HEAT TRANSFER TO
BOILING HYDROCARBON MIXTURES

By

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Signature of Author _

Signature of Professor in Charge of Research

Signature of Chairman of Departmental
Committee on Graduate Students_____________

√

The Graduate House
Mass. Inst.of Tech.
Cambridge, Mass.
August 30, 1938

Prof. George W. Swett
Secretary of the Faculty
Mass. Inst. of Tech.
Cambridge, Mass.

Dear Sir:

I submit herewith a copy of my thesis entitled "Heat Transfer to Boiling Hydrocarbon Mixtures," in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering.

Respectfully submitted,

ACKNOWLEDGEMENT

The author wishes to express his appreciation of the valuable assistance and advice of Prof. W. H. Mc Adams and Mr. W. Kelly Woods, under whom this work was completed. The author is also deeply indebted to Mr. Woods and Mr. D. J. Bringardner for their cooperation in obtaining mutual data.

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I SUMMARY

Using the apparatus built by W. H. Spalding (1) but modified by the author, mixtures of benzene and oil were investigated for the effects of temperature difference, velocity and viscosity on heat transfer coefficients to boiling hydrocarbon mixtures. The apparatus, described in detail in the appendix, consists of a vertical nickel tube evaporator, .465 inches inside diameter and 20.75 inches in length, heated by steam at 10 to 170 lbs./sq.in. gauge. Forced convection was obtained by a pump, and a preheater was located before the main heating section in order to have the liquid enter this section at its boiling temperature.

Wall temperatures were measured by three thermocouples imbedded in the tube wall. The temperature of the liquid and vapor leaving the heating section was taken to be the temperature within the heating section. The velocity of the entering liquid was measured by a calibrated orifice and viscosity determinations were made with a Saybolt Universal Viscosimeter.

Data was taken on benzene oil mixtures ranging from 5% oil to 67% oil by volume. The oil used in these mixtures was a close cut lube oil, Chlorex treated, iso-vis 50, from the Wood River Refinery of the Standard Oil Company (Indiana).

The entire apparatus was well lagged and the heat losses, calculated approximately, were found to be negligible. The

measurements were accurate to 1%, as checked by calculations.

The data taken covers only the left hand side of the $Q/A\Theta$ versus Δ curve, except for a 5% oil mixture, for which a maximum of 183,000 Btu/hr./sq.ft. at a Δ of 140°F was obtained. The data covers only the right hand side of the h versus Δ curves.

Below the maximum, increases of concentration of oil were found to reduce the heat transfer at a given delta and to increase the value of the critical delta. By extrapolation of the data plots, it appears that for concentrations of oil in benzene between 5 and 70% oil the maximum heat flow is approximately the same, although at different deltas. Plotting $Q/A\Theta$ against oil concentration on semi-logarithmic paper, straight lines at constant delta are obtained.

It has been found that the data can be correlated by the empirical equation

$$Q/A\Theta = 63\,(\Delta)^{.76}\left(\frac{DV\rho}{\mu}\right)^{.4}$$

which is applicable only within limits of 5 to 70% oil, at atmospheric pressure, on the left hand side of the critical delta and with velocities of 2 to 7 feet per second. This equation is based primarily on variations in temperature difference and viscosity and the exponent assigned to velocity is highly questionable.

II INTRODUCTION

In recent years much investigation has been made on the factors influencing heat transfer coefficients to liquids, but very little work has been reported on the effects of these factors on boiling mixtures.

Among the variables that have been investigated are temperature difference in the heating unit, pressure and, with forced convection, velocity. The effect of temperature difference has been fairly well determined for natural convection,(2) (10), the heat transfer coefficients and the heat transfer plotted against temperature difference going through a maximum, or "hump". The hump in the heat transfer curves occurs at that point when the heat transfer coefficient is decreasing more rapidly than the temperature difference is increasing. Hence, a plot of heat transfer coefficient versus temperature difference will show a critical temperature difference lower than the critical temperature difference obtained for the heat transfer versus temperature difference plots. The location of this maximum is dependent to a large extent upon the liquid under consideration and the condition of the heating surface,(8) varying over a large range of temperature difference. Of the pure liquids upon which work has been reported, water gives the highest maximum heat flow and butyl alcohol and carbon tetrachloride the lowest.

Pressure has also been found to influence heat transfer rates, low pressure (8) reducing them and high pressure (11) causing an increase. This is in all probability due to viscosity effects; higher pressure raising the boiling temperature and lowering the viscosity of the liquid under consideration. Likewise, reduced pressure reduces the boiling temperature and correspondingly raises the viscosity at the boiling point.

It is already established that there are at least two types of boiling (3), nuclear and film. Pictures taken by Sauer (2) and others have clearly illustrated these two types. Nuclear boiling takes place at lower temperature differences and consists in bubbles forming at points on the heating surface and rising through the liquid. Larger temperature differences bring on a transition to film boiling, in which a film of superheated vapor forms between the pipe wall and the liquid, reducing the rate of heat transfer. Hence the "hump" that is found as temperature difference is increased.

It has also been shown by numerous investigators (6) (9) (12) (13) that velocity has a marked effect upon the rate of heat transfer, the liquid film being reduced in thickness and allowing a greater heat transfer. Spalding (1) shows that an increase in velocity moves the hump in the direction of higher temperature differences, the velocity sweeping away the vapor film that otherwise would have formed on the heating surface. The amount of heat flow at the maximum is, however, apparently independent of velocity.

To date, the literature on boiling liquid mixtures is very meager, previous investigators having used only pure liquids or dilute solutions of solids in pure liquids. Viscosity has not been an important variable, although it has been stated (4) that a rough correlation may be obtained by plotting the overall thermal resistance 1/U against $\mu^{0.4}/G^{0.8}$. This relation, however, breaks down at higher temperature differences. An increase in viscosity increases the liquid film thickness and reduces convection, hence the coefficient of heat transfer decreases.

It is the purpose of this investigation to follow up previous work on the effects of temperature difference and velocity on heat transfer and to go further into the problem of viscosity and its correlation with the rate of heat transfer.

III PROCEDURE

Details of the apparatus used in these experiments are given in Fig. I and in the section "Detailed Description of Apparatus," Appendix A. Six concentrations of mixtures of benzene and oil were used in the apparatus. The oil used in these mixtures was a close cut lube oil, Chlorex treated, iso-vis 50, from the Wood River Refinery of the Standard Oil Company (Indiana).

In beginning a run, the apparatus was filled to about four inches from the bottom of the vapor liquid separator, and the pump, preheater steam, main heating section steam and condenser water were turned on. When the boiling temperature was almost reached, as determined by the temperature in the top header, the liquid cooler water was turned on. When boiling actually began, the steam in the preheater, the condenser water and liquid cooler water were regulated to the desired values.

The system was then allowed to come to equilibrium and a run was begun. Temperature measurements and cooling water rates were taken for heat balances around the condenser and the liquid cooler. The temperature difference in the heating section was calculated from the average of the thermocouple readings on the inside tube walls and the temperature of the liquid and vapor in the top header. The temperature difference was controlled by the pressure of the condensing steam in the heating section and to a small extent by the velocity of the liquid.

The velocity of the liquid through the heating section was controlled by a by-pass on the pump and measured by the pressure drop across a calibrated orifice located about two feet from the union of the pump and by-pass streams.

During the run a sample of the liquid in the system was drawn off at the bottom header for analysis as to its composition and viscosity.

The method of analysis of samples consisted in determining its boiling point and locating its composition on a plot of boiling temperature versus per cent oil, given in Fig. XI. Viscosities of mixtures of 40% oil and above were taken in a Saybolt Universal Viscosimeter at various temperatures; below 40% the values were obtained by interpolation between the viscosities of the higher concentrations and that of pure benzene.

Data was taken on various fluid velocities in the apparatus from two to seven feet per second entering the heating section, although in some runs wide variations were impossible, due to discrepancies in the pump. Temperature differences were taken ranging from those corresponding to 12 lbs./sq.in. to 168 lbs./sq.in. gauge steam. After equilibrium was reached a run took about twenty minutes.

For the details of the procedure see "Details of Procedure," Appendix B.

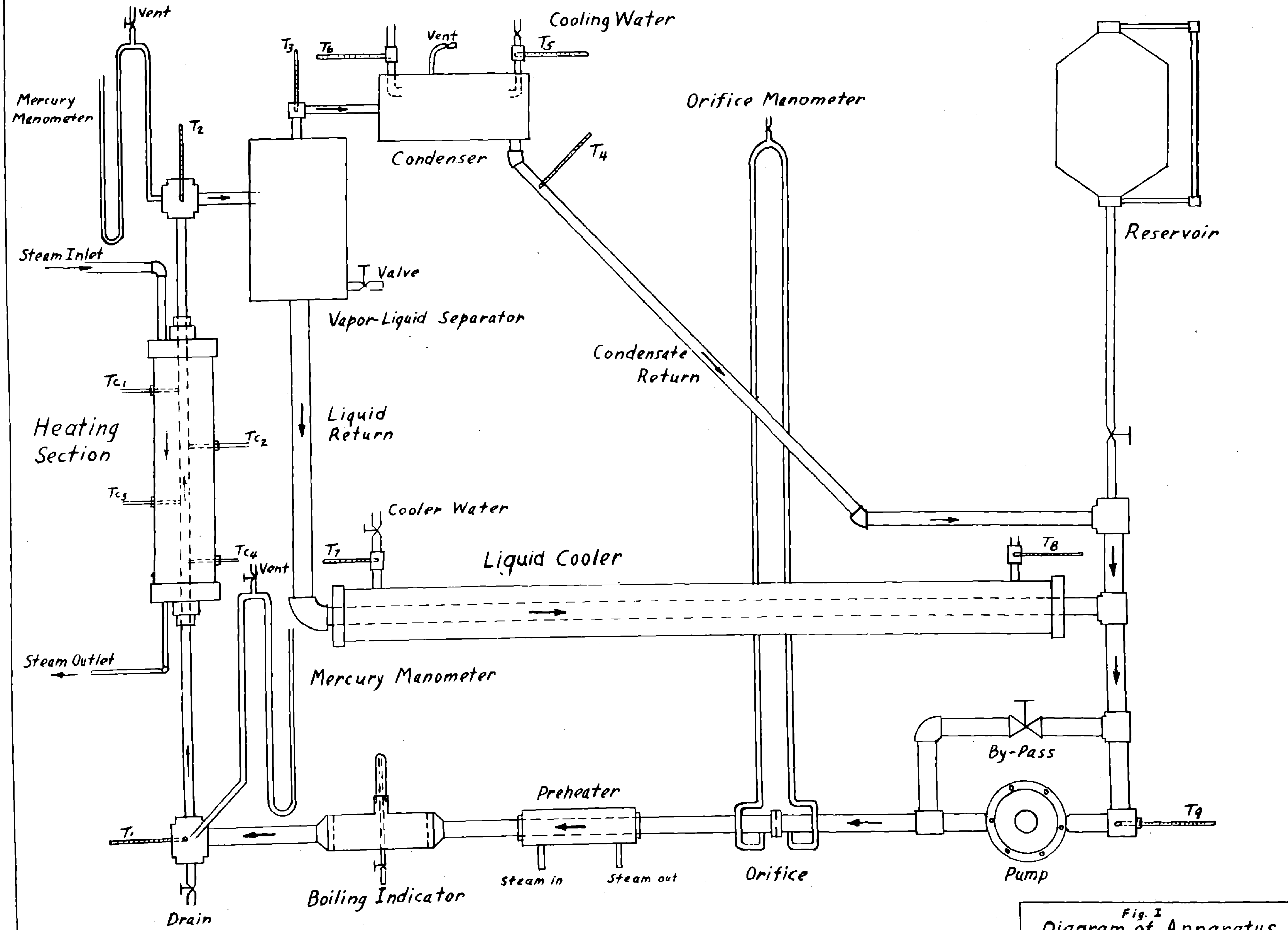

Fig. I
Diagram of Apparatus
M.I.T. 8/13/38 J.W.W.

IV RESULTS

1. Fig. III A,B,C,D,E - Heat transfer, Btu/sq.ft./hr. versus Δ t, °F.
2. Fig. IV Heat transfer, Btu/sq.ft./hr. versus concentration of mixture at Δ t's of 40, 50, 70, 100, 140, and 170 °F.
3. Fig. V Film coefficient, Btu/sq.ft./hr./°F. versus Δ °F with varied concentrations.
4. Fig. VI Heat transfer versus Reynolds number at constant Δ's.
5. Fig. VII α versus Δ °F, where α is constant in equation $Q/A\theta = \alpha(Re)^{.4}$

