A Study of the Methods of Controlling Boiler Operation and Their Application in the Virginia Polytechnic Institute Heat and Power Plant

By

Charles Stoakes Bilisoly

B. S. Mechanical Engineering, V.P.I., 1931

and

Dale Carson Calhoun

B. S. Mechanical Engineering, V.P.I., 1931

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Approved -	Approved -
Dean of Engineering	Head of Department

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A Study of the Methods of Controlling Boiler Operation and Their Application in the Virginia Polytechnic Institute Heat and Power Plant

A detail study of three different methods of boiler control was made as basis for this thesis. These methods are namely, Mechanical Method, Synthetic Method, and Analytical Method. The objects in view were to determine which method was the most applicable to the V.P.I. plant, to locate all controllable heat loss and make recommendation for their reduction, and to devise some method of determining boiler efficiency with the minimum delay.

In order that a detail study be made it was necessary to perform two very careful boiler tests. The first test extended over a period of twenty-four hours, all readings being taken by actual observation. The second test extended over a period of ten days. All data was obtained in such a manner that the plant engineer could duplicate the test without encountering any considerable difficulties. In this test recording instruments were used as much as possible.

The results obtained from the study of the three different methods of determining boiler efficiency leads the author to believe that the Analytical Method is far superior to either the Mechanical or Synthetic Methods. Since the operating engineer is concerned primarily with the controllable heat losses and since the Analytical Method of determining boiler efficiency is based on the controllable heat losses, it is obvious that this method is of greatest importance. With the accompanying curves all heat loss calculations necessary to determine boiler efficiency have been eliminated making the operation very simple for the engineer.

For the determination of overall boiler efficiency a curve has been drawn whereby the desired results may be obtained instantaneously with an accuracy of within one per cent. The only two factors necessary for this determination are flue gas temperature and per cent carbon dioxide in the flue gas.

Preparation For Boiler Test

Before beginning the boiler test all recording gages and recording thermometers and pressure gages had to be calibrated and corrected for errors. The boiler gages were tested with an Ashton Special Gage Testing set. The Ashton test gage was checked at the mechanical laboratory by means of a hydraulic gage test set and found to be correct. Having checked the test gage each pressure gage in the power plant was checked and the average error in each gage was found to be approximately five pounds in excess. Adjustments were made on each gage to compensate for the error. The recording pressure gages were then checked with the steam header pressure gage and proper adjustments made to insure correct recordings. This test was the first performed on all the pressure gages in the plant since its construction. Due to the continual use of the gages they had become weaker and, consequently were recording higher pressures than were actually being maintained. For the same reason the safety valve springs had weakened and were responding to pressures lower than they normally should. Undoubtedly this error has had some effect on lowering the operating efficiency of the turbine unit.

It was also necessary to check the feedwater temperature recorder and the steam temperature recorder for possible errors.

The steam temperature recorder was checked by placing a suitable thermometer in the thermometer well in the superheater outlet main and checking the readings of this thermometer with the recording thermometer. The recording thermometer was found to be correct.

The recording thermometer for the feedwater was checked by two different methods.

In the first method, the regular feedwater line to the boiler in which the feed is controlled by means of a Copes Regulator was closed and the auxiliary line opened. This was necessary because the feedwater line in which the Copes regulating valve was located did not contain a thermometer well. The boiler rating was held constant as nearly as possible and the feed through the auxiliary line was maintained nearly constant. A thermometer was placed in the thermometer well in the auxiliary line and readings of the test thermometer and the recording thermometer were taken every five minutes. By changing the steam flow to the feedwater heater the temperature of the water was gradually raised and lowered, and in this manner the recording thermometer was checked over a wider range of temperatures.

Reading No.	Recordg. Thermo. °F	Test Thermo. °F	Diff. °F	Reading No.	Recordg. Thermo. °F	Test Thermo. °F	Diff. °F
1	212	216	4	13	211	216	5
2	212	216	4	14	211	216	5
3	207	214	7	15	212	216	4
4	206	210	4	16	213	216.5	3.5
5	207	210	3	17	214	218	4
6	205	208	3	18	214.5	218	3.5
7	208	211	3	19	215	218	3
8	210	212	2	20	215	219.5	4.5
9	210	214	4	21	215	219.5	4.5
10	211	216	4	22	213	218.5	5.5
11	211.5	216	4.5	23	212	218.5	6.5
12	211	216	5	24	211.5	217	5.5

Average Difference = 4.25°

The average difference in the readings of the two thermometers was found to be 4.25°F. A small percentage of this gain in heat was contributed to the feedwater pump, however the greatest error was due to the incorrect recording of the thermometer.

As a further check on this instrument the recording thermometer bulb was removed from the well and placed in a can of oil and the oil gradually heated by means of a blow torch and the readings of the recording and test thermometers were taken simultaneously on heating and cooling of the oil. By this method the thermometer was checked over a wider range of temperatures than by the preceding method. Readings were as follows:

Temperature Oil Increasing

Reading No.	Recordg. Thermo. °F	Test Thermo. °F	Diff. °F.	Reading No.	Recordg. Thermo. °F	Test Thermo. °F	Diff. °F
1	202	197	5	9	216	211	5
2	204	198	6	10	218	212.5	5.5
3	206	200	6	11	220	214	6
4	208	202	6	12	222	216	6
5	210	204	6	13	224	217.5	6.5
6	212	207.5	4.5	14	226	220	6
7	214	208	6	15	228	222	6
8	216	214	2	16	230	223	7

Average Difference = 5.59 °F.

Temperature Oil Decreasing

Reading No	Recordg. Thermo.	Test Thermo.	Diff. °F	Readings No.	Recordg. Thermo. °F	Test Thermo. °F	Diff. °F
1	228	223	5	8	214	210	4
2	226	222	4	9	212	208	4
3	224	220	4	10	210	207	3
4	222	218	4	11	208	205	3
5	220	216	4	12	206	203	3
6	218	214	4	13	204	202	2
7	216	212.5	3.5				

Average Difference = 3.65

Determination of Setting For Boiler Meters

Due to the fact that the air-flow setting for the Bailey Boiler Meter had been changed from time to time and there were no specifications on file to give the original setting of this meter, it was necessary to carry on a test to determine as near as possible, the present setting of the meter for the amount of excess air. It was very necessary that the correct setting of the meter be determined in order to calculate the total excess air going through the boiler for any given period of time. Knowing the total excess air and flue gas and entrance air temperatures, calculations could be made for the per cent heat loss due to excess air.

The above requirements could only be accomplished by means of flue gas analyses taken when both the steam-flow and air-flow pens were coinciding for under these conditions the furnace is receiving the proper amount of excess air for maximum efficiency. Approximately 75 flue gas analyses were made for this test; however, only a small part of these were used because of too large a variation in the steam and air-flow readings. From the flue gas analyses, the per cent excess air was computed for each analysis and the average of these calculations taken as the setting of the meter or as the per cent excess air going through the furnace when the two pens are in coincidence. The result amounted to 49 per cent excess air. Knowing the setting of the meter, curve sheet No. 1 was plotted giving the total excess air passing through the furnace for different per cent ratings of the steam and air-flow pens.

Results of flue gas analyses are shown as follows:

$$\% \text{ Excess Air} = \frac{O_2}{.264N_2 - O_2}$$

Steam Flow %	Air Flow %	CO_2 %	O_2 %	CO %	Total	N_2 %	$.264N_2 - O_2$ %	Excess Air %
111	110	11.1	7.4	0.0	18.5	81.5	14.10	52.4
101	101	13.2	5.0	.2	18.4	81.6	17.6	28.4
113	115	11.6	7.3	.0	18.9	81.1	14.09	51.8
100	100	12.5	6.0	.1	18.6	81.4	15.48	38.8
116	117	12.6	6.1	.1	18.8	81.2	15.35	39.7
123	122	10.9	7.9	.1	18.9	81.1	13.49	58.6
120	123	11.8	6.6	.0	18.4	81.6	15.6	42.3
110	110	9.6	9.0	.8	19.4	80.6	12.3	73.2
135	135	11.0	6.8	1.0	18.8	81.2	14.65	46.4
170	170	12.6	6.0	1.0	19.6	80.4	15.25	39.4
180	180	11.7	7.3	0.6	19.6	80.4	13.95	52.3
100	100	10.4	8.6	.4	19.4	80.6	12.7	67.7
95	95	12.0	7.4	.6	20.0	80.0	13.7	54.0
110	110	10.5	8.4	.2	19.1	80.9	12.95	64.8
110	110	11.2	8.3	.7	20.2	79.8	12.75	65.1
110	110	10.8	8.0	.8	19.6	80.4	13.25	60.3
140	140	11.2	7.5	.0	18.7	81.3	13.95	53.7
155	160	11.0	7.3	.0	18.3	81.7	14.25	51.3
120	120	11.4	7.0	.0	18.4	81.6	14.53	48.2
105	105	12.6	5.8	.2	18.6	81.4	15.68	37.0
137	135	13.0	5.7	.1	18.8	81.2	15.75	36.2
115	115	10.2	6.8	1.1	18.2	81.8	14.8	46.0
112	128	10.4	8.4	..0	18.8	81.2	13.05	64.4
115	120	10.4	8.6	.0	19.0	81.0	12.80	67.2

Steam Flow %	Air Flow %	CO_2 %	O_2 %	CO %	Total	N_2 %	$.264N_2 - O_2$ %	Excess Air %
114	116	11.6	7.0	.0	18.6	81.4	14.5	48.3
111	110	11.1	11.4	.0	18.5	81.5	14.12	52.4
113	115	11.6	11.3	.0	18.9	81.1	14.1	51.8
119	114	11.2	7.5	.0	18.7	81.3	13.95	53.8
115	123	9.5	9.0	.1	18.6	81.4	12.5	72.0

Average Excess Air 49%

Twenty-four Hour Boiler Test

The main object in performing this 24-hour boiler test was to calculate a heat balance for the 350 hp. boiler and from this heat balance determine a fair figure which would represent the radiation and unaccounted for losses for the boiler. It was necessary to determine this item in order to make a fair allowance for this loss in the calculation of the heat balances by the three different methods used in this report.

The 24-hour boiler test was performed according to specifications of the A.S.M.E. Power Test Codes of 1923 and all data were obtained as accurately as was possible. Readings were taken every fifteen minutes and at the end of the 24-hour period all readings were averaged and recorded. Flue gas analyses were made continuously during the test. All averaged data are recorded on the accompanying sheet.

Some difficulty was experienced with the operation of the Orsat apparatus during the test due to poor absorbing solutions and defective valves on the apparatus and as a consequence some little time was lost in the corrections of these defects. However, it is believed that the error due to this misfortune was negligible and that the average of the flue gas analyses that were made were substantially correct in the calculation of the heat balance.

As a result of the heat balance for the test it was found that the loss due to radiation and the unaccounted-for losses amounted to approximately four per cent. This loss, as listed in the heat balance accounts for the loss due to unconsumed hydrogen and hydrocarbons, radiation and unaccounted-for losses, so it was assumed that the radiation loss would amount to approximately three per cent. This amount was used in other calculations of heat balances in this report.

Log For Drafts and Temperature

Furnace Draft In. H_2O	Uptake Draft In. H_2O	Room Temp. °F	Front Furnace Temp. °F	Boiler Press. Lb.	Sup. Temp. Steam °F	Back Furnace Temp. °F
-.085	-.10	80	2225	170	420	2240
-.085	-.07	80	2190	170	420	↓
-.085	-.10	83	2150	170	410	↓
-.082	-.10	82	2400	170	438	↓
-.085	-.12	80	2250	170	442	↓
-.085	-.08	84	2175	170	438	↓
-.090	-.12	80	2475	170	440	↓
-.080	-.13	80	2350	170	444	↓
-.082	-.10	80	2680	170	442	↓
-.085	-.08	81	2425	170	438	↓
-.090	-.20	80	2500	170	442	↓
-.090	-.22	80	2675	170	444	↓
-.085	-.25	79	2400	170	456	↓
-.085	-.12	83	2375	170	448	↓
-.085	-.10	82	2225	170	442	↓
-.085	-.10	84	2450	170	438	↓
-.085	-.10	84	2275	170	440	↓
-.085	-.10	85	2250	173	434	↓
-.082	-.10	85	2300	170	432	↓
-.085	-.09	85	2425	170	434	↓
-.085	-.10	86	2275	170	432	↓
-.085	-.10	88	2325	170	440	↓
-.085	-.15	86	2175	170	444	↓
-.085	-.14	87	2275	170	444	

Log For Drafts and Temperature (Cont'd.)

Furnace Draft In. H_2O	Uptake Draft In. H_2O	Room Temp. °F	Front Furnace Temp. °F	Boiler Press. Lb.	Sup. Steam Temp. °F	Back Furnace Temp. °F
-.090	-.12	87	2315	170	440	2240
-.090	-.11	88	2150	170	442	2240
-.090	-.10	87	2325	170	437	2210
-.110	-.12	92	2375	170	438	2425
-.100	-.12	91	2150	170	442	2310
-.090	-.10	92	2275	170	440	2200
-.090	-.09	87	2325	170	436	2260
-.090	-.10	90	2275	170	420	2410
-.090	-.10	89	2255	172	426	2450
-.090	-.10	88	2225	172	428	2480
-.090	-.10	85	2240	173	428	2230
-.090	-.10	85	2260	173	430	2370
-.095	-.10	85	2230	170	432	2450
-.090	-.10	86	2230	173	430	2475
-.090	-.10	86	2190	170	428	2280
-.090	-.10	88	2130	170	436	2225
-.090	-.10	87	2200	172	434	2100
-.090	-.08	87	2320	170	432	2410
-.090	-.10	86	2220	172	436	2380
-.090	-.10	87	2350	172	440	2490
-.090	-.10	86	2300	172	438	2500
-.090	-.10	87	2325	172	437	2550
-.090	-.10	92	2135	170	432	2440
-.090	-.12	92	2225	170	442	2250
-.090	-.10	91	2175	170	434	2475

Log For Drafts and Temperature (Cont'd.)

Furnace Draft In. H_2O	Uptake Draft In. H_2O	Room Temp. °F	Front Furnace Temp. °F	Boiler Press. Lb.	Sup. Steam Temp. °F	Back Furnace Temp. °F
-.090	-.10	94	2210	170	432	2450
-.090	-.10	93	2100	170	434	2400
-.090	-.10	94	2375	175	432	2350
-.090	-.10	88	2250	172	432	2500
-.090	-.10	94	2225	172	430	2425
-.090	-.10	91	2225	173	430	2400
-.090	-.10	88	2300	174	430	2350
-.090	-.10	85	2325	174	426	2350
-.100	-.10	86	2375	175	430	2575
-.100	-.10	83	2300	175	430	2300
-.100	-.10	83	2225	175	430	2525
-.090	-.10	80	2050	172	432	2350
-.090	-.10	82	2400	173	435	2400
-.090	-.10	82	2415	173	438	2425
-.095	-.20	80	2300	173	440	2450
-.095	-.10	81	2210	175	439	2450
-.095	-.10	82	2300	173	434	2420
-.095	-.10	85	2380	173	434	2450
-.095	-.10	86	2390	175	438	2480
-.095	-.13	86	2450	174	440	2480
-.095	-.20	85	2400	173	438	2480
-.095	-.13	85	2380	170	442	2450
-.095	-.13	85	2265	173	445	2250
-.095	-.10	89	2295	175	442	2495

FLUE GAS ANALYSIS

March 2, 1932

$\%CO_2$	$\%O_2$	%CO	%B.R.	%A.F.
8.8	8.8	0.4	90	80
10.2	7.9	0.4	88	75
10.5	7.5	0.4	100	105
11.2	6.0	0.5	110	95
11.2	6.6	0.8	110	105
12.2	5.0	0.4	111	100
11.8	6.2	0.6	112	95
12.8	4.8	0.2	120	115
11.2	7.0	0.6	100	82
11.0	8.0	1.0	110	110
10.4	7.1	0.6	120	118
10.4	7.6	0.4	120	120
10.8	6.8	0.0	110	110
10.8	7.4	0.4	100	100
10.4	8.0	0.6	100	85
10.4	9.2	0.8	100	90
8.3	10.0	0.6	100	70
12.0	7.0	0.4	110	85
11.6	6.6	0.2	118	90
10.4	7.4	0.8	100	90
11.0	7.0	0.4	100	95
11.6	7.2	0.6	115	110
10.4	8.6	0.4	108	98
13.8	4.4	0.6	115	110
11.4	3.2	0.4	100	90
10.6	7.8	0.8	100	90
11.4	6.1	0.4	110	95
10.0	7.2	0.8	108	98
12.4	6.6	0.6	100	90
12.4	6.2	0.6	100	73
12.2	6.0	0.4	105	80
12.8	5.2	1.0	102	80
12.2	6.4	0.8	105	100
11.4	6.4	0.6	105	85
12.0	5.0	0.8	105	80
11.6	6.6	0.6	110	100
11.8	6.4	0.6	108	100
11.2	6.4	0.8	100	95
11.6	6.2	0.9	95	85
11.8	6.0	1.0	90	85
11.2	6.8	0.4	85	72
12.0	5.8	0.8	90	70

B.R. - Boiler Rating
A.F. - Air Flow

FLUE GAS ANALYSIS March 2, 1932

$\%CO_2$	$\%O_2$	%CO	%B.R.	%A.F.
10.6	7.0	0.9	88	65
11.3	6.5	1.0	100	80

THROTTLING CALORIMETER DATA March 2, 1932

B. P. Lbs.	Ex.Press. In. hg.	Ex.Steam Temp. °F	B. P. lb.	Ex.Press. In. hg.	Ex.Steam Temp. °F
172	6.4	264	170	5.9	288
171	5.5	296	170	5.6	294
170	5.8	294	170	5.7	294
170	5.7	294	169	5.9	294
170	5.9	294	170	6.1	292
170	6.1	294	172	6.3	294
170	6.2	295	170	6.2	292
173	6.1	294	170	6.4	294
170	6.6	292	172	6.5	292
169	6.4	292	172	6.8	290
172	6.7	294	169	6.5	295
173	6.9	294	172	6.7	294
169	7.1	296	168	7.2	296
168	7.4	292	172	7.7	295
173	7.7	296	171	7.6	297
173	7.6	297	172	7.6	295
173	7.6	296	173	7.5	296
173	7.3	296	172	7.2	296
172	7.2	296	170	7.0	296
170	7.1	296	172	7.3	297
172	7.2	296	170	7.1	296
171	7.0	295	172	7.2	296
171	7.2	295	170	7.1	295
170	7.1	295	173	7.0	296
172	9.4	294	172	7.5	296
173	7.5	296	173	7.5	295
173	7.1	295	173	7.2	296
173	8.6	296	173	8.0	296
172	7.8	294	174	8.0	296
174	7.8	296	174	7.6	296
173	7.2	296	174	7.4	296
173	7.2	296	172	7.0	295
173	7.2	295	173	7.2	295
171	7.4	295	172	7.3	295
174	7.5	296	174	7.5	296
172	7.2	294	174	7.7	296

B.P.-Boiler Pressure

THROTTLING CALORIMETER DATA - (con't)

B.P. lbs.	Ex.Press. In. hg.	Ex.Steam Temp. ^{o}F	B.P. lbs.	Ex. Press. In. hg.	Ex.Steam Temp. ^{o}F
174	7.6	295	172	7.4	295
174	7.4	296	173	7.3	295
174	8.1	296	174	8.1	296
171	7.7	296	171	7.6	296
173	7.6	296	175	7.9	297
175	7.4	296	176	7.7	296
175	7.4	296	175	7.4	296
175	7.5	296	172	7.5	296
177	7.5	296	177	7.5	296
176	7.1	296	170	6.7	295
170	6.7	294			

MOISTURE LOG - HOURLY READINGS - AIR ENTERING BOILER

Wet Bulb Temp. ^{o}F	Dry Bulb Temp. ^{o}F	Wet Bulb Temp. ^{o}F	Dry Bulb Temp. ^{o}F
67	96	82	122
78	162	82	120
80	122	80	118
80	121	78	116
81	123	78	116
80	123	80	124
78	116	82	120
79	118	80	120
82	123	82	122
82	124	78	110
83	123	82	122
84	124	80	122
78	114		

Averaged Data - Twenty-four Hour Boiler Test

Calorimeter:

Boiler Pressure - Gage	172 lb/sq. in
Exhaust Steam Temperature	294.7 °F
Exhaust Pressure	7.09 In. Hg.

