up. When this happened, bed temperature dropped rapidly. The operator would then increase air flow, the piled-up material would be fluidized and start to burn, and bed temperature would rise again. The air flow would then be returned to its normal setting, and again a blanket of raw fuel would develop. At one time the bed temperature dropped to 150°C (300°F), but when air flow was increased, it rose to 550°C (1020°F) in a few minutes. Data from this test are also summarized in Tables 1 and 2.

During the night it became progressively more difficult to maintain bed temperature, and the combustor was shut down. A possible explanation is that the moisture content of the fuel had exceeded the limit for self-supporting combustion. However, the plant staff considered this unlikely on the grounds that they had in the past successfully burned what appeared to be wetter fuel. They postulated instead that the supports holding the fuel

TABLE 1

SUMMARY OF TEST DATA

	Test 1	Test 2
Feedwater Rate, Boiler No. 1, kg/h (lb/hr)	8015 (17,634)	8061 (17,734)
Feedwater Temp, Boiler No. 1, °C (°F)	49.5 (121)	41.0 (105.8)
Feedwater Rate, Boiler No. 2, kg/h (lb/hr)	7851 (17,273)	8488 (18,673)
Feedwater Temp, Boiler No. 2, °C (°F)	36.4 (97.5)	36.2 (97.1)
Steam Pressure, Boiler No. 1, kPa (psi)	74.4 (10.8)	76.5 (11.1)
Steam Pressure, Boiler No. 2, kPa (psi)	44.8 (6.5)	38.6 (5.6)
Stack Temp, Boiler No. 1, °C (°F)	142.8 (289.1)	143.1 (289.5)
Stack Temp, Boiler No. 2, °C (°F)	146.1 (294.9)	145.7 (294.3)
Combustion Air Temp, °C (°F)	-6.4 (20.4)	-8.2 (17.2)
Feeder Drive, rpm	1546	1532
O_2 in Flue Gas, %	9.2	10.1
CO_2 in Flue Gas, %	9.8	8.6
Vapour Space Temperature		
Controller Set Point, °C (°F)	927 (1700)	997 (1826)
Controller Indicator, °C (°F)	908 (1666)	1000 (1833)
Bed Temp. Controller Set Point, °C (°F	760 (1400)	611 (1131)
Bed Temp. Controller Indicator, °C (°F)	847 (1557)	601 (1114)
Fluidizing Blower Pressure, cm H_2O (in. H_2O)	76 - 89 (30 to 35)	91 - 102 (36 to 40)
Bed Differential Pressure, cm H_2O (in. H_2O)	33 - 51 (13 to 20)	25 - 38 (10 to 15)
Flue Gas Pressure at Boilers, cm H_2O (in. H_2O)	-7 - -15 (-3 to -6)	-13 - -15 (-5 to -6)
Thermocouple #1 Bed, °C (°F)	875 (1607)	591 (1096)
Thermocouple #8 Bed, °C (°F)	861 (1582)	647 (1196)
Thermocouple #6 Vapour Space, °C (°F)	948 (1738)	898 (1648)
Thermocouple #5 Boiler No. 1 Exit, °C (°F)	129 (264)	126 (258)
Thermocouple #3 Flue Gas at Cyclone, °C (°F)	108 (227)	106 (223)

splitter under the feed chute had failed, resulting in a non-uniform distribution of fuel over the bed, and the localized smothering of fluidization which was observed.

Table 3 contains a summary of the data required to calculate heat lost by radiation and convection from the combustor and the ductwork to the boilers. Because of inaccessibility, some dimensions were determined by estimate rather than by measurement. Simplifying assumptions were also made with respect to ductwork orientation. However, these have a minor effect on calculation of the total heat lost.

Table 4 contains analytical data for the wood waste. This information was used to generate the combustion and heat loss charts given in Appendix 1.

TABLE 2

SUMMARY OF FLY ASH DATA

	Test 1	Test 2
Vol from Boiler No. 1, m^3(cu ft)	0.221 (7.82)	0.156 (5.52)
Vol from Boiler No. 2, m^3(cu ft)	0.079 (2.76)	0.065 (2.30)
Total, m^3(cu ft)	0.30 (10.58)	0.221 (7.82)
Bulk Density, kg/m (cu ft)	1278.2 (79.8)	1323.1 (82.6)
Total wt from Test, kg (lb)	383.6 (844)	293.6 (646)
Combustible Content, kg (lb)	5.5	3.3
Total wt of Combustible in Fly Ash, kg (lb)	21.1 (46.4)	9.7 (21.3)

TABLE 3

SUMMARY OF COMBUSTOR AND DUCTING

SURFACE TEMPERATURE AND AREAS

1. Combustor Lower Section

Height: 244 cm (8 ft)	Circum: 13.6 m (44 ft 9 in.)	Area: 33.3 m^2 (358 sq ft)
Orientation:	Vertical Surface	
Mean Temp:	(25 measurements)	71°C (159°F)

2. Combustor Middle Section

Height: 226 cm (7 ft 5 in.)	Circum: 13.6 m (44 ft 9 in.)	Area: 30.8 m^2 (332 sq ft)
Orientation:	Vertical Surface	
Mean Temp:	(7 measurements)	85°C (185°F)

3. Combustor Top Section

Height:	Circum: 13.6 m (44 ft 9 in.)	Area: 31.9 m^2 (343 sq ft)
Orientation:	Vertical Surface	
Mean Temp:	(4 measurements)	78°C (173°F)

4. Combustor Roof

Circum: 13.6 m (44 ft 9 in.)		Area: 14.8 m^2 (159 sq ft)
Orientation:	Horizontal Surface Facing Upwards	
Mean Temp:	(12 measurements)	93°C (199°F)

5. Combustor Outlet Duct

Length: 305 cm (10 ft)	Diam: 152 cm (5 ft)	Area: 14.6 m^2 (157 sq ft)
Orientation:	91 cm (3 ft) vertical axis	
	213 cm (7 ft) horizontal axis	
Mean Temp:	(14 measurements)	174°C (345°F)

TABLE 3 (cont'd)

SUMMARY OF COMBUSTOR AND DUCTING

SURFACE TEMPERATURE AND AREAS

6.	Duct to Boiler No. 1		
	Length: 518 cm (17 ft)	Diam:118 cm (3 ft 10 in.)	Area:19.2 m^2 (207 sq ft)
	Orientation:	213 cm (7 ft) vertical axis 305 cm (10 ft) horizontal axis	
	Mean Temp:	(8 measurements)	185°C (266°F)
7.	Duct to Boiler No. 2		
	Length: 610 cm (20 ft)	Diam: 118 cm (3 ft 10 in.)	Area: 22.6 m^2 (243 sq ft)
	Orientation:	213 cm (7 ft) vertical axis 396 cm (13 ft) Horizontal axis	
	Mean Temp:	(5 measurements)	118°C (243°F)
8.	Burner Box, Boiler No. 1		
	Length: 213 cm (7 ft)	Diam: 152 cm (5 ft)	Area:10.2 m^2 (110 sq ft)
	Orientation:	Horizontal Axis	
	Mean Temp:	(12 measurements)	118°C (243°F)
9.	Burner Box, Boiler No. 2		
	Length: 213 cm (7 ft)	Diam: 152 cm (5 ft)	Area: 10.2 m^2 (110 sq ft)
	Orientation:	Horizontal Axis	
	Mean Temp:	(11 measurements)	107°C (224°F)

NOTE: The paint on the combustor and ductwork is a medium grey-blue colour with a dull finish. An emissivity of 0.95 is assumed for calculation of radiant heat loss.

TABLE 4

ANALYSES OF WOOD WASTE

Proximate Analysis		As Fired	Dry	As Fired	Dry
Moisture	%	33.87	0.00	30.56	0.00
Ash	%	1.02	1.54	1.98	2.86
Volatile Matter	%	52.37	79.19	54.06	77.85
Fixed Carbon (by diff)		12.74	19.27	13.40	19.29
Ultimate Analysis					
Carbon	%	41.02	62.03	39.11	56.32
Hydrogen	%	2.61	3.94	2.52	3.63
Sulphur	%	0.06	0.08	0.04	0.05
Nitrogen	%	0.08	0.12	0.06	0.09
Ash	%	1.02	1.54	1.98	2.86
Oxygen (by diff)	%	21.35	32.29	25.73	37.05
Calorific Value					
MJ/kg		13.94	21.08	14.29	20.58
Btu/hr (gross)		5996	9066	6144	8848

SYSTEM EFFICIENCY

Calculations of the various heat losses are detailed in Appendix 2, and the results are summarized in Table 5. The calculations show overall fuel-to-steam efficiencies of 73.2% for Test 1 and 74.9% for Test 2. The increase in efficiency for Test 2 is due to drier fuel and a somewhat higher firing rate.

Because various assumptions were made in the calculations, the margin of error in the efficiency figures is estimated to be 2%. It was assumed, for example, that dry steam was produced. It was also assumed that the temperature of the fuel was the same as that of the combustion air. The measured relationships between O_2 and CO_2 in the flue gas did not coincide with the relationships calculated from the ultimate analyses, and the O_2 measurement was assumed to be correct. The loss due to combustible in fly ash was calculated by measuring the volume of fly ash collected, then determining the combustible content and bulk density of a composite sample. The resulting calculated loss was higher than that theoretically possible for the ash content indicated by the ultimate analysis. This implies an unrepresentative sample of fuel, an unrepresentative sample of fly ash, or an error in the bulk density determination for the fly ash. Also, the measurements used to calculate heat lost from the combustor and ductwork were rather crude, and the formulae themselves involve several assumptions such as emissivity of the hot surfaces. However, none of the foregoing sources of error have a strong influence on the results, and the quoted margin of error is considered conservative.

Assuming that fuel composition on a dry basis is fairly constant, system efficiency for different conditions of excess air and fuel moisture can be readily determined by using the heat loss charts provided in Appendix 1. If the combustor is operating at or near full capacity the values shown in Table 5 for losses due to radiation and convection, and the unaccounted-for loss, can be assumed to remain unchanged. Fuel moisture has the strongest influence on system efficiency. If the moisture increases from 30% to 60%, the heat loss increases from about 7% to about 20%.

The hourly weight of flue gas produced by the combustor during the tests is calculated in Appendix 3. The results are given in Table 5, on both dry and wet bases. The manufacturer's capacity rating for the combustor is 38,600 kg/h (85,000 lb/hr) of flue gas, but whether on wet or dry basis is not specified. Thus, it can only be said that the combustor was operating at 88% to 95% of rated capacity during the tests.