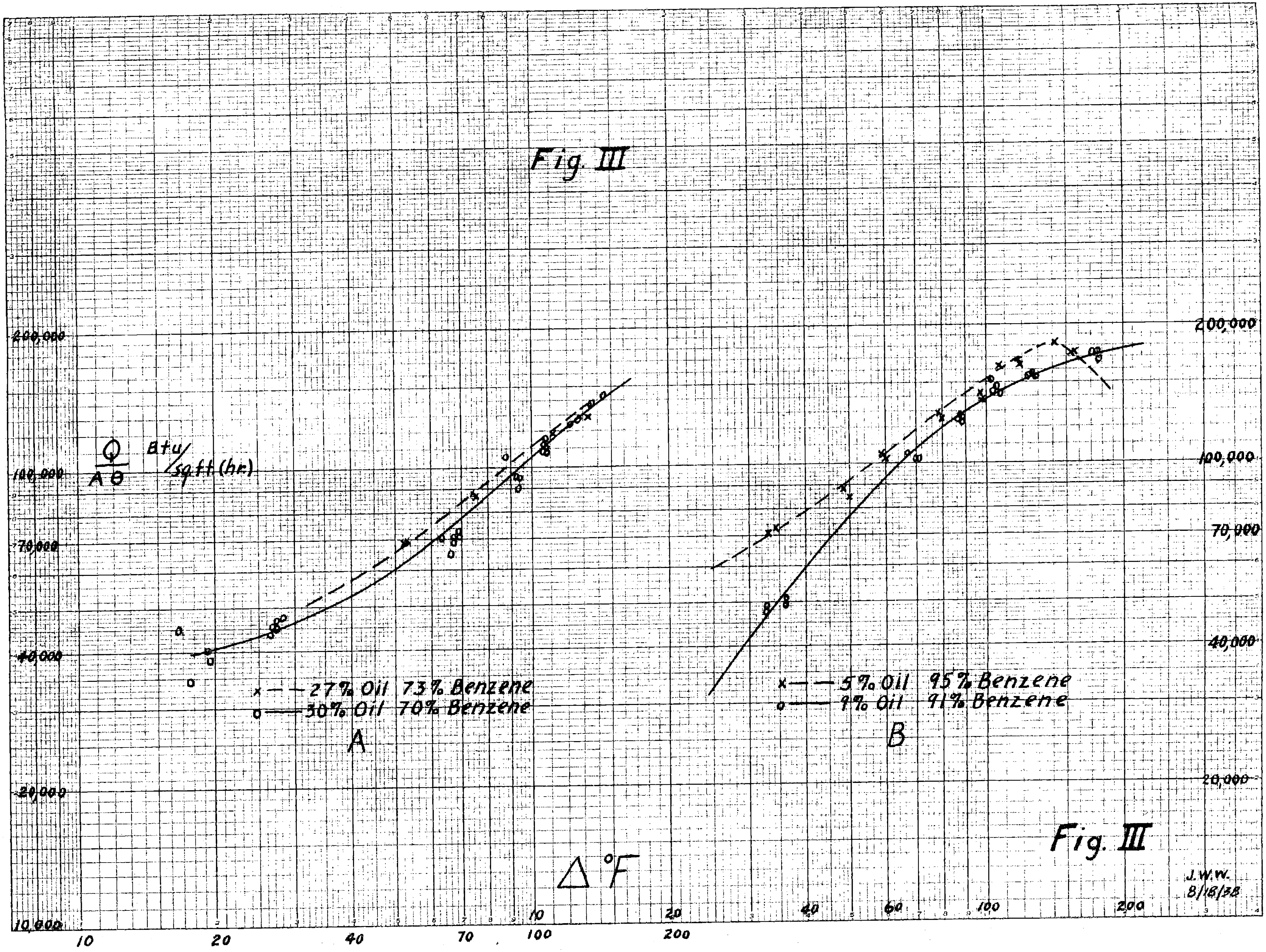

Fig. III

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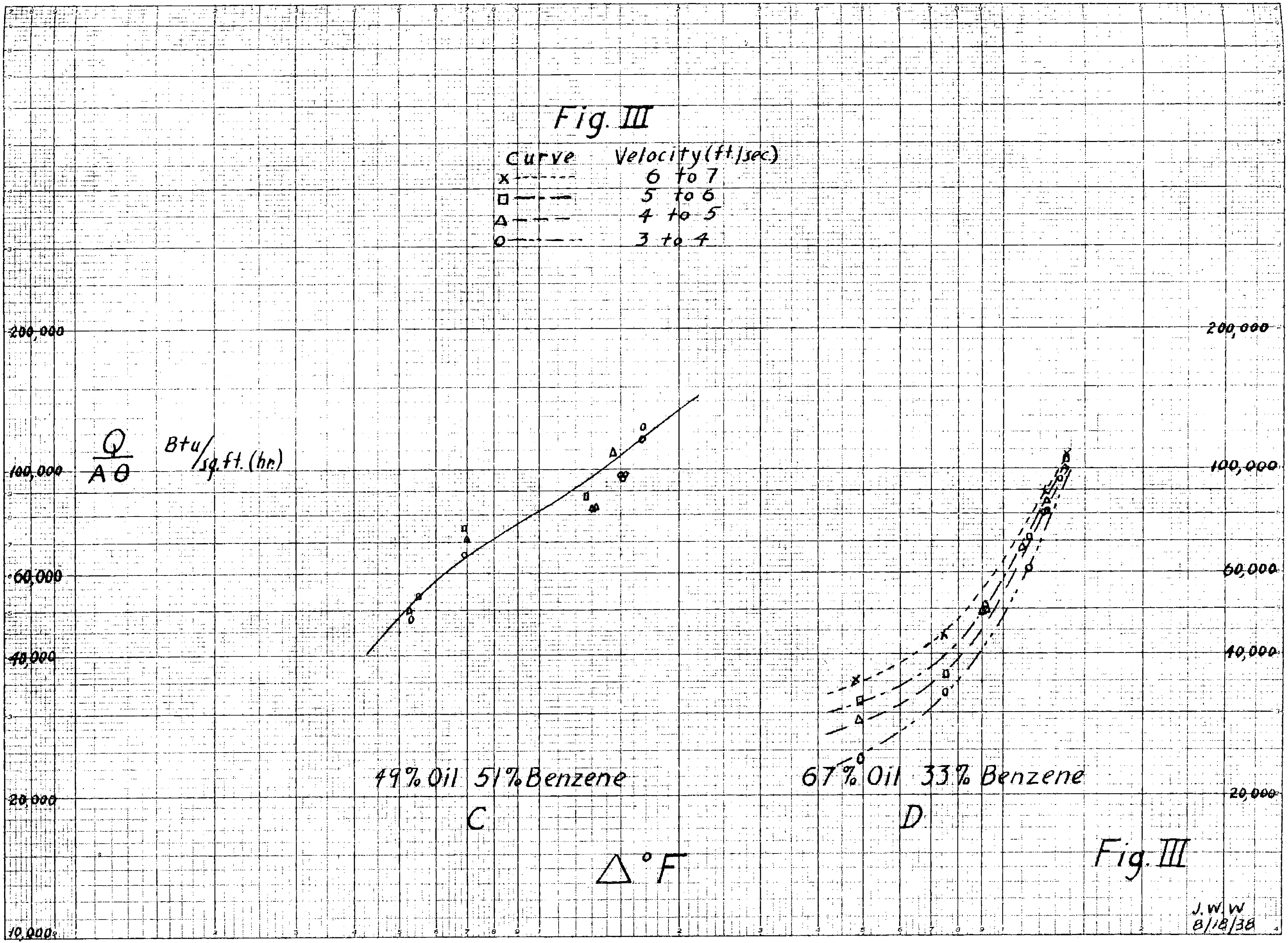

Fig. III

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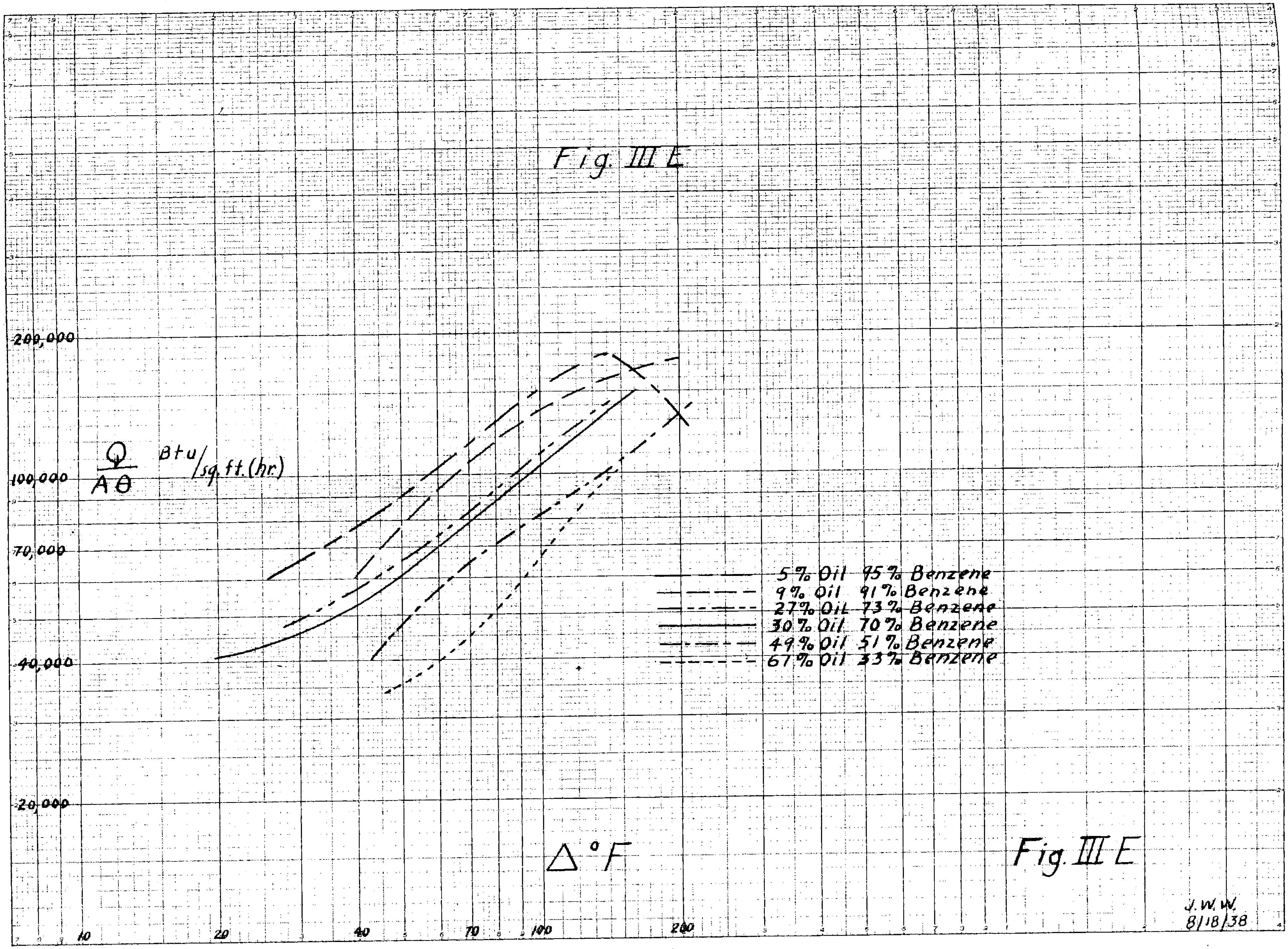

Fig. III E

Fig. III E

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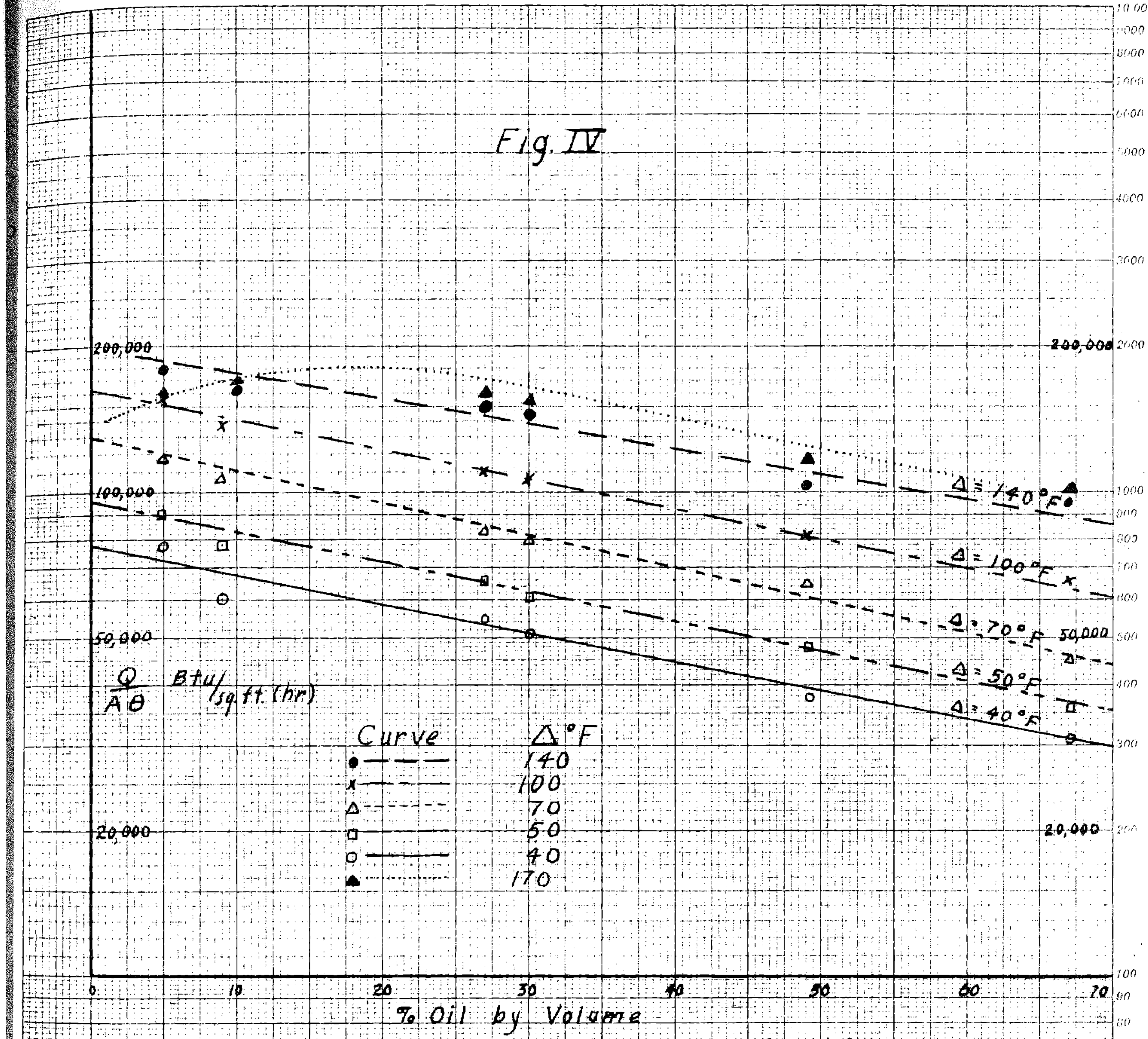

Fig. IV

$\frac{Q}{A\theta}$ versus Concentration at Constant Δ°F

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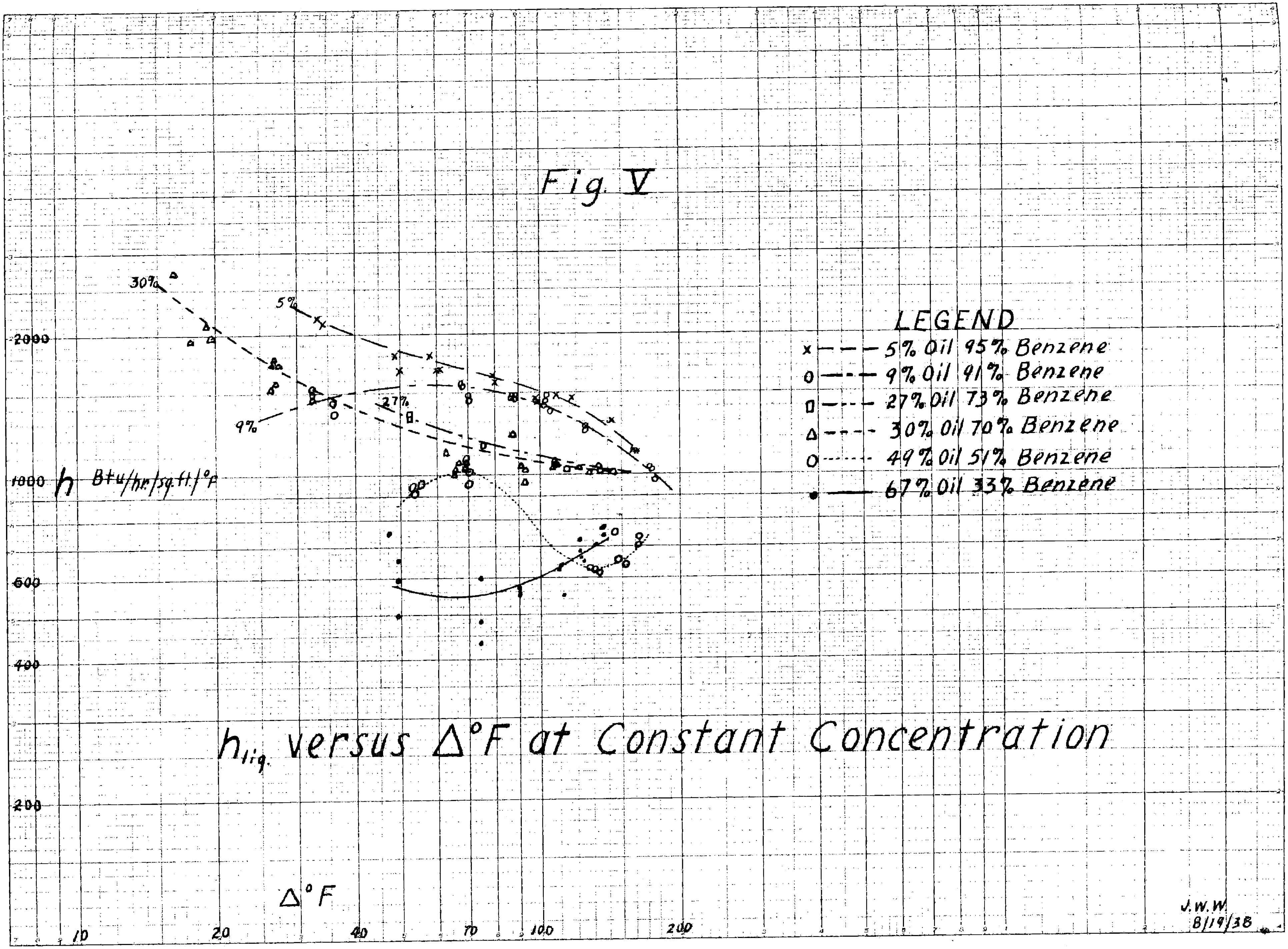
Fig. V



