

MEASUREMENT OF RADIANT HEAT TRANSFER

By

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the Degree of

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Department of Chemical Engineering, May 11, 1939

Signature of Professor

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Signature of Head of Department.....



159 College Street
Buffalo, New York

May 11, 1939

Professor Walter G. Whitman
Chemical Engineering Department
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

We are submitting this thesis on "Measurement of
Radiant Heat Transfer" in partial fulfillment of the
requirements for the degree of Bachelor of Science in
Chemical Engineering.

Very truly yours

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Henry R. Landwehr

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Norman G. Farquhar

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I SUMMARY

It was desired to design, construct and calibrate a radiation probe for use in determining the rate of radiant heat transfer in high temperature industrial furnaces. Three types of probes were designed and built, each consisting essentially of two nickel disks separated by a layer of refractory and having a thermocouple peened into the center of each disk.

The variations in probes were mainly in the way in which they were attached to the handle of the instrument, a 3/8" iron pipe with a water jacket. Probe "A", (Fig. II), was supported by nickel strips, probe "B", (Fig. III), by fitting the refractory over the end of the iron pipe and probe "C", (Fig. IV), by means of alundum cement.

An attempt was made to calibrate these instruments in a continuous billet reheating furnace where the temperature was about 2300°F. However, only one probe of type "C" was strong enough to withstand the high temperature long enough to obtain readings. The instrument constant was found experimentally to be 44, as compared to 11.Btu/(hr)(sq.ft)(°F) when calculated from the properties of the probe.

The net radiant heat transfer at a point near the hot end of the furnace was found to be 18,700 Btu/(hr)(sq.ft) by probe measurements and was calculated to be 23,000 Btu/hr./sq. ft. from the rate of billet feed and the rise in surface temperature of the billets. The calculated value of the instrument constant was used in the probe determination.

It is recommended that a porcelain frame designed by Professor Hottel be used in future construction of probes because of its strength and ease of assembling. Also it is recommended that the calibration of the instrument be done at a temperature low enough so that convection is of more importance.

The rate of feed of the billets should be measured before and after each probe reading as it varies widely.

II. INTRODUCTION

In the construction of high temperature furnaces it is desirable that the design be based on scientific calculations rather than empirical data. At the present time there are methods for calculating that part of the heat which is transferred by convection, but there has been found no accurate method to determine the rate of radiant heat transmission. It is common knowledge that the radiant heat transfer is not the same on all surface areas in a furnace, and, thus far, calculations have been based on average overall radiant heat transfer values. Investigation of the transfer values at various points in a furnace would be of extreme importance to the engineer, because knowledge of this nature might result in increased capacity of existing furnaces or saving in costly surface areas of proposed ones.

An instrument with which one could determine these point values of radiant heat transfer has already been investigated and is known as a radiation probe. An early devised probe was a solid metallic sphere, known as a thermoprobe, and measured the rate of heat absorption by means of the rate of temperature rise, as measured by thermocouples at the center and on the surface of the sphere (3). Another probe was in the form of a water cooled short cylindrical tube, and the heat transfer was measured by means of the rise in temperature and the rate of flow of the cooling water (8). Both of these instruments were

discarded due to unwieldiness and the disadvantage that only the radiation toward the tube, or stock was measured. The net heat transfer could not be calculated without knowing the heat which was reflected, or reradiated. These instruments measured the combined convection and radiation values, and when the convection values were high, poor results were obtained for the radiation values. Other similar probes have been developed but will not be discussed herein.

The most recent development in radiation probes, and that used in the present investigation, is that developed by Hottel, Meyer, and Stewart (4, 6, 9). This type of probe consists of two metal disks separated by refractory and supported by a refractory ring. Thermocouples are attached to the back of each metallic disk, and the wires are led out through the refractory frame. When placed parallel to a heat receiving surface, the probe records two temperatures, and the net radiant heat transfer is a function of the fourth power of these temperatures. The exact expression for the net heat transfer is *:

$$\frac{Q}{A}(\text{net}) = E_1 - E_2 = \sigma (T_1^4 - T_2^4) + \left[\frac{h_c + \frac{2k}{L}}{\rho} \right] (T_1 - T_2)$$

* For the derivation and nomenclature of this equation see appendix.

The bracketed expression is known as the instrument constant, and its determination is essential before the probe can be used. This constant can either be calculated, if the values for the terms within the brackets are known, or it can be experimentally determined.

In the past probes have been calibrated in the laboratory, and experimental and calculated values have checked within 4% for rates of heat transfer up to 18,000 B.T.U. per hour per square foot (4). In the case of the present investigation, however, it was believed better to try to calibrate the instrument under conditions similar to that in which it would be industrially used. It was intended that the investigation would be divided into three parts: that is, construction, calibration, and industrial use. However, the high temperatures involved in industrial furnaces caused the investigation to be concentrated on the construction of a probe to withstand such operating conditions.

This recent type of probe has several advantages over previously designed probes (4). First, it enables one to calculate directly the net heat flow across any plane surface. Second, it reduces the time of readings by recording two temperatures at once. Third, the results obtained agree very closely with calculated values. Fourth, at high temperatures the readings of a protected thermocouple are nearer the true radiation temperature than the true gas temperature. Fifth, the heat flow through the instrument can be determined, an advantage in evaluating the rate of heat transmission to nearby surfaces.

III. PROCEDURE

The investigation was divided into three portions as stated in the introduction: the construction, the calibration and the plant use of the instrument.

The method of construction of the probe was a modification of that used by Hottel, Meyer and Stewart (4). For the frame and support of the probe it was decided to use a porcelain ring designed by Professor Hottel and manufactured especially for that purpose. However, since it would take several weeks to secure these rings, it was necessary to use a different design.

Three types of probes were designed and built, each of which consisted essentially of two nickel discs with thermocouples peened into their centers and separated by a slab of Babcock and Wilcox insulation brick, K26. The nickel discs were 1/16" thick and each had three circles of perforations around the center to prevent, as much as possible, the flow of heat from the center to the outer edges.

