THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Chemical and Metallurgical Engineering
Department of Mechanical Engineering

Second Quarterly Progress Report

INVESTIGATION OF LIQUID METAL BOILING HEAT TRANSFER

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FOREWORD

This report summarizes progress during the period August 15, 1963 to November 15, 1963 on Contract AF 33(657)-11548. This contract provides for continuation of the experimental programs initiated under the original contract between the University of Michigan and ASD. The investigation is being conducted in the Liquid Metals Laboratory of the Department of Chemical and Metallurgical Engineering. Professor Richard E. Balzhiser is serving as Project Director at the University of Michigan. Misters Barry, Caswell, Padilla and Smith, all graduate students in chemical engineering are responsible for specific portions of the program.

Progress on the agravic studies with boiling mercury will be summarized in these reports. This work is being conducted by Professor Herman Merte, Jr. and Mr. Samuel Walker in the Mechanical Engineering Department.

Mr. Charles L. Delaney is project engineer for ASD.

ABSTRACT

The high flux nucleate pool boiler has been cleaned of potassium and recharged with water in an attempt to obtain burnout data which might be compared with existing data for other geometries. Two burnouts were experienced accidently and neither yielded accurate values. One more attempt will be made before charging sodium.

Recalibration of thermocouples used in the film boiler has revealed substantial drift. The results presented in the preliminary draft of the Final Report on the original contract will be modified before release of the final draft. Efforts to stabilize and calibrate the microthermocouples prior to rerunning the potassium are continuing.

Additional pressure drop data was obtained prior to draining the loop of potassium and sodium. Proposed test section modifications have been studied in detail. Removal of the test section has been accomplished. Based on the results of an examination by MSAR a decision will be made as to the type of heating to be used.

Agravic studies have progressed to the assembly and checkout stage. Operation is anticipated in the next quarter.

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NUCLEATE POOL BOILING STUDIES

B. F. Caswell

The equipment used to obtain high flux pool boiling data for potassium was cleaned of potassium and reassembled for similar studies with sodium and rubidium. The results obtained with potassium suggested that the hydronamic theories of burnout might not adequately account for behavior in liquid metal systems. In order to check any possibility of the results being biased due to the geometry of the apparatus it was decided to attempt to obtain several burnout points for water which might be compared with existing values in the literature. Prior to making these measurements some modifications in the apparatus were deemed desirable.

The equipment was modified in order to obtain better control of heat losses from the boiling mixture such that subcooling could definitely be eliminated. The test vessel was completely wrapped with coiled electric heater elements covered with asbestos paper. The heater is in three sections so that independent control can be maintained of the vessel outside wall temperature near the bottom, in the middle and near the top. The 1/4-in by 2-in bus bar connected to the test vessel just below the boiling tube was reduced at a point to 1/4-in by 1/2-in by cutting out two V-notches. The "necked-down" section was then wrapped with guard heater. This should minimize heat losses through the bus bar. A second layer of guard heaters was then installed on the test vessel with two independently controlled sections. Five temperature measuring points were added at various positions around the outside of the test vessel. These will be used to control the guard heaters such that the surface temperatures are maintained at the temperature of the saturated liquid.

Some nucleate boiling data was taken on water and is plotted in Figures 1 and 2. The results are in close agreemtne with those of Colver and other investigators. In attempting to get burnout results with water two boiling tubes were ruined without getting accurate values for the burnout flux. This problem may be eliminated in the future because a safety system has been devised which will shut off the electric current whenever the boiling tube surface temperature exceeds a certain set point.

One more attempt will be made to secure burnout data for water. When the next series of runs is completed, the apparatus will be dried and prepared for sodium or rubidium runs.

FILM BOILING

Andrew Padilla, Jr.

The film-boiling apparatus has been operated at reduced pressure and data obtained. The evaluation of the data based on initial thermocouple calibration data was found to be unsatisfactory because of the unreliability of the previous method of calibration and the high probability of drift of the micro-thermocouples used in the boiling plate. This has led to a careful evaluation of the reliability and stability of the micro-thermocouples.