$h_{liq.}$ versus Δ°F at Constant Concentration

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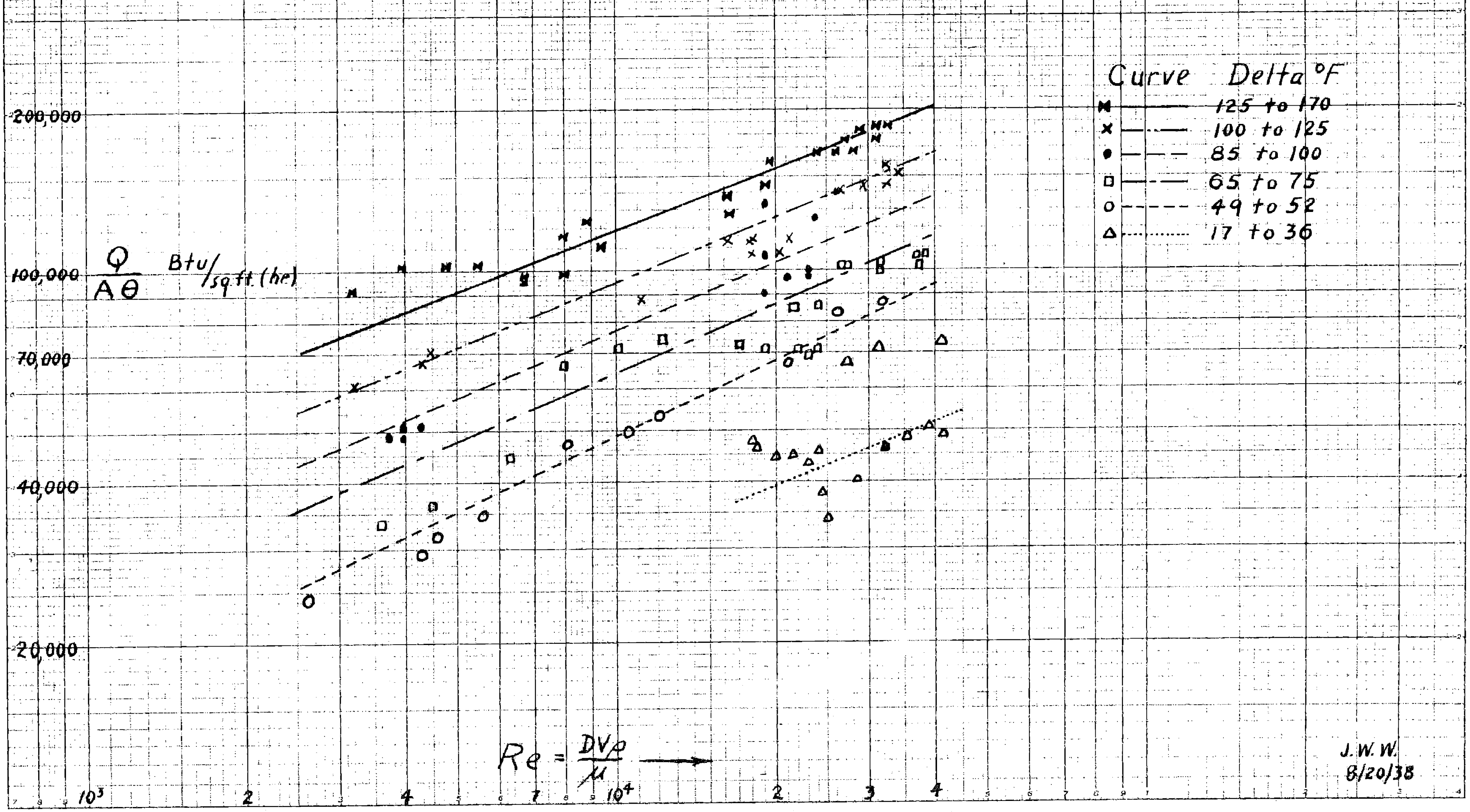
Fig. VI

$\frac{Q}{A\theta}$ versus Reynolds Number of Entering Liquid



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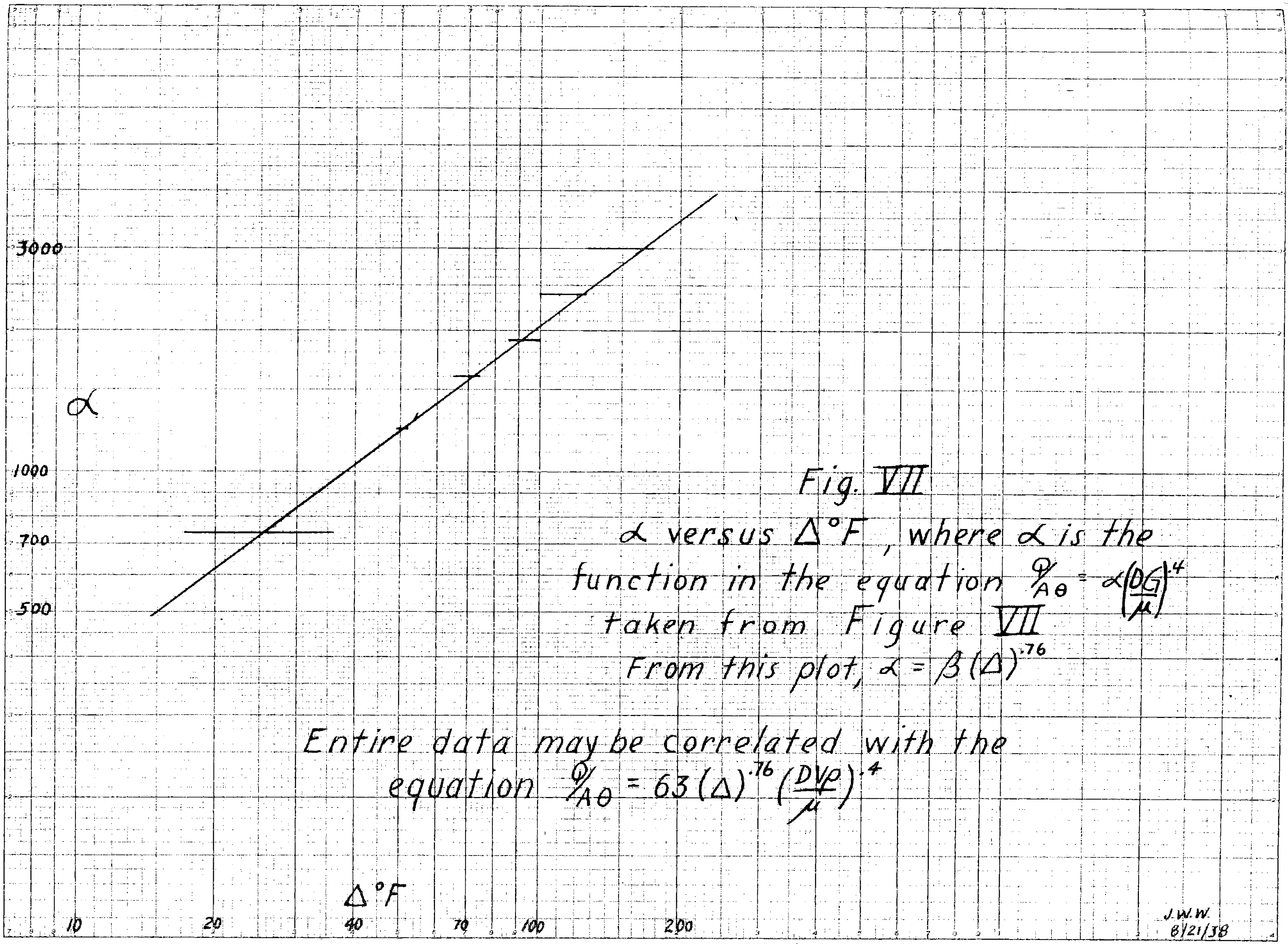

Fig. VII

α versus Δ °F, where α is the function in the equation $\frac{Q}{A\theta} = \alpha\left(\frac{DG}{\mu}\right)^{.4}$ taken from Figure VII

From this plot, $\alpha = \beta(\Delta)^{.76}$

Entire data may be correlated with the equation $\frac{Q}{A\theta} = 63(\Delta)^{.76}\left(\frac{DV\rho}{\mu}\right)^{.4}$

J.W.W.
8/21/38

V DISCUSSION OF RESULTS

The results of this investigation are summarized in Appendix C, "Summary of Data and Results" and are plotted in the preceeding section, "Results."

Only the low Δ side of the heat transfer "hump" has been obtained, with the exception of the 5% oil 95% benzene mixture, where the curve began to drop at the highest steam temperature available to the apparatus. The hump may still be in some doubt, although the data obtained gives a positive indication of a downward turn.

It was planned in the research to have a pure benzene run, but once oil was run through the apparatus it was found impossible to remove it without dissembling the entire apparatus. The oil was run through it in order to to boil out any water that might have remained from previous use of the equipment or that leaked in before the data runs were begun. Hence it is impossible to state exactly the effect on heat transfer that is caused by adding varied amounts of oil to pure benzene.

Figure III shows that an increase in the percentage of oil, in general, shifts the curve of the heat transfer versus temperature difference to the right. For a given increase in the percent of oil, the magnitude of this effect is greater at low percents than at high. Thus, the curves for 5% and 9% oil mixtures are approximately as widely separated as the curves for 50% and 70% oil mixtures. The Q/AΘ versus Δt plots gave comparatively smooth curves for a constant composition, although some points varied appreciably for no apparent reason. The slopes of the curves for various compositions were not found to be the same, although they were roughly parallel at high Δt's.

There is some indication that the maximum Q/AΘ would be about the same for all concentrations of oil and benzene from 5% to 67% oil. More work should be done, however, to verify these conclusions.

Velocity was found to have little effect on the rate of heat transfer except in the run with 67% oil and 33% benzene, where a large percentage of the heat flow went to heating the liquid before boiling. Here an increase in velocity markedly increased the heat flow, as might be expected from the Dittus and Boelter equation for heating liquids. No attempt was made to correlate the results from this run by the Dittus and Boelter equation, however, because of the uncertainty of the value of the thermal conductivity of the mixture under investigation and the varied values for the film coefficient h.

The same pump was used in this thesis as was used by Spalding (1). It was felt that the unsatisfactory operation of this pump would be remedied by the installation of a liquid cooler, but unfortunately this was not the case and wide variations in velocity were not obtained in this research. The velocity range which could be investigated varied with the various runs, covering from 3 to 7 feet per second for 67% oil as compared with 2.2 to 4.7 feet per second for 5% oil.

It is interesting to note that, at constant Δ, $Q/A\theta$ plotted against concentration in Figure IV on semi-logarithmic paper gave a straight line with only small variations. This was, of course, on the low Δt side of the heat transfer curve.

It was desired to obtain Δt's lower than those that were possible with the apparatus used in this investigation. Had atmospheric steam been used, the minimum overall Δ for boiling benzene would still have been $36^{\circ}F$. For Benzene-oil mixtures this minimum overall Δ would have been less, but poor functioning of the cooling liquid valves at low rates of flow rendered satisfactory operation of the apparatus difficult unless fair rates of heat transfer were taking place. In consequence, the data does not include as low Δ's as would be desirable. In Figure V, h is plotted against Δ, and it is seen that these curves lie on the right hand side of the hump. The points on Figure V are more scattered than the points in Figure III, which is due to the magnification of errors occurring when the heat transfer (as determined) is divided by the Δ (as determined).

By plotting $Q/A\theta$ against the Reynolds number of the entering liquid on logarithmic paper, it was found that straight lines could be drawn through the points at constant Δ with slopes of approximately 0.4. Taking the equation from this curve, Figure VI, $Q/A\theta = \alpha(Re)^{.4}$ and solving for α at each Δ, a second plot was made, given in figure VII, plotting the α obtained from Figure VI against Δ °F. From these plots an empirical equation was obtained

$$Q/A\theta = 63\ (\Delta)^{.76}\ \left(\frac{DV\rho}{\mu}\right)^{.4} \qquad (1.)$$

where $Q/A\theta$ is heat flow in Btu/hr./sq.ft., Δ is temperature difference °F and $\left(\frac{DV\rho}{\mu}\right)$ is the Reynolds number of the liquid entering the heating section. This equation was found to check the experimental data remarkably well, giving an accuracy of about 25% in extreme cases and about 10% as an average. This equation is offered as a correlation of data for any benzene-oil mixtures between the limits of 5% oil to 70% oil, at atmospheric pressure with velocities of 2 to 7 feet per second. However, the results of Spalding (1), using water and 98% methanol in approximately the same apparatus were checked to 5% in some cases, while others were off by 70%. Only random values were selected in attempting the correlation of Spalding's data.

It was stated previously that velocity had little effect on the rate of heat transfer. Equation 1 states that the heat transfer increases with the 0.4 power of the velocity. Because of the small variation in velocities as compared with the large variation in viscosity (0.3 to 3.3

centipoises) the Reynolds number obtained in this investigation was primarily a function of viscosity alone, and the arbitrary imposition of a 0.4 power did not affect the precision of the correlation.

In determining the Δt in the heating section, the pipe wall temperature was taken by three thermocouples imbedded in the wall near the inner surface and their readings corrected for their distance from the from the inside wall. The temperature of the liquid was taken as that at the top, after the liquid had been partly vaporized. While it is true that this is not the exact temperature of the liquid within the heating section, it was felt that it was more representative than the average of the top and bottom header temperatures.

An attempt was made by means of a preheater to hold the bottom header temperature at the same value as the top header temperature. While this was accomplished satisfactorily in some cases, in others the temperature at the bottom header was as much as 10°F lower than the top header temperature, which would represent an arithetic average liquid temperature 5°F lower than that which would have been obtained were the preheater accomplishing its full purpose. However, since the liquid temperature rises rapidly upon entering the heating section to a maximum (14) temperature determined only by the vapor pressure of the liquid and the pressure on the liquid, it was felt that in these experiments the true average wall temperature would not vary by more than a degree or so at the most and that an empirical delta based only on the top header would be more nearly correct. Due to the composition of the thermocouples, (nickel-Nichrome), the average wall temperature was accurate to only about 5°C.

Viscosity determinations were made in a Saybolt Universal Viscosimeter at room temperature and at higher temperatures, but only for 50% oil and higher could ckecking results be obtained at elevated temperatures. For mixtures containing between 30 and 50% oil, the viscosity was determined at room temperature and extrapolated to higher temperatures as shown in the Appendix, Figure IX. Viscosities of pure benzene at various temperatures were taken from the International Critical Tables. It was assumed that the viscosity measurements and extrapolations were within the accuracy of the other data of this research inasmuch as the viscosity only entered into the correlation to the 0.4 power.

In determining the accuracy of the measurements taken with the main apparatus, a check was made on random sets of data by setting up a heat balance around the apparatus from top header to a point just before the pump, excluding the condenser. The losses calculated in this manner, illustrated in Appendix E, were about the same as the calculated losses by heat transfer equations. The accuracy of the measurements, then, may be taken as 1%.

VI CONCLUSIONS

1. The data covers only the left hand side of the $Q/A\Theta$ versus Δ curve, except for the 5% oil run, when the maximum $Q/A\Theta$ was obtained. The data covers only the right hand side of the h versus Δ curves.
2. The maximum heat transfer for boiling a 5% oil-95% benzene mixture was found to be 183,000 Btu/hr./sq.ft. at a delta of approximately 140°F.
3. Below the maximum, increases of concentration of oil in oil-benzene mixtures reduce the heat transfer at a given delta.
4. Increases of oil in oil-benzene mixtures increase the critical delta.
5. By extrapolation of the data, the maximum $Q/A\Theta$ appears to be the same for different concentrations of oil and benzene between 5% oil and 70% oil, the higher the oil concentration the higher delta necessary.
6. $Q/A\Theta$ plotted against oil concentration of oil-benzene mixtures on semi-logarithmic paper gives straight lines of constant slope for a given delta.
7. The data can be correlated by the empirical equation.

$$Q/A\Theta = 63\ (\Delta)^{.76} \left(\frac{DV\rho}{\mu}\right)^{.4}$$

which is applicable only within limits of 5% to 70% oil at atmospheric pressure, on the left hand side of the critical delta and with velocities of 2 to 7 feet per second. This equation is based primarily on variation in viscosity and temperature difference and the exponent assigned to the velocity is highly questionable.

VII RECOMMENDATIONS

Before further data be taken with the apparatus used in this thesis, it is recommended that:

1. A larger pump be installed to give wider ranges of liquid velocity through the evaporator tube.
2. A surge tank be placed between the orifice and the preheater to eliminate orifice manometer fluctuations.
3. The preheater be enlarged in order to properly handle higher boiling mixtures.
4. The steam supply be so arranged that data can be taken in the range of lower deltas.

