THE HEMISPHERICAL METHOD FOR DETERMINING SPONTANEOUS IGNITION TEMPERATURES

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PREFACE

Previous investigations show that spontaneous ignition temperatures are affected by various experimental factors. In this investigation an attempt is made to design an ignition chamber in which these experimental variables have no effect.

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THE HEMISPHERICAL METHOD FOR DETERMINING SPONTANEOUS IGNITION TEMPERATURES

INTRODUCTION AND LITERATURE SURVEY

"A system ignites when the rate of gain of heat due to oxidation is greater than the rate of loss of heat." (22). This is usually recognized by the presence of a flame. Ignition caused by sources other than spark or flame is designated as spontaneous ignition.

Ignition temperatures are not characteristic of the substance alone but are dependent upon certain experimental variables of the particular system. Previous experiments indicate the following variables definitely influence the values of spontaneous ignition temperatures.

1. Fuel to air ratio.
2. Inert and other foreign gases.
3. Surface to volume ratio of the system.
4. Pressure of the system.
5. Time lag or induction period before ignition.
6. Surface in contact with the gases.

There is a certain fuel to air ratio that gives a minimum ignition temperature. This is very near the theoretical mixture. Above and below this composition the ignition temperature increases.

The ignition temperatures of hydrogen and carbon monoxide are raised when the nitrogen of the air is replaced with carbon dioxide (2, 3). In a hydrogen mixture with an oxygen to nitrogen ratio of one, the ignition temperature is lower than for mixtures with air. When the nitrogen in air is replaced by argon, the ignition temperature of hydrogen is raised but is still lower than when carbon dioxide is the replacing gas (22). Pure carbon monoxide in dry air has a much higher ignition temperature than impure carbon monoxide (from steel flask, 1.5% hydrogen content) in dry air. Various carbon monoxide-hydrogen mixtures in dry air have different ignition temperatures but tend to be nearer that of pure hydrogen (1). Moisture affects the ignition temperatures of fuel mixtures in different ways. In the ignition of methane-air mixtures the effect of water vapor less than 20% saturation is too slight to be detected (13). However, small amounts of water vapor lower the ignition temperature of carbon monoxide but increase the ignition temperature of hydrogen (2, 3).

Dixon and Coward (5) used a cylindrical chamber made of silica that was heated by an electrical resistance furnace. They found that the ignition temperatures of hydrogen, carbon monoxide, cyanogen and hydrogen sulphide varied with an increase in the diameter of the chamber until a limit was reached where an increase in the diameter produced no further change. The ignition temperature of some paraffins (methane, ethane and propane) and ammonia varied considerably over the range of diameters they investigated.

The ignition temperature of methane in air regularly decreases with an increase in pressure. On the other hand, the ignition temperature of hydrogen in air goes through a maximum at about 1000 mm. of mercury (6). Carbon monoxide has a maximum ignition temperature at a pressure of 600 mm. of mercury. Addition of small amounts of hydrogen to carbon monoxide-air mixtures causes this maximum to decrease and the point of maximum ignition temperature to shift to a higher pressure (4). This fall in ignition temperatures at very low pressures as well as at high pressures appears to be a general property of combustible gases. Methane appears to be the exception.

Induction period is the time between mixing of the fuel with air or oxygen and ignition. Upon mixing, some kind of rearrangement and/or reaction takes place which in some gases causes an increase in the initial mixing temperature and in others a decrease. When the initial temperature increases, the induction period can be very short; when it decreases, relatively long (order of magnitude of 10 seconds). Disregarding other influences, higher ignition temperatures are necessary when the induction period is decreased (14). Dixon and Higgins (6) found that by their method of mixing the preheated gases in a concentric tube, long periods of induction (up to 15 seconds) were required for the ignition of hydrogen-air mixtures. According to Jost (14) this delay in ignition is principally due to the processes of mixing. Other authors (23) in experiments by other methods have been unable to find significant induction periods.

Surfaces in contact with the fuel have been found to affect the temperature of ignition. Freitag (9) found that the spontaneous ignition temperatures of several solvents varied according to whether the vapors were in contact with glass or with steel. In some cases the variation was as much as 100°C. Experiments by Prettre (24, 25) show that a salt-covered glass wall retards the reaction of hydrogen and oxygen fifty times more than plain glass. Vitreous surfaces heated to 500-600°C, either covered with alkaline salt or not, catalyze the reaction and adsorb large amounts of hydrogen and water vapor. Lewis (16) performed experiments by using glass bulbs and found the following as to the catalytic effect of surfaces: powdered glass and pumice increased the ignition temperature of paraffins; charcoal caused an increase for paraffins and a decrease for olefins; tin, zinc and aluminum had no effect; and silver, platinum, lead and copper caused an increase.

Much of the variation in ignition temperatures of a given system, as illustrated above, can be attributed to the types of experiments performed. The important experimental methods that have been used for determining ignition temperatures can be listed as the following (14):

"1. The explosive mixture flows through a combustion tube of known maximum temperature.
2. The mixture is introduced into a container of known temperature.
3. The mixture is compressed adiabatically, and the temperature is computed from the relation between the initial and final volumes or pressure.
4. The individual gases are heated separately in concentric tubes and mixed at a known temperature.
4a. The gases are heated individually until just before the maximum temperature, are mixed very quickly, and the mixture is then brought immediately to the maximum temperature.
5. A drop of liquid fuel, or a stream of combustible gas, is introduced into a space of known temperature containing air or oxygen.
5a. A stream of combustible gas and a stream of air or oxygen are individually heated to a known temperature and then impinged upon each other.
6. The mixture is brought to ignition in a soap bubble by means of a platinum wire of known temperature.
7. The mixture is ignited by the shooting in of bodies heated to a known temperature.
8. The mixture is heated by inserting metal rods heated to a known temperature."

Various investigators, each using one of the above methods, report ignition temperatures for hydrogen-air mixtures. These values have a maximum variation of 500°C, which show that the conditions of the experiment have a decisive effect on the ignition temperatures obtained.

EVOLUTION OF IGNITION CHAMBER DESIGN

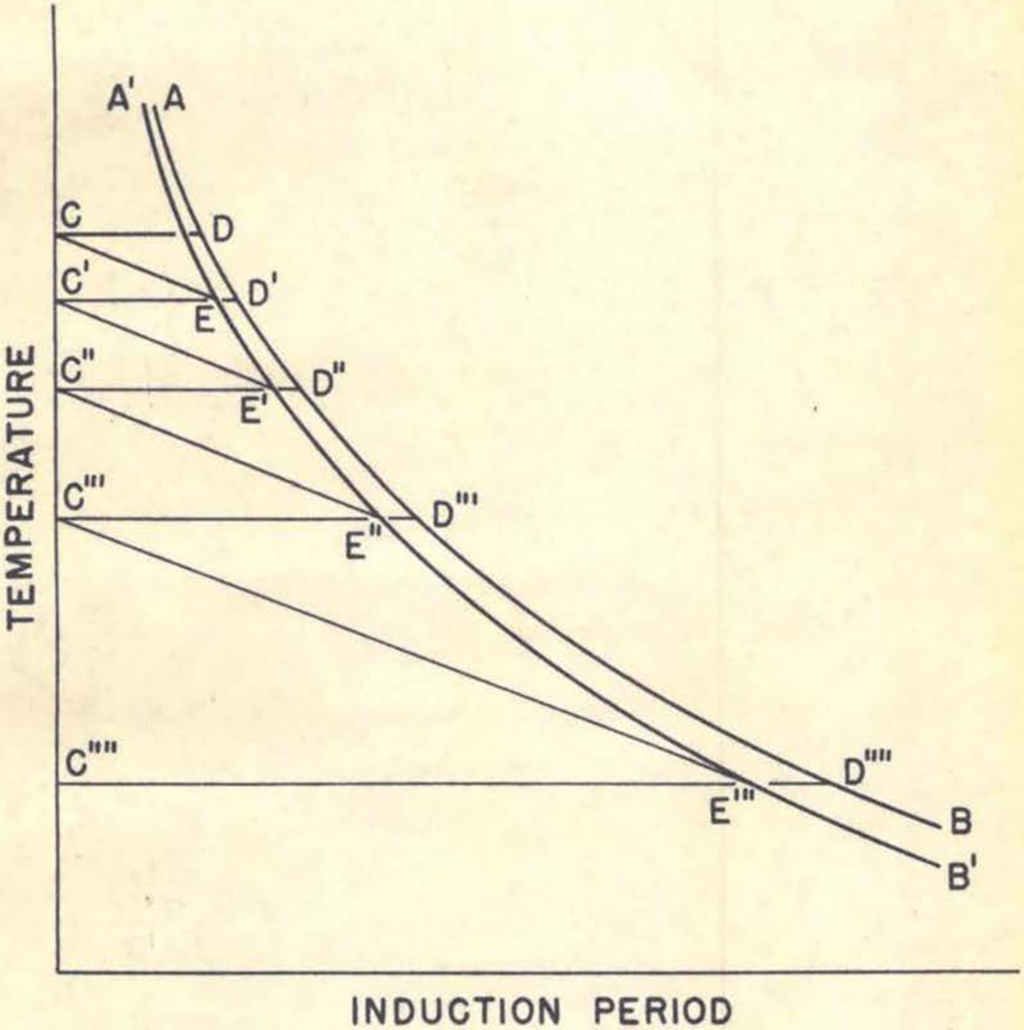
In any apparatus in which the gases remain for any time whatsoever, heat will be transmitted to or from the gas depending on whether the surface of the container is hotter or colder than the gases. An ignition chamber that has a surface/volume ratio of zero would eliminate any surface effect. Gases traveling radially outward from the center of a sphere would satisfy this condition. Conveying the gases to the center of a sphere without having catalytic surfaces within the chamber is impossible.

A hemisphere has many characteristics of a sphere, the chief one being a low surface to volume ratio. The surfaces that come in contact with the fuel-air mixture can easily be kept cooler than the mixture. Ignition will initiate where the hotter mixture is located; namely, in some position away from the cooler surfaces.

Since the velocity of gases flowing in a radial direction decreases rapidly, the throughput for the hemispherical chamber must be high. A high local velocity is also needed at the mixing zone to keep the residence time in the mixing zone negligible compared to the induction period. This local velocity can be increased further by restricting the volume of the mixing zone.

If the ignition temperature as a function of induction period for a given system is plotted as in Figure 1, a curve such as AB or A'B' is obtained. The temperature at which the gases are mixed is the temperature at zero time and are indicated as points C, C', etc. As the mixed gases flow through the ignition chamber, heat will, or will not, be transfered from the hot gases to the chamber, depending upon the mixture and the system. If no heat is lost by the hot mixture, its history as it flows through the chamber can be indicated by lines CD, C'D', etc. for a specific mixing temperature. For

FIGURE 1



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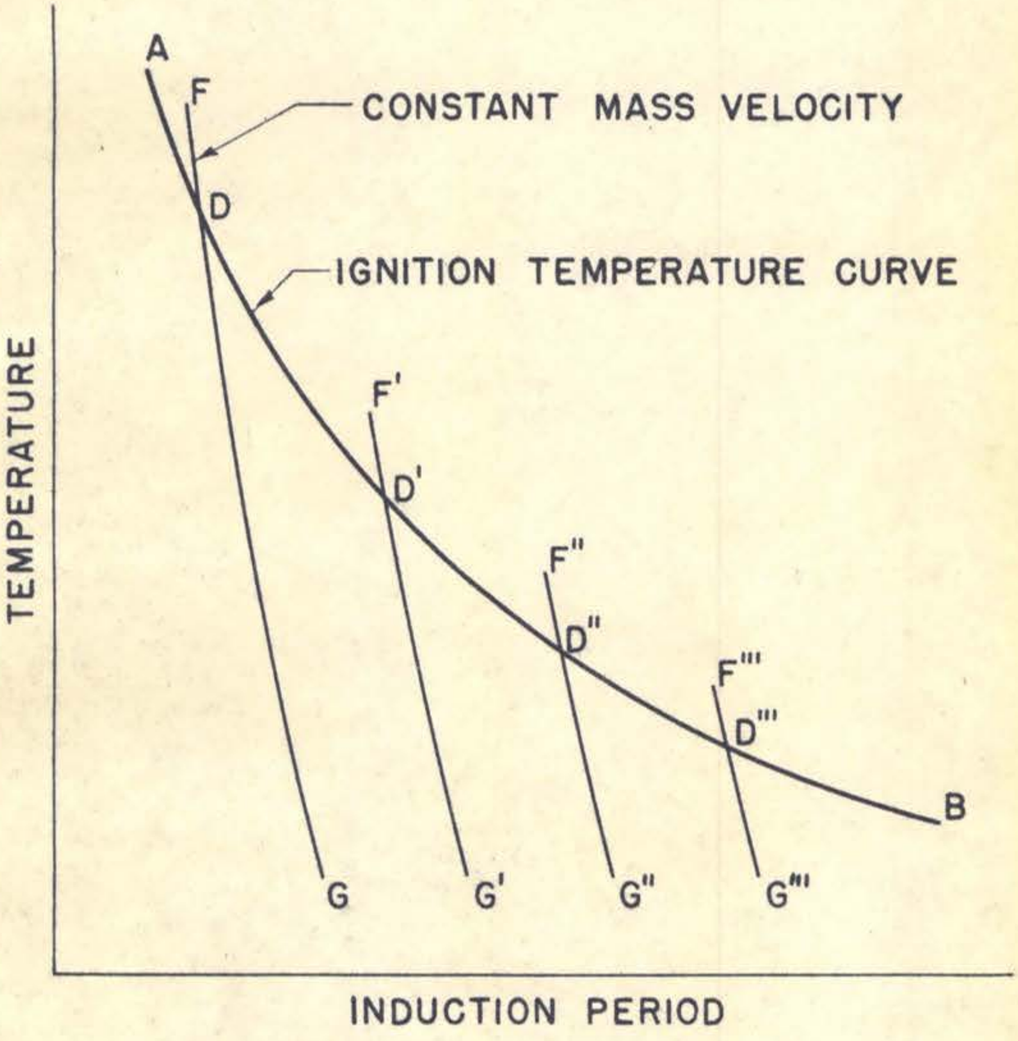
this case the actual ignition temperatures are obtained as the intersections of curves CD, C'D', etc. with AB. If the hot mixture loses heat by convection and/or radiation, its history as it flows through the chamber can be indicated by lines CE, C'E', etc. In this case ignition will occur at an induction time greater than that for no heat loss, when the gases are mixed at temperature C, but at an induction time less than that for no heat loss when the gases are mixed at temperature C'. The condition where heat is lost by the mixture will give a different ignition temperature-induction period curve, as indicated by curve A'B'.

