UNIVERSITY OF IOWA STUDIES IN ENGINEERING

BULLETIN 8

RADIATION INTENSITIES AND HEAT-TRANSFER IN BOILER FURNACES

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I. INTRODUCTION

1. *Introduction.*—There have been several methods suggested for the computation of the radiant-heat exchange occurring in boiler furnaces. Of these, probably the best known are the Hudson-Orrok formula and the Wohlenberg Method.

The purposes of this investigation were: *First,* to secure experimental data on the radiation intensities in boiler furnaces under varying conditions for comparison with results as computed by the above methods; *second,* to measure the radiation absorbed on a steel surface exposed in a boiler furnace; and *third,* to express the relations for radiation intensities and absorptions in the form of practical equations.

In order to obtain the experimental data, a quartz-window calorimeter was used to measure the radiation intensities at various openings in a boiler furnace during a series of boiler tests conducted in co-operation with the "Committee on Utilization of Iowa Coals" of the University of Iowa.

The heat absorption by a steel surface was determined in the same boiler by using a steel-plate calorimeter or probe, similar to the quartz-window calorimeter.

II. DESCRIPTION AND CALIBRATION OF CALORIMETER

2. *Description of the Quartz-window Calorimeter.*—The principle of operation of the radiation calorimeter developed for this investigation is to absorb in a stream of water, the radiant energy passing through a fused-quartz window. The energy absorbed by the water is indicated by the increase in the temperature of a measured quantity of flow.

The calorimeter is shown in Fig. 1*. The pyralin-walled, water chamber, A, is surrounded by an air chamber, except at the front end, which is closed by means of the fused-quartz window W, held in place by an aluminum tube T against a bakelite partition D. This partition in addition to being the support for the inner assembly, consisting of the absorption chamber and its surrounding air chamber (shown in detail in Fig. 1-A), is also the boundary

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* All cuts used in this bulletin were furnished by the American Society of Mechanical Engineers.

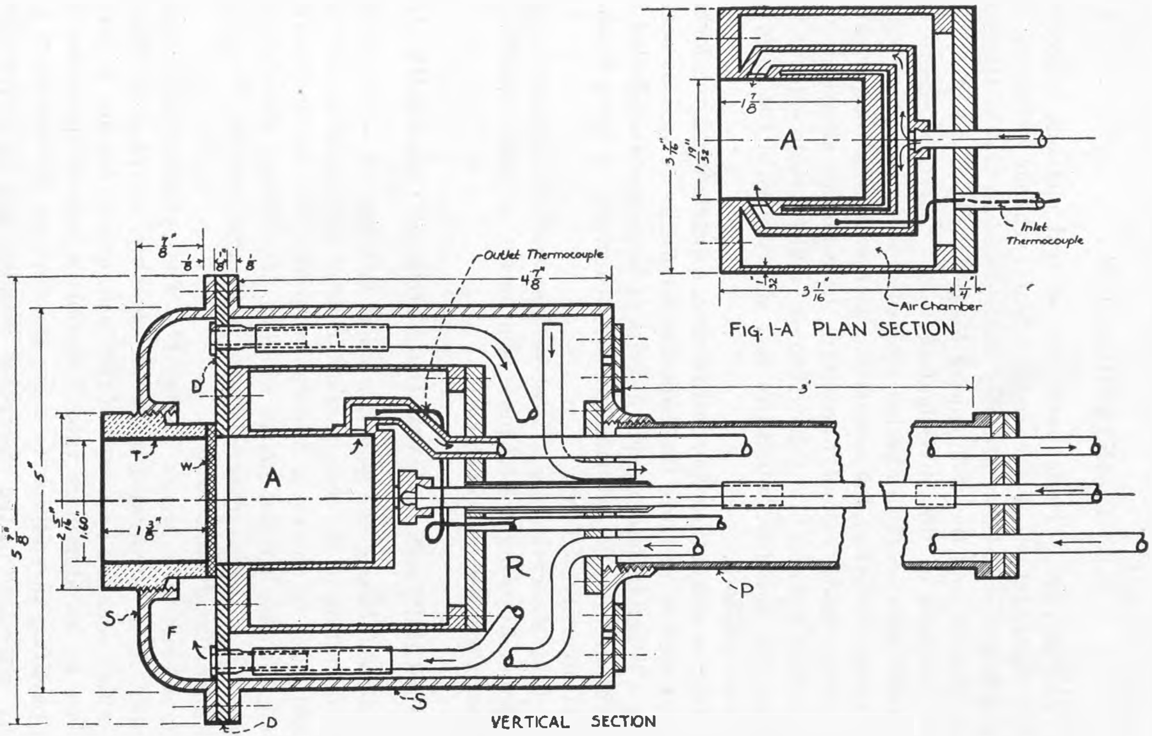

FIG. 1-A PLAN SECTION

VERTICAL SECTION

FIG. 1. DETAILS OF THE QUARTZ-WINDOW RADIATION CALORIMETER

between the front cooling chamber F and the rear cooling chamber R. Into the rear of the outer copper shell S, is screwed an iron water-cooled pipe P, through which are led the water tubes to the absorption and cooling chambers, A, F, and R, together with the thermocouple leads.

The thermocouples for the main chamber are made of No. 22 copper and constantan wires with the junctions formed by soldering the two wires together. These couples are insulated with a thin layer of pyralin and sealed into the inlet and outlet pyralin water tubes of the absorption-chamber A. These couples were calibrated in air, and in flowing water before installation, and the calibration was checked after assembly in the tubes.

The thermocouple leads, insulated with silk and two coats of varnish, are carried out through a glass tube to the rear of the supporting pipe, P.

3. *Operation of the Calorimeter.*—In operation, the three chambers, A, F, and R were supplied with water from a constant level tank. The flow through the absorption chamber was regulated to about 30 to 35 lb. per hr., which should give turbulent flow about the outlet thermocouple.

The electromotive forces of the couples were determined against a third copper-constantan junction placed in a thermos jar of ice water, by means of a Leeds and Northrup precision potentiometer; the electromotive forces were determined for both the inlet and the

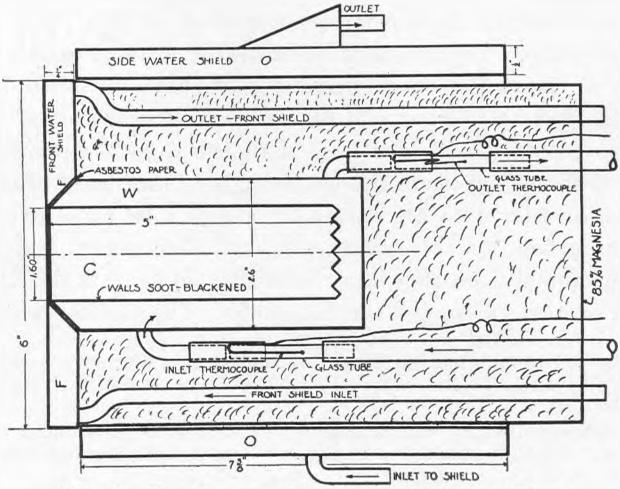

FIG. 2. DETAILS OF THE BLACK-BODY ABSORBER

outlet thermocouple about 15 separate times in the course of observations of approximately six minutes duration, readings being made to 0.005 millivolt, corresponding to a temperature interval of 0.2 F.

The water discharged from the absorption chamber was collected in a calibrated glass flask, the time of collection being noted with a stopwatch. The probable error in the water-rate determinations is less than one-half of 1 per cent.

4. *Calibration of the Calorimeter.*—The calibration of the calorimeter consisted in comparing the radiation received by the calorimeter from an electrically heated carbofrax plate, with that received by a special ''black-body'' absorber in the same location.

The black-body absorber was similar to those which have been used by H. C. Hottel and J. D. Keller[1], and by T. Schmidt[2]. It consists of a cylindrical cavity C, Fig. 2, with blackened walls which are surrounded by water chamber W. Pyralin-insulated, copper-constantan thermocouples are sealed in the inlet and outlet tubes of the water chamber. The outer walls of the water chamber W, are thermally insulated with 85 per cent magnesia. Water-cooled shields F, and O, protect the absorption chamber from radiation at the front and sides, and define the opening of C, which is of the same size as the opening of the quartz-window calorimeter.

The calibration arrangements are shown in Figs. 3 and 4. In Fig. 3, the absorption of the black-body was determined for a series of different temperatures of the heated plate, as indicated by the chromel-alumel thermocouple imbedded in the front surface of the hot-plate. Then in another series of tests (Fig. 4), the absorption of the radiation calorimeter with the quartz-window was determined for the corresponding hot-plate temperatures. A special water-cooled shield was used with the quartz-window instrument in order to duplicate the shape of the black-body absorber.

The calibration data are shown in Fig. 5. In these graphs the energy absorbed by the quartz-window calorimeter, and by the special black-body absorber, have been plotted against the radiation intensity at the surface of the hot plate. The radiation intensity

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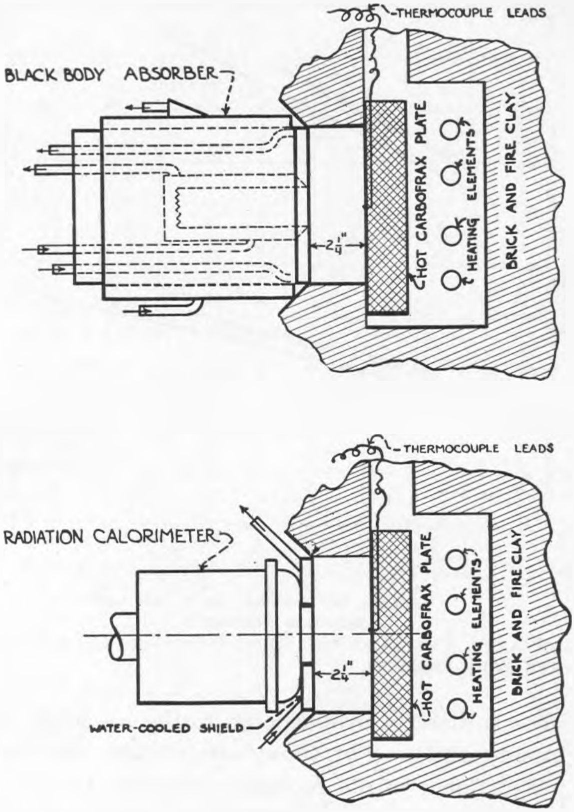
[1] ''Effects of Reradiation on Heat Transmission in Furnaces and Through Openings,'' by H. C. Hottel and J. D. Keller, Trans. A.S.M.E., vol. 55, 1933, paper IS-55-6-39.