Air:

Wet Bulb Temperature	79.7 °F
Dry " "	118.7 °F

Temperatures:

Boiler Room	85.9 °F
Furnace	2338 °F
Total Temperature Steam	438 °F
Flue Gases	458 °F
Feedwater	212.5 °F
Fuel	61 °F

Total Coal	26850 lb.
" Steam	272,000 lb.
" Refuse	3050 lb.

Flue Gas Analysis:

CO_2	10.9 %
O_2	6.84 %
CO	.607 %
N_2	81.66 %

Data and Results of Stationary Steam Boiler Test

A.S.M.E. Power Test Codes of 1923

As Fired Basis

General Information:

Date of Test - March 2, 1923

Duration of Test - 24 hours

Location - Virginia Polytechnic Institute Power Plant

Maker & Type of Boiler - 354 Hp. Casey-Hedges, Cross Drum, Water Tube

Maker & Type of Superheater - Foster-Wheeler

Type of Fuel Burning Equipment - Detroit Underfeed Stoker

Object of Test - To determine the efficiency and calculate heat balance.

Description, Dimensions, etc:

Boiler heating surface - 3540 sq. ft.

Superheater surface - 540 sq. ft.

Grate surface - 49 sq. ft.

Fuel Burning Equipment - Stokers

Draft - Induced

Fuel - Bituminous - Nut and Slack

Volume of Combustion Space - 441 cu. ft.

Furnace, - center of grate to nearest heating surface 9 ft.

Furnace volume per sq. ft. of Boiler Heating Surface - .1246 cu. ft.

Fuel and Gas Analysis and Data

Fuel Proximate Analysis:

Volatile matter	32.46 %
Fixed Carbon	60.60 %
Ash	5.85%
Moisture	1.09 %
Heating value per pound (as fired)	14,000 B.t.u.
Fusion temperature of ash	2464 °F
Size of Coal as fired	0 - 1/4"

Fuel Ultimate Analysis:

Carbon	81.71 %
Hydrogen	4.95 %
Oxygen	5.55 %
Nitrogen	1.45 %
Sulphur	.52 %
Ash	5.79 %

Gas Analysis - Boiler Outlet:

CO_2	10.9 %
O_2	6.84 %
CO	.6%
N_2	81.66

Dry gas per lb. fuel, boiler outlet - 17.57 lb.

Dry gas per lb. fuel (theoretical) - 11.51 lb.

Pressure and Drafts:

Moisture in air	.012 lb.per lb. air
Steam pressure by gage, boiler ..	172 lb. per sq. in.
Superheater outlet	172 lb. per sq. in.
Draft in furnace	.091 in. water
Draft at boiler outlet	.1176 in. water

Temperatures:

Steam temperature	369.4 °F
Moisture in steam	1%
Superheat	68.7 °F
Temperature of air surrounding boiler (T_1)	85.9 °F
Temperature of air for combustion (T_4)	118.7 °F
Temperature of furnace (T_5) ...	2338 °F
Temperature of gases leaving boiler (T_6)	458 °F
Temperature of feedwater entering boiler (T_9)	212.5 °F
Temperature of water in boiler at point where gases leave boiler (T_{11})	375.6 °F
Temperature of fuel (T_{12})	61 °F

Hourly quantities:

Fuel as fired per hour	1118.7 lb.
Fuel as fired per sq. ft. of grate per hour	22.8 lb.
Combustion space per lb. coal/hr.	.39 cu. ft.
Refuse per hour	127 lb.
Actual water per hour	11,333.3 lb.

Hourly Quantities, (Cont'd)

Factor of evaporation	1.09
Equivalent evaporation per hour	12353.3 lb.
Units of evaporation .... U.E.	11,985.2
(a) Boiler horsepower, average ...	347.4

Refuse:

Refuse, per cent of fuel	11.36 %
Percentage of combustible in refuse ..	5.51 %
Carbon burned per lb. fuel	.81 lb.

Evaporation:

Actual evaporation per lb. fuel	10.13 lb.
Equivalent evaporation per lb. fuel ...	11.04 lb.
Equivalent evaporation per sq. ft. heating surface per hour	34.89 lb.
Units of evaporation absorbed per sq. ft. of boiler heating surface	33.86 U.E.
(a) Percentage rating	98.13 %

Efficiency:

Efficiency of boiler, superheater, furnace and grate	76.5 %

Heat Balance of Steam - Generating

Comprising Boiler and Superheater

Heat Values	B.t.u.	Per Cent
Heat per pound of coal	14000	
Heat absorbed by water and steam in boiler and superheater	10711	76.5
Heat absorbed by steam in superheater	418.27	2.99
Unavoidable Losses		
Heat loss due to moisture in coal, moisture accompanying theoretical air and water from combustion of hydrogen up to T_{11}	577.4	4.12
Heat loss due to theoretical dry gases, T_4 to T_{11}	683.76	4.89
Total unavoidable losses	1261.16	9.01
Other Losses		
Heat loss due to combustible in refuse	804	5.74
Heat loss due to unburned gaseous combustibles	429	3.06
Heat loss due to theoretical dry gases, moisture in coal, moisture accompanying theoretical air, and moisture from combustion of hydrogen, T_{11} to T_6	275.2	1.97
Heat loss due to unconsumed hydrogen and hydrocarbons, radiation, and unaccounted for	519.64	3.72

Ten Day Boiler Test

General Description

All data for this test was collected in a way similar to that which would be used by the plant personnel should an attempt be made to duplicate this test. As much data as possible was taken from automatic recording instruments and daily logs. Such data as temperatures and pressures were taken from recorder charts by means of a radial planimeter; from the planimeter reading calculations were made which gave the average for the twenty-four hours which it covered.

In securing such data as amount of blowdown, combustible in refuse and moisture content of coal as fired, it was necessary to perform daily tests which are described in detail on the following pages.

In order that the error in computing heat losses be reduced to a minimmm and a fair average for the plant obtained, complete calculations were made for an average of all observed data in addition to the complete daily computations.

Determination of Grate Loss

During the time of the ten day boiler test it was necessary to determine the potential heat loss through the grate. Because the ashes are cooled by water in the pits before being dropped into the cars, they contain a large percentage of moisture at the time of weighing. In order to determine the average amount of water in the ashes at the time of weighing, samples of considerable size were taken from ashes which had been cooled with the usual amount of water. These samples were taken at the time the ash was weighed. In every case the sample was weighed immediately and then spread on the floor in the fan room where the temperature ranges between 100°F and 110°F. As will be seen from the following tables the first sample was allowed to remain on the fan room floor for a period of twenty-four hours at the end of the time it was carefully collected in the original containers and again weighed. From the original net weight and the loss in weight the per cent moisture lost by drying in this manner was calculated.

After weighing the first sample of ash the second time and finding the loss in weight on air drying at the temperatures mentioned the sample was crushed and quartered until a half gallon remained. This was sealed in a fruit jar and taken to the laboratory where it was ground to pass a twenty mesh sieve and thoroughly mixed. Upon placing a portion of this sample in an oven maintained at a temperature of 104^{o} C, it was found that the percentage of moisture was less than two tenths of one per cent and thus negligible. From these results it was decided that it was unnecessary to carry the test for moisture further than air drying in the fan room of the plant. The period of drying, however, was increased to some extent.

Test No. I - Sample taken 3 P.M., April 8

Time of air drying - 24 hours
Average temperature - 100 °F
Weight of wet ash and container = 87.5 lbs.
" " air dry ash and " = 68
Loss in weight due to moisture = 19.5 lbs.
Weight of container = 7 lbs.

87.5 - 7 = 80.5

$\frac{19.5}{80.5}$ = 24.2% = moisture loss on air drying

Final Test for Moisture

Wt. of watch glass and ash ..... = 36.2774 gr.
" after drying in oven .... = 36.2440
Loss in weight due to moisture 0.0334 gr.
Wt. at watch glass .... = 20.7845 gr.

Original net wt. of ash = 36.2774 - 20.7845 = 15.4929 gr.

$\frac{0.0334}{15.4930}$ = 0.21% = Moisture on air dry basis

100 - 24.2 = 75.8

21 x 75.8 = 0.16 % = Moisture in ash after air drying taken on original wet basis.

24.2 + 0.16 = 24.16 % = total moisture taken on original wet basis.

Test No. II - Sample taken 10:00 P.M. April 11, 1932.

Time of air drying	36 hours
Average temperature	100 °F
Wt. of wet ash and container	95.7 lbs.
" " air dry ash and "	74.7 "
Loss of wt. on air drying	21.0 lbs.
Wt. of container =	6.0 lbs.

Net wt. of wet ash = 95.7 - 6 = 89.7 lbs.

$\frac{21.0}{89.7}$ = 23.4 % Moisture

Test No. III - Sample taken 8:00 P.M. April 13, 1932

Time of air drying	48 hours
Average temp.	100 °F
Wt. of wet ash & container	91 lbs.
" " air dry ash and container	68.2
Loss of wt. on air drying	22.8
Wt. of container	6.0
Net wt. of wet ash	85 lbs.

$\frac{22.8}{85}$ = 26.9 % Moisture

Average Results: $\frac{24.2 + 23.4 + 26.9}{3} = 25.2$

In collecting samples to be used in the determination of combustibles in the refuse, average samples were taken at various times throughout each day and deposited in a barrel. When the boiler test was finished the refuse contained in the barrel was spread on the floor and prepared according to instructions for preparing coal sample by U. S. Bureau of Mines.

Results of Laboratory Test on Grate Refuse:

Analysis

Watch glass + coal .... 15.1370 g

Watch glass 12.2305

Wt. Coal ..... 2.9065 g

Per cent of Moisture - .32

Wt. Cruc. 8 + coal 14.1110

" " 8 ....11.0870

Wt. Coal 3.024

Wt. Cruc. 8 + Coal 14.1110

(Wt. Cruc.8 + Coal) = Vol. Mat. + Moisture = 14.0580

Wt. Vol. Mat.+ Moisture = .0530

% Vol. Mat. = 1.75 - .32 = 1.43 %

Wt. Cruc. 8 + ash 13.1437

" " 8 .... 11.0870

Wt. ash 2.0567

% Ash .... 67.8 %

Oven Dry Basis

Wt. Cruc. 12 + Coal - (Oven dry)	14.3220
" " "	10.5775
Wt. Coal	3.7445

Wt. Cruc. 12 + Coal	14.3220
" " 12 " " - Vol. Mat.	14.2710
Wt. Vol. Matter	.0510

Per cent of Vol. Mat. = 1.35%

Wt. Cruc. 12 + Ash	13.0808
" " "	10.5775
Wt. Ash	2.5033

Per cent of Ash = 66.8

Average Analysis

Vol. Matter	1.39%
Ash	67.41%
Fixed Carbon	31.20%
	100.00%

Determination of Moisture in Coal

In order that the moisture content of the coal fired during the test might be known with some degree of accuracy the following method of procedure was followed.

Each day a sample of approximately two pounds of coal was collected from the stoker bin and sealed immediately in a fruit jar to prevent the possible loss of moisture until the test was run. These samples were tested at the end of the fifth and tenth days.

In the test for moisture content the sample was accurately weighed and then spread on a board over steam pipes in the steam pipe tunnel at the heating plant. The temperature of the air around the sample averaged about 110°F. The sample in each case was allowed to dry for the time indicated in the chart. Upon a final laboratory test for moisture in the coal after drying in the steam pipe tunnel it was found that it contained less than one tenth of one per cent. It was decided that this would compensate for the small amount of coal lost in the form of dust while handling.

Results from Moisture Tests on Coal as Fired

Test No. I - Samples taken during first five days.

Time of drying - 47 hours

Wt. of coal and container before drying - 9.44 lbs.

" " " " " after " 9.203 lbs.

Loss in Wt. on drying .... .237 lbs.

Wt. of container .... 3.469 lbs.

Original net Wt. of sample - 9.44 - 3.469 = 5.971 lb.

Moisture content = $\frac{.237}{5.971}$ = 3.96 %

Test No. II - Samples taken during second five days.

Time of drying - 72 hours

Wt. of coal and container before drying - 10.08 lbs.

" " " " " after " 9.89 lbs.

Loss in Wt. on drying .... .19 lbs.

Wt. of container - 3.86 lbs.

Original net Wt. of sample = 10.08 - 3.86 = 6.22 lbs.

Moisture content = $\frac{.19}{6.22}$ = 3.05 %

Average - $\frac{3.96 + 3.05}{2}$ = 3.5 % Moisture

Coal used - 3/8" Stoker - Nut and Slack -

From - Dante, Virginia

Clinchfield Fuel Company

Laboratory Test -

Proximate Analysis:

Moisture -	.70 %
Volatile Matter -	34.97
Fixed Carbon -	53.95
Ash	10.38
	100.00 %

Moisture in coal as fired 3.5 %

B.t.u. per lb. .... 13,800 dry basis

B.t.u. " " .... 13,320 as fired.

Ultimate Analysis:

(As found in Coal Buyers Catalog)

Carbon ---	81.71 %
Hydrogen	4.95
Oxygen	5.55
Nitrogen	1.45
Sulphur	.52
Ash	5.79

Analysis of Refuse:

Volatile Matter	-	1.39 %
Fixed Carbon	-	31.20
Ash	-	67.41

Observed Data for Ten Day Boiler Test - Boiler No. 4

Date April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
Coal (1000-lbs)	26.67	28.22	27.63	26.18	30.32	31.83	30.18	33.64	38.92	36.50	310.09
Steam (1000-Lbs)	258	262	273	258	300	305	308	335	366	362	3,027
Pressure (Lbs.Abs.)	179.0	179.4	178.0	181.0	178.4	177.4	178.3	177.9	182.8	184.9	179.7
Sat.Steam Temp.(°F)	372.6	372.8	372.2	373.5	372.3	371.8	372.3	372.1	374.4	375.3	372.9
Sup.Steam Temp.(°F)	436.3	442.0	444.7	438.0	446.5	440.5	455.0	462.9	465.3	470.0	450.1
Feedwater Temp.(°F)	213.0	213.5	214.9	211.6	212.0	211.6	212.7	211.7	214.7	214.8	213.0
Temp.Inlet Air (°F)	113.9	114.6	114.5	114.3	112.2	110.5	110.0	109.6	110.4	114.0	113.3
Exit Gas Temp. (°F)	441.5	441.0	452.0	442.0	476.0	475.0	475.0	494.0	490.5	502.0	468.9
Blowdown 100-Lbs.	30	30	38	70	50	111	100	99	99	100	637
Tracyfier Loss (Lbs.)	400	400	600	360	160	680	400	400	360	520	4,280
Boiler Rating (%)	97.17	98.6	102.8	96.7	112.6	113.9	115.2	125.9	137.0	136.5	113.63
Air - Flow (%)	113	112	121	117	148	148	145	158	158	163	138.3
CO_2 (%)	10.40	10.50	10.12	10.00	10.24	10.50	10.60	10.28	10.28	10.58	10.35
CO (%)	.016	.018	.010	.008	.012	.018	.021	.014	.014	.020	.015

The Mechanical Method

In this method the basic control factors are determined by weighing the fuel consumed and the steam produced over a given period of time. By dividing the weight of the steam by the weight of the coal the actual evaporation is obtained. This calculation may be made mechanically by any fireman with the circular chart designed by the writers and shown on page 38. This chart is a special simplified radial slide rule so divided that the average fireman should have no trouble operating it.

The writers have also constructed a number of logarithmic charts for determining actual evaporation. These charts are simple to operate and may be made in ranges according to the need.

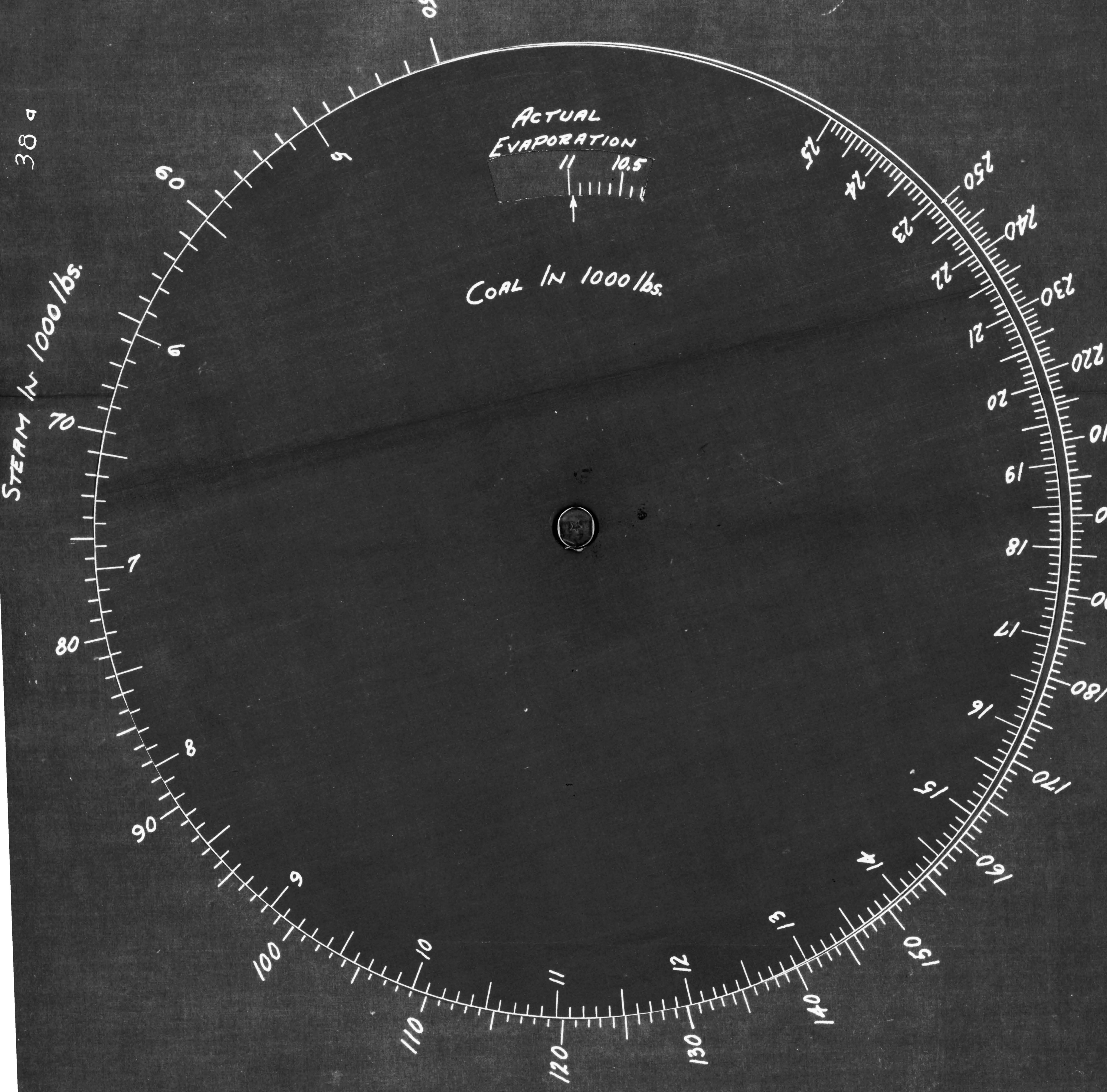
The actual evaporation is used to determine equivalent evaporation and boiler efficiency by means of the Mechanical Method. Alone it is of little value except in making comparisons of the efforts of different firemen and of different coals. Even for these uses there are many factors which may vary, causing false impressions and conclusions.

Variations in evaporations due to changes in the temperatures of the steam and the feedwater may be corrected by calculating the equivalent evaporation. By equivalent evaporation is meant the amount of water that would have been evaporated had the temperature of both the feedwater and the

Dear Patron,

The following two scans show minimum and maximum positions on the chart. For further information please request to view the physical item in Special Collections by placing a request through the catalog interface.