Thermocouples were made of #22 gauge chromel and alumel wires welded together and then flattened. The nickel discs were held together by iron screws and nuts through the refractory. A layer of cobaltic oxide was applied to the discs over a base of sodium silicate solution to insure a uniform emissivity of known value.

The first probe, "A", (Fig. II), was supported by nickel strips extending from the plates to the iron pipe on the end of the water-cooled handle. (Fig. I) It was felt that this

construction would give sufficient strength for use at high temperatures and that the perforations would be efficient enough to prevent heat losses along the strips. The slab of refractory was cut $1/16$ " larger than the nickel in order to lessen radiation from the edges of the discs.

The second probe, "B". (Fig. III), was attached to the handle by enlarging the refractory slab and fitting it over the end of the iron pipe in the handle. Another design, "C", (Fig. IV), consisted of nickel discs separated by refractory, the whole unit being cemented onto the handle and baked hard. Altogether, six probes were constructed and tested in #1 billet reheating furnace of Mill #6 at the Lackawanna plant of the Bethlehem Steel Company.

The water-cooled handle, (Fig. I), was made about 15 feet long and consisted of three concentric iron pipes for carry the thermocouple leads and the cooling water. The thermocouple leads were insulated in the iron pipe by the use of five foot lengths of glass tubing. The necessary size of the water jackets was estimated in designing the handle by assuming a furnace temperature of 2500°F . and allowing a 150°F . rise in cooling water temperature.

In calibrating the probe in the billet furnace, the probe was held at one station a few inches above the moving billets and readings taken at regular intervals on the millivoltmeter. The temperature of the surface of the billets was measured with an optical pyrometer four feet on either side of the probe toward the ends as well as at the probe, in order to determine the rise in temperature of the surface

as it moved. From these data it was possible to calculate the heat received by the billets using an equation developed by Eberhardt. (2)

Since so much difficulty was experienced in making a probe which would stand the high temperatures of the furnace, no other plant application was made.

IV RESULTS

The net rate of radiant heat transfer at a point about ten feet from the discharging end of the billet reheating furnace was found to be:

- A. Calculated: 23,000 B.T.U./hr(sq ft)
(from experimental data)
- B. By Probe: 18,700 B.T.U./hr(sq ft)

Instrument constants were calculated for each probe constructed and were found to be: (insulating material in all cases was B. & W. insulating brick, type K26)

- A. 1/2 inch thickness: 12 B.T.U./hr(sq ft)(Temp. difference in plates, °F)
- B. 5/8 inch thickness: 11 B.T.U./hr(sq ft)(Temp. difference in plates, °F)
- C. 3/4 inch thickness: 9 B.T.U./hr(sq ft)(Temp. difference in plates, °F)

If the above calculated rate of radiant heat transfer is used as a calibration for the radiation probe, the corresponding instrument constant, K, for a 5/8 inch thickness of refractory will be 44 B.T.U./hr(temp. difference in plates, °F.) (ft.²). Other experimental values were not obtained due to the failure of the instruments to withstand the high temperatures long enough to get consistent data.

The first probe, "A", (Fig. II), failed when the nickel strips holding it on the handle sheared off and the probe drooped from its horizontal position. The shearing was probably caused by the disks being slightly eccentrically located and under enough stress to tear the nickel at a temperature above 2000°F. This probe was reconstructed with new nickel disks, but the same shearing action was observed when the

probe was dismantled to repair a broken thermocouple lead.

Probe "B", (Fig. III), was found to be too fragile to be practical and broke in pieces from mechanical shock before any readings could be obtained.

Three probes of type "C", (Fig. IV) were constructed and baked in the reheating furnace where they were used. The first one gave a strong heat-resistant support, but had to be taken apart to correct a short circuit in the thermocouple leads. The second withstood the heat only long enough to obtain a few readings which were apparently not at equilibrium. It then had to be taken apart because of a broken thermocouple.

The last probe also failed because it could not support its own weight, but it was with this probe that the observed readings were taken. Failure occurred after the first readings had been taken and before check readings could be obtained.