VIII APPENDIX

A. DETAILED DESCRIPTION OF APPARATUS

The apparatus used in this research was built by W. H. Spalding (1) but has been rebuilt and adapted for the purposes of this investigation, as shown in Fig.I. By means of a pump, liquid is forced through a vertical evaporating tube, where it is partially vaporized. The vapor and liquid are separated in a separator, the vapor passing into a condenser and the liquid through a cooler. The cooled liquid and condensed vapor are mixed and reenter the pump.

The main heating and evaporating section consists of 20.62 inches of a four foot nickel tube 0.465 inside diameter and 0.625 inches outside diameter. Steam enters the top of a steam jacket of heavy 4 inch pipe and passes out the bottom, counter current to the flow of the liquid through the nickel tube. The nickel tube runs through the center of the steam jacket, which is sealed with packing glands on each end, packed with garlock packing.

Four nickel-nichrome thermocouples were imbedded at intervals in the wall of the nickel tube. These consisted of a section of .010 inch nichrome wire inside a nickel tube, .030 X .003/.0035 inches. The nichrome wire was insulated from the nickel tube around it by a thin coating of Insalute Cement and the junction soldered with braising metal. The thermocouples were soldered into place with silver solder and passed out through the steam jacket wall through packing glands consisting of 1/4 inch hexagonal steel bars about an inch long and threaded into the wall of the steam jacket. The thermocouple passed through a 1/8 inch hole in the steel bar and the hole was filled with bakelite cement, hardened by heating in place. "Smooth-On" and Insalute cement were applied to the outside of the gland as an added precaution against leaks.

The thermocouples were imbedded in holes drilled tangentially and as close to the inside surface as possible. The method employed to approximate the location of the thermocouple tips was to measure the distance in by means of calipers and the angle with the horizontal at the outside surface of the pipe. From these measurements a scale drawing was made and the location determined thereby; the average distance of the tips from the inside surface of the tube was found to be approximately .025 inches.

The leads of nickel and nichrome wire from the thermocouples were soldered to the protruding ends and to switches, thence to potentiometer and cold junction. The cold junction was immersed in melting ice and its temperature checked with an alcohol thermometer in all but the first run. Readings were taken on a Leeds and Northrup portable potentiometer calibrated to .1 millivolt and which could be read to .02 millivolt. Thermocouples were calibrated before installation and checked roughly after installation by the temperature of a known pressure of steam in the jacket.

After passing through the pump, the liquid flows through a sharp edged orifice of .61 inches diameter placed two feet down stream from the pump in a one inch standard pipe. The manometer taps are located 1 inch up stream and 3/4 inch down stream and are connected by 1/4 inch copper tubes to an inverted U tube to measure the rate of flow. The orifice was calibrated with water before installation.

From the orifice the liquid passes through a preheater, consisting of a threaded one inch pipe inside a steam jacket of 2 inch pipe, six inches in length. The heat supply comes from condensing steam at 40 lbs./sq.in. gauge pressure to atmospheric pressure.

Leaving the preheater, the liquid passes into a boiling indicator where the liquid level is observed for bubbles due to boiling. This consists in the one inch line expanding to a 5 inch section of 2 inch pipe with perforated plates on each end. A 1/2 inch pipe threaded into the wall of the 2 inch pipe, with a 14 mm. Pyrex glass test tube inverted and sealed in the end permits the liquid to be observed. A section of 1/8 inch pipe extends inside the test tube from its end through the bottom of the 2 inch pipe and is closed with a valve, permitting the removal of air that might collect in the test tube. This piece of equipment was found satisfactory except with concentrations of oil above 50%, when frothing developed.

Headers before and after the heating section are two inch pipe crosses, fitted with leads of copper tubing to mercury manometers. Vents in the tops of the leads permit removal of any air in the line. Thermometers, graduated to 1°C were also placed in each header.

After leaving the boiling indicator, the liquid passes through the bottom header, through a two foot calming section of the nickel tube and thence into the main heating section. From here it flows through the top header into the vapor liquid separator by means of a tangential entrance. The separator is 18 inches long by 8 inches inside diameter and has a glass leg to indicate its liquid level.

The vapor passes out the top of the separator into the condenser, consisting of two 20 foot coils of 3/8" copper tubing inside a sheet metal cylinder, the tubing having an area of 3.92 sq.ft. A vent in the top of the condenser fitted with a stopcock permits removal of air at the beginning of a run. From the condenser, the condensate flows through a 1/2 inch pipe back to the pump.

The liquid from the separator flows through a 1 1/2 inch pipe to the liquid cooler, consisting of four feet of 1 1/2 inch pipe inside a 2 1/2 inch water jacket containing cooling water. From the liquid cooler the liquid mixes with the condensate in returning to the pump.

The pump is a single blade, brass rotary pump with 3/4 inch inlet and outlet and a rated capacity of 10 gallons per minute against a 30 foot water head. The pump is driven by a 1/4 h.p. electric motor. The packing was packed with 3/16 inch Garlock packing, which gave poor service in the presence of benzene, having to be replaced almost daily.

The entire system with the exception of manometer leads and the reservoir was lagged with 1/2 to 1 inch of magnesia lagging.

B DETAILS OF PROCEDURE

Six different concentrations of benzene and oil have been used in the apparatus described in detail in Appendix A, "Detailed Description of Apparatus". The mixtures run were 5% oil, 9% oil, 27% oil, 30% oil, 49% oil and 67% oil with benzene. The oil used in the mixtures was a close cut lube oil, Chlorex treated, iso-vis 50, from the Wood River Refinery of the Standard Oil Company (Indiana).

To begin a run, the reservoir was filled almost to capacity with about two gallons of the mixture and the valve below the reservoir opened. The pump was turned on and the liquid forced up into the separator. When the reservoir was emptied, as observed by the glass leg, the reservoir valve was closed and the steam turned on in the preheater and in the main heating section. The condenser water was also turned on at this time, but the liquid cooler water was not until the mixture began to boil. While heating the liquid, the vent in the top of the condenser was left open in order that air might be forced out of the apparatus.

The steam in the preheater and the main heating section was controlled by throttling through a valve and venting a suitable amount through a valve in the exhaust line.

The system was allowed to come to equilibrium, the adjustment of the heat input in the preheater and the heat removed in the liquid cooler being largely a process of trial and error. The maximum heat was added in the preheater that could be obtained without boiling and thereby causing the orifice manometer to fluctuate. The presence of boiling was detected by means of the boiling indicator described in Appendix A, "Details of Apparatus." When only occassional bubbles of vapor were observed to rise in the test tube it was assumed that the liquid was just at its boiling temperature with no vapor entering the main heating section. In a majority of the runs, however, it was found impractical to heat the liquid above about three degrees below its boiling temperature because of the fluctuations induced in the orifice manometer.

The liquid velocity was regulated with a by-pass around the pump. It was found that the velocity could not be varied over a wide range with the pump in use except in certain exceptional cases; the cause of this irregularity could not be determined. The maximum rate of flow obtained was about three gallons per minute against a two foot head of water, as compared with the rated capacity of 10 gallons per minute against a 30 foot head of water.

About ten minutes were necessary for equilibrium after a change in velocity, and about twenty to thirty minutes after a change in temperature difference in the heater.

The condenser water rate was always regulated so that its exit temperature would be near 50°C in order that measurements of its flow would be more accurate. The rates of flow of condenser water and cooler were measured by recording the time necessary to fill a 1000 cc graduate. At higher rates of flow when short times were necessary to fill the graduate, these values were checked to insure the accuracy of the readings.

In these experiments it was originally planned to take a heat balance on the steam side as well as the liquid side and the apparatus arranged accordingly, but difficulty in preventing steam leaks in the steam jacket and the infeasibility of preheating the steam because of fire hazards caused these plans to be abandoned. Preheating the steam would have been necessary to obtain dry steam, which is imperative for a proper heat balance.

After equilibrium was reached, the following measurements were taken.

Temperatures by thermometers:

1. Liquid in bottom header.
2. Vapor and liquid in top header.
3. Vapor in top of separator.
4. Condensate from condenser.
5. Condenser water entering.
6. Condenser water leaving.
7. Liquid cooler water entering.
8. Liquid cooler water leaving.
9. Liquid before entering pump.

Temperatures by thermocouples:

1. Tube wall four inches from top of heating section.
2. Tube wall eight inches from top of heating section.

3. Tube wall twelve inches from top of heating section.
4. Tube wall sixteen inches from top of heating section.

Flow measurements:

1. Orifice measurements in centimeters of fluid flowing.
2. Condenser water by measuring with a stop watch the time to fill a 1000cc graduate.
3. Liquid cooler water by the same method as above.

Pressure measurements:

1. Static pressure in bottom header by means of a mercury manometer.
2. Static pressure in top header by means of a mercury manometer.
3. Steam pressure by means of a calibrated 250 lb. gauge.

Four thermocouples were imbedded in the evaporator tube wall but the second from the top failed to function after installation. In one run the bottom thermocouple became short circuited outside the steam jacket, necessitating deleting its readings. This was repaired and all three thermocouples gave good service for the rest of the runs. Thermocouple readings were taken on a Leeds and Northrup potentiometer, M.I.T. No. 376, and the cold junction kept at 0°C with melting ice.

After the first run the inside of the evaporator tube was inspected for any changes and a check run made, from which it was found that the surface did not change noticeably during the runs. If any change took place within the tube it occurred before any data was taken, for liquid mixtures were run through several times before the data runs were begun.

It was impossible to keep the liquid in the orifice manometer at the temperature of the fluid flowing, but corrections due to difference in density were not made in determining the actual velocity of the liquid. With the uncertainty as to the true temperature as well as the exact composition of the liquid in the manometer, this seemed an unnecessary refinement. The composition of the liquid in the manometer was in some doubt because the leads were never completely drained between runs.

Once during each run a 250cc sample was drawn off at the bottom header to be analyzed for its composition as described in Appendix D, "Calibrations." In one run a second sample was also drawn off after the apparatus was shut down in order to check the first sample.

One set of readings were taken after each change in velocity or temperature difference, which required from five to ten minutes.

C. SUMMARY OF DATA AND RESULTS

Run No.I 70% Benzene 30% Oil

Temperatures °C	A1	A2	A3	A4	B1	B2	B3
Bottom header	85.0	85.0	85.5	85.6	84.0	84.0	84.0
Top header	84.2	84.2	84.2	84.4	84.8	84.7	84.6
V-L Separator	80.5	80.5	80.5	80.7	80.8	80.8	80.8
Condensate	58.4	61.5	61.6	60.5	58.5	59.5	60.2
Condenser water							
in	23.6	24.2	24.2	24.0	22.8	22.8	22.9
out	48.3	55.5	55.6	52.0	48.7	50.7	52.0
Liquid cooler water							
in	23.8	24.5	24.5	24.5	22.8	22.8	22.9
out	53.6	61.4	65.0	69.5	46.5	50.7	44.5
Before pump	79.0	79.5	79.0	79.0	79.5	79.0	78.5
Orifice reading (cm. fluid flowing)	8	11	5.5	8.4	7	6	4
Velocity (ft./sec.)	5.35	6.15	4.52	5.45	5.02	4.70	3.95
Bottom pressure (cm. mercury) (above atm.)	26.4	26.4	21.8	25.6	20.2	21.9	20.1
Top pressure (cm. mercury) (above atm.)	3.0	4.9	1.9	4.0	1.7	1.6	0.4
Thermocouples							
1.	2.26	2.28	2.23	2.22	2.54	2.50	2.50
3.	2.22	2.28	2.16	2.25	2.30	2.29	2.30
4.							
Rates of flow(lbs/hr)							
Condenser water	202	165	184	159	200	198	198
Liquid cooler water	74	49.7	32.4	29.4	30.0	102	102
Avg. wall temp.(°C)	97	98	95	96.5	101	101.3	101.4
Temp.diff. (°C)	12.8	13.8	10.8	11.1	16.2	16.6	16.8
Temp.diff. °F (Δ°F)	23	24.8	19.4	20	29.2	29.9	30.2

Run No.I (con't.) 70% Benzene 30% Oil

Temperatures °C	B4	B5	C1	C2	C3	C4	C5	C6
Bottom header	84.0	84.5	84.0	84.0	84.0	83.5	84.0	84.0
Top header	84.4	84.3	84.2	84.1	84.0	83.9	84.0	84.1
V-L Separator	80.8	80.8	81.0	81.4	81.1	81.1	81.1	81.1
Condensate	59.8	61.7	60.0	61.4	60.6	60.2	61.8	61.3
Condenser water								
in	22.9	22.9	22.9	23.1	22.9	22.9	23.1	23.2
out	51.7	54.7	48.0	50.4	49.1	49.5	51.0	50.3
Liquid cooler water								
in	22.9	22.9	22.9	23.4	22.9	22.9	23.2	23.2
out	47.0	44.2	48.2	46.5	47.5	48.6	46.1	49.0
Before pump	79.0	78.0	79.0	78.0	78.0	79.0	78.0	78.6
Orifice reading (cm.fluid flowing)	8	4	6	4.5	5.5	8	3.5	7
Velocity (ft/sec.)	5.35	3.95	4.70	4.15	4.52	5.35	3.75	5.02
Bottom pressure (cm. mercury) (above atm.)	22.9	22.4	28.4	25.4	28.4	28.4	25.9	30.4
Top pressure (cm. mercury) (above atm.)	1.4	1.4	2.4	1.6	1.4	2.4	1.4	2.4
Thermocouples								
1.	2.55	2.52	3.00	3.00	3.00	3.10	3.10	3.00
3.	2.34	2.30	2.89	2.85	2.90	2.90	2.95	2.91
4.								
Rates of flow(lbs/hr)								
Condenser water	197.5	193	338	334	339	336	336	332
Liquid cooler water	100.0	96.5	94.5	94.5	90.5	91.0	87.8	88
Avg.wall temp. °C	101	101	123	122	124	125	125	124
Temp.Diff.(°C)	16.6	16.7	38.8	37.9	40.	41.1	41.0	399
Temp.Diff.(°F)	29.8	30.0	69.8	68.2	72.0	74.0	73.8	71.8

Run No.I (con't.) 70% Benzene 30% Oil

Temperatures °C	D1	D2	D3	D4	E1	E2	E3	E4
Bottom header	84.0	84.0	82.5	82.5	81.0	79.0	77.0	78.0
Top header	83.5	83.6	81.6	83.1	83.1	83.1	82.8	83.1
V-L Seperator	80.3	80.5	79.0	80.6	80.7	80.7	79.9	80.7
Condensate	61.8	62.2	62.5	60.5	61.7	60.9	60.5	61.5
Condenser water								
in	22.9	22.9	22.9	22.5	22.5	22.5	22.6	22.6
out	53.6	54.5	55.1	50.0	53.5	52.0	51.5	53.1
Liquid cooler water								
in	23.6	23.8	23.9	22.9	23.5	23.7	23.9	23.9
out	56.5	56.0	65.0	54.0	66.0	64.8	64.0	64.1
Before pump	76	77	75	75	78	76	76	76
Orifice reading (cm. fluid flowing)	7	6	4.5	5	5.5	4	4	3
Velocity(ft/sec.)	5.02	4.70	4.15	4.35	4.52	3.95	3.95	3.53
Bottom pressure (cm. mercury) (above atm.)	31.4	27.4	28.4	31.9	25.9	22.9	21.4	24.5
Top pressure (cm. mercury) (above atm.)	2.4	2.4	2.1	2.4	1.4	2.4	2.4	8.3
Thermocouples 1.	3.38	3.39	3.24	3.50	3.60	3.60	3.62	3.62
3.	3.35	3.30	3.22	3.32	3.60	3.60	3.58	3.62
4.								
Rates of flow (lbs./hr.)								
Condenser water	397	392	434	413	418	414	413	413
Liquid cooler water	48	45.6	43	43.5	20.9	20.7	20.6	20.5
Avg.wall temp. °C	137.5	137	134	138	146	146	146.0	146.5
Temp.difference(°C)	54	53.6	52.4	54.9	62.9	62.9	63.2	63.4
Temp.difference (°F)	99.2	98.5	94.5	99.0	113	113	113.5	114

