TESTS OF BOILER EFFICIENCY INDICATOR

BY

G. F. WETZEL

ARMOUR INSTITUTE OF TECHNOLOGY

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A STUDY AND TEST OF A

BOILER EFFICIENCY INDICATOR

A THESIS

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GUY FOOTE WETZEL

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H M Raymond

-o:INTRODUCTION:o-

This thesis is based on work started November 1915 with the idea of applying the principles worked out by I.H.Wilsey for his electrically actuated Boiler Efficiency Indicator in a new instrument using air. In Part One the theory is worked out, together with a description of the electric instrument. Part Two follows thru the work done with the air instrument. Part Three contains a discussion of the results and applications

As the investigation was not primarily started to be written up as a thesis a number of observations were made but not recorded permanently. There was also a lot of detail work done which is not at all essential in the summing up and discussion of results.Tables and diagrams are included in the following pages which will give a good idea of the scope of the work and the results obtained.

-: CONTENTS :-

-: ILLUSTRATIONS :-

THE DESIGN, CONSTRUCTION, AND TEST OF A BOILER EFFICIENCY INDICATOR-RECORDER.

PART ONE

The process of getting the potential energy out of coal and converting it into useful work is at best very wasteful. There are losses in all the various steps of the process, some of which are avoidable or capable of reduction and some which are inherent and can not be eliminated.

To burn coal and release its energy in the form of heat oxygen must be supplied in a quantity sufficient to support combustion of the carbon, hydrogen, and sulphur, which comprise the combustable elements, carbon being the principal constituent. Of course this oxygen is supplied from the air which means that it is diluted with 77% by weight of nitrogen. Further it is found from practice that not less than 30% excess air must be supplied in addition to the theoretical requirements to get complete combustion, and it is only under the very best of conditions that the excess can be cut to that figure.

The average temperature of the gases leaving the boiler is about 500 deg.F. unless an economizer is used. This means that a large amount of heat is unavoidably lost in the chimney gases which are composed of the gases of combustion,

inert nitrogen, and water vapor from the combustion of the hydrogen in the coal, and that contained in the air supplied. The amount of this loss can be determined approximately by multiplying the number of pounds of air supplied per pound of coal plus the weight of combustable in a pound of coal, by the product of the number of degrees above the temperature of the incoming air and the specific heat of the gas.

In the greater number of boiler plants the steam generating equipment is in the hands of cheap labor, ignorant of the true principles of efficient combustion, and whose chief interest is not in the most economical operation but in keeping steam up with the least effort to themselves. It is true that in many cases the engineer checks up from time to time the performance of his plant, but in most cases the steam producing end does not receive any where near the attention it should. Under these conditions a much greater excess of air is admitted to the furnace than is required. This is due to too much draft, too thin a fire, holes burned in the fire or leaks in the setting, and some times all of these. The air excess increases very rapidly, and consequently the heat loss, so that while the unavoidable loss is large, it can be reduced considerably from the average results obtained. It is true that some of the heat escaping

up the chimney is utilized in the mechanical work of producing the draft and moving the air, but this amount is small as the chimney is very inefficient as a mover of air.

From this brief discussion of the steam producing process, it will be seen that any appliance or method which will increase the efficiency has a very real value to the power plant operator.

One reason there are so many inefficient boiler furnaces is the fact that it is difficult to tell just what the apparatus is doing. Holes in the fuel bed can be seen and covered up, but no one can tell without an instrument how much CO_2 there is in the flue gases, or whether there is any CO. In other words,the steam gauge may give a constant reading, but with out a definite determination the air excess or completeness of combustion, are unknown factors. It is impossible to tell, also, whether the draft, thickness of fire and rate of firing are the best for the particular conditions existing, without exhaustive tests which in many plants cannot be made.

The first requisite for high efficiency is to know what is going on in the boiler and furnace, and how conditions may be improved for the unit under consideration. Within the limits of practice, a clean boiler will absorb nearly all the heat that is available, so that the most

fertile field for improved conditions is in the furnace.

The standard method of determining what a boiler unit is doing is to run an evaporation test of 8 hours or more, and then compute the efficiency by comparing quantity of heat given to the water with the quantity of heat available in the coal. However it is the instantaneous value of efficiency that is most valuable in improving the economy, and also the most difficult to obtain. The CO_2 machine gives some indication as to conditions, but its result is only relative. This is also subject to the great difficuly of obtaining a truly representative sample of flue gas.

When the intensity of the process of liberating the heat in coal and the rapidity with - which it is carried on, are considered, the value of knowing the instantaneous efficiency will be appreciated.

With these ideas in mind, I.H.Wilsey started experimenting in 1912. After considering and trying several plans, he decided that an instrument which considered heat quantities,- in the gases entering the boiler from the furnace, and in the gases leaving the boiler,- offered the greatest possibilities for scientific, practical and commercial success.

Boiler and furnace efficiency is a matter of heat quantities, whether heat in coal and water, or heat in the entering and leaving gases, is considered, and may be determined with equal accuracy in either case when the different conditions are allowed for.

Of the heat liberated from the fuel, part radiates directly to the boiler and setting, but the greater part enters the gases of combustion and raises their temperature to a point dependent on their mass and specific heat. As these gases pass thru the boiler, part of the heat is absorbed and used in making steam, while the rest is carried out the stack and lost.

Efficiency in general is the ratio of the part utilized to the whole present to be utilized. In this case it is the heat utilized by the boiler compared with the heat liberated from the coal. Since the bulk of the heat enters the gases, the ratio of the heat absorbed by the boiler to that originally in the gases closely approximates the total efficiency and will exactly equal it if corrected for radiation and minor losses.

The heat absorbed by the boiler is equal to the difference between that contained in the gases as they enter and leave. Therefore, this

difference compared with the heat originally contained approximates true efficiency, and if corrected for radiation and minor losses will equal it.

The ratio of these total amounts of heat is necessarily the same as the ratio for each individual mass, therefore to find the total or true ratio of heat utilized to heat liberated, it is not necessary to know the whole amount of heat present but simply the ratio of the amount per mass in the gases before the boiler minus the amount after the boiler as related to the amount present before the boiler, and to correct this for radiation, etc.

When mass is unity, quantity of heat is the product of temperature and specific heat, so we can express the efficiency by the formula $\frac{TS - T'S'}{TS}$, where T and S are temperature and specific heat of the gases in the combustion chamber, and T' and S' temperature specific heat of the gases in the uptake. If we let R equal the correction for radiation, etc., the real efficiency is shown by

$$\frac{TS - T'S'}{TS} \pm R = E$$

It is necessary to consider S and S' because of the change in specific heats of gases

Figure 1. Indicating Gauge.

FIGURE 1

FIGURE 1 A

that occur over the wide range of temperatures found in boiler practice.

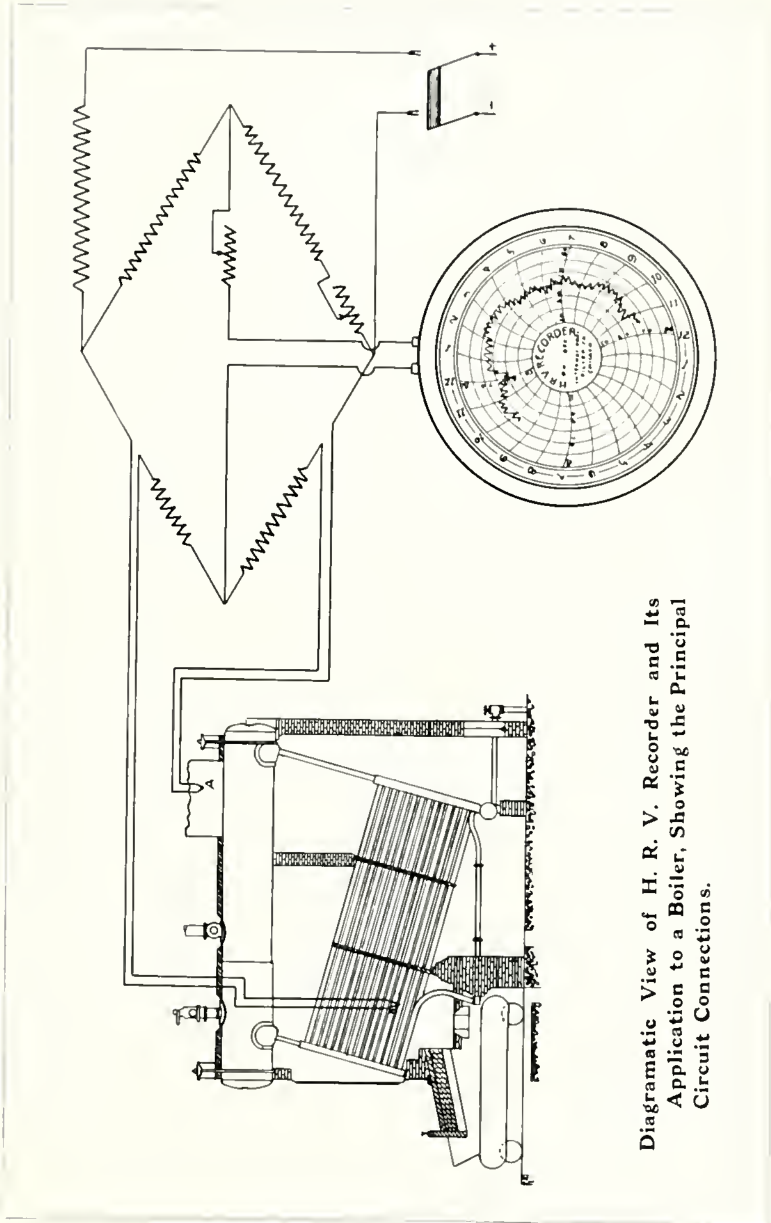
From the reasoning followed above it will be seen that heat liberation, that is, combustion, was included, so that both absorption and combustion are considered. Examination of the formula will show that E may be increased either by increasing T or decreasing T', that is by better combustion or better absorption. Thus combustion is taken care of in the only proper manner,- according to the heat made available for the boiler to absorb.

The instrument Mr. Wilsey finally developed after more than a year of experimenting and testing, was called the Wilsey Fuel Economy Gauge, and was handled by the Adkins-Wilsey Co. Early in 1915 the International Filter Co. took over the business and are now handling it.

The Wilsey Fuel Economy Gauge is shown in Figure 1. A recorder was included when desired, and is shown in Figure 2. This recorder is a Hoskins recording millivoltmeter with a special front and internal resistance. When the ownership of the instrument changed hands the name was changed to the H R V Recorder, the letters standing for Heat Ratio Variation, and it was redesigned completely, and several improvements made. The present form of the instrument is shown in Figure 1A.

Figure 2. Recording Gauge.