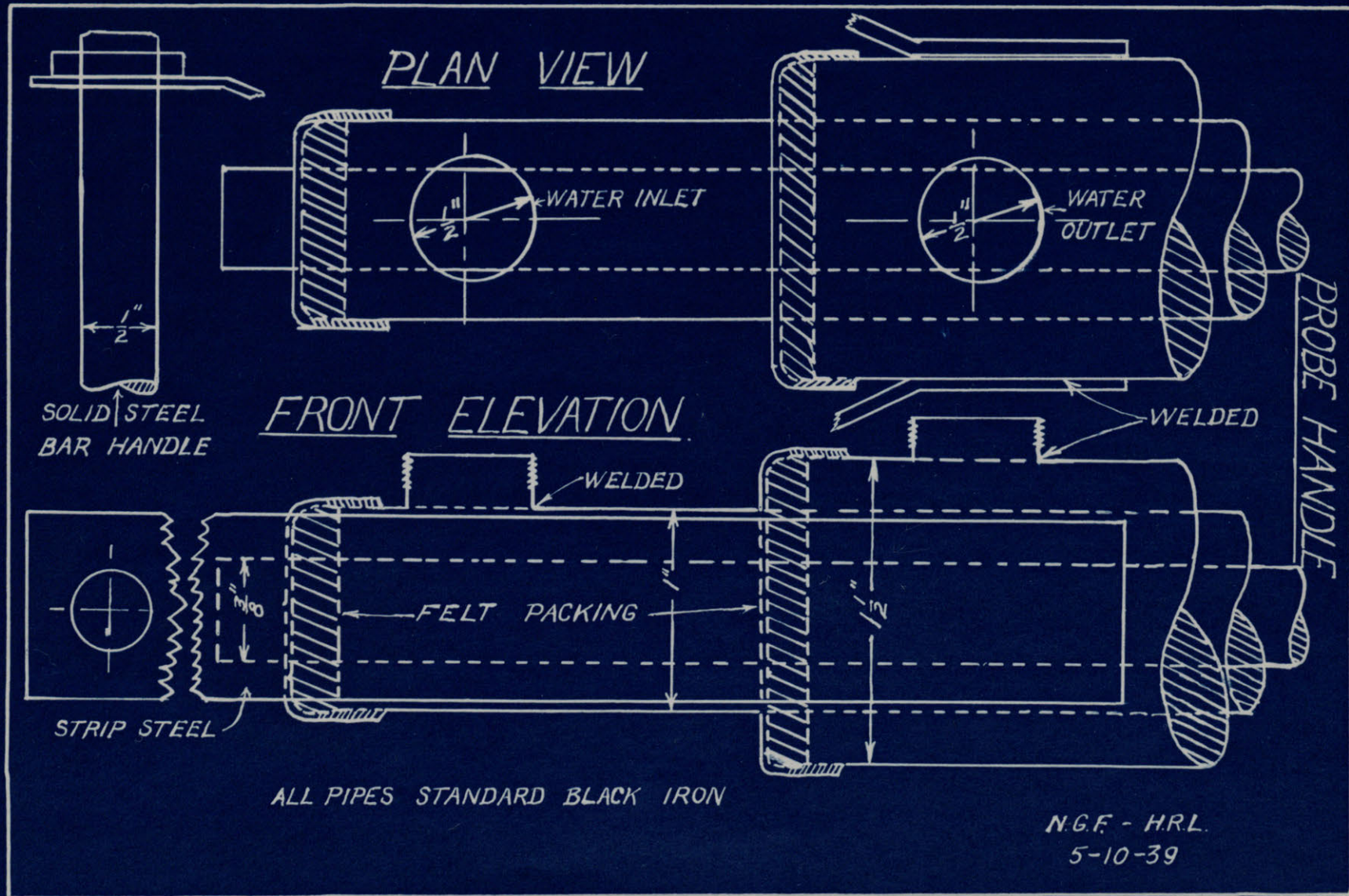


FIG. 1

FIG. II.

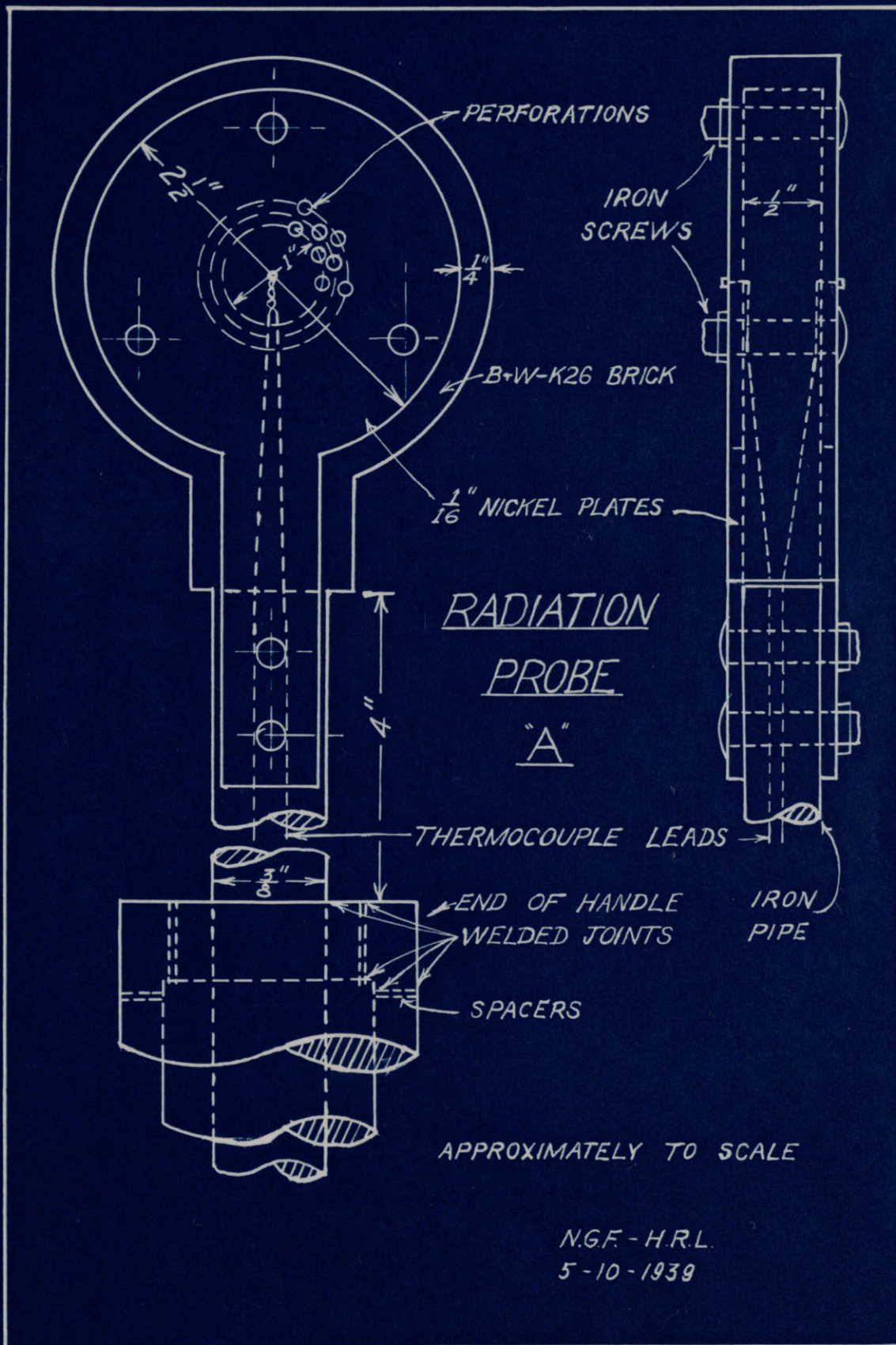
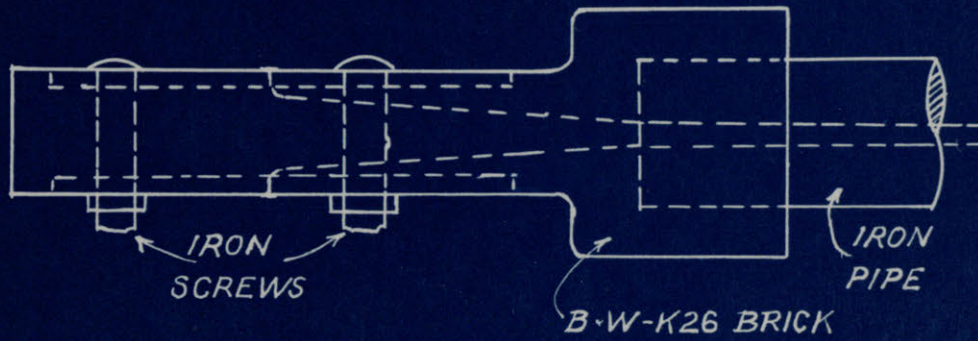
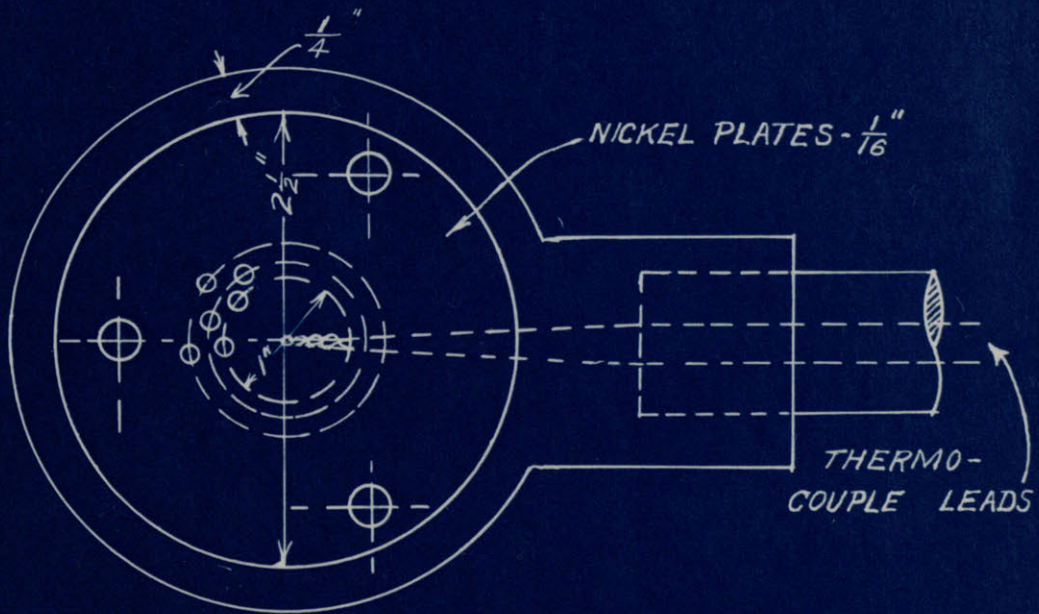