The film boiling of potassium at reduced pressures produced data which was somewhat surprising since the fluxes obtained in the film-boiling regime were of the same order of magnitude as those in the nucleate regime. The difference in temperature between two thermocouples in the boiling plate together with a knowledge of the thermal conductivity of the Cb-1Zr plate and the distance between the two thermocouples provided the necessary data for calculation of the flux. Pairs of thermocouples located at two different radii in the boiling plate provided an estimation of the radial variation in heat flux. The temperature profile was extrapolated to the surface and the temperature difference between the surface and boiling liquid determined.

The initial method of calibrating the micro-thermocouples used in the boiling plate utilized a transient technique without an equilizing block and did not insure that the thermocouples had reached the same temperature as the secondary standard Pt/Pt 10% Rh thermocouple. Upon recalibration, after the boiling runs, the micro-thermocouples were found to have drifted significantly from their original calibration. In place of an equilizing block, the present method uses a stainless steel thermowell which does not extend to the outside of a Leeds and Northrup thermocouple-checking furnace (Cat.No.9004). It was determined that approximately 30 minutes was required at each temperature level to insure that both the secondary standard and the micro-thermocouples had attained equilibrium. The calibration method will be described in detail later in this report.

After the boiling runs under reduced pressure, the micro-thermocouples used in the boiling plate were recalibrated up to 1600°F. A least-squares analysis was applied to the data and the resulting equations used in calculating the boiling curves. A recheck on the calibration up to 1600°F could detect no drift in the micro-thermocouples. Since this last calibration differed considerably from the original, it is necessary to assume that the thermocouples had stabilized by the time that the data had been taken. This assumption seems reasonable since the micro-thermocouples had been used considerably during the heater development stage and were not used to an excessively high temperature during the boiling runs. The final draft of the final report of project 04526 will incorporate the results of these recalibrations.

The investigation into the stability of the micro-thermocouples was initiated unexpectedly. Since the original thermocouples had undergone much abuse during the debugging of the experimental system, it was decided to replace them with new ones. Eight new micro-thermocouples were therefore calibrated up to 1800°F (see Table 1). However, upon checking the calibration while decreasing the temperature, only three thermocouples decreased along the same curve. The other five experienced significant drops in emf for the same temperature. A second calibration produced different curves for all eight micro-thermocouples, with the same five again exhibiting marked hysteresis effects (see Table 1).

To investigate the nature of the drift, these micro-thermocouples were heated to 1200°F and maintained at this temperature for over 7 hours. The emf outputs varied widely and corresponded to temperatures as low as 120°F below the secondary standard (see Table 2). However, the readings were stable with time. To check for hysteresis effects, the thermocouples were cooled to 300°F and then reheated to 1200°F. The same stable readings were obtained over a period of almost 8 hours. (See Table 2.)

It therefore appeared that after the initial aging process, consisting of heating the micro-thermocouples to 1800°F twice, they were stable up to 1200°F. (See Table 3.) To determine whether they would also be stable at higher temperatures, the thermocouples were heated to 1800°F (the maximum temperature of the L & N thermocouple-checking furnace). Widely-varying, but stable, temperatures were again obtained over a period of 7 hours. The effect of hysteresis was again checked by cycling down to 450°F. Upon reheating to 1800°F, a drop in emf in all thermocouples was detected. After another 3 hours at 1800°F, some thermocouples seemed to be stabilizing, but it became definitely clear after 8 hours that all eight micro-thermocouples were drifting. They were still drifting after over 18 hours at 1800°F when the experiment was finally terminated.

The investigation of the micro-thermocouples indicates that they are stable in an oxidizing atmosphere to at least 1200°F. It should be noted that the original set of micro-thermocouples had been used up to 1600°F and did not exhibit any changes in the calibration. The findings impose severe limitations on the use of these micro-thermocouples although they can probably still be used to determine the location of the film-boiling regime at one atmosphere. Potassium boils at approximately 1400°F and the minimum heat flux has been estimated to occur at a temperature difference of 323°F.

It should be noted that the micro-thermocouples were tested under conditions much more severe than they are actually intended to be used. During operation, they are contained entirely within the evacuated environmental chamber whereas they were exposed to an oxidizing atmosphere during the calibration. It may be necessary later to devise a system for calibrating the thermocouples under vacuum.

Procedure for Furnace Calibration of Micro-Thermocouples

The micro-thermocouples were calibrated using a Leeds and Northrup No.9004 thermocouple checking furnace with a maximum temperature of 1800°F. Measurements were made on a L & N Model 8662 laboratory potentiometer.