FIGURE 2



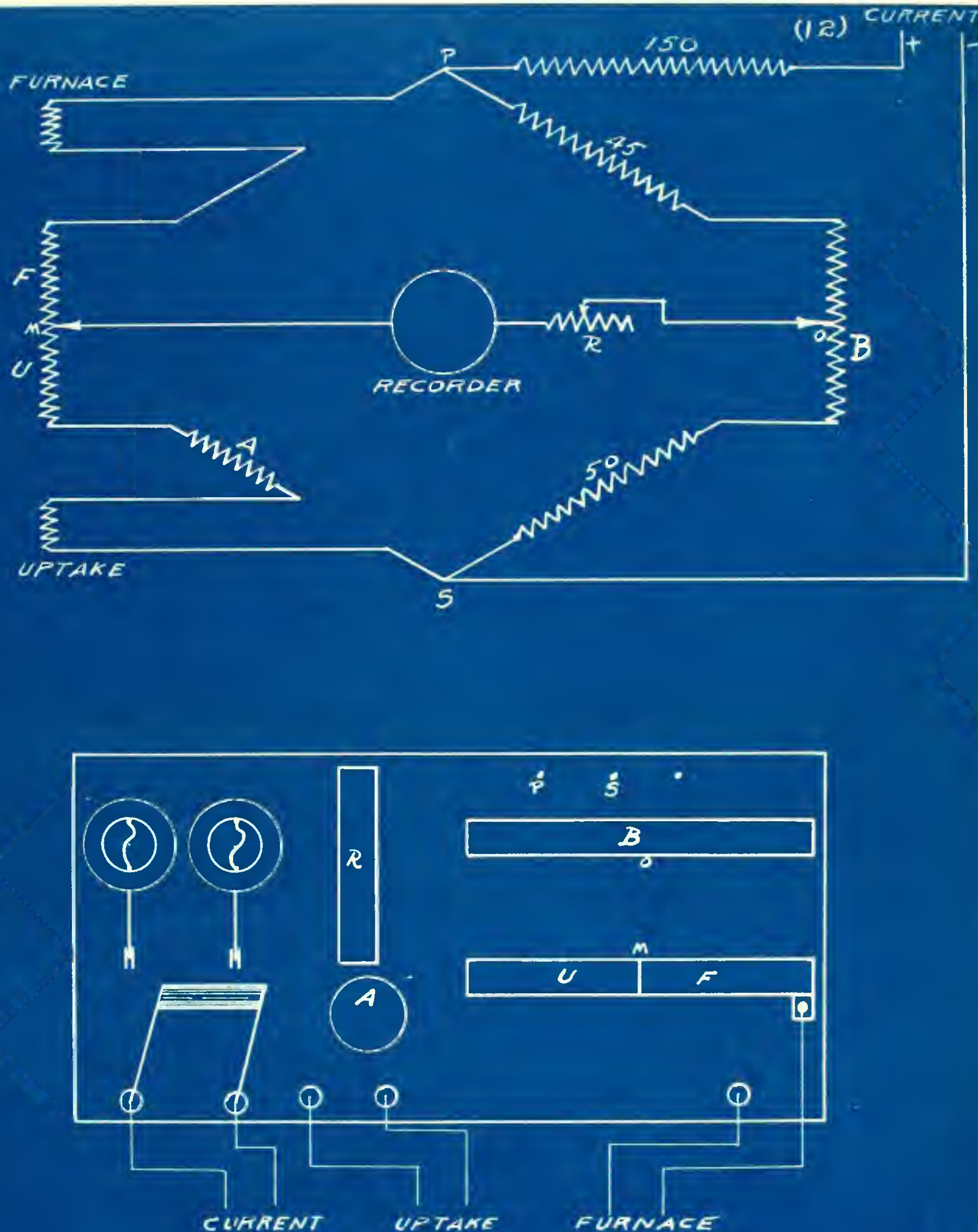
Diagramatic View of H. R. V. Recorder and Its Application to a Boiler, Showing the Principal Circuit Connections.

FIGURE 2 A

The instrument consists essentially of a Wheatstone bridge, two platinum resistance pyrometers, and the indicating and recording millivoltmeters. The pyrometers are located as shownin Figure 2A, one among the lower tubes of the boiler at B, and and the other in the path of the gases leaving the boiler at A. The former is called the furnace pyrometer and the latter the uptake pyrometer. These are connected respectively with two sides of the Wheatstone bridge, and the galvanometer or millivoltmeter is connected across the centers of the two current paths. In the case of a return tubular boiler the furnace pyrometer would be placed under the deflection arch at the rear of the boiler in the path of the heated gases.

The diagram of the arrangement of the Wheatstone bridge for the instrument as now built is shown in Figure 3. The current source is any direct current line, usually 110 volts, in series with which is the 150 ohm coil to cut down the entering current and reduce heating in the smaller resistance units. The right hand current path (in Figure 3) contains a 45 ohm resistance, adjustable rheostat B of 10 ohms, and a 50 ohm resistance. The 45 and 50 ohm units are standard coils, purchased from the General Electric Co.

FIGURE 3



KEY

FIGURE 3

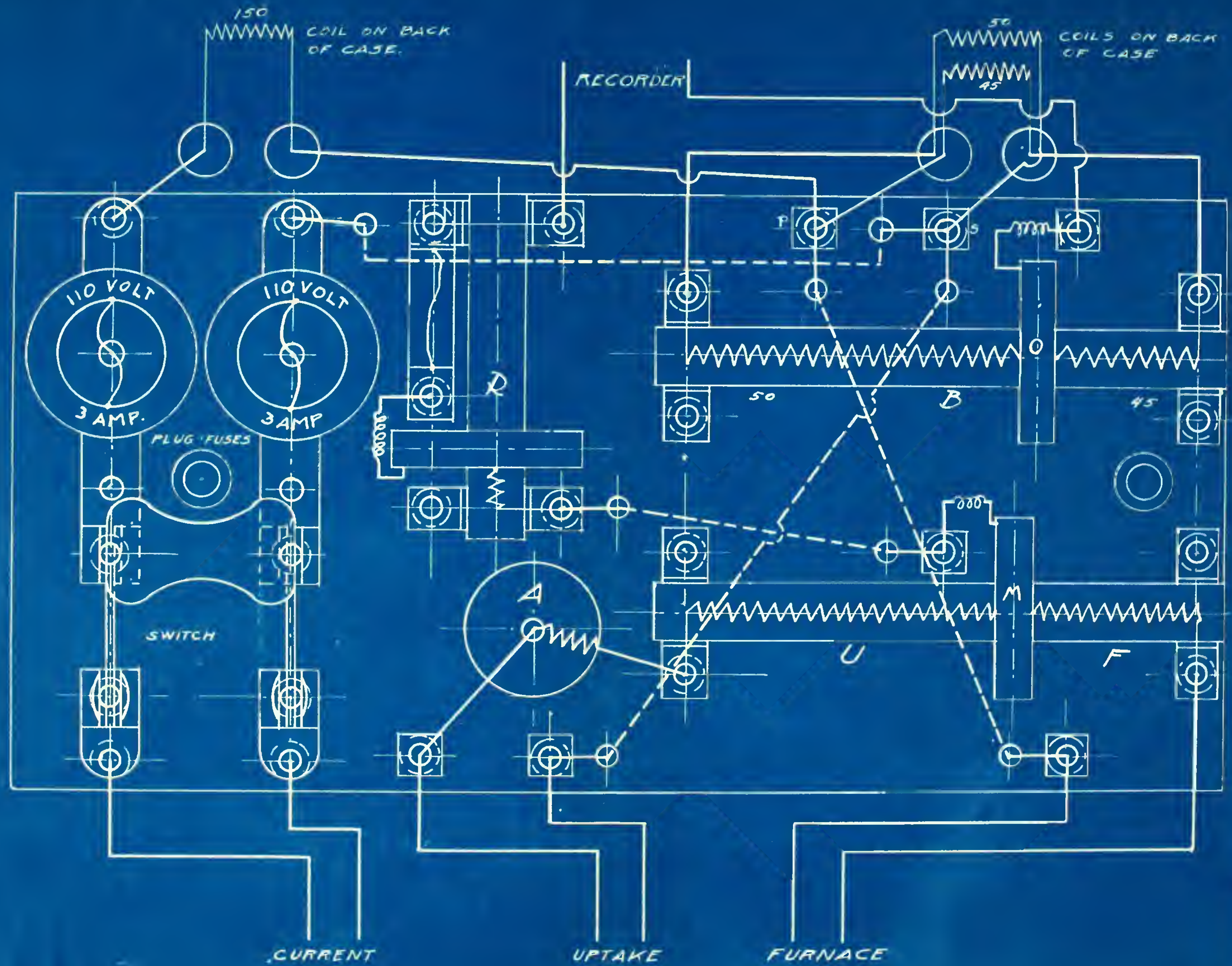
H-R-V RECORDER CIRCUIT

INTERNATIONAL FILTER CO

CHICAGO.

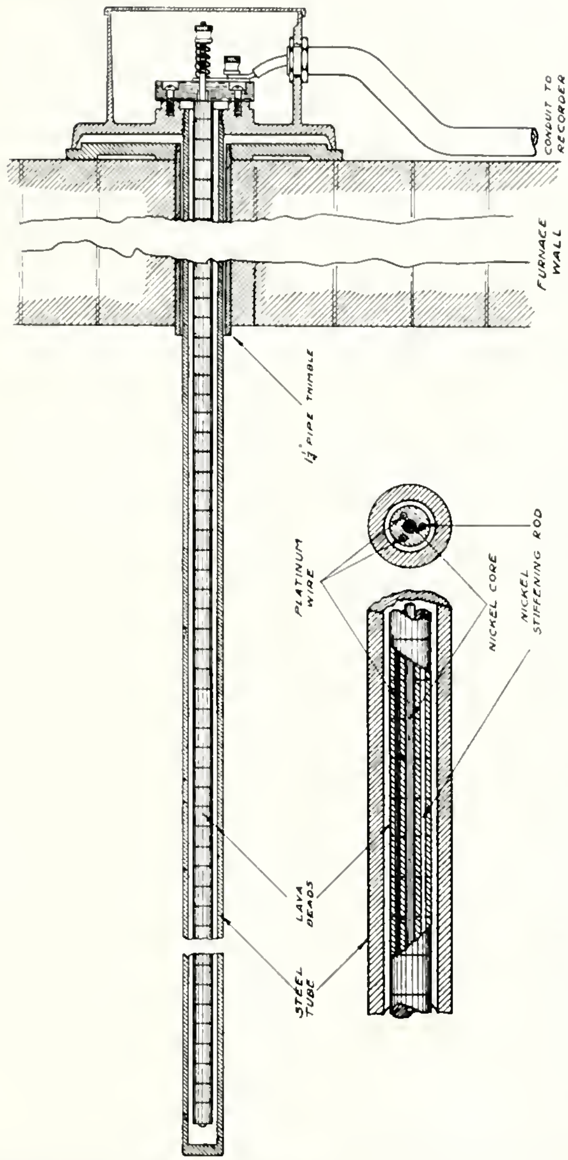
W 352

FIGURE 4


150
COIL ON BACK OF CASE.
RECORDER
50
45
COILS ON BACK OF CASE
P
S
110 VOLT
3 AMP.
110 VOLT
3 AMP
R
O
50
B
45
PLUG FUSES
SWITCH
A
M
U
F
CURRENT
UPTAKE
FURNACE

The left hand path consists of the furnace pyrometer and its leads; F and U combined in a single adjustable rheostat of 10 ohms, A a 5 ohm resistance, and the uptake pyrometer with its leads. In series with the recorder circuit is R, a 5 ohm resistance which makes the curve of the recorder parallel itself above or below the uncorrected reading to allow for radiation and minor losses.