38 a



38 a


ACTUAL EVAPORATION
COAL IN 1000 lbs.
STEAM IN 1000 lbs.
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
6
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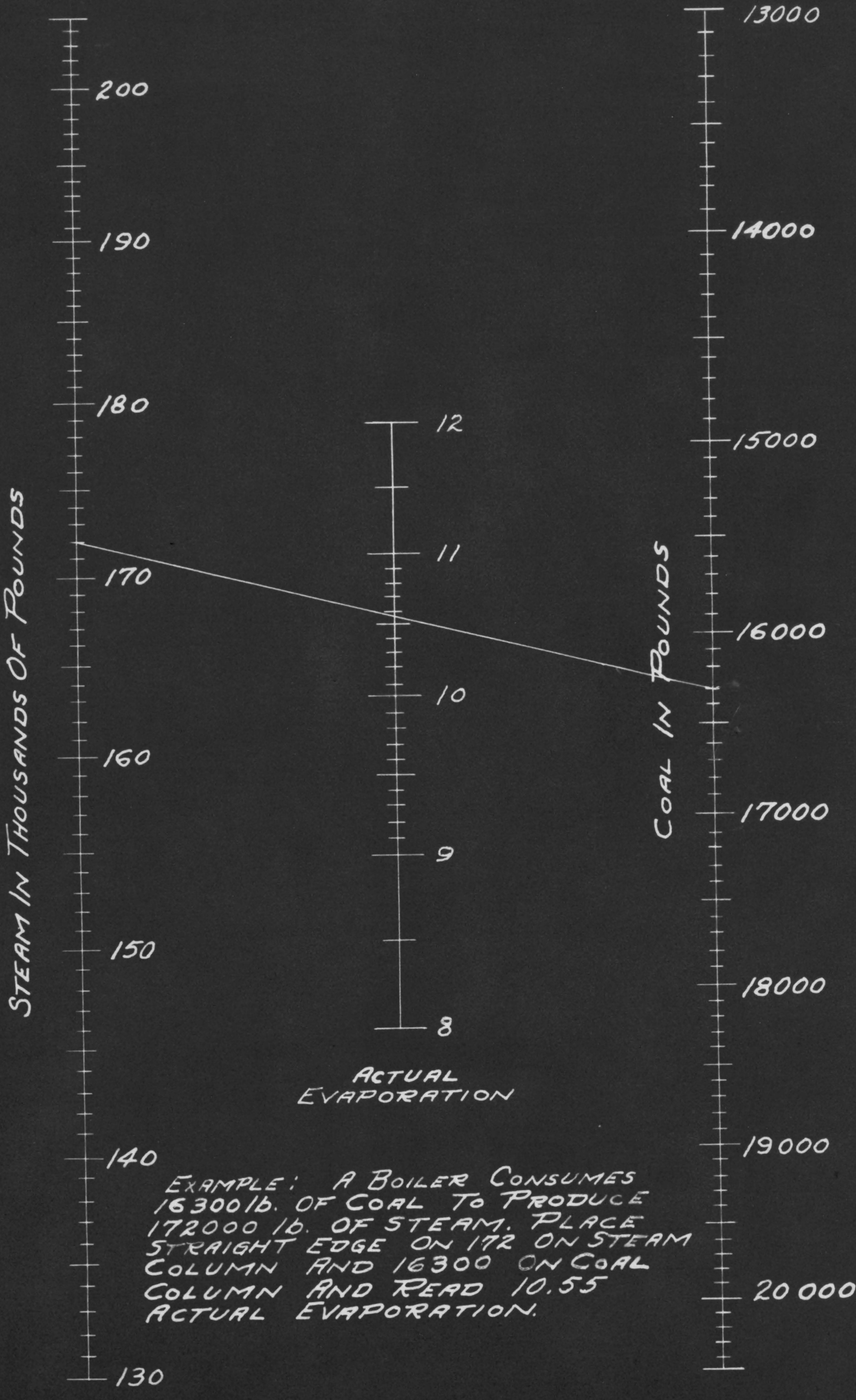
STEAM IN THOUSANDS OF POUNDS
200
190
180
170
160
150
140
130
12
11
10
9
8
ACTUAL
EVAPORATION
COAL IN POUNDS
13000
14000
15000
16000
17000
18000
19000
20 000
EXAMPLE: A BOILER CONSUMES 16300 lb. OF COAL TO PRODUCE 172000 lb. OF STEAM. PLACE STRAIGHT EDGE ON 172 ON STEAM COLUMN AND 16300 ON COAL COLUMN AND READ 10.55 ACTUAL EVAPORATION.

steam produced been 212 ^{o}F. The following formula may be used to get equivalent evaporation:

Equ. Evap. = Act. Evap. x Factor of Evap.

$$\text{Factor of Evap.} = \frac{H_1 - h_L}{970.2}$$

Where H_1 = Total heat in 1 lb. of steam produced.

h_L = Heat of liquid at feedwater temperature.

970.2 = Latent heat of evaporation at a pressure of 14.7 lb. per sq. in.

Equivalent evaporation is used in determining the boiler efficiency by the Mechanical Method and to make comparisons between the operating efficiencies of different plants. This comparison, however, would not be correct if the heating value of the coals used varied. This error may at least be partially corrected by stating the amount of coal consumed in "pound carbon" units instead of pounds and thus getting both actual and equivalent evaporation per P. C. unit of fuel. This is true because the heating value of the P. C. unit is practically constant for each class of coal.

Equiv. Evap. = Act. Evap. x Factor of Evap.

After having calculated the equivalent evaporation it is necessary to know only the heating value of the coal and the blowdown losses in order to be able to calculate the operating boiler efficiency.

$$\text{Operating Boiler Eff.} = \frac{(E.E.) \times 970.2 + (H_B \times A.E.)}{(\text{B.t.u. Heating Value of I lb.Coal})}$$

$$H_B = Bd \times H_1$$

$$Bd = \frac{\text{Blowdown (lbs.)}}{\text{Water Evaporated (lbs.)}}$$

Where E.E. = Equivalent Evaporation

A.E. = Actual Evaporation

H_B = Heat lost in blowdown per lb. steam generated (B.t.u.)

Bd = Blowdown (per cent)

H_1 = Heat loss in I lb. of blowdown, above the feedwater temp. (B.t.u.)

970.2 = Latent heat of evaporation at atmospheric pressure and 212 °F

Sample Calculation:

Coal Fired (lbs.) =	26,670
Water Evaporated (lbs.) =	258,000
Pressure (lbs./ sq. in.Abs.) =	179
Temperature of Steam (Deg.F)=	436.3
Temp. of Feedwater (Deg.F) =	213
Total Blowdown (lbs.) =	3,400
Heating value of coal (B.t.u. per lb.) =	13,320

$$\text{Actual Evap.} = \frac{\text{Wt. of steam}}{\text{Wt. of coal}}$$

$$= \frac{258,000}{26,670}$$

= 9.67 (lbs. water per lb. coal)

$$\text{Factor of Evap.} = \frac{H_1 - h_L}{970.2}$$

$$= \frac{1235 - 181}{970.2}$$

$$= 1.0864$$

Equivalent Evap. = Act. Evap. x Factor of Evap.

$= 9.67 \times 1.0864$

$= 10.50$ (lbs. water per lb. coal)

$$Bd = \frac{3400}{258,000}$$

$= 1.32\ \%$

$H_B = Bd \times H_1$

$= .0132 \times 164.7$

$= 2.17$ (B.t.u.)

$$\text{Opr. Boiler Eff.} = \frac{(E.E. \times 970.2) + (H_B \times A.E.)}{\text{B.t.u. heating value of I lb. coal}}$$

$$= \frac{(10.50 \times 970.2) + (2.17 \times 9.67)}{13,320}$$

$$= \frac{10,187 + 21}{13,320}$$

$= 76.53\ \%$

Discussion of the Mechanical Method of Determining Boiler Efficiency

The directness and simplicity of the Mechanical Method of determining boiler efficiency appeals first to the management because it furnishes the principal data required to keep track of the cost of power and make comparisons between the efforts put forth by different firemen and second to the operating engineer because of its simplicity. The calculations are simple and involve no factors with which he is not familiar.

In spite of these advantages there are a number of disadvantages. First, the lag is too great. By the time the efficiency has been correctly determined by this method it is too late for the boiler operator to make any improvements or even to remember the conditions which produced the results. The roughest calculations are seldom completed in less than a day. Under normal operating conditions in the Virginia Polytechnic Institute Heat and Power Plant there is a lag in these calculations of two days. However, in any case if results of a high degree of accuracy are to be obtained the lag is greatly increased. Under the most favorable conditions at least a week is required for the engineer to get results from a coal analysis. Since the heating value of coal may vary as much as ten per cent, due to variations in moisture and ash content, it is impossible to get reasonable accurate results in less than a week. Since it is very necessary that frequent analysis of

the fuel be made the expense encountered will be considerable.
Second: The accuracy of the method decreases as the interval of time for which the efficiency is determined decreases. This is due to the fact that the weight of coal fired is not the same as the weight consumed during the same period. The fuel bed may be thicker or thinner at the end of the period than it was at the beginning or it may be fresh at the start and pretty well burned out at the finish or vice versa. Of course the degree of accuracy may be increased by an attempt to bring the fire to the same condition at the end of the period as it was at the beginning. For the same reason care should be taken that the water level at the end of the period is the same as that at the beginning.
Third: Without elaborate or expensive instruments this method is not suitable for calculating the efficiency of the individual boilers. In cases where this system of determining efficiency is employed, the results obtained from a battery of boilers may be satisfactory even though one or more boilers in the battery operates wastefully. Should some system be employed whereby the efficiency of each boiler was determined the ones operating at a low efficiency would be known to the engineer and in such case an effort made by him to improve the operating conditions of that or those particular boilers.
Fourth: Unless tests are checked by scientific instruments factors may enter over which the operating personnel have no control and thus cause them to be unduly praised or censored for results obtained.

"In general it may be said of the Mechanical Method of control that it is, by itself, of no help to the operating engineer, except as an incentive to improve the operation of his boilers. However, it is of great value to the manager as a direct control over cost of his power, and, in a way, also over his operating personnel. Fuel is by far the largest single item in the cost of power and the Mechanical Method of boiler control furnishes the data required for keeping close watch over its consumption. Its importance to the management is, therefore, evident."

(Quoted from: Uehling's, Heat Loss Analysis)

Data for Determination of Boiler Efficiency - Mechanical Method - Boiler No. 4

Date April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
Coal (1000-lbs)	26.67	28.22	27.65	26.18	30.32	31.85	31.18	33.64	38.92	36.50	310.09
Steam (1000-lbs)	258	265	273	258	300	305	308	335	366	362	3,027
Pressure (lbs.Abs.)	179.0	179.4	178.0	171.0	178.4	177.4	178.3	177.9	182.8	184.9	179.7
Sup. Steam Temp.(°F)	436.3	442.0	444.7	438.0	446.5	440.5	455.0	462.9	465.3	470.0	450.1
Feedwater Temp.(°F)	213.0	213.5	214.9	211.6	212.0	211.6	212.7	211.7	214.7	214.8	213.0
Total Blowdown (100-lbs)	34	34	44	74	52	118	100	99	103	105	680
Per cent Blowdown	1.318	1.298	1.602	2.850	1.718	3.860	3.250	2.950	2.810	2.910	2.540
Heat Loss per lb.Blow-down (B.t.u.)	164	164	162	170	165	165	165	165	165	166	165
Heat Loss in Blowdown per lb.steam generated(Btu)	2.16	2.13	2.59	4.83	2.83	6.27	5.37	4.82	5.63	4.81	4.17
Actual Evaporation	9.67	9.28	9.88	9.85	9.89	9.58	10.20	9.96	9.40	9.92	9.77
Efficiency Per cent	76.53	73.78	78.61	78.53	79.05	76.57	82.04	80.40	77.72	79.48	78.10

Synthetic Method

There are five major heat losses taken into account in the calculation of boiler efficiency by the Synthetic Method; namely, heat loss in unburned coal, heat loss in unburned gas, heat loss in products of combustion, heat loss in excess air, and heat loss in water vapor. The above five items include the controllable and fixed losses in the power plant. Most of the controllable heat losses cannot be entirely eliminated and to greatly reduce some of them may tend to increase others. The important object in the power plant is to keep the sum total of the controllable losses at a minimum if high boiler efficiency is expected.

The Synthetic Method of controlling boiler operation is based on the assumption that it is just as logical to assume that air is burned by fuel as it is that fuel is burned by air, and that a definite amount of air has a practically constant heating value when burned with a given class of fuel. One pound of carbon will completely burn 11.6 lbs. of air and liberate 14,600 B.t.u.. Therefore one lb. of air will liberate 1,260 B.t.u. To insure practically complete combustion of the fuel in any furnace, the air must be supplied in excess of that theoretically required. Consequently, the air is in no case completely burned by the fuel, and the more excess air the greater the effect on the heating value of the air for the given class of fuel; i.e., the actual heating value of the air decreases as the percentage excess air increases.

This method of boiler control depends on the air and steam-flow ratio to guide the fireman in his attempt to secure the proper air-fuel supply to the boiler for maximum efficiency. The steam flow is measured directly while the rate of air flow is measured indirectly. Both are graphically recorded on the same chart. For economic boiler operation the air-steam flow pens should be made to coincide at all times because under this condition the proper amount of air and fuel is being supplied to the furnace for the indicated steam output and the conditions inside of the furnace are normal for the particular operating condition. In order to make the proper adjustment to the air-flow pen to make it coincide with the steam flow pen for best operating conditions, a series of flue gas analyses must be made and the percentage of excess air determined for complete combustion of the fuel supplied to the furnace. As long as the two pens are kept together the air-flow, steam-flow ratio will remain constant regardless of the rate of driving of the boilers. When the air-flow pen reads above the steam flow, there is an excess of air passing through the furnace for the indicated steam output with a consequent loss of heat in the hot flue gases; and when the air-flow pen reads less than the steam-flow pen there is a deficiency of air with a consequent loss of heat in unburned gases and fuel.

The proper regulation of excess air in a furnace is an important item in the combustion of fuels and the importance of maintaining a low percentage of excess air is recognized by most power plant engineers of today. If the air for combustion is reduced to a point too close to the theoretical requirements for a particular class of fuel, a poorer efficiency and likewise a higher operating cost is likely to be encountered than if a higher percentage of excess air had been used. The three foremost factors related to excess air are: furnace temperature, unburned fuel and unburned gases in chimney or heat loss in the chimney and the relationship of these three factors is an important one if high boiler efficiency is expected. The reduction in excess air means higher furnace temperatures, which is good for combustion efficiency; however, consideration must be given to the cost of furnace maintenance (stoker parts, refractories, clinker trouble, etc.). And further reduction in excess air too close to that theoretically required will result in incomplete combustion of the fuel and the result will greatly increase the heat loss in the flue gas and ashpit.

Too many engineers have mistaken ideas concerning CO_2 as an indication to the boiler losses. What CO_2 really shows is the amount of excess air going up the stack. Many engineers believe that the highest percentage of CO_2 should be striven for as this is an indication of complete combustion. This is an erroneous idea, as the percentage of CO_2 desired depends upon the chemical composition of the fuel being used in the furnace. The percentage of CO_2 in the escaping flue gases does not tell whether combustion is complete or incomplete. There is a certain minimum amount of air that must be used to obtain complete combustion with a given class of fuel and furnace and anything beyond this represents avoidable waste. When burning a certain weight of a given fuel per hour, the total weight of CO_2 produced per hour is constant, but the percentage of CO_2 in the flue gases will depend on the total weight of the flue gases or the dilution of the flue gases with excess air. If the weight of the flue gases is doubled, then the same weight of CO_2 will only be half the former percentage of the total. Thus, very high percentages of CO_2 in the flue gases could indicate that the percentage of excess air had been so decreased thereby, decreasing the total weight of the flue gases to such an extent that the percentage of CO_2 to the total weight of the flue gases will appear to be very high. It can clearly be seen that more than likely under such conditions, combustion in the furnace is not complete and further analysis of the flue gas would probably show high loss of combustible gases. Therefore it can be easily seen that the highest percentage of CO_2 is not always the more economical percentage from a standpoint of boiler efficiency. For a given class of fuel to be used in a power plant a series of flue gas analysis should be made to determine the proper percentage of CO_2 with regards to excess air, that will give the best operating results, that is, with minimum heat loss in the flue gases.

From these flue gas analyses the boiler meter can be set for the proper amount of excess air that will give the maximum CO_2 with complete combustion and the recording pen on the boiler meter so set such that its coincidence with the steam flow pen will always give the above result regardless of the rating of the boiler. Of course the fuel bed must be maintained in the proper condition for the above adjustment to the boiler meter and thereafter any irregularities in the fuel bed will show up on the boiler chart.

In boilers operating at fairly <u>constant</u> ratings, the flue gas temperature is a further check on the excess air passing through the boilers. Any increase in excess air in the furnace will result in a higher exit temperature due to the fact that the time for the burning of the combustible gases is greatly decreased and the gases are rushed past the boiler tubes at such a high rate the boiler does not absorb all the heat in the gases. Excess air in the furnace increases the volume and weight of gases passing through it, thereby increasing the velocity of the gases and decreasing the time the gases can remain in contact with the heating surface, and necessarily resulting in high flue gas temperature. The use of flue gas temperatures as an indirect check on excess air is based upon the assumption that the boiler tubes are kept clean and all baffles are tight. Unless these conditions are known to exist, it is a poor policy to use the flue gas temperature as an indication of excess air.

Explanation of Heat Losses For Boiler Heat Balance

1. Heat Loss in Unburned Coal.

In carrying out the ten-day boiler test it was impractical to take a test sample of the refuse for each day and run a complete analysis on the sample. To simplify this and still obtain fiirly accurate results, a sample of the refuse was taken daily and at the end of the boiler test the total test refuse for the ten days was prepared for the laboratory as prescribed by the U. S. Bureau of Mines. A proximate analysis of the test sample was made on the dry basis and from this analysis the per cent loss in the refuse was calculated. The loss in refuse was assumed to be constant throughout the ten-day test.

In calculating the per cent loss due to unburned coal, the result will be close enough if we assume the B.t.u. per pound of combustible in the refuse the same as that of the combustible in the coal and calculate the loss from the following formula:

$$X = 100 \frac{ac}{(100-a)(100-c)}$$

Where "a" = per cent ash in coal by analysis

"c" = per cent combustible in refuse

x = per cent loss

$$x = \frac{31.2 \times 10.38}{(100-31.2)(100-10.38)} \times 100 = 5.25\%$$

2. Heat Loss in Unburned Gasses.

This loss constitutes the loss due to CO in the flue gases due to incomplete combustion of the coal in the furnace and serious loss will be the result if the flue gases are not checked. To determine this loss for the boiler test it was not practical to continually run complete flue gas analyses each 24 hours of the boiler test and so, to supply this, some two hundred flue gas analyses were made, covering a wide range of operating conditions, with the idea in view of plotting a curve showing the average relationship of CO_2 to Co for the particular boiler averaging the CO_2 readings for each 24 hours as recorded by the Hays CO_2 recorder and assuming the CO_2 - CO relationship to be substantially correct the per cent loss was calculated as follows:

$$\text{Loss} = \frac{10160\ C \dfrac{CO}{CO_2 + CO}}{B}$$

Where C = per cent carbon in fuel

B = B.t.u. of fuel

10,160 = Heat of combustion of one lb. of carbon from CO to CO_2

Sample: $$\frac{10160 \times 53.95 \quad \dfrac{.016}{10.4 + .016}}{13320} = .06\ \%$$

3. Heat Loss in Products of Combustion.

The calculation of the heat loss in the products of combustion involve the ultimate analysis of fuel, weight of air required for combustion, weight of individual gases produced and their different and variable specific heats. The formula below is a somewhat shorter method of calculating these losses and is accurate to within 1/4 of 1%.

Heat Loss in Products of Combustion = .02(T-t)

Where: T = Temp. of gases in degrees F just as they leave the heating surface

t = temp. of entering air

.02 = a factor that applies to most commercial fuels.

Sample: .02(475 - 110) = 7.3% Loss

4. Heat Loss in Excess Air.

It is not necessary to know the air flow in either pounds or cubic feet to determine the per cent of excess air for this can be obtained from the boiler chart, knowing the setting of the meter when the steam and air flow pens read the same. The meter is set for a known percentage of excess air when conditions in the furnace are best, i.e., when the two pens read the same and for any deviation from this condition, the per cent excess air can be calculated. To illustrate this:

Air flow = 158%

Steam " = 137%

and the meter set for 49% excess air or a total of 1.49 times the theoretical, the excess air = $\frac{158}{137} \times 1.49 = 1.72$

This means that the total air is 1.72 times the theoretical or 72% excess. Then the loss due to excess air:

$$\%\text{Loss} = .019 \times E \times (T-t)$$

$$= .019 \times .72 \times (490 - 110.4) = 5.2\%$$

Where E = Excess Air expressed as a decimal

T = Temperature of flue gases ^{o}F

t = " " entering furnace air ^{o}F

.019 = a constant including specific heat.