FIG. III.



RADIATION PROBE
"B"

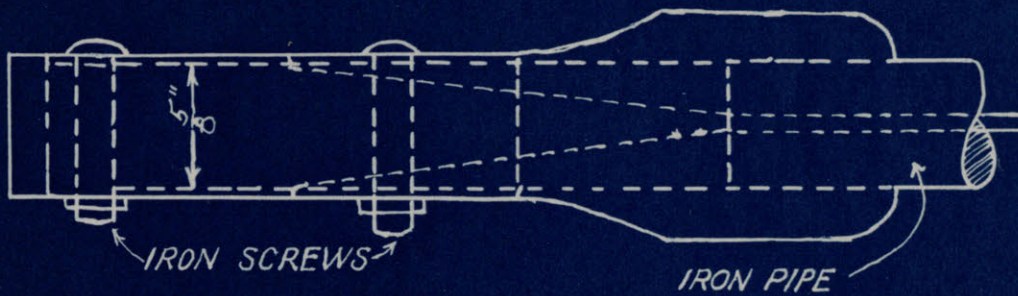


APPROXIMATELY TO SCALE

N.G.F. & H.R.L.

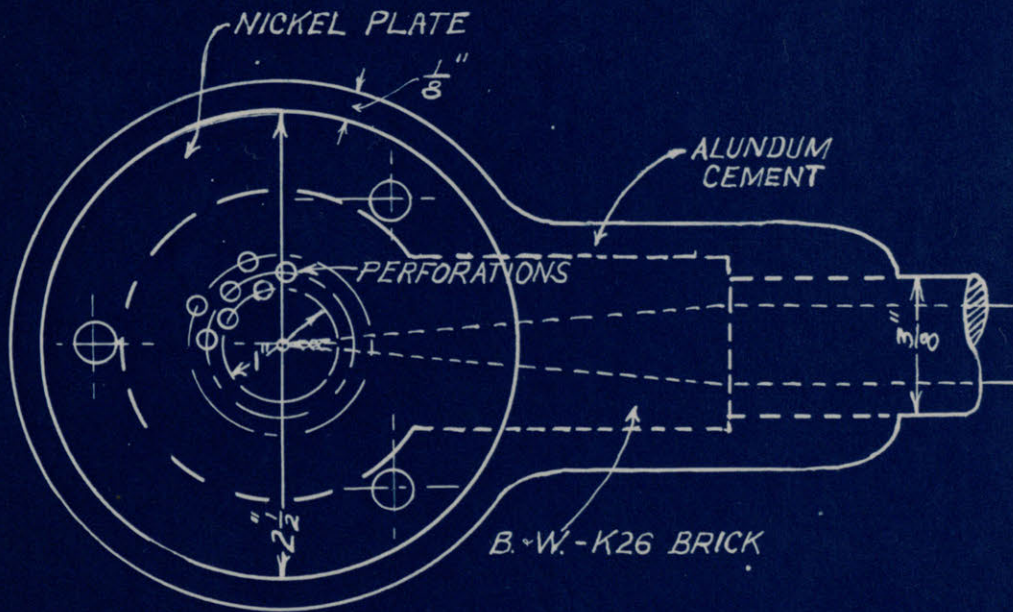
5-10-39

FIG. IV.