The arrangement of the Wheatstone bridge is shown in Figure 4. The corners of the bridge are marked to correspond in both Figures 3 and 4 so that the wiringmay be easily traced out. The 150, 45 and 50 ohm units are contained in a ventilated cover, mounted on the back of the instrument case. The wires marked "Current", "Uptake" and "Furnace" come out thru an opening in the back of the case where the conduit for the wires to the current source and pyrometers is connected. The rheostats, fuses, etc. are mounted on an asbestos fiber board and the apparatus as a unit is then screwed into the lower compartment of the case. The upper part contains the recording instrument shown in Figure 2. In case an indicating instrument is desired in connection with the H R V Recorder, this is held by a special bracket on the top of the case, and is connected in parallel with recording millivoltmeter.



Platinum Resistance Extending Through the Furnace Wall, Showing the Method of Protecting the Platinum Wires.

FIGURE 5

After the H R V recorder is installed and connected it is calibrated. This is necessary for each particular instrument as there are probably no two plants which have just the same conditions of operation, or identical settings, etc. The Recorder is very nearly in balance when installed, and the final balance is obtained by changing the positions of points M and O (Figure 3). This arrangement makes it possible to make either the uptake or furnace pyrometer more sensitive or to exaggerate if desired, any one point of operation. The size of the variations on the chart can also be controlled by changing the positions of M and O.

When properly calibrated the average reading will be within one or two per cent of that value of efficiency given by an evaporation test. As there is no way except the CO2 machine or pyrometer of checking up the efficiency variations, the actual size of these is not important, since the fact that there are variations is a guide to improving conditions.

At first considerable trouble was experienced with the platinum resistance pyrometers. These were made by stringing the #30 B&S platinum wire thru clay tubes about 3/16" in diameter and 4" long, containing two holes about 1/32" in diameter, and laying it thus protected in a horizontal

Shelby steel tube 11/16" inside diameter with 3/16" walls, plugged and welded at its inner end. Some constituent of the clay tubes evidently affected the platinum in some way, and made it very brittle, so that it soon broke if subject to any vibration. The present construction as shown in Figure 5 is giving very good satisfaction, and no trouble has been caused by broken wires with this type.

The protecting and insulating material now used is called "Lavite", and is the same material from which the old style open flame gas burners were made. It seems to be entirely unaffected by heat up to temperatures of 2000 deg. F. This is made up in the form of beads 1/2" in diameter and 1/2" long, pierced with a 5/32" hole in the center and three 1/16" holes around it. The beads are slipped on 5/32" nickel rod 5'-8" long and 1-16" rod of the same material is run thru one of the small holes. This prevents the rod from turning and shearing the platinum wire, which runs thru the other two holes. The wire is 10'-0" long, and a piece of 1/16" nickel rod, length equal to the thickness of the furnace wall, is soldered on each end with pure gold. This eliminates the uncertain effect of the heated wall on the pyrometer. The details of the outside connection may be seen from the drawing, Figure 5.

It is well known that when no current is flowing thru the galvanometer properly connected with a Wheatstone bridge that the resistances of the sides are proportional, i.e. $R_1:R_2::R_3:R_4$. In the H R V Recorder there must be current flowing thru the galvanometer to give a reading so that a slight error is introduced in the ratio of the two resistances which are proportional to the temperatures. However this error is small and is corrected in the coils in series with the pyrometers which also correct the ratio to allow for the different specific heats in uptake and furnace gases. The Wheatstone bridge thus enables us to get a reading on the galvanometer which is very closely proportional to the ratio of heat quantities mentioned before. There is a theoretical error that it is impossible to get away from,but practical considerations and the difficulty of checking results make this negligible. Looking at it from another standpoint, it may be seen that the amount of current flowing from one current path to the other thru the millivoltmeter will be affected by a change in either pyrometers. The instrument is so made that the temperature variations at either point have the proper effect on the result as shown by calculation, and testing and experience. The instrument, there-

fore shows the ratio of heat quantities and not temperature differences.

Figures 6 and 7 are copies of charts made by the Wilsey Fuel Economy Gauge installed at the Fox River Paper Co. at Appleton, Wis. They are self-explanatory and show the results that were actually accomplished in one plant. The equipment there is five 250 horse power return tubular boilers with Taylor Stokers.

BEFORE

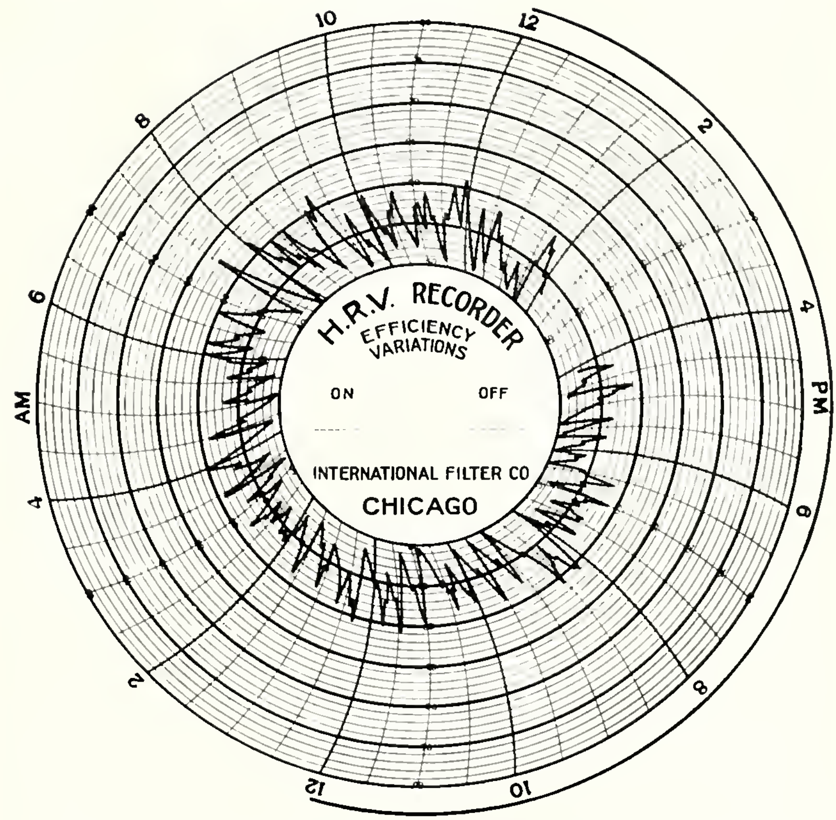


Chart Showing Variations in Working of a Stoker-Fired Boiler under Ordinary Conditions, when the Fireman was Not Permitted to See the Indications of the H. R. V. Chart.

FIGURE 6

AFTER

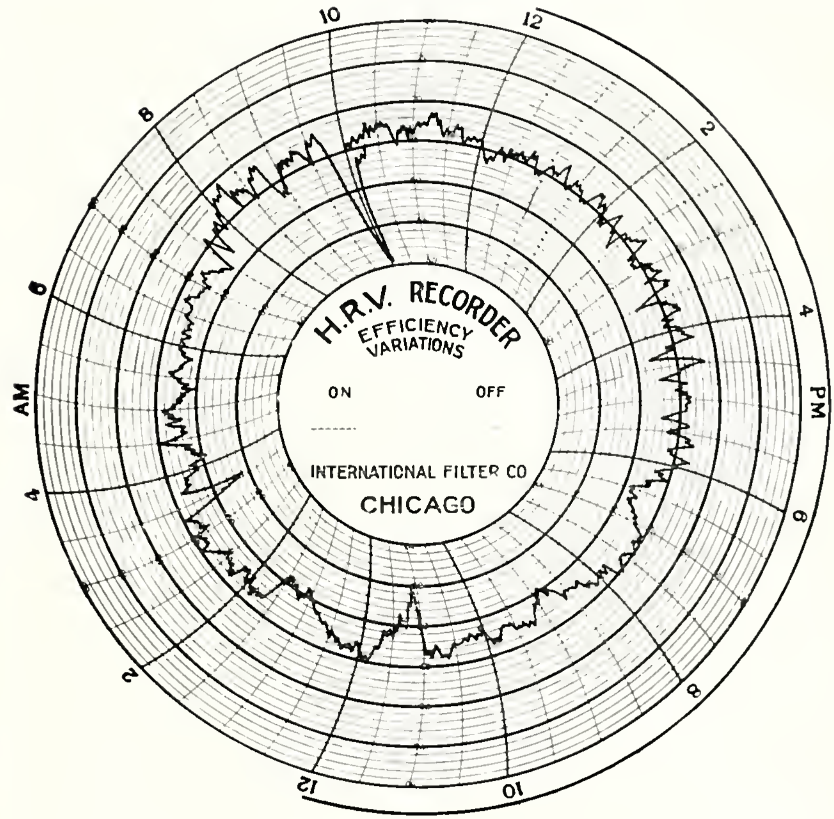


Chart Showing Improved Efficiency and More Even Operation of Same Boiler with Fireman Watching the H. R. V. Recorder.

FIGURE 7

-: PART TWO :-

The H R V Recorder previously described is an excellent and useful instrument in the boiler room, but it is expensive to manufacture and sell, that the price of $350.00 per boiler limits it commercially to a comparitively small number of plants. This led Mr. Walter H.Green, chief engineer of the International Filter Co. to endeavor to apply the principles worked out for the Wilsey instrument to another one which could be made to sell at a lower price. Air was the medium chosem instead of electricity, using constant volume air thermometers connected with expansion chambers, which in turn were connected, each with one side of a differential manometer.

The diagrammatic arrangement of the new instrument is shown in Figure 8. The thermometers are located in the same positions relatively as the electrical pyrometers as shown in Figure 2A.

The instrument was designed to be filled and sealed with the tubes at room temperature. Thetwo pyrometer tubes had equal volumes, as did the two expansion chambers. This gave equal weights of air in the two tubes, and in the two chambers. Inserting the thermometers in their respective places will of course raise their temperature and cause the air contained to expand, and increase