5. Heat Loss in Water Vapor Resulting from the Combustion of Hydrogen in the Fuel forming H_2O.

This vapor not only carries away the heat required to raise it from the temperature of the air and fuel to 212^{o}F, but also the 970 B.t.u. required to evaporate each pound of water vapor as well as the heat used to superheat this steam to the temperature of the exit gases.

The formula previously stated for calculating the loss in Products of Combustion includes all water vapor losses except the latent heat, because they vary with the temperature of the escaping gases. The latent heat loss for any one fuel is fixed and cannot be affected in any way by the fireman.

When hydrogen burns to form H_2O; for each pound of hydrogen burned, 9 pounds of H_2O are formed. The latent heat per pound of steam at 13.6 pounds per sq. in. pressure (atmospheric pressure at V.P.I.), is 972.8 B.t.u. Therefore

$$\frac{9 \times 972.8 \times H}{\text{Btu of Coal} \times 100} = \%\ \text{Latent heat loss}$$

$$\frac{9 \times 972.8}{100} = 87.55 = \text{A constant for this locality}$$

The product is divided by 100 so the H can be used in percentage.

Therefore % Latent heat loss $= \dfrac{87.55H}{\text{B.t.u.}}$

Sample: $\dfrac{87.55 \times 4.89}{13320} = 3.21\ \%$ Loss

Test Data - Synthetic Method

April	4	5	6	7	8	9	10	11	12	13
Steam (1000-lbs.)	258	262	273	258	300	305	308	335	366	362
Inlet Air Temp.(°F)	113.9	114.6	114.5	114.3	112.2	110.5	110.0	109.6	110.4	114.1
Flue Gas Temp.(°F)	442	441	452	442	476	475	475	494	491	502
Boiler Rating(%)	97.17	98.60	102.80	96.70	112.58	113.90	115.20	125.90	137.00	136.50
Air Flow (%)	113	112	121	117	148	128	145	158	158	163
CO_2 (%)	10.40	10.50	10.12	10.00	10.24	10.50	10.60	10.28	10.28	10.58
Co (%)	.016	.018	.010	.008	.012	.018	.021	.014	.014	.020

Synthetic Method - Calculated Data

Chart No. 300D26

Fuel - Coal

Stoker - Detroit U. F.

Date - April	4	5	6	7	8	9	10	11	12	13
% Boiler Rating	97.17	98.60	102.80	96.70	112.58	113.90	115.20	125.90	137.00	136.50
Steam (1000 lbs.)	258	262	273	258	300	305	308	335	366	362
Average Air Flow Equivalent Rating	113	112	121	117	148	148	145	158	158	163
Ratio - Air to Steam Flow	1.163	1.137	1.179	1.210	1.314	1.300	1.260	1.256	1.153	1.194
Actual to Theoretical Air For Meter Setting	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Actual to Theoretical Air - Chart	1.732	1.695	1.755	1.802	1.959	1.939	1.896	1.869	1.720	1.780
Average Flue Gas Temperature (°F)	441.5	441.0	452.0	442.0	476.0	475.0	475.0	494.0	490.5	502.0

Losses in Per Cent

Losses in Products of Combustion	6.550	6.505	7.750	6.550	7.220	7.290	7.290	7.580	7.510	7.740
Loss in unburned Gases	.06	.07	.04	.03	.04	.07	.08	.06	.06	.08
Loss Due to Excess Air	4.60	4.27	4.85	4.91	6.54	6.48	6.20	6.35	5.17	5.82
Loss in Latent Heat of Water Vapor	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21
Loss Due to Unburned Coal	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Loss Due to Radiation	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Total Losses	22.67	22.30	24.10	23.95	25.26	25.33	25.03	25.44	24.20	25.10
Efficiency	77.33	77.70	75.90	76.05	74.74	74.67	74.97	74.56	75.80	74.90

Average Efficiency = 75.66%

The synthetic method of boiler control has many practical advantages over other methods and is well adapted to the V.P.I. Power Plant. The power plant is well equipped with Bailey Boiler Meters, CO_2 Recorders and Draft Gages and if particular attention is paid to these instruments by the firemen, improved boiler efficiency may be expected. A few of the advantages of this method of boiler control over the mechanical method are as follows:

1. It gives immediate information of changes in the operating condition.
2. It is applicable to the individual boilers.
3. It records all information on the same chart, thereby enabling the fireman to see how his boilers are operating.
4. The control factors are graphically recorded and therefore free from personal error.
5. The engineer can see whether each of his boilers are operating with normal efficiency without making troublesome calculations.
6. Being based on air as a fuel this method is independent of the variation in the heating value of the fuel.

Aside from the advantages, this method has some defects which should be mentioned:

1. The air-flow meter is appreciably affected by dirty flues and defective baffling, also abnormal air and feedwater temperatures.

2. The record does not give directly the information necessary to calculate and analyze the heat losses.
3. The ratio of the rates of steam flow to air flow that will give maximum boiler efficiency must be determined by actual tests and these tests and the recorder adjustments must be made by an expert.

The determination of the various losses for this method of boiler control has been simplified to a great extent by the use of the curves made by the authors. For a given coal the latent heat lost in the water vapor will be a fixed loss and can be calculated and assumed to be constant as long as that particular coal is being used by the plant. Likewise the radiation loss is assumed to be constant at three per cent and the loss in the ashpit will run fairly constant and if a fair sample is made each week as a check, there will be little error in calculating the boiler efficiency if this assumption is made. The above mentioned losses can be calculated and used as constants in the tabulation of the heat losses. The heat loss in products of combustion, heat loss in excess air, and heat loss in unburned gases are variable and with the exception of the latter can be obtained from the curve sheets.

For instance, from the inspection of the boiler chart a rough estimate of the average steam flow, air flow and exit temperature can be made. Knowing the average exit temperature the per cent heat loss in products of combustion can be obtained from curve No. 3 and tabulated. The loss due to excess air can be obtained from curves No. 1 and No. 2 and tabulated. By the use of curve No. 4 the per cent CO is found for the average per cent CO_2 and by means of a simple formula as described previously, the heat loss due to CO can be calculated and tabulated. The sum of the variable losses and the fixed losses subtracted from 100 will give the boiler efficiency. Of course this determination will only give an approximate efficiency and if more accurate results are desired the averages for the steam flow, air flow, exit temperature and CO_2 should be obtained by means of a radial planimeter and the losses calculated from the curves and the efficiency determined as described above.

The Analytical Method of Boiler Control

The analytical method of boiler control is based entirely on the controllable heat losses. Since the uncontrollable heat losses are unavailable to the boiler and are practically constant for any given fuel and operating condition, they are ignored as far as heat loss reduction is concerned. The controllable heat losses depend on three factors: excess air, of which CO_2 is an index; incomplete combustion, of which CO is an index, and excess temperature, of which T - Tw is an index. These indexes give all the necessary information for attaining maximum boiler efficiency.

In this method of boiler control all calculations are based on the heat wasted instead of the heat utilized by the boiler and therefore, it is immaterial whether the heat comes from the fuel, the air, or the feedwater. The boiler will always absorb the difference between the heat supplied and the heat lost. (It is hoped that the necessary efficiency calculations can be reduced to a minimum for this method so that the determination of the boiler efficiency can be made in short yet accurate manner.) By ignoring the uncontrollable heat losses, the heat loss calculations are greatly simplified without appreciably affecting their accuracy.

All calculations and formulas used in the analytical method of boiler control are based on the P. C. fuel unit or the pound-carbon unit as this unit is practically constant in heating value. The P.C. unit is defined as the amount or weight of coal containing one pound of carbon. This fact makes the control of boiler operation independent of the variation in the heating value of the coal being used. The standard heating value of bituminous coal or the P. C. heating value is practically constant at 17,900 B.t.u. and this figure has been used throughout all heat loss calculations. The P.C. unit heating value or the standard heating value does away with the difficulties of the variable heating value of the coal as fired, thereby eliminating the sampling and analyzing of coal which is very troublesome and by no means accurate. Other methods of boiler control require that the heating value of the coal be known in the determination of the boiler efficiency. The heating value of the coal as fired can only be found by sampling and analyzing and in plants using large amounts of coal it is practically impossible to get a true sample of the coal for analysis. From the analyses of all the important coal seams in the United States it has been found that the average heating value of the P. C. unit runs fairly constant at 17,900 B.t.u. Altho' this figure is not exact, it is practically correct and more nearly the correct heating value of the class of coal being used than can be determined by coal analyses. The fact that all calculations are based on the P. C. fuel unit tends to make the analytical method of boiler control a more exact method than either of the other two methods.

The uncontrollable heat losses in the boiler are listed as follows: (1) B.t.u. uncontrollable heat in dry gas, (2) B.t.u. of latent heat in water vapor, (3) B.t.u. uncontrollable sensible heat in water vapor, (4) B.t.u. loss due to radiation. These losses will be nearly constant in any given plant and for a given class of coal. The engineer is not concerned at all in the uncontrollable heat losses in the boiler because there is nothing he can do to reduce these losses. Therefore for any one plant the above losses may be calculated and the total uncontrollable heat loss held constant for all heat balance determinations. The heat loss through the grate although not exactly constant may be assumed to be constant without affecting the efficiency a great deal. In most all plants the refuse is inspected at regular intervals by the engineer to see that the combustible loss in the refuse is not above normal. So it may be safe to say, that the average loss through the grate is very nearly constant and can be added to four losses described above.

The operating engineer is chiefly concerned with the controllable heat losses in the boiler and to these he should endeavor to keep the sum total as low as possible. The controllable heat losses are listed as follows: (1) B.t.u. heat loss due to excess air, (2) B.t.u. loss due to excess temperature, (3) B.t.u. loss due to both excess air and excess temperature, (4) B.t.u. potential heat in dry gas, (5) B.t.u. sensible heat in water vapor. The necessary data for computing the above losses are temperature of flue gases, CO_2 , and pressure in the boiler, all graphically recorded and available to the operating engineer at all times. By means of a few simple calculations, as described later, the engineer can quickly compute a heat balance for an individual boiler and determine the distribution of the waste heat. By this method he can determine at a glance who is responsible for any appreciable increase in heat loss which tends to lower the boiler efficiency and the individual responsible for this loss can be reprimanded.

The analytical method of boiler control has many advantages and is not affected by any of the factors that more or less affect the other two methods. First, the heating value of the coal used is based on the P. C. unit and is constant in heating value; second, the method is based on the heat wasted rather than the heat used by the boiler; third, it enables the operating engineer to tell at a glance at the operating data who is responsible for the excessive losses; fourth, by ignoring the uncontrollable heat losses, the efficiency calculations can be made with minimum effort on the part of the engineer; fifth, the authors have devised a system of curves (Nos. 9, 10, 11, 12, and 13) based on per cent CO_2 and flue gas temperature which eliminates all calculations necessary for a boiler heat balance and enables the engineer to determine the total heat losses in the boiler from the two factors, CO_2 and temperature of flue gas. The curves were drawn up on the assumption that the average operating conditions at the V.P.I. plant will be practically constant. The curves were made to conform with the class of coal now in use.

The formulas used in computing the data for these curves are fully explained under a separate heading.

Average Operating Data - V.P.I. Plant

Pressure .... 183.6 lbs.-Abs.

Total Hydrogen Coal (H_6) .. 4.95%

Temp. Water .... 374.7°F

Boiling Temp. Water .... 208 °F

Sum of Uncontrollable Heat Loss and Those Assumed to be Constant for V.P.I. Plant

(B) - B.t.u. Loss in Dry Gas

Xm x Tw = 3.37 x 374.7 °F = 1263.0

(I) - B.t.u. Latent Heat in Water Vapor

H_t x 10641 = .0485 x 10641 = 527.0

(K) - B.t.u. Sensible Heat in Water Vapor

Ht x 4x (Tw - 208) = .0495 x 4 x (374.7-208) .= 33.0

(N) Loss Due to Radiation - 3% = 537.0

(M) Loss Through the Grate - 3.5% = 626.0

Total Uncontrollable Loss = 2986.0 B.t.u.

Knowing the total uncontrollable heat loss to be 2986 B.t.u. and with the two factors CO_2 and T, the engineer can find the total heat loss by referring to curves Nos. 9, 10, 11, 12 and 13, which will give the total controllable losses.

The sum of the total uncontrollable and controllable heat losses divided by the heating value of the P. C. unit will give the per cent loss and this subtracted from 100 will give the operating efficiency.

The authors have made a combination of the curves Nos. 9, 10, 11, 12 and 13 and together with the uncontrollable loss of 2986 B.t.u. have devised a curve, No. 14, which enables the engineer to determine the operating efficiency of his boiler with the minimum delay. The only two factors that need to be known are CO_2 and temperature of flue gases. Although this curve gives no information as to the distribution of the heat loss, it enables him to tell at a glance how efficient his boilers are operating. This curve is accurate within one per cent of the calculated efficiency as can be seen by reference to curve No. 16 which gives a comparison of the efficiencies by days as computed by the three different methods of boiler control. It can be seen from the curves that the synthetic and analytical methods of control are very nearly the same thus showing the accuracy of the two methods. Neither the analyticalnor synthetic method is affected by the conditions of the fire bed and this fact renders these two methods of calculating boiler efficiency far better than the mechanical method. To show the effect of the variation in the condition of the fuel bed on the efficiency by the mechanican method, reference to curve No. 16, it will be noted that the efficiency for 4, 9, 32 was considerably decreased below that of the preceding day. This being caused by an increase in thickness in fuel bed which necessarily lowered the evaporation for that day. The following day (4-10-32) the efficiency was increased considerably due to the fact that the heavy fuel bed was burned down and this increased the evaporation, thereby increasing the efficiency. These two facts more or less account for the irregularity of the mechanical efficiency curve.

Another short method of determining boiler efficiency has been devised based on flue gas temperature and heating value of the coal used. The relation of excess air and high or low CO_2 to flue gas temperature has been previously brought out so it might be said that the flue gas temperature is more or less a check on the operating efficiency. By multiplying a certain constant by the temperature of the flue gases and dividing by the B.t.u. of the coal used, the per cent loss is obtained and this loss subtracted from 100 gives the operating efficiency for the particular operating condition. A curve has been drawn (Curve No. 15) to eliminate all computations necessary to calculate the efficiency by this method. The formula used in determining values for this curve is $100 - \frac{735\ T}{B.t.u.}$. The accuracy of this method is within one per cent of the analytical method as can be seen by reference to curve No. 16, and can be used in the plant in determining the operating efficiency with the minimum delay. This method of determining boiler efficiency will prove to be accurate only when baffles are tight and tubes are clean.

To give some idea as to the heat distribution as calculated by the analytical method a heat distribution chart based on the average losses for the ten days has been drawn, (Curve. No. 17). It will be noticed that over one half of the total heat lost in the boiler is uncontrollable and cannot be reduced by the fireman. The total controllable losses are approximately 12% and to these losses the firemen should strive to reduce as much as possible.

List of Symbols Used in Formulas for the Analytical Method.

A = B.t.u. of sensible heat in dry gas per P. C. unit.

B = B.t.u. of Uncontrollable heat in dry gas per P. C. unit.

C = B.t.u. of controllable heat in dry gas per P. C. unit.

D = B.t.u. of controllable heat loss due to excess air per P. C. unit.

E = B.t.u. of controllable heat loss due to excess temperature per P. C. unit.

F = B.t.u. of controllable heat loss due to both excess air and excess temperature per P. C. unit.

G = B.t.u. controllable potential heat in dry gas per P. C. unit.

H. = B.t.u. of total heat in water vapor per P. C. unit.

I = B.t.u. of latent heat in water vapor per P. C. unit.

J = B.t.u. of sensible heat in water vapor per P. C. unit.

K = B.t.u. of uncontrollable sensible heat in water vapor per P. C. unit.

L = B.t.u. of controllable sensible heat in water vapor per P. C. unit.

M = B.t.u. of controllable potential heat in ash per P. C. unit.

N = B.t.u. of uncontrollable heat loss due to radiation per P. C. unit

a = Wt. of ash and clinker through the grate per P. C. unit.

pc = Per cent of carbon in ash and clinker.

G_1 = Uncontrollable heat losses (B.t.u. per P. C. unit.)

G_2 = Heat loss chargeable to grate (B.t.u. per P. C. unit)

G_3 = Heat loss component chargeable to furnace (B.t.u. per P. C. unit.)

G_4 = Heat loss component chargeable to boiler (B.t.u. per P. C. unit.)

$G_5 = G_2 + G_3 + G_4$ = Sum of available heat losses (B.t.u. per P. C. unit).

$G_6 = G_1 + G_5$ = Sum of heat losses (B.t.u. per P. C. unit).

CO_2 = Per cent of carbon dioxide.

CO = Per cent carbon monoxide.

T = Exit flue gas temperature (Degrees F.)

t = Temp. of air supplied to force draft (Degrees F)

Tw = Temp. of water in boiler (Degrees F)

X = B.t.u. contained in gas resulting from the combustion of I lb. of carbon per degree of temperature.

Xm = B.t.u. contained in gas resulting from the combustion of I lb. of carbon for maximum CO_2 per degree of temperature.

Y = Weight of carbon contained in the CO.

Explanation of Heat Losses Formulas, and Sample Calculations Used in Determination of Boiler Efficiency by the Analytical Method.

The greatest single heat loss in a boiler results from the sensible heat in the dry flue gas. In medium size boilers this loss ranges between ten and twenty per cent with even a greater loss in extreme cases. In general it may be said that excess losses due to excess flue gas temperature are due to either too much excess air, dirty tubes, leaking baffles, or a combination of these. Any one plays an important part in reducing the temperature of the air passing through the boiler.

In calculating the heat loss up the stack it is necessary to know the percentage of carbon dioxide in the flue gas along with the class of fuel being used, and the exit flue gas temperature. The percentage of carbon dioxide in the flue gas is generally obtained from a recording instrument except in short tests where it is practical to use an Orsat apparatus. The exit gas temperature may be determined by use of a pyrometer or may be taken from some type of recording instrument.

The sensible heat (A) in the dry flue gas is calculated from the formula:

$$A = X(T - t)$$

$$X = (0.24 + \frac{58.46}{CO_2})$$

Sample Calculation:

$CO^2 = 12\%$ $T = 450°F$ $t = 110°F$

$$X = (0.24 + \frac{58.46}{12})$$

$$= 4.912$$

$$A = 4.912\ (450 - 110)$$

$$= 1670$$ B.t.u. per P. C. unit of coal fired.

The values of X for different percentages of carbon dioxide have been tabulated and a curve drawn (Curve Sheet No. 7) to show the relation between the two.

Since it is impossible to lower the temperature of the exit gases below the temperature of the water in the boiler only a portion of the heat lost in the exit gases is controllable. That portion (B) of the loss which is uncontrollable is calculated from the formula:

$$B = Xm \times Tw$$

Sample Calculation:

$$Xm = 3.37 \qquad Tw = 373\ ^{o}F$$

$$B = 3.37 \times 373$$

$$= 1258$$ B.t.u. per P.C. unit of fuel fired.

That portion (C) of the loss which is controllable is the difference between the total loss and the uncontrollable loss or: $C = A-B$

Sample Calculation:

$$A = 1670$$

$$B = 1258$$

$$C = 1670 - 1258$$

$C = 412$ B.t.u. per P. C. unit of fuel fired.

A portion (D) of the controllable heat loss in the dry gas will be due to excess air and may be calculated from the formula:

$$D = (X - Xm)Tw$$

Sample Calculation:

$X = 6.1$ $Xm = 3.37$ $Tw = 373\ ^{o}F$

$D = (6.1 - 3.37)\ 373$

$= 1020$ B.t.u. per P. C. unit of fuel fired.

Since Tw is practically constant for the average operating conditions in any single plant and since Xm is constant for a given class of coal, the values of D for different values of X have been tabulated and a curve drawn (curve sheet 9) which will show the relation between these two factors for average operating conditions in the V.P.I. plant.

That portion (E) of the controllable heat loss which is due to excess temperature may be calculated from the formula: $E = Xm(T - Tw)$

Sample Calculation:

$Xm = 3.37$ $T = 450\ ^{o}F$ $Tw = 373\ ^{o}F$

$E = 3.37\ (450 - 373)$

$= 260$ B.t.u. per P. C. unit of fuel fired.

Since both Tw and Xm are practically constant in the V.P.I. plant a curve (Curve Sheet 10) has been drawn to show the relation between T and E.