The micro-thermocouples are swaged assemblies with 0.020 ± 0.0005-in OD Inconel sheaths. The wires are 38-ga Chromel-Alumel and are electrically insulated from each other and the sheath by magnesium oxide. The junctions are grounded to the sheath. The 10-in long Inconel sheath is connected to high-temperature Chromel-Alumel lead wire by means of a stainless-steel transition fitting.

The micro-thermocouples along with a Pt/Pt 10% Rh thermocouple were inserted into a 1/2-in ID by 3/4-in OD by 9-in long stainless steel thermowell tied to a Haynes rod for support. A Pt/Pt 10% Rh thermocouple calibrated by the Bureau of Standards was tied to the outside of the thermowell with its junction flush with the bottom of the thermowell. All thermocouples were firmly pressed down to insure contact with the horizontal bottom of the thermowell.

The assembly was inserted into the furnace and the nect of the furnace packed with fiberfrax insulation to minimize heat losses. Approximately seven inches of the thermowell extended into the furnace with the remaining two inches located in the neck. The insulation completely covered the thermowell but the transition fittings of the micro-thermocouples extended just above the neck and were thus kept cool and could be checked for thermal contact with the bottom of the thermowell. The Pt/Pt 10% Rh and Chromel-Alumel thermocouples were hooked to separate switches which went through cold junctions immersed in an ice bath to the potentiometer.

The furnace was brought up to temperature with full power and then switched to manual control. Adjustment of a rheostat was then used to stabilize the temperature inside the furnace. A check on the transient response of the thermocouples inside the thermowell showed that approximately one-half hour was required for all temperatures to reach steady state. Careful adjustment of the rheostat could maintain the temperatures within two degrees F while the measurements were being taken.

Prior to taking a set of measurements, the potentiometer was checked against its internal standard cell. The secondary standard and then the Pt/Pt 10% Rh thermoxouple in the thermowell were read. Then all Chromel-Alumel thermocouples were read followed by the two Pt/Pt 10% Rh thermocouples. The actual temperature, taken as that of the secondary standard, was linearly interpolated to give the true temperature for each micro-thermocouple. The Pt/Pt 10% Rh thermocouple in the thermowell may be sent to the Bureau of Standards at a later data as a further check on accuracy.

The recommended procedure for the furnace involved an immersion depth of 18 inches. This was not possible due to the short sheaths of the microthermocouples. Use of a copper equilizing block was not recommended for temperatures above 1000°F. The stainless-steel thermowell which did not extend outside the furnace was used in place of a stainless-steel equilizing block. Careful adjustment of the furnace rheostat after 30 minutes gave a furnace temperature drift of not more than 3°F per 5 minutes except at the highest temperatures, where a maximum of 8°F per 5 minutes was encountered.

FORCED CIRCULATION STUDIES

R. E. Barry

The objective of this program is to compare the two-phase heat transfer characteristics of liquid metals in swirl and straight-tube flow. The studies are to be carried out in the forced circulation loop constructed under Contract AF33(616)-8277. In this loop, potassium is preheated to a desired quality by means of external resistance heaters and then passed through a test section consisting of a length of 1/2-in tube. Sodium vapor condensing on the outside of this tube supplies a flux of 1-million Btu/(hr)(sq ft). A condenser, a cooler and a pump complete the circuit.

A number of operating problems developed in connection with the forced circulation loop which were described in some detail in the Final Report of the above Contract (1). Briefly, these problems were:

1. Cavitation in the electromagnetic pump.
2. Excessive heat losses in the loop resulting in substantial subcooling at the preheaters.
3. Burnout of the heaters in the preheater and the sodium boilers.
4. Boiling instabilities.
5. Mechanical failure of the test section.

Further operating experience has produced methods by which cavitation can be reduced. It has occurred primarily at flow rates in excess of 0.6 GPM and at low temperatures. Apparently, a vapor pressure of about 5 psia is required in the hotwell to prevent cavitation. Therefore, flow rates at startup in future runs will be held at 0.4 GPM until the required pressure in the hotwell is achieved.

The excessive heat losses have occurred primarily in the condenser and subcooler and will be corrected by the use of radiation shields and insulation and by adding more heating capacity in the preheaters.

Discussions with the manufacturer of the radiant heaters are in progress to determine if the burnout of the heaters can be corrected.