TABLE 5

SUMMARY OF SYSTEM EFFICIENCY CALCULATIONS

	Test 1	Test 2
Dry Flue Gas Loss	9.6	9.4
Loss Due to Combustion of Hydrogen	4.7	4.4
Loss Due to Moisture in the Fuel	7.6	6.7
Loss Due to Combustible in Fly Ash	0.3	0.2
Loss Due to Radiation and Convection		
from the Two Boilers	2.3	2.2
from the Combustor and Ductwork	1.3	1.2
Unaccounted-for Loss (assumed)	1.0	1.0
Total Losses	26.8	25.1
Combustion System Efficiency	73.2	74.9
Fuel Firing Rate, kg/h (lb/hr) as fired	3884 (8545)	3920 (8625)
Rate of Dry Flue Gas, kg/h (lb/hr)	34,290 (75,440)	34,300 (75,460)
Rate of Total Flue Gas from Fuel as fired kg/h (lb/hr)	36,500 (80,310)	36,310 (79,890)

CONCLUSIONS

In two tests of four hours each, the fluidized-bed combustor successfully burned hogged wood waste containing approximately 35% moisture at a rate of about 3860 kg/h (8500 lb/hr). Average excess air level was 79% in one test and 95% in the other. The fuel energy in the wood waste was converted to low pressure steam at overall efficiencies of 73% and 75%.

Combustion efficiency was high; loss due to elutriated carbon was approximately 0.25% of heat input and concentration of CO in the flue gas was less than 0.1%.

With fuel containing about 35% moisture, the dry flue gas loss, at approximately 9.5%, constitutes the largest single heat loss. However, if fuel moisture were to increase to about 45%, the heat required to evaporate it and superheat it to the stack temperature would constitute the largest single heat loss.

The nature of the fuel feed control system is such that excess air level cycles between 40% and 150%. This could probably be overcome by modifying the metering bin so that it discharges fuel at a uniform rate.

Serious difficulties were experienced at times with fuel smothering the fluidization of the bed. This strongly suggests too low a pressure drop through the distributor plate and the bed, which could be overcome by decreasing the size of the orifices in the standpipe nozzles, or by increasing the bed depth. However, if either of these measures were taken, a combustion air blower having a higher static head might be required.

ACKNOWLEDGEMENTS

The assistance of Mr. D. L. Desai of the Canadian Combustion Research Laboratory (CCRL) in reducing data and carrying out computations is gratefully acknowledged, as is the cheerful co-operation of the operating staff at Chapleau Lumber Company Ltd.

APPENDIX 1

COMBUSTION DATA AND HEAT LOSS CHARTS

FOR THE WOOD WASTE BURNED DURING THE TESTS

TABLE A1

ANALYSIS OF WOOD WASTE; DRY BASIS

		Test 1	Test 2
Proximate Analysis			
Ash	%	1.54	2.86
Volatile Matter	%	79.19	77.85
Fixed Carbon (by diff)	%	19.27	19.29
Ultimate Analysis			
Carbon	%	63.03	56.32
Hydrogen	%	3.94	3.63
Sulphur	%	0.08	0.05
Nitrogen	%	0.12	0.09
Ash	%	1.54	2.86
Oxygen (by diff)	%	33.29	37.05
Calorific Value			
MJ/kg (Btu/lb), gross		21.08 (9066)	20.58 (8848)

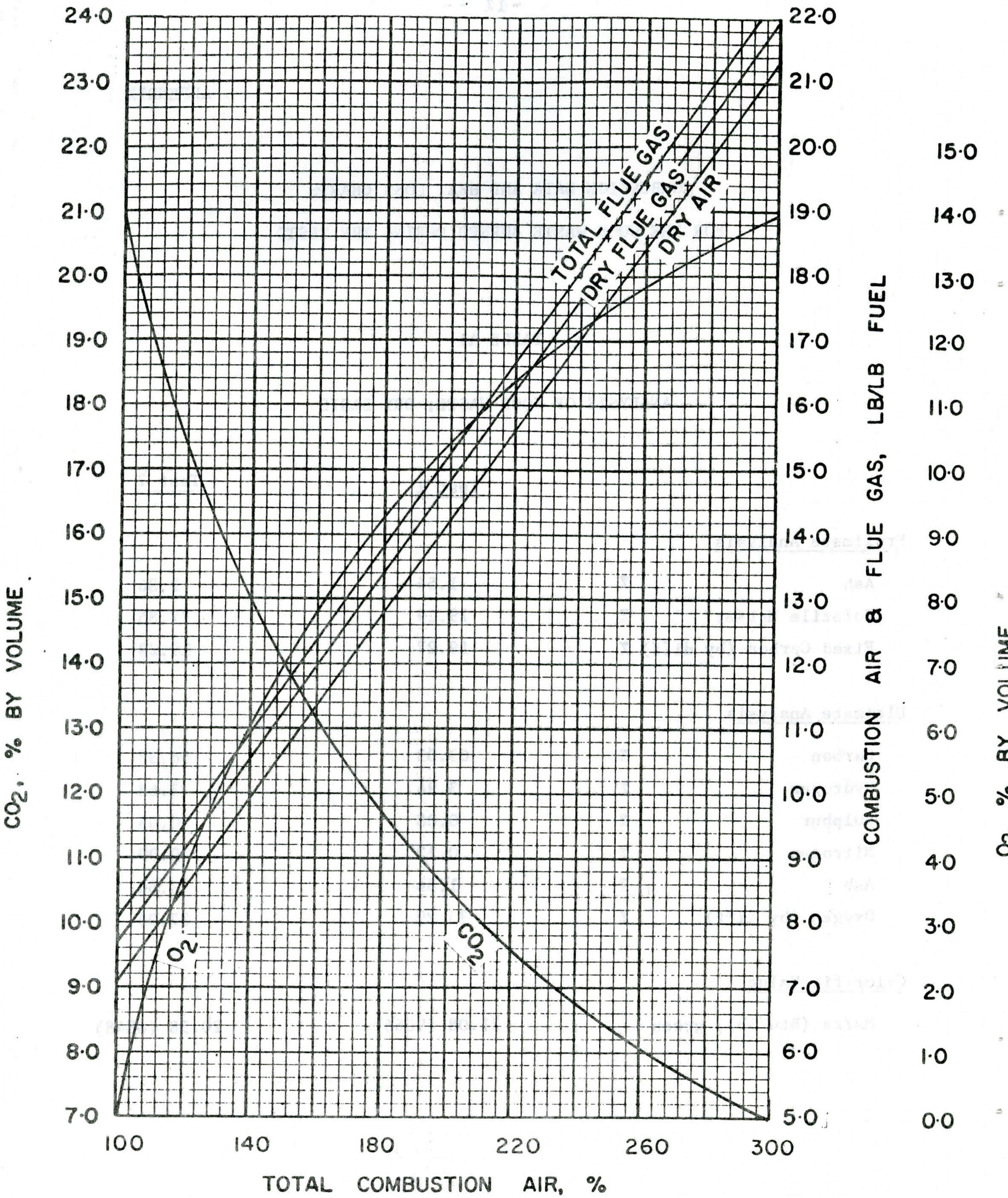

FIGURE I· COMBUSTION DATA, WEIGHT BASIS

TEST I.
WOOD WASTE

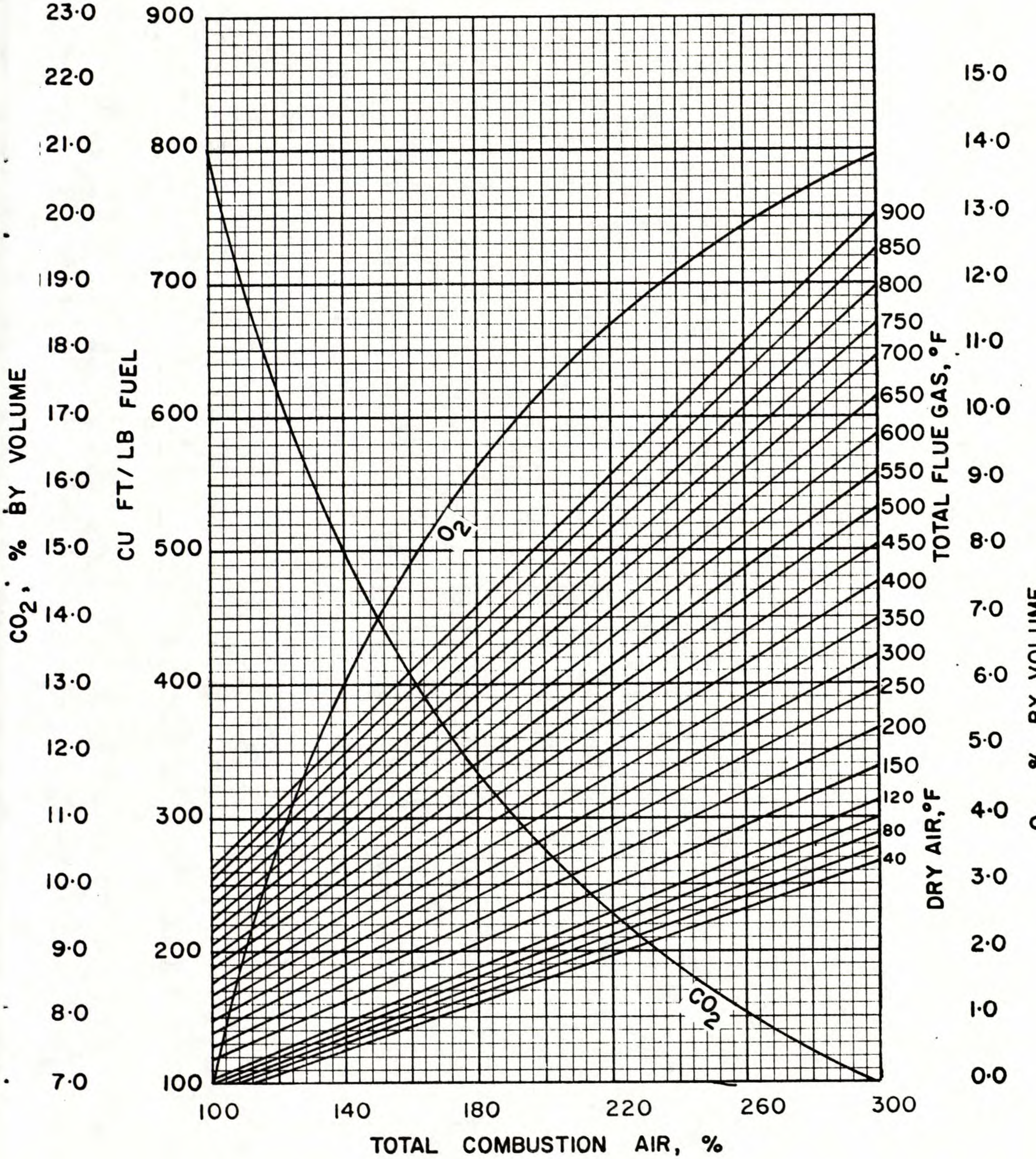

FIGURE 2. COMBUSTION DATA, VOLUME BASIS.