The temperature of the exit gas depends upon the condition of the boiler tubes and the baffles as well as the rate at which the gas is passing through the boiler. As the amount of excess air increases the rate at which the gas travels through the boiler increases and thus the time allowed for the absorption of the heat in the gas is decreased and as a result, the gas passes into the stack at a higher temperature. Leaking baffles increase the flue gas temperature by allowing the gas to pass out without coming in contact with all the boiler tubes. Soot deposits on the outside or lime deposits on the inside of the boiler tubes decreases the absorption efficiency of the boiler and allows the gas to pass into the stack at a higher temperature.

In cases where there are controllable heat losses due to both excess air and excess temperature there is an additional controllable heat loss (F) chargeable to either or both excess air and excess temperature. This loss is calculated from the formula:

$$F = (X - Xm)\ (T - Tw)$$

Sample Calculation:

X = 6.1 Xm = 3.37 T = 450 °F Tw = 373 °F

$$F = (6.1 - 3.37)\ (450 - 373)$$

$$= 210 \text{ B.t.u. per P. C. unit of fuel fired.}$$

As has already been stated, the values of Xm and Tw are practically constant for any plant. With this in view a curve has been drawn (Curve Sheet 11) from which the value of F might be determined for any values of X and T (CO_2 substituted for X on the curve because X depends upon the CO_2).

Potential heat (G) is usually contained in the flue gas in the form of carbon monoxide which results from incomplete combustion due either to a deficiency of air or lack of turbulence in the furnace. This heat loss is calculated from the formula:

$$G = 10{,}160\ Y$$

$$\text{Where}\quad Y = \frac{CO}{CO+CO_2}$$

Since all calculations are based upon the assumption that there is a constant relation between CO and CO_2 a curve (curve sheet No. 12) was plotted to show the relation of CO_2 and G.

Sample Calculation:

$$CO_2 = 12\% \qquad CO = 0.08\%$$

$$Y = \frac{.08}{12.0 + 12.08}$$

$$= 0.00662$$

$$G = 10{,}160 \times 0.00662$$

$$= 67.2 \text{ B.t.u. per P.C. unit of fuel fired.}$$

Because of water vapor in the air, moisture in the fuel, and hydrogen in the fuel which burns to water, the heat carried to waste by the wet gas must be calculated. This heat loss (H) is accounted for in the formula:

$$H = Ht\ (10{,}641 + A(T - 208))$$

Where Ht = total hydrogen in the coal (per cent by Wt)

Sample Calculation:

$$Ht = 4.95\% \qquad T = 450\ ^{o}F$$

$$H = 0.0495\ (10{,}641 + 4(450 - 208)$$

$$= 0.0495\ (10{,}641 + 968)$$

$$= 475 \text{ B.t.u. per P. C. unit of fuel fired.}$$

The heat loss due to water vapor in the flue gas is divided into two principal losses, i.e., latent heat (I) in the water vapor and sensible heat in the water vapor. The former is an uncontrollable loss and is calculated from the formula:

$$I = 10{,}641 \times Ht$$

Sample Calculation:

$$Ht = 4.95\%$$

$$I = 10{,}641 \times 0.0495$$

$$I = 526 \text{ B.t.u. per P. C. unit of fuel fired.}$$

The sensible heat loss (J) due to water vapor is divided into an uncontrollable loss (K) and a controllable loss (L). These values are calculated from the formulas:

$$K = Ht \times 4 \times (Tw - 208)$$

$$L = Ht \times 4 \times (T - Tw)$$

Sample Calculations:

$$Ht = 4.95\% \qquad Tw = 373\ ^{o}F \qquad T = 450\ ^{o}F$$

$$K = 0.0495 \times 4 \times (373 - 208)$$

$$= 32.7 \text{ B.t.u. per P. C. unit of fuel fired.}$$

$$L = 0.0495 \times 4 \times (450 - 373)$$

$$= 15.5 \text{ B.t.u. per P.C. unit of fuel fired.}$$

The values of L for different flue gas temperatures have been calculated and a curve drawn to show their relationship for the particular type of coal used in the V.P.I. plant.

In order to determine the potential heat (M) in the refuse, samples were collected and analyzed for combustibles and ash. All of this loss is chargeable to the grates and considered controllable. It is calculated from the formula:

$$M = a\left(\frac{Pc}{100}\right) \times 14,600$$

Where a = Weight of refuse through the grates per P.C. unit of fuel fired

Pc = Per cent of carbon in the refuse

14,600 = Heating value of carbon (B.t.u. per lb.)

Sample Calculation:

a = 132 Pc = 31.2%

$$M = 132\left(\frac{31.2}{100}\right) 14,600$$

$$= 600 \text{ B.t.u. per P.C. unit of fuel fired.}$$

All heat losses (N) not accounted for in the preceding calculation were determined from a heat balance made up from the twenty-four hour test made previous to the ten-day test. These losses consisted of potential heat through the grates, radiation losses, and unaccounted for losses.

Test Data - Boiler No. 4

Date April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
Coal (1000-lbs)	26.67	28.22	27.63	26.18	30.32	31.83	31.18	33.64	38.92	36.50	310.09
Pressure (1000-lbs)	179.0	179.0	178.0	171.0	178.4	177.4	178.3	177.9	182.8	184.9	179.7
Sat.Steam Temp.(°F)	372.6	372.8	372.2	373.5	372.3	371.9	372.3	372.1	374.4	375.3	372.9
Temp.Inlet Air (°F)	113.9	114.6	114.5	114.3	112.2	110.5	110.0	109.6	110.4	114.4	112.4
Exit Gas Temp. (°F)	442	441	452	442	476	475	475	494	491	502	469
CO_2 (%)	10.40	10.50	10.12	10.00	10.24	10.50	10.60	10.28	10.28	10.58	10.38
Wet Refuse Lbs.	3,830	4,000	4,180	4,060	4,710	4,600	4,810	4,970	5,240	5,180	45,580

Calculated Data

Date April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
CO_2 Per cent	10.40	10.50	10.12	10.00	10.24	10.50	10.60	10.28	10.28	10.58	10.35
CO Per cent	.016	.018	.010	.008	.012	.018	.021	.014	.014	.020	.015
Excess Air Per cent	76.5	75.0	81.5	83.5	79.5	75.0	73.5	79.0	79.0	74.0	77.65
X	5.90	5.82	6.00	6.10	5.97	5.82	5.78	5.93	5.93	5.77	5.90
Xm	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37
X - Xm	2.53	2.45	2.63	2.73	2.60	2.45	2.41	2.56	2.56	2.40	2.53
T	441.5	441.0	452.0	442.0	476.0	475.0	475.0	494.0	490.5	502.0	468.9
t	113.9	114.6	114.5	114.3	112.2	110.5	110.0	109.6	110.4	114.1	112.5
T - t	327.6	326.4	337.5	327.7	363.8	364.5	365.0	384.4	380.1	387.9	356.5
Tw	372.6	372.8	372.2	373.5	372.3	371.9	372.3	372.1	374.4	375.3	372.9
T - Tw	68.9	68.2	79.8	68.5	103.7	104.1	102.7	111.9	116.1	126.7	96.0
Y	.0003	.0004	.0001	.0000	.0002	.0004	.0005	.0002	.0002	.0005	.0003
Y x 10,160	3.0	4.1	1.0	.0	2.0	4.1	5.1	2.0	2.0	5.1	3.5

Calculated Data

Date April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
Wet Refuse	3,830	4,000	4,180	4,060	4,710	4,600	4,810	4,970	5,240	4,180	45,480
Dry Refuse	2,857	2,984	3,118	3,029	3,514	3,432	3,588	3,708	3,909	3,864	34,000
Coal Burned (Lbs.)	26,670	28,220	27,630	26,180	30,320	31,830	30,180	33,640	38,920	36,500	310,090
Coal Burned P.C. Units	21,600	22,900	22,400	21,200	24,600	25,800	24,050	27,250	31,500	29,600	251,000
a	.1320	.1305	.1390	.1340	.1430	.1330	.1495	.1360	.1240	.1305	.1355
M	600	594	632	650	650	605	680	618	565	594	616

M = B.t.u. of controllable potential heat per P. C. unit of coal burned.

31.2% = Carbon in refuse

81% = Carbon in coal (Ultimate Analysis)

25.4% = Moisture in Refuse

a = Weight (in lbs.) of refuse through grate per P. C. Unit of fuel fired.

Calculated Data

April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
A	1,932	1,900	2,025	1,999	2,172	2,121	2,110	2,280	2,254	2,238	2,103
B	1,256	1,256	1,254	1,259	1,255	1,253	1,255	1,254	1,262	1,265	1,257
C	677.2	643.3	770.7	740.2	917.2	868.1	855.1	1025.5	997.3	973.3	846.7
D	942.7	913.4	978.9	1019.6	968.0	911.1	952.6	958.5	958.5	900.7	943.4
E	232.2	229.8	268.9	230.8	349.5	350.8	346.1	377.1	391.3	427.0	323.5
F	174.3	167.1	209.9	187.0	269.6	255.0	247.5	286.5	297.2	304.1	242.9
G	3.0	4.1	1.0	0	3.0	4.1	5.1	2.0	2.0	5.1	3.5
H	573.0	573.0	575.0	573.1	579.8	579.6	579.6	583.4	582.7	584.9	578.4
I	526.7	526.7	526.7	526.7	526.7	526.7	526.7	526.7	526.7	526.7	526.7
J	46.2	46.2	48.3	46.3	53.1	52.9	52.9	56.6	55.9	58.2	51.7
K	32.6	32.6	32.5	32.8	32.5	32.5	32.5	32.5	32.9	33.1	32.7
L	13.6	13.5	15.8	13.6	20.5	20.6	20.3	22.2	23.0	25.1	19.0
M	600	594	632	650	650	605	680	618	565	594	616
N	537	537	537	537	537	537	537	537	537	537	537

Tabulated Results

Date April	4	5	6	7	8	9	10	11	12	13	Averages & Totals
G_1	2,351	2,353	2,351	2,355	2,351	2,350	2,351	2,350	2,358	2,362	2,353
G_2	600	994	632	650	650	605	680	618	565	594	616
G_3	1,062	1,029	1,120	1,144	1,150	1,085	1,123	1,151	1,159	1,008	1,107
G_4	304	299	355	307	460	456	449	495	513	553	423
G_5	1,966	1,922	2,107	2,101	2,260	2,147	2,251	2,264	2,237	2,156	2,146
G_6	4,317	4,275	4,458	4,456	4,611	4,496	4,602	4,615	4,595	4,518	4,498
% Loss	24.12	23.88	24.91	24.89	25.76	25.12	25.71	25.78	25.67	25.24	25.13
% Efficiency	75.88	76.12	75.09	75.11	74.24	74.88	74.29	74.22	74.33	74.76	74.87

$G_1 = B + I + K + N$ = Uncontrollable heat losses.

$G_2 = N$ = Controllable heat loss chargeable to grate.

$G_3 = D + 2/3\ F + G$ = Controllable heat loss chargeable to furnace.

$G_4 = E + 1/3\ F + L$ = Controllable heat loss chargeable to boiler.

$G_5 = G_2 + G_3 + G_4$ = Sum of the controllable heat losses.

$G_6 = G_1 + G_5$ = Sum of all heat losses.

$$\%\ \text{Loss} = \frac{G6}{17,900}$$

Efficiency = 100% - % Loss.

(All units are B.t.u. per P. C. Unit of fuel fired.)

Conclusion

1. The use of the analytical method of boiler control is recommended for the V.P.I. Power Plant.

   From a detailed study of the three methods of boiler control considerable knowledge has been gathered relative to the advantages, disadvantages and efficiency of each method.

2. A system of curves has been devised for the determination of heat balances which eliminates all calculations.

3. These curves are applicable to the operating conditions at the V.P.I. Power Plant. With a detailed study, similar curves may be drawn that would be applicable to any power plant.

4. From a combination of the curves devised, a single curve has been made enabling the operating engineer to determine the efficiency instantaneously.

5. It is recommended that the analytical method of calculating boiler efficiency be adopted at the V.P.I. Plant because of its simplicity and accuracy of calculation and because it gives a direct index to the controllable heat losses

Recommendations

Since the carbon content in the refuse at the V.P.I. Plant exceeds thirty per cent and since the grate loss is more than five per cent, it is believed that some step should be made to reduce this loss.

Undoubtedly the installation of perforated dump plates or some type of clinker grinder is worth considering.

Since Bailey Boiler Meters are depended upon to measure or weigh the steam output from each boiler, it is believed that some postive method of checking these meters for accuracy should be employed. By overhauling the feedwater weigh-meter now in the plant and checking it for accuracy a convenient means of checking the accuracy of the Bailey Boiler Meters will be provided.

A small powered crusher suitable for crushing ash and coal samples would be of great value in seaving ash and coal samples. Since the number of such samples taken in a year in the V.P.I. Plant is comparatively large, it is recommended that a machine of this type be purchased.

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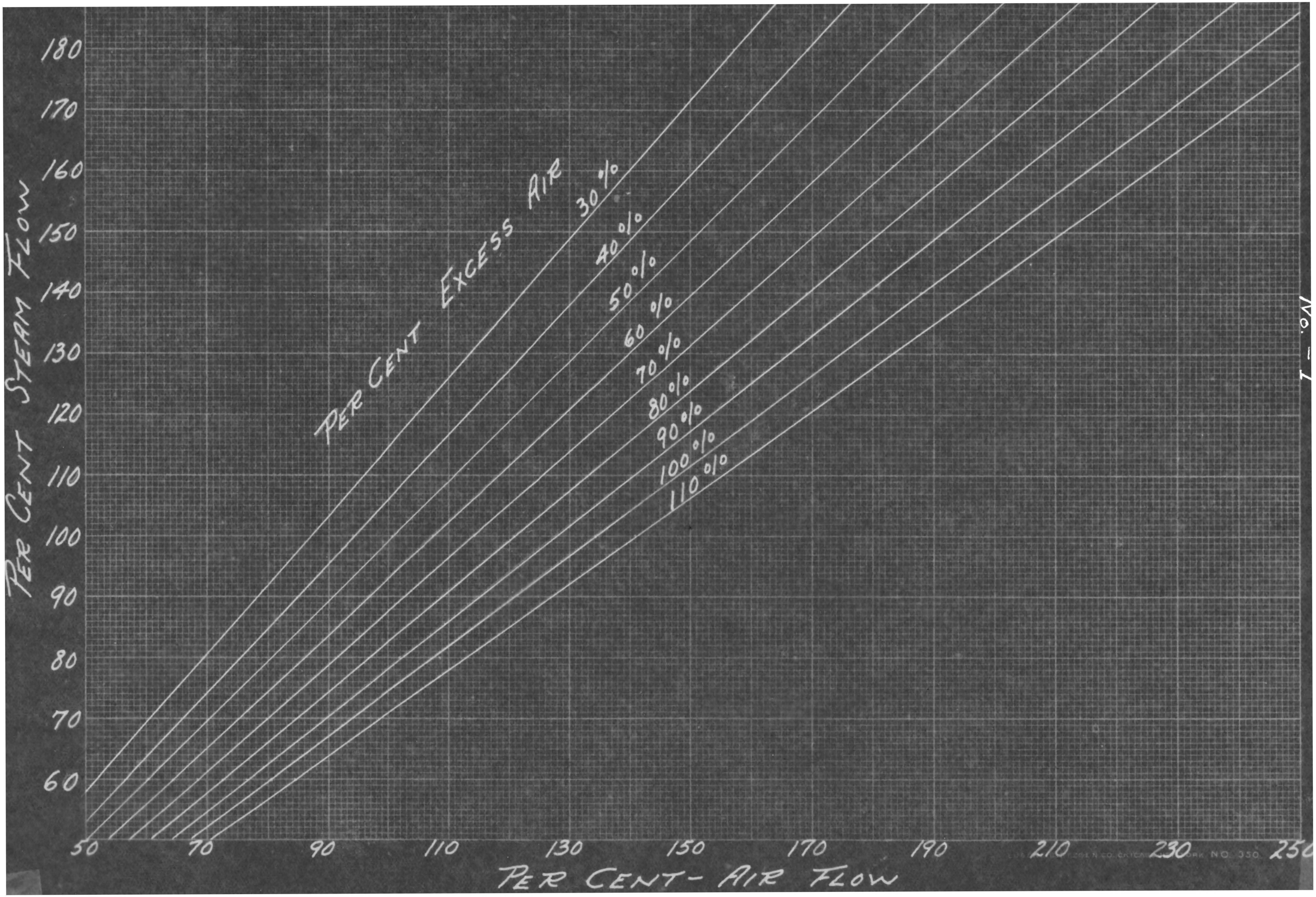
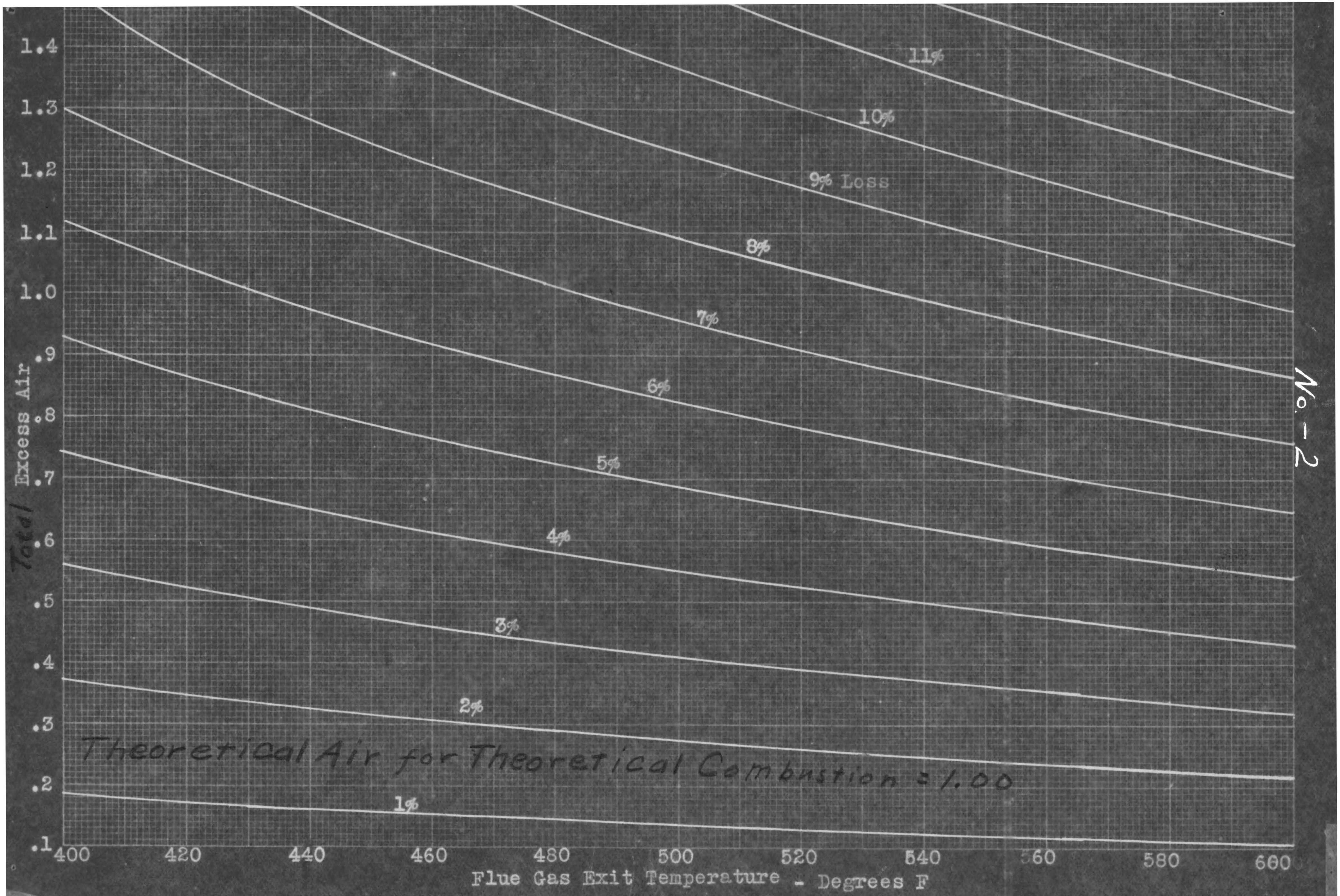
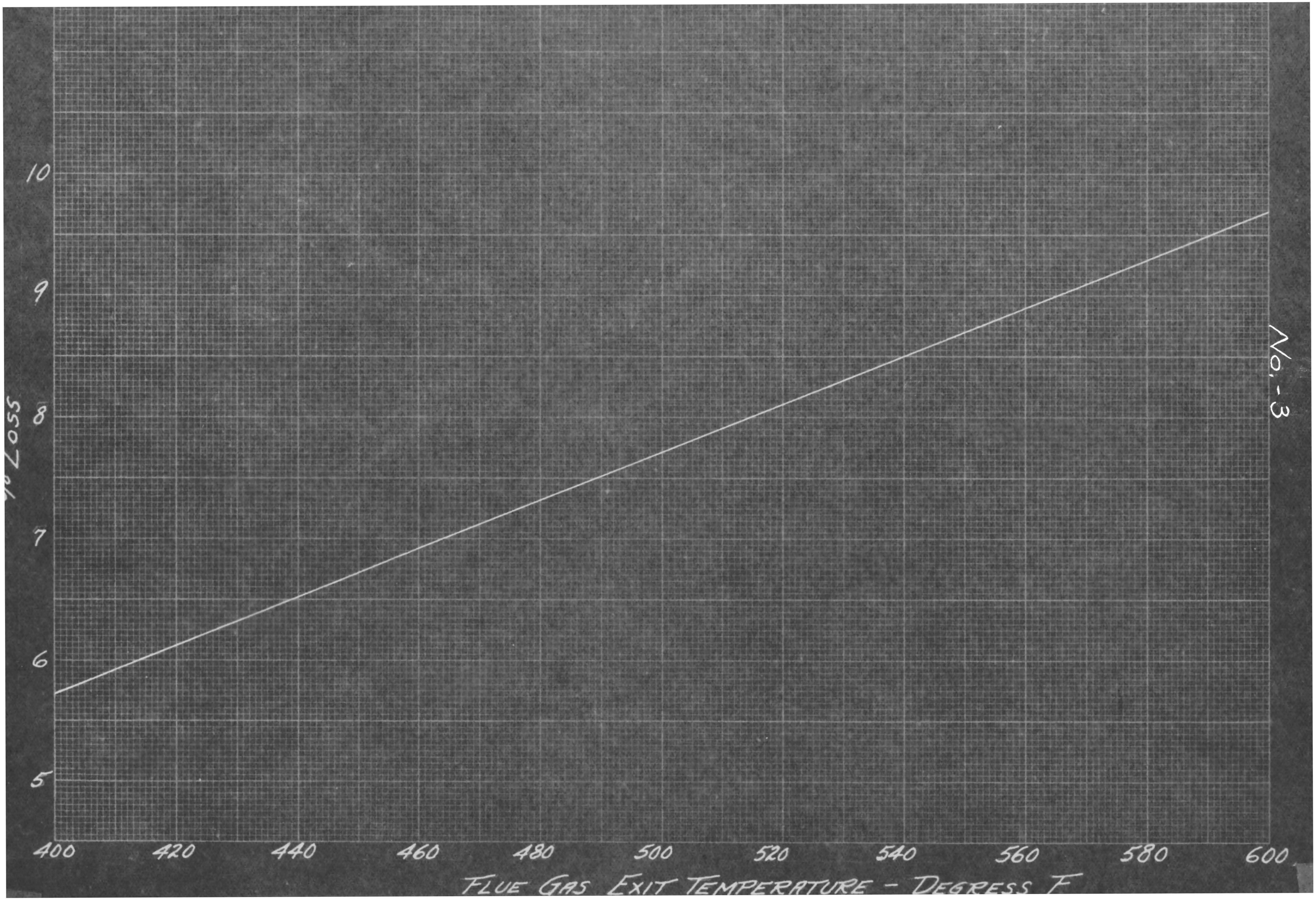
G. B. Mulloy - Guiding Boiler Operation From CO_2 and Uptake Temperature.