Superheating of the liquid metal in the boiler and preheater leads to instabilities. It has been suggested (2) that a localized heating zone held at a minimum of 70°C above the saturation temperature would alleviate this condition by generating bubbles and thus affording a vapor-liquid interface for vaporization. This is not a readily achievable solution for the preheaters since the location of saturated conditions varies and if the bubbles were generated in a region of substantial subcooling, they would collapse before having the desired effect. Fortunately, this is not a serious problem in the preheaters since instability has thus far amounted to a range of 18°F. In the boiler, however, superheating of 250°F has been noted and a fix is definitely required. However, because of temperature limitations of Haynes-25, it may prove undesirable to heat a localized region about 100°F above saturation since this would limit the boiler operating temperatures. Since striking the boiler induced nucleation, it may be that a low frequency striker would prove useful.

Since the failure of the test section, the concept of transferring a high flux to the boiling potassium has been re-examined. It appears that even if the flux can be independently determined, at least one measurement of the wall temperature is highly desirable because of the possibility of unknown film-wall resistances both on the sodium and potassium sides. Once it has been decided to place a thermocouple in the wall, this immediately increases the wall thickness to at least two times the size of the smallest couple that can be inserted. Thermocouples with diameters less than .040-in have been shown to exhibit instabilities and premature failures. If the conditions are set such that a temperature of 1800°F is set for the ID of the 1/2-in tube and a minimum flux of 500,000 Btu/(hr)(sq ft) is specified under this condition, then an estimate can be made of the heating possibilities.

1. Condensation: A .080-in wall of Haynes-25 would result in a 200°F drop through the wall and an 80°F drop through the sodium film. Since the estimated drop through the film is only approximate, this would probably result in boiler temperatures in excess of 2100°F. However, a .080-in wall of Mo-.5Ti would produce a temperature drop of only 50°F and hence appears attractive for this application. Mo-5Ti alloy was considered two years ago but was rejected because of its low resistance to oxidation. In the test section, however, it would not be exposed to the atmosphere. It appears that Mo-.5Ti can be successfully brazed to Haynes-25 but it is not a routine operation. The estimated cost for this change is $7,000.
2. Induction Heating: This method involves using a 15 KVA, 450 KC generator to heat a 1/2-in ID tube with .160-in wall. The heavy wall is required to enable two thermocouples to be placed radially for determination of flux and a generation zone which does not interfere with the flux determination. The outside wall would operate at 2110°F for a flux of 500,000. There has been developed a coating for Haynes-25 which would reduce the oxidation rate at this temperature and it is felt that the problems of AC pickup by the couple and determination of the flux profile can be solved. This would require an outlay of approximately $21,000 of which $15,000 would be for the generator. The cost could be lowered to $10,000 by using a lower frequency

generator (i.e., 10 KC) but this would require a wall thickness of .280-in and an outside surface temperature of 2240°F.

3. Bi-metal Conduction: This method utilizes a thin-wall tube of Haynes-25 surrounded by a copper disc which serves to amplify the flux at the tube wall. The diameter of the disc is made large enough so that commercially available heating elements can be used to supply the lower flux required at the OD of the disc. The flux is determined from thermocouples placed radially in the disc. This method is inapplicable to our conditions since it results in excessive temperatures at the OD of the disc and the bi-metal interface tends to separate at high temperatures, resulting in indeterminate wall temperatures.

4. Resistance Heating: In this method, a 1/2-in tube of Haynes-25 with a .130-in wall is sheathed by a tube of boron nitride which in turn is sheathed by a tube of tantalum. A low-voltage source generates heat in the tantalum which is conducted through the boron nitride and the tube-wall. Two couples located radially in the wall measure the flux. This method results in 2060°F on the OD of the Haynes tube, and around 2100°F on the OD of the boron nitride tube. The assembly is enclosed in an evacuated chamber to prevent oxidation of the tantalum. This concept requires some development (i.e., it may be possible to flame-spray the tantalum on the boron-nitride base) and the method of feeding power to the tantalum while maintaining a satisfactory vacuum has not been designed. The problem in this design is that it requires 1500 amps for a tantalum film thickness of .003 inches to generate 15 KW and such a thin foil is readily subject to failure. The system would cost about $13,000 to install.