TEST 1.
WOOD WASTE

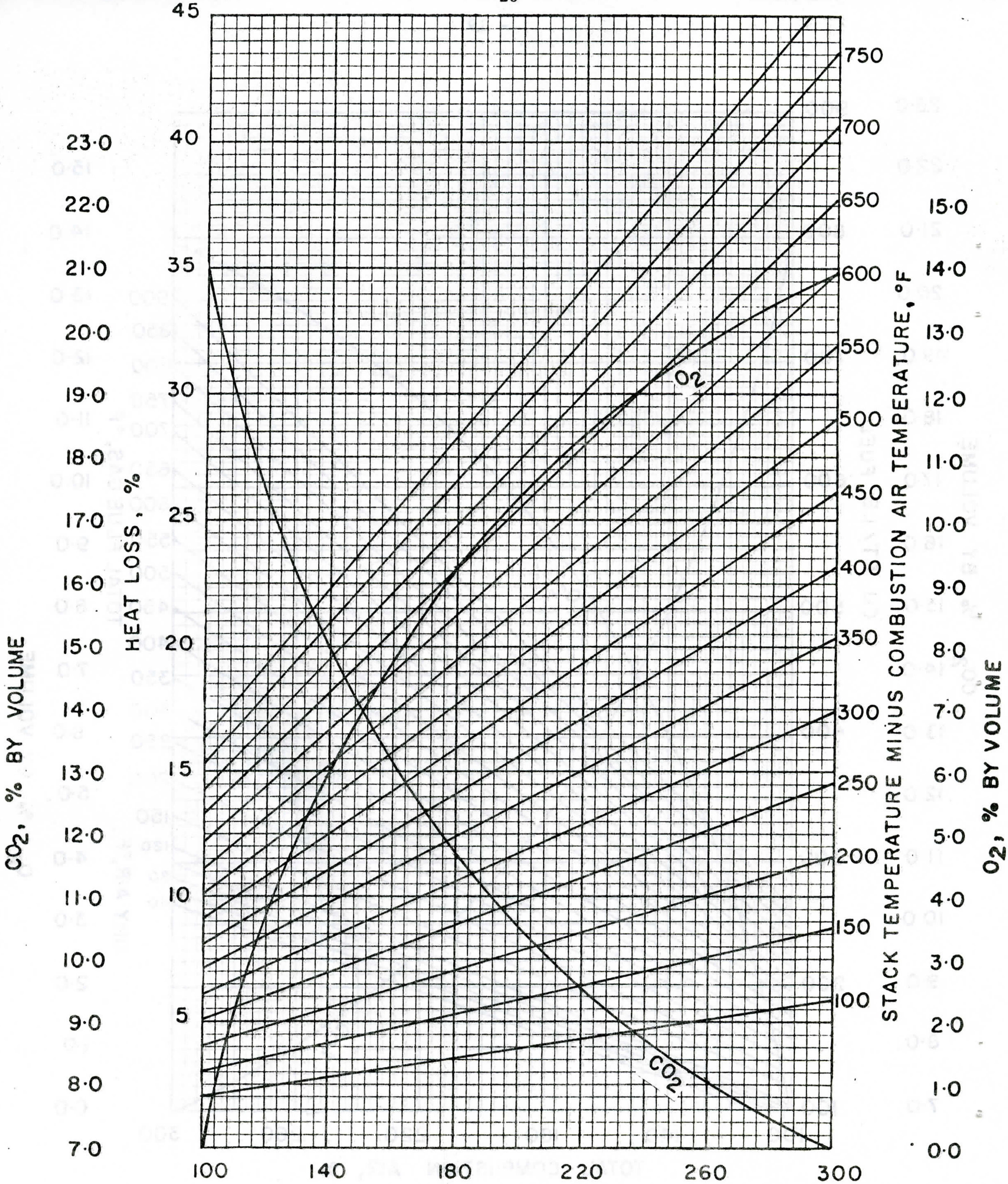

FIGURE 3· DRY FLUE GAS LOSS FOR A RANGE OF TEMPERATURE DIFFERENTIALS.

TEST I·
WOOD WASTE

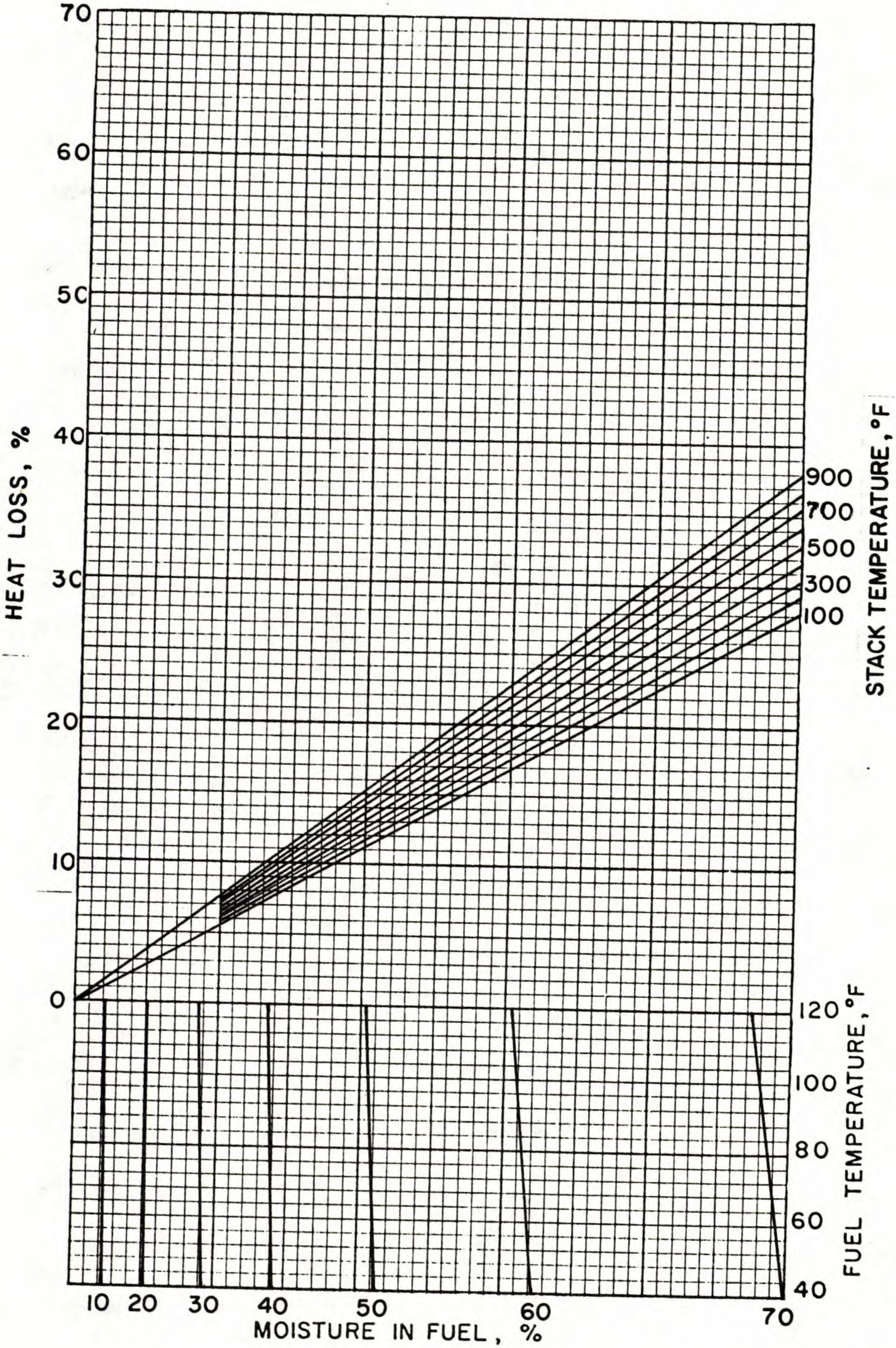

FIGURE 4 · HEAT LOSS DUE TO MOISTURE IN FUEL

TEST I.
WOOD WASTE

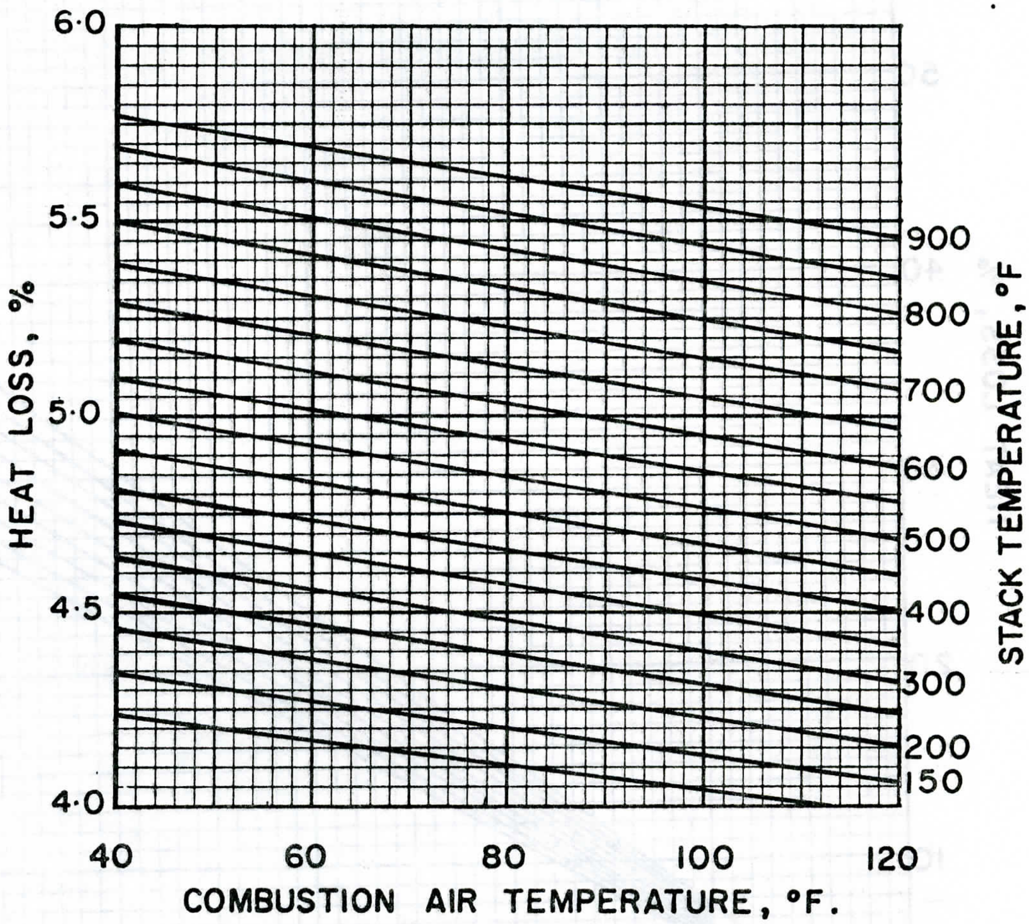

FIGURE 5 HYDROGEN LOSS FOR A RANGE OF STACK TEMPERATURES.