Run No. I (con't.) 70% Benzene 30% Oil

Temperatures °C	F1	F2	G1	G2
Bottom header	18	79	78	78
Top header	84.1	83.1	83.1	82.1
V-L Separator	81.7	80.6	80.5	80.0
Condensate	62.6	62.7	61.3	61.3
Condenser water				
in	22.5	22.6	22.5	22.7
out	55.0	55.2	53.3	53.5
Liquid cooler water				
in	23.9	23.9	23.7	23.8
out	63.8	65.0	63.5	61.5
Before pump	75	76	75	73
Orifice reading (cm.fluid flowing)	3	4.5	4.5	3
velocity (ft./Sec.)	3.53	4.15	4.15	3.53
Bottom pressure (cm.mercury) (above atm.)	24.9	27.4	27.4	33.4
Top pressure (cm. mercury) (above atm.)	3.4	2.6	5.4	4.4
Thermocouples				
1.	4.00	3.9	4.38	4.15
3.	4.00	3.8	4.20	4.05
4.				
Rates of flow (lbs/hr)				
Condenser water	436	439	509	500
Liquid cooler water	16.5	16.5	16.5	16.5
Avg.wall temp. °C	160	155	166.5	162
Temp. diff.(°C)	75.9	71.9	83.4	79.9
Temp. diff.(°F)	136.5	129.5	150	143

Run No.2 9% Oil 91% Benzene Density .866

Temperature (°C)	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2
Bottom header	78.5	78.5	78.5	80.0	76.5	76.0	76.0	75.0	77.0	78.0
Top header	81.5	81.3	81.5	81.5	81.5	81.5	81.5	81.5	81.3	81.5
V-L Separator	80.3	80.0	80.4	80.2	79.8	79.7	79.0	79.5	79.4	80.0
Condensate	58.5	59.2	60.0	60.0	61.3	61.7	61.6	60.5	62.2	62.1
Condenser water										
in	23.2	23.5	23.7	23.4	23.2	23.2	23.2	23.0	23.1	23.1
out	51.5	54.0	54.2	51.3	55.0	55.0	54.7	53.0	56.0	54.0
Liquid cooler water										
in	23.4	23.8	23.9	23.8	23.5	23.5	23.5	23.5	23.5	23.5
out	53.4	52.3	53.8	52.2	51.5	50.5	51.0	49.0	50.0	51.2
Before pump	77.0	76.5	77.0	76.0	75.0	75.0	74.0	74.0	74.0	76.0
Orifice reading (cm. fluid flowing)	7	4	6	5	5	4	4	2	2.5	5.5
Velocity (Ft/sec.)	5.02	3.95	4.70	4.35	4.35	3.95	3.95	2.95	3.25	4.52
Bottom pressure (cm. mercury)	20.9	19.9	18.4	20.4	31.9	33.4	34.1	25.9	25.9	30.4
Top pressure (cm. mercury)	3.4	1.4	3.4	1.4	4.4	4.4	3.4	2.4	4.4	4.4
Thermocouples										
1.	2.40	2.40	2.42	2.41	3.18	3.20	3.15	3.20	2.85	2.90
3.	2.30	2.30	2.39	2.40	3.15	3.10	3.16	3.20	2.85	2.86
4.	2.48	2.42	2.42	2.43	3.50	3.50	3.50	3.50	3.18	3.18
Rates of flow (lbs./hr.)										
Condenser water	167	159	166	208	441	430	437	467	347	384
Liquid coolerwater	65	65	67	68	67	65	58.5	59.0	59.0	57.2
Avg. wall temp. (°C)	101.5	101	103	103	134.5	134	134.5	135	124.0	124.0
Temp. diff. (°C)	20	19.7	21.9	21.9	53	52.5	53	53.5	42.7	42.5
Temp. diff. (°F)	36	35.5	39.4	39.4	95.4	94.5	95.4	96.4	77	76.5

Run No.2 (con't.) 9% Oil 91% Benzene

Temperatures °C	C3	C4	D1	D3	D2	D4
Bottom header	78.0	78.0	74.0	75.0	73.0	75.0
Top header	81.5	81.5	81.5	81.8	81.5	82.0
V-L Separator	80.5	80.3	80.4	80.5	80.4	80.9
Condensate	60.5	61.0	61.8	61.8	61.4	61.8
Condenser water						
in	23.1	23.5	23.4	23.4	23.4	23.4
out	53.3	54.5	54.5	54.0	53.5	53.8
Liquid cooler water						
in	23.5	23.9	24.0	24.1	24.0	24.2
out	53.0	52.0	56.0	55.5	55.5	55.5
Before pump	76	76	74	75.5	74	75.5
Orifice reading (cm.fluid flowing)	6	5.5	4	4.5	2.5	3
Velocity(ft/sec.)	4.70	4.52	3.95	4.15	3.25	3.53
Bottom pressure (cm. mercury)	28.9	30.9	25.4	38.4	33.4	36.4
Top pressure	3.4	4.4	4.4	6.4	4.4	5.4
Thermocouples						
1.	2.90	2.90	3.39	3.42	3.42	3.42
3.	2.85	2.84	3.39	3.42	3.42	3.42
4.	3.10	3.10	3.80	3.75	3.80	3.75
Rates of flow(lbs/hr)						
Condenser water	390	382	494	512	512	530
Liquid cooler water	56.8	56.8	37.9	37.3	37.6	37.6
Avg. wall temp.(°C)	123	123	143.5	143.5	144	143.5
Temp.diff. (°C)	41.5	41.5	62	61.7	62.5	61.5
Temp.diff. (°F)	74.6	74.6	111.5	111.0	112.5	110.8

Run No.2 (con't.) 9% Oil 91% Benzene

Temperatures (°C)	E1	E2	E3	E4	F1	F2	F3
Bottom header	74.5	74.0	76.0	74.5	73	74	72
Top header	82.0	81.6	81.5	81.7	82.5	82.0	81.6
V-L Separator	82.3	80.4	80.5	82.0	82.5	80.5	81.5
Condensate	62.2	61.9	62.3	62.4	63.1	62.3	62.1
Condenser water							
in	23.4	23.4	23.4	23.4	23.4	23.4	23.4
out	54.8	54.3	54.3	54.2	53.9	54.5	55.0
Liquid cooler water							
in	24.3	24.3	24.3	24.3	24.4	24.1	24.0
out	58.5	57.0	55.5	56.5	56.5	57.0	54.0
Before pump	76.0	75.0	74	74	74	74	73
Orifice reading (cm.fluid flowing)	4	5.5	3.5	3	3	4	2
Velocity(ft/sec.)	3.95	4.52	3.75	3.53	3.53	3.95	2.95
Bottom pressure (cm. mercury)	37.4	39.9	37.4	31.9	33.4	41.9	35.4
Top pressure (cm. mercury)	5.4	3.4	4.4	3.4	4.4	5.4	5.4
Thermocouples							
1.	3.85	3.85	3.85	3.86	4.70	4.68	4.70
3.	3.70	3.70	3.70	3.70	4.70	4.70	4.68
4.	4.20	4.20	4.20	4.18	4.91	4.76	4.81
Rates of flow (lbs/hr.)							
Condenser water	544	547	575	568	611	611	580
Liquid cooler water	35.3	35.3	36.0	35.5	33.8	33.8	33.8
Avg.wall temp (°C)	157	157	157	156.5	185	183	184
Temp.diff.(° C)	75	75.4	75.5	74.8	102.5	101	102.4
Temp.diff.(°F)	135	136	136	135	184	182	184

Run No3. 5% Oil 95% Benzene

Temperatures (°C)	A1	A2	B1	B2	C1	C2	D1	D2
Bottom header	78	78	78	77.5	78	75	73.5	73
Top header	80.7	80.6	80.8	80.8	81.7	81.5	82.6	82.1
V-L Separator	79	79.0	79.0	79.0	81.0	80.5	82.0	81.5
Condensate	60.7	61.3	61.9	60.9	61.0	60.5	60.6	60.5
Condenser water								
in	25.0	25.0	24.7	24.7	24.6	24.6	24.4	24.4
out	54.7	55.2	55.1	52.0	52.3	51.2	52.0	52.2
Liquid cooler water								
in	26.6	26.8	26.5	26.6	26.5	26.9	26.6	27.0
out	67.5	67.5	66.0	67.0	69.5	68.0	69.0	70.0
Before pump	77	76	76	76	76	76	76	76
Orifice reading (cm.fluid flowing)	6	3	3	2	3	2	2	1.5
Velocity (Ft./Sec.)	4.70	3.53	3.53	2.95	3.53	2.95	2.95	2.65
Bottom pressure (cm.mercury above atm.)	22.1	15.9	19.9	15.4	17.4	19.9	22.4	18.9
Top pressure (cm mercury above atm.)	4.4	5.4	4.4	2.4	2.4	.4	2.4	2.4
Thermocouples								
1.	2.30	2.34	2.55	2.60	2.75	2.76	3.10	3.10
3.	2.40	2.30	2.60	2.58	2.78	2.77	3.15	3.10
4.	2.40	2.39	2.70	2.70	2.95	2.95	3.28	3.30
Rates of flow (lbs./hr.)								
Condenser water	265	269	331	352	424	424	496	490
Liquid cooler water	12.4	12.4	12.0	12	12	12	12	12
Avg.wall temp. °C	102.5	101.5	111	111.5	119	117.5	131	131
Temp.diff. °C	21.8	20.9	30.2	30.7	37.3	36.0	48.4	48.9
Temp.diff. °F	39.2	37.6	54.4	55.2	67.1	64.8	87	88

Run No.3 (con't.) 5% Oil 95% Benzene

Temperatures (°C)	E1	E2	F1	G1	G2	H1	J1	J2
Bottom header	72	72	73	73	73	73	74	74
Top header	81.6	82.3	81.5	81.5	81.6	81.3	81.5	81.5
V-L Seperator	80.5	81.0	80.5	80.5	80.5	80.1	80.0	80.0
Condensate	61.3	62.3	62.5	62.7	62.2	62.9	62.7	62.9
Condenser water								
in	24.4	24.4	24.2	24.2	24.2	24.2	24.2	24.2
out	53.5	54.1	55.5	54.0	54.1	55.0	54.0	54.0
Liquid cooler water								
in	27.1	27.2	27.5	27.5	27.9	27.8	28.5	28.3
out	66.0	67.0	66.0	65.5	65.0	64.0	63.0	64.0
Before pump	74.5	74	74.5	72.5	72.5	71.5	72.5	71.5
Orifice reading (cm.fluid flowing)	2	1	1	2.5	2	3	3	2.5
Velocity (ft/sec.)	2.95	2.20	2.20	3.25	2.95	3.53	3.53	3.25
Bottom pressure (cm.Hg.above atm.)	22.4	22.4	27.4	29.4	29.4	27.4	27.4	22.1
Top pressure (cm.Hg.above atm.)	2.4	2.4	3.9	4.4	5.4	4.4	4.4	.4
Thermocouples								
1.	3.31	3.25	3.45	3.60	3.60	3.95	4.25	4.25
3.	3.35	3.35	3.55	3.61	3.61	4.00	4.25	4.31
4.	3.65	3.65	3.90	4.15	4.15	4.55	4.75	4.74
Rates of flow (lbs./hr.)								
Condenser water	508	508	558	620	620	645	645	645
Liquid cooler water	12	12	12	12	12	12	12	12
Avg.wall temp °C	140.5	140	147	153	153	166	175	175
Temp.diff.°C	58.9	58.7	65.5	71.5	71.4	84.7	93.5	93.5
Temp.diff.°F	106	105.5	118	129	128.5	152.5	168	168

Run No. 4 Check on 30% Oil run. 27% Oil 73% Benzene.

Temperatures (°C)	A1	A2	B1	B2	C1	D1
Bottom header	83	83	83.5	81	81	80
Top header	83.5	83.5	83.8	83.7	84.1	84.6
V-L Separator	80.0	80.0	80.8	80.8	81.1	81.3
Condensate	61.2	61.2	61.8	62.0	61.9	61.4
Condenser water						
in	25.4	25.5	25.5	25.1	25.1	25.0
out	54.5	54.6	54.4	54.5	55.3	55.0
Liquid cooler water						
in	27.9	28.2	28.2	28.3	28.0	27.9
out	68.0	68.0	67.0	68.0	67.0	67.0
Before pump	77	77	76.5	76.5	76	75.0
Orifice reading (cm.fluid flowing)	10	6	11	6	6	4
Velocity (ft/sec.)	5.90	4.70	6.15	4.70	4.70	3.95
Bottom pressure (cm.Hg.above atm.)	17.4	19.4	24.4	21.4	21.4	21.4
Top pressure (cm.Hg.above atm.)	2.4	2.4	4.4	4.4	4.4	2.4
Thermocouples						
1.	2.70	2.70	3.00	3.00	3.60	4.00
3.	2.70	2.70	3.00	3.00	3.50	4.00
4.	2.80	2.80	3.30	3.30	3.90	4.25
Rates of flow (lbs./hr.)						
Condenser water	300	305	378	378	422	450
Liquid cooler water	9.25	9.25	9.25	9.25	9.25	9.25
Avg.wall temp. °C	115	115	128.5	128.5	150.5	163
Temp.diff. °C.	31.5	31.5	44.7	44.8	66.4	78.4
Temp.diff. °F.	56.7	56.7	80.5	80.7	119.5	141

Run No.5 49% Oil 51% Benzene

Temperature (°C)	A1	A2	A3	B1	B2	B3	C1	C2	C3
Bottom header	84	83.5	83.5	84	83	83.5	83	81	80.5
Top header	86	86	85.9	85.5	85.5	85.5	87	86.2	86.3
V-L Separator	82	82	82	81.5	81.5	81.3	82	81.8	81.8
Condensate	60.8	60.7	61.3	60.0	60.1	60.6	61.3	59.5	59.5
Condenser water									
in	24.5	24.7	24.6	25.0	24.9	25.3	24.5	24.5	24.5
out	53.7	54.0	55.0	54.6	54.1	55.3	53.4	51.3	51.6
Liquid cooler water									
in	28.0	28.3	28.0	28.5	28.9	28.9	25.0	24.5	24.8
out	69.0	69.5	68.5	70.0	69.0	70.0	47.0	47.5	46.5
Before pump	79	80	80	81	81	82	78	77.5	77.0
Orifice reading (cm.fluid flowing)	8	6	3	6	3	8	4.5	5	7
Velocity(ft/sec.)	5.35	4.70	3.53	4.70	3.53	5.38	4.15	4.35	5.02
Bottom pressure (cm.Hg.above atm.)	19.4	18.9	11.4	13.4	11.4	15.4	17.4	15.4	17.4
Top pressure (cm.Hg.above atm.)	2.4	3.4	0.4	0.4	0.4	1.4	0.4	0.4	0.4
Thermocouples									
1.	3.00	3.05	3.00	2.65	2.65	2.75	4.05	4.00	3.98
3.	3.00	3.00	3.00	2.64	2.65	2.75	4.08	4.01	3.98
4.	3.18	3.17	3.18	2.85	2.85	2.83	4.20	4.20	4.20
Rates of flow (lbs./hr.)									
Condenser water	289	266	248	192	181	185	303	305	296
Liquid cooler water	4.96	4.96	4.96	4.96	4.96	4.96	56.8	56.8	56.8
Avg.wall temp(°C)	127	127.5	127	114.5	114.5	116	164	162	161
Temp.diff.(°C)	41	41.5	40.9	31	31	32.5	77	75.8	74.7
Temp.diff.(°F)	73.7	74.7	73.5	55.7	55.7	58.5	138.5	136.5	134.5