5. It is also possible to repair the system as originally conceived but with a redesign of the bellows. Since no wall temperature would be measured, the results of the investigation would be the determination of the quality at which the overall heat transfer coefficient showed a decided decrease. This procedure would, of course, meet the objectives of the program as originally defined, but the determination of the absolute magnitude of the potassium heat transfer coefficient would be in some doubt. The cost is estimated at $5,000.

In conclusion, if a satisfactory test section can be designed using Mo-.5Ti, condensation appears to be the best choice on the basis of cost alone. The uncertainty as to whether the instability can be eliminated makes this choice somewhat of a gamble. It is felt that resistance heating still requires development with a consequent delay in the program and that satisfactory operation is doubtful. Hence, this possibility is being discarded. Induction heating, although expensive, offers the greatest advantages with regard to operation and ease of fabrication. The critical area here is the design of a coil to obtain an efficient flux linkage.

Recent Operations: The forced circulation loop was operated intermittently during October to obtain further pressure drop data. At the conclusion of these runs, the sodium and potassium in the primary and secondary loops were drained into buckets. The liquid metals were then poured onto the ground and burned. No serious difficulties were associated with this procedure. In the initial phases of sodium drainage, the metal carried with it a black liquid which was assumed to be a carbon compound (possibly carbon from the Haynes-25). Since this material burned upon drainage we were not able to have it analyzed. The liquid metals were drained in this fashion to avoid contamination of the material in the supply tanks.

The preheater heaters were then disassembled and it was found that internal burnout of the element accounted for the majority of failures. All failures occurred at about the same location on the heater(i.e., within a 5-in length on the entering wire). The failure of these heaters can compromise the preheater design concept unless a fix can be made. The estimates for loop repair have been made on the basis that a satisfactory solution to this problem can be found without altering the piping comprising the preheater section.

TWO-PHASE FLOW STUDIES

Lowell R. Smith

Prior to draining the potassium loop and shutting it down for overhaul, several experimental runs were made in October. The purpose of these runs was to:

(a) Extend the two-phase pressure drop data into the low-quality region for mass flows corresponding to 1, 4, and 5 millivolt flowmeter outputs (125, 480, and 610 lb/hr mass flows),

(b) Try and ascertain the influence of system pressure on the two-phase pressure drop,

(c) Obtain a few all-liquid pressure drop readings.

Item (b) was of particular interest, since it was felt that the variation of vapor-phase density with pressure would lead to a pressure influence on pressure drop. This influence was suggested in the original data, but to clearly see the effect the pressure level range needed extension.

First, a series of runs was made in order to make the desired data extensions with respect to quality. The points obtained permit extension of the 125 lb/hr curve to lower qualities, as shown in Figure 3a. It also is now possible to graphically present the 480 and 610 lb/hr data--Figures 3b and 3c. For the sake of comparison, all experimental curves are shown on a common plot in Figure 4 (data points are omitted for clarity). It is seen that the location of the 380 lb/hr curve is somewhat anamolous, probably due to data scatter.

In order to achieve higher temperatures in the loop, the condenser and subcooler were stuffed with insulation. The voltage to the preheaters was also stepped up. A series of data were taken at 1 and 2 millivolt nominal flowmeter outputs. Operation was limited to low flow rates because several of the preheater units had burned out, allowing only a small quality range to be attained at higher flow rates. The pressure level was significantly increased for the 2 millivolt flows, but for the 1 millivolt flows the inlet pressure span was about the same as for the data previously reported. For the 2 millivolt flows the inlet pressure ran from 5.9 to 15.4 psia, and for the 1 millivolt flows it ran from 8.0 to 13.7 psia. The inlet pressures for the data previously reported had the ranges 0.5 to 8.6 psia and 0.6 to 15.8 psia, respectively. For the 2 millivolt flows, the pressure drops fell significantly lower than the previous data.

The data from this series also were more nearly isothermal than the previous data. The maximum temperature drop observed was 26°F, whereas 50 to 75°F temperature drops were common formerly. As a result of the low temperature drops, and because heat losses from the pressure drop section are small, nearly constant qualities occurred. This data set, then, gives pressure drops which are almost purely frictional.

The entire set of 260 lb/hr (2 millivolt) data is presented in Figure 5. In this plot the data are grouped according to inlet pressure. The trend of lower pressure drops with higher inlet pressure is in keeping with all physical expectations. The lowest curve are the essentially-isothermal data discussed in the preceding paragraph. The ranges of vapor phase density are indicated on the figure. (It should be recalled that the overall mixture composition contains 8 weight per cent sodium.) The lowest curve, representing only a frictional pressure drop, has a much lower slope than the curves which also include significant momentum effects.