TEST I ·
WOOD WASTE

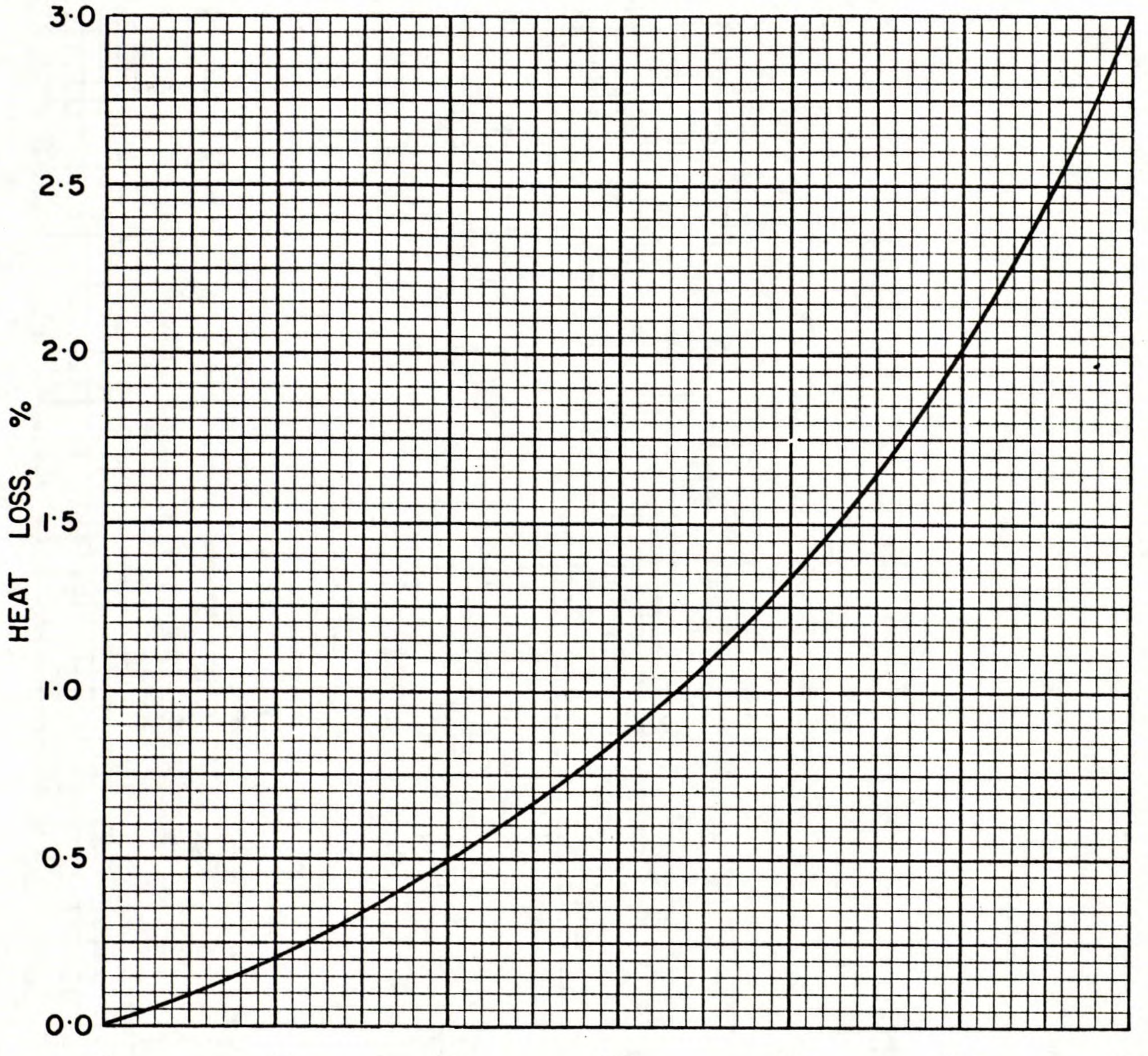

FIGURE 6 HEAT LOSS FOR A RANGE OF COMBUSTIBLE CONCENTRATIONS IN REFUSE

<u>TEST 1.</u>
WOOD WASTE

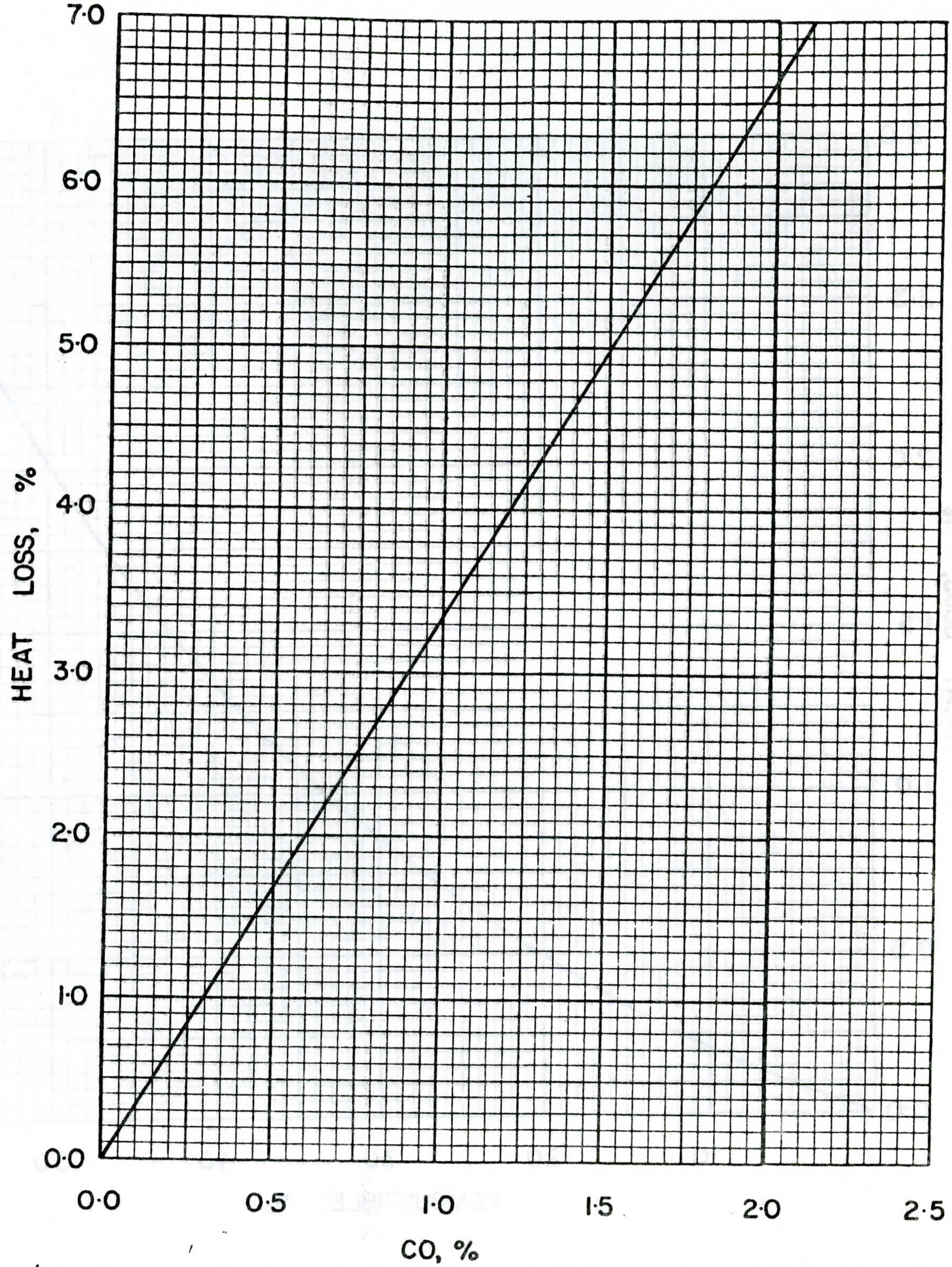

FIGURE 7 · HEAT LOSS FOR A RANGE OF CO CONCENTRATIONS, ASSUMING NEGLIGIBLE EXCESS AIR

TEST I ·
WOOD WASTE