For the hemispherical chamber the heat loss by the main body of the flowing mixture will be due principally to radiation. The amount of heat the mixture will lose depends on the gases used. For gases with symmetrical molecules, hydrogen, oxygen, nitrogen, etc., radiation losses are negligible (18). For all other gases radiation losses must be taken into account.

By placing a cooling grid a known distance from the mixing zone, the residence time for the mixture in the chamber can be determined from the mass rate through the apparatus. A plot of this residence time against temperature will appear as FG, F'G', etc. in Figure 2 for individual mass rates. If the mass rate through the chamber is kept constant as the temperature is increased, curve FG will be followed from G toward F. As the temperature is increased, the ignition temperature for the mixture will follow along curve AB (Figure 2) from B toward A. Ignition will occur for this mass rate and mixture at point D, where the curve FG intersects curve AB. In this way point D, itself, can be established.

From a series of runs for one mixture in which the mass rate is varied, the location of points D, D', etc. may be obtained. In this manner curve AB may be constructed.

FIGURE 2



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DESCRIPTION OF APPARATUS

An attempt was made to design an ignition chamber in which the conditions of the experiment, namely, surface to volume ratio and type of surface, would have no affect. This led to the design of an ignition chamber, hemispherical in shape, with the outer boundary covered by a cooling grid.

A 4 inch-radius ignition chamber was designed to give an induction period of 0.2 seconds at 50 pounds of air per hour and a temperature of 1200°F. The chamber was constructed of annealed stainless steel, Type 304, 18-8 low carbon, to stand temperatures up to 1800°F. The base plate was made from 16 gauge steel and the distributor 28 gauge.

This ignition chamber is shown in Figures 3, 4 and 5 with a detail drawing in Figure 23. The chamber consists of a base plate, distributor and cooling grid. The base plate (1 in Figure 3) has a cooling chamber for keeping the base plate and distributor cooler than the flowing mixtures. In the center of the base plate there is one opening for the air to enter inside the inside portion of the distributor; five other openings for the fuel are located so that the fuel may be introduced directly into the annular space between the inside and outside portions of the distributor. The inside portion of the distributor (2 in Figure 3) is inserted into a tight-fitting groove in the plate. The outside portion of the distributor (3 in Figure 3) is bolted to the base plate. The wire grid (5 in Figure 3) is held to the base plate by a retaining ring (4 in Figure 3) that is bolted to the rim of the base plate. Figure 4 shows the base plate with the distributor attached. Figure 5 shows the ignition chamber assembled as a unit. In this unit the heated gases are mixed in a small annular space of the distributor of $\frac{1}{2}$ inch radius and emerge radially at a high velocity into the chamber,

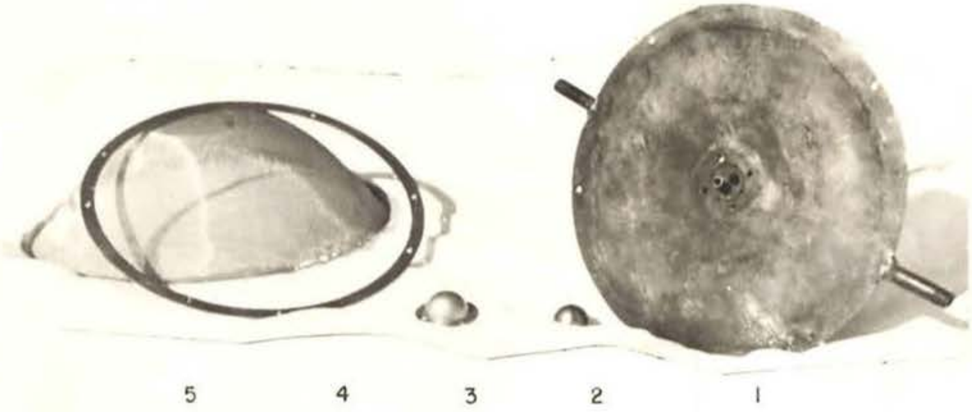

Figure 3

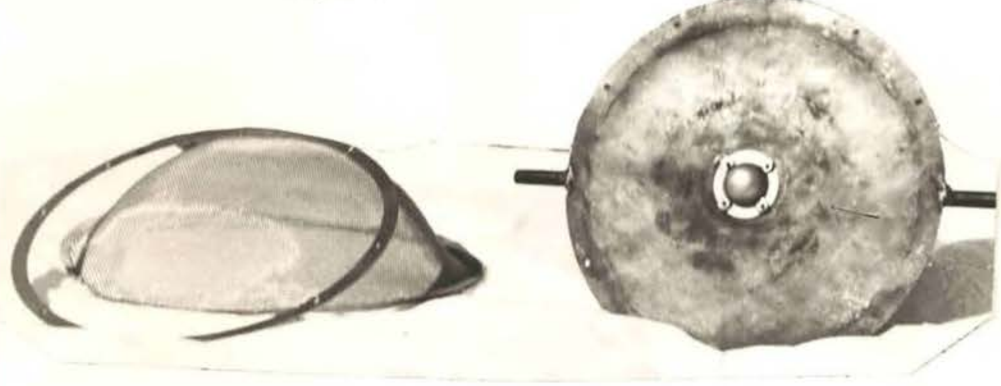

Figure 4

Figure 5

HEMISPHERICAL COMBUSTION CHAMBER

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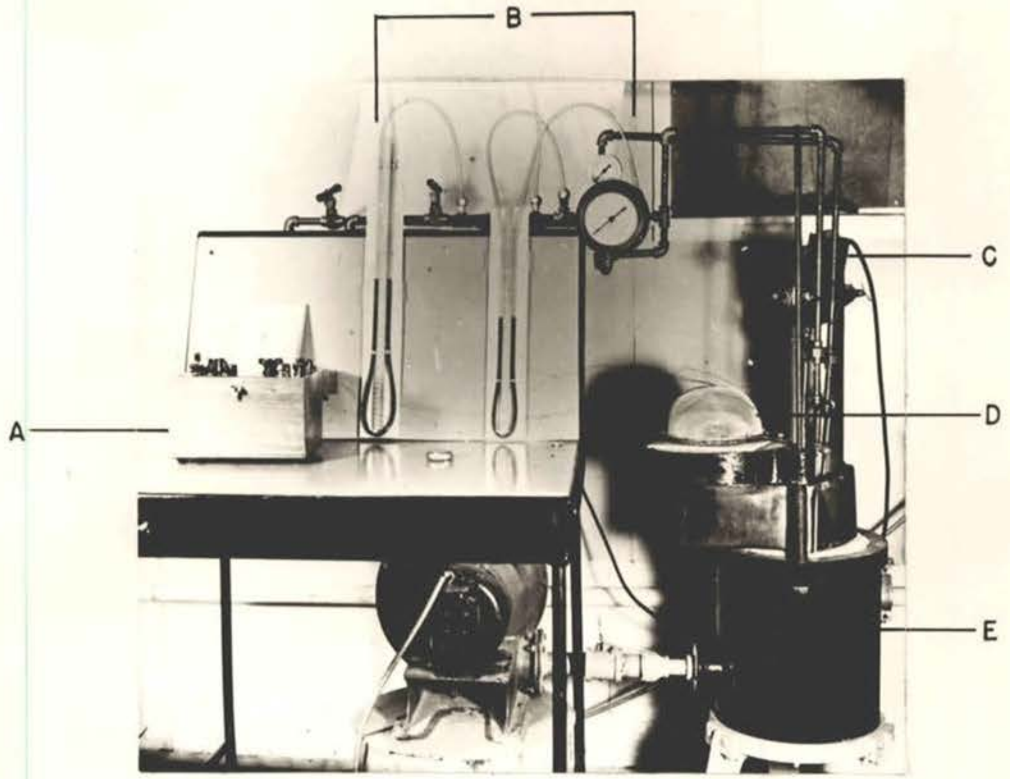
where the velocity decreases rapidly. The gases after flowing through the chamber contact the cooling grid in order to quench any reaction and remove the possibility of ignition after the measured time in the chamber. With the base plate sufficiently cool, there should be no surface effect from it. The surface to volume ratio for this chamber is low.

The preheater (Figure 24) for heating the gases separately before mixing in the distributor of the ignition chamber was constructed of annealed stainless steel, Type 304, 18-8 low carbon. It consists of heating coils submerged in a lead bath that is heated by a gas fired furnace. The air coil is in two lengths, each 22½ feet of 5/16" o.d. 20 gauge tubing, connected in parallel. The fuel coil is 21 feet of ¼" o.d. 20 gauge tubing. The lead bath container is 1/8" welded plate. This container has a stirrer that extends inside the draft tube and is turned by a variable speed motor.

The flowmeters used to measure the gas rates are orifice plates with flange taps connected to manometers made of "Saran" tubing. The orifice openings are 0.250" for the air and 0.156" for the fuel. The manometer fluid is a red oil with a specific gravity of 1.000.

Chromel-alumel thermocouples were used to measure temperatures. Thermocouple Number 1, used in the lead bath, is No. 20 B. & S. Gauge wire and Thermocouple Number 2, used in measuring the gas temperature in the calibration runs, is No. 28 B. & S. Gauge wire. The thermocouple leads were connected to a Leeds and Northrup potentiometer.

The complete assembly is shown in Figure 6. A schematic drawing of the equipment is given in Figure 7.



(A) Potentiometer with Thermocouple Connected.

(B) Manometers and Pressure Gages.

(C) Stirrer Motor for Gas Preheater.

(D) Hemispherical Combustion Chamber as shown in Figure 3.

(E) Furnace containing Gas Preheater.

Figure 6

HEMISPHERICAL COMBUSTION CHAMBER with AUXILIARY EQUIPMENT

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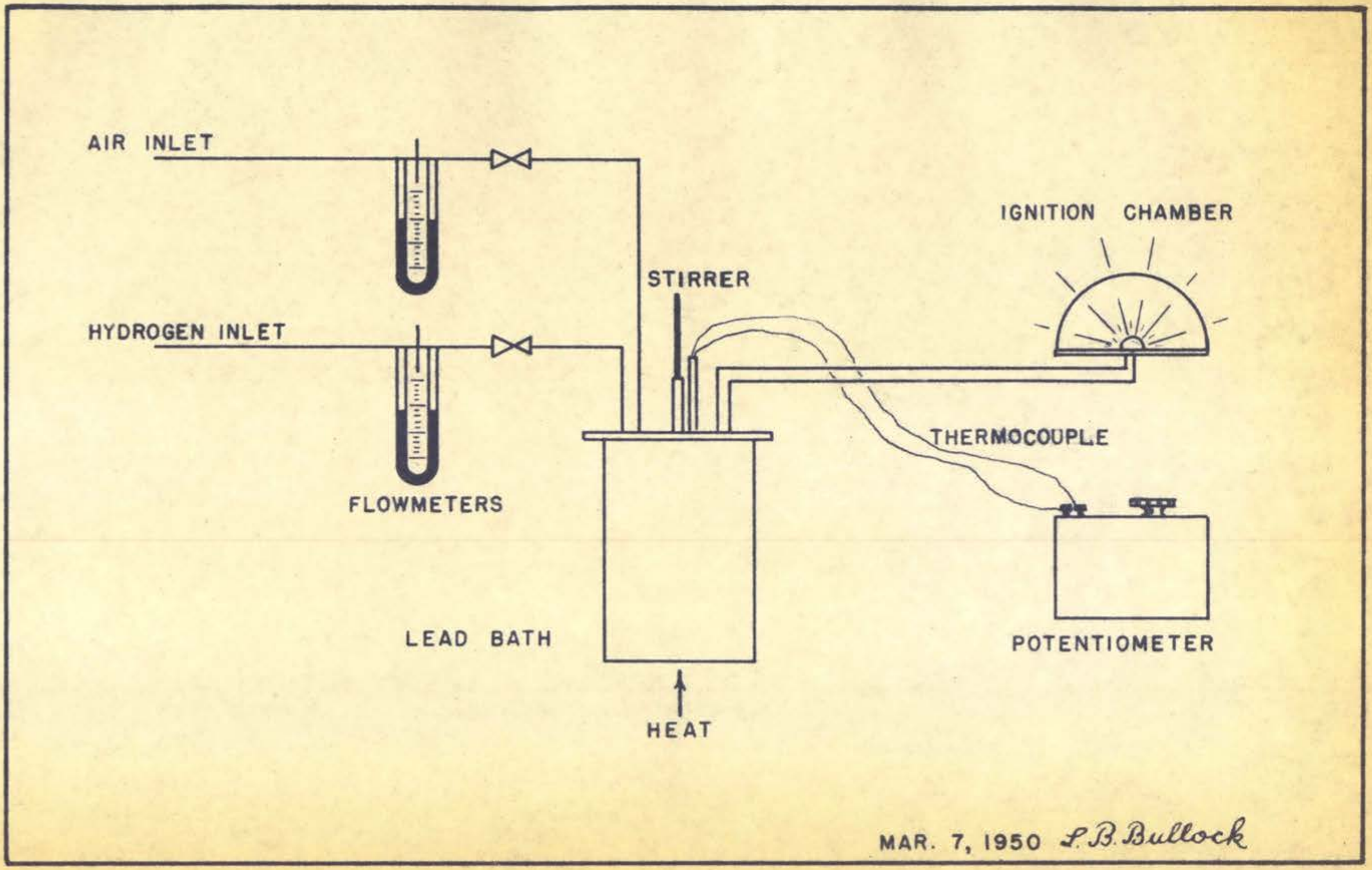
FIGURE 7



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PROCEDURE

Thermocouple Number 1 was calibrated using the melting points of tin, lead, zinc, aluminum and copper. Thermocouple Number 2 was calibrated against Thermocouple Number 1 in an electric furnace.

The flowmeters were calibrated using carbon dioxide as a tracer gas. The rotameter used for measuring the carbon dioxide was previously calibrated against a standard gas holder.

The hydrogen used was commercial grade obtained in cylinders. The compressed air used was from the laboratory compressed air supply.

The apparatus was calibrated as a unit in order that there would be no objects to interfere with the flow of gases in an ignition experiment and so that no catalytic surface would be present in the mixture leaving the hemispherical distributor. The apparatus was calibrated with the cooling grid and distributor removed from the ignition chamber. This was done by placing one thermocouple in the gas stream outlet and another in the lead bath. For constant gas rates simultaneous readings were taken while heating the lead bath. These calibration runs were made at various gas rates.

Then, the thermocouple was removed from the gas outlet, and the distributor and the cooling grid were replaced. Ignition runs were made by heating the bath along the same temperature-time schedule as in the calibration runs for the same gas rates. A run was terminated when ignition took place.