H. R. Clark - Basic Combustion Engineering.

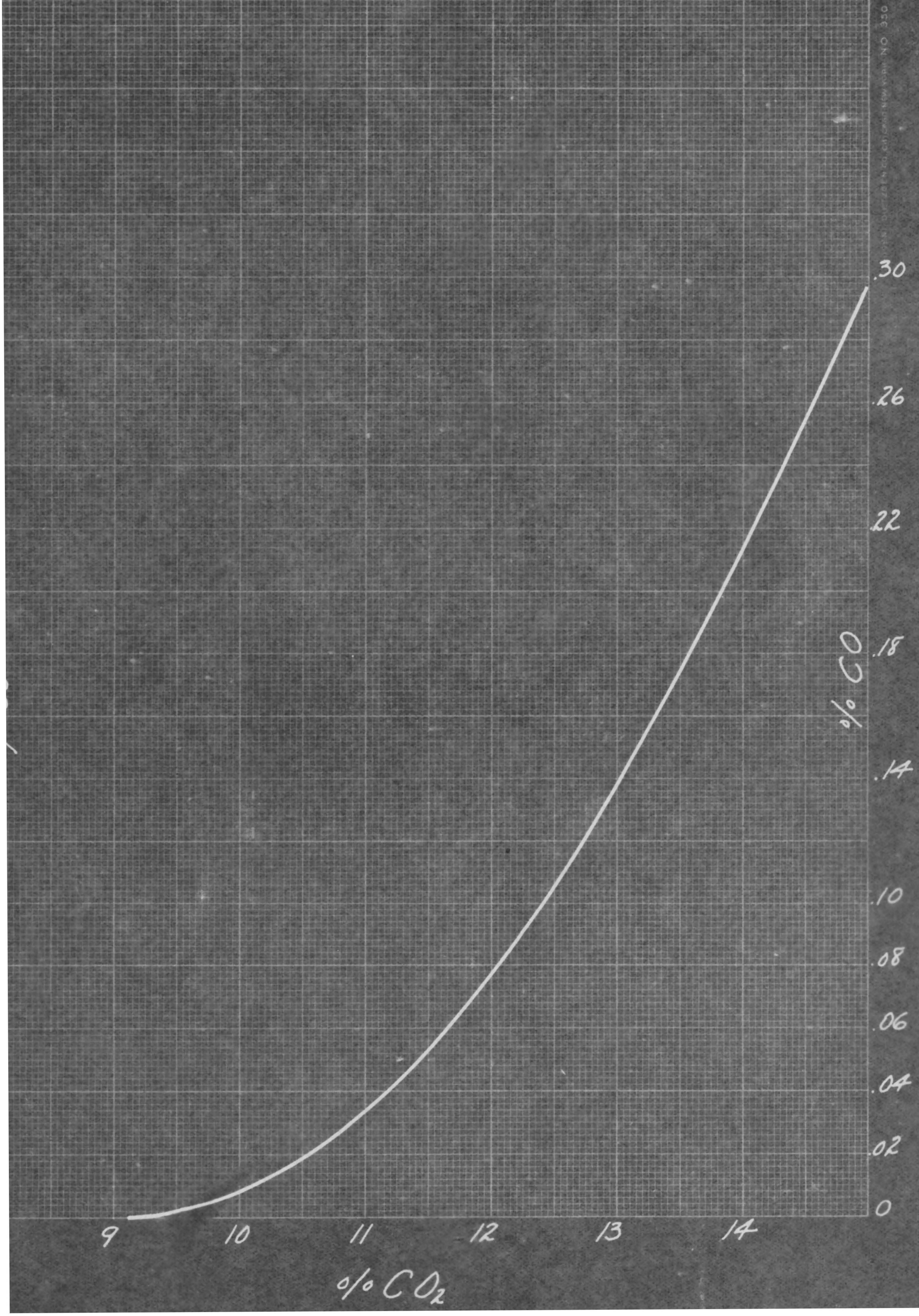


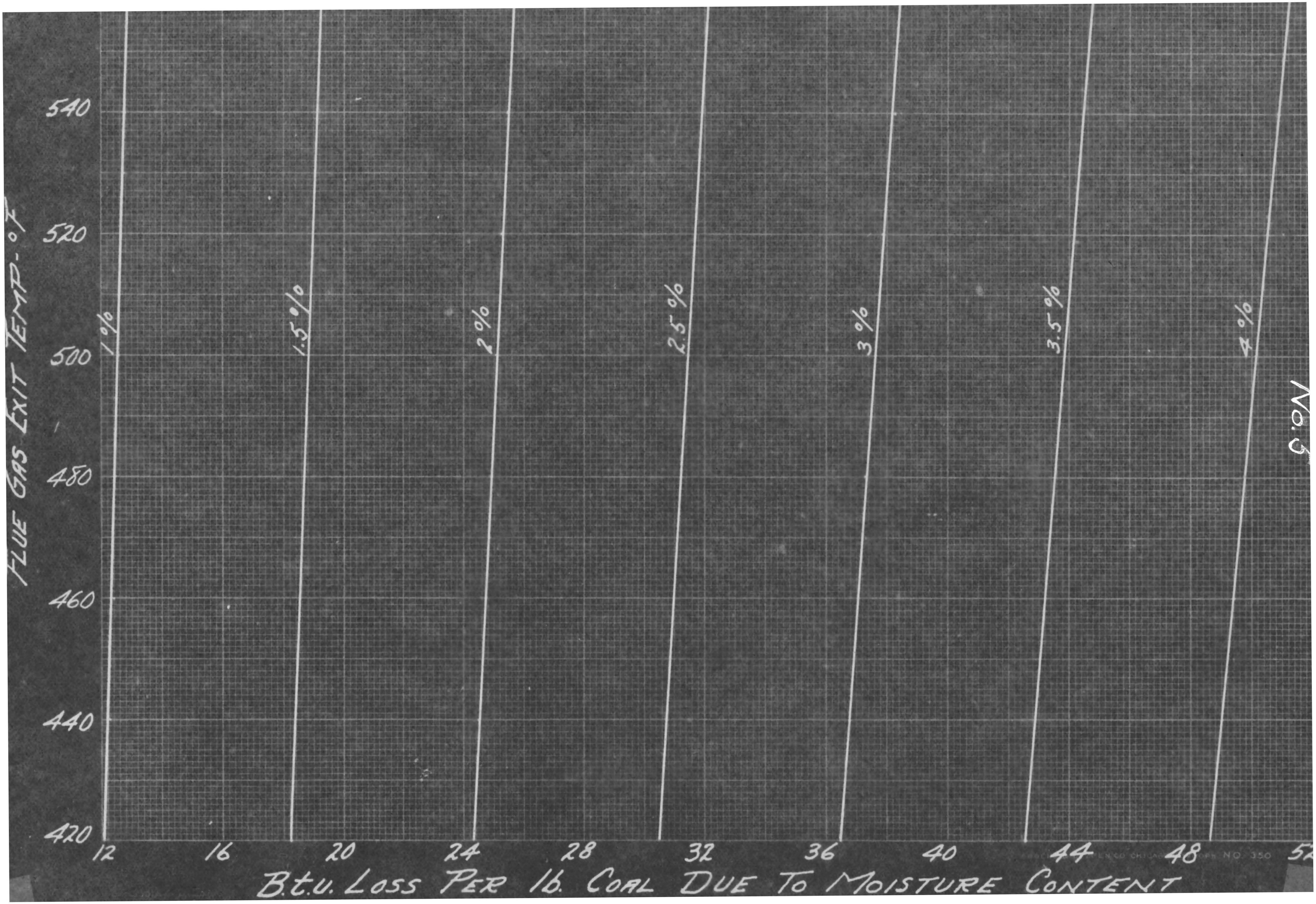
PER CENT EXCESS AIR
30 %
40 %
50 %
60 %
70 %
80 %
90 %
100 %
110 %
PER CENT STEAM FLOW
180
170
160
150
140
130
120
110
100
90
80
70
60
50
70
90
110
130
150
170
190
210
230
250
PER CENT - AIR FLOW
No. 1

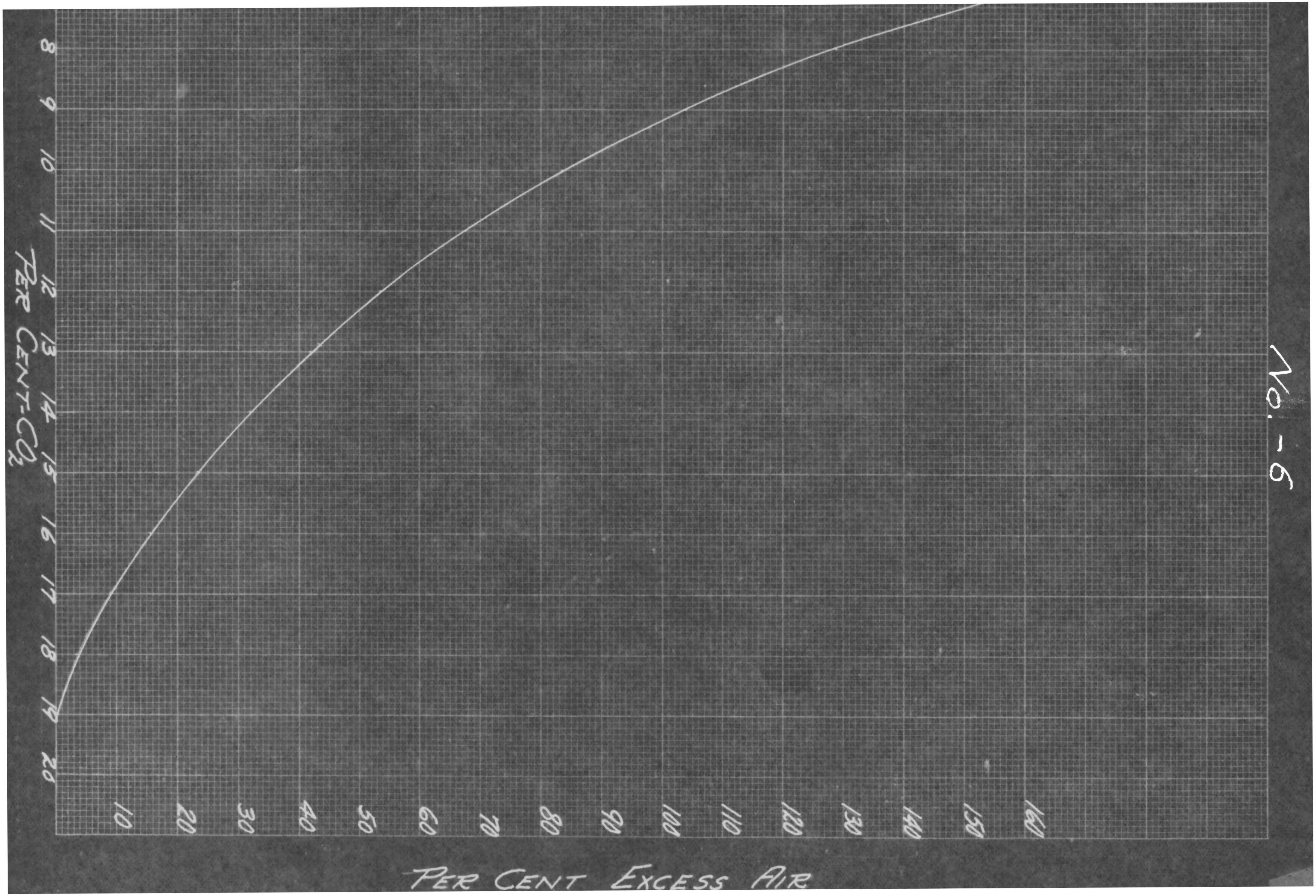

11%
10%
9% Loss
8%
7%
6%
5%
4%
3%
2%
1%
Total Excess Air
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
400
420
440
460
480
500
520
540
560
580
600
Flue Gas Exit Temperature - Degrees F
Theoretical Air for Theoretical Combustion = 1.00
No. - 2