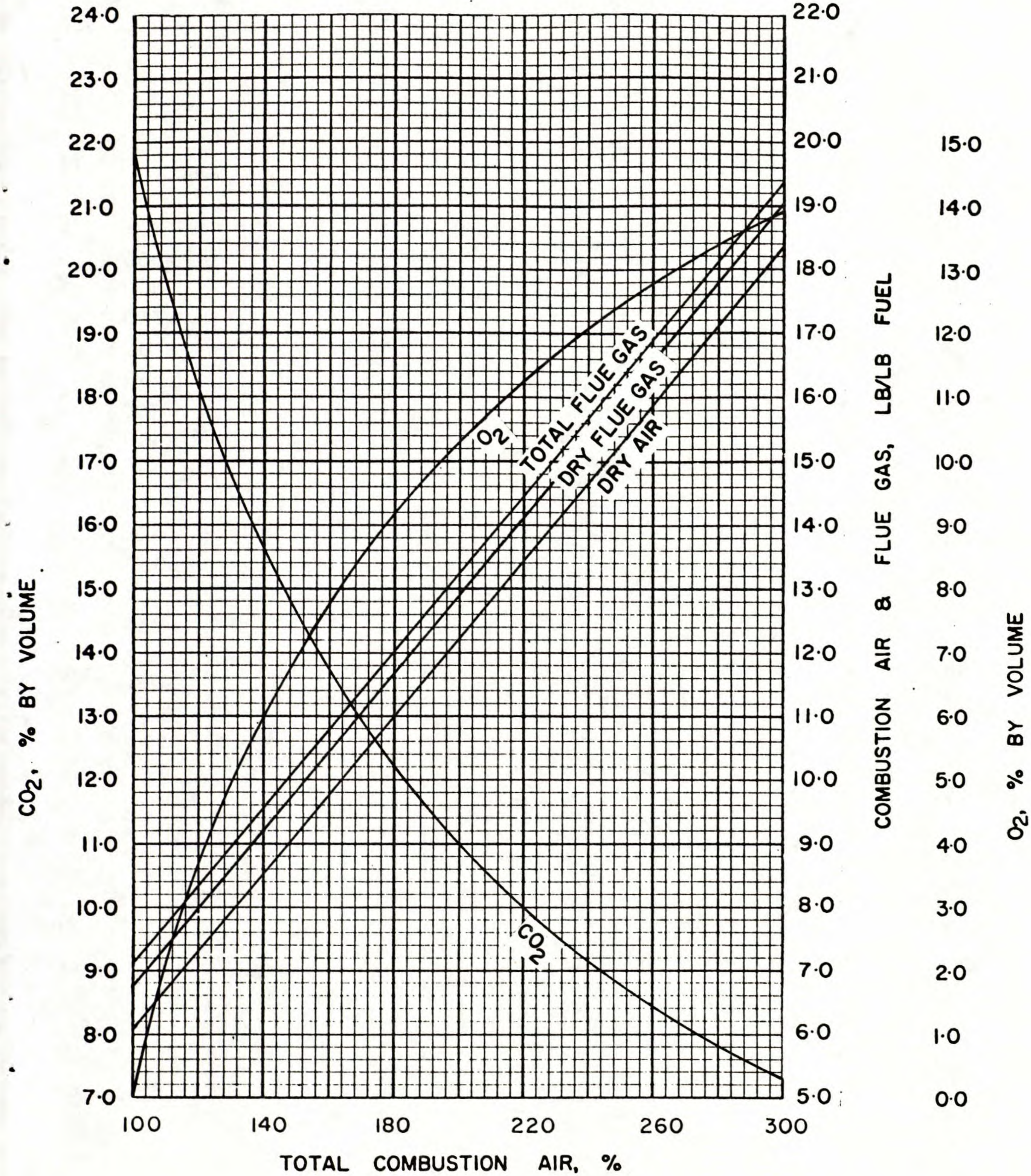

FIGURE I· COMBUSTION DATA, WEIGHT BASIS

TEST 2.
WOOD WASTE

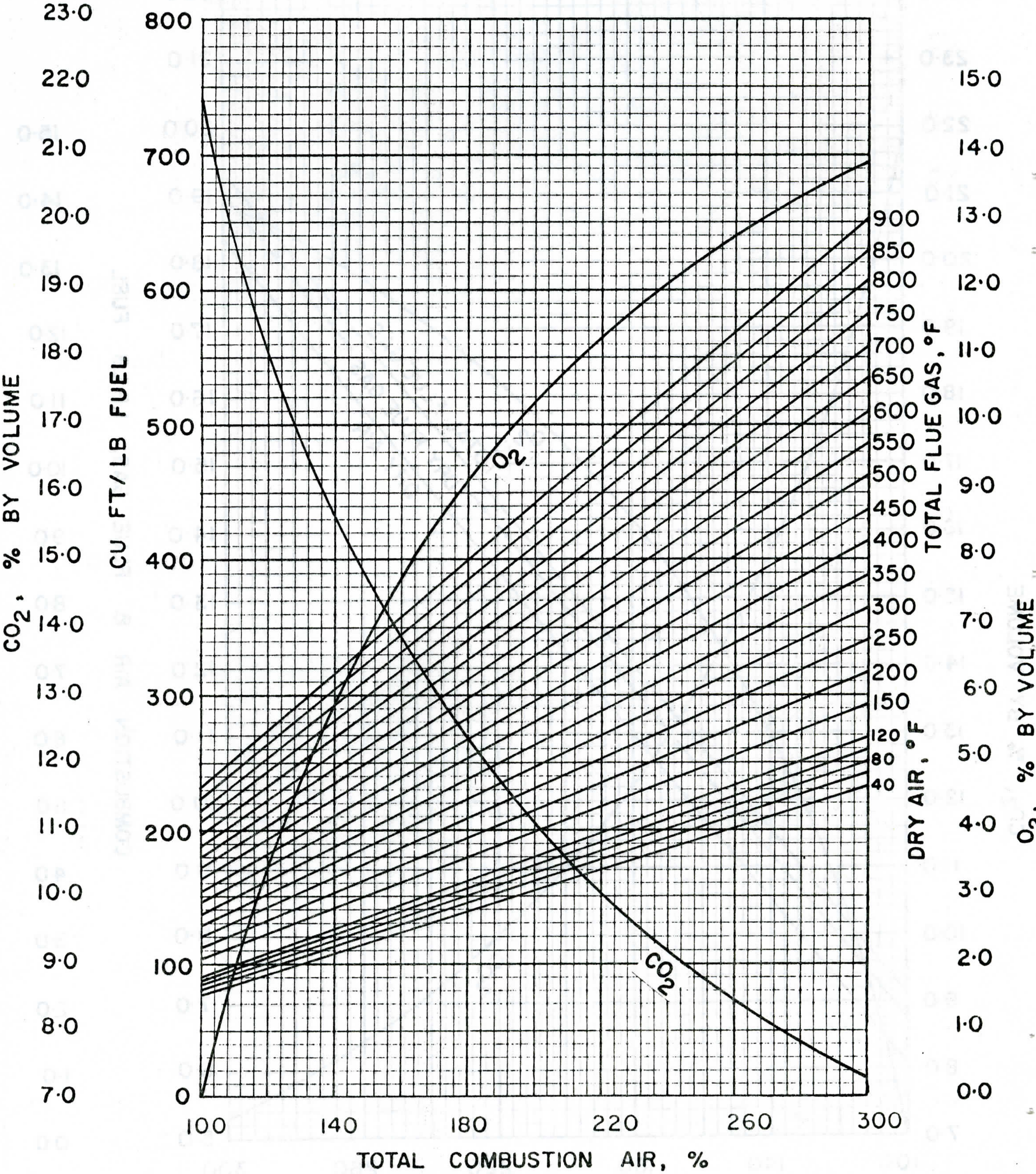

FIGURE 2. COMBUSTION DATA, VOLUME BASIS.

TEST 2.

WOOD WASTE

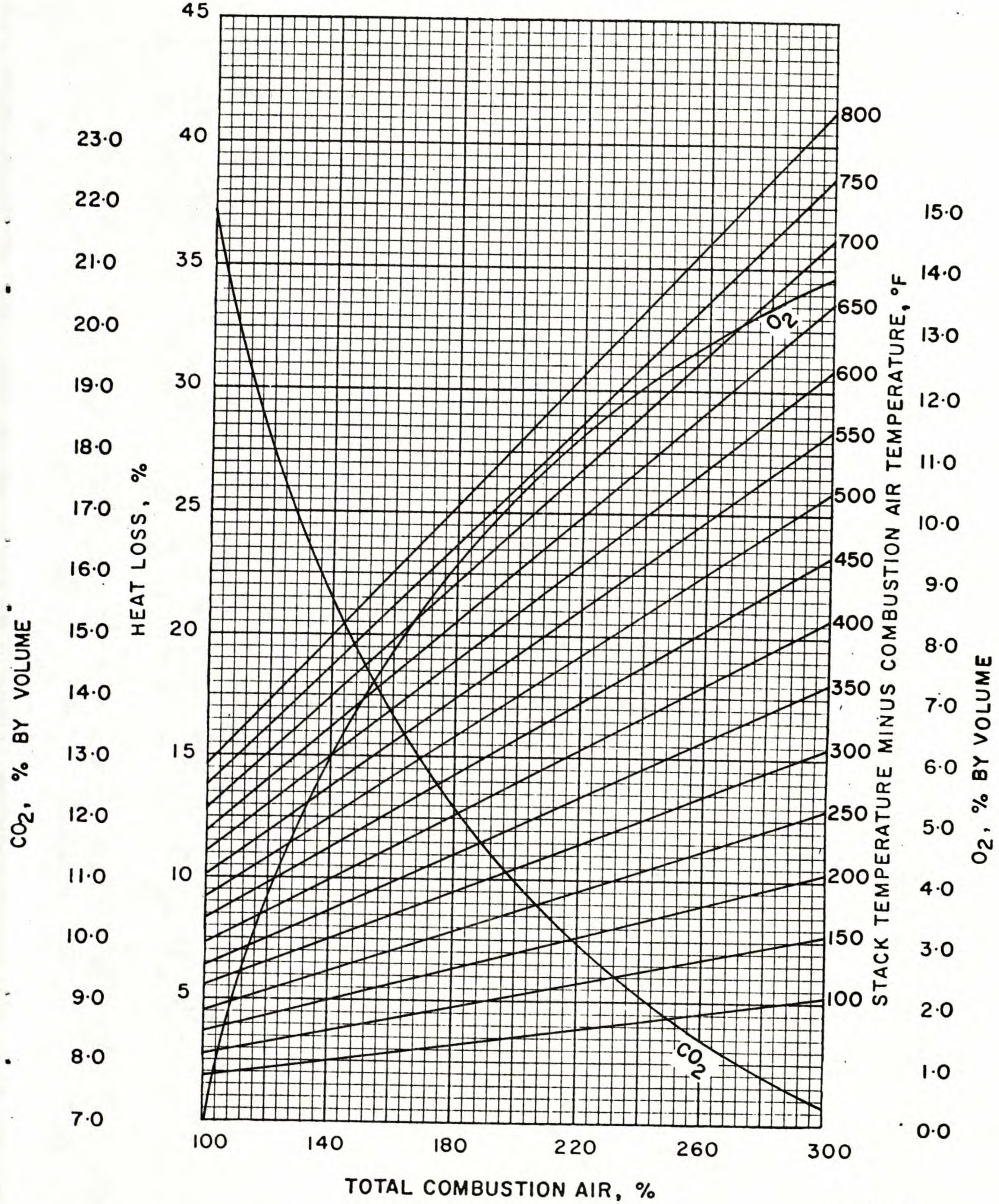

FIGURE 3· DRY FLUE GAS LOSS FOR A RANGE OF TEMPERATURE DIFFERENTIALS.