RESULTS AND DISCUSSION

Calibration data for the thermocouples, flowmeters and the equipment as a unit appear in the appendix.

The results of the temperature calibration runs are tabulated in Tables VII and VIII and are plotted in Figures 17-22. In each figure are plotted data for a fuel rate and air rate which when combined will give a stoichiometric mixture for complete combustion. The temperature of the gas mixture (middle line in each figure) was computed by assuming that each gas stream will contribute a portion to the enthalpy of the mixture based on its own enthalpy and that there is no enthalpy of mixing. The heat capacity data used were those reported by Rossini (26). From these charts the temperature of the gases entering the ignition chamber can be determined by reading the temperature of the lead bath only.

At the beginning of some of the runs the points deviate from the hydrogen line. This can be seen clearly in Figure 20. Here the hydrogen line was found by making two separate calibration runs: one beginning at a lead bath temperature of 1115°F; the other at about 1180°F. These deviations were caused by beginning the runs before complete steady state conditions were obtained between the gas leaving the preheater and the tube walls leading to the ignition chamber.

The distributor (No. 1) used in ignition runs 1-3 was drilled with 34 holes, 1/16" diameter, in inside portion and 66 holes, 1/16" diameter, in outside portion. A wire screen was inserted in the annular space of the distributor to improve the flow pattern from the distributor. For run 4 the inside portion of the distributor was drilled with 65, 3/64" holes and the outside portion with 80 holes, 1/32" diameter. With this distributor (No. 2) the flow distribution was improved. The inside portion of the distributor used in run 4 was also used in runs 5-10. The outside portion for these runs was drilled with 102 holes, 1/32" diameter. This distributor (No. 3) offered little improvement in flow distribution over No. 2.

Ignition was recognized by a loud noise that sounded like the popping of a large inflated balloon. After ignition the flame would flash back into the annular space of the distributor, and the distributor began to melt. Only a few seconds passed between ignition and the melting of the distributor.

To prevent burning out the distributor, a quick shut-off arrangement was attached to the hydrogen control valve. This method was effective until the highest velocity run (Run 10) was made. At this velocity it is estimated that the distributor burned out in much less than a second after ignition.

The burned out distributor (No. 1) used in run 3 is shown in Figure 8. In this run all portions of the distributor were burnt. In Figure 9 is the distributor (No. 2) that was used in run 4. In this run only the outside portion was burnt. The inside portion of this distributor was used for the remaining runs without damage. Distributor No. 3 after being burned out in run 10 appears in Figure 10.

In all cases the distributors burned out at places where the velocity from the outside portion of the distributor was the highest. These places of high velocity were where the holes in the inside portion of the distributor were in almost direct line with some of the holes of the outside portion of the distributor. The air entered the annular space from the holes of the inside portion of the distributor at a much higher velocity than that of the hydrogen, entering directly into the annular space. Where the holes of the two portions of the distributor were in line, mixing would not be good and would give a leaner mixture than that of other parts of the distributor. At regions

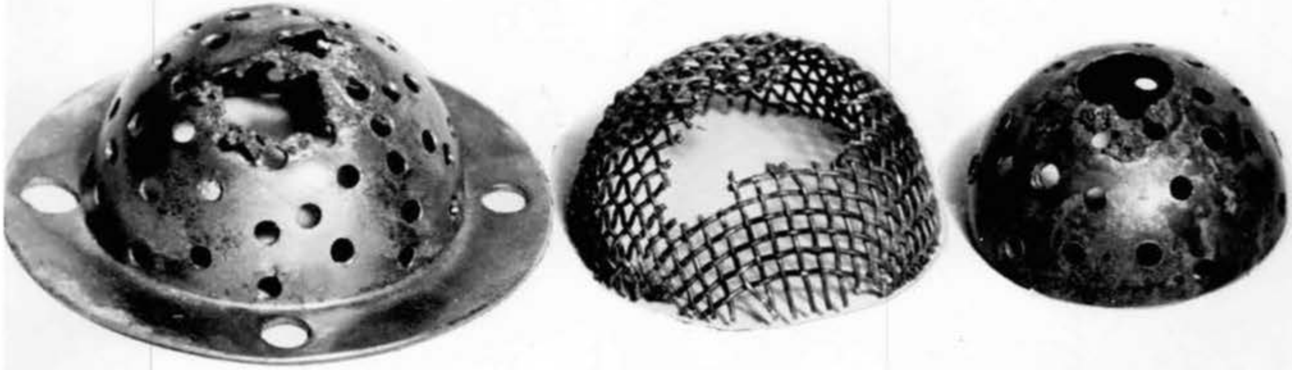

FIGURE 8

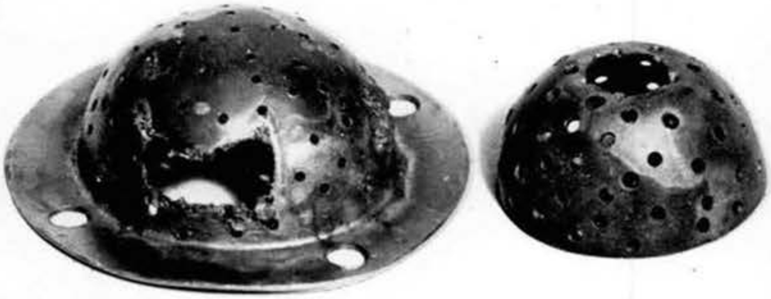

FIGURE 9

FIGURE 10

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of lean mixtures the flame was stabilized and burning out of the distributor occurred. This is in accordance with findings of other investigators (11) on combustion, who have found that the flame velocities on the lean side are higher than on the rich side of the stoichiometric proportions.

Distributor No. 3 has a smaller portion of burned out area than the other distributors. This is believed, but cannot be proved, to be due to better mixing in distributor No. 3 than in the other two. The time of burning was not necessarily the same in each case.

The ignition temperatures obtained in the present experiments are listed in Table I and Figure 11.

TABLE I

Run No.	Distributor Number	Induction Period Seconds	Ignition Temperature °F
3	1	0.36	1330
4	2	0.37	1255
5	3	0.36	1302
6	3	0.27	1309
7	3	0.53	1286
8	3	0.23	1284
9	3	0.20	1298
10	3	0.18	1316

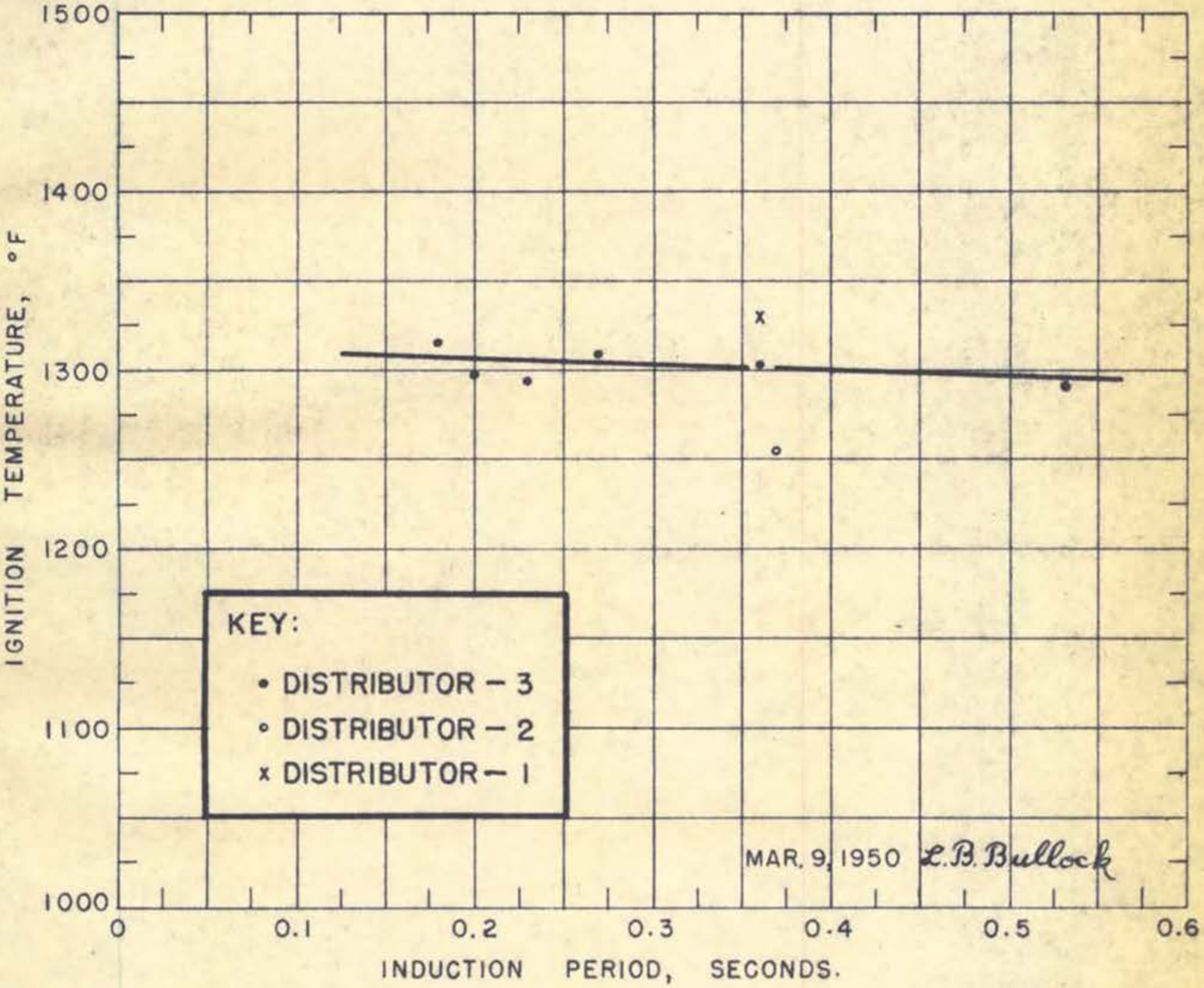
From these data it can be seen that for this apparatus the ignition temperature of stoichiometric mixtures of hydrogen and air remains almost constant at about 1300°F over the range of induction periods investigated.

The largest deviations in Figure 11 are the points obtained with different distributors. This is probably due to different mixing and velocity distribution produced by the different distributors. Other deviations were probably due to the slight differences in pressure for the different runs.

A distributor that gives more uniform mixing and more even velocity

FIGURE 11

IGNITION TEMPERATURE-INDUCTION PERIOD



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distribution is needed to produce better results with this apparatus. This could possibly be accomplished by having a high pressure drop through the outside portion of the distributor. A distributor of this type could be constructed from either thicker stainless steel with smaller holes or from a porous material. Another possibility would be to impinge the fuel and air upon each other inside a single-shelled distributor.

CONCLUSIONS

1. The mixing of the preheated gases and their velocity distribution through the hemispherical ignition chamber are important factors in the results obtained with this apparatus.
2. Uniform mixing and even distribution are difficult to obtain with a distributor made from a thin material.
3. For this apparatus the ignition temperature of stoichiometric mixtures of hydrogen and air remains almost constant at about 1300°F over the range of induction periods from 0.18 to 0.53 seconds.

RECOMMENDATIONS

1. For the hemispherical method to be useful for determining true spontaneous ignition temperatures a better distributor is needed. This distributor should give uniform mixing and an even radial flow.
    a. The flow pattern could be improved by making the outer portion of the distributor from thicker material with smaller holes. This, however, might not give uniform mixing.
    b. Another arrangement that might solve the problems of mixing and velocity distribution would be to impinge the hot gases upon each other inside a single-shell distributor. This distributor would have to be very small (possibly $\frac{1}{2}$" radius) to keep residence time short and should have a large number of very small holes. To accomplish this, a complete new ignition chamber would have to be constructed.
    c. The use of an outer shell of porous material for either of the above types of mixer-distributor should give very uniform velocity distribution.
2. For a complete investigation of induction periods the cooling grid of the hemispherical chamber would have to be made larger so that longer induction periods could be obtained.
3. For better results the hemispherical ignition chamber should be enclosed in a larger chamber to enable a control over the pressure.
4. For studies under dry air conditions a method must be devised to dry the air.

SUGGESTIONS FOR OTHER TYPES OF IGNITION CHAMBERS

Even though this author cannot recommend the following types of ignition chambers over the hemispherical chamber, they could be helpful for studying certain phases of spontaneous ignition temperatures.

1. A method that might prove satisfactory would be to have the fuel and air mix by diffusion as they flow through a cylindrical chamber at the same velocity. The fuel and air would have to be injected separately into the chamber through concentric porous membranes. This would produce a flat velocity distribution curve that would remain throughout the length of the tube, if high velocities and a short chamber are used. This would enable the average velocity to be used as the true velocity without error. The fuel would enter through a small opening at the center of the tube and would diffuse laterally outward as it traverses the length of the tube. The air would enter and flow in the annular space, diffusing laterally inward, into the fuel core as it traverses the tube. In this type of apparatus induction periods could be measured accurately, but the compositions could not be determined or controlled.
2. The use of concentric spheres could possibly be made effective. A metal outside sphere could be heated by being submerged in a molten metal bath. The inside sphere could be made of thin glass and have a diameter slightly less than that of the outer sphere. (The spheres could be small, possibly 2" in diameter.) The inside sphere would be filled with the combustible mixture. Heat would be radiated from the inside wall of the outer sphere and would converge upon the stagnant mixture at the center of the glass sphere. Ignition of the mixture would occur first at the center. The mixture at the center would be free of all surfaces. This chamber would

give ignition under conditions of a surface/volume ratio equal to zero. The mixture would be uniform and its composition known. In this apparatus induction periods could not be measured accurately.

APPENDIX

TABLE II

THERMOCOUPLE CALIBRATION

Thermocouple No. 1: Chromel-Alumel, No. 20 B. & S. Ga.

Thermocouple Reading °F	Corrected Reading °F
446	449
619	621.3
788	787
1212	1220
1974	1981.4

Thermocouple No. 2: Chromel-Alumel, No. 28 B. & S. Ga.