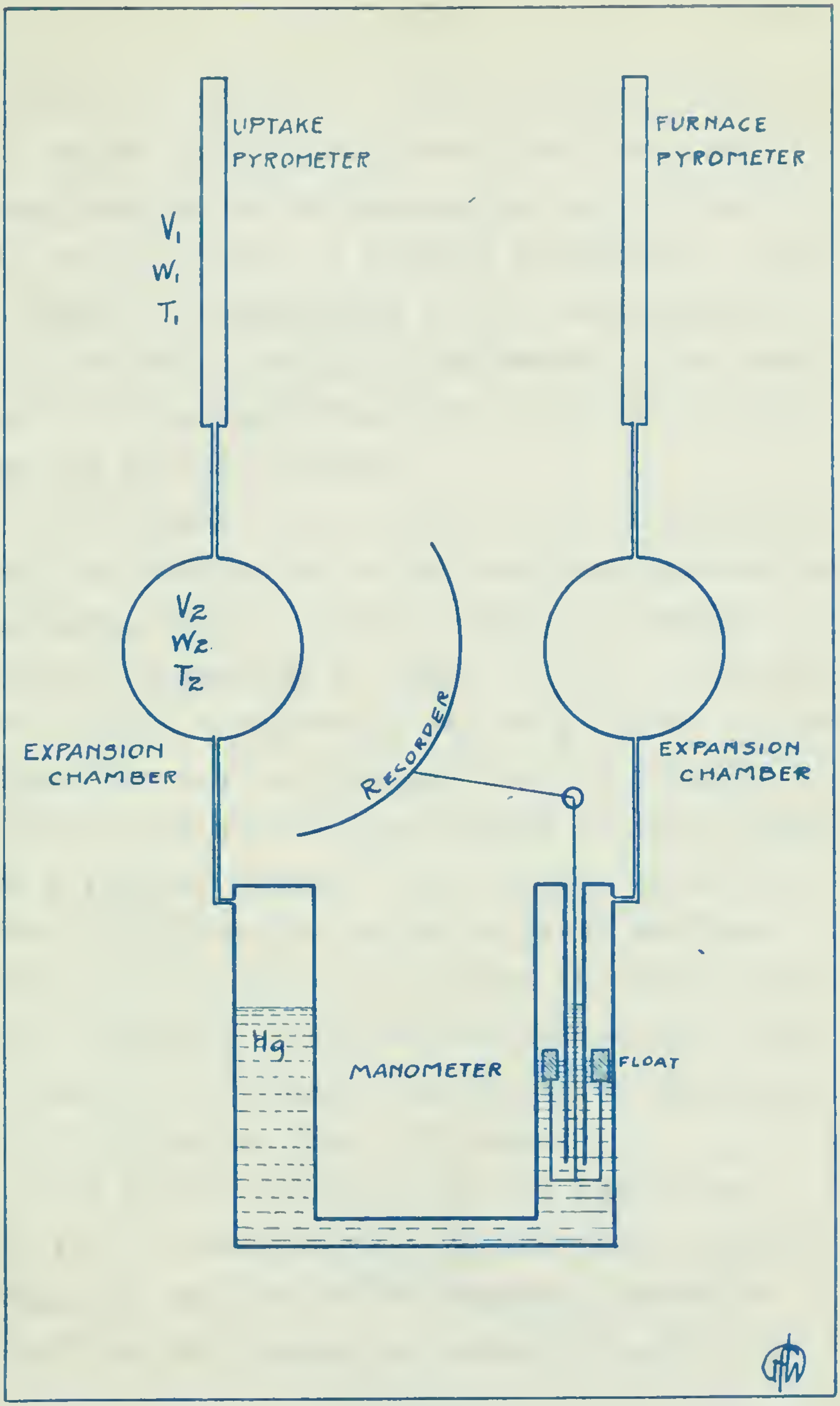
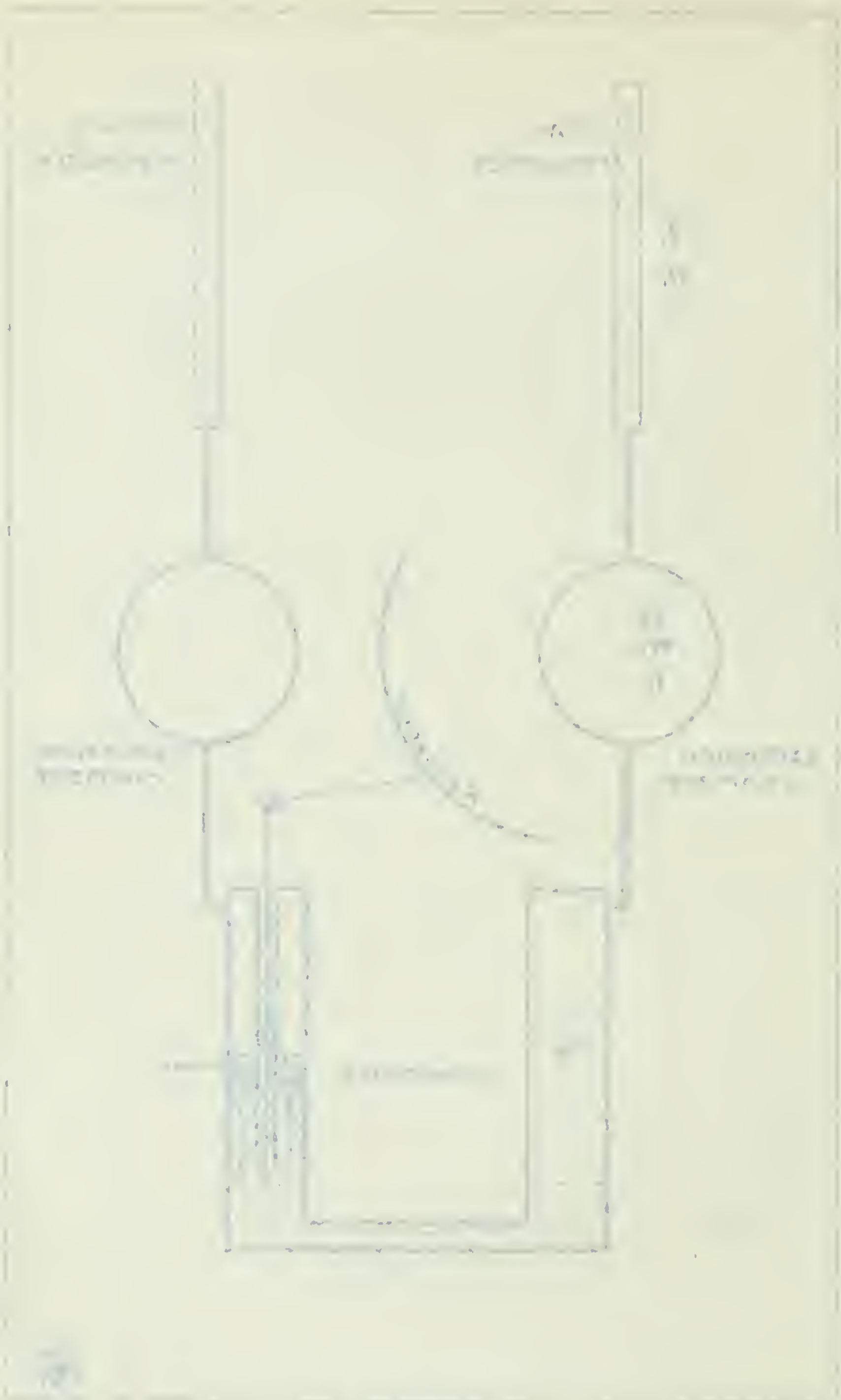

UPTAKE
PYROMETER
FURNACE
PYROMETER
V_1
W_1
T_1
V_2
W_2
T_2
EXPANSION
CHAMBER
RECORDER
EXPANSION
CHAMBER
Hg
MANOMETER
FLOAT

FIGURE 8



the pressure in the whole system. The air in the tube in expanding will be forced out into the cappilary tubing and the expansion chamber and be cooled, until a state of balance is reached. With every change in temperature at the tube there will be a corresponding change in pressure and thus the float in the manometer will move, and actuate the pen arm of the recorder.

The weight of air left in the thermometer tube will be a function of the absolute temperature and the effectiveness of that tube will depend on this weight. Referring to table 1, it will be seen that the uptake temperature has more effect on the efficiency for a given change than the furnace temperature, but as the temperature is lower there will be a greater weight of air there, which will make each side have its proper effect, and make the difference in pressure between the uptake and furnace a function of the boiler and furnace efficiency, which if corrected for radiation and minor losses will give the true efficiency.

The temperature, T_2, of the expansion chamber will be same as that of the room, and in this work was assumed to be constant. Therefore the weight in the expansion chamber, V_2, will be

1	2	3	4	5
$\frac{T_1 - T_2}{T_1}$	VALUE OF "I"	100° CHANGE IN FURNACE TEMP.	100° CHANGE IN UPTAKE TEMP.	RATIO "4" TO "3"
$\frac{2000-500}{2000}$	.750			
$\frac{2100-500}{2100}$	.762	.012		
$\frac{2000-400}{2000}$	.800		.050	
$\frac{2000-600}{2000}$	.700		.050	4.16
$\frac{1900-500}{1900}$	.737	.013		3.85
$\frac{1500-500}{1500}$	.667			
$\frac{1600-500}{1600}$	.688	.021		3.2
$\frac{1500-400}{1500}$	.734		.067	
$\frac{1400-500}{1400}$	.643	.024		2.8
$\frac{1500-600}{1500}$	.600		.067	
			AVERAGE	3.67

TABLE 1

a function of the pressure, and if one is known the other may be determined easily.

If weight is held constant, $PV/T = P'V'/T'$, and similarly, if volume is held constant, $P/WT = P'/W'T'$ In determining the pressure existing in the instrument, each side will be considered separately. Let the volume and temperature in the thermometer tube be V_1 and T_1, respectively. The pressure P will be equal in both tube and expansion chamber.

Let $V_2/V_1 = R$

Then $T_1W_2R = T_2W_2$ (1)

Let $W1+W_2 = M$ (2)

$T_1W_1R - T_2W_2 = 0$ (3)

$T_1W_1R + T_1W_2R = MT_1R$ (from (2)) (4)

Therefore $W_2(T_1R+T_2) = MT_1R$ (5)

$$W_2 = \frac{MT1R}{T_1R+T_2} = MR \times \frac{T_1}{T_1R+T_2} \qquad (6)$$

Let W_2' be original weight of air in V_2

Let P_o be original pressure in V_2

Then $P = W2/W_2' \times P_o$

$$= \frac{MR}{W_2'} \times \frac{T_1}{T_1R+T_2} \times P_o$$

From this formula the pressures given in tables 2 and 3 were calculated. The ratio V_2/V_1 was

T_1 F°	T_1 Absolute	P LBS.
400	860	16.89354
500	960	17.31575
600	1060	17.67337
700	1160	17.98102
-•-	-•-	-•-
910	1370	18.50284
980	1440	18.65022
1050	1510	18.78451
1190	1650	19.02353
1260	1720	19.13038
1330	1790	19.22996
1120	1580	18.93568
1400	1860	19.32297

% Efficiency	Difference (LBS)	Temperatures		Change for 1% Change in Efficiency	
		Furn.*	Upt.	LBS.	In. Hg.
50	.66920	980	700		
53.3	.80659	1050	700	.0418	.0853
57.2	.97658	980	600	.0436	.0890
61.5	1.15644	910	500	.0484	.0987
64.3	1.33447	980	500	.0635	.1297
66.7	1.46876	1050	500	.0560	.1142
68.7	1.61993	1120	500	.0756	.1542
70.5	1.70778	1190	500	.0486	.1091
73.2	1.88407	1050	400	.0653	.1332
75	2.04214	1120	400	.0767	.1585
75	2.00722	1400	500	.0666	.1358
77.7	2.23684	1260	400	.0665	.1357
80	2.42943	1400	400	.0837	.1707

* AT PYROMETER, = .7 IN FURN.

$\frac{V_2}{V_1} = 2$ $T_2 = 65°F$

TABLE 2 TABLE 3

taken as 2 and the temperatures assumed as shown. The efficiency was calculated from (T-T')/T, as only relative results were wanted and there was some doubt about the accuracy of the assumptions in regard to furnace conditions. After studying the results as shown in tables 2 and 3 it was seen that the pressures were higher than practicable as these had to be balanced by a mercury column, and the space was limited. For this reason, R was taken as 3, and tables 4 and 5 calculated. These pressures were within the required limits, so that the instrument was built using that ratio.