TEST 2.
WOOD WASTE

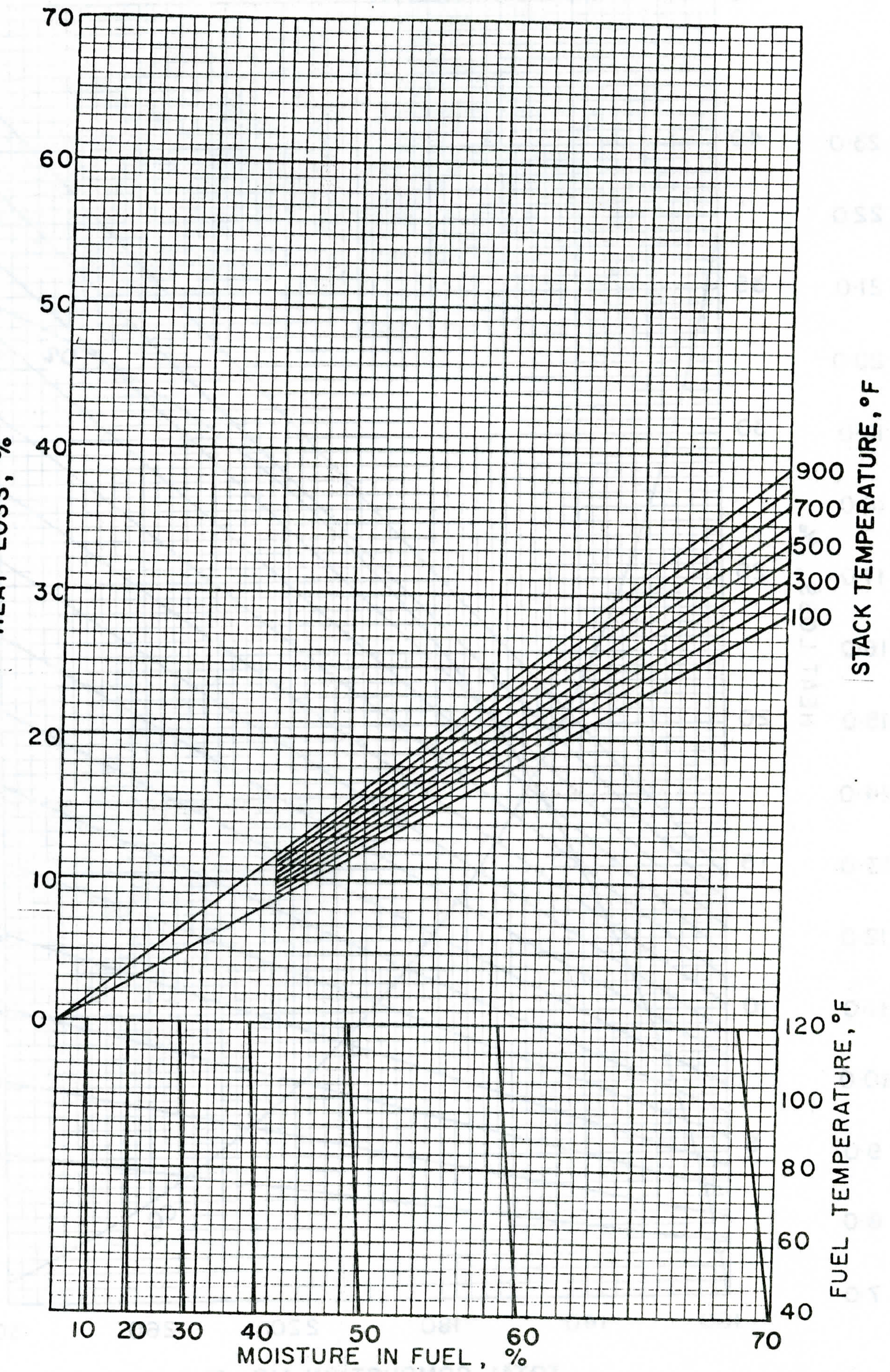

FIGURE 4 · HEAT LOSS DUE TO MOISTURE IN FUEL

TEST 2.
WOOD WASTE

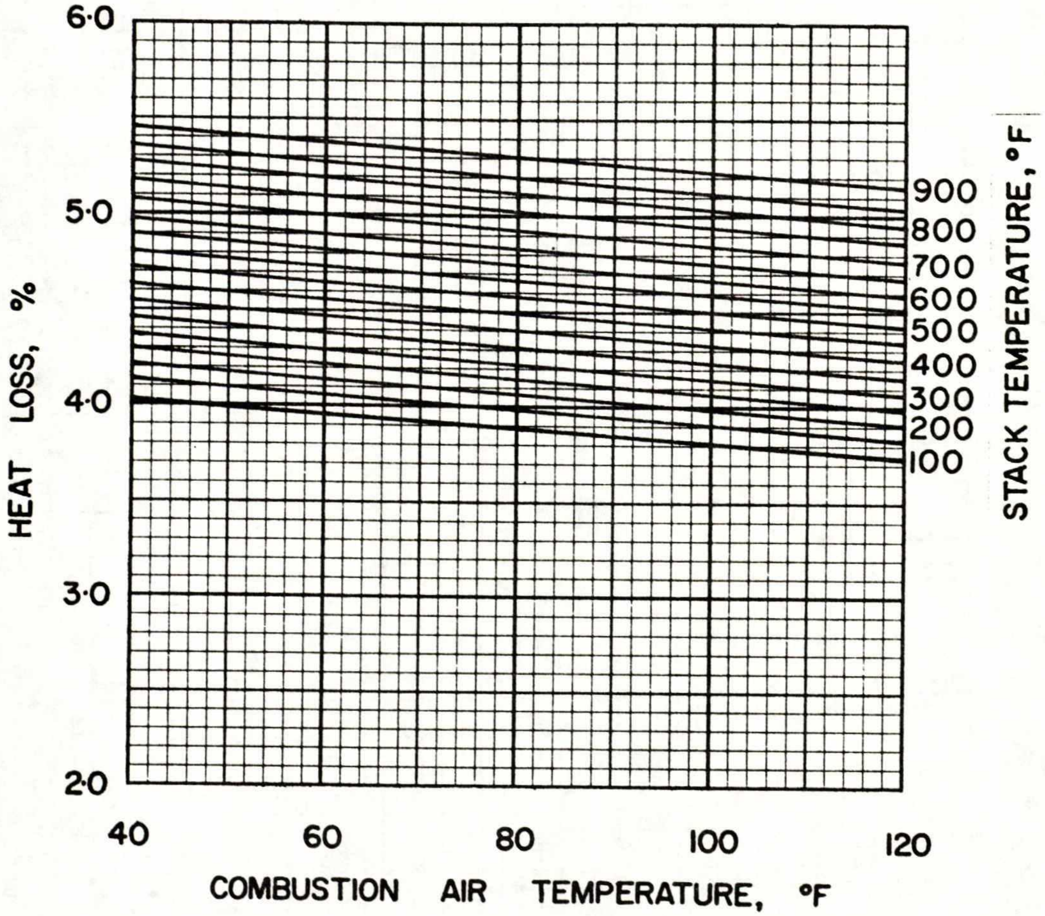

FIGURE 5 · HYDROGEN LOSS FOR A RANGE OF STACK TEMPERATURES

TEST 2.
WOOD WASTE

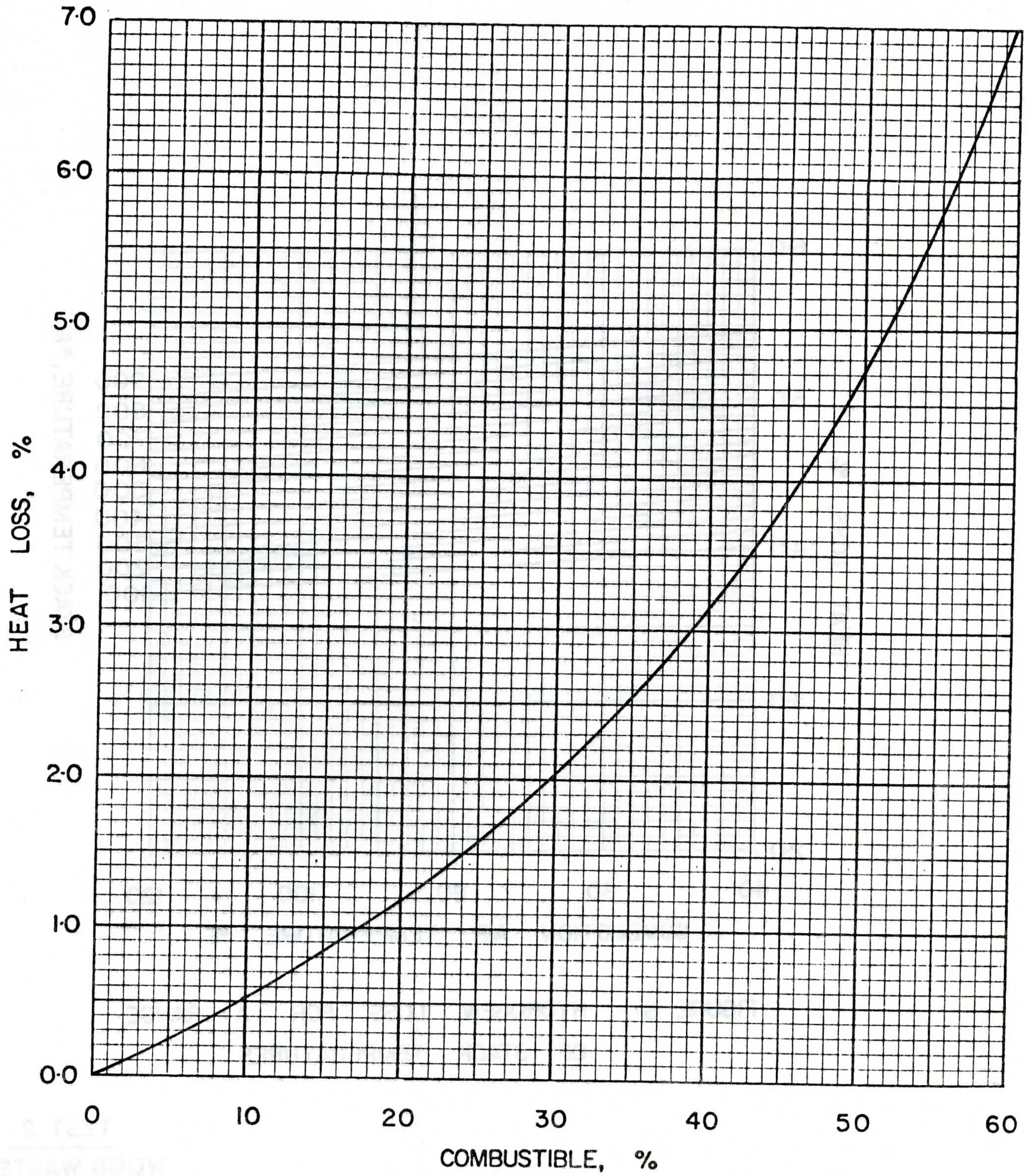

FIGURE 6 HEAT LOSS FOR A RANGE OF COMBUSTIBLE CONCENTRATIONS IN REFUSE

TEST 2

WOOD WASTE

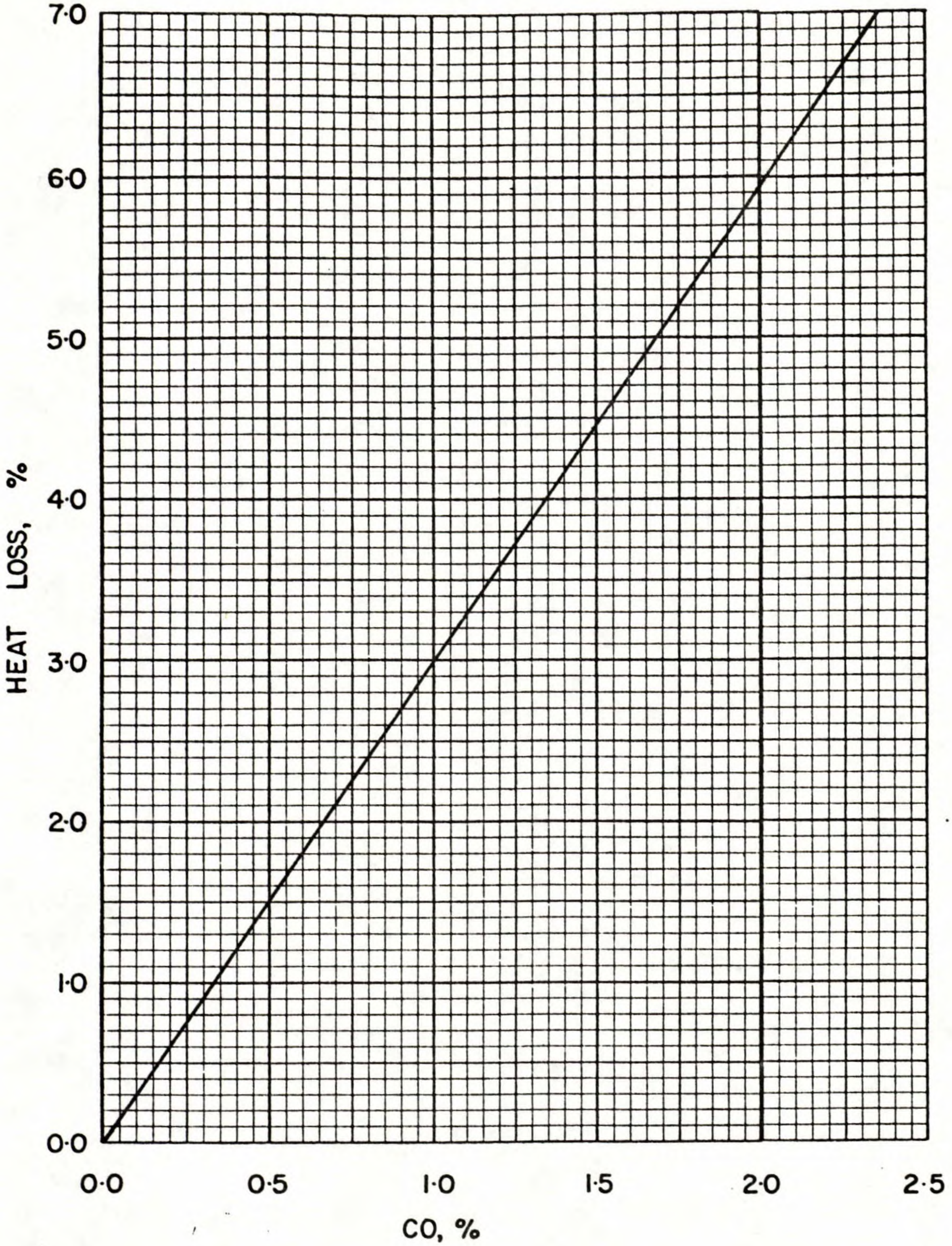

FIGURE 7 · HEAT LOSS FOR A RANGE OF CO CONCENTRATIONS, ASSUMING NEGLIGIBLE EXCESS AIR

TEST 2 ·
WOOD WASTE

APPENDIX 2

CALCULATION OF HEAT LOSSES

A. Test No. 1

A.1 Dry Flue Gas Loss

Stack Temp, Boiler No. 1:	289.1°F
Stack Temp, Boiler No. 2:	294.9°F
Avg:	292°F
Comb Air Temp:	20.4°F
Stack Temp — Comb Air Temp:	271.6°F

O_2 in Flue Gas: 9.2%
(Excess air = 79%)

Heat Loss (from App. 1, Fig. 3 Test 1) = 9.6%

A.2 Loss Due to Combustion of Hydrogen in Fuel

Avg. Stack Temp:	292°F
Comb. Air Temp:	20.4°F

Heat Loss (extrapolated from App. 1, Fig. 5, Test 1) = 4.7%

A.3 Loss Due to Moisture in the Fuel

Moisture in Fuel:	33.9%
Avg. Stack Temp:	292°F
Fuel Temp (assumed):	20.4°F
Gross Calorific Value of Fuel as Fired:	5996 Btu/lb

Note: App. 1, Fig. 4 Test 1 is based on the following formula for stack temp less than 575°F:

$$\text{Heat Loss, Btu/lb} = \frac{\text{lb moisture}}{\text{lb fuel as fired}} \times \{1089 - \text{fuel temp} + (0.46 \times \text{stack temp})\}$$

$$= 0.339 \times \{1089 - 20.4 + 0.46(292)\} = 407.8 \text{ Btu/lb}$$

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

To this must be added a correction for heat of fusion since the fuel temperature is below freezing. The correction is calculated as follows:

$$\text{Heat Loss, Btu/lb} = \frac{\text{lb moisture}}{\text{lb fuel}} \times 144$$

$$= 0.339 \times 144 = 48.8 \text{ Btu/lb}$$

Total Heat Loss Due to Moisture in Fuel

$$= \frac{(407.8 + 48.8) \times 100}{5996} = \underline{\underline{7.6\%}}$$

A.4 Loss Due to Combustible in Fly Ash

Total wt of Fly Ash From Test:	844 lb
Combustible Content of Fly Ash:	5.5%
Gross Calorific Value of Combustible Content (assume pure carbon):	14,600 Btu/lb

$$\text{Heat Loss} = \frac{844 \times 0.055}{4} \times 14{,}600 = \underline{\underline{169{,}400 \text{ Btu/hr}}}$$

Note: This heat loss cannot be calculated as a percentage of heat input until the heat input is known (See Sec A.7.1).

A.5 Loss Due to Radiation and Convection

The loss due to radiation and convection from boilers can be determined from the ABMA chart, knowing the boiler rated capacity, the actual output at test conditions, and the number of watercooled walls.

The loss due to radiation and convection from pipes, ducts and plane surfaces can be computed from the following formulae:

for cylindrical pipes (Eq. 1)*

$$q = 0.848LD^{0.75} (t - t_a)^{1.25} + 0.543DLe\left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right]$$

for large vertical plane surfaces: (Eq. 2)*

$$q = A\left\{0.27 (t - t_a)^{1.25} + 0.173e\left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right]\right\}$$