Run No.5 (con't.) 49% Oil 51% Benzene

Temperatures (°C)	D1	D2	D3	E1	E2	F1
Bottom header	80	79.5	79	80	79	80
Top header	86.5	86.5	86.5	87.5	87.5	87.0
V-L Separator	82	82	82.1	83.0	83.0	82.0
Condensate	60.7	60.4	61.0	62.0	61.2	61.6
Condenser water						
in	24.0	24.0	24.0	23.8	23.8	23.8
out	51.6	51.5	51.9	54.0	54.0	53.5
Liq.cooler water						
in	24.5	24.3	24.3	24.2	24.4	24.3
out	46.0	44.8	42.5	43.0	46.0	46.0
Before pump	76	75	74	73	74	76
Orifice reading (cm.fluid flowing)	3	2	2	3	4	4.5
Velocity (ft/sec.)	3.53	2.95	2.95	3.53	3.95	4.15
Bottom pressure (cm.Hg.above atm.)	18.9	15.4	13.4	15.4	19.4	17.4
Top pressure (cm.Hg.above atm.)	1.4	2.4	0.4	0.4	2.4	0.4
Thermocouples						
1.	4.35	4.35	4.30	4.70	4.65	4.25
3.	4.20	4.10	4.15	4.55	4.40	4.00
4.	4.50	4.65	4.62	4.88	4.88	4.50
Rates of flow (lbs./hr.)						
Condenser water	364	364	364	400	400	361
Liq.cooler water	56.8	56.8	56.8	56.8	56.8	56.8
Avg.wall temp.(°C)	174.5	174	172.5	185	182	171.5
Temp.diff.(°C)	88	87.5	86	97.5	97.5	84.5
Temp.diff.(°F)	158	157	155	175	175	152

Run No. 6 33% Benzene 67% Oil Sp.Gr. .878

Temperatures °C	A1	A2	A3	A4	B1	B2	B3	B4
Bottom header	85	85	85	85	85.5	85.5	86	86
Top header	92.5	93.0	93.5	94	93.5	93.0	93.0	93.1
V-L Separator	83	84.5	85.5	86	85.2	84.5	84.0	84.7
Condensate	59.3	60.3	60.5	60.2	60.0	60.5	60.6	60.5
Condenser water								
in	24.0	24.0	24.1	24.1	24.4	24.4	24.5	24.5
out	51.8	52.6	53.0	52.0	52.7	51.8	55.2	53.9
Liq.cooler water								
in	24.5	24.6	24.6	24.8	24.8	25.0	25.1	25.0
out	53.0	47.0	45.0	43.5	44.8	51.6	58.5	47.0
Before pump	80.0	79.0	79	78	79	80	82	79
Orifice reading (cm.fluid flowing)	11	8	5	3	3.5	6	13	3
Velocity (ft/sec.)	6.15	5.35	4.35	3.53	3.75	4.70	6.68	3.53
Bottom pressure (cm.Hg.above atm.)	13.4	13.4	12.4	10.9	9.4	12.4	14.9	9.4
Top pressure (cm.Hg.above atm.)	.4	1.4	1.4	1.4	.4	.4	2.4	1.4
Thermocouples								
1.	4.25	4.25	4.25	4.23	4.15	4.15	4.15	4.15
3.	4.30	4.25	4.30	4.25	4.15	4.15	4.13	4.15
4.	4.55	4.60	4.60	4.50	4.30	4.30	4.30	4.30
Rates of flow (lbs./hr.)								
Condenser water	305	303	303	303	251	251	202	249
Liq.cooler water	48	48	48	48	48	48	48	48
Avg.wall Temp.°C	173	173	173.5	171	165	165	165	165
Temp.diff.°C	80.5	80	80	77	71.5	72	72	71.9
Temp.diff.°F	145	144	144	138.5	128.5	129.5	129.5	129

Run No.6 (con't.) 33 % Benzene 67% Oil

Temperatures (°C)	C1	C2	C3	D1	D2	D3	D4
Bottom header	87	87	87	88.5	89	89	89
Top header	92.7	92.5	92.5	93.0	92.7	93.1	93.4
V-L Separator	84.2	84.2	84.7	84.0	83.8	83.9	84.5
Condensate	60.4	60.0	59.8	58.0	60.0	59.2	59.1
Condenser water							
in	24.6	24.5	24.5	24.7	24.8	24.8	25.0
out	54.6	53.2	52.5	52.8	53.7	52.5	52.0
Liq.cooler water							
in	25.3	25.3	25.2	25.5	25.3	25.4	25.3
out	48.6	47.0	46.0	47.0	48.0	49.0	49.0
Before pump	82	82	82	86	88	88.5	88
Orifice reading (cm.fluid flowing)	3	7	6.5	5	6	5	4.5
Velocity (ft./sec)	3.53	5.02	4.75	4.35	4.70	4.35	4.15
Bottom pressure	9.4	9.4	7.4	5.4	11.4	7.4	7.4
Top pressure (cm.Hg.above atm.)	1.4	0.2	0.2	0.4	0.4	0.4	0.4
Thermocouples							
1.	3.85	3.85	3.80	3.50	3.50	3.50	3.55
3.	3.85	3.85	3.80	3.50	3.50	3.50	3.55
4.	3.95	3.96	3.95	3.70	3.70	3.70	3.70
Rates of flow (lbs./hr.)							
Condenser water	184.5	209	209	157	160	158	158
Liq.cooler water	48	48	48	48	48	48	48
Avg.wall temp.°C	157	157	156	145	145	145	146
Temp.diff.°C	64.3	64.5	63.5	52	52.3	51.9	52.6
Temp.diff.°F	115.8	116	114	93.5	94	93.5	94.6

Run No. 6 (con't.) 33% Benzene 67% Oil

Temperature (°C)	E1	E2	E3	F1	F2	F3	F4
Bottom header	89.5	90.0	89.5	89	89	89	89
Top header	92.5	92.5	92.3	92	92	92	92
V-L Separator	82.5	83.0	82.0	80.5	80.0	80.0	79.5
Condensate	59.4	57.8	58.8	59.0	57.5	58.8	58.0
Condenser water							
in	25.5	25.1	25.2	25.7	26.0	26.0	26.0
out	54.0	51.5	53.3	52.0	50.8	53.9	51.8
Liq. cooler water							
in	25.8	25.5	25.5	26.0	26.0	26.3	26.2
out	49.5	50.5	52.5	55	50	50	50
Before pump	88.5	89	86	86	86	88	88
Orifice reading (cm.fluid flowing)	4	7	14	11	2	6	7
Velocity (ft/sec.)	3.95	5.02	6.95	6.15	2.95	4.70	5.02
Bottom pressure	10.4	11.4	9.9	9.4	7.4	9.4	10.9
Top pressure (cm.Hg.above atm.)	2.4	1.4	00	0.4	00	1.4	0.4
Thermocouples							
1.	3.25	3.25	3.25	2.85	2.85	2.85	2.85
3.	3.25	3.25	3.25	2.85	2.85	2.85	2.85
4.	3.40	3.40	3.40	2.87	2.90	2.90	2.89
Rates of flow (lbs./hr.)							
Condenser water	101	122	122	91.4	75.6	74.1	90.1
Liq. cooler water	48	48	48	48	48	48	48
Avg.wall temp.°C	135.5	135.5	135.5	119.5	120	120	120
Temp.diff.°C	42.5	42.5	42.7	27.5	28	28	28
Temp.diff.°F	76.5	76.5	76.8	49.5	50.5	50.5	50.5

Run I 30 % Oil 70% Benzene

Number	Steam #/sq.in. Gauge	V ft./sec.	$\frac{Q}{A\theta}$	% heat to vaporize	corrected Δ °F	h	% vaporized	Re
A1	9	5.35	38,700	100	19.6	1975	4.07	24,500
2	9	6.15	40,500	100	19.2	2110	3.69	28,200
3	9	4.52	45,000	100	16.6	2710	4.60	20,700
4	9	5.45	34,600	100	17.8	1945	4.28	25,000
B1	24	5.02	43,700	92	26.4	1650	4.47	23,000
2	24	4.70	45,600	92.6	27.0	1690	5.10	21,500
3	24	3.95	47,000	95.4	27.2	1730	6.37	18,100
4	24	5.35	46,300	95.7	26.9	1720	4.65	24,500
5	24	3.95	48,100	100	27.0	1785	6.84	18,100
C1	57	4.70	65,600	100	65.7	1000	7.81	21,500
2	57	4.15	71,000	100	63.7	1115	9.62	19,000
3	57	4.52	69,300	100	67.6	1025	8.37	20,700
4	57	5.35	71,500	97.5	69.5	1030	7.30	24,500
5	57	3.75	73,500	100	69.2	1065	11.0	17,200
6	57	5.02	70,000	100	67.4	1050	7.86	23,000
D1	77	5.02	95,500	100	93.2	1030	10.70	23,000
2	77	4.70	96,700	100	92.4	1050	11.55	21,500
3	77	4.15	108,000	100	87.7	1230	14.75	19,000
4	77	4.35	90,800	97.5	93.3	974	11.40	19,900
E1	105	4.52	109,000	96.5	106.1	1030	12.50	20,700
2	105	3.95	109,100	86.7	10 6.1	1030	13.50	18,100
3	106	3.95	112,000	81.6	106.4	1050	12.95	18,100
4	107	3.53	115,000	86.2	106.7	1080	15.90	16,200
F1	143	3.53	129,000	85.4	128.4	1005	17.45	16,200
2	143	4.15	127,000	88.0	121.5	1045	15.10	19,000
G1	166	4.15	142,000	86.7	141.	1005	16.62	19,000
2	166	3.53	139,000	87.0	134.2	1065	19.10	16,200

Run II 9% Oil 91% Benzene

Number	Steam #/sq.in. Gauge	V ft./sec.	$\frac{Q}{A\theta}$	% heat to vaporize	Corrected $\Delta^{\circ}F$	h	% vaporized	Re
A1	13	5.02	49,800	73.2	32.9	1515	4.28	41,300
2	13	3.95	47,300	80.0	32.5	1455	5.56	32,500
3	13	4.70	51,400	76.6	36.2	1420	4.88	38.600
4	13	4.35	49,200	88.6	36.3	1355	5.83	35,800
B1	71	4.35	129,000	85.5	87.3	1480	14.70	35,800
2	71	3.95	127,000	85.4	86.5	1470	15.88	32,500
3	71	3.95	126,500	85.4	87.4	1450	16.00	32,500
4	71	2.95	126,000	87.0	88.4	1445	21.60	24,300
C1	45	3.25	102,000	88.4	70.6	1440	16.10	26,700
2	45	4.52	102,100	91.4	70.0	1460	11.60	37,200
3	45	4.70	106,000	86.8	67.9	1560	11.40	38,600
4	45	4.52	106,200	87.3	67.9	1565	11.95	37,200
D1	97	3.95	145,500	82.6	102.3	1420	17.70	32,500
2	97	4.15	151,000	80.0	101.5	1485	16.85	34,100
3	97	3.25	142,000	87.2	103.5	1370	22.10	26,700
4	97	3.53	145,000	86.5	101.7	1425	20.7	29,000
E1	123	3.95	159,000	84.0	125.2	1270	19.60	32,500
2	123	4.52	158,000	84.4	126.2	1250	17.10	37,200
3	123	3.75	157,000	88.8	126.1	1245	21.60	30,800
4	123	3.53	158,500	86.5	125.2	1260	22.60	29,000
F1	160	3.53	174,500	83.6	173	1010	24.00	29,000
2	160	3.95	176,500	84.7	171	1030	22.00	32,500
3	160	2.95	168,000	85.5	173	972	28.40	24,200

Run III 5% Oil 95% Benzene

Number	Steam #/sq in Gauge	V ft/sec.	$\frac{Q}{A\theta}$	%heat to vaporize	corrected $\Delta^{o}F$	h	% vaporized	Re
A1	14	4.70	73,000	85.0	34.6	2110	7.6	41,500
2	14	3.53	71,600	89.0	33.1	2160	10.35	31,100
B1	24	3.53	88,000	90.5	48.9	1800	12.90	31,100
2	24	2.95	84,000	90.0	49.9	1685	14.70	26.000
C1	40	3.53	102,000	89.0	60.7	1680	14.75	31,100
2	40	2.95	104,500	84.3	58.2	1800	17.10	26,000
D1	56	2.95	129,000	82.0	78.9	1640	20.55	26,000
2	56	2.65	126,500	83.5	80.0	1580	22.90	23,400
E1	71	2.95	140,000	82.5	97.2	1440	22.40	26,000
2	71	2.20	136,500	85.5	96.9	1410	30.40	19,400
F1	87	2.20	161,000	90.0	107.9	1490	37.80	19,400
G1	108	3.25	169,500	86.0	118.3	1430	25.80	28,700
2	108	2.95	168,500	87.0	117.9	1430	28.40	26,000
H1	143	3.53	183,000	86.0	141.0	1300	25.50	31,100
J1	168	3.53	174,000	87.0	157.0	1110	24.60	31,100
2	168	3.25	173,800	88.0	157	1110	26.80	27,700

Run IV 27% Oil 73% Benzene

Number	Steam #/sq.in. Gauge	V ft./sec.	$\frac{Q}{A\theta}$	% heat to vaporize	Corrected $\Delta^{o}F$	h	% vaporized	Re
A1	30	5.90	68,500	100	52.4	1310	6.51	27,100
2	30	4.70	69,500	100	52.3	1330	8.31	21,600
B1	55	6.15	86,000	100	75.1	1145	7.80	28,300
2	55	4.70	86,000	100	75.3	1140	10.28	21,600
C1	103	4.70	113,000	88.5	112.4	1010	11.90	21,600
D1	123	3.95	123,000	86.6	133.2	1015	15.00	18,200

Run V 49% Oil 51% Benzene

Number	Steam #/sq.in. Gauge	V Ft./sec.	$\frac{Q}{A\theta}$	% heat to vaporize	corrected Δ °F	h	% vaporized	Re
A1	50	5.35	75,000	87.0	69.0	1090	6.86	12,100
2	50	4.70	71,000	85.0	70.2	1010	7.25	10,700
3	50	3.53	66,500	88.8	69.3	960	9.42	8,000
B1	24	4.70	50,200	87.2	52.5	955	5.24	10,700
2	24	3.53	48,800	83.6	52.6	928	6.53	8,000
3	24	5.38	53,400	81.2	55.1	968	4.56	12,200
C1	92	4.15	83,000	82.0	133.3	620	9.22	9,400
2	92	4.35	83,000	81.2	131.3	630	8.74	9,850
3	92	5.02	88,500	70.0	128.9	638	6.95	11,400
D1	122	3.53	98,700	79.0	151.8	650	12.45	8,000
2	122	2.95	96,500	80.5	150.9	640	14.80	6,780
3	122	2.95	98,500	79.6	148.8	662	15.00	6,780
E1	163	3.53	118,000	79.7	167.5	704	15.00	8,000
2	163	3.95	124,000	75.5	167.2	742	13.35	8,950
F1	148	4.15	110,000	76.0	145.1	758	11.35	9,400

Run VI 67% Oil 33% Benzene

Number	Steam #/sq.in. Gauge	V Ft./sec.	$\frac{Q}{A\theta}$	% heat to evaporate	corrected $\Delta^{o}F$	h	% vaporized	Re
A1	166	6.15	107,200	60.5	138.2	775	5.87	5,570
2	166	5.35	106,000	62.6	137.3	773	6.88	4,850
3	166	4.35	101,800	66.2	137.6	740	8.60	3,940
4	160	3.53	93,600	68.5	132.6	706	10.15	3,200
B1	127	3.75	81,800	66.0	123.3	664	8.05	3,400
2	127	4.70	85,300	61.9	124.1	686	6.25	4,250
3	127	6.68	89,600	52.0	123.8	725	3.90	6,050
4	127	3.53	80,500	71.2	123.9	650	9.00	3,200
C1	97	3.53	61,000	69.6	112.0	545	6.70	3,200
2	97	5.02	71,500	64.2	111.5	640	5.11	4,550
3	97	4.75	68,800	64.9	109.7	630	5.23	4,300
D1	77	4.35	51,400	64.9	90.3	570	4.29	3,940
2	77	4.70	51,300	68.6	90.8	565	4.18	4,250
3	77	4.35	49,900	67.0	90.4	552	4.28	3,940
4	77	4.15	49,300	61.6	91.5	540	4.39	3,760
E1	56	3.95	33,000	66.8	74.4	432	3.12	3,580
2	56	5.02	36,100	67.9	74.2	487	3.47	4,550
3	56	6.95	44,300	59.4	74.0	600	2.12	6,300
F1	30	6.15	35,400	52.1	47.3	750	1.69	5,570
2	30	2.95	24,400	66.5	49.0	498	2.75	2,670
3	30	4.70	29,100	55.1	48.7	598	1.91	4,250
4	30	5.02	32,000	56.4	48.5	660	2.00	4,550