[2] ''Die Warmestrahlung von Wasser und Eis, von bereiften und benetzten Oberflachen,'' by E. Schmidt, Forschung auf dem Gebiete des Ingenieurwesens, vol. 5, 1934, p. 1.



FIGS. 3 AND 4. VERTICAL SECTIONS THROUGH CALIBRATION ARRANGEMENTS

has been computed by means of the Stefan-Boltzmann law, which may be expressed as

$$I = 0.172 \times 0.92 \left[(T_f/100)^4 - (T_c/100)^4 \right] \qquad (1)$$

in which I is the radiation intensity in Btu per sq. ft. per hr.; 0.172 is the radiation constant; 0.92 is the emissivity of the hot plate as determined experimentally in an earlier investigation[3]; T_f is the absolute temperature of the surface of the hot plate as measured by the chromel-alumel thermocouple; and T_c is the absolute temperature of the receiver.

It will be noted in Fig. 5 that the energy absorbed by the black-

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[3] "The Construction and Calibration of an Instrument for the Measurement of Radiant Energy in Boiler Furnaces," by L. P. Meade, Thesis, State University of Iowa, 1934.

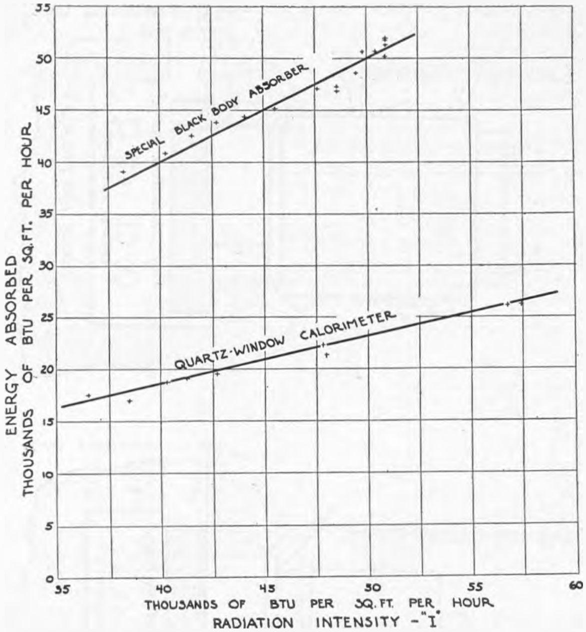

FIG. 5. CALIBRATION CURVES OF THE QUARTZ-WINDOW CALORIMETER AND THE BLACK-BODY ABSORBER

body absorber is directly proportional to the radiation intensity I. Also, the energy absorbed by the quartz-window instrument is apparently proportional to the radiation intensity I.

The ratio between the energy absorbed by the quartz-window instrument and the energy which would be absorbed by the special black-body absorber is 0.464 from Fig. 5. The calibration equation for the quartz-window instrument is

$$I = M/0.464 = 2.155M \qquad (2)$$

in which I is the radiation intensity in Btu per sq. ft. per hr.; and M is the measured energy-absorption rate of the calorimeter in Btu per sq. ft. per hr. The radiation intensity, I, which has been studied in this investigation, is the rate of radiant-energy absorption in Btu per sq. ft. per hr., which would be experienced by a perfectly black surface at 90 F.

It was the object of the calibration tests to have the two arrangements of Figs. 3 and 4 such that it would not be necessary to determine the exact temperature of the front surface of the hot plate, but to use the temperature as indicated by the chromel-alumel thermocouple as a guide to show when the true surface temperatures were identical in the two separate arrangements.

Then, for a given hot-plate temperature, the energy absorbed by the quartz-window calorimeter could be compared directly with that received by a black-body absorber of similar size for the same radiation intensity. Thus the calibration does not depend upon the accurate determination of the temperature at the exact boundary of the hot-plate, nor upon geometrical "form factors." It depends, rather, almost wholly upon how nearly the so-called black-body absorber approximates a true black-body (which absorbs all incident radiation, reflecting none).

It has been assumed in the foregoing discussion, that the emissivity of the black-body absorber (Fig. 2) is 1.00, i.e., that the absorber is a true black-body. Actually, the emissivity might be slightly less than unity. The emissivity of the inner, acetylene-soot-covered surfaces is about 0.945[4]. But the net emissivity of the cavity is considerably greater than the individual emissivities of the surfaces which form its walls, because the absorbing surfaces form an inclosure, and since the amount of incident radiation which is not completely absorbed at the blackened surface which it strikes inside the cavity will be more likely to be absorbed at another part of the blackened surface than to escape through the front opening. It is reasonable to suppose that the resultant emissivity is about 0.98.

If it were assumed that the emissivity of the special absorber is 0.98, the calibration equation for the quartz-window instrument would be changed by 2 per cent. Since the resulting correction for emissivity is only 2 per cent or less, it will not be used at this time.

III. USE OF CALORIMETER IN BOILER TESTS

5. *Description of Boiler and Furnace.*—The tests herein described were conducted on a steam-generation unit equipped with an underfeed stoker, located in the heating plant of the State University of Iowa. The unit tested (Fig. 6) has a 6000 sq.-ft., straight tube boiler, equipped with an extended-tube superheater. The rear water wall, consisting of twenty-one 3¼-in. bare tubes, spaced 6 in. on centers, provides 91 sq. ft. of cold surface. The side walls, with four 3¼-in. bare slag-drip tubes, and five 3¼-in. armored side wall

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[4] "Surface Heat Transmission," by R. H. Heilman, Trans. A.S.M.E., vol. 51, 1929, p. 289, paper FSP-51-41.

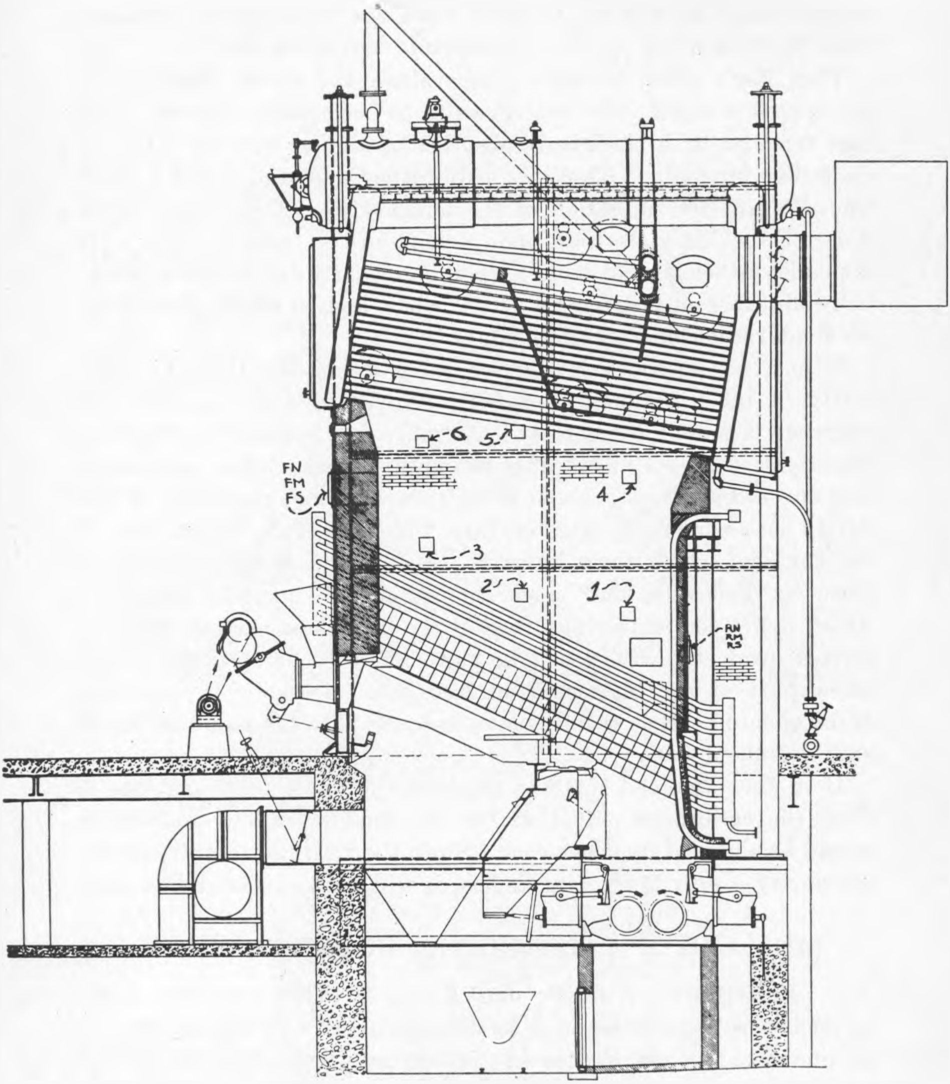

Fig. 6. Cross-Section of Boiler, Stoker, and Setting, Showing the Location of the Observation Doors

tubes on each side, have a total of 95 sq. ft. of cold surface; the top of the furnace has 150 sq. ft. of cold surface. All the surfaces have been computed as projected areas. The total cold surface in the furnace is 336 sq. ft. The total wall area of the furnace is 835 sq. ft., so the "fraction cold" of the furnace is 336/835, or 0.402.

6. *Radiation Observations.*—Radiation observations were made through ten special observation doors, during a series of 8-hr. boiler tests. The locations of these doors are shown in Figs. 6 and 11.