The nearly-isothermal pressure drop data have been compared with values predicted by the Lockhart-Martinelli procedure. The comparison is given in Figure 6, which shows that the correlation predicts frictional components which are too high. Since much of the data obtained in this study occurred under non-isothermal conditions which included significant acceleration components in the pressure loss, the Lockhart-Martinelli correlation has been written in a step-wise iteration routine for the IBM 7090 computer. The routine allows for variation of fluid properties with flow direction. The program has just been debugged, but check runs showed that this technique also yields high values. This result is not surprising in view of the fact that the frictional components are too high from the start. The worst deviations occur at very low inlet pressures where in some cases the correlation is questionable for systems where the inlet pressure level is below about 4 psia. The correlation is based on data obtained in air-liquid systems where the average pressure varied from 16 to 52 psia.

In the Martinelli procedure, it is necessary to use single-phase friction factors. In the iterative non-isothermal computer program, the following empirical relationship for single-phase friction factor was adopted, as suggested by Knudsen and Katz (3).

$$\frac{f}{4} = 0.00140 + 0.125\,(\mathrm{Re})^{-0.32} \qquad (1)$$

This relationship was said to be valid for Reynolds numbers between 3,000 and 3,000,000. To verify the use of Equation (1), three experimental all-liquid points were obtained. The average deviation between experimental and predicted f values is 7.7 per cent.

These all-liquid runs also allowed a check on possible aging of the Pt-Pt Rh thermocouples, since flows should be isothermal. The signals from thermocouples TC26, TC29, TC30, and TC31 all read within 6 microvolts, indicating that the thermocouples had functioned correctly throughout the two-phase flow experiments.

Present efforts are concerned with correlation of the two-phase pressure drop data. The two-phase friction factor approach is being examined. The theoretical annular flow model is still being investigated. In addition, the effect of variations in detector temperature on the void fraction data are being investigated. It may be possible to smooth the data if the temperature coefficient of the counting system can be determined.

LIQUID METAL BOILING IN AGRAVIC FIELDS

Herman Merte

The modification of the small centrifuge for accepting the mercury boiling test vessel has been completed, and the assembly of the accessory equipment is virtually complete, awaiting only the installation of the test vessel.

The external electrical power wiring for the main heater and the two independently controlled guard heaters is complete and includes appropriate voltmeters, ammeters, variacs, and fusing in each circuit. Since only 4 copper slip rings are available on the centrifuge it was necessary to employ a common ground. All three circuits are connected to the main power source through a single relay controlled by a pressure switch on the test vessel. Should an accidental pressure rise occur within the vessel all electrical power would automatically be disconnected.

The above pressure switch is attached to the test vessel via a 3/16-in OD stainless steel tubing, which in turn connects to the inert gas pressure source via the rotating union. In order to connect to the rotating union, which also transmits the cooling water, it was necessary to reduce the pressurizing line to 1/16-in in diameter. A pressure relief valve has been installed on the stationary portion of the pressurizing system, but should a very sudden rise in pressure within the test vessel occur, as might be possible should the thin stainless steel skirt on the heater surface rupture and dump the mercury into the high temperature guard heaters, then the small line would not be capable to transmitting the fluid at a sufficient rate to the relief valve. Also, the high temperature powder insulation within the test vessel might be carried along and clog the line under the proper circumstances.

The pressure vessel has been tested to 600 psi, but with certain operating conditions and a failure such as that above this might be exceeded unless a satisfactory venting system is provided. Pressure relief valves of the desired port area are too massive for installation directly on the rotating system, so a rupture disc is being procured for installation on the pressure vessel. The sudden relief of this rupture disc with the attendant release of mercury vapor would be contained within the 8-ft high 14-ga steel enclosure which terminates below a building exhaust fan. This fan will be operating during all testing periods.

The only conceivable cause for a rapid pressure rise would be the rupture of the thin stainless steel skirt, as mentioned above. Calculations have indicated that the skirt can withstand the maximum hydrostatic head of mercury anticipated, approximately 45 psi. It was felt, however, that it would be prudent to experimentally verify this at this time, and a fixture is being constructed to test an equivalent sample of the thin foil up to 75 psi.