The diagram, Figure 8, shows in a general way the apparatus. The pyrometers were made from Shelby steel tubing, 5'-10" long, 11/16" inside diameter, with 3/16" walls, plugged and welded at the inner end. The outer end was plugged with a piece of steel, 11/16" in diameter, with a length equal to the furnace wall thickness, grooved and drilled so that connection could be made with the inside. This piece was welded in place also. Each expansion chamber was made of a piece of steel tube, 3" in diameter, with a piece of brass plate soldered in each end to make an air tight compartment. The manometer was arranged as shown in the

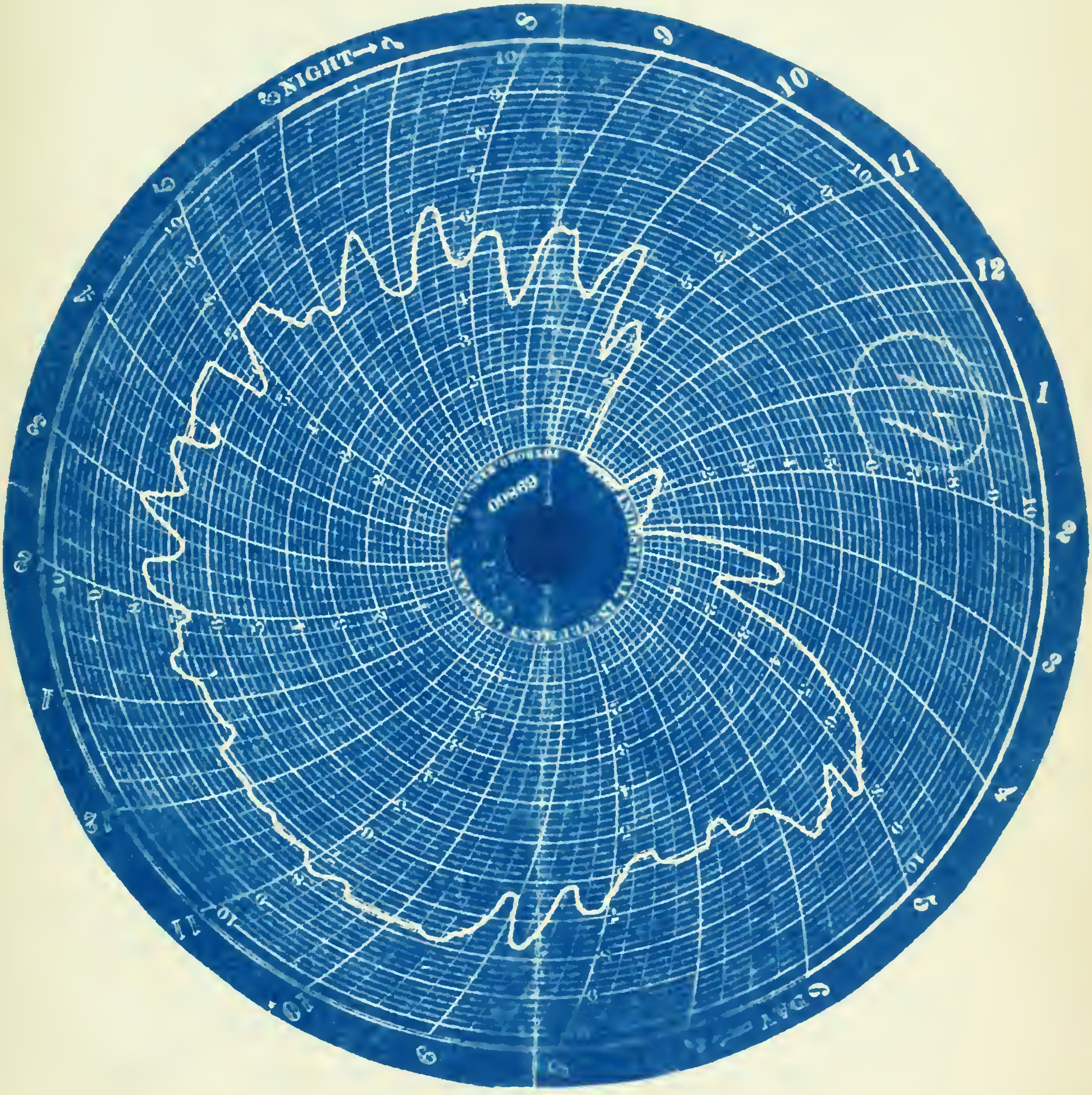


FIGURE 9

figure, the vertical members being of 1" steel tube, connected by 1/8" pipe. The float was made of cast iron, 5/8" deep with 1/32" allowed around the outside for clearance. The thermometers were connected with the expansion chambers and manometer by 1/16" brass tubing.

On December 1,1915, the instrument was completed, and taken to Armour Institute of Technology for testing in connection with the 320 horse power Stirling boiler. The first chart was removed from the recorder the following day. During the night or when starting up the fire from bank apparently the pressure rose too high and forced the mercury out thru the sealing tube. The next day leaks developed in the mercury manometer, and then in the air chamber or tubing so that the pressure was lost. These faults were corrected and the instrument started again. It soon became apparent that there was not variation enough in the curve produced by the recorder to be of any value, so the value of R was cut to 2, and a longer sealing tube inserted. This gave results that were somewhat better but still the instrument was not sensitive enough.

On December 11, the volumes in the expansion chambers were cut down by filling with oil so that their volumes were proportional to the weights of

T_1 F° Actual	T_1 F° at Pyrometer	T_1 Abs.	P Lbs.	% Efficiency	Difference Lbs.	Temperatures (Actual) Furn.	Upt.	Change for 1% Change in Efficiency Lbs.	In. Hg.
450	450	910	16.43871	59.4	.63147	1200	525		
500	500	960	16.57797	60.7	.67444	1300	550	.0330	.0673
525	525	985	16.64310	62.7	.73683	1300	525	.0312	.0636
550	550	1010	16.70549	63.7	.77067	1400	550	.0338	.0690
-o-	-o-	-o-	-o-	64.7	.80196	1300	500	.0310	.0632
1200	840	1300	17.27457	65.5	.83306	1400	525	.0388	.0792
1300	910	1370	17.37993	67.4	.89819	1400	525	.0343	.0700
1400	980	1440	17.47616	68.6	.94122	1300	450	.0307	.0626
1500	1050	1510	17.56439	68.4	.94005	1600	550	.0293	.0602
1600	1120	1580	17.64554	69.7	.98642	1500	500	.0356	.0726
1700	1190	1650	17.72053	71.1	1.03745	1400	450	.0365	.0745
1800	1260	1720	17.78997	71.7	1.06757	1600	500	.0406	.0828
1900	1330	1790	17.85445	71.8	1.07743	1700	525	.0429	.0872
2000	1400	1860	17.91449	73.2	1.12568	1500	450	.0344	.0702
				73.3	1.14256	1700	500	.0434	.0885
				73.6	1.14896	1900	550	.0397	.0890
				74.9	1.20683	1600	450	.0445	.0908
				74.9	1.21200	1800	500	.0484	.0987
				76.3	1.27648	1900	500	.0461	0940
				77.5	1.33652	2000	500	.0417	.0851

TABLE 4 $\frac{V_2}{V_1} = 3$ TABLE 5 $T_2 = 65°F$

gas in the heated thermometer tubes when under atmospheric pressure. The charts obtained under these conditions were much better and gave promise of a successful machine.

To be sure that the fluctuations in the curve really corresponded to changes in the efficiency, on December 16, readings of the uptake and furnace temperatures, the latter with a radiation pyrometer, CO_2, steam pressure, and notes on the condition of the fire were taken every fifteen minutes during the day. The chart for that day checked up very well with these observations, showing that the variations indicated were dependable. It was found that all the charts from December 11 to 16 showed the efficiency changes quickly and accurately as near as these could be checked up from observations and data taken. Figure 9 is a copy of a typical chart obtained. The charts used were of the standard form furnished by the Foxboro Co. with the recording instrument, graduated from 0 to 100.

While the form of the daily charts was the same approximately, and showed very clearly when the fire was banked, and started again in the morning, the actual efficiency varied considerably, from near the center of the chart to the outside.