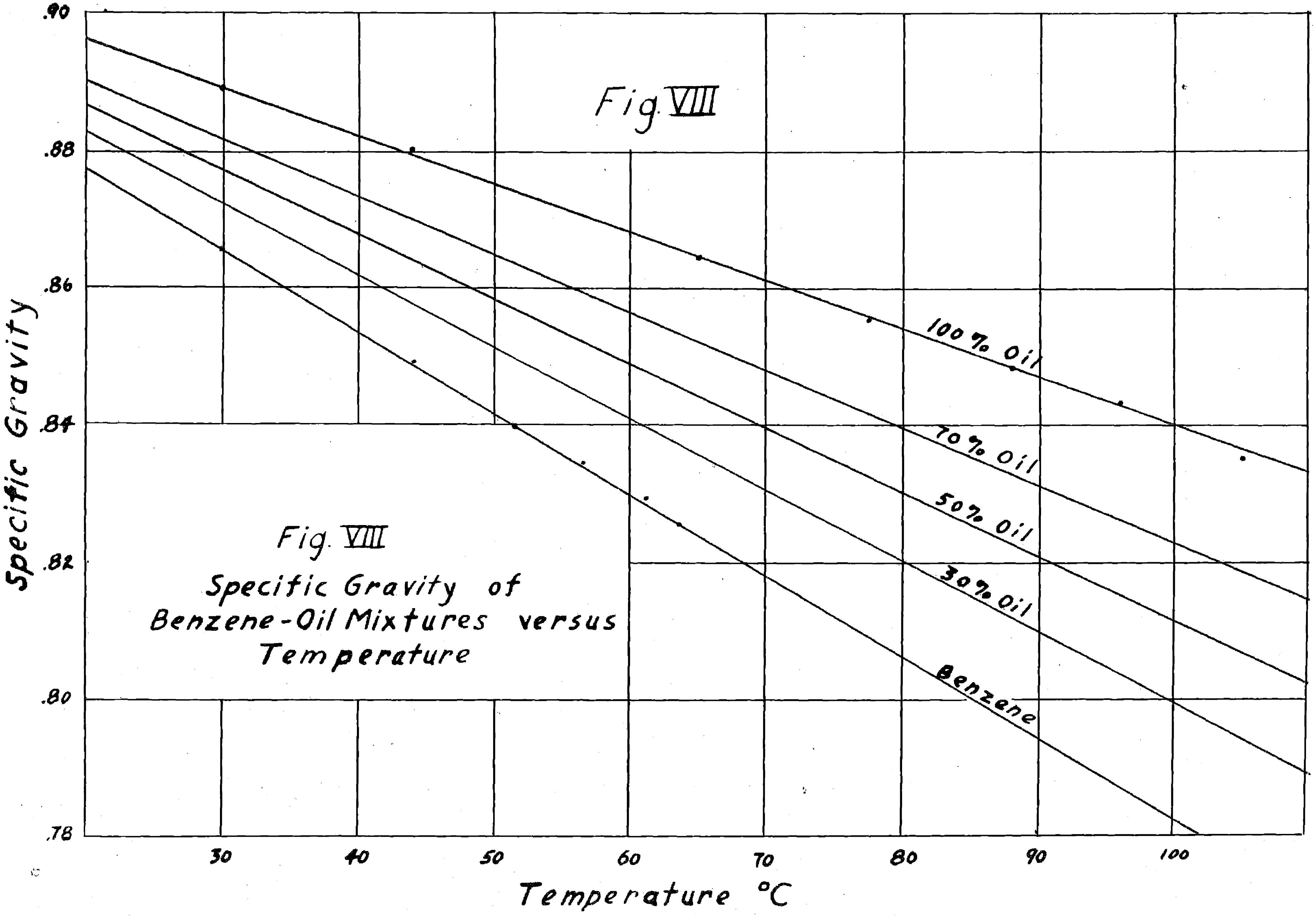

Fig. VIII
Specific Gravity of
Benzene-Oil Mixtures versus
Temperature

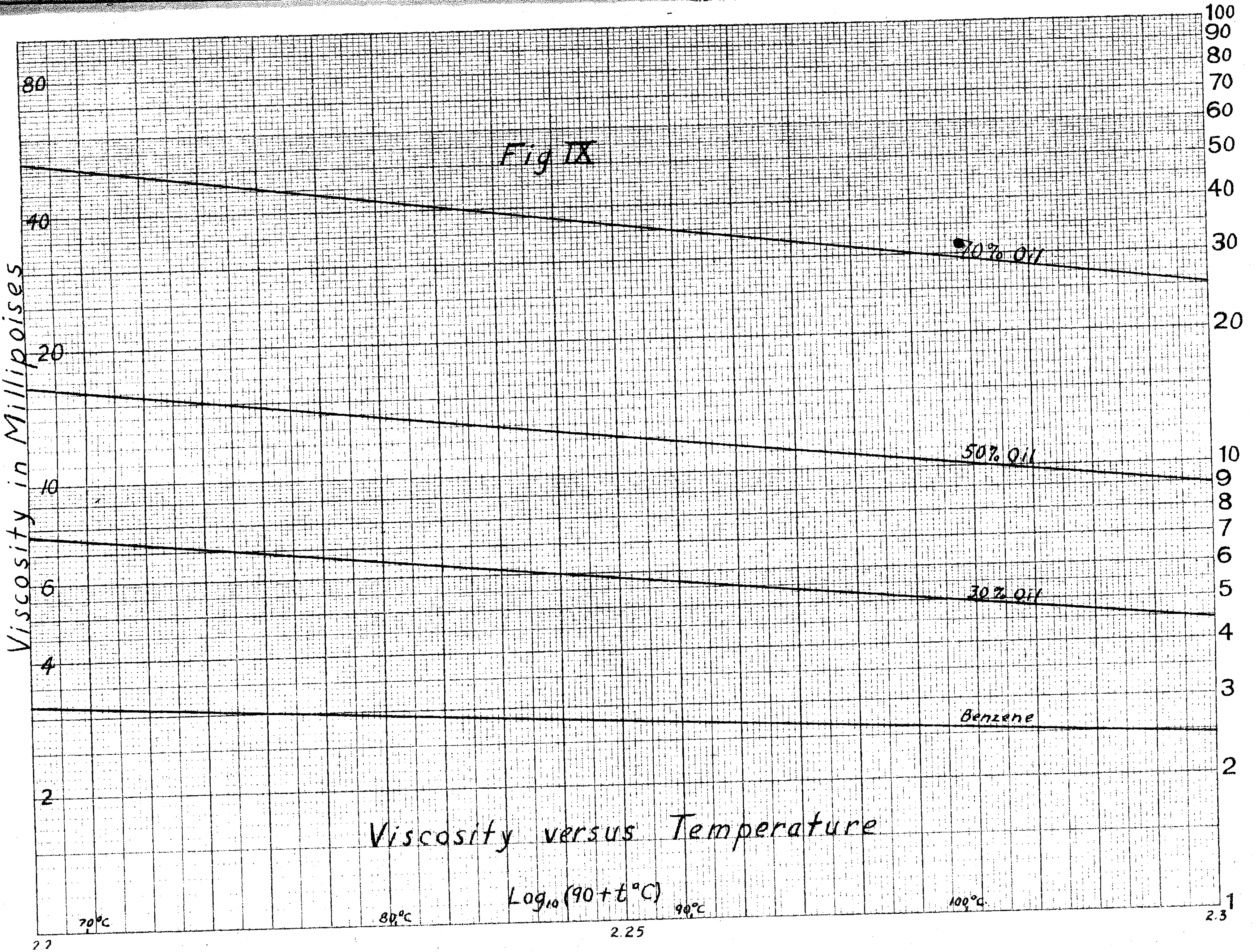

Fig IX

Viscosity versus Temperature

D CALIBRATIONS

1. Thermocouples

The thermocouples were calibrated in the range 20°C to 150°C against fractional thermometers graduated to 0.1°C. From 150°C to 250°C they were calibrated against a 250°C thermometer, graduated to 1°C. The thermocouple to be calibrated was tied to the bulb of the thermometer and heated in an oil bath, points being taken both when heating and cooling the bath. The bath was constantly stirred, especially before taking a reading.

The e.m.f.'s of the thermocouple were measured with a Leeds and Northrup portable potentiometer, M.I.T. No. 376, calibrated to 0.1 millivolt. This potentiometer gave consistently low readings when compared to another potentiometer known to be correct, but the discrepancy was constant and was checked after the runs were completed. The calibration curve is given in Fig. X.

2. Orifice

The orifice was calibrated with water flowing from a main, as it was impractical to calibrate it in place. The water flowing through the orifice was weighed and timed for eight different manometer readings. A plot on logarithmic paper of mass velocity against liquid head gave a straight line with a slope of 2.38. A plot was also made on coordinate paper of velocity in feet per second versus manometer head of water.

3. Thermometers

All nine thermometers were calibrated against fractional thermometers calibrated to 0.1°C and their readings corrected in the tabulated data.

4. Steam gauge

The steam gauge was calibrated by a dead weight tester and the corrections made in recording the data.

5. Sample analysis

Mixtures of oil and benzene ranging from pure benzene to 95% oil by volume were made up and their boiling points determined with fractional thermometers. The apparatus used consisted in a 500cc three neck Pyrex flask with a water condenser approximately ten inches in length. About 260cc of the mixture to be tested were placed in the flask and heated by a sand bath until the liquid boiled. The standard boiling point taken for purposes of this investigation was that temperature at which a drop of benzene a second was condensed in the condenser over a period of a minute. A plot of boiling temperature versus composition is given in Fig. XI.

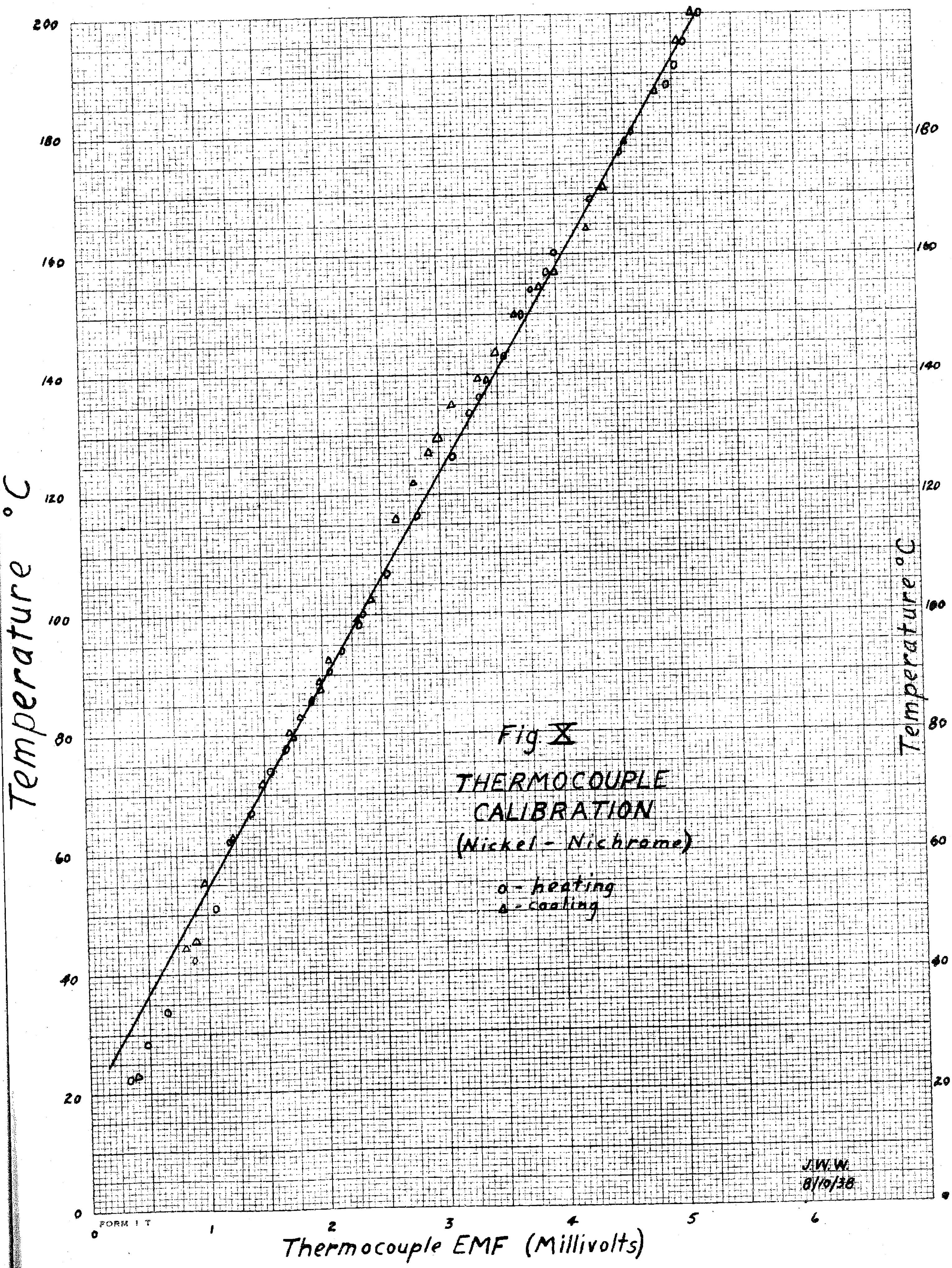

Fig. X

THERMOCOUPLE CALIBRATION (Nickel - Nichrome)