Thermocouple Reading °F	Corrected Reading °F
382	390
565	570
1055	1057
1254	1260
1578	1585
1704	1713
2133	2147

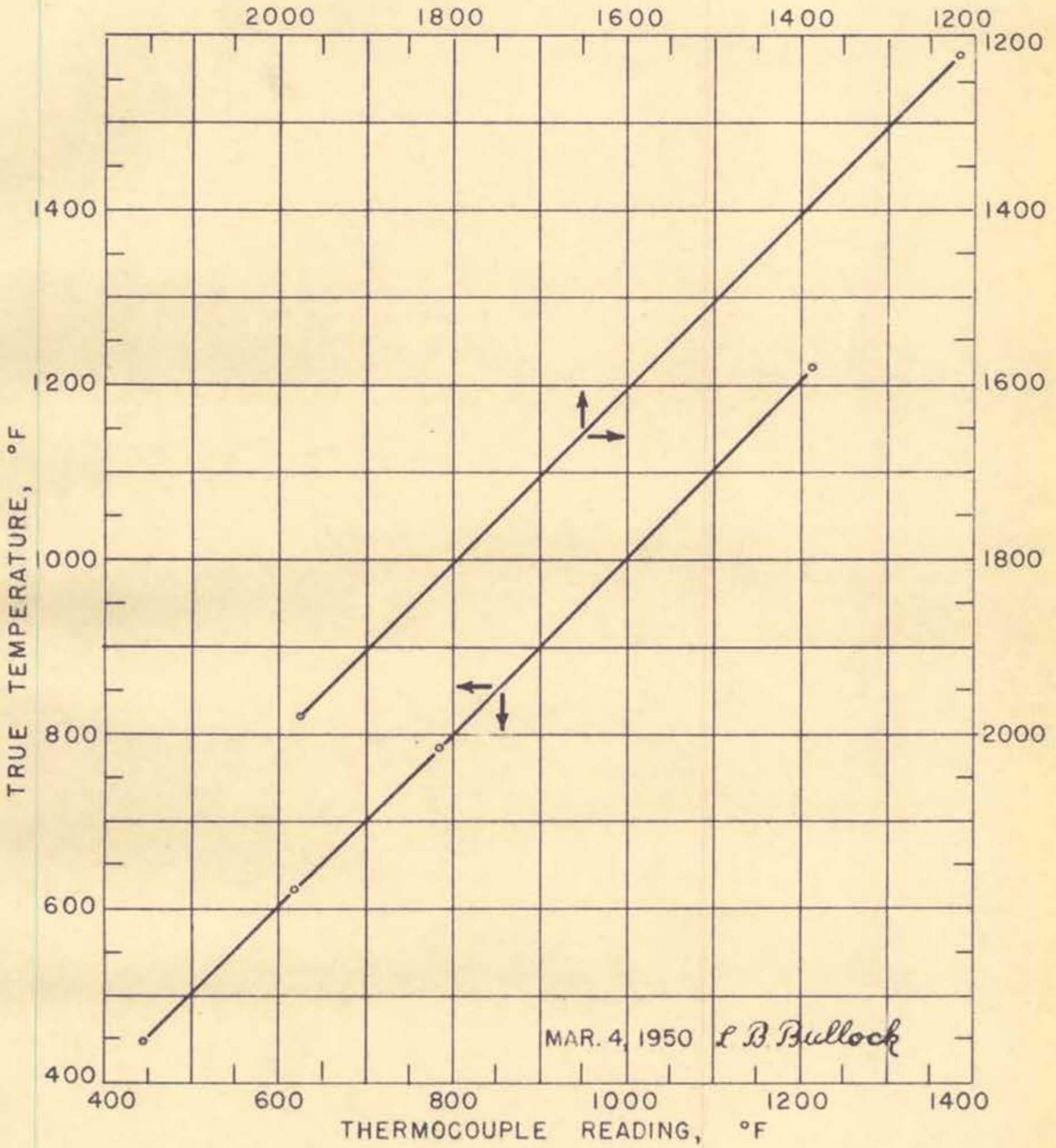

FIGURE 12- THERMOCOUPLE CALIBRATION NO.1.

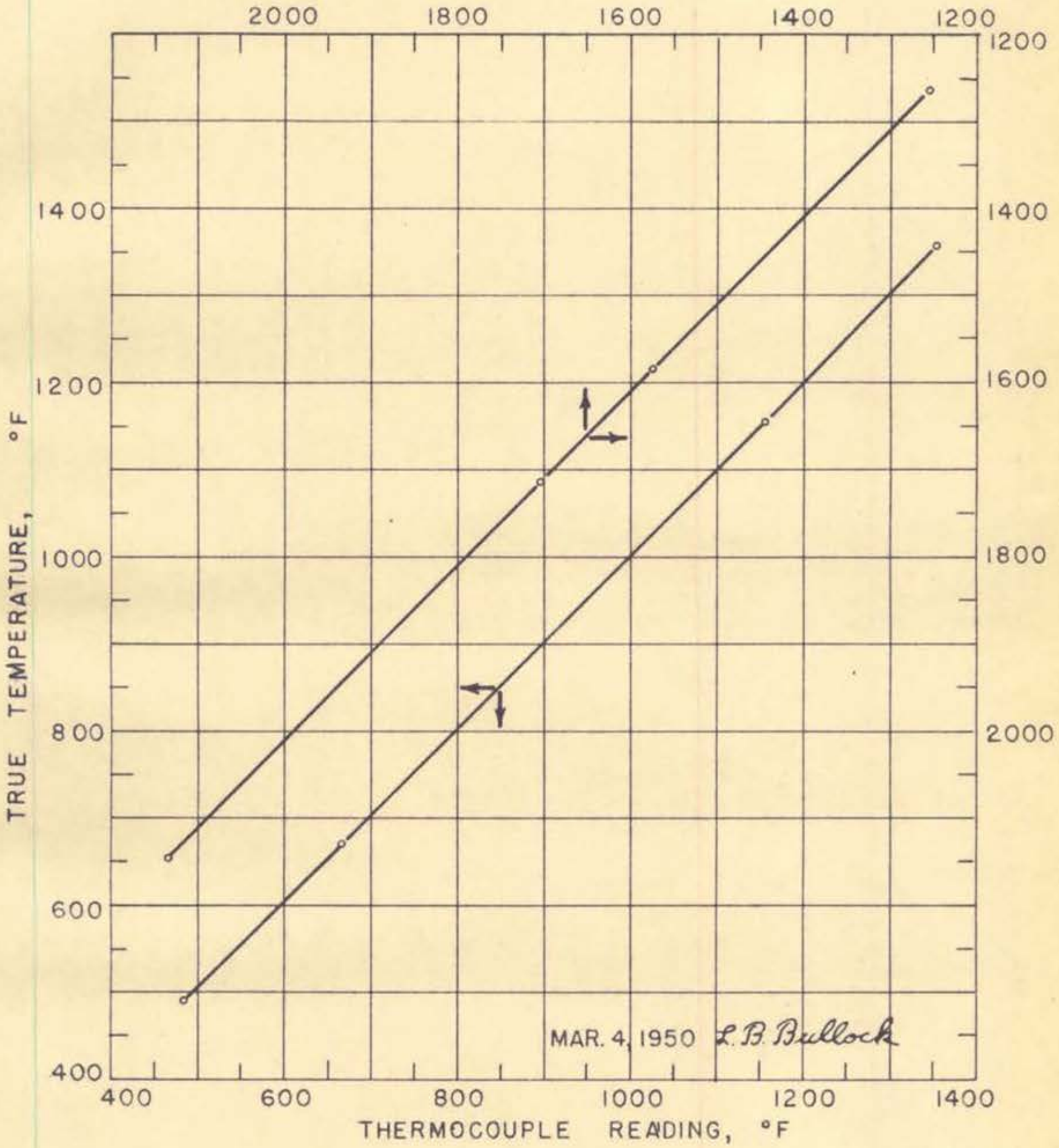

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FIGURE 13- THERMOCOUPLE CALIBRATION NO. 2.

TABLE III

CALIBRATION OF WET TEST METER WITH STANDARD GAS HOLDER

Temperature - 78° F
Barometric pressure - 29.10 inches of Hg
Time of each run was within specifications for accurate results.

Run No.	Actual Air Passed Through Meter cu. ft.	Meter Indicated cu. ft.
MC 1	0.100	0.0973
MC 2	0.100	0.0972
MC 3	0.100	0.0970
MC 4	0.100	0.0974
MC 5	0.100	0.0975
MC 6	0.100	0.0973
MC 7	0.100	0.0971
MC 8	0.100	0.0973
MC 9	0.100	0.0975
TOTAL		0.8756

Average reading $= \frac{0.8756}{9} = 0.0973$ cu. ft.

0.100 cu. ft. of gas is equivalent to 0.0973 cu. ft. as read on Wet Test Meter.

TABLE IV

CALIBRATION OF ROTAMETER WITH WET TEST METER

Fluid - carbon dioxide
Molecular weight - 44
Barometric pressure - 29.00 inches of Hg

Run No.	Static Pressure in. of Hg	Rotameter Reading mm.	Temp. °F	Actual Gas Passed cu. ft.	Time sec.	Flow Rate (1 atms., 80°F) moles per sec. $M \times 10^5$
MC 10	29.265	18	80	0.305	119.74	0.618
MC 11	29.298	50	80	0.305	94.80	0.783
MC 12	29.349	86	80	0.305	75.40	0.978
MC 13	29.386	107	80	0.305	67.30	1.092
MC 14	29.430	135	80	0.305	58.94	1.246
MC 15	29.518	174	80	0.305	50.24	1.460
MC 16	29.621	212	80	0.305	43.00	1.697
MC 17	29.666	226	81	0.305	40.89	1.785
MC 18	29.599	205	82	0.305	44.70	1.633
MC 19	29.548	183	82	0.305	47.97	1.530
* MC 20	29.467	157	83	0.305	54.62	1.224
MC 21	29.401	118.5	83	0.305	63.77	1.153
MC 22	29.327	76	82	0.305	80.03	0.921
MC 23	29.309	62	82	0.305	87.55	0.847
MC 24	29.581	190	82	0.305	46.75	1.565
MC 25	29.276	33	82	0.305	107.62	0.688