During an observation, the radiation calorimeter was placed in the observation door as shown in Fig. 7. The water rate in the absorption chamber of the calorimeter was determined by noting the time required to fill a calibrated glass flask B (Fig. 7) to a mark on its narrow neck, while the electromotive forces of the inlet and outlet thermocouples were determined continuously by means of the potentiometer shown. During a single observation, lasting about six minutes, about 15 sets of temperature determinations were made, of which the average values were used in determining the temperature increase of the water.

The actual radiation intensities as measured and corrected by Equation (2), are shown in Table 1. The average value of the radiation intensity for each boiler test, shown in Table 1, is the arithmetic average of all the observations made in all the doors. For this paper, no attempt has been made to determine a weighted

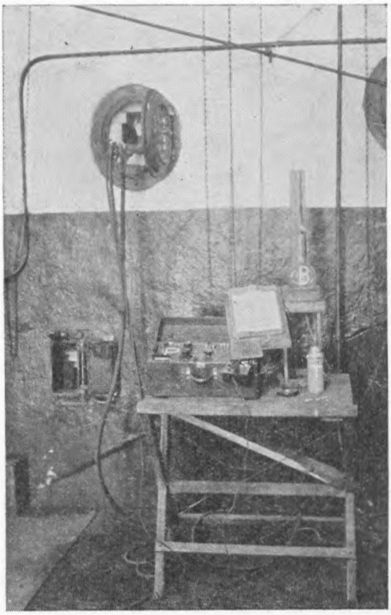

FIG. 7. VIEW OF RADIATION CALORIMETER IN DOOR NO. 1, WITH ACCESSORY EQUIPMENT

TABLE 1 ACTUAL RADIATION INTENSITIES,[a] *I*[b]

Door No.[c] Test No.	1	2	3	4	6	RS	RM	RN	FM	FN	Average
53	30.5	49.6	34.0	28.5	----	----	----	----	----	----	36.1
	34.8	----	----	----	----	----	----	----	----	----	
54	36.9	49.9	46.9	30.6	----	----	----	----	----	----	41.0
	37.1	55.2	----	41.2	----	----	----	----	----	----	
	19.5	----	----	----	----	----	----	----	----	----	
	18.5	----	----	----	----	----	----	----	----	----	
55	36.6	49.2	50.0	44.4	----	41.4	42.5	51.9	----	----	44.1
						----	46.8	33.2	----	----	
*S*2	33.8	45.8	48.8	23.3	----	34.0	38.8	37.2	27.4	----	37.1
						----	41.2	----	----	----	
						----	50.6	----	----	----	
*S*3	41.6	70.1	52.1	43.6	50.1	40.0	57.5	47.5	70.5	----	49.5
						----	60.0	33.2	----	----	
						----	----	30.4	----	----	
56	57.8	79.0	65.9	62.4	----	35.7	48.1	32.6	75.9	----	62.0
	58.9	78.3	----	----	----	51.6	62.6	----	76.0	----	
						----	66.0	----	77.5	----	
57	33.5	89.0	76.1	49.3	----	51.5	65.9	47.5	74.0	----	64.9
	72.0	88.0	77.6	63.5	----	----	----	----	70.1	----	
	48.0	----	----	----	----						
58	48.4	77.6	84.6	55.2	----	69.7	78.1	57.8	81.0	67.8	64.9
						52.2	72.6	43.0	56.5	79.0	
59	86.9	62.5	72.9	88.8	----	71.6	70.1	80.6	----	----	75.6
						70.5	97.0	68.9	----	----	
60	52.0	75.0	60.6	40.2	----	76.0	53.0	64.0	65.4	67.6	65.9
	69.7	79.7	76.2	66.4	----	61.7	73.3	61.0	72.8	72.7	
*S*5	87.6	107.0	77.6	71.5	----	40.6	60.0	43.6	----	----	62.6
						----	61.1	67.5	----	----	
						----	60.4	----	----	----	
*S*6	57.7	79.1	65.9	52.4	----	54.3	51.6	40.3	80.3	47.3	63.4
	----	86.1	84.5	33.7	----	46.5	55.5	39.3	48.1	80.3	
	----	83.3	----	----	----	----	----	----	97.0	83.0	
*S*7	67.0	105.3	71.2	72.0	----	62.1	89.1	83.1	----	----	81.9
	----	103.5	76.0	----	----	88.4	90.2	75.4	----	----	
69	46.5	77.8	79.6	58.3	----	52.1	62.8	49.4	----	----	61.2
	41.4	75.9	90.7	59.1	----	54.6	59.1	44.6	----	----	
						57.7	63.3	53.5	----	----	
70	76.6	89.4	81.8	79.7	----	63.1	84.4	73.2	----	----	65.2
	49.4	86.0	72.1	58.8	----	57.1	62.5	71.0	----	----	
						48.9	----	52.2	----	----	
						----	----	32.1	----	----	
*S*8	66.0	80.6	77.3	70.5	----	51.3	56.0	44.1	----	----	68.9
	73.0	65.4	79.4	78.9	----	52.9	54.1	38.2	----	----	
						----	64.9	----	----	----	
*S*9	23.9	64.3	48.1	31.2	----	38.5	49.6	55.8	----	----	45.5
	31.2	55.2	59.3	38.8	----	46.6	51.0	35.6	----	----	
	25.8	55.8	64.2	42.7	----	37.6	47.2	----	----	----	
*S*10	29.3	78.6	60.4	45.3	----	52.1	56.5	43.1	----	----	51.0
	29.3	62.6	74.0	63.9	----	44.5	53.0	44.2	----	----	
	40.8	50.9	----	54.9	----	44.1	47.6	46.2	----	----	
*S*11	16.4	42.0	38.6	19.3	----	36.3	50.1	38.9	----	----	34.6
	27.0	39.0	36.6	29.0	----	32.1	31.8	30.4	----	----	
	20.5	53.2	47.1	23.6	----	36.2	49.2	28.1	----	----	
*S*12	24.3	41.0	48.1	21.9	30.9	43.4	42.9	35.2	----	----	40.3
	24.0	55.7	50.6	26.5	35.8	44.4	50.6	44.9	----	----	
	21.9	58.6	49.2	26.2	32.0	38.4	64.4	59.8	----	----	
*S*13	36.6	53.6	37.7	45.5	33.7	31.5	50.6	37.4	----	----	42.7
	40.5	59.0	43.1	39.1	31.3	39.4	52.7	33.6	----	----	
						34.3	54.3	47.5	----	----	
*S*17	20.8	39.4	39.4	29.0	29.9	30.4	38.6	22.5	37.8	25.0	32.3
	19.4	43.9	51.5	23.9	23.4	20.2	41.7	----	42.8	34.4	
*S*18	25.3	51.1	56.6	24.1	34.3	28.9	39.4	23.9	42.3	35.4	35.8
	30.7	43.1	39.1	24.1	31.2	32.1	41.3	33.2	43.1	37.6	
71	24.5	38.6	34.1	25.4	20.9	25.0	28.1	26.1	30.3	24.2	27.9
	24.8	33.3	24.0	19.7	17.9	38.3	32.6	24.7	34.6	30.7	
72	27.3	48.0	31.3	26.8	22.6	22.6	29.5	26.2	32.7	28.7	34.1
	29.6	86.8	40.3	40.5	31.0	25.3	41.6	25.6	34.3	32.3	
78	27.6	42.4	29.9	34.3	21.9	27.3	40.5	26.5	31.0	34.2	35.4
	37.6	63.2	32.6	30.8	31.6	31.6	41.9	28.2	45.2	37.2	
						----	----	----	56.5	----	
79	30.2	45.6	33.5	40.8	22.3	46.0	54.4	39.1	46.2	39.4	38.2
	19.9	57.4	35.7	24.5	29.3	33.4	45.3	37.0	44.4	34.1	
80	12.6	54.0	30.6	20.1	41.9	49.2	61.5	46.4	61.1	24.2	44.2
	44.5	67.0	44.8	43.8	45.1	57.1	53.2	43.4	44.4	34.1	

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[a] All intensities expressed in thousands of Btu per sq ft per hr.

[b] $I = 2.155\ M$, see Equation [2].

[c] For location of various doors see Figs. 6 and 11.

TABLE 2 VARIOUS FACTORS USED IN COMPUTING RADIATION BY THE HUDSON-ORROK FORMULA

Test No.	A	C_r	μ	U	X_h
53	8.83	16.88	0.427	9209	67100
54	9.32	13.05	0.447	9639	56300
55	8.65	12.83	0.466	9383	56100
S2	10.24	11.69	0.430	10185	51200
S3	10.22	15.61	0.400	9209	57500
56	8.85	12.32	0.474	8375	49000
57	8.42	14.45	0.456	8475	55900
58	9.51	16.80	0.409	8874	61000
59	8.35	17.36	0.437	8790	66600
60	9.06	13.33	0.449	8514	51000
S5	8.92	14.62	0.416	9888	60100
S6	10.45	10.59	0.443	10385	48700
S7	9.50	13.90	0.433	9894	59600
S8	9.70	14.38	0.424	9821	59900
S9	9.77	12.35	0.430	9997	53000
S10	9.49	14.75	0.426	9708	60900
S11	10.82	10.13	0.440	10408	46300
S12	10.48	12.40	0.422	10316	54000
S13	8.75	15.03	0.452	9296	63200
S17	9.94	14.88	0.443	9674	63700
S18	10.16	15.83	0.448	10203	72400
69	9.11	13.55	0.446	9965	60100
70	7.65	15.83	0.469	10572	78500
71	9.55	11.98	0.394	8704	41100
72	9.92	12.86	0.431	8772	48600
78	8.65	14.42	0.452	8995	58600
79	9.40	12.30	0.450	9539	52900
80	8.99	15.90	0.447	9364	66500

$\mu = \dfrac{1}{1 + \dfrac{A\sqrt{C_r}}{27}}$ = fraction of energy released which is transferred to the cold surfaces in the furnace by radiation.

A = lb of air per lb of fuel.

U = heat release per lb of coal.

$X_h = C_r U \left[\dfrac{1}{1 + \dfrac{A\sqrt{C_r}}{27}}\right]$ = heat transfer rate by radiation, Btu per sq ft per hr.