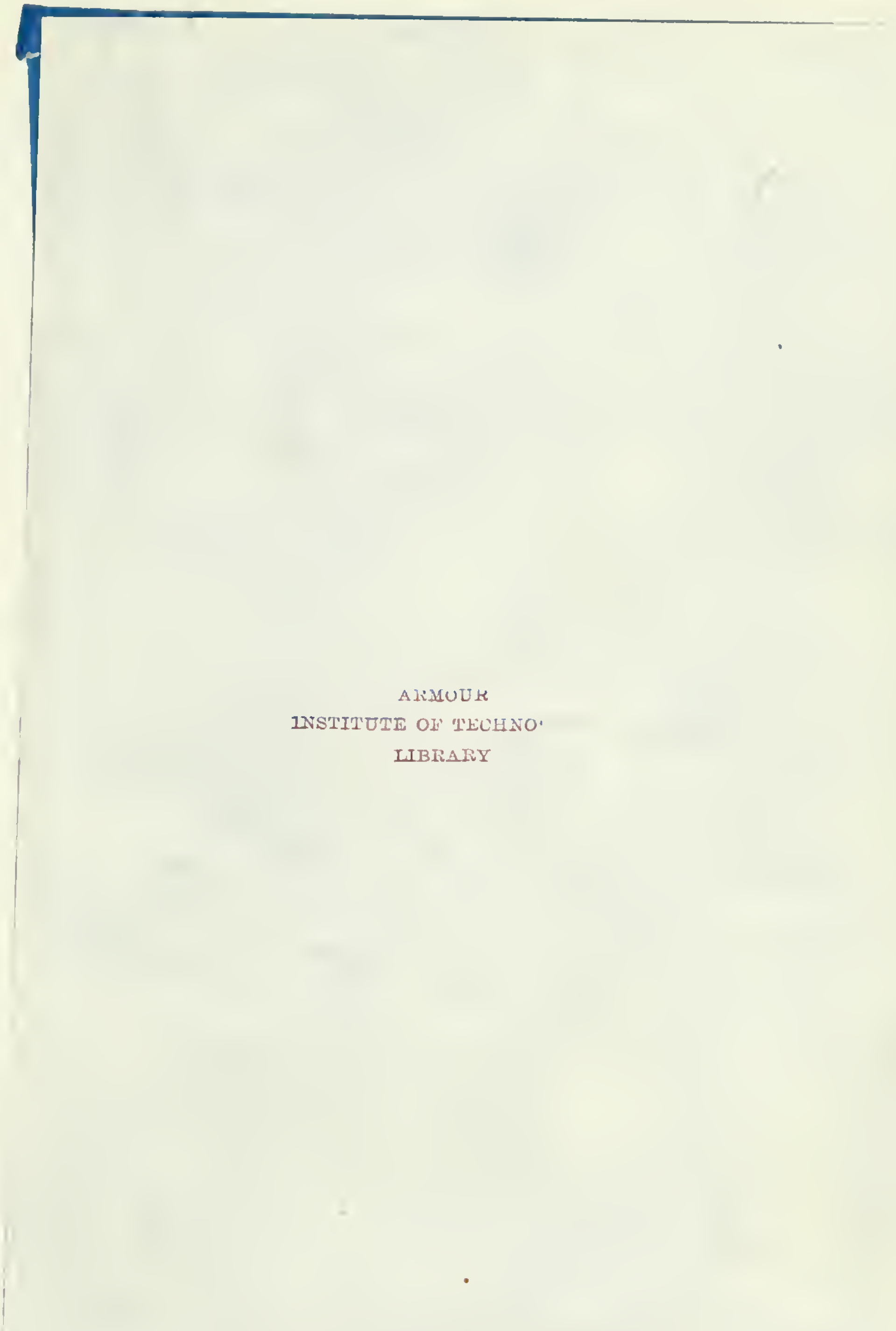


FIGURE 10

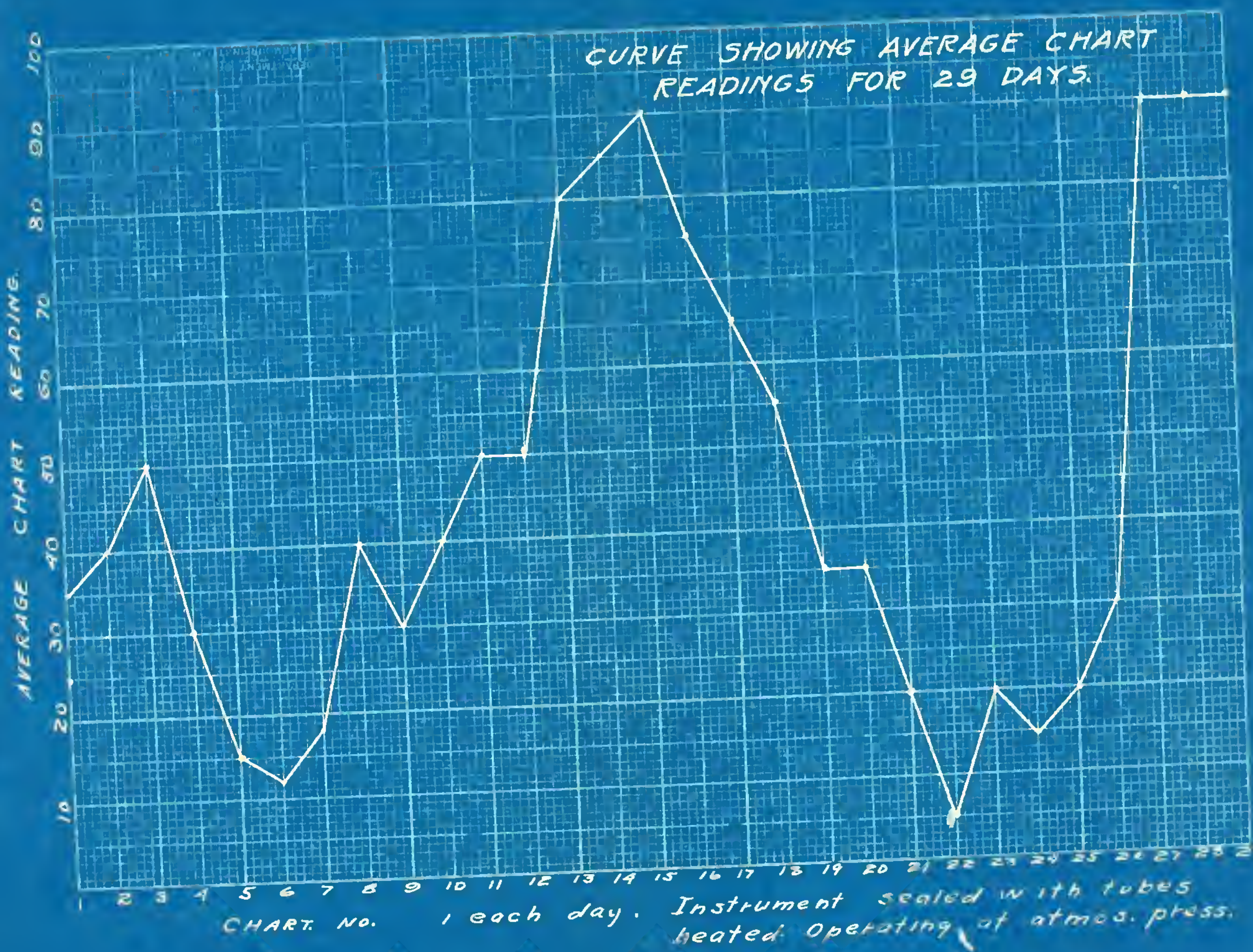

CURVE SHOWING AVERAGE CHART READINGS FOR 29 DAYS.
AVERAGE CHART READING.
10 20 30 40 50 60 70 80 90 100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
CHART. NO. 1 each day. Instrument sealed with tubes heated. Operating at atmos. press.

FIGURE 10

pump was removed, to about 3" of mercury, and this held for three days with further loss.

The instrument was taken apart once more, and by testing each part under water, several small leaks were discovered, which were repaired. After assembling, the instrument was again started, but still would not hold up the pressure.

On February 5,1916 the machine was again put in operation to work at a pressure which would vary slightly above and below atmospheric. The volumes of the expansion chambers were proportioned in this test to be theoretically accurate, compensated correctly for the relative affectiveness of uptake and furnace ends, and specific heat change from 500 deg. to 2000 deg. F. The affectiveness enters in here because we will have different weights of air in each side, so that it will not automatically compensate and give true efficiency as when sealed and filled at room temperature.

1 cu. ft. air at 1500 deg. weighs .02041 lb.

1 cu. ft.air at 500 deg. weighs .04150 lb..

Therefore, if W_{1f} and W_{1u} are the weights in V_1 for furnace and uptake tubes, respectively, $W_{1u}/W_{1f} = 2.04$. From table 1,(effect of 100 deg. change in uptake)/(effect of 100 deg. change in furnace) is equal to 3.5 approximately. Allowing for the change in specific heat, this value is

3.5/1.2 or 2.92 where 1.2 is the ratio of the specific heat in the furnace to the specific heat in the uptake. The volume of the thermometer tubes is 17.76 cu. in. Therefore the uptake expansion chamber will be

2.04/2.92 x 17.76 cu.in. or 12.41 cu. in.

The value of R for the furnace side was shown by experience to be most satisfactory when equal to 1.

For the instrument to work at approximately atmospheric pressure, there will be some pressure below this which will exist in each side when the tubes are at room temperature, assumed as 70 deg. From the formula deduced to find the pressure in each side when the tubes are heated, the initial pressures which in the case under consideration will be different, must be found.

Total vol. in upt. side 17.76 + 12.41
or 30.17 cu. in.

Relative wt. in V_2 @ 70 deg. = 12.41 x .07491
or .9296

Relative wt. V_1 @ 500 deg. = 17.76 x .04135
or .7344

Therefore total rel. wt. is 1.6640 when sealed.

Relative wt. of 30.66 cu.in. at room temperature is 30.17 x .07491 or 2.260

Therefore initial pressure P_o = 1.6640/2.260 atmos.
= .7363 atmospheres or 22.089 in. mercury.

T_1 actual F°	T_{1F} $(=\frac{2}{3}T_1)$	T_{1U} F°	% Efficiency	P_F Atmos.	P_F In. Hg.	P_U Atmos.	P_U In. Hg.	Difference In. Hg.	In. Hg. for 1% change in eff.
1050	700	525	50	.8724	26.172	1.0195	30.585	-4.413	
1200	800	525	56.2	.8967	26.901	1.0195	30.585	-3.684	.118
1200	800	500	58.4	.8967	26.901	1.0035	30.105	-3.204	.220
1350	900	500	63.0	.9146	27.438	1.0035	30.105	-2.667	.117
1350	900	475	64.8	.9146	27.438	.9895	29.685	-2.247	.223
1500	1000	500	66.7	.9325	27.975	1.0035	30.105	-2.130	.062
1500	1000	475	68.3	.9325	27.975	.9895	29.685	-1.710	.153
1650	1100	500	69.7	.9487	28.461	1.0035	30.105	-1.644	.162
1800	1200	525	70.8	.9634	28.902	1.0195	30.585	-1.683	.119
1800	1200	500	72.7	.9634	28.902	1.0035	30.105	-1.203	.147
1950	1300	525	73.1	.9768	29.304	1.0197	30.585	-1.282	.310
1950	1300	500	74.3	.9768	29.304	1.0035	30.105	-.801	.250
2250	1500	550	75.5	1.000	30.0	1.0244	30.732	-.732	.230
2100	1400	500	76.2	.9895	29.675	1.0035	30.105	-.430	.20
2250	1500	525	76.6	1.00	30.0	1.0195	30.585	-.585	.19
2100	1400	475	77.4	.9895	29.675	.9895	29.685	-.40	.19
2250	1500	500	77.8	1.00	30.00	1.0035	30.105	-.003	.26

TABLE 6

In a similar manner P_o for the furnace side was determined, and found to be .6354 atmospheres or 19.062 in. of mercury. Using these values table 6 was calculated. The last column, (Inches change for 1% change in efficiency) was obtained by subtracting the difference in pressure, in inches of mercury, from each preceding difference, and dividing the result by the corresponding change in efficiency.

The constants used for this table are:-

Furnace side	Uptake side
P_o, .6354 atmos.	P_o, .730 atmos.
W_1, 1 (relative)	W_1, 1
W_2, 3.701 (tubes heated)	W_2, 1.266
M, 4.071	M, 2.266
R, 1	R, .699
W'_2, 2.35	W'_2, .9323

The changes in the volume of the expansion chamber were made in accordance with the information obtained above, by filling with oil, and the instrument was then put in operation once more. The record charts were very good for the day time, but did not show the effect of banking the fire. As there was some doubt about just what took place at that time, a series of observations was made

STEAM	TIME	UPTAKE TEMP. AS READ	UPTAKE TEMP. CORRECT.	FURNACE TEMP. AS READ	FURNACE TEMP. CORRECT	T_1 ASSUMED AS = $\frac{3}{2}$ OF FURN. CORRECT.	% EFFICIENCY
	P.M. 11:30	57.6	540	680	765	1150	52
	11:40	57.7	545	680	765	1150	52
	11:50	57.1	500	660	740	1110	54
PRESS. 100#	12:00	56.7	480	600	680	1050	54
	A.M. 12:05	56.0	435	470	560	840	48
	12:10	55.8	420	400	485	725	42
	12:20	55.2	380	320	400	600	36.5
PRESS. DROPPED TO 40#	12:30	55.2	380	305	385	580	34.5
	12:40	55.5	400	340	425	640	40
	12:50	56.0	435	450	530	793	45
	1:00	56.0	435	500	580	870	50
	1:10	56.0	435	500	580	870	50
	1:20	56.0	435	500	580	870	50
PRESS. 55#	1:30	55.8	420	500	580	870	52
	1:40	55.5	400	465	545	820	51
	1:50	55.3	385	440	520	780	50.8

NOTE:- 50° was added to Furn. Pyrometer readings as corrected by calibration curve to allow for outer connection of thermocouple being heated above room temperature.-
Feb. 22-23, 1916

TABLE 7.