* Probable error in time measurement

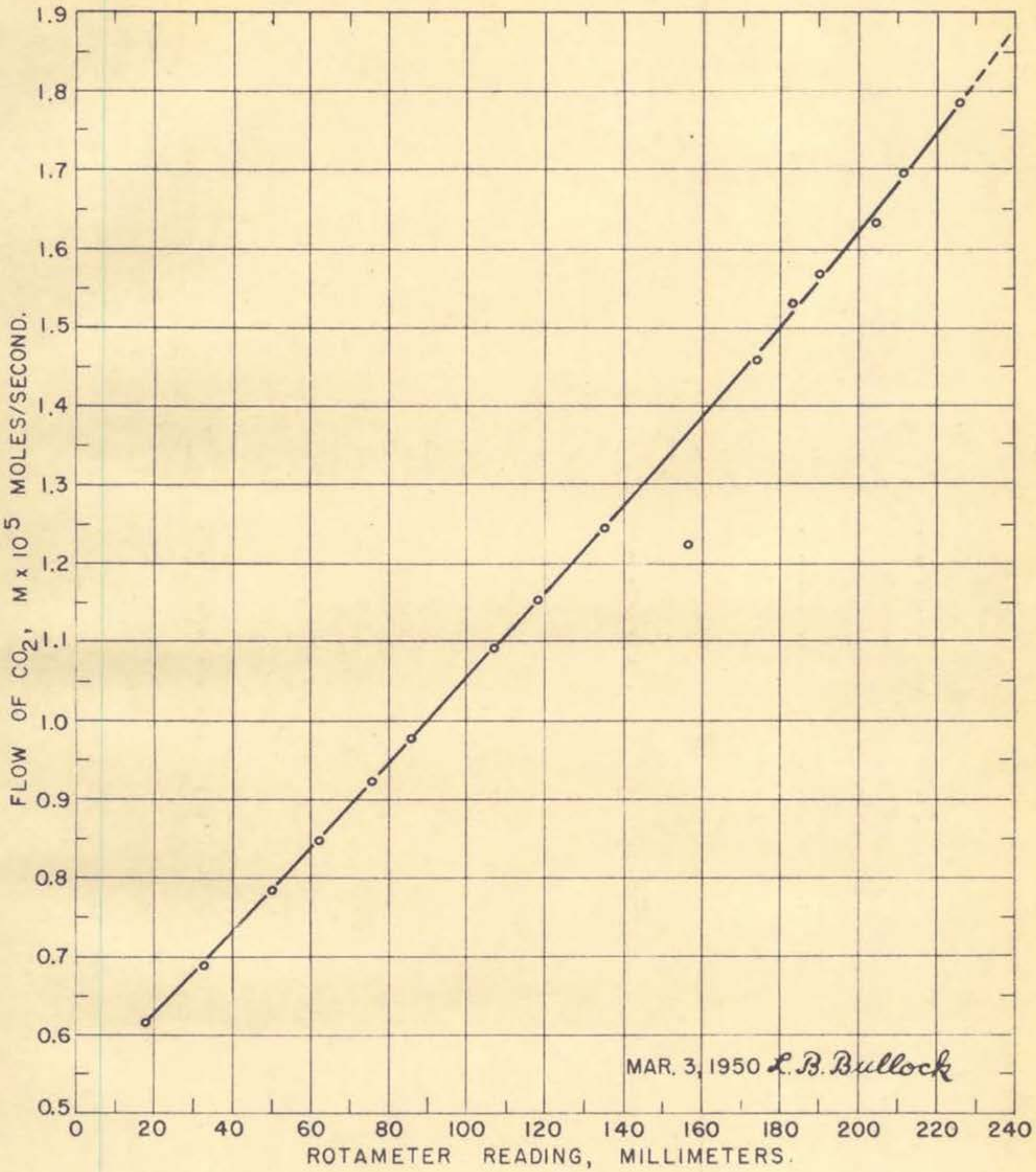

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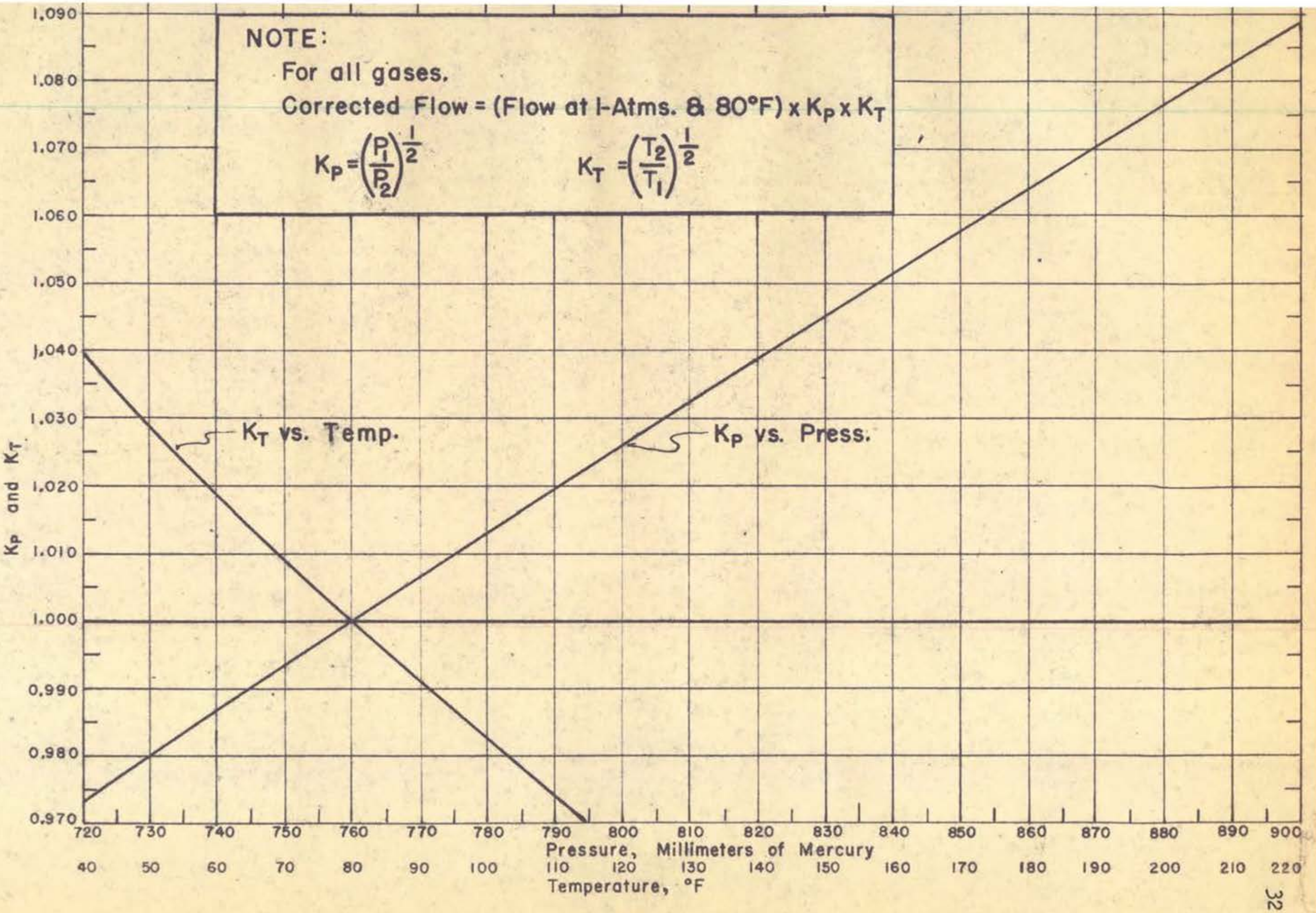
FIGURE 14- ROTAMETER CALIBRATION

AT 1-ATMOSPHERE & 80°F. FOR OTHER CONDITION: SEE FIGURE 15



NOTE:

For all gases.

Corrected Flow = (Flow at 1-Atms. & 80°F) x K_P x K_T

$$K_P = \left(\frac{P_1}{P_2}\right)^{\frac{1}{2}} \qquad K_T = \left(\frac{T_2}{T_1}\right)^{\frac{1}{2}}$$

CORRECTION CHART FOR ROTAMETER FLOW

FIGURE 15

TABLE V

CALIBRATION OF HYDROGEN ORIFICE WITH CARBON DIOXIDE TRACER

Fluid - Hydrogen
Size of Orifice - 0.156 inches
Pressure on Orifice - 30 pounds per sq. in. gauge

Run No.	Barometric Pressure mm.	Temp. Of Mixture °F	Rotameter Static Pressure (above Atms.) in. of water	Rotameter Reading mm.	Actual CO_2 Passed moles per sec. $M \times 10^5$	Manometer Reading cm. of water	CO_2 In Mixture per cent	Hydrogen Flow moles per sec. $M \times 10^5$
MC 26	748.0	60	7.55	83.5	0.975	5.1	5.92	15.50
MC 27	748.6	58	6.90	107.5	1.119	1.1	12.92	7.53
MC 28	748.6	58	10.65	129	1.247	12.7	5.34	22.06
MC 29	748.6	58	14.40	183	1.562	19.9	5.60	26.35
MC 30	748.6	58	15.45	177	1.539	25.8	5.23	27.80
MC 31	744.2	68	10.00	181	1.523	2.4	12.24	10.92
MC 32	744.2	68	13.25	176	1.490	15.65	5.45	25.90

TABLE VI

CALIBRATION OF AIR ORIFICE WITH CARBON DIOXIDE TRACER

Fluid - Air
Size of Orifice - 0.250 inches
Pressure on Orifice - 75 pounds per sq. in. gauge

Run No.	Barometric Pressure mm.	Temp. Of Mixture °F	Rotameter Static Pressure (above Atms.) in. of water	Rotameter Reading mm.	Actual CO_2 Passed moles per sec. $M \times 10^5$	Manometer Reading cm. of water	CO_2 In Mixture per cent	Air Flow moles per sec. $M \times 10^5$
MC 33	745.0	70	15.12	157	1.393	1.3	9.93	12.61
MC 34	745.0	70	22.60	191	1.607	2.7	6.53	23.0
MC 35	744.7	68	26.90	199	1.667	3.45	7.95	19.33
MC 36	744.7	68	57.2	214	1.833	12.5	4.89	35.55
MC 37	744.7	68	80.2	213	1.860	22.3	4.19	42.5
MC 38	746.6	70	19.7	212	1.733	2.02	10.51	14.75
MC 39	746.6	70	40.0	221	1.840	6.89	6.43	26.7
MC 40	746.6	70	65.5	230	1.932	15.55	4.66	39.53

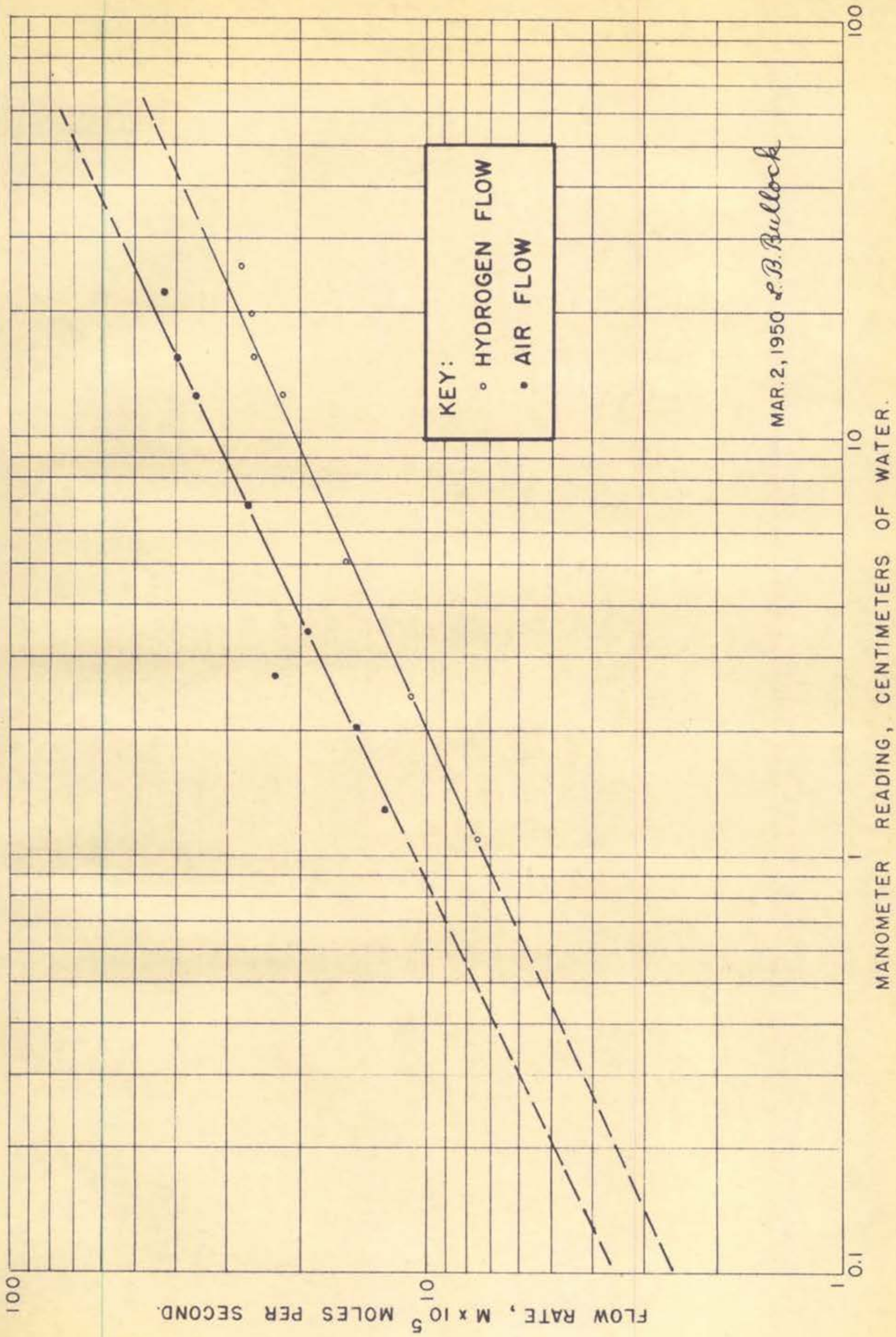


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FIGURE 16- FLOW CALIBRATION CURVES.

TABLE VII

AIR TEMPERATURE CALIBRATION

Run TC-16

Air flow constant at 7.58 x 10^{-5} moles per second.
Readings made at one-half $(\frac{1}{2})$ minute intervals.

Bath Temperature $^{\circ}$F	Air Temperature at Distributor $^{\circ}$F	Bath Temperature $^{\circ}$F	Air Temperature at Distributor $^{\circ}$F
842	754	1083	985
852	768	1092	989
859	784	1098	996
863	790	1107	1000
867	795	1116	1010
873	799	1124	1015
878	806	1133	1023
884	812	1143	1032
888	816	1151	1038
893	820	1162	1046
897	825	1166	1053
904	831	1173	1057
910	835	1181	1065
916	840	1190	1072
923	848	1196	1078
931	859	1199	1082
936	863	1201	1082
946	873	1206	1089
952	877	1208	1091
963	884	1212	1095
969	888	1216	1099
974	895	1220	1103
982	899	1226	1107
989	903	1230	1112
995	911	1236	1116
1004	919	1242	1120
1010	926	1248	1128
1017	930	1252	1134
1026	937	1257	1138
1035	943	1263	1142
1042	949	1270	1148
1050	958	1276	1154
1060	964	1280	1160
1068	972	1285	1164
1077	977		

TABLE VII (Continued)

Run TC-1

Air flow constant at 10.9×10^{-5} moles per second.
Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Air Temperature at Distributor °F	Bath Temperature °F	Air Temperature at Distributor °F
822	755	1295	1209
841	801	1300	1221
897	827	1315	1226
925	871	1319	1230
965	885	1320	1238
1003	935	1329	1244
1037	950	1342	1252
1042	972	1345	1262
1062	995	1354	1264
1069	1010	1359	1284
1091	1023	1369	1286
1101	1040	1376	1288
1123	1051	1389	1294
1146	1071	1393	1303
1156	1073	1403	1306
1170	1095	1403	1311
1187	1101	1412	1322
1190	1120	1420	1336
1203	1129	1434	1337
1210	1140	1436	1339
1225	1142	1438	1341
1232	1159	1443	1350
1245	1164	1445	1350
1254	1173	1448	1354
1265	1178	1452	1357
1271	1190	1456	1360
1280	1194	1467	1381
1289	1205		

TABLE VII (Continued)

Run TC-2

Air flow constant at 15.1×10^{-5} moles per second.
Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Air Temperature at Distributor °F	Bath Temperature °F	Air Temperature at Distributor °F
823	769	1030	975
826	778	1041	981
831	782	1043	985
836	790	1049	990
839	795	1051	992
849	797	1055	998
855	804	1057	1000
859	808	1062	1006
862	812	1067	1008
870	818	1076	1017
874	825	1081	1019
877	827	1083	1023
890	839	1086	1026
892	839	1089	1029
896	847	1095	1033
902	852	1099	1035
911	859	1100	1039
915	863	1104	1043
920	869	1107	1047
923	873	1116	1052
930	877	1117	1055
934	882	1120	1059
943	888	1127	1063
953	894	1131	1067
958	899	1136	1070
966	907	1140	1072
971	913	1146	1076
975	914	1150	1078
979	915	1158	1085
982	920	1164	1089
984	926	1169	1095
992	930	1172	1097
995	932	1174	1101
1000	939	1177	1103
1004	941	1180	1107
1006	943	1185	1110
1012	949	1190	1114
1016	952	1194	1118
1021	958	1199	1121
1026	962	1201	1123
1030	972	1204	1130

TABLE VII (Continued)

Run TC-3

Air flow constant at 18.2 x 10^{-5} moles per second.
Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Air Temperature at Distributor °F
854	808
883	827
890	842
909	854
923	871
941	877
950	892
971	905
984	919
997	926
1006	941
1022	951
1031	967
1045	975
1061	992
1071	996
1074	1006
1086	1012
1091	1024
1102	1029
1107	1035
1113	1041
1120	1047
1131	1059
1142	1067
1152	1080
1162	1085
1166	1093
1174	1099
1182	1107
1188	1111
1192	1114
1196	1119
1201	1124
1209	1126
1213	1133
1217	1136

TABLE VII (Continued)

Run TC-4

Air flow constant at 20.8×10^{-5} moles per second.
Readings made at one-half $(\frac{1}{2})$ minute intervals.

Bath Temperature °F	Air Temperature at Distributor °F
882	848
900	857
911	865
932	882
938	892
949	899
956	905
963	911
971	920
982	926
988	935
997	939
1001	947
1003	951
1010	958
1016	964
1027	972
1030	981
1045	984
1051	992
1061	997
1067	1002
1071	1008
1077	1015
1081	1023
1088	1029
1095	1033
1099	1037
1109	1047
1116	1052
1128	1057
1129	1059
1142	1072
1146	1076
1152	1082
1162	1093
1170	1099
1174	1101
1180	1107
1185	1112
1190	1119
1193	1123
1206	1132
1213	1138

TABLE VII (Continued)

Run TC-5

Air flow constant at 23.1 x 10^{-5} moles per second.
Readings made at one-half (½) minute intervals.