RADIATION PROBE

"C"



N.G.F - H.R.L.
5-10-39

APPROXIMATELY TO SCALE

V DISCUSSION OF RESULTS

The values of net radiant heat transfer as found by calculations and from probe readings agree within 25% of each other although there were no check readings obtained on the probe. The calculated value can probably be in error by 25% of itself as it depends on the measurement of the surface temperatures and the rate of feed of billets, both of which were difficult to obtain. Values of radiant heat transfer determined by the probe are probably accurate to 10% of the values obtained.

Errors in radiation temperatures recorded by the probe might cause an error of about 6% in the net radiant heat transfer while errors in the calculated instrument constant might cause it to be in error by 5%. The error in the instrument constant is due to the uncertainty of the thermal conductivity of the insulating brick and of the coefficient of convection which is dependent on the rate of gas flow. The thickness of the refractory and the emissivity of the cobaltic oxide were known within 5% of their values.

Since, at high temperatures, the instrument constant has little effect on the total radiant heat transfer, it can not be accurately determined experimentally at high temperatures. However, if it were determined at lower temperatures, it would have a large effect on the total heat transfer and might be used to check the calculated value.

The following table shows the comparison of calculated values of instrument constants with those experimentally determined.

	<u>Calculated Constant</u> (Btu/hr./sq. ft./ F.)	<u>Experimental Constant</u> (Btu/hr./sq. ft./ F.)
Probe "C"	11	44
Howard & Milleville (12)	8	11
Hottel, Meyer & Stewart (4)	11.4	11.9

The difficulty in the construction of probe "A" was that there were five holes in each nickel disk that had to be lined up perfectly with the holes in the opposite disk. This was very difficult and even a small stress was enough to shear the plates when weakened by high temperature. The insulation brick supporting probe "B" was very easily cracked and, since it was exposed, was very likely to be broken.

Probe "C", supported by alundum cement, had sufficient strength when baked on properly, but the wires tended to set in the cement under a strain so that they broke easily when heated. Because of lack of time probe "C" was baked in a reheating furnace at a temperature of about 2300°F. immediately after assembling. This resulted in cracking the supporting cement and caused the probe to droop in the furnace while readings were being taken. Alundum cement should be dried thoroughly at a temperature slightly above 100°C. and then baked at a high temperature. If a probe were made in this way it should give satisfactory results, but would not be

easily reassembled if it had to be repaired.

The porcelain ring designed by Professor Hottel would eliminate most of the difficulties of construction experienced in making the above probes. It would provide a fairly strong heat-resistant frame which could be taken down and reassembled easily and which could be easily reproduced.

The 1/16" nickel plates appeared to stand the high temperature without much oxidation probably because they were protected by the layer of cobaltic oxide. The layer of cobaltic oxide was also in good condition after being exposed to the flames.

The nickel disks were perforated to cut down the flow of heat out from the center, but at the high temperatures where the probe was used radiation across the perforations may have been a large factor. However, it is believed that the perforations helped in bringing the thermocouples to equilibrium within one minute.

Since it was difficult to keep the thermocouple wires free from tension it was found that #22 chromel and alumel were not strong enough to stand the high temperatures. A larger size wire should be as accurate and give the necessary strength.

The water-cooled handle worked very successfully but was unnecessarily large due to the glass insulators. If four-hole alundum insulators were used in place of the glass tubing they would provide stronger insulation and at the same time allow the use of smaller pipes which would reduce the weight considerably.

VI. CONCLUSIONS

It is concluded that:

1. All of the types of probes built would have to be revised to make an instrument satisfactory for industrial use.
2. The rate of radiant heat transfer as calculated from probe readings is probably accurate to 10%, but no check readings were obtained.
3. The optical pyrometer is the best method of measuring the surface temperature of the billets at temperatures over 1500°F.
4. The instrument constant has little effect on the calculated value of the rate of heat transfer at high temperatures and, therefore, the instrument constant can not be accurately determined by the method used.
5. The billet rate was not known accurately as it varied widely.
6. The perforations in the nickel discs were satisfactory in cutting down the heat losses from the center.
7. Nickel plates 1/16" thick are satisfactory for resisting corrosion at high temperatures.
8. A layer of cobaltic oxide when applied over a layer of sodium silicate solution adheres to the nickel plate and does not peel off noticeably.
9. #22 gauge chromel and alumel wire is too small to stand the effects of the high temperature.

10. Glass is too fragile to be used for insulators in the handle as they may have to be moved in the pipe and there is danger of them breaking and clogging the pipe.

11. Porcelain rings might serve better as supports than the frame used.

12. The water-cooled handle used, (Fig. I), is of satisfactory design.

VII. RECOMMENDATIONS

It is recommended that:

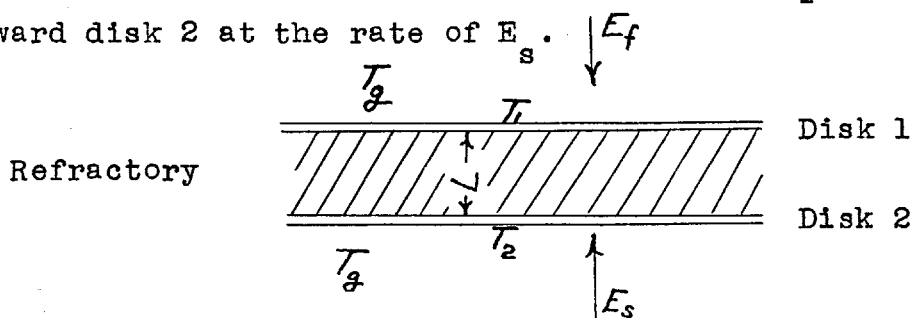
1. The porcelain frame which was designed by Professor Hottel for supporting the nickel discs and thermocouples should be tried.
2. The rate of radiant heat transfer be checked with more probe readings.
3. The instrument constant, K , be determined at lower temperatures where convection is a larger portion of the total heat transferred.
4. In future work the rate of feed of billets be accurately measured before and after all probe readings.
5. $1/16$ " nickel discs with perforations be tried in future probes.
6. Cobaltic oxide be applied to the nickel discs by first applying a layer of sodium silicate.
7. #14 or #18 gauge chromel and alumel wires be tried.
8. Four-hole alundum insulators be tried for insulating the thermocouples leads in the handle.
9. A water-cooled handle similar to the one used be tried in future work.