C_r = fuel burned, lb per hr per sq ft of water-cooled surface exposed to radiation.

average; the authors believe that the system of averaging here used is best for the purposes of this paper, because the radiation intensity was not constant at the various observation points throughout an entire test.

IV. METHODS OF COMPUTING HEAT ABSORPTION

7. *Computation of Radiation by the Hudson-Orrok Formula.*—There are shown in Table 2 the average heat-transfer rates by

radiation, as computed by means of the Hudson-Orrok formula[5]. These heat-transfer rates are plotted in Fig. 9. The quantity U in this table is the heat released in the furnace per lb. of fuel burned. U also enters into the calculation of radiation by the Wohlenberg method, and is computed in Table 3, in which it is shown as the calorific heating value of the fuel, in Btu per lb., minus the losses due to (a) incomplete combustion of carbon to carbon-dioxide, (b) combustible in the refuse, and (c) evaporation of moisture.

8. *Computation of Radiation by the Wohlenberg Method.*—In the computations of furnace heat balances by the Wohlenberg method[6, 7, 8], as shown in Table 3, some shortcuts have been taken, the most important one being in evaluating the solid angles which enter into the computations of the radiation coefficients. The "fraction cold" for the furnace used in these tests was found to be 0.402. This corresponds to the Type B cubical furnace mentioned by Wohlenberg and Lindseth, which has one wall and the top cold. It has been assumed that the furnace in question is approximately represented, in so far as our purposes are concerned, by the Type B furnace, even though its shape differs from that of a cube. Hence the values for the various solid angles have been taken for those quoted for the Type B cubical furnace.

The radiation from the carbon dioxide and water vapor present in the burning gases is a function of the temperature, and of the product of the percentage concentration and the thickness of the radiating gas; this product may be expressed as $c = ps/328$, where p is the percentage by volume of the carbon dioxide or water vapor, and s is the thickness of the gas column in feet[7]. For a given temperature, the radiation from these gases increases with the factor c, until $c = 0.15$. Any further increase of c above 0.15 produces no increase in the radiation intensity from the gases at constant temperature.

In all the boiler tests of this investigation, the factor c was great-

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[5] "Radiation in Boiler Furnaces," by Geo. A. Orrok, Trans. A.S.M.E., vol. 47, 1925, pp. 1148-1155.

[6] "Radiation in the Pulverized-Fuel Furnace," by W. J. Wohlenberg and D. G. Morrow, Trans. A.S.M.E., vol. 47, 1925, p. 127.

[7] "The Influence of Radiation in Coal-Fired Furnaces on Boiler Surface Requirements and a Simplified Method for Its Calculation," by W. J. Wohlenberg and E. L. Lindseth, Trans. A.S.M.E., vol. 48, 1926, p. 848.

[8] Complete details of the computations and boiler test data are given in a thesis, "Radiation in Steam Boiler Furnaces," by C. F. Schmarje, which is on file in the library of the State University of Iowa.

TABLE 3 SUMMARY OF CALCULATIONS BY THE WOHLENBERG METHOD

	BOILER TEST NO.	53			54			55			S-2			S-3		
	T_u °F	2450			2350			2375			2315			2405		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
	Product of Combustion															
	CO_2	1.993	616	1229	2.08	585	1217	2.02	593	1199	2.207	575	1270	2.263	602	1364
	O_2	0.299	531	159	0.368	499	184	0.22	506	111	0.468	468	227	0.414	515	213
	N_2+CO	7.032	577	4060	7.38	546	4030	6.87	554	3805	8.05	535	4310	8.045	562	4520
	Refuse	0.147	565	83	0.112	531	62	0.154	539	83	0.190	521	57	0.124	547	68
	H_2O	0.498	1167	581	0.501	1105	576	0.485	1120	544	0.527	1083	572	0.525	1139	598
	$\Sigma G_b a h_b \div G$	6112			6069			5742			6436			6763		
G	POUNDS OF FUEL PER HOUR	5666			4384			4309			3901			5209		
	HEATING VALUE OF FUEL – BTU/LB.	9930			10360			9960			10975			10870		
	LOSSES (FROM H) BTU/LB															
	(a) DUE TO UNCONSUMED CARBON (CO)	80			82			10			25			4		
	(b) DUE TO COMBUSTIBLE IN REFUSE	95			68			36			187			380		
	(c) DUE TO EVAPORATION OF MOISTURE	546			571			531			578			576		
L	TOTAL LOSSES BTU/LB.	721			721			577			790			960		
U	HEAT RELEASED (H−L) BTU/LB	9209			9639			9383			10185			9910		
$\Sigma G_b a h_b$	BTU/HR.	34,650,000			26,600,000			24,730,000			25,100,000			35,210,000		
Z_c	BTU/HR	685,000			576,000			589,000			564,000			664,000		
Q_R	BTU/HR	16,780,000			14,680,000			15,600,000			14,010,000			15,770,000		
	$\Sigma G_b a h_b + Z_c + Q_R$ BTU/HR	52,115,000			41,856,000			40,473,000			39,674,000			51,644,000		
G·U	HEAT RELEASED PER HOUR BTU/HR	52,130,000			41,800,000			49,500,000			39,670,000			51,600,000		
ERR	GU ÷ VOLUME = GU/2160 BTU/FT³/HR	24,100			19,320			18,720			18,350			23,800		
X_R	HEAT-TRANSFER RATE BY RADIATION: = Q_R/AREA = Q_R/336 BTU/FT²/HR	49,900			43,600			45,100			41,700			46,900		

	BOILER TEST NO.	56			57			58			59			60		
	T_u °F	2155			2343			2330			2423			2195		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
	Product of Combustion															
	CO_2	1.922	524	1010	1.916	552	1059	1.99	579	1152	1.935	607	1175	1.958	538	1053
	O_2	0.644	483	279	0.436	462	201	0.486	491	238	0.246	521	1.28	0.549	446	242
	N_2+CO	7.15	486	3478	6.86	513	3520	7.486	540	4040	6.746	567	3823	7.36	498	3665
	Refuse	0.172	474	81	0.180	500	90	0.093	525	49	0.095	552	52	0.164	486	80
	H_2O	0.711	985	700	0.646	1039	671	0.696	1093	761	0.636	1151	731	0.720	1009	726
	$\Sigma G_b a h_b \div G$	5348			5541			6240			5909			5766		
G	POUNDS OF FUEL PER HOUR	4114			4486			5650			5831			4481		
	HEATING VALUE OF FUEL – BTU/LB.	9260			9390			9847			9920			9405		
	LOSSES (FROM H) BTU/LB															
	(a) DUE TO UNCONSUMED CARBON (CO)	0			0			154			366			0		
	(b) DUE TO COMBUSTIBLE IN REFUSE	106			206			56			66			101		
	(c) DUE TO EVAPORATION OF MOISTURE	780			709			763			698			790		
L	TOTAL LOSSES BTU/LB.	886			915			973			1130			891		
U	HEAT RELEASED (H−L) BTU/LB	8374			8475			8874			8790			8514		
$\Sigma G_b a h_b$	BTU/HR.	22,850,000			24,860,000			35,250,000			34,450,000			25,840,000		
Z_c	BTU/HR	436,000			516,000			615,000			660,000			502,000		
Q_R	BTU/HR	11,130,000			12,660,000			14,280,000			16,160,000			11,800,000		
	$\Sigma G_b a h_b + Z_c + Q_R$ BTU/HR	34,416,000			38,036,000			50,145,000			51,270,000			38,140,000		
G·U	HEAT RELEASED PER HOUR BTU/HR	34,455,000			38,019,000			50,138,000			51,250,000			38,150,000		
ERR	GU ÷ VOLUME = GU/2160 BTU/FT³/HR	16,720			18,500			24,300			24,900			18,530		
X_R	HEAT-TRANSFER RATE BY RADIATION: = Q_R/AREA = Q_R/336 BTU/FT²/HR	33,100			37,700			42,700			48,100			35,100		

	BOILER TEST NO.	S-5			S6			S-7			S-8		
	T_u °F	2438			2268			2380			2365		
		A	B	C	A	B	C	A	B	C	A	B	C
	Product of Combustion												
	CO_2	2.155	612	1319	2.285	559	1280	2.190	595	1305	2.186	590	1290
	O_2	0.174	526	91	0.492	470	231	0.319	506	161	0.38	502	191
	N_2+CO	7.16	572	4100	8.27	520	4300	7.57	554	4200	7.757	550	4265
	Refuse	0.102	557	52	0.094	507	48	0.125	540	67	0.183	535	100
	H_2O	0.717	1160	831	0.655	1054	690	0.675	1123	758	0.692	1114	770
	$\Sigma G_b a h_b \div G$	6398			6544			6491			6616		
G	POUNDS OF FUEL PER HOUR	4918			3560			4674			4827		
	HEATING VALUE OF FUEL – BTU/LB.	11010			11223			10853			10710		
	LOSSES (FROM H) BTU/LB												
	(a) DUE TO UNCONSUMED CARBON (CO)	246			43			47			28		
	(b) DUE TO COMBUSTIBLE IN REFUSE	90			76			172			101		
	(c) DUE TO EVAPORATION OF MOISTURE	786			719			740			760		
L	TOTAL LOSSES BTU/LB.	1122			838			959			889		
U	HEAT RELEASED (H−L) BTU/LB	9888			10385			9894			9821		
$\Sigma G_b a h_b$	BTU/HR.	31,450,000			25,315,000			30,360,000			31,900,000		
Z_c	BTU/HR	660,000			490,000			610,000			595,000		
Q_R	BTU/HR	16,500,000			13,120,000			15,260,000			14,960,000		
	$\Sigma G_b a h_b + Z_c + Q_R$ BTU/HR	48,610,000			36,925,000			46,230,000			47,455,000		
G·U	HEAT RELEASED PER HOUR BTU/HR	48,630,000			36,930,000			46,220,000			47,406,000		
ERR	GU ÷ VOLUME = GU/2160 BTU/FT³/HR	22,450			17,200			21,460			21,900		
X_R	HEAT-TRANSFER RATE BY RADIATION: = Q_R/AREA = Q_R/336 BTU/FT²/HR	49,100			39,000			45,400			44,500		

NOTE: COL. C = (COL. B) × (COL. A) COL. "B" = HEAT CAPACITY OF PRODUCT ABOVE 80°F [FOR WATER, ABOVE 212°F] PER POUND.
COL. A = LBS. OF PRODUCT PER POUND OF FUEL.