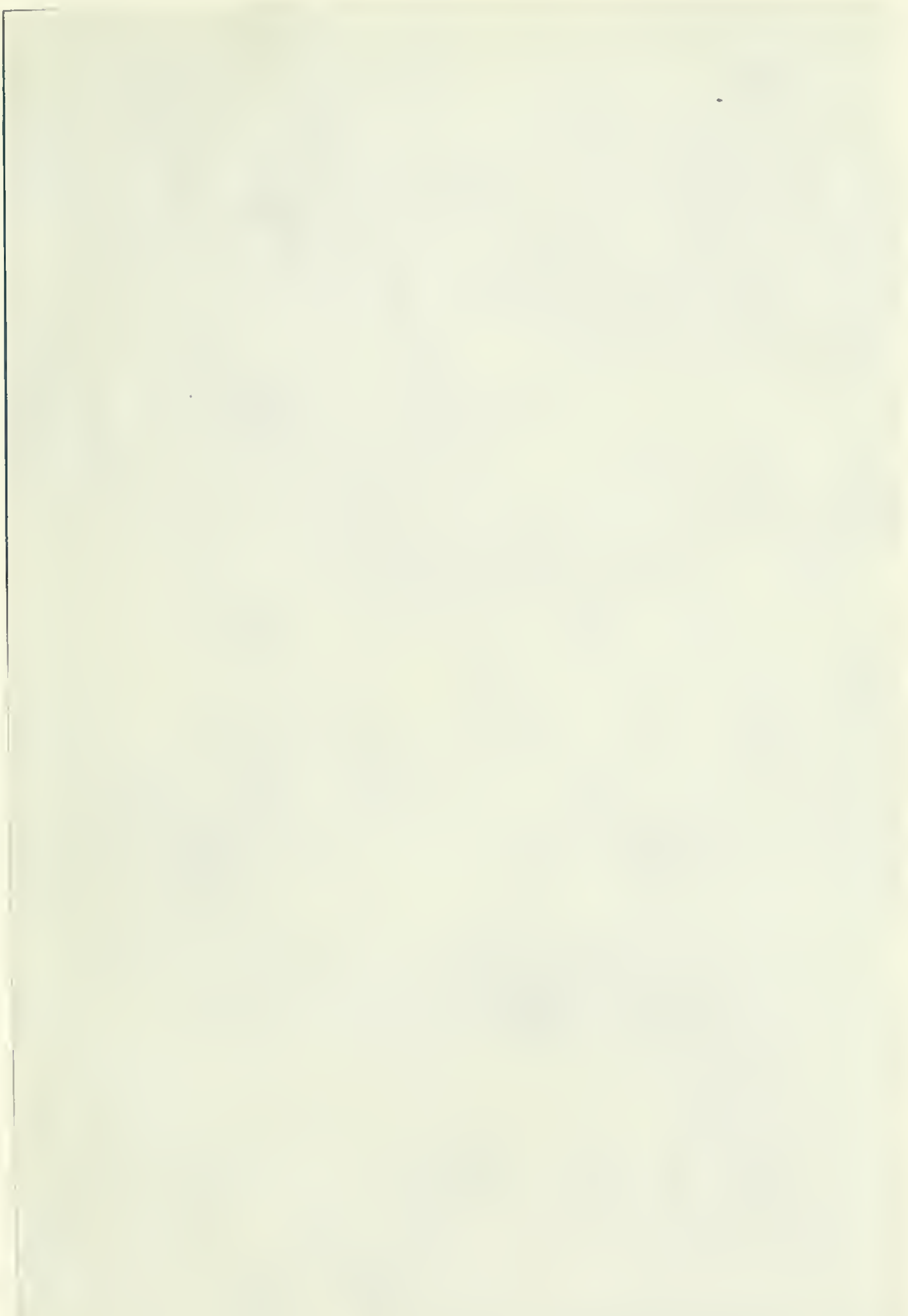


FIGURE 11.

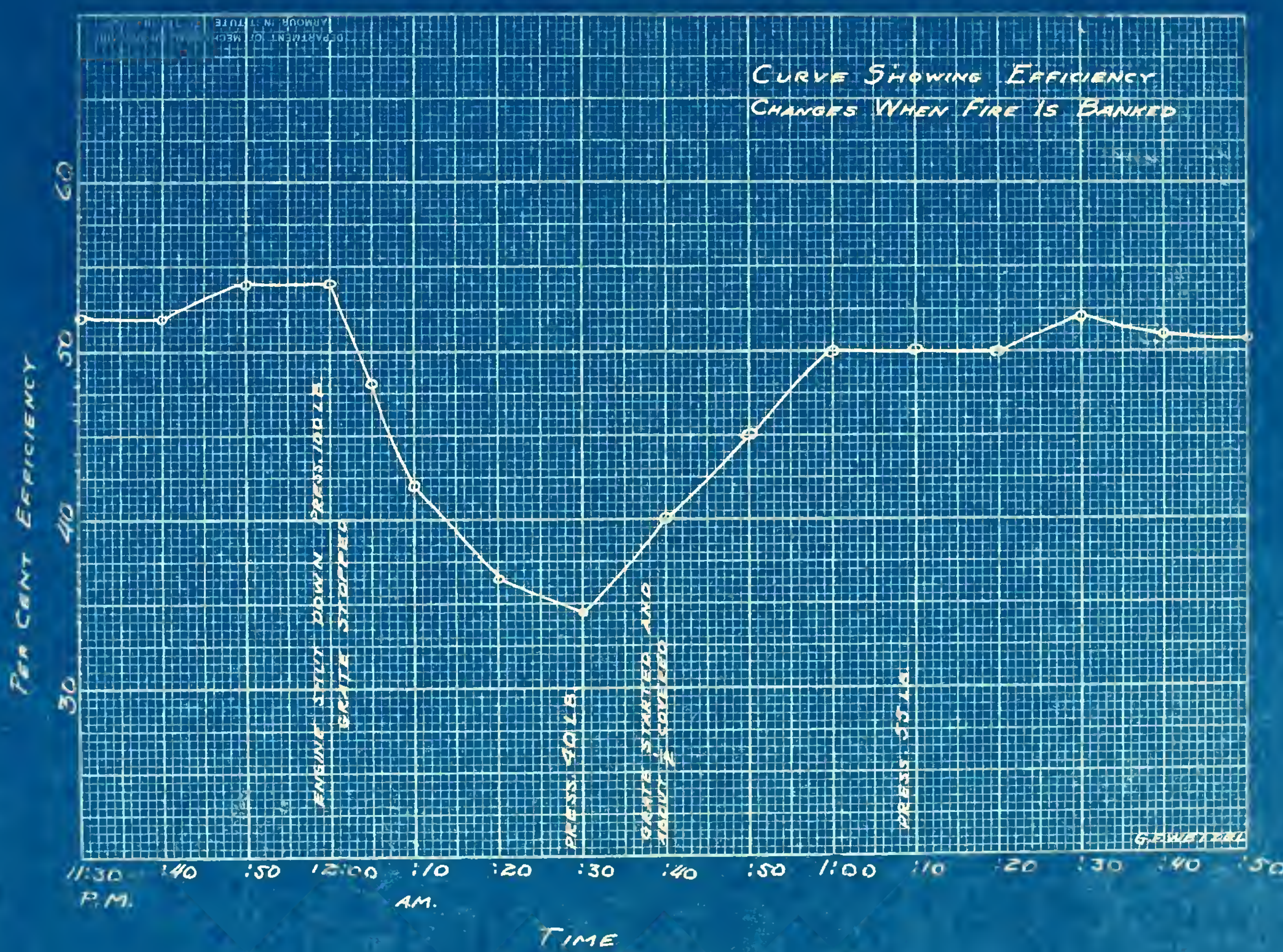

CURVE SHOWING EFFICIENCY
CHANGES WHEN FIRE IS BANKED
PER CENT EFFICIENCY
30
40
50
60
ENGINE SHUT DOWN PRESS. 100 LB.
GRATE STOPPED
PRESS. 40 LB.
GRATE STARTED AND
ABOUT ½ COVERED
PRESS. 55 LB.
G.F. WETZEL
11:30 :40 :50 12:00 :10 :20 :30 :40 :50 1:00 :10 :20 :30 :40 :50
P.M.
AM.
TIME

FIGURE 11

takingdata every ten minutes from 11:30 P.M. until 1:50 A.M. beginning on February 22. The data taken is given in Table 7 and is shown graphically in Figure 11.

These results showed that the machine was in error in not dropping the curve when the fire was allowed to burn down for the night, so the furnace expansion chamber was decreased in volume. The result of this change made the curve of efficiency consistant with the observations which had been made, and seemed to offer an instrument that would be useful and satisfactory in the power plant.

In determining the specific heats of gases the equations given in the paper by Lewis and Randall were used. (A Summary of the Specific Heats of Gases, Journal of the American Chemical Society, vol. 34, 1912, p. 1128.)

For oxygen, nitrogen and carbon monoxide

$$C_p = 6.50 + 0.0010\ T$$

For water vapor

$$C_p = 8.81 - 0.0019T + 0.0000022 2T^2$$

For carbon dioxide

$$C_p = 7.0 - 0.0071T - 0.00000186T^2$$

For the furnace gases, allowing 15% CO2, C_p is 0.3198, (T = 2000 + 460 deg. abs.) For the uptake, C_p = 0.253 (T = 500 + 460 deg. abs.)

This is a change of approximately 20%.

Because of the high cost of mercury a new instrument was built, designed for oil in the manometer. The U-tube was made of two pieces of 3" pipe 48" long connected by a return bend. These nipples capped and in one a sealing tube of 1/8" pipe and a float were placed in a manner similar to the instrument shown in Figure 8. The upper part of the U-tube itself formed the expansion chambers so that no separate ones were needed.

This instrument did not show any variations at all, because the pressures were so low that the changes in volume offset the changes in pressure. In the instrument using mercury this effect was not important as the ratio of volume change was smaller and the pressures much greater. There were pressure variations shown on the small attached glass U-tubes, one on each expansion chamber, but the differences were not transmitted to the recorder.

Table 8 was computed to give the pressures to be expected in the oil manometer machine in the same way the previous tables were.

A different arrangement was devised as shown in Figure 12 , in which the change in volume is so small as to be negligible. Each vertical member

1	2	$3 = \frac{3}{2} \times 2$	4	5	6	7	8
UPTAKE TEMPERATURE F°	TEMPERATURE AT FURN. PYROMETER	TEMPERATURE OF GASES ENTERING BOILER.	% EFFICIENCY	PRESS. UPT. IN. OIL	PRESS. FURN. IN. OIL	DIFFERENCE (6 - 5)	CHANGE FOR 1% CHANGE IN EFFIC. IN. OIL
400	800	1200	66.6	11.12	16.92	5.80	—o—
380	700	1050	67	10.62	15.80	5.18	—o—
420	900	1350	69	11.48	17.82	6.34	.27
440	1000	1500	70.6	11.86	18.65	6.79	.28
460	1100	1650	72.2	12.24	19.35	7.11	.20
500	1200	1800	72.2	12.87	20.03	7.16	.23
480	1200	1800	73.3	12.60	20.03	7.43	.25
520	1300	1950	73.5	13.27	20.56	7.19	—o—
490	1300	1950	74.7	12.80	20.56	7.76	.23
520	1400	2100	75.2	13.27	21.08	7.81	.21
480	1300	1950	75.5	12.60	20.56	7.96	.24
530	1500	2250	76.3	13.46	21.51	8.05	.24