% LOSS
10
9
8
7
6
5
400
420
440
460
480
500
520
540
560
580
600
FLUE GAS EXIT TEMPERATURE - DEGRESS F
No. -3

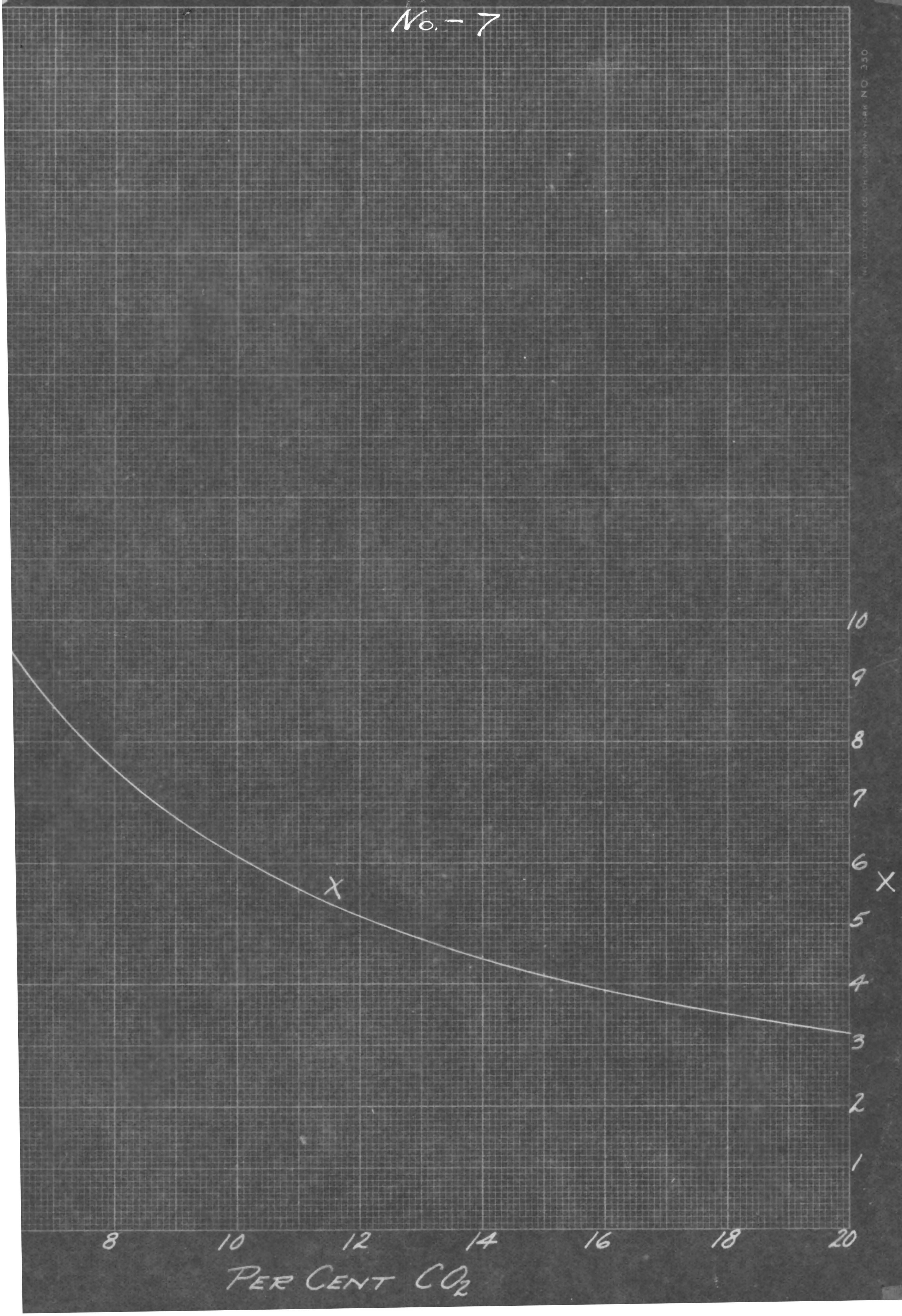
No. 4



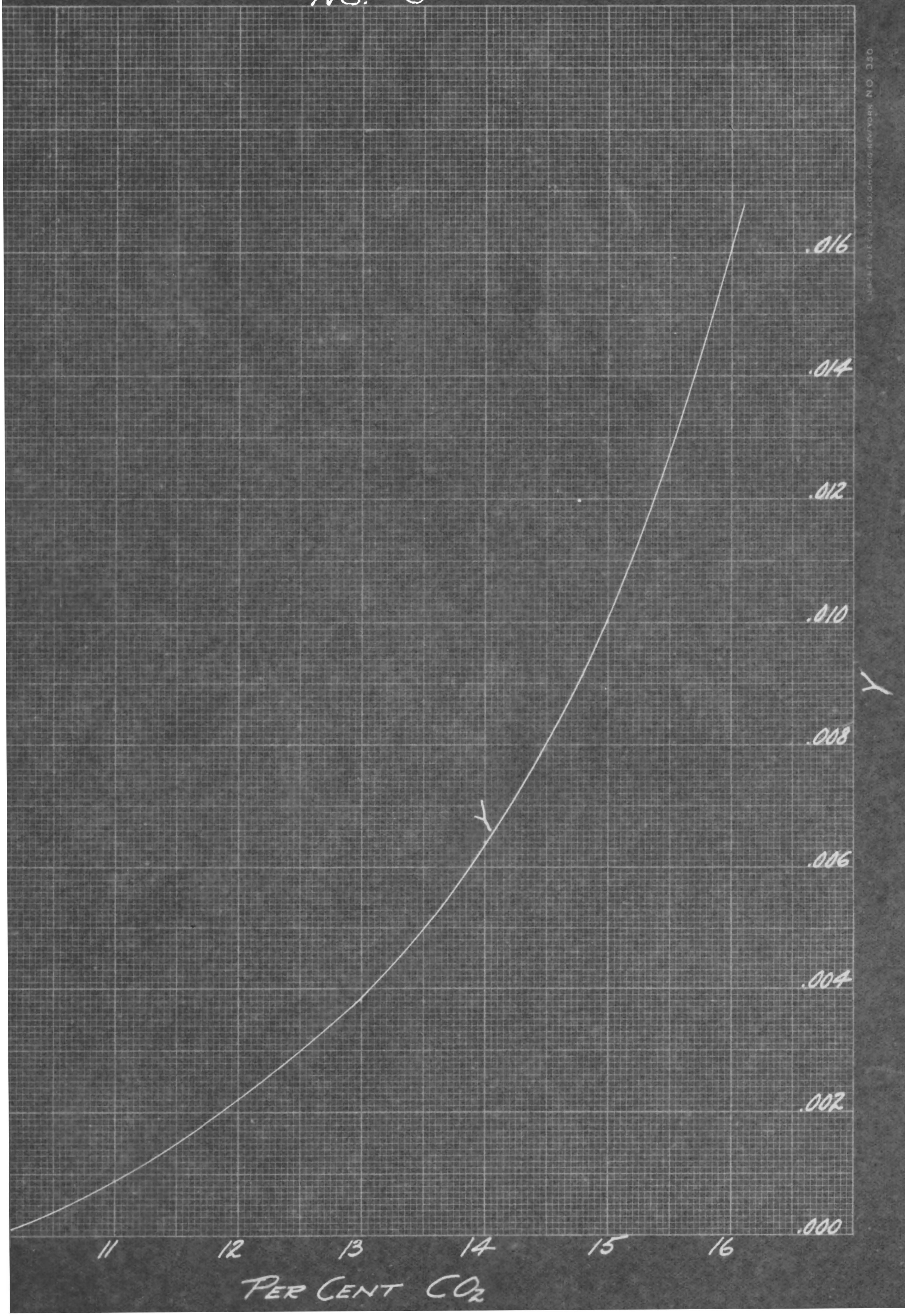

FLUE GAS EXIT TEMP. - °F
540
520
500
480
460
440
420
1%
1.5%
2%
2.5%
3%
3.5%
4%
12
16
20
24
28
32
36
40
44
48
52
B.t.u. LOSS PER lb. COAL DUE TO MOISTURE CONTENT
No. 5

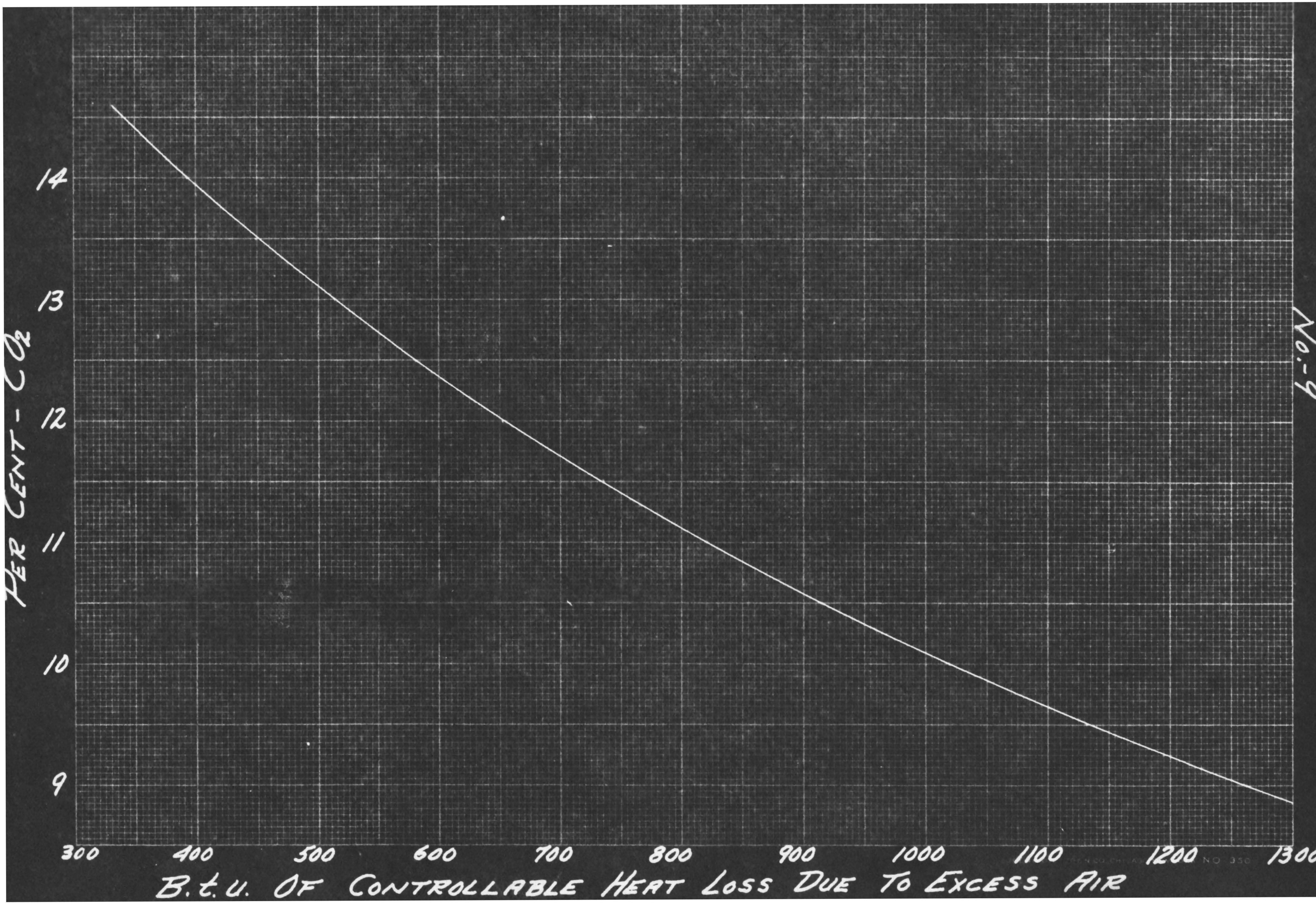

No.-6
PER CENT-CO_2
8
9
10
11
12
13
14
15
16
17
18
19
20
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
PER CENT EXCESS AIR

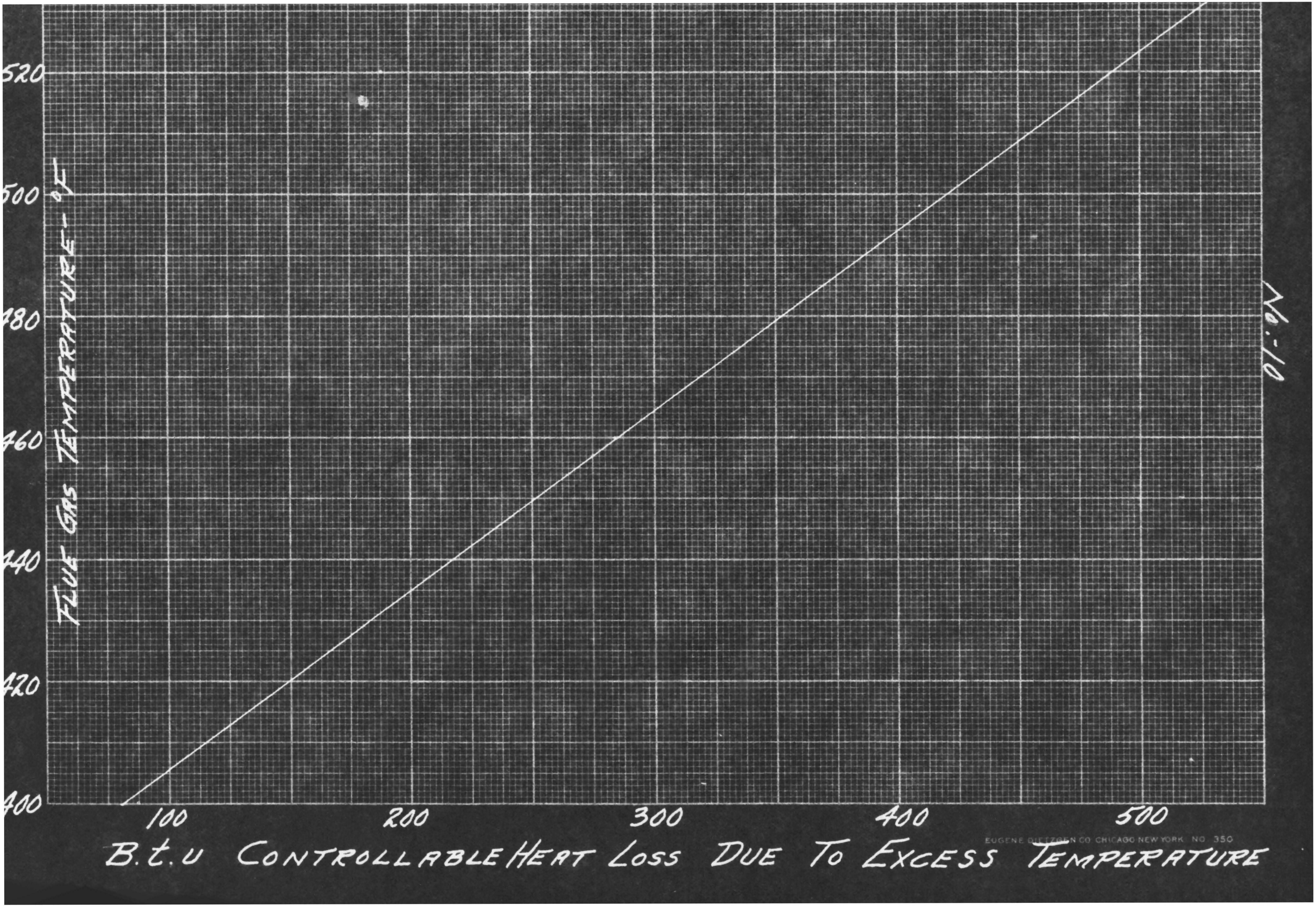
No. - 7

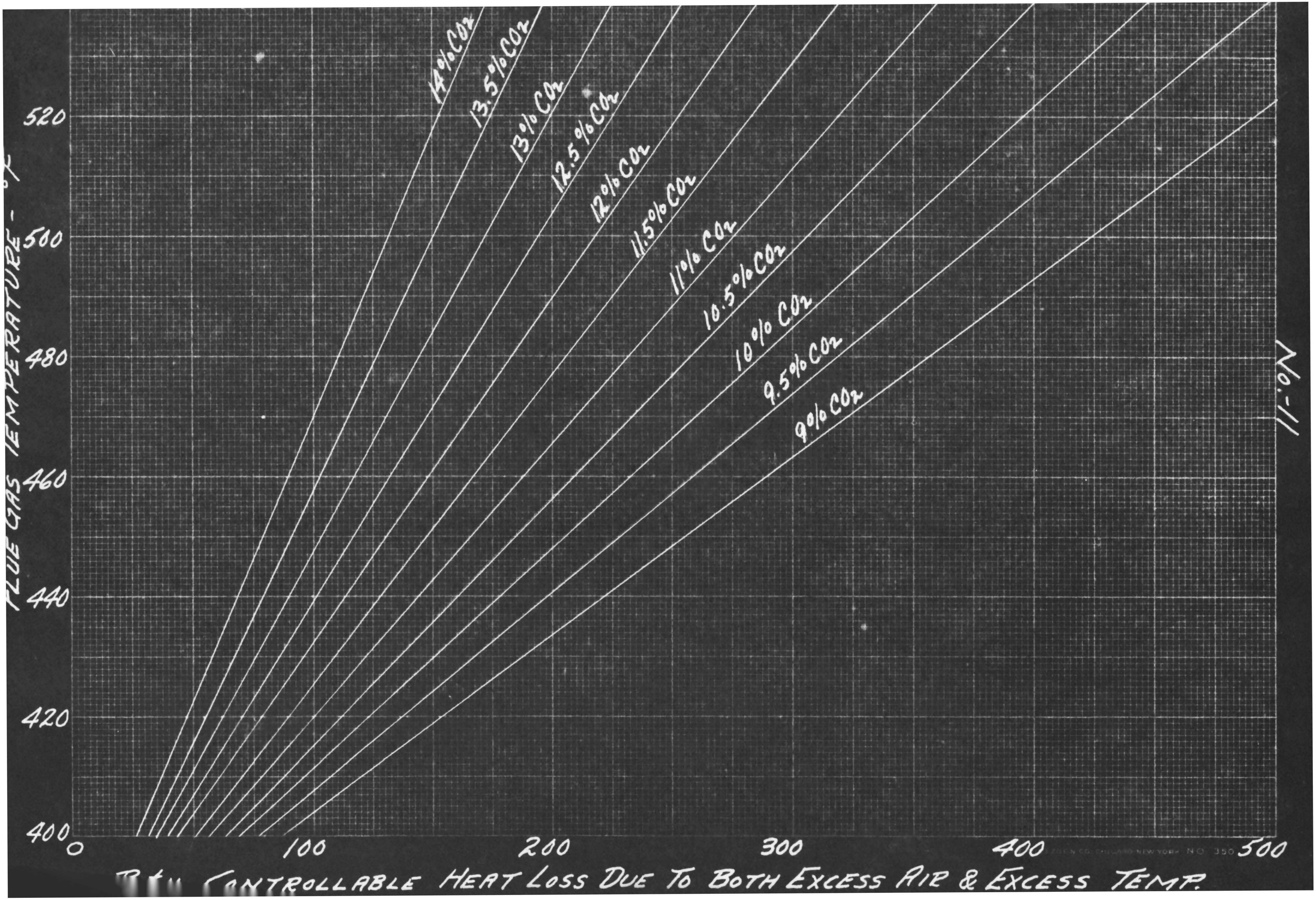


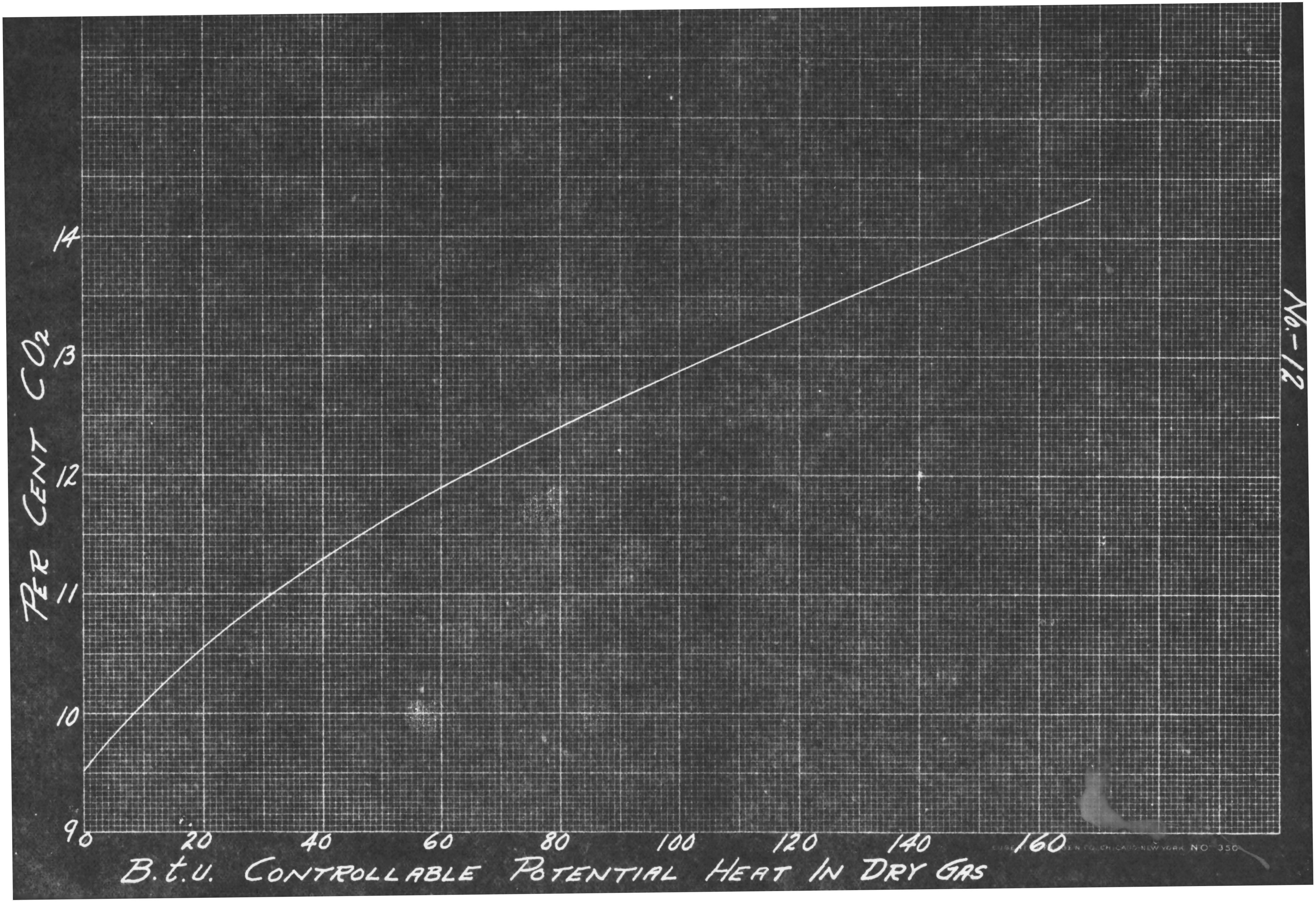
No.-8


.016
.014
.012
.010
.008
.006
.004
.002
.000
Y
Y
11
12
13
14
15
16
PER CENT CO_2

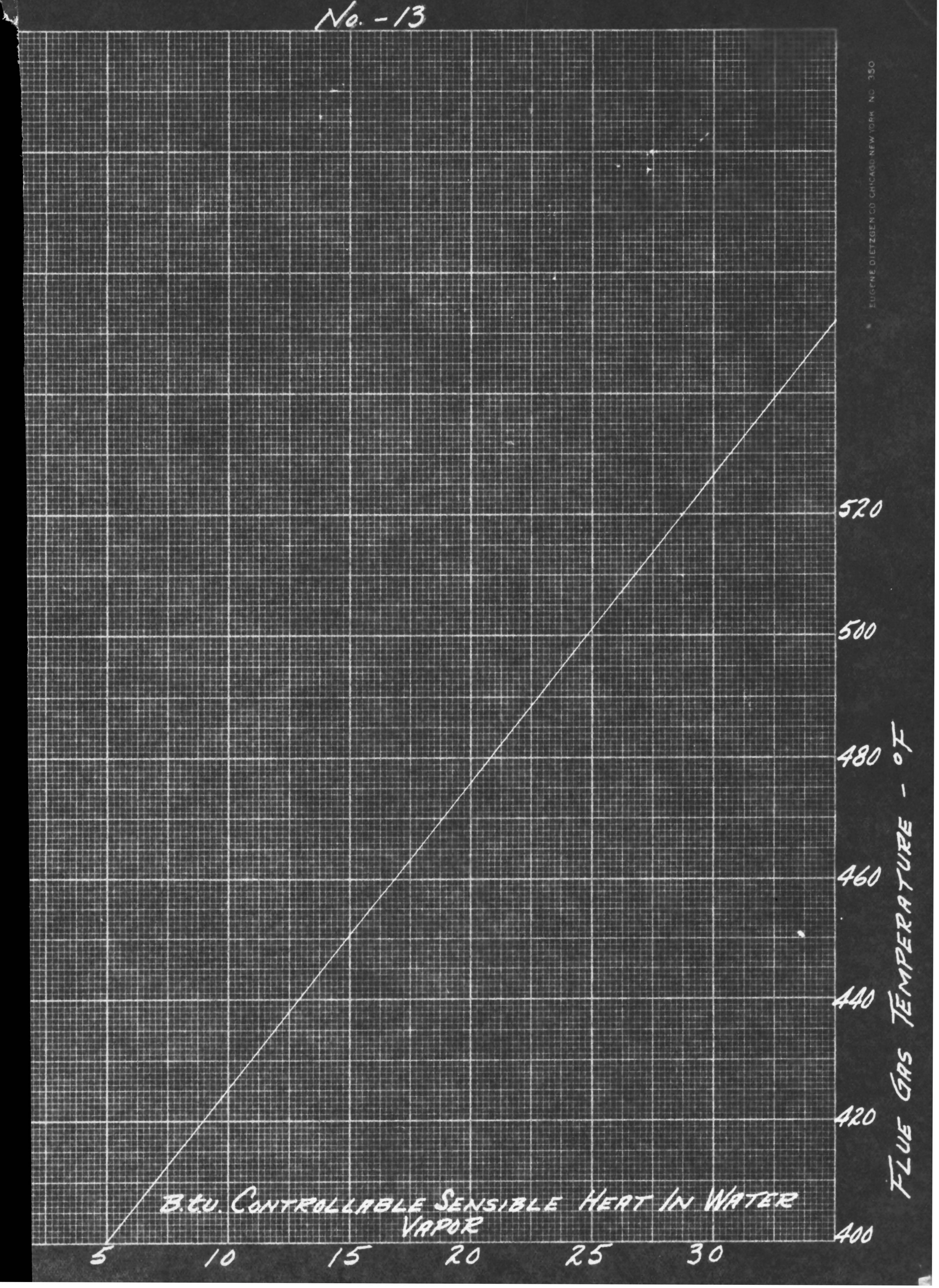

PER CENT - CO_2
14
13
12
11
10
9
300
400
500
600
700
800
900
1000
1100
1200
1300
B.t.u. OF CONTROLLABLE HEAT LOSS DUE TO EXCESS AIR
No. 9