	BOILER TEST NO.	S-9			S-10			S-11			S-12			S-13		
	T_u °F	2330			2378			2230			2325			2393		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
	Product of Combustion															
	CO_2	2.200	580	1273	2.147	595	1278	2.317	549	1272	2.300	577	1325	2.065	598	1238
	O_2	0.450	490	199	0.366	506	185	0.586	457	268	0.526	489	257	0.318	511	162
	N_2+CO	7.775	540	4200	7.575	553	4190	8.545	509	4350	8.277	537	4442	0.935	558	3870
	Refuse	0.116	525	61	0.119	539	64	0.066	496	33	0.078	523	41	0.154	544	84
	H_2O	0.628	1093	686	0.706	1123	791	0.660	1031	680	0.660	1090	719	0.675	1132	765
	$\Sigma G_b a h_b \div G$	6419			6508			6603			6784			6119		
G	POUNDS OF FUEL PER HOUR	4151			4959			3405			4165			5054		
H	HEATING VALUE OF FUEL – BTU/LB.	10890			10670			11210			11180			10250		
	LOSSES (FROM H) BTU/LB.															
	(a) DUE TO UNCONSUMED CARBON (CO)	81			62			0			9			0		
	(b) DUE TO COMBUSTIBLE IN REFUSE	123			125			78			131			214		
	(c) DUE TO EVAPORATION OF MOISTURE	688			775			724			724			740		
L	TOTAL LOSSES BTU/LB.	893			962			802			864			954		
U	HEAT RELEASED (H−L) BTU/LB.	9997			9708			10408			10316			9296		
$\Sigma G_b a h_b$	BTU/HR.	26,630,000			32,370,000			22,480,000			28,260,000			30,900,000		
Z_c	BTU/HR.	570,000			615,000			470,000			550,000			600,000		
Q_R	BTU/HR.	14,290,000			15,220,000			12,420,000			14,190,000			15,500,000		
	$\Sigma G_b a h_b + Z_c + Q_R$ BTU/HR	41,490,000			48,105,000			35,370,000			43,000,000			47,000,000		
G·U	HEAT RELEASED PER HOUR BTU/HR	41,500,000			48,100,000			35,400,000			43,000,000			47,000,000		
ERR	GU ÷ VOLUME = GU/2160 BTU/FT³/HR	19,200			22,200			16,400			19,900			21,800		
X_R	HEAT-TRANSFER RATE BY RADIATION: = Q_R/AREA = Q_R/336 BTU/FT²/HR.	42,500			45,300			37,000			42,200			46,100		

	BOILER TEST NO.	S-17			S-18			69			71			72		
	T_u °F	2360			2413			2395			2155			2170		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
	Product of Combustion															
	CO_2	2.114	588	1243	2.240	605	1356	2.045	600	1223	1.961	525	1030	1.970	562	1108
	O_2	0.426	500	213	0.460	518	239	0.420	512	215	0.688	432	297	0.736	472	348
	N_2+CO	7.88	548	4320	8.20	564	4628	7.297	559	4085	7.697	485	3738	7.986	522	4165
	Refuse	0.092	534	49	0.132	550	73	0.117	544	63	0.170	471	80	0.185	509	80
	H_2O	0.68	1111	755	0.68	1140	779	0.731	1133	827	0.68	984	669	0.68	1059	720
	$\Sigma G_b a h_b \div G$	6580			7075			6413			5824			6421		
G	POUNDS OF FUEL PER HOUR	4998			5312			4558			4032			4322		
H	HEATING VALUE OF FUEL – BTU/LB.	10700			11130			10853			9600			9580		
	LOSSES (FROM H) BTU/LB.															
	(a) DUE TO UNCONSUMED CARBON (CO)	208			0			7			0			0		
	(b) DUE TO COMBUSTIBLE IN REFUSE	73			182			75			151			63		
	(c) DUE TO EVAPORATION OF MOISTURE	745			745			801			745			745		
L	TOTAL LOSSES BTU/LB.	1026			927			883			896			808		
U	HEAT RELEASED (H−L) BTU/LB.	9674			10203			9965			8704			8772		
$\Sigma G_b a h_b$	BTU/HR.	32,900,000			37,600,000			29,240,000			23,460,000			26,150,000		
Z_c	BTU/HR.	610,000			620,000			600,000			460,000			470,000		
Q_R	BTU/HR.	14,850,000			15,950,000			15,550,000			11,250,000			11,360,000		
	$\Sigma G_b a h_b + Z_c + Q_R$ BTU/HR	48,360,000			54,170,000			45,390,000			35,045,000			37,980,000		
G·U	HEAT RELEASED PER HOUR BTU/HR	48,400,000			54,200,000			45,420,000			35,095,000			37,913,000		
ERR	GU ÷ VOLUME = GU/2160 BTU/FT³/HR	22,400			25,100			21,000			16,200			17,600		
X_R	HEAT-TRANSFER RATE BY RADIATION: = Q_R/AREA = Q_R/336 BTU/FT²/HR.	44,200			47,500			46,300			33,500			33,800		

	BOILER TEST NO.	78			79			80		
	T_u °F	2322			2280			2390		
		A	B	C	A	B	C	A	B	C
	Product of Combustion									
	CO_2	2.000	576	1152	2.135	563	1203	2.08	597	1242
	O_2	0.397	487	194	0.436	474	206	0.436	510	222
	N_2+CO	7.09	536	3800	7.628	524	4010	7.26	557	4045
	Refuse	0.13	522	68	0.121	510	62	0.115	543	61
	H_2O	0.68	1087	738	0.68	1061	722	0.68	1130	769
	$\Sigma G_b a h_b \div G$	5952			6203			6339		
G	POUNDS OF FUEL PER HOUR	4851			4132			5340		
H	HEATING VALUE OF FUEL – BTU/LB.	9840			10340			10230		
	LOSSES (FROM H) BTU/LB.									
	(a) DUE TO UNCONSUMED CARBON (CO)	36			12			19		
	(b) DUE TO COMBUSTIBLE IN REFUSE	73			44			102		
	(c) DUE TO EVAPORATION OF MOISTURE	745			745			745		
L	TOTAL LOSSES BTU/LB.	854			801			846		
U	HEAT RELEASED (H−L) BTU/LB.	8995			9539			9564		
$\Sigma G_b a h_b$	BTU/HR.	28,860,000			25,620,000			33,900,000		
Z_c	BTU/HR.	570,000			520,000			620,000		
Q_R	BTU/HR.	14,130,000			13,350,000			15,460,000		
	$\Sigma G_b a h_b + Z_c + Q_R$ BTU/HR	43,560,000			39,490,000			49,980,000		
G·U	HEAT RELEASED PER HOUR BTU/HR	43,610,000			39,420,000			50,000,000		
ERR	GU ÷ VOLUME = GU/2160 BTU/FT³/HR	20,200			18,250			23,100		
X_R	HEAT-TRANSFER RATE BY RADIATION: = Q_R/AREA = Q_R/336 BTU/FT²/HR.	42,000			39,700			46,000		

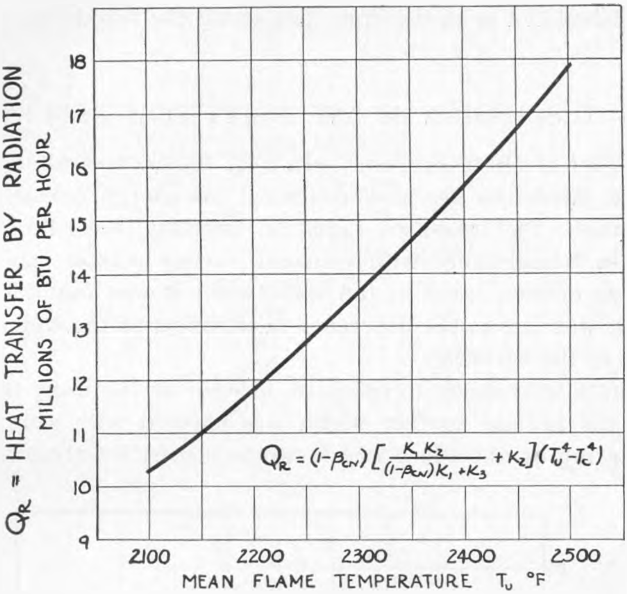

FIG. 8. HEAT TRANSFERRED BY RADIATION AS COMPUTED BY THE WOHLENBERG METHOD

er than 0.15 for both the carbon dioxide and water vapor; hence, the radiation from these gases could be plotted as a function of the temperature alone.

The radiation term in the heat balance for this furnace, then, may be plotted as a function of the ''mean flame temperature'' as shown in Fig. 8. From this graph, the total value of the radiation term may be determined for any assumed mean flame temperature.

The solution of the heat-balance equation consists of finding the mean flame temperature, T_u, for this temperature, the energy released in the furnace per hr (called GU in Table 3) is equal to the sum of the three quantities, (a) the radiation term, Q_r, (b) the heat transferred by convection to the surfaces exposed to radiation (except for that radiant surface in the aperture through which the gases leave the furnace), and (c) the sensible heat of the products of combustion leaving the furnace at the mean flame temperature (represented in Table 3 by $\Sigma G_b \Delta h_b$). It was usually possible to select the correct mean flame temperature after a choice of three or four values.

The radiation-heat-absorption rates as computed by the Wohlenberg method are shown in Fig. 8. It is interesting to compare the results calculated from the same data using the two different methods.

V. DISCUSSION OF INTENSITY-TEST RESULTS

9. *Effect of Dirty Surfaces.*—In Fig. 10, the measured average radiation intensities are plotted against the energy release rate in the furnace. The measured radiation intensity, according to Fig. 10, varies considerably with constant energy release rate. This effect was noticed early in the tests, when it was found that the variation was due to the difference in dirtiness of the water-cooled surfaces in the furnace.