VIII. APPENDIX

A. DERIVATION OF INSTRUMENT EQUATION

Consider any point in a furnace at which the gases are at temperature T_g . A radiation probe consisting of two parallel metal disks, separated by refractory of thickness L and thermal conductivity k , and having a thermocouple mounted on the back of each disk, is placed in the furnace. One disk is exposed to the heat source, and the other to a heat sink.

When equilibrium is reached the disks have attained the temperatures T_1 and T_2 respectively. Heat is being radiated by the furnace toward disk 1 at the rate of E_f , and the sink toward disk 2 at the rate of E_s .



Setting up a heat balance per unit area for disk 1:

$$E_f a_1 + h_{c1}(T_g - T_1) = \sigma p_1 T_1^4 + (k/L)(T_1 - T_2) \quad (1)$$

and for disk 2:

$$E_s a_2 + h_{c2}(T_g - T_2) = \sigma p_2 T_2^4 + (k/L)(T_2 - T_1) \quad (2)$$

where:

a = absorptivity; i.e., the radiant energy absorbed and converted into heat, expressed as a fraction of the radiation incident on the surface.

h_c = coefficient of heat transfer by convection and conduction, B.T.U./hr(sq ft)(deg. F.)

σ = sigma, Stefan-Boltzmann constant, equals 0.173×10^{-8} B.T.U./hr(sq ft)(deg. F.)⁴

p = emissivity, equals the fraction of radiant emissive power of a surface to that of an ideal black body.

T = temperatures in absolute scale, degrees Rankine.

If it is assumed that:

$$a_1 \text{ at } T_1 = p_1 \text{ at } T_1 ; \text{ and } a_2 \text{ at } T_2 = p_2 \text{ at } T_2 ;$$

And that:

$$p_1 = p_2 ; \text{ and } h_{c1} = h_{c2}$$

Then equation (2) can be subtracted from equation (1) to give:

$$E_f - E_s = \sigma(T_1^4 - T_2^4) + \left[\frac{h_c + 2k/L}{p} \right] (T_1 - T_2)$$

Since $E_f - E_s$ = the net radiant heat transfer across the plane of the probe, this becomes:

$$Q/A \text{ (net)} = \sigma(T_1^4 - T_2^4) + \left[\frac{h_c + 2k/L}{p} \right] (T_1 - T_2) \quad (3)$$

or:

$$Q/A \text{ (net)} = \sigma(T_1^4 + T_2^4) + K(T_1 - T_2) \quad (4)$$

B SUMMARIZED DATA

I. Billet Reheating Furnace

A. Dimensions

1. Length, 35 feet.
2. Width, 10 feet.
3. Height, 1.5 feet.

B. Billets

1. 4 inches x 4 inches x 7 feet
2. 600 billets discharged in about 6 hours from two furnaces. Observed about 10 billets discharged in about 10 minutes from one furnace.

C. Fuel

1. Mixture of coke oven gas and blast furnace gas.
2. Rate of about 200,000 cu ft per hour, recorded for 60°F and 30 inches, Barometer.
3. Approximate analyses (from literature (2))

<u>Fuel Gas</u>	<u>Flue Gas</u>
CO ₂ = 1.9%	CO ₂ = 9.0%
C ₂ H ₄ = 2.6%	O ₂ = 1.5%
O ₂ = 1.5%	CO = .5%
CO = 5.0%	H ₂ = .5%
CH ₄ = 28.0%	N ₂ = 88.5%
H ₂ = 48.0%	<u>100.0%</u>
N ₂ = 13.0%	
<u>100.0%</u>	

D. Stations for observation (distances from cold end)

1. 35.0 feet	T _s = 2497°F
2. 32.5 feet	
3. 29.0 feet	T _s = 2319°F
4. 25.5 feet	T _s = 2231°F
5. 22.0 feet	T _s = 2075°F
6. 18.5 feet	
7. 15.0 feet	
8. 11.5 feet	(Surface temperatures
9. 1.0 feet	of the billets)

II. Probe

A. Readings at station 4

1. T₁ = 2270°F
2. T₂ = 2140°F

B. Properties for calculating instrument constant

1. Thermal conductivity, k , 0.2 BTU/
(sq ft)(hr)(°F/ft)
2. Thickness of refractory, L , 1/2, 5/8,
and 3/4 inch
3. Emmissivity of plates, p , 0.9

C SAMPLE CALCULATIONS

1. To find the size pipes necessary for water cooled handle.

It was assumed that the overall coefficient of heat transfer was about 75 B.T.U./((hr)(sq ft)(°F)).

If a standard 1 1/2 inch pipe were used as the outside pipe for three concentric pipes:

$$Q = U A \Delta T = W C_p \int_{T_1}^{T_2} dT$$

$$W = \frac{75 \times 1.9/12 \times \pi \times 15 \times 2500}{1 \times 150} = \frac{9,400 \text{ lbs of water}}{\text{hr.}}$$

where 1.9 is the outside diam. of 1 1/2 in. pipe, in inches
15 is the length of the pipe in feet.
2500 is the assumed temperature difference between the pipe and the surroundings
150 is the allowable temp. rise of the cooling water.

Area for water to flow, assuming a velocity of 10 feet per second will be:

$$A = \frac{9,400}{3,600} \times \frac{1}{62.5} \times \frac{1}{10} \times 144 = 0.605 \text{ square inches}$$

Then if the center pipe is a 3/8 inch pipe whose outside diam. is 0.68 inches,

A second pipe whose inside area is 0.605 plus $(0.68)^2 \times \pi/4$ can be used.

$$0.605 + 0.36 = 0.96 \text{ sq. in.}$$

Such a pipe would have an inside diameter equal to the square root of $(0.96 \times 4/\pi)$ or 1.11 inches.

Assuming:

- a. Not all the pipe will be in the furnace.
- b. Higher water velocities can be obtained.

A one inch pipe could be used.