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

for the top surface of warm horizontal planes (Eq. 3)*

$$q = A\left\{0.38\ (t - t_a)^{1.25} + 0.173e\left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right]\right\}$$

where q = heat loss, Btu/hr
L = length of pipe, ft
D = diameter of pipe, ft
t = surface temp., °F
t_a = ambient temp., °F
e = emissivity
T = surface temp., °R
T_s = ambient temp., °R
A = area of plane surface, sq ft

*Kent's Mechanical Engineers Handbook 12th Edition, Power Volume P.3-30
J. Kenneth Salisbury, Editor

A.5.1 Loss from Boiler No. 1

Boiler Rated Capacity:	20×10^6 Btu/hr
Steaming Rate During Test:	17,630 lb/hr
Steam Pressure:	10.8 psig
Feedwater Temp:	121°F
No. of Watercooled Walls:	4

$$\text{Heat Output} = 17{,}630 \times \{1161 - (121-32)\} = 18.9 \times 10^6\ \text{Btu/hr}$$

Heat Loss (from ABMA Chart) = 1.1%

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

A.5.2 Loss From Boiler No. 2

Boiler Rated Capacity:	23.5 x 10 Btu/hr
Steaming Rate During Test:	17,270 lb/hr
Steam Pressure:	6.5 psig
Feedwater Temp:	97.5 °F
No. of Watercooled Walls:	4

$$\text{Heat Output} = 17{,}270 \times \{1157.4 - (97.5 - 32)\} = 18.9 \times 10^6 \text{ Btu/hr}$$

Heat Loss (from ABMA Chart) = 1.2%

A.5.3 Loss From Combustor Lower Section

Area:	358 sq ft
Mean Temp:	159 °F
Ambient Temp:	75 °F
Orientation:	vertical surface
Emissivity (assumed):	0.95

From Eq. 2

$$\text{Heat Loss} = 358 \left\{ 0.27\ (159 - 75)^{1.25} + 0.173(0.95)\left[\left(\frac{619}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= 62{,}760 \text{ Btu/hr}$$

A.5.4 Loss From Combustor Middle Section

Area:	332 sq ft
Mean Temp:	185 °F
Ambient Temp:	75 °F
Orientation:	vertical surface
Emissivity (assumed):	0.95

From Eq. 2

$$\text{Heat Loss} = 332 \left\{ 0.27\ (185 - 75)^{1.25} + 0.173\ (0.95)\left[\left(\frac{645}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= 81{,}670 \text{ Btu/hr}$$

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

A.5.5 Loss From Combustor Top Section

Area:	343 sq ft
Mean Temp:	173 °F
Ambient Temp:	75 °F
Orientation:	vertical surface
Emissivity (assumed):	0.95

From Eq. 2

$$\text{Heat Loss} = 343\left\{0.27\ (173 - 75)^{1.25} + 0.173\ (0.95)\left[\left(\frac{633}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= \underline{\underline{72{,}880\ \text{Btu/hr}}}$$

A.5.6 Loss From Combustor Roof

Area:	159 sq ft
Mean Temp:	199 °F
Ambient Temp:	75 °F
Orientation:	horizontal surface facing upward
Emissivity (assumed):	0.95

From Eq. 3

$$\text{Heat Loss} = 159\left\{0.38\ (199 - 75)^{1.25} + 0.173\ (0.95)\left[\left(\frac{659}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= \underline{\underline{52{,}880\ \text{Btu/1h}}}$$

A.5.7 Loss From Combustor Outlet Duct

Length:	10 ft
Diameter:	5 ft
Mean Temp:	345 °F
Ambient Temp:	75 °F
Emissivity (assumed):	0.95

From Eq. 1

$$\text{Heat Loss} = \left\{0.848\ (10)(5)^{0.75}\ (345 - 75)^{1.25}\right\} + \left\{0.543\ (5)(10)(0.95)\left[\left(\frac{805}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= \underline{\underline{118{,}200\ \text{Btu/hr}}}$$