Attempts were made to estimate, in each of the tests, the fraction of the radiant surface which was covered with slag or ash. The covering on the tubes was found to consist mostly of patches

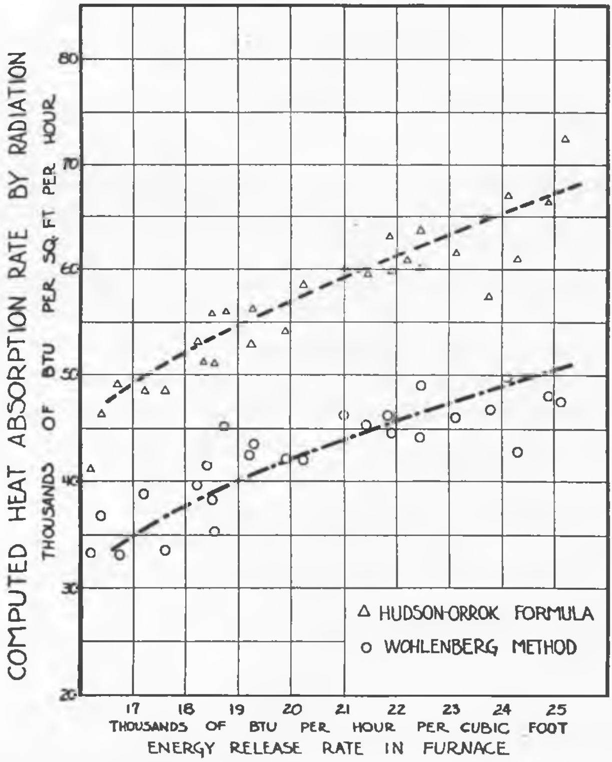

FIG. 9. RADIANT-HEAT-ABSORPTION RATES COMPUTED BY THE HUDSON-ORROK FORMULA AND THE WOHLENBERG METHOD

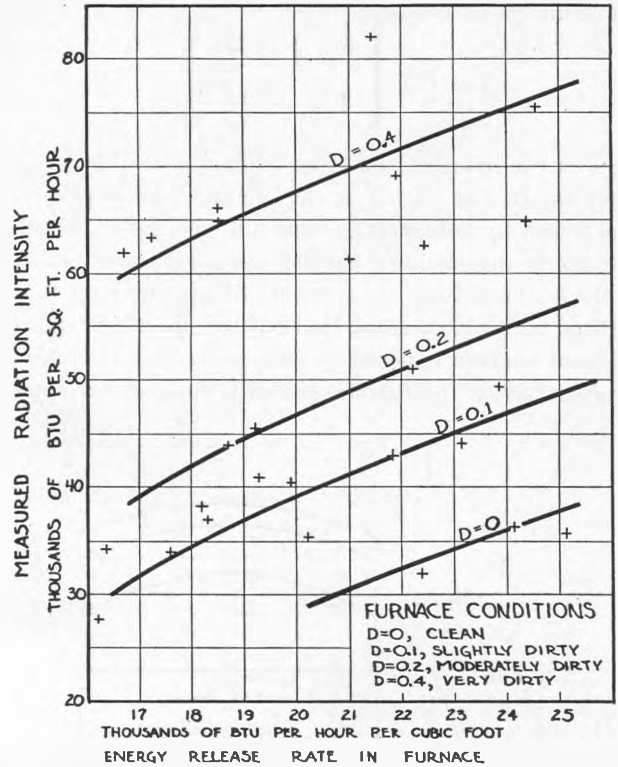

FIG. 10. RADIATION INTENSITIES, I, DETERMINED DURING THE BOILER TESTS

of powdery ash, between 1/8 in. and 1 1/8 in. in thickness. At times, after the boiler had been operated at high ratings, the slag-drip tubes of the side walls were covered with slag. In Table 4 are listed the values of the furnace dirtiness D, which is the estimated fraction of the total water-cooled surface in the furnace that is covered with slag or ash.

In Fig. 10 curves of equal dirtiness, D, have been drawn for the furnace clean ($D = 0$), slightly dirty ($D = 0.1$), moderately dirty ($D = 0.2$), and very dirty ($D = 0.4$). Since there was a similarity between the constant dirtiness curves and the Orrok curve of Fig. 9, and also an increase in intensity with D, at a given energy-release rate, a tentative formula (based upon the Hudson-Orrok formula) for calculating the average radiation intensity has been derived.

This formula[9] is as follows:

$$I = C_r U \left[\frac{0.5 + 1.7D}{1 + \frac{A\sqrt{C_r}}{27}} \right] \qquad (3)$$

in which I is the average radiation intensity at the furnace walls in Btu per sq. ft. per hr.; U is the energy release per lb. of fuel burned as found by subtracting from the heating value of the fuel the losses due to unconsumed carbon, evaporation of moisture, and combustible in the refuse; A is the lb. of air entering the furnace per lb. of fuel burned; C_r is the fuel burned, lb. per hr. per sq. ft. of projected cold surface exposed to radiation; and D is the fraction of the cold surface in the furnace which is covered with slag or ash.

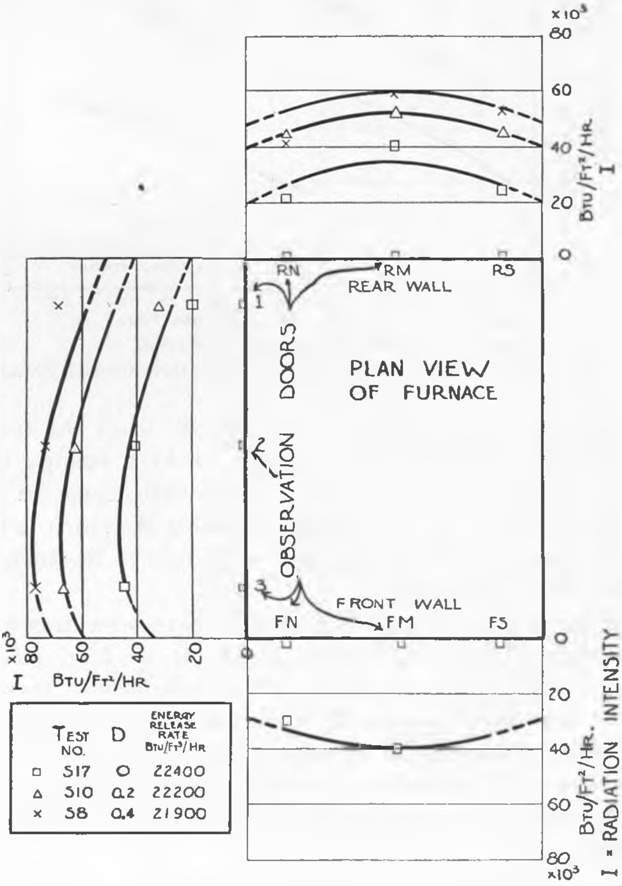

Fig. 11. Distribution of Radiation Intensities About the Boiler Furnace

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[9] See Equation (12) for the final form of this equation.

TABLE 4 DIRTINESS FACTORS, D

Test No.	*D*	*Test No.*	*D*
53	0.1	70	0.4
54	0.1	S8	0.4
55	0.1	S9	0.2
S2	0.1	S10	0.2
S3	0.1	S11	0.1
56	0.4	S12	0.1
57	0.4	S13	0.1
58	0.4	S17	0.0
59	0.4	S18	0.0
60	0.4	71	0.1
S5	0.4	72	0.1
S6	0.4	78	0.1
S7	0.4	79	0.1
69	0.4	80	0.15

It is to be noted that Equation (3), here tentatively proposed, gives "radiation intensity," as contrasted to "heat-transfer rate" by radiation. The two quantities may be very nearly equal for a clean furnace, but for a dirty furnace the average radiation intensity is probably much greater than the average heat-transfer rate by radiation.

10. *Distribution of Radiation Intensity.*—The typical distribution of radiation intensities about the furnace is shown in Fig. 11 for three different tests of approximately equal energy-release rates.

During one of these tests, the furnace was clean, having been in operation only two days following a thorough cleaning; in the other tests the fractions of the radiant surface dirty were approximately 0.2 and 0.4.

VI. DESCRIPTION OF, AND TESTS WITH, STEEL SURFACE CALORIMETER

11. *Description of Steel Surface Calorimeter.*—The calorimeter employed in these tests is shown in Fig. 12. It consists of a hollow steel block, S, through which water circulates. The outer surface of this steel block has a thick layer of black oxide which was formed when the steel was maintained at a dull red heat for about one hour. This block is surrounded on all sides except for the front surface, by a water-cooled jacket, J, which is insulated from the steel block with 85% magnesia.