Bath Temperature °F	Air Temperature at Distributor °F
902	861
911	871
921	886
941	897
953	905
971	920
988	932
1001	949
1021	964
1033	979
1043	985
1049	994
1063	1002
1071	1012
1081	1019
1083	1025
1086	1031
1095	1033
1099	1039
1102	1041
1107	1045
1113	1055
1115	1059
1126	1066
1129	1068
1138	1078
1144	1082
1150	1089
1152	1093
1158	1097
1168	1101
1172	1107
1177	1112
1180	1114
1185	1121
1192	1126
1199	1133
1201	1137

TABLE VIII

HYDROGEN TEMPERATURE CALIBRATION

Run TC-17

Hydrogen flow constant at 3.30×10^{-5} moles per second.
Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1046	820
1057	820
1079	822
1096	827
1114	833
1139	835
1156	837
1162	840
1166	846
1181	848
1190	854
1199	861
1208	863
1225	863
1231	869
1246	875
1252	880
1265	884
1270	888
1276	892
1284	897
1291	903
1302	907
1310	913
1319	917
1327	922
1336	924
1349	930
1357	935
1364	937
1372	939
1379	943
1387	947
1394	951
1401	952
1405	958
1409	962

TABLE VIII (Continued)

Run TC-6

Thermocouple at distributor position moved during run.

Run TC-11

Hydrogen flow constant at 4.58×10^{-5} moles per second. Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1074	754
1075	776
1087	788
1095	806
1105	814
1107	820
1110	831
1123	837
1142	857
1167	867
1196	901
1215	909
1227	928
1241	941
1250	956
1265	964
1269	979
1273	983
1278	994
1280	996
1281	1002
1284	1006
1286	1008
1290	1010
1295	1012

TABLE VIII (Continued)

Run TC-7

Hydrogen flow constant at 6.34×10^{-5} moles per second. Readings made at one minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1067	868
1081	873
1095	890
1126	899
1136	905
1154	924
1164	932
1168	941

Run TC-12

Hydrogen flow constant at 6.34×10^{-5} moles per second. Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1189	913
1194	939
1200	939
1209	956
1215	962
1225	979
1232	990
1243	1000
1251	1006
1260	1015
1271	1021
1278	1026
1286	1033
1295	1038
1301	1043

TABLE VIII (Continued)

Run TC-8

Hydrogen flow constant at 7.64 x 10^{-5} moles per second.
Readings made at one minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1111	869
1123	903
1128	917
1134	928
1134	939
1144	943
1150	949
1161	962
1168	963
1172	970
1174	977
1180	981
1182	985

Run TC-13

Hydrogen flow constant at 7.64 x 10^{-5} moles per second.
Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1181	922
1187	949
1193	985
1207	996
1213	1002
1221	1012
1234	1024
1243	1031
1255	1039
1267	1047
1275	1057
1288	1065
1300	1074
1312	1082
1317	1091

TABLE VIII (Continued)

Run TC-9

Hydrogen flow constant at 8.72 x 10^{-5} moles per second. Readings made at one minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1069	901
1086	909
1095	917
1106	930
1117	935
1129	943
1144	947
1152	956
1159	962
1180	972
1188	983
1199	990

Run TC-14

Hydrogen flow constant at 8.72 x 10^{-5} moles per second. Readings made at one-half ($\frac{1}{2}$) minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1203	964
1215	1011
1229	1017
1232	1027
1241	1032
1246	1038
1256	1048
1265	1055
1269	1057

TABLE VIII (Continued)

Run TC-10

Hydrogen flow constant at 9.70 x 10^{-5} moles per second.
Readings made at one minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1092	905
1106	926
1111	951
1123	956
1129	962
1139	968
1144	977
1152	981
1154	985
1168	990
1172	994
1179	996
1190	1000
1199	1004

Run TC-15

Hydrogen flow constant at 9.70 x 10^{-5} moles per second.
Readings made at one-half (½) minute intervals.

Bath Temperature °F	Hydrogen Temperature at Distributor °F
1195	970
1203	1015
1211	1041
1228	1041
1239	1057
1254	1061
1265	1067
1273	1072
1275	1076
1290	1080
1295	1085
1301	1095

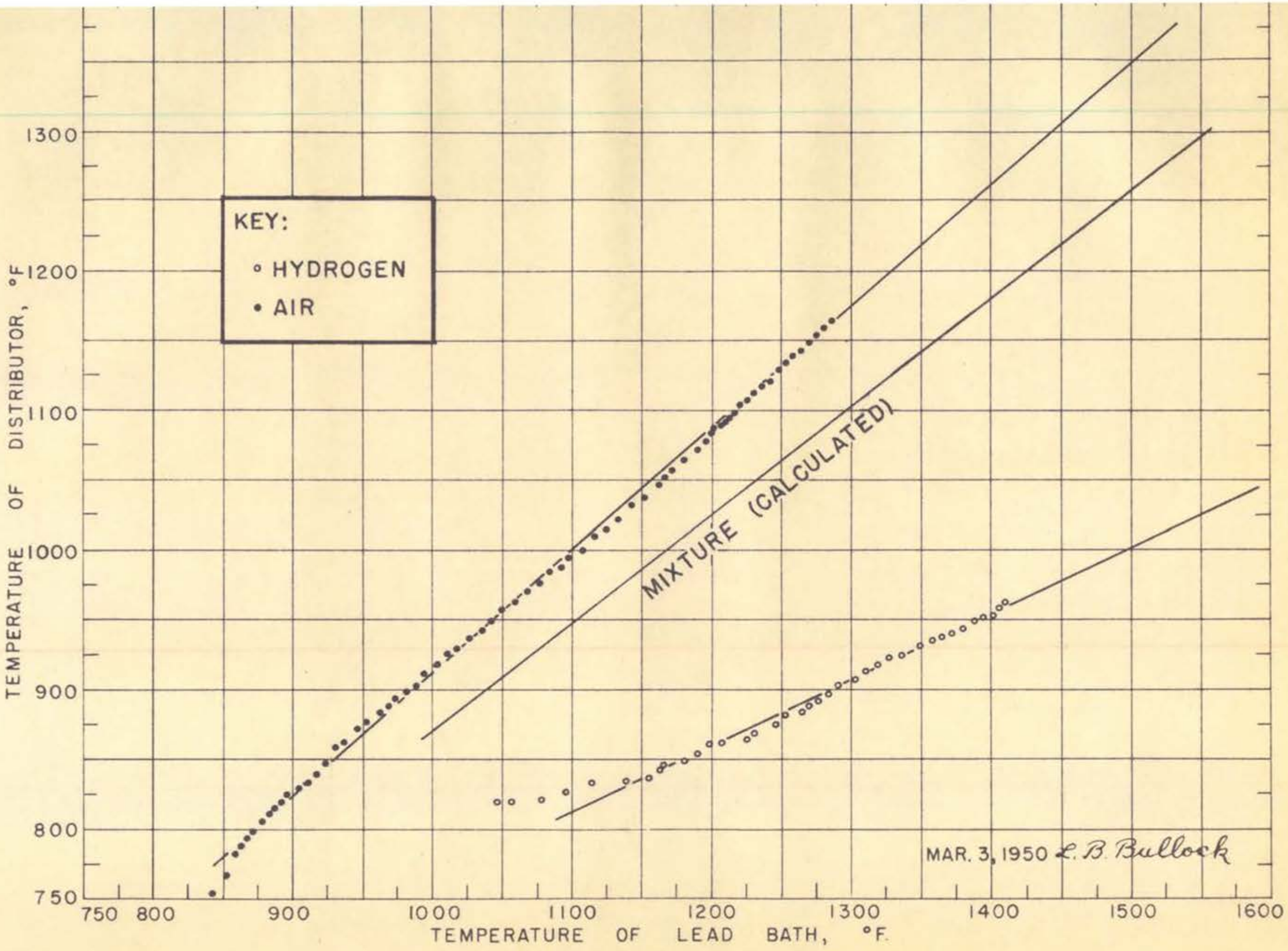

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FIGURE 17—TEMPERATURE CALIBRATION

FLOW: HYDROGEN= 3.30×10^{-5} MOLES/SECOND, AIR= 7.85×10^{-5} MOLES/SECOND.

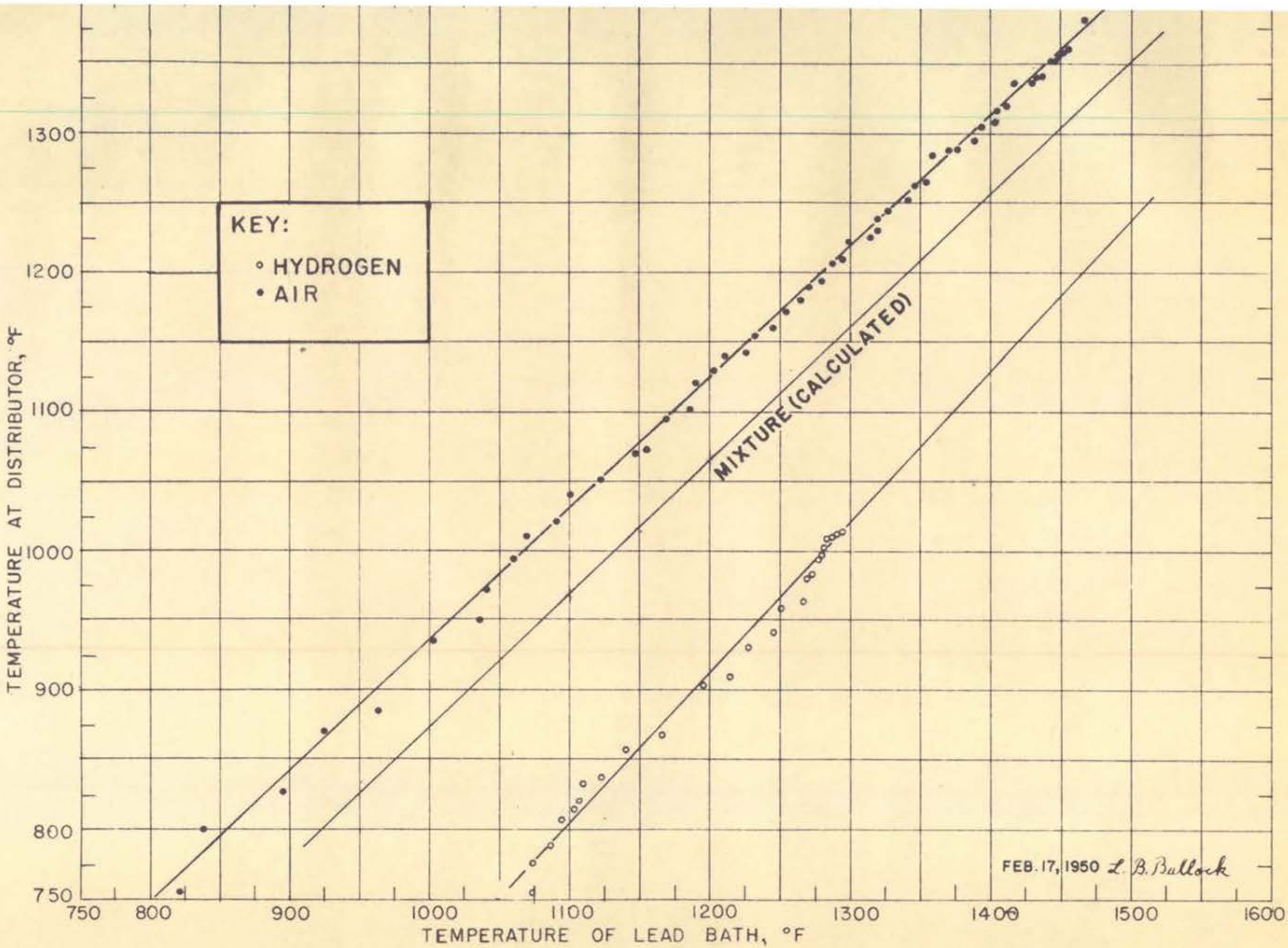

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FIGURE 18— TEMPERATURE CALIBRATION

FLOW: HYDROGEN= 4.58 x 10^{-5} MOLES/SECOND, AIR= 10.9 x 10^{-5} MOLES/SECOND.

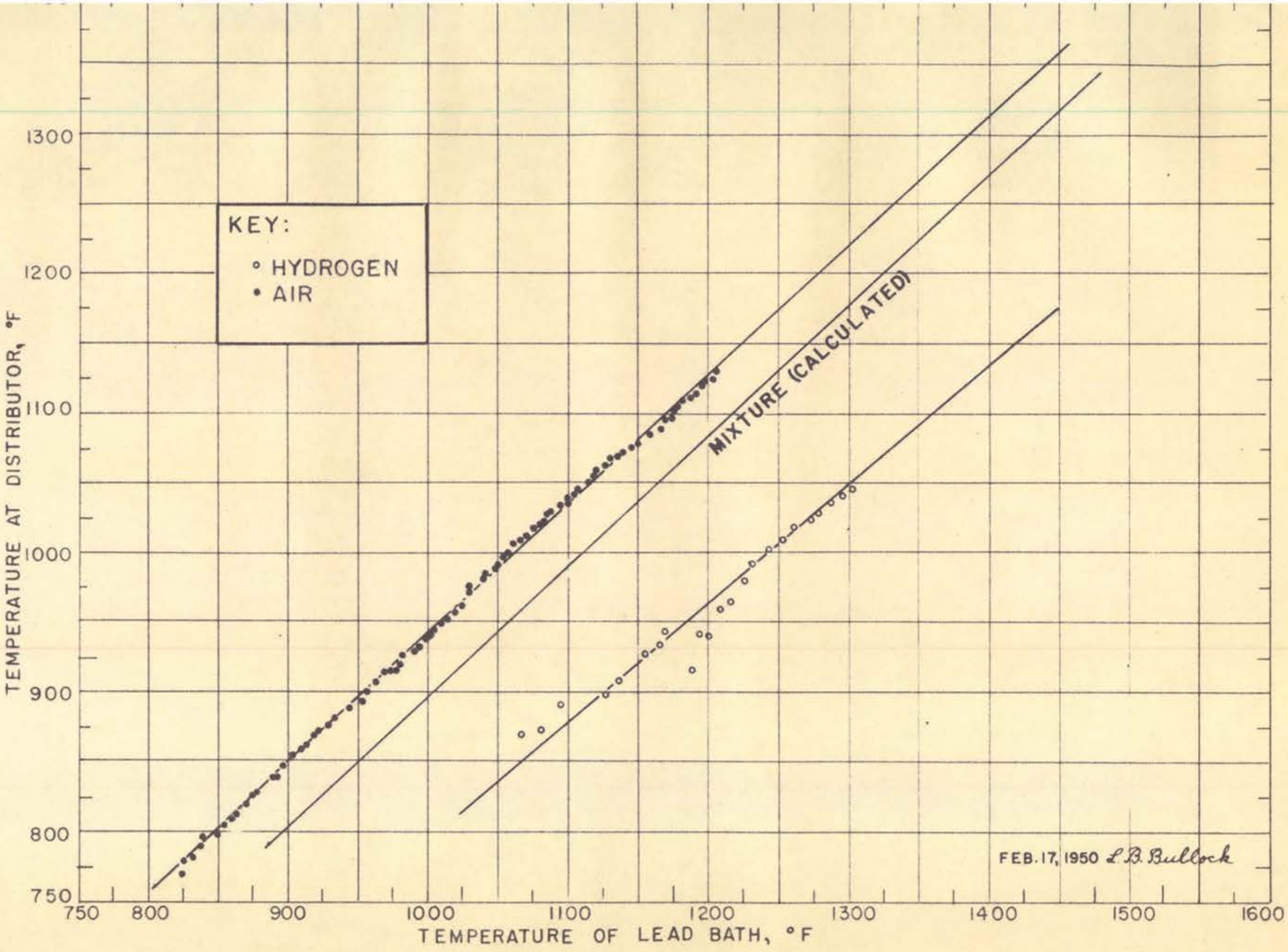

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FIGURE 19— TEMPERATURE CALIBRATION

FLOW: HYDROGEN= 6.34 x 10^{-5} MOLES/SECOND, AIR= 15.1 x 10^{-5} MOLES/SECOND.