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

A.5.8 Loss From Duct to Boiler No. 1

Length:	17 ft
Diameter:	3.875 ft
Mean Temp:	266 °F
Emissivity (assumed):	75 °F

From Eq. 1

$$\text{Heat Loss} = \left\{0.848\ (17)(3.875)^{0.75}\ (266 - 75)^{1.25}\right\}$$
$$+ \left\{0.543\ (3.875)\ (17)\ (0.95)\left[\left(\frac{726}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$
$$= \underline{\underline{94,840\ \text{Btu/hr}}}$$

A.5.9 Loss From Duct to Boiler No. 2

Length:	20 ft
Diameter:	3.875 ft
Mean Temp:	243 °F
Ambient Temp:	75 °F
Emissivity (assumed):	0.95

From Eq. 1

$$\text{Heat Loss} = \left\{0.848\ (20)(3.875)^{0.75}(243 - 75)^{1.25}\right\}$$
$$+ \left\{0.543\ (3.875)(20)0.95)\left[\left(\frac{703}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$
$$= \underline{\underline{93,220\ \text{Btu/hr}}}$$

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

A.5.10 Loss From Burner Box on Boiler No. 1

Length:	7 ft
Diameter:	5 ft
Mean Temp:	243 °F
Ambient Temp:	75 °F
Emissivity (assumed):	0.95

From Eq. 1

$$\text{Heat Loss} = \left\{0.848\ (7)(5)^{0.75}(243 - 75)^{1.25}\right\} + \left\{0.543\ (5)(7)(0.95)\left[\left(\frac{703}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= \underline{\underline{41,310\ \text{Btu/hr}}}$$

A.5.11 Loss From Burner Box on Boiler No. 2

Length:	7 ft
Diameter:	5 ft
Mean Temp:	224 °F
Ambient Temp:	75 °F
Emissivity (assumed):	0.95

From Eq. 1

$$\text{Heat Loss} = \left\{0.848\ (7)(5)^{0.75}(224 - 75)^{1.25}\right\} + \left\{0.543\ (5)(7)(0.95)\left[\left(\frac{684}{100}\right)^4 - \left(\frac{535}{100}\right)^4\right]\right\}$$

$$= \underline{\underline{35,060\ \text{Btu/hr}}}$$

APPENDIX 2

CALCULATION OF HEAT LOSSES (cont'd)

A.5.12 Summary of Losses Due to Radiation and Convection

Boiler Losses:

Boiler No. 1	1.1%
Boiler No. 2	1.2%
Total	2.3%

Combustor and Ductwork Losses:

Combustor Lower Section	62,760 Btu/hr
Combustor Middle Section	81,670
Combustor Top Section	72,880
Combustor Roof	52,880
Combustor Outlet Duct	118,200
Duct to Boiler No. 1	94,840
Duct to Boiler No. 2	93,220
Burner Box on Boiler No. 1	41,310
Burner Box on Boiler No. 2	35,060
Total	652,820 Btu/hr

NOTE: This heat loss cannot be calculated as a percentage of heat input until the heat input is known. (See Sec A.7.2).

A.6 Unaccounted for Loss

To cover minor losses due to moisture in the combustion air, carbon and combustibles in the flue gas, sensible heat in the ash, boiler blowdown, etc.

Assume a loss of 1.0%

A.7 Calculation of Heat Input

Heat Input = heat output + losses

Heat Input = qwhw

where qw = firing rate of wood, lb/hr as fired

hw = gross calorific value of wood, as fired

= 5996 Btu/lb

Heat Output (from Sec A.5.1 and A.5.2)

$$= (18.6 \times 10^6) + (18.9 \times 10^6)$$

$$= 37.5 \times 10^6 \text{ Btu/hr}$$

Losses = Sum of losses computed in Sec A.1 through A.6, converted to Btu/hr.

$$5996\ qw = 37.5 \times 10^6 + 0.096\ (5996)qw + 0.047\ (5996)qw + 0.076\ (5996)qw + 169{,}400 + 0.023\ (5996)qw + 652{,}820 + 0.01\ (5966)qw$$

qw = <u>8545 lb/hr</u>

It is now possible to calculate as a percentage heat losses previously determined in Btu/hr.

A.7.1 Loss Due to Combustible in Fly Ash

From Sec A.4, Heat Loss = 169,400 Btu/hr

$$= \frac{169{,}400 \times 100}{8545 \times 5996} = \underline{\underline{0.33\%}}$$

A.7.2 Loss Due to Radiation and Convection from Combustor and Ductwork

From Sec A.5.12, Heat Loss = 652,820 Btu/hr

$$= \frac{652,820 \times 100}{8545 \times 5996} = \underline{\underline{1.27\%}}$$

B. Test No. 2

B.1 Dry Flue Gas Loss

Stack Temp., Boiler No. 1:	289.5 °F
Stack Temp., Boiler No. 2:	294.3 °F
Avg:	291.9 °F
Combustion Air Temp:	17.2 °F
Stack Temp - Comb. Air Temp:	274.7 °F

O_2 in Flue Gas: 10.1%
(Excess Air = 95%)

Heat Loss (from App 1, Fig. 3 Test 2) = 9.4%

B.2 Loss Due to Combustion of Hydrogen in Fuel

Average Stack Temp:	291.9 °F
Combustion Air Temp:	17.2 °F

Heat Loss (extrapolated from App. 1, Fig. 5 Test 2) = 4.4%

B.3 Loss Due to Moisture in the Fuel

Moisture in Fuel: 30.5 %

Average Stack Temp: 291.9 °F

Fuel Temp (assumed): 17.2 °F

Gross Calorific Value of Fuel as Fired: 6144 Btu/lb

Calculation as in Sec A.3

$$\text{Heat Loss} = 0.305 \times \{1089 - 17.2 + 0.46(291.9)\} + (0.305 \times 144)$$

$$= 412 \text{ Btu/lb}$$

$$= \frac{412 \times 100}{6144} = \underline{\underline{6.7\%}}$$

B.4 Loss Due to Combustible in Fly Ash

Total wt of Fly Ash from Test: 646 lb

Combustible Content of Fly Ash: 3.3 %

Gross Calorific Value of Combustible Content (assume pure carbon): 14,600 Btu/lb

$$\text{Heat Loss} = \frac{646 \times 0.033}{4} \times 14{,}600 = \underline{\underline{77{,}810 \text{ Btu/hr}}}$$

NOTE: This heat loss cannot be calculated as a percentage of heat input until the heat input is known. (See Sec B.7.1).

B.5 Loss Due to Radiation and Convection

Calculated as in Sec A.5

B.5.1 Loss From Boiler No. 1

Boiler Rated Capacity: 20×10^6 Btu/hr

Steaming Rate During Test: 17,730 lb/hr

Steam Pressure: 11.1 psig

Feedwater Temp: 105.8 °F

No. of Watercooled Walls: 4

$$\text{Heat Output} = 17{,}730 \times \left\{1161.1 - (105.8 - 32)\right\} = 19.3 \times 10^6 \text{ Btu/hr}$$

Heat Loss (from ABMA Chart) = 1.1%

B.5.2 Loss from Boiler No. 2

Boiler Rated Capacity: 23.5×10^6 Btu/hr

Steaming Rate During Test: 18,670 lb/hr

Steam Pressure: 5.6 psig

Feedwater Temp: 97.1 °F

No. of Watercooled Walls: 4

$$\text{Heat Output} = 18{,}670 \times \left\{1156.6 - (97.1 - 32)\right\} = 20.4 \times 10^6 \text{ Btu/hr}$$

Heat Loss (from ABMA Chart) = 1.1%

B.5.3 Loss From Combustor and Ductwork

From Calculations Summarized in Sec A.5.12

Heat Loss = 652,820 Btu/hr

NOTE: This heat loss cannot be calculated as a percentage of heat input until the heat input is known. (See Sec B.7.2).

B.6 Unaccounted for Loss

As in Sec A.6,

Assume a Loss of 1.0%

B.7 Calculation of Heat Input

Calculate as in Sec A.7.

hw = 6144 Btu/lb as fired

heat output (from Sec B.5.1 and B.5.2)

$$= (19.3 \times 10^6) + (20.4 \times 10^6)$$

$$= 39.7 \times 10^6 \text{ Btu/hr}$$

losses = sum of losses computed in Sec B.1 through B.6, converted to Btu/hr

$$6144\ qw = 39.7 \times 10^6 + 0.94(6144)qw + 0.044(6144)qw + 0.067(6144)qw + 77{,}810 + 0.022(6144)qw + 652{,}820 + 0.01(6144)qw$$

qw = 8625 lb/hr

It is now possible to calculate as a percentage heat losses previously determined in Btu/hr.

B.7.1 Loss Due to Combustible in Fly Ash

From Sec B.4, heat loss = 77,810 Btu/hr

$$= \frac{77{,}810 \times 100}{8625 \times 6144} = 0.15\%$$

B.7.2 Loss Due to Radiation and Convection from Combustor and Ductwork

From Sec B.5.3, Heat Loss = 652,820 Btu/hr

$$= \frac{652{,}820 \times 100}{8625 \times 6144} = 1.23\%$$

APPENDIX 3

CALCULATION OF FLUE GAS RATE

A. TEST NO: 1

Fuel Firing Rate, as fired: 8545 lb/hr

Fuel Moisture Content: 33.87 %

Fuel Firing Rate, dry basis

$$= 8545 \times \left\{\frac{100 - 33.87}{100}\right\} = 5651 \text{ lb/hr}$$

From App. 1, Fig. 1, Test 1, at 9.2% O_2 (79% excess air)

wt of dry flue gas: = 13.35 lb/lb fuel

wt of total flue gas from dry fuel = 13.7 lb/lb fuel

Rate of Dry Flue Gas = 13.35 x 5651 = 75,440 lb/hr

Rate of Total Flue Gas from Dry Fuel = 13.7 x 5651 = 77,420 lb/hr

Rate of Total Flue Gas from Fuel as Fired

= 77,420 + (8545 - 5651) = 80,310 lb/hr

B. TEST NO. 2

Fuel Firing Rate, as fired: 8625 lb/hr

Fuel Moisture Content: 30.56 %

Fuel Firing Rate, dry basis

$$= 8625 \times \left\{\frac{100 - 30.56}{100}\right\} = 5989 \text{ lb/hr}$$

From App. 1, Fig. 1, Test 2 at 10.1% O_2 (95% excess air)

wt of dry flue gas = 12.6 lb/lb fuel

wt of total flue gas from dry fuel = 12.9 lb/lb fuel

Rate of Dry Flue Gas = 12.6 x 5989 = 75,460 lb/hr

Rate of Total Flue Gas from Dry Fuel = 12.9 x 5989 = 77,260 lb/hr

Rate of Total Flue Gas from Fuel as Fired

= 77,260 + (8625 - 5989) = 79,890 lb/hr