Heat transfer by convection to the front surface of the steel block was minimized by a shield of cold air produced by a series of air jets. These jets provided an outward flow of cold air which prevented the hot furnace gases from making contact with the surface tested. Since air is transparent to radiation, and the air shield

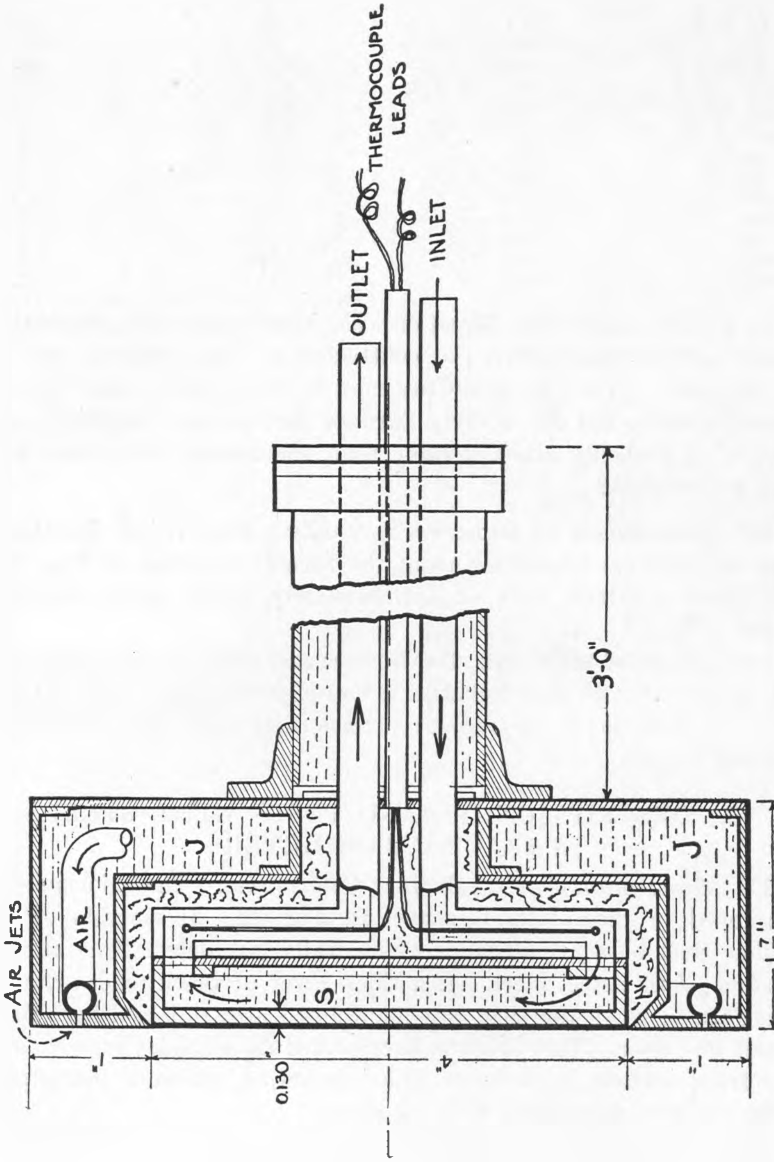

FIG. 12. THERMAL PROBE

was arranged to keep the absorbing surface free of hot gases, the heat absorbed by the steel surface was practically all transmitted by radiation.

12. *Tests in the Boiler Furnace.*—The heat transfer tests were made at observation door number 2, whose location is shown in Fig. 6. The probe was placed in the opening in the furnace wall so that its front surface was approximately in line with the inner surface of the furnace wall. Alternate readings, each about three minutes in duration, were taken through this door with the probe and with the quartz-window radiation calorimeter.

A number of sets of observations were made with the clean, oxidized, steel surface. The data for these tests are given in Tables 5 and 6. In this tabulation, X_r is the measured heat transfer

TABLE 5. TESTS WITH A CLEAN, OXIDIZED, STEEL SURFACE

Test No.	Heat Absorbed Btu/sq ft/hr. X_r	Radiation Intensity Btu/sq ft/hr. I	X_r/I
C-1	34.35	36.1	
	33.9	39.7	
	32.7		
	33.6	37.9	0.887
C-2	60.6	66.1	
	58.6	61.8	
	53.3		
	57.5	63.9	0.899
C-3	53.6	50.0	
	43.9	50.3	
	49.9	47.0	
	41.4	55.1	
	39.4	56.6	
		49.5	
	45.6	51.4	0.887
C-4	57.5	67.4	
	42.0	58.1	
	38.1	42.6	
	36.1	38.8	
		37.2	
	43.4	48.8	0.889
C-5	47.5	45.3	
	40.6	47.7	
	39.8	42.7	
	38.4	46.7	
	42.6	42.6	
	39.4	53.6	
	41.4	46.4	0.893
C-6	24.9	33.4	
	28.2	34.8	
	43.3	44.4	
	43.4	46.6	
	36.1	36.9	
	28.4	34.0	
	34.06	38.35	0.888

rate by radiation to the steel surface of the probe, and I is the radiation intensity as determined with the quartz-window calorimeter. The average value of the ratio X_r/I for the six tests is 0.89. In other words, the radiation absorption coefficient for the clean, oxidized, steel surface is 0.89.

A series of tests were also made with the steel surface partially

TABLE 6. TESTS WITH PARTIALLY DIRTY STEEL SURFACES

Test No.	D	X_r	I	X_r/I
D-1	0.9	15.65	45.6	
		16.0	46.1	
		16.1	48.9	
		15.3	46.8	
		14.3		
		15.47	46.85	0.330
D-2	0.9	18.5	38.6	
		18.3		
		14.1	52.4	
		15.0		
		14.0	46.5	
		14.7		
		15.77	46.17	0.341
D-3	0.76	14.2		
		15.0	51.5	
		13.9		
		16.2	50.5	
		19.1		
		16.3	48.6	
		14.4		
		14.6	53.2	
		15.46	50.95	0.304
D-4	0.30	36.9		
		42.4	63.6	
		37.9		
		41.7	64.0	
		41.2		
		40.0	63.8	0.626
D-5	0.475	29.9	55.8	
		27.1	56.3	
		27.8	62.0	
		29.6	56.5	
		28.9	66.4	
		31.8	57.6	
		29.18	59.0	0.494
D-6	0.423	39.3	63.5	
		40.4	59.0	
		39.85	61.2	0.651

D = fraction of the steel surface covered with slag or ash.

X_r = Heat absorption rate in thousands of Btu per sq ft per hour, determined with the thermal probe.

I = radiation intensity in thousands of Btu per sq ft per hr, determined with the quartz-window calorimeter.

covered with slag and ash. The ash formations were fastened to the steel surface by a layer of refractory cement about 1/16″ thick. In Test No. D-1, a dense black slag about one-half inch thick covered nine-tenths of the surface. In the remaining tests, the ash coverings consisted of a porous material which had been formed of particles of fly ash stuck together on cooled surfaces in the furnace. The thicknesses of these ash coverings were as follows: Test No. D-2, 5/8″; test No. D-3, 1 3/4″; Test No. D-4, 1 3/8″; Test No. D-5, 1 3/4″; Test No. D-6, 3/16″. The test data for these tests are given in Table 6.

VII. DERIVATION OF PRACTICAL EQUATIONS

13. *Equation for Heat Absorption.*—The ratio X_r/I as determined above is plotted against the dirtiness, D, in Fig. 13. These data may be represented by the straight line whose equation[10] is

$$X_r/I = 0.89(1 - 0.8D). \tag{4}$$

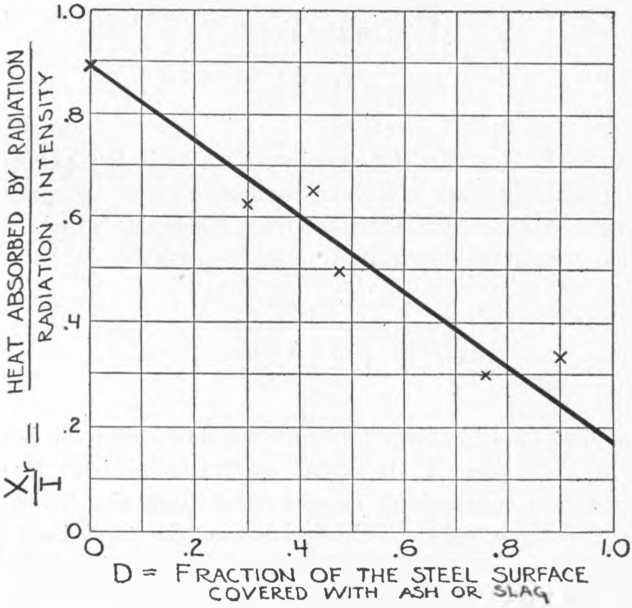

FIG. 13. VARIATION OF HEAT TRANSFER BY RADIATION FOR AN ASH-COVERED STEEL SURFACE

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[10] This ratio, X_r/I, actually varies with the thickness of the slag or ash layer, but since this variation is apparently not very great, an average such as taken in Figure 13 will serve for the purposes of this investigation.

During the tests represented by Equation (A), the cooling water temperature was about 70°F, while in the actual heating surfaces in the furnace, the temperature was about 400°F. Making a correction for this difference in temperature on the basis of the Stefan-Boltzmann law, it is found that Equation (4) should be decreased by about 2%, so that

$$X_r/I = 0.98 \times 0.89(1 - 0.8D) = 0.872(1 - 0.8D). \qquad (5)$$

Substituting in Equation (5) the value of I as given by Equation (3), there results,

$$X_r = \frac{0.872(1 - 0.8D)\ (0.5 + 1.7D)\ C_rU}{1 + \frac{A\sqrt{C_r}}{27}} \qquad (6)$$

14. *Radiation and Convection in a Clean Furnace.*—For the special case in which the furnace is clean, ($D = 0$), Equation (6) reduces to

$$X_r = \frac{0.436\ C_rU}{1 + \frac{A\sqrt{C_r}}{27}} \qquad (7)$$

where X_r is the heat transfer rate by radiation in Btu per sq. ft. per hr. to the cold surfaces in a clean furnace.

However, the similar Hudson-Orrok formula, which gives the *total* heat transferred by radiation and convection is

$$X = \frac{C_rU}{1 + \frac{A\sqrt{C_r}}{27}} \qquad (8)$$

A comparison of Equations (7) and (8) shows that the heat transferred by radiation, X_r is 43.6% of the total heat transferred (radiation and convection) as computed from the Hudson-Orrok formula for these tests. This division of the total heat transfer between radiation and convection for $D = 0$ (clean furnace) is shown graphically in Fig. 14.

To investigate the division of the total heat transfer between radiation and convection for dirty furnaces, it will be necessary to find how the total heat transferred to the cold surfaces in the furnace varies with the furnace dirtiness.