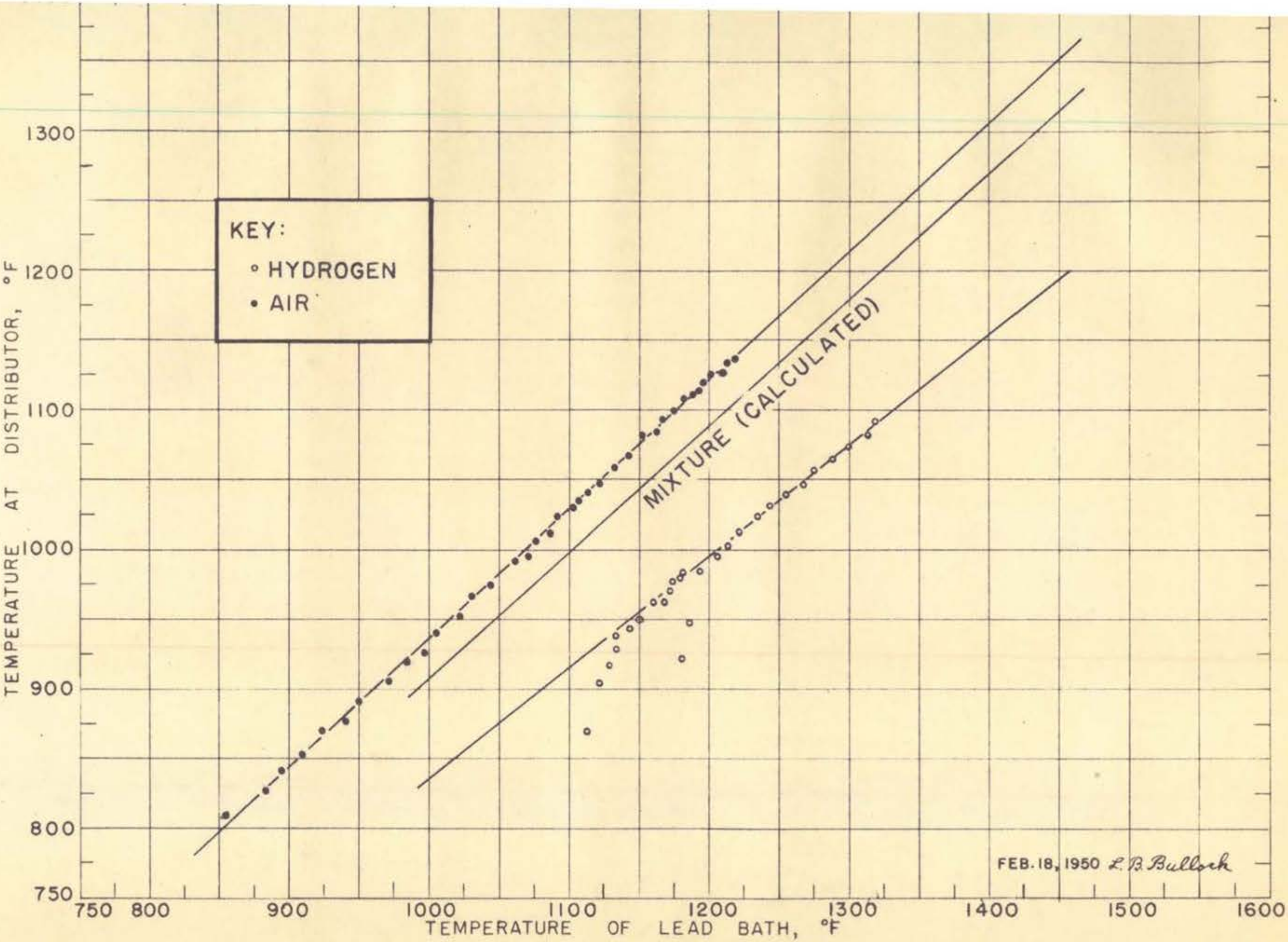

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FIGURE 20— TEMPERATURE CALIBRATION

FLOW: HYDROGEN = 7.64×10^{-5} MOLES/SECOND, AIR = 18.2×10^{-5} MOLES/SECOND.

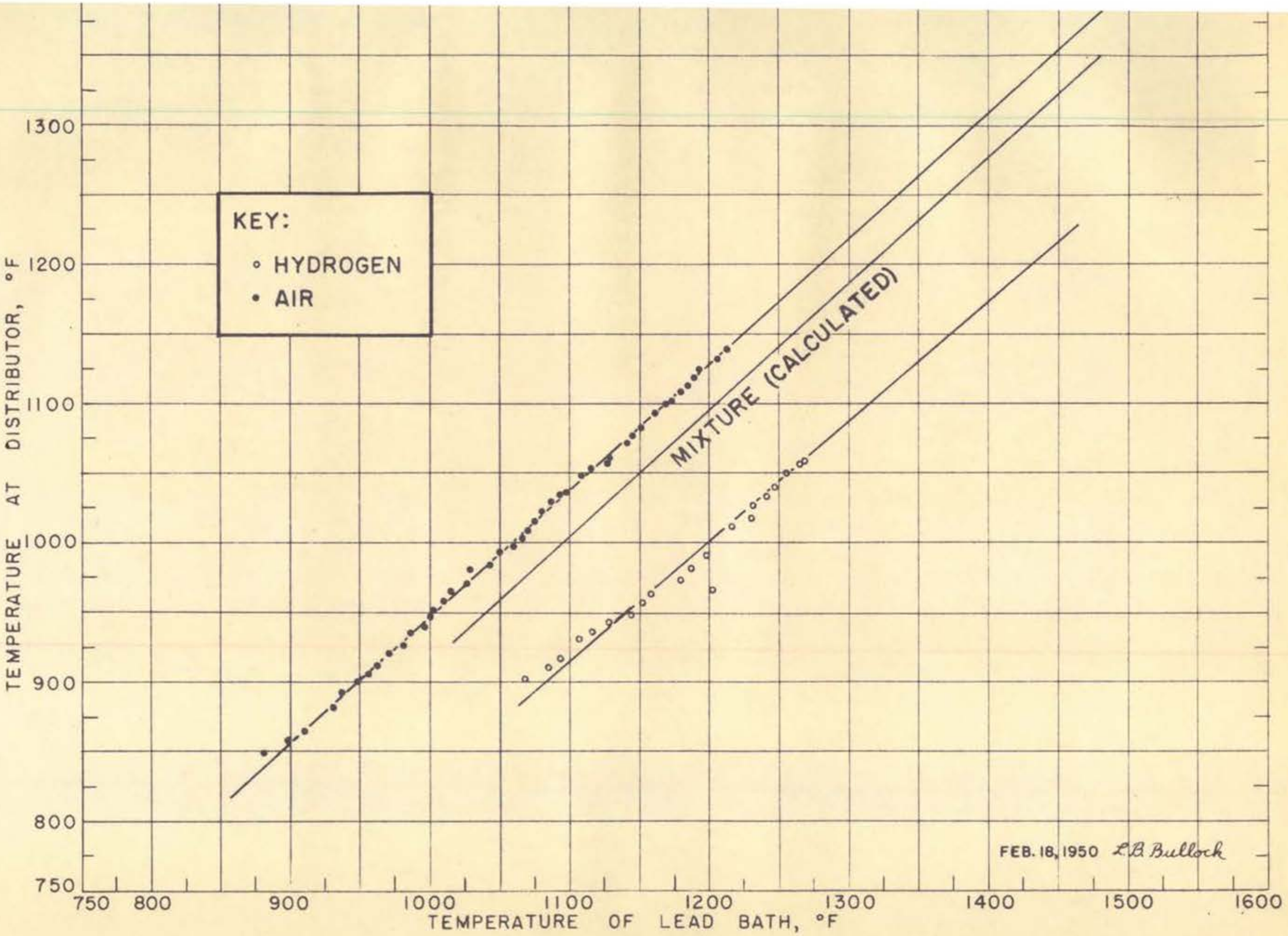

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FIGURE 21 — TEMPERATURE CALIBRATION

FLOW: HYDROGEN = 8.72×10^{-5} MOLES/SECOND, AIR = 20.8×10^{-5} MOLES/SECOND.

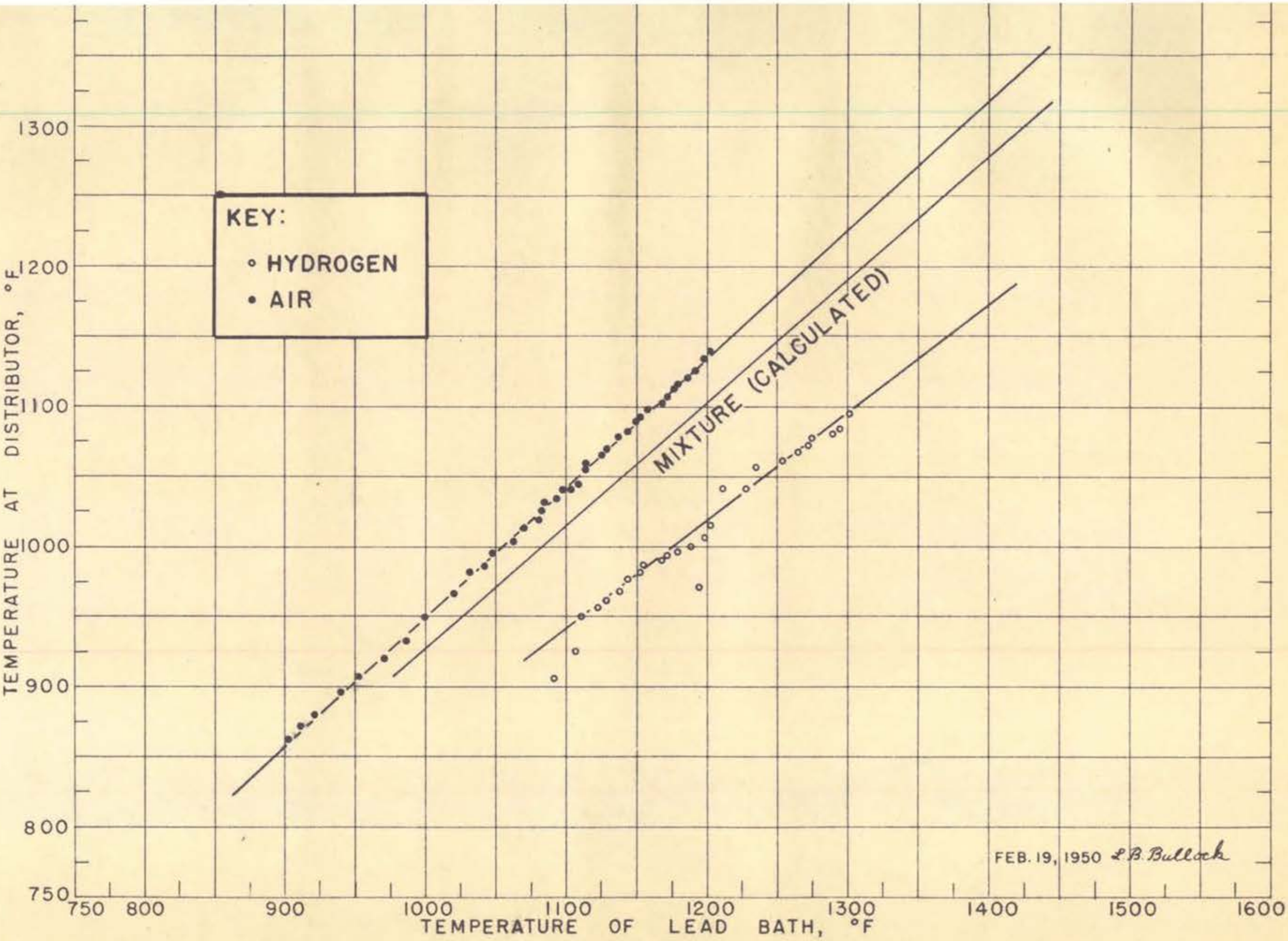


FIGURE 22— TEMPERATURE CALIBRATION

FLOW: HYDROGEN= 9.70×10^{-5} MOLES/SECOND, AIR= 23.1×10^{-5} MOLES/SECOND.

TABLE IX

IGNITION TEMPERATURE RUNS

Run 1

Air flow - 10.9×10^{-5} moles per second.
Hydrogen flow - 4.58×10^{-5} moles per second.
Barometric pressure - 748 mm. of Hg.

Heated gases to 1220°F without ignition.

Run 2

Air flow - 10.9×10^{-5} moles per second.
Hydrogen flow - 4.58×10^{-5} moles per second.
Barometric pressure - 748 mm. of Hg.

Bath thermocouple broke at gas temperature of 1230°F. No ignition.

Run 3

Air flow - 10.9×10^{-5} moles per second.
Hydrogen flow - 4.58×10^{-5} moles per second.
Barometric pressure - 748 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1230
0.5	1240
1	1253
:	:
:	:
:	:
27	1464
27.5	1468
28	1472
28.5	1478
29	1482

Ignited at 28.75 minutes.
Bath temperature: 1480°F.
Mixture temperature: 1330°F.