J.W.W.
8/10/38

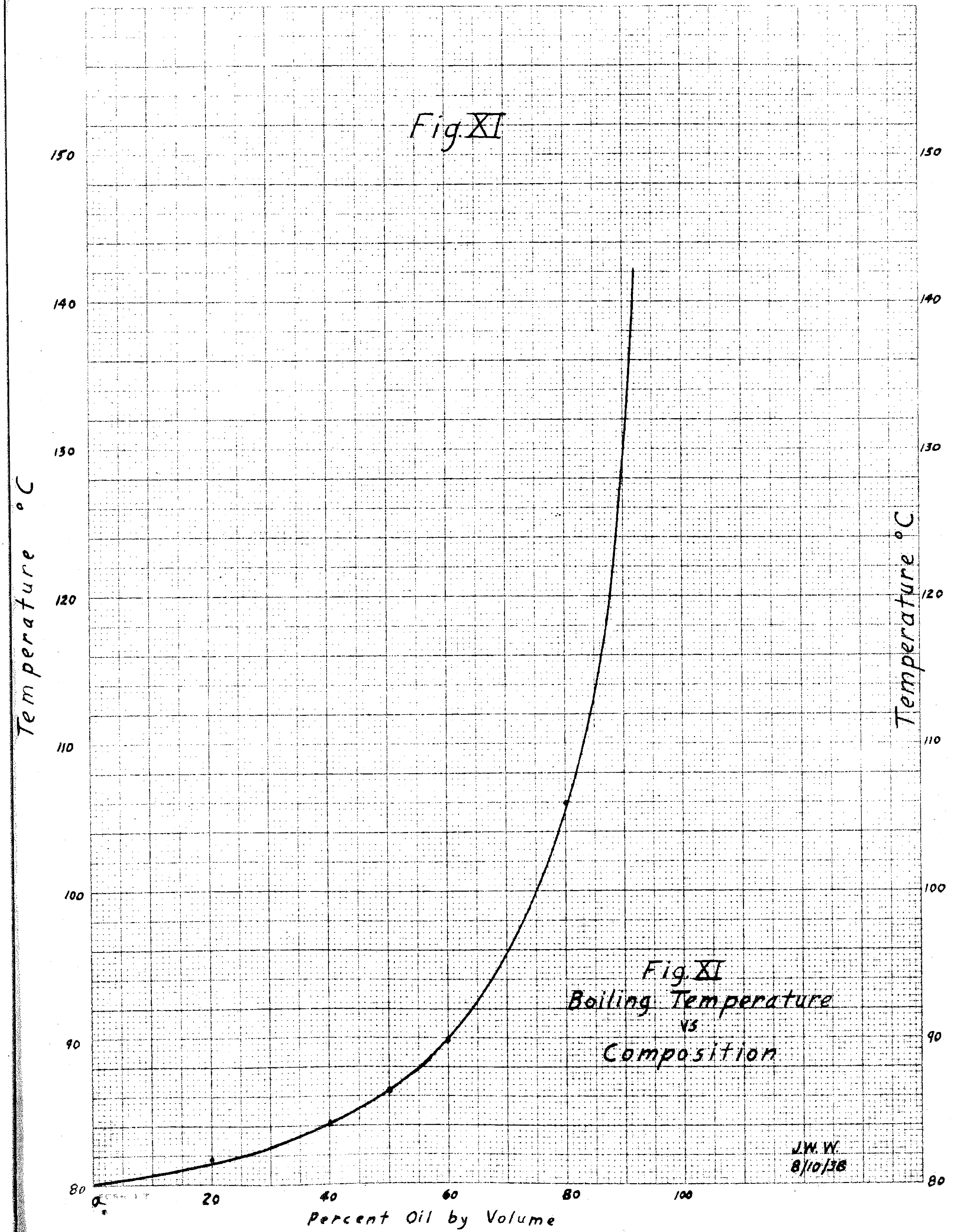

Fig. XI

Fig. XI
Boiling Temperature
vs
Composition

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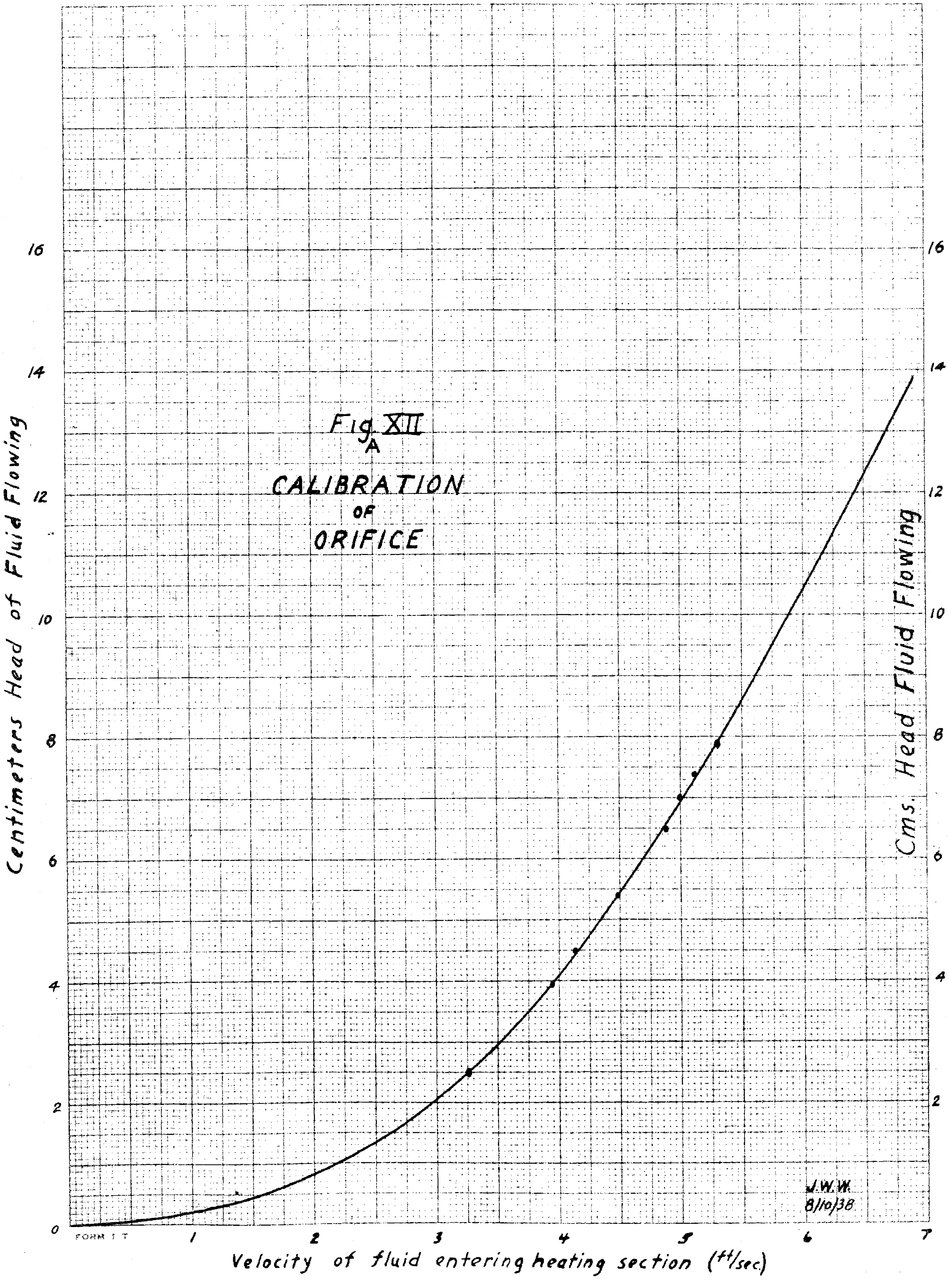
Fig XII A
CALIBRATION OF ORIFICE
Centimeters Head of Fluid Flowing
Cms. Head Fluid Flowing
Velocity of fluid entering heating section (ft/sec)
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
7
FORM 1 T
J.W.W.
8/10/38

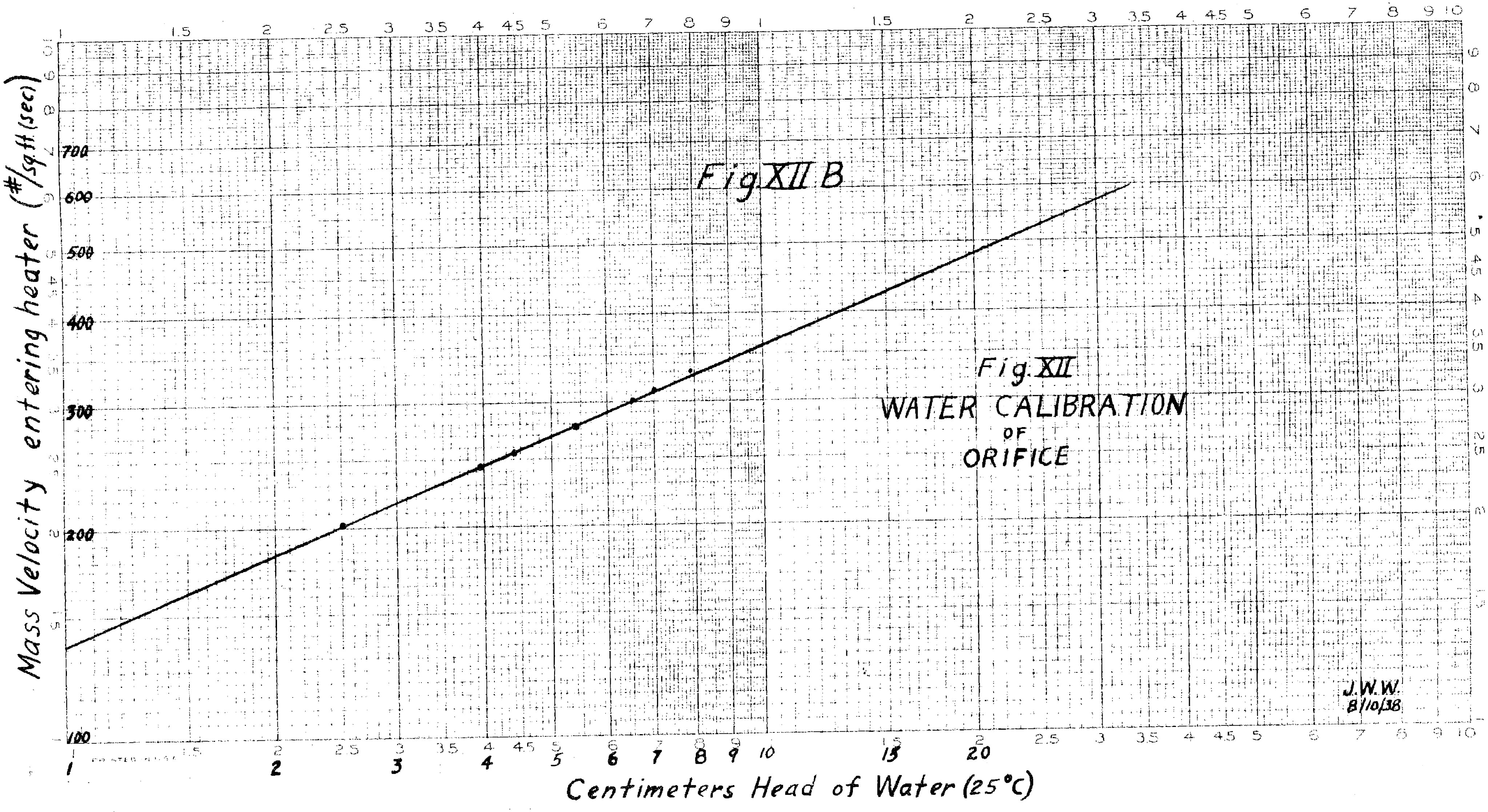

Fig. XII
WATER CALIBRATION
OF
ORIFICE

E SAMPLE CALCULATIONS

The physical properties used in the calculations were taken from Perry's Chemical Engineer's Handbook, Lange's Handbook of Chemistry, the International Critical Tables, or were determined experimentally.

The following calculations are for Run No. 2A1, using a boiling mixture of 9% oil and 91% benzene.

1. Calculation of velocity of liquid entering tube.

Orifice manometer reading= (53-46) = 7 c m.

From Fig. XII, V= 5.02 ft./sec.

and pounds per hour

$$= \frac{5.02 \times 62.4 \times .805 \times 3600 \times (.465)^2 \times \pi}{144 \times 4} = 1070$$

.805 = specific gravity mixture, from Fig. VIII

$\frac{(.465)^2 \times \pi}{144 \times 4}$ = cross sectional area of tube (sq.ft.)

2. Calculation of $\frac{Q}{A\theta}$.

A. Calculation of heat out in condenser water.

167 (51.5-23.2) 1.8 = 8540 Btu./hr.

167 = lbs. water / hr.

(51.5 - 23.2) 1.8 = Δ°F condenser water

B. Calculations of specific heat of mixture.

$$\text{Cp oil} = \frac{0.415}{\sqrt{d}} + 0.0009\,(t-15) = .499$$

d = specific gravity of oil at 15°C with respect to water at 4°C = .899 by Fig. VIII

t = temperature °C = 80

$.09\ (.499) + .91\ (.465) = .468$

.465 = specific heat benzene

C. Calculation of heat from cooling condensate.

$.465\ (80.3-58.5)\ 1.8\ b = 16.6\ b$

.465 = specific heat benzene

$(80.3 - 58.5)\ 1.8 = \Delta\ ^{\circ}F$ condensate

b = lbs. benzene vaporized per hour.

D. Calculation of lbs. benzene vaporized per hour.

$16.6\ b + 169.5\ b = 8540$ Btu.

$b = 45.8$ lbs. benzene vaporized

16.6 b = heat from cooling condensate (c)

169.5 b = latent heat of benzene at 80°C, Btu/lb.

8540 = heat out in condenser water, from (A)

E. Calculation of heat to heat liquid.

$.468 \times 3 \times 1.8 \times 1070 = 2700$ Btu.

.468 = specific heat of mixture

$3 \times 1.8 = \Delta\ ^{\circ}F$ bottom to top header

1070 = lbs./hr. fluid through tube.

F. Calculation of $\frac{Q}{\theta}$

$(169.5 \times 45.8) + 2700 = 10,470$ Btu/hr.

169.5 = latent heat benzene, Btu/lb.

45.8 = lbs. benzene vaporized from (D)

2700 = heat to heat liquid from (E)

G. Calculation $\frac{Q}{A\theta}$

$$\frac{10,470 \times 144}{.465 \times \pi \times 20.75} = 49,800 \text{ Btu/sq.ft.(hr.)}$$

$.465 \times \pi$ = inside circumference tube in inches.

20.75 = length heating surface in inches.

3. Calculation of observed wall temperature.

1. 2.40

3. 2.30 $\frac{7.18}{3}$ = 2.36 millivolts, which corresponds to 101.5°C.

4. $\underline{2.48}$

7.18

4. Calculation of Δ°F observed.

(101.5 - 81.5) 1.8 = 36 °F

101.5 = wall temp., °C

81.5 = temperature at top header, °C

5. Calculation of h wall.

$$h \text{ wall} = \frac{33 \times 12}{.025} = 15,850 \text{ Btu/hr./ft}^2/^\circ\text{F}.$$

33 = conductivity of nickel

$\frac{.025}{12}$ = Average distance of thermocouple from wall (approximated)

6. Calculation of correction on Δt

$$\frac{49,800}{15,850} = 3.14 \ ^\circ\text{F}$$

49,800 = $Q/A\theta$, Btu/(hr.) (sq.ft.)

15,850 = h wall

7. Calculation to correct Δt.

36 - 3.1 = 32.9 °F

36 = observed Δt °F

3.1 = correction, °F

8. Calculation of film coefficient, h.

$$\frac{49,800}{32.9} = 1515 \text{ Btu/hr./sq.ft./}^\circ\text{F}$$

$49,800 = Q/A\theta$, Btu./hr /(sq.ft.)

$32.9 = \Delta t$, °F.

9. Calculation of % vaporized.

$$\frac{45.8}{1070} \times 100 = 4.28\%$$

45.8 = lbs. benzene vaporized / hr.

1070 = total pounds through heater /hr.

10. Calculation % heat to vaporization.

$$\frac{169.5 \times 45.8}{10470} \times 100 = 73.2$$

169.5 = latent heat benzene

45.8 = # benzene vap./hr.

$10470 = Q/\theta$

11. Calculation of Reynolds number

$$\frac{.465 \times 5.02 \times 62.4 \times .81}{12 \times .354 \times .000672} = 41,300$$

$\frac{.465}{12}$ = diameter of tube in feet.

5.02 = velocity, ft./sec.

.354 = viscosity in centipoises, from Fig. IX.

.81 = Sp.gr. of liquid, from Fig. VIII.

12. Calculation of check on orifice.

A. Calculation of heat removed in cooler.

$65\ (53.4 - 23.4)\ 1.8 = 3500$ Btu/hr.

65 = lbs. cooler water per hour.

$(53.4 - 23.4)\ 1.8 = \Delta$°F cooler water.

B. Calculation of rate of flow through cooler.

$1070 - 45.8 = 1024.2$ lbs./hr.

1070 = total rate of flow, lbs./hr.

45.8 = lbs. benzene vaporized /hr.

C. Heat balance around apparatus from top header to just before pump, excluding condenser.

$W C_{p_w} t_w +$ losses $= C\, C_{p_c} t_c + L\, C_{p_1} t_1 -$ Q cooler

Take 0°C as base temperature with zero enthalpy.

W = total lbs./hr. liquid flowing, from orifice.

CP_w = specific heat liquid before vaporization.

t_w = temperature of mixture before pump.

C = lbs./hr. condensate.

Cp_c = Specific heat of benzene.

t_c = temperature condensate, °C.

L = lbs./hr. liquid through cooler.

Cp_1 = specific heat liquid in cooler.

t_1 = temperature of liquid before entering cooler.

Q cooler = heat removed in cooler, Btu.

$$1070\ (.468)\ 77 \times 1.8 + \text{losses} = 45.8 \times .465 \times 58.5 \times 1.8 +$$
$$(1070 - 45.8)\ (.469) \times 1.8 \times 81.5 - 3500$$

losses by this calculation = 400 Btu

D. Approximation of accuracy of measurements.

$$\frac{400}{10470} \times 100 = 3.82\ \%$$

400 = losses by calculation

10470 = heat flow/hr.

F. TABLE OF NOMENCLATURE

h...Liquid coefficient of heat transfer, Btu/hr./sq.ft/^{o}F.

Q...Heat flow, Btu.

A...Area of heating surface, sq.ft.

θ...Time, hours,

Δ ..Temperature difference, ^{o}F.

D...Diameter evaporator tube, ft.

V...Velocity of liquid entering evaporator tube,ft/sec.

ρ ..Density, lbs./cu.ft.

μ...Viscosity, centipoises.

Re..Reynolds number, $(\frac{DV}{U})$

α..Function of Δ in equation $\frac{Q}{A\theta} = \alpha(Re)^{.4}$

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