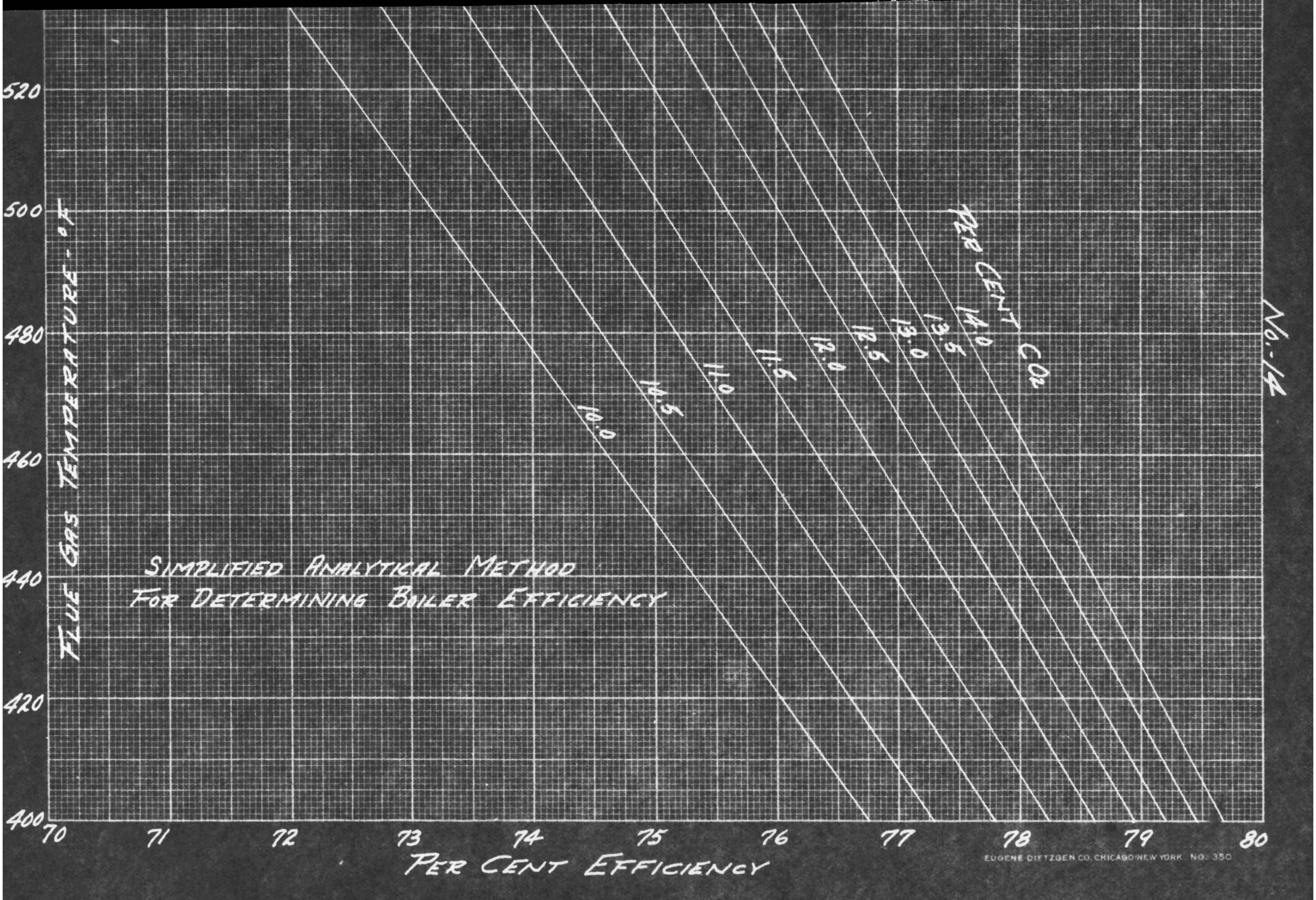

FLUE GAS TEMPERATURE - °F
520
500
480
460
440
420
400
100
200
300
400
500
EUGENE DIETZGEN CO. CHICAGO NEW YORK NO. 350
B.t.u CONTROLLABLE HEAT LOSS DUE TO EXCESS TEMPERATURE
No:10


FLUE GAS TEMPERATURE - °F
400
420
440
460
480
500
520
0
100
200
300
400
500
BTU CONTROLLABLE HEAT LOSS DUE TO BOTH EXCESS AIR & EXCESS TEMP.
14% CO2
13.5% CO2
13% CO2
12.5% CO2
12% CO2
11.5% CO2
11% CO2
10.5% CO2
10% CO2
9.5% CO2
9% CO2
No.-11

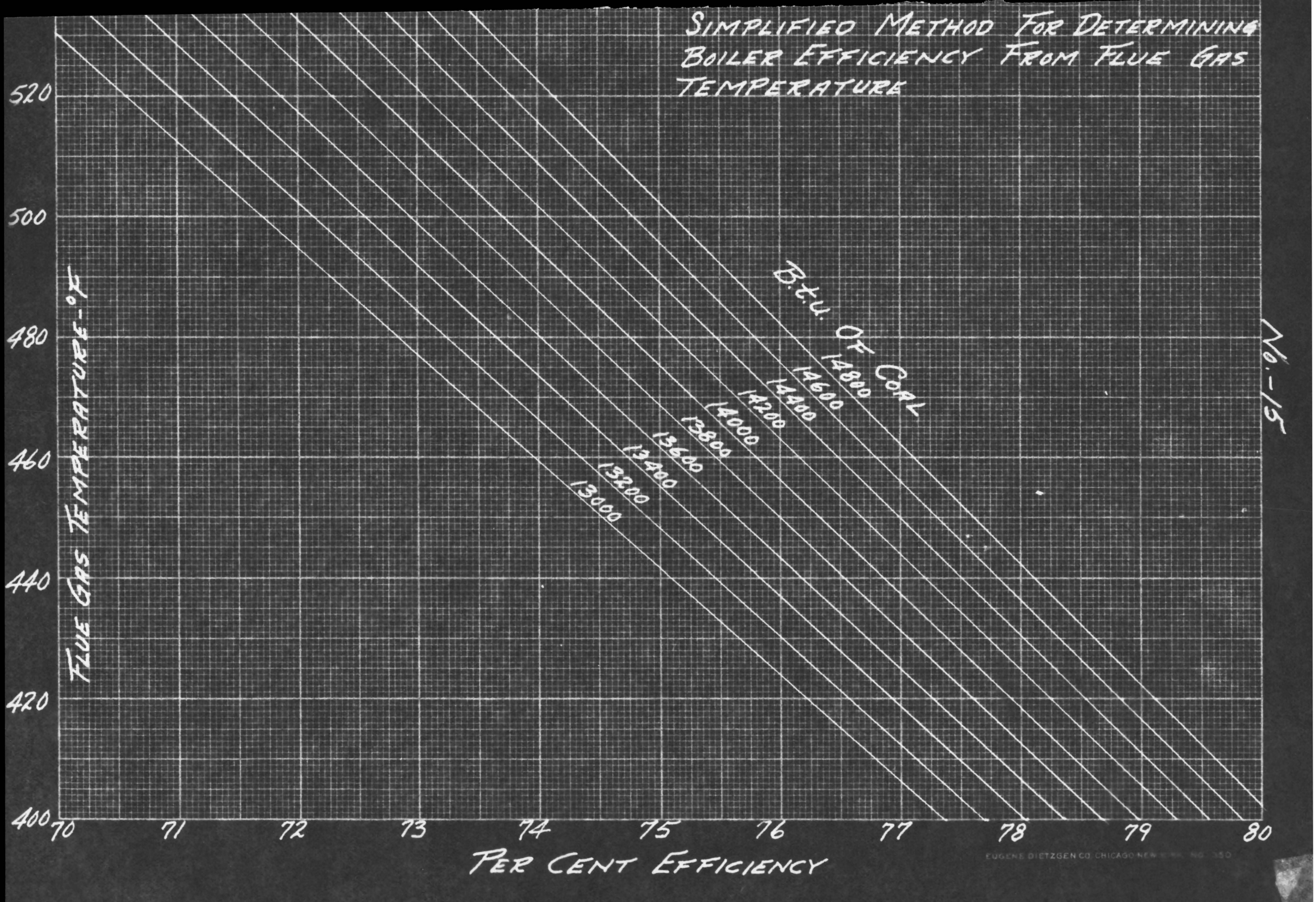


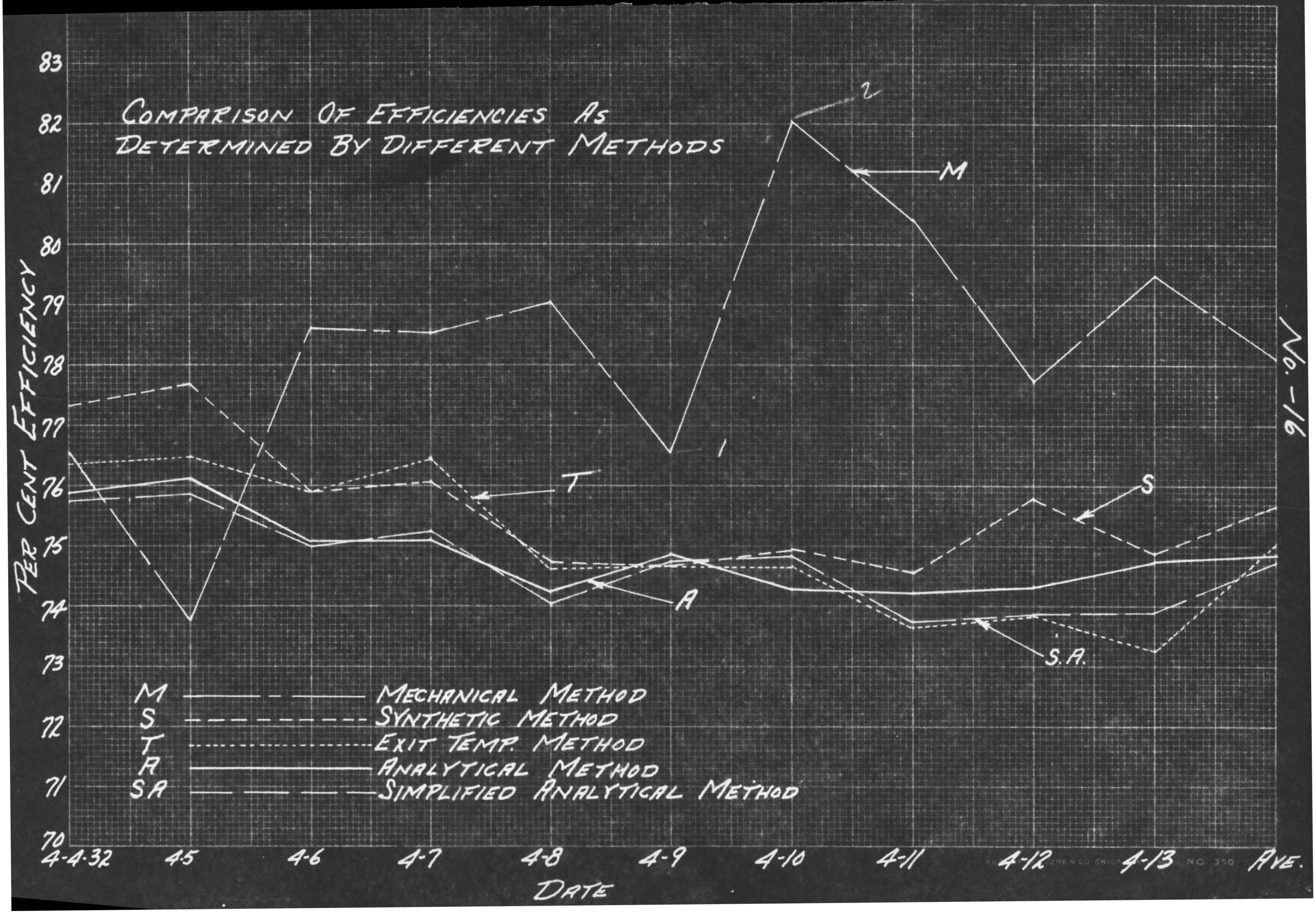
PER CENT CO_2
14
13
12
11
10
9
0
20
40
60
80
100
120
140
160
B.t.u. CONTROLLABLE POTENTIAL HEAT IN DRY GAS
No-12


No. -13
B.t.u. CONTROLLABLE SENSIBLE HEAT IN WATER VAPOR
5
10
15
20
25
30
FLUE GAS TEMPERATURE - °F
400
420
440
460
480
500
520
EUGENE DIETZGEN CO. CHICAGO-NEW YORK NO. 350

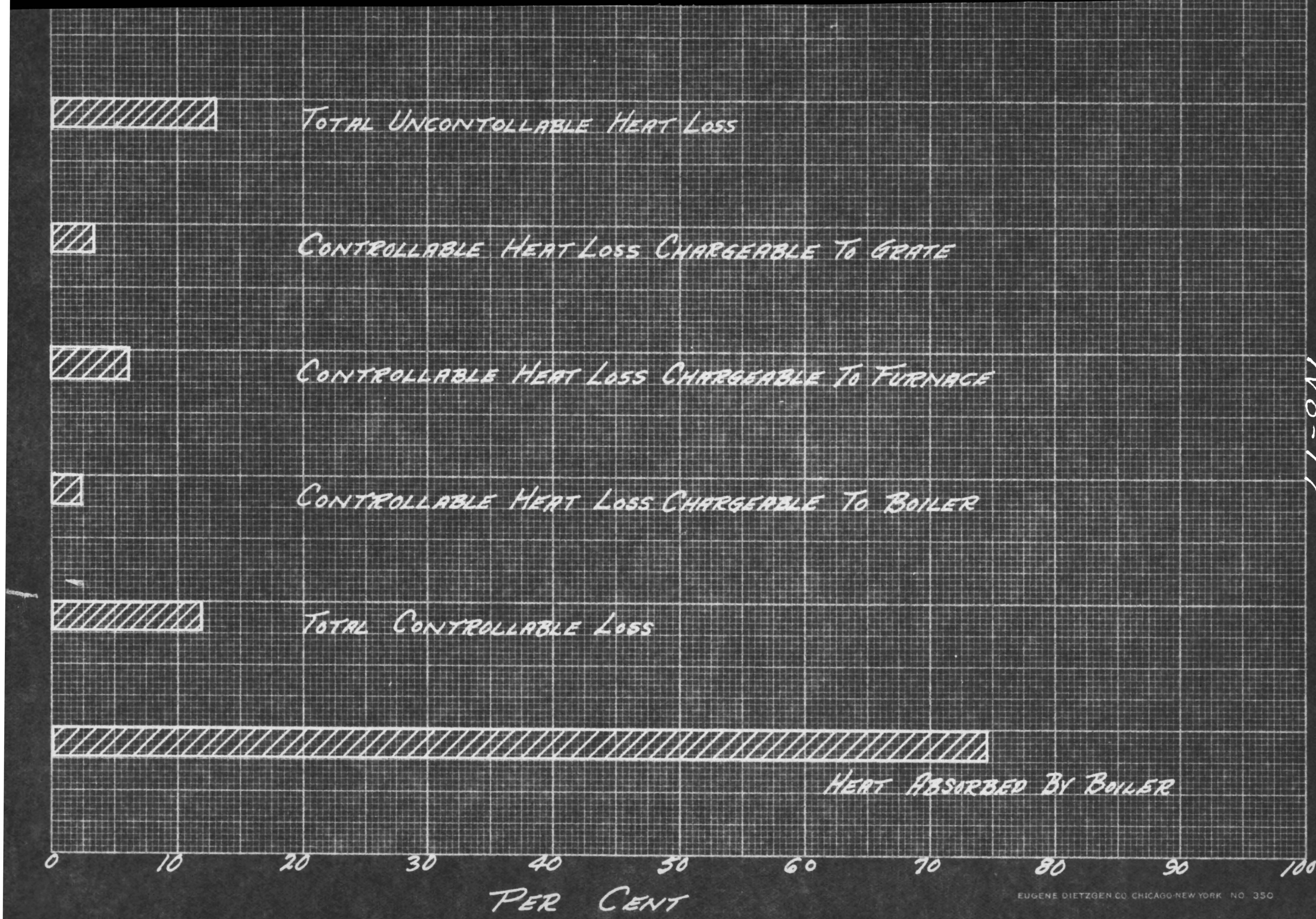


No.-14
SIMPLIFIED ANALYTICAL METHOD
FOR DETERMINING BOILER EFFICIENCY
FLUE GAS TEMPERATURE - °F
PER CENT EFFICIENCY
PER CENT CO2
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
400
420
440
460
480
500
520
70
71
72
73
74
75
76
77
78
79
80
EUGENE DIETZGEN CO. CHICAGO-NEW YORK NO. 350


SIMPLIFIED METHOD FOR DETERMINING BOILER EFFICIENCY FROM FLUE GAS TEMPERATURE
FLUE GAS TEMPERATURE - °F
520
500
480
460
440
420
400
B.t.u. OF COAL
14800
14600
14400
14200
14000
13800
13600
13400
13200
13000
70
71
72
73
74
75
76
77
78
79
80
PER CENT EFFICIENCY
No.-15



Comparison Of Efficiencies As
Determined By Different Methods
Per Cent Efficiency
83
82
81
80
79
78
77
76
75
74
73
72
71
70
4-4-32
4-5
4-6
4-7
4-8
4-9
4-10
4-11
4-12
4-13
Ave.
Date
M
T
S
A
S.A.
M — Mechanical Method
S — Synthetic Method
T — Exit Temp. Method
A — Analytical Method
SA — Simplified Analytical Method
No. -16


TOTAL UNCONTOLLABLE HEAT LOSS
CONTROLLABLE HEAT LOSS CHARGEABLE TO GRATE
CONTROLLABLE HEAT LOSS CHARGEABLE TO FURNACE
CONTROLLABLE HEAT LOSS CHARGEABLE TO BOILER
TOTAL CONTROLLABLE LOSS
HEAT ABSORBED BY BOILER
0
10
20
30
40
50
60
70
80
90
100
PER CENT
EUGENE DIETZGEN CO. CHICAGO-NEW YORK NO. 350

No-17