The external pressurization system is completely piped up with the exception of the precision pressure gage. It was necessary to return the gage to the manufacturer for repair and calibration, and this opportunity will be used to reduce the range of the instrument to permit greater precision within the pressures of interest, 0-300 psig.

Early testing will be conducted at the lower values of pressure. Under this condition it is possible that the cooling water supply within the rotating union could be at a higher pressure than the pressurizing gas. It might thus be possible for water to leak into the pressurizing line and hence the test vessel, an undesirable event. Careful leak testing of the entire cooling water and pressurizing system will be conducted prior to any operation.

It is anticipated at this time that testing under boiling conditions can begin within the next 4 to 5 weeks.

REFERENCES

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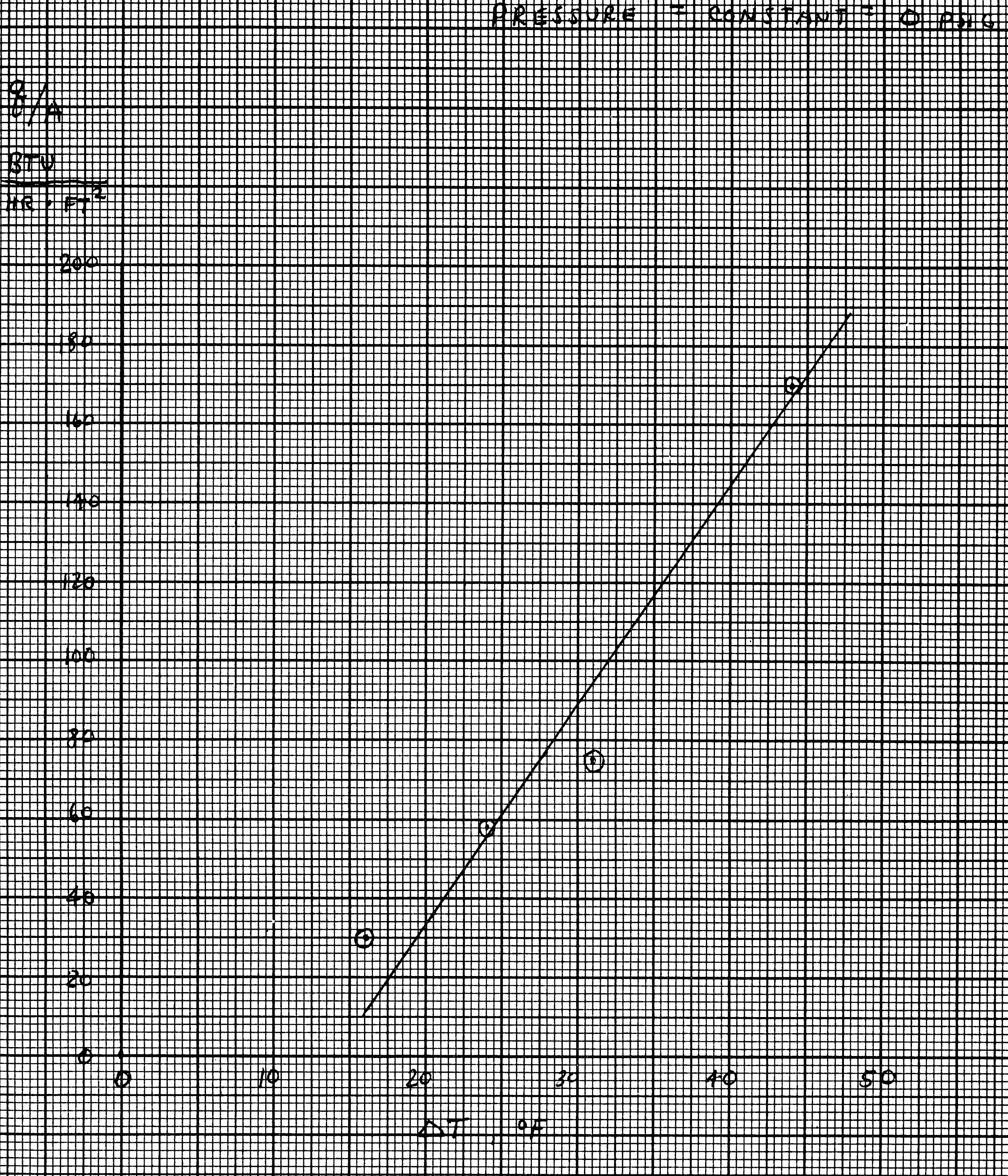


FIGURE 1. HEAT FLUX VS. TEMPERATURE DIFFERENCE AT CONSTANT PRESSURE

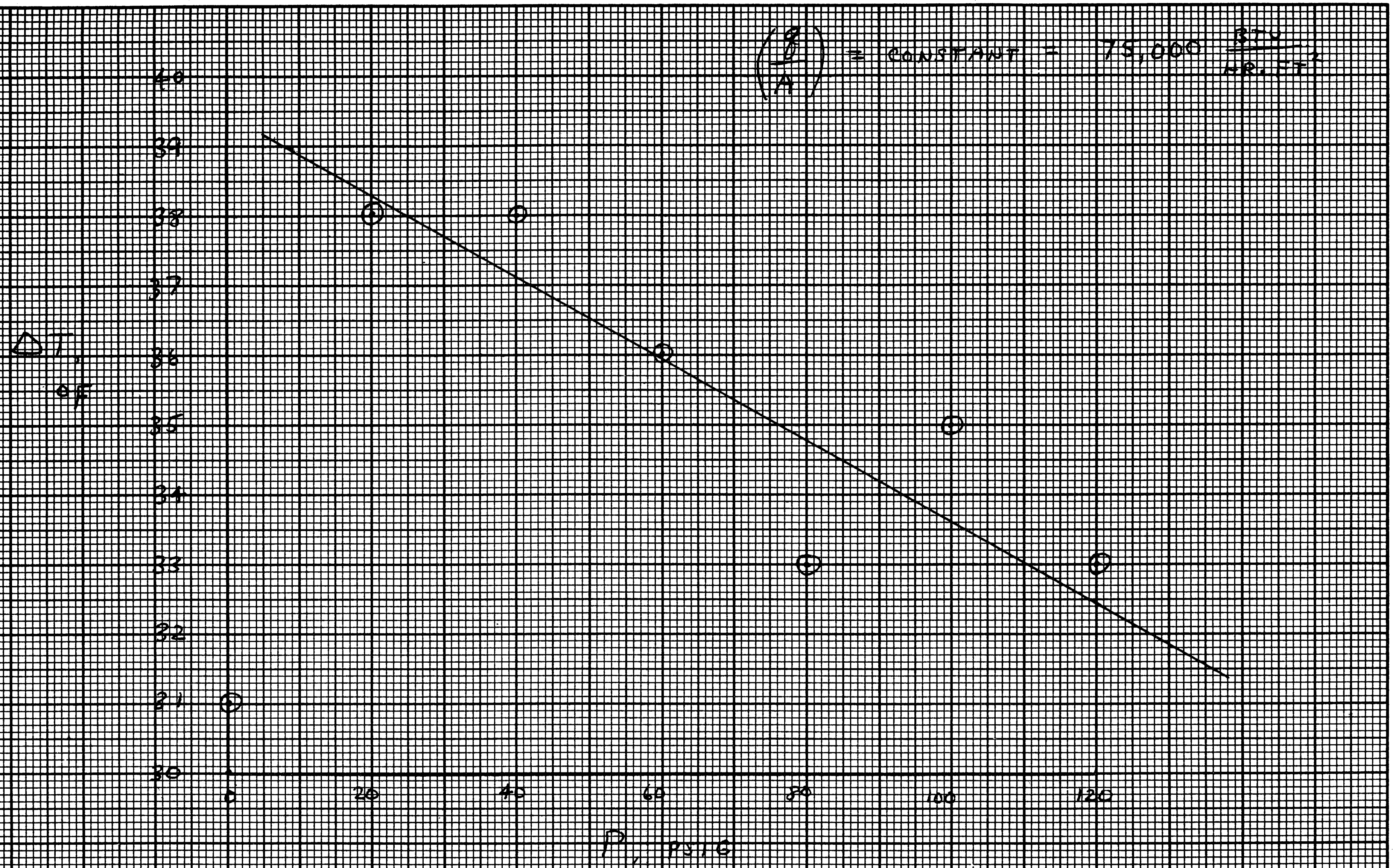