The area free for the return passage of the water will be:

$$A = (1.6)^2 \times \pi/4 - (1.3)^2 \times \pi/4 = 2.01 - 1.33 = 0.68 \text{ sq in}$$

where 1.6 is the inside diam. of a 1 1/2 in. pipe
1.3 is the outside diam of a 1 in. pipe

2. To calculate an instrument constant it is first necessary to determine the coefficient of heat transfer due to convection.

Since the billets in a reheating furnace approximate a plane surface, it was decided to make use of equation 22, page 132, in Walker, Lewis, McAdams, and Gilliland (11).

$$\left(\frac{h_{av.}}{C_p V_{\infty} \rho_{\infty}} \right) \left(\frac{C_p \mu}{k} \right)^{2/3} = \frac{f}{2}$$

where:

h_{av} = average coefficient of heat transfer due to convection, from a gas to a plane surface, B.T.U./hr(sq ft)(deg. F./ft).

C_p = the specific heat of the gas at constant pressure, B.T.U./lb.(deg. F.)

V_{∞} = the linear velocity of the gas, measured at a substantial distance from the plane, ft/sec.

ρ_{∞} = the density of the gas, at a substantial distance from the plane, lbs./cu ft

μ = mu, the viscosity of the gas at the bulk temperature, lb./hr(ft), equals 2.42 times centipoises.

k = thermal conductivity of the gas, B.T.U./hr(sq ft)(deg. F./ft)

f = friction factor in the Fanning equation, dimensionless.

No data was obtained in the present investigation as to the composition of the gases in the furnace, but analyses were approximated from data found by Eberhardt (2).

Fuel Gas Analysis
(approx)

CO ₂	1.9%
C ₂ H ₄	2.6%
O ₂	1.5%
CO	5.0%
CH ₄	28.0%
H ₂	48.0%
N ₂	13.0%
	<u>100.0%</u>

Flue Gas Analysis
(approx)

CO ₂	9.0%
O ₂	1.5%
CO	0.5%
H ₂	0.5%
N ₂	88.5%
	<u>100.0%</u>

Per 100 mols of fuel gas, there are 40.1 atoms of carbon, and 109.2 mols of H₂ (free and combined).

Or: the ratio of $\frac{\text{mols of H}_2}{\text{atoms of C}} = 2.73$

Per 100 mols of flue gas there are 9.5 atoms of C.

To which there should be associated $9.5 \times 2.73 = 25.9$ mols of H₂

Therefore, $25.9 - 0.5 = 25.4$ mols of H₂ must have gone to form water.

A revised analysis of the flue gas, so as to include the water, will be:

CO ₂	=	7.2%
O ₂	=	1.2%
CO	=	0.4%
H ₂	=	0.4%
N ₂	=	70.6%
H ₂ O	=	20.2%
		100.0%

Temperatures of the gas were assumed to be 3000°F at the hot end of the furnace, and 1500°F at the cold end.

To find the specific heat of the gas, C_p, the molecular specific heats of the individual components were used and weighted in proportion to their percentage in the gas.

At 3000°F:

Mc _p of CO ₂	=	12.8		12.8/44	x	0.072	=	0.021
" " O ₂	=	8.3		8.3/32	x	0.012	=	0.003
etc.		etc.		etc.				etc.

$$C_p \text{ of flue gas} = 0.317 \frac{\text{B.T.U}}{(\text{lb.})(\text{deg. F})}$$

To find the viscosities of the gas, the viscosities of the individual components were used and weighted in proportion to their percentage in the gas.

At 3000°F

Viscosity of CO ₂	=	0.080	centipoises
" " O ₂	=	0.090	"
etc.		etc.	
CO ₂	0.080 x 0.072	=	0.0058
O ₂	0.090 x 0.012	=	0.0011
	etc.		etc.

Viscosity of flue gas = 0.0719 centipoises

The thermal conductivity of gases at temperatures above 212°C could not be found in the tables. Extrapolation was used to the range of temperatures in the furnace, since no better means was known. Again, the conductivities of the individual components were weighted in proportion to their percentage in the gas.

Two equations were used for the extrapolation to the high temperatures.

$$k = k_0 + aT \quad \text{or} \quad k = k_0 \left(\frac{273 + C}{T + C} \right)^{3/2}$$

where:

k = the thermal conductivity of the gas at temperature T , B.T.U./hr(sq ft)(deg. F./ft)

k_0 = the thermal conductivity of the gas at 0°C.

C) = experimentally determined constants for the gas.

T = temperature in degrees Centigrade

Example of determination of thermal conductivity:

$$CO_2 \text{ at } 3000^\circ F: \quad k_0 = 0.0081 \quad a = 3.67 \times 10^{-5}$$

$$k = 0.0081 + (3.67 \times \frac{1650}{10^5}) = 0.0687$$

Summary of the properties of the gases:

	FLUE GAS		
	at 3000°F	at 1500 F	
Molecular Weight	27.1	27.1	lbs/mol
Heat Capacity	0.317	0.296	B.T.U./lb.(deg. F.)
Viscosity	0.072	0.046	centipoises
Density	0.0107	0.0190	lbs./cu ft.
Thermal Conductivity	0.052	0.032	B.T.U./hr(sq Ft)(deg F/ft)

Plant data indicated about 200,000 cu ft of fuel gas were being fed to the twin furnaces in No. 6 mill per hour. This would mean that each furnace received about 100,000 cu ft per hour, recorded for 60°F, and 30 inches, Barometer.

100,000 cu ft of fuel gas would require about 440,000 cu ft of air, if it were burned with a 4% excess of air which the flue gas indicates.