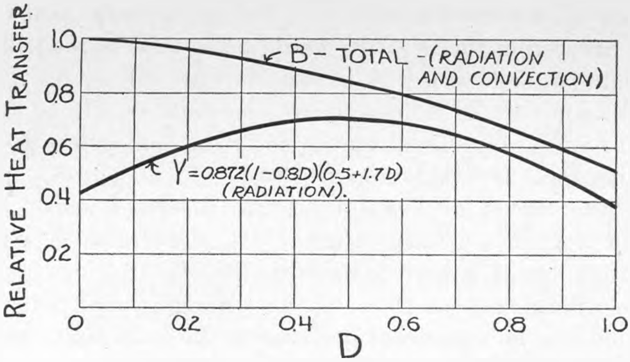

Fig. 14. Radiation and Total Heat Transfer (Not Corrected)

15. *Effect of Dirtiness on Total Heat Transfer in the Furnace.*—A probable relationship between the total heat absorbed in the furnace and the dirtiness is shown by Curve "B" in Fig. 14. This curve expresses the commonly observed fact that as the water-wall tubes become dirty, less heat is absorbed by the cold surfaces in the furnace for a given energy release rate.

The effect of decrease of total heat transferred in the furnace as the furnace becomes dirty is illustrated in a series of tests reported by DeBaufre.[11] These tests show that the effect of "considerable amounts of slag" is to reduce by about 20%, the total heat transferred to the cold surfaces in the furnace. For this condition, D was probably more than 0.4, and less than 0.8. A reasonable value for D would be $D = 0.6$. Then for $D = 0.6$, the total heat transfer is 80% as much as it is for the clean furnace with the same energy release rate. This established the trend of Curve "B" of Fig. 14.

The corresponding dependence of the radiation (as predicted by Equation 6) upon the furnace dirtiness is shown by the second curve (Curve Y, Fig. 14). The factor in the radiation equation (Equation 6) involving the dirtiness is

$$Y = 0.872\,(1 - 0.8D)(0.5 + 1.7D). \qquad (9)$$

16. *Modification of Radiation Equation.*—The need for some correction is indicated from a consideration of the relative magnitude of the rates of heat transfer by radiation and by convection in a dirty furnace. For instance, for $D = 0.5$, the half of the surface which is clean will absorb at least as much heat by convection as it

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[11] Heat Absorption in Water-Cooled Furnaces, W. L. DeBaufre, Transactions, A.S.M.E., Vol. 53, 1931, p. 257 (Manchester Tests).

does when all the surface is clean. Hence, the average heat transfer rate by convection for $D = 0.5$ would be at least one-half as much as it would be for $D = 0$ with the same energy release rate.

But this is not the conclusion which would be drawn from inspection of Fig. 14. These curves show the convection to be only 27% as much at $D = 0.5$ as at $D = 0$.

Since the curves of Fig. 14 lead to incorrect conclusions, at least one of them is wrong. Curve "B" was drawn in with little information, but if it were to be shifted upward far enough to correct this discrepancy at $D = 0.5$, the change would be such that there would be no significant decrease in the total heat transfer in the furnace as D increases. Hence, it is concluded that "Y" is the offending member, and should be modified to correct this apparent defect.

Such a modification is shown in Fig. 15. The resulting value of Y from this graph is

$$Y' = 0.872(1 - 0.8D)(0.5 + 1.1D). \qquad (10)$$

This change of Y to Y′ has been accomplished by changing the radiation intensity factor $(0.5 + 1.7D)$ to $(0.5 + 1.1D)$. This change may be justified on the grounds that the estimates of the fraction dirty during the boiler tests could be in error. The indications are that these estimates were low. It is unlikely that the necessary change should be made in the factor $(1 - 0.8D)$, for the reason that when it was determined, the dirty area of the thermal probe was measured, rather than estimated.

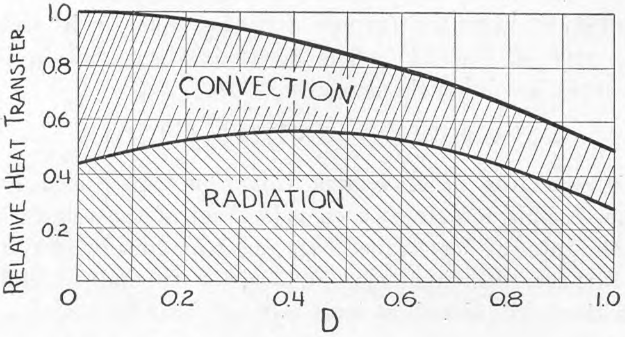

FIG. 15. COMPARISON OF HEAT TRANSFERRED BY RADIATION AND CONVECTION IN THE FURNACE

When Y′ is substituted in Equation (6) in place of Y, the radiation equation becomes

$$X_r = \frac{0.872\,(1 - 0.8D)(0.5 + 1.1D)\,C_rU.}{1 + \frac{A\sqrt{C_r}}{27}} \tag{11}$$

This radiation equation has been set up from considerations of the variation of radiation and convection with the furnace dirtiness at constant energy release rate. The relative importance of the heat transfer by radiation and by convection probably varies with the energy release rate in the furnace. But since the boiler tests of

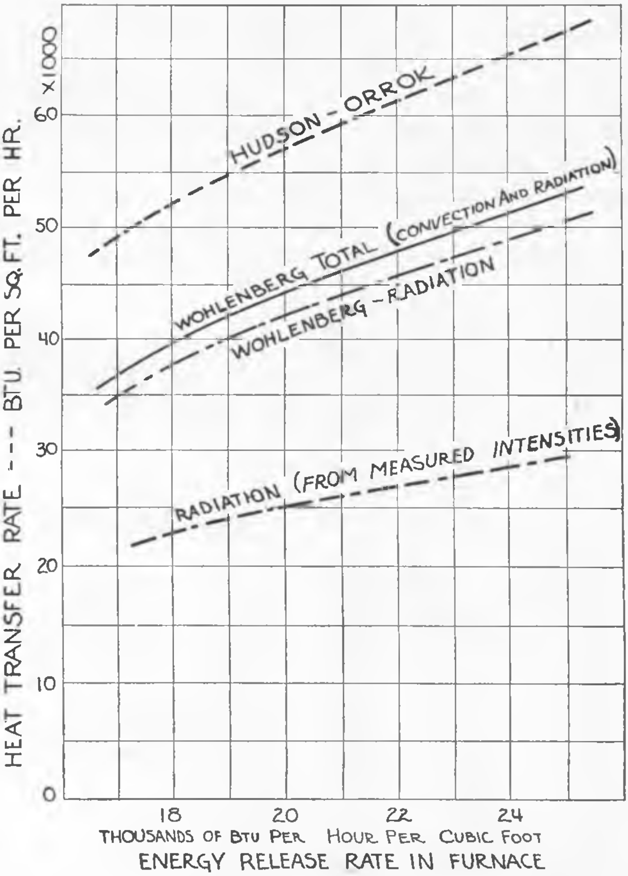

FIG. 16. COMPARISON OF RADIATION BASED UPON THE MEASURED RADIATION INTENSITIES TO THE HUDSON-ORROK AND WOHLENBERG FORMULAS. CLEAN FURNACE (D = O).

this investigation were made under regular operating conditions, the range of energy release rates was not great enough to permit a prediction of its effect upon the relative heat transfer by radiation and by convection.

17. *Comparison of Modified Radiation Equation to the Hudson-Orrok Formula and to the Wohlenberg Formula.*—A graphical comparison of the results of the Hudson-Orrok formula, and the Wohlenberg method, to the modified radiation equation is shown in Fig. 16 for the clean furnace condition.

It is to be noted that the radiation predicted by means of the Wohlenberg method is greater than that computed from the measured radiation intensities. Also, the total of radiation and convection (Wohlenberg method) is considerably lower than the total indicated by the Hudson-Orrok formula.

For one of the boiler tests (clean furnace) the radiation term in the Wohlenberg heat balance equation has been made to agree with the measured radiation intensity. The result has been to reduce the "mean flame temperature" from 2360°F to 2116°F, and thus to reduce the computed heat capacity of the gases leaving the furnace. To satisfy the heat balance equation the convection term is

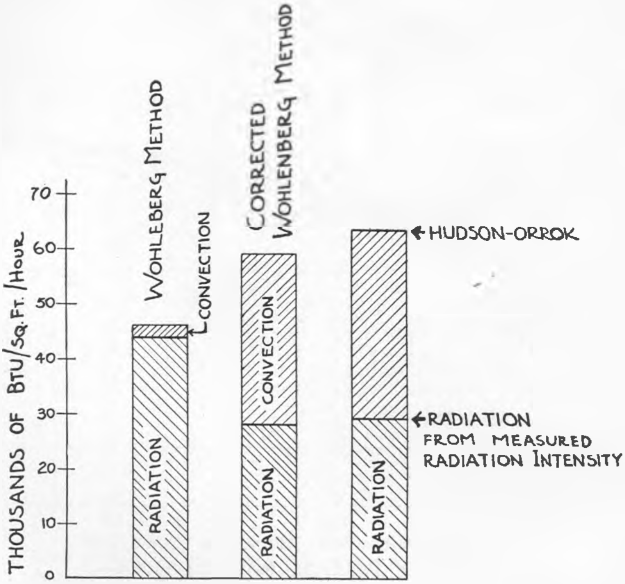

FIG. 17. EFFECT OF CORRECTION TO WOHLENBERG METHOD (BOILER TEST NO. 17.)

increased. This change in the convection term which corresponds to the modification of the radiation term in the computations for Boiler Test No. 17 is displayed in the chart of Fig. 17.

For this test, when the radiation term was made to agree with the measured radiation intensities, the convection term was increased, with the result that the total radiation and convection as computed from the Wohlenberg method is seen to be in close agreement with the value computed by the Hudson-Orrok formula.

VIII. CONCLUSIONS

18. *Summary.*—In view of the fact that the experimental data herewith presented has been determined for one type of furnace and fuel only, judgment should be exercised in applying these data to other sets of conditions.

The intensity of radiation (not including convection) has been determined for the physical boundaries shown in Fig. (6) by using a quartz-window calorimeter. The results of this experimental work are well represented by the Equation:

$$I = \frac{0.5 + 1.1D}{1 + \frac{A\sqrt{C_r}}{27}} C_r U \qquad (12)$$

The absorption of radiation by a steel surface as determined experimentally by the steel-surface calorimeter is well represented by the equation:

$$X_r = \frac{0.872\ (0.5 + 1.1D)(1 - 0.8D)}{1 + \frac{A\sqrt{C_r}}{27}} C_r U. \qquad (11)$$