$\frac{V_2}{V_1} = 15$

TABLE 8

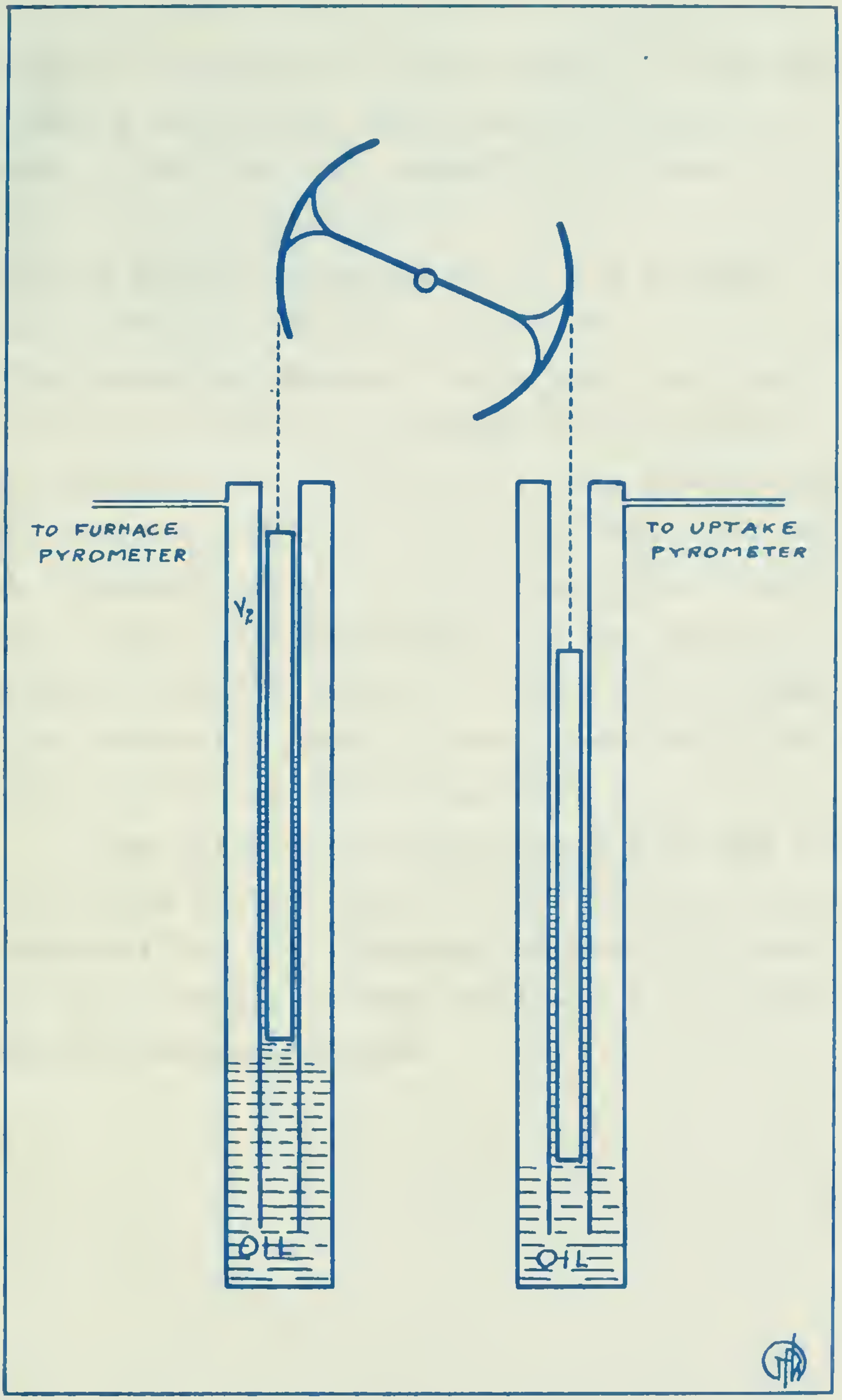


FIGURE 12

was made of a piece of 3" pipe capped at the lower end, with a reducer at the upper end. Into the reducer a 3/4" pipe was screwed which came to within about 3" of the botton of the 3" pipe, as shown. A piece of brass tubing was hung from a rocker arm in each 3/4" pipe. The upper part of the large pipe was the expansion chamber, while the lower part contained oil. When the pressure was increased by the expansion of the air in the thermometer tubes, oil would rise in the inner tube. This would exert a buoyant effort on the brass tube. The difference between the effects on the two tubes is a function of the efficiency of boiler and furnace. Thus the mechanism shown in the figure will give a graphical record of the efficiency.

Some trouble was experienced with the brass tube sticking to the side of the 3/4" pipe, due both to roughness and the viscosity of the oil. This effect can probably be over come and a successful commercial instrument made.

Comparative Value of Methods

Steam Flow Meters Draft Meters	Gas Analysis	Wilsey Fuel Economy Gauge
Flow meters show capacity but do not follow efficiency. Same capacity can be had with very different efficiencies.	Basis chemical.	Basis physical.
	Works within narrow limits considering combustion only.	Covers entire process considering every factor.
	Regulates combustion relative to itself.	Regulates combustion relative to efficiency.
Draft gauges or meters show amount of resistance to flow of air, not amount of air flowing. Scientific tests made in government fuel testing investigation and reported in bulletins show there is no relation at all between draft and efficiency and only an indefinite relation to capacity.	Tends to force even combustion regardless of varying conditions.	Tends to secure best possible combustion under all conditions.
	Ignores ability of boiler to absorb heat as liberated.	Considers ability of boiler to absorb the heat.
	Overlooks quality of fuel.	Includes quality of fuel.
	Does not provide method of checking and improving conditions.	Provides direct method of checking and improving every condition for best effect on efficiency.
	Does not show effect of soot, scale, etc.	Shows effect of soot and scale.
	Readings include relatively large and uncertain error.	Readings accurate.
	Readings have no definite meaning, nothing can be figured from them.	Meaning of readings definite and exact.
	Not understood by average firemen.	Readings understood by fireman at a glance.
	Operations complicated.	Operation simple.
	Economy effected partial and uncertain.	Economy definitely shown and maximum fuel saving secured.
		Shifts fuel burning from a mere quantity to a quality basis.

TABLE 9

-: PART THREE :-

Discussion

There is little doubt that when the H R V Recorder has had time to be developed, and the necessary educational work done that seems needed in selling an instrument like this, that it will be a good commercial proposition in spite of the present price. It has already demonstrated its value in a number of plants where it has been in service for over a year.

The idea of carrying on this work with the air thermometer instrument was to enable the International Filter Co. to bring a cheaper machine on the order of the H R V Recorder, which would be much easier to sell, and thus automatically create a demand for the electric machine in plants where more money is available for improvements, and a higher grade instrument is desired. The time has been too short to reach a definite conclusion as to value of the air instrument, but the indications are that it will be well worth while.

The instrument using the mercury manometer, operating at approximately atmospheric pressure seemed to be capable of developement into a commercial proposition. The results obtained were

good as can be seen from Figure 9. With the pressures changing from slightly above to slightly below atmospheric the leakage, if any, will be equal in and out. This is important in a machine which is to be sold, as any one who has worked with air knows the great difficulty in making a large number of joints absolutely air tight under pressure.

The test of the oil manometer efficiency gauge was not completed at the time of writing, but from the observed results, it probably will prove to be a valuable instrument. The constuction is very simple so that the manufacturing cost would be low, and consequently the selling price could be made very reasonable.

Naturally the question will come up as to just how an instrument which indicated and records boiler efficiency will prove valuable in saving fuel and increasing the efficiency of the steam producing process.

If the boiler setting is tight and the boiler is clean, its efficiency as a heat absorber is fixed, but the furnace may be operated either with a high or a low degree of economy. To burn coal with the best results the excess air should be cut down as low as possible and still get complete

combustion. This can only be done by eternal vigilance. The condition of the fire is constantly changing; the load in most plants is far from constant; the fuel will change from time to time; and atmospheric conditions will change. The effect of all these changes is to change the proportionate amount of air supply. If conditions are to be kept right it means that knowledge of conditions is necessary. An instrument of the type discussed in this paper will give this information, and give it in time and to the right man, to be of value in keeping efficiency high.

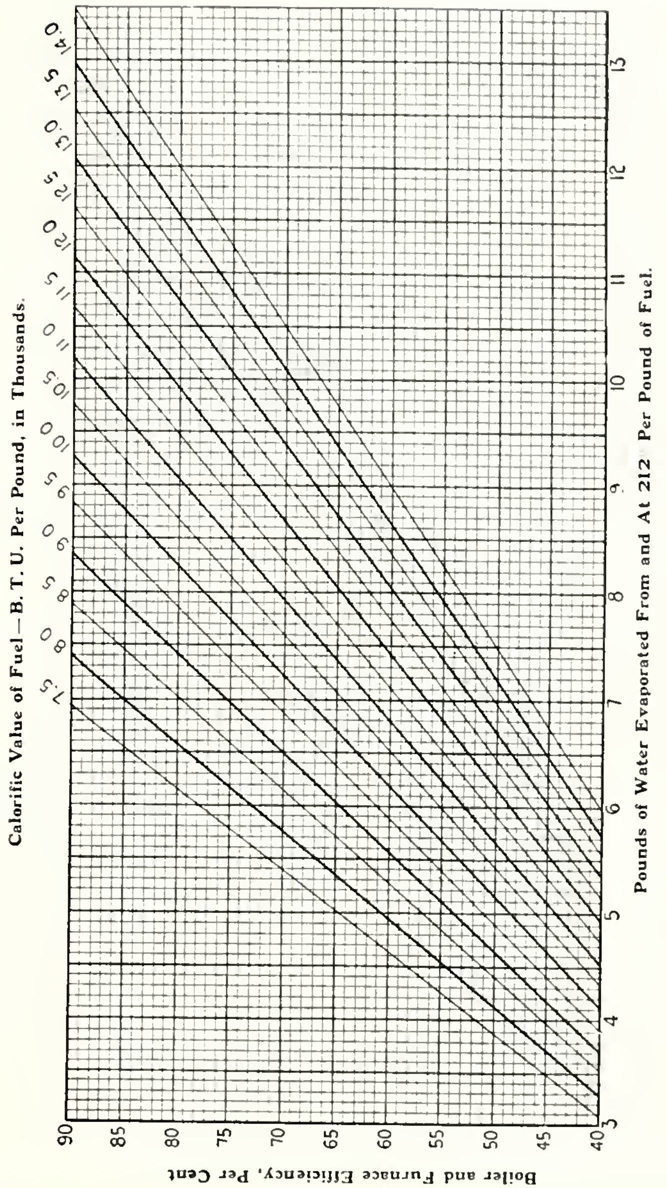
If a hole burns in the fire, or the draft is not correct for the best combustion, the curve will fall, while if the damper opening is changed the right way, or the thickness of fuel bed changed so that draft, speed of firing, and thickness are properly co-ordinated, the curve will rise. Thus it will be seen that the fireman has a constant guide by which he may bring about and maintain the best conditions possible with the given equipment.

Considering what takes place in the furnace will show at once that the correctly calibrated instrument will give the same result as an analysis of the flue gases in as much as they affect the efficiency. When The CO_2 is high it means that

combustion is good, and a small amount of excess air is diluting the gases in the furnace. There fore T will be higher and E will be high. The efficiency instrument goes farther than the CO_2 machine because it will show at once if anything has happened to the setting such as a fallen baffle. Also by means of it, the action and value of soot blowers, value of wet or dry firing, influence of size of coal, etc. may be determined. The H R V Recorder or the new air machine will not actually do the work of building up efficiency, but acts as a compass for the firemen to steer by.

Table 9 sums up in a concise way the different methods now available for getting information by means of which efficiency may be increased, but it shows that the method herein described is the best brot forward to date, except in plants where a high priced man is available for continued testing and supervision.

Figure 13 shows curves by means of which the evaporation and efficiency to expect from a given coal may be easily determined.



Curves Showing Evaporation and Efficiency to Expect from Different Fuels.

FIGURE 13