TABLE IX (Continued)

Run 4

Air flow – 10.9×10^{-5} moles per second.
Hydrogen flow – 4.58×10^{-5} moles per second.
Barometric pressure – 745 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1311
0.5	1313
1	1316
:	:
:	:
:	:
13.5	1388
14	1390
14.5	1394
15	1396
15.5	1400

Ignited at 15.5 minutes.
Bath temperature: 1400°F.
Mixture temperature: 1255°F.

Run 5

Air flow – 10.9×10^{-5} moles per second.
Hydrogen flow – 4.58×10^{-5} moles per second.
Barometric pressure – 744 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1294
0.5	1299
1	1307
:	:
:	:
:	:
17	1433
17.5	1438
18	1442
18.5	1446
19	1450

Ignited at 19 minutes.
Bath temperature: 1450°F.
Mixture temperature: 1302°F.

TABLE IX (Continued)

Run 6

Air flow - 15.1 x 10^{-5} moles per second.
Hydrogen flow - 6.34 x 10^{-5} moles per second.
Barometric pressure - 744 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1331
0.5	1338
1	1344
:	:
:	:
:	:
10	1420
10.5	1424
11	1430
11.5	1436
12	1443

Ignited at 12 minutes.
Bath temperature: 1443°F.
Mixture temperature: 1309°F.

Run 7

Air flow - 7.85 x 10^{-5} moles per second.
Hydrogen flow - 3.30 x 10^{-5} moles per second.
Barometric pressure - 744 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1305
0.5	1309
1	1316
:	:
:	:
:	:
17.5	1508
18	1515
18.5	1521
19	1531
19.5	1539

Ignited at 19.4 minutes.
Bath temperature: 1537°F.
Mixture temperature: 1286°F.

TABLE IX (Continued)

Run 8

Air flow - 18.2×10^{-5} moles per second.
Hydrogen flow - 7.46×10^{-5} moles per second.
Barometric pressure - 744 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1350
0.5	1352
1	1354
:	:
:	:
:	:
9	1404
9.5	1406
10	1408
10.5	1412
11	1415

Ignited at 11 minutes.
Bath temperature: 1415°F.
Mixture temperature: 1284°F.

Run 9

Air flow - 20.8×10^{-5} moles per second.
Hydrogen flow - 8.72×10^{-5} moles per second.
Barometric pressure - 740 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1286
0.5	1294
1	1307
:	:
:	:
:	:
9.5	1412
10	1416
10.5	1422
11	1424
11.5	1426

Ignited at 11.2 minutes.
Bath temperature: 1425°F.
Mixture temperature: 1298°F.

TABLE IX (Continued)

Run 10

Air flow - 23.1×10^{-5} moles per second.
Hydrogen flow - 9.70×10^{-5} moles per second.
Barometric pressure - 740 mm. of Hg.

Time Minutes	Bath Temperature °F
0	1303
0.5	1307
1	1313
:	:
:	:
:	:
16	1433
16.5	1435
17	1437
17.5	1442
18	1446

Ignited at 17.75 minutes.
Bath temperature: 1444°F.
Mixture temperature: 1316°F.

SAMPLE CALCULATIONS

A. Calculations for mixture temperature calibration line.

$$n_a H_a + n_b H_b = n_a H_m + n_b H_m$$

$$n_a MCp_a \int_{60^\circ}^{t_a} dt + n_b MCp_b \int_{60^\circ}^{t_b} dt = n_a MCp_a \int_{60^\circ}^{t_m} dt + n_b MCp_b \int_{60^\circ}^{t_m} dt$$

$$n_a MCp_a (t_a - 60) + n_b MCp_b (t_b - 60) = n_a MCp_a (t_m - 60) + n_b MCp_b (t_m - 60)$$

Heat capacity data from Rossini (26).

Refer to Figure 17.

$n_a = 7.85 \times 10^{-5}$ moles/second.

$n_b = 3.30 \times 10^{-5}$ moles/second.

Reference: Lead bath temperature of 1100°F.

$t_a = 1000^\circ F.$ $MCp_a = 7.23$ Btu/mole °F.

$t_b = 813^\circ F.$ $MCp_b = 6.98$ Btu/mole °F.

First trial:

$$(7.85 \times 10^{-5})(7.23)(1000-60) + (3.30 \times 10^{-5})(6.98)(813-60)$$

$$= (7.85 \times 10^{-5})(7.23)(t_m-60) + (3.30 \times 10^{-5})(6.98)(t_m-60)$$

$t_m - 60 = 887$

$t_m = 947^\circ F.$

Second trial with new MCp:

$MCp_a = 7.21$ Btu/mole °F.

$MCp_b = 7.00$ Btu/mole °F.

$t_m - 60 = 888$

$t_m = 948^\circ F.$

B. Calculations for induction period.

$A = 2 \pi r^2$

$Q = V A$

$V = dr/d\theta$

$Q = 2\pi r^2 \, dr/d\theta$

$Q \int_0^{\theta} d\theta = 2\pi \int_{r_1}^{r_2} r^2 \, dr$

$\theta = \frac{2\pi}{3Q}(r_2^3 - r_1^3)$

$r_1 = 0.0417$ feet

$r_2 = 0.3333$ feet

Refer to Table IX, Run 7.

Ignition temperature: 1746°R.

Barometric pressure: 744 mm. of Hg.

Air flow: 7.85×10^{-5} moles/second.

Hydrogen flow: 3.30×10^{-5} moles/second.

Total mixture flow: 11.15×10^{-5} moles/second.

$Q = (11.15 \times 10^{-5})(359)\frac{(1746)(760)}{(492)(744)} = 0.145$ cubic feet per second.

$\theta = \frac{2(3.14)}{3(0.145)}(\overline{0.3333}^3 - \overline{0.0417}^3)$

$\theta = 0.53$ seconds.

TABLE OF NOMENCLATURE

A = area of hemisphere.

H = enthalpy.

MCp = mean molal heat capacity.

n = flow in moles per second.

Q = volumetric flow rate in cubic feet per second.

r = radius of surface through which gas flows.

r_1 = radius of distributor.

r_2 = radius of cooling grid.

t = temperature, °F.

V = velocity in feet per second.

θ = induction period in seconds.

Subscripts:

a = air.

b = hydrogen.

m = mixture.

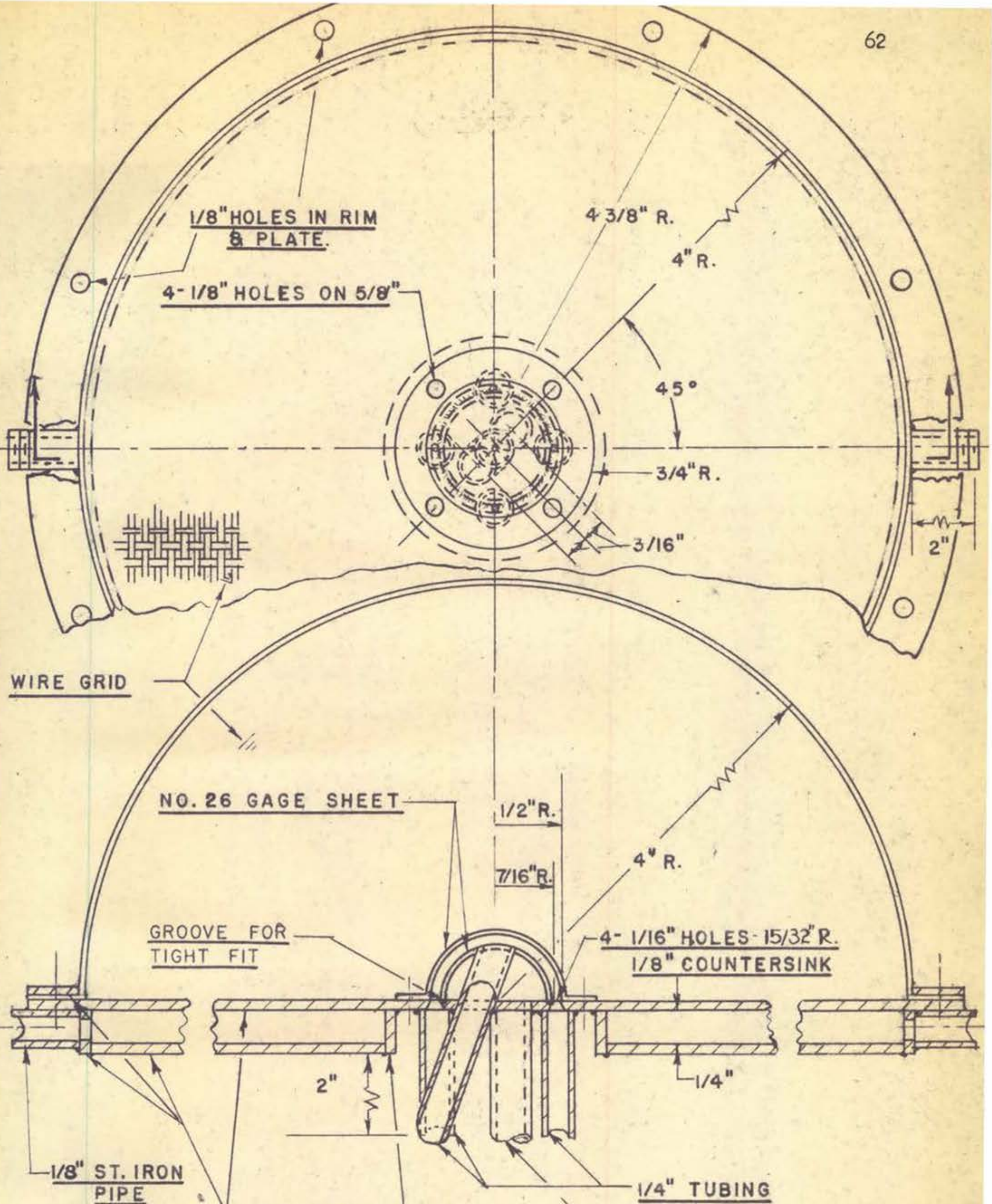


FIGURE 23

HEMISPHERICAL IGNITION CHAMBER

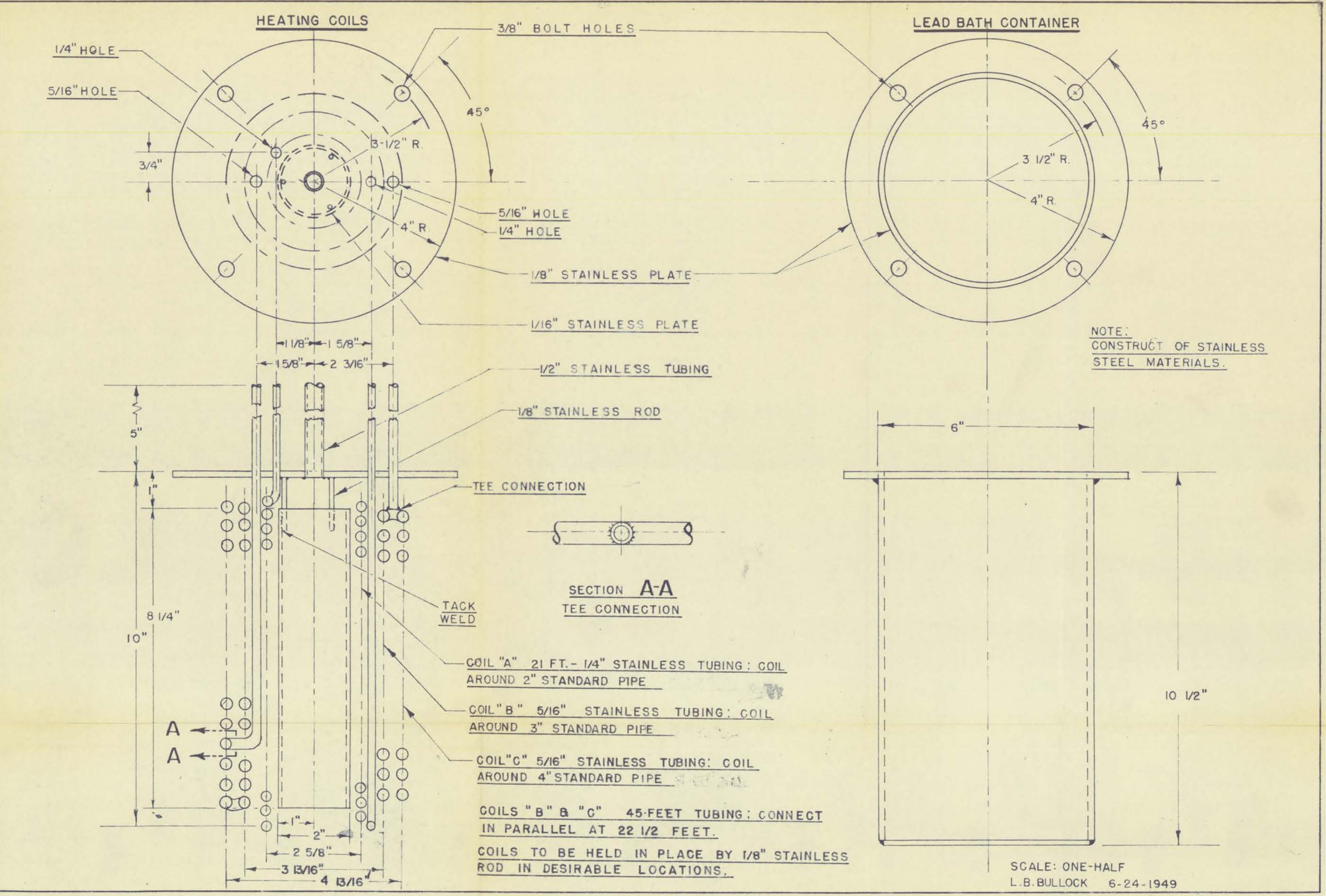
SCALE: FULL

L.B. BULLOCK 6-28-1949

NOTE:

ALL STAINLESS STEEL MATERIAL, UNLESS OTHERWISE NOTED.

FIGURE 24



COILS "B" & "C" 45 FEET TUBING: CONNECT IN PARALLEL AT 22 1/2 FEET.

COILS TO BE HELD IN PLACE BY 1/8" STAINLESS ROD IN DESIRABLE LOCATIONS.

NOTE:
CONSTRUCT OF STAINLESS STEEL MATERIALS.

SCALE: ONE-HALF
L.B. BULLOCK 6-24-1949

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