$V\rho$ is the constant mass rate of flow of the gas in the furnace, designated by the symbol G, and can be determined as: (cross section of furnace was 10 ft x 1.5 ft)

$$550,000 \times (3460/520) \times (1/10 \times 1/1.5) \times 0.011 = G$$

$$G = 2630 \text{ lbs./}(\text{sq ft of cross section})(\text{hr})$$

f/2 is a function of $NV\rho/\mu$, or NG/μ .

at 3000°F.

$$NG/\mu = \frac{35 \times 2630}{2.42 \times 0.072} = 528,000$$

$$\text{Therefore, } f/2 = 0.036(NG/\mu)^{-0.2}$$

$$\text{And } C_p \mu/k = (0.317)(2.42 \times 0.072)/0.052 = 1.07$$

And: (see page 23)

$$h = 0.036(528,000)^{-0.2} (1/1.07)^{2/3} (0.317)(2630)$$

$$h = 2.07 \text{ at } 3000^\circ\text{F}$$

$$h = 1.82 \text{ at } 1500^\circ\text{F}$$

$$h \text{ (average for furnace)} = \frac{2.07 + 1.82}{2} = 1.95 \text{ or } 2.0$$

3. Instrument Constant.

$$h = 2.0 \text{ B.T.U./}(\text{hr})(\text{sq ft})(\text{temp. difference in deg. F.})$$

$$k = \text{was assumed to be about } 0.2 \text{ B.T.U./}(\text{hr})(\text{sq ft})(\text{deg F./ft})$$

$$L = \text{was } 1/2 \text{ inch, } 5/8 \text{ inch, and } 3/4 \text{ inch}$$

$$p = \text{was assumed to be } 0.9 \text{ for the cobaltic oxide layer on the disks.}$$

$$K = \frac{2.0 + \left(\frac{2 \times 0.2}{5/8 \times 1/12}\right)}{0.9} = 10.8 \text{ B.T.U./}(\text{hr})(\text{sq ft})(\text{temp difference between disks, } ^\circ\text{F})$$

4. Heat being transferred at station 4 in the furnace.

billets were 4 inches x 4 inches x 7 feet.

surface temperatures of the billets:

station 5	2060°F	3.5 feet
station 4	2210°F	
station 3	2271°F	3.5 feet
station 1	2497°F	7.0 feet

About 60 billets were discharged from the furnace per hour.

The average temperature of the billets can be obtained from the following equation, found in Eberhardt (2).

$$T_s - T = \frac{1}{2\alpha} (R^2 - X^2) (dT_s/d\theta)$$

where:

- T_s is the temperature of the heated surface, °F.
- T is the temperature in the billet at position X.
- α is the thermal diffusivity, ft²/hr.
- R is the thickness of the billet.
- θ is the time in hours.
- X is the distance from the unheated side of the billet.

This equation may be rewritten as:

$$(T_s - T) \text{ average} = \left(\frac{1}{2\alpha}\right) (dT_s/d\theta) \left(\frac{1}{R-\theta}\right) \int_0^R (R^2 - X^2) dX$$

$$\text{Or: } (T_s - T) \text{ average} = \left(\frac{1}{2\alpha}\right) (dT_s/d\theta) (2/3)(R)^2$$

For use in the equation, $dT_s/d\theta$ was calculated between stations in the furnace, and the point values of $dT_s/d\theta$ were taken from a rough plot of $dT_s/d\theta$ vs. distance in the furnace from the cold end.

Between stations 4 & 3:

$$dT_s/d\theta = \frac{2319 - 2231}{3.5/(60 \times 4/12)} = 503 \text{ degrees F./hr.}$$

The average T at station 4.

$$\begin{aligned} \text{using } T_s &= 2231^\circ\text{F} \\ dT_s/d\theta &= 730^\circ\text{F/hr} \\ \alpha &= 0.20 \text{ ft}^2/\text{hr} \end{aligned}$$

$$(T_s - T) \text{ average} = 1/0.4 \times 730 \times 2/3 \times (4/12)^2 = 135^\circ\text{F}$$

$$T \text{ (average)} = 2231 - 135 = 2096^\circ\text{F.}$$

The amount of heat absorbed between stations was calculated from the equation:

$$Q = W \times C_p \times \int_{T_1}^{T_2} dT$$

where:

Q = amount of heat absorbed, B.T.U./hr

W = weight of billets, lbs/hr.

C_p = specific heat of billets, B.T.U./ $(lb)(^{\circ}F)$

T = average temperatures of billets, $^{\circ}F$.

$$Q/A = (4/12 \times 1 \times 485) (0.16) (2096 - 1870) \text{ per } 3.5/20 \text{ hrs.}$$

$$Q/A = 33,400 \text{ B.T.U./}(hr)(sq \text{ ft})$$

The values for Q/A were also plotted against the distance from the cold end of the furnace. From the plot, a value of Q/A for station 4 was taken and found to be:

$$Q/A \text{ (total)} = 24,500 \text{ B.T.U./}(hr)(sq \text{ ft})$$

Of this quantity of heat, part is due to heat transfer by convection. This may be calculated as:

$$Q/A \text{ (convection)} = h \times \Delta$$

where:

Q/A is the rate of heat transfer per unit area by convection, B.T.U./ $(hr)(sq \text{ ft})$

h - is the coefficient of heat transfer by convection, already determined as 2.0 B.T.U./ $(hr)(sq \text{ ft})(\text{temp difference in deg. } F.)$

Δ - is the temp difference between the gas and the surface of the billet, $^{\circ}F$.

$$Q/A = 2.0 (1400) - (25.5/35)(1400 - 500)$$

$$Q/A = 2.0 (1400 - 655) = 1490 \text{ B.T.U./}(hr)(sq \text{ ft})$$

Therefore the heat transferred by radiation at station 4 will be:

$$Q/A \text{ (radiation)} = 24,500 - 1,500 = 23,000 \frac{\text{B.T.U.}}{(\text{hr})(sq \text{ ft})}$$

5. Radiant heat transfer as recorded by the probe:

$$T_1 = 2270^{\circ}F + 460 = 2730^{\circ}R$$

$$T_2 = 2140^{\circ}F + 460 = 2600^{\circ}R$$

$$K = 11$$

$$Q/A \text{ (net)} = 0.173 \left[\left(\frac{2730}{100} \right)^4 - \left(\frac{2600}{100} \right)^4 \right] + 11(2730 - 2600)$$

$$Q/A \text{ (net)} = 17,300 + 1,400$$

$$Q/A \text{ (net)} = 18,700 \text{ B.T.U./}(hr)(sq \text{ ft})$$

6. Or from the calculated value of heat transfer,

$$K = (23,000 - 17,300)/130 = 43.8 \text{ B.T.U./}(hr)(sq \text{ ft})$$

(temp diff. in disks, $^{\circ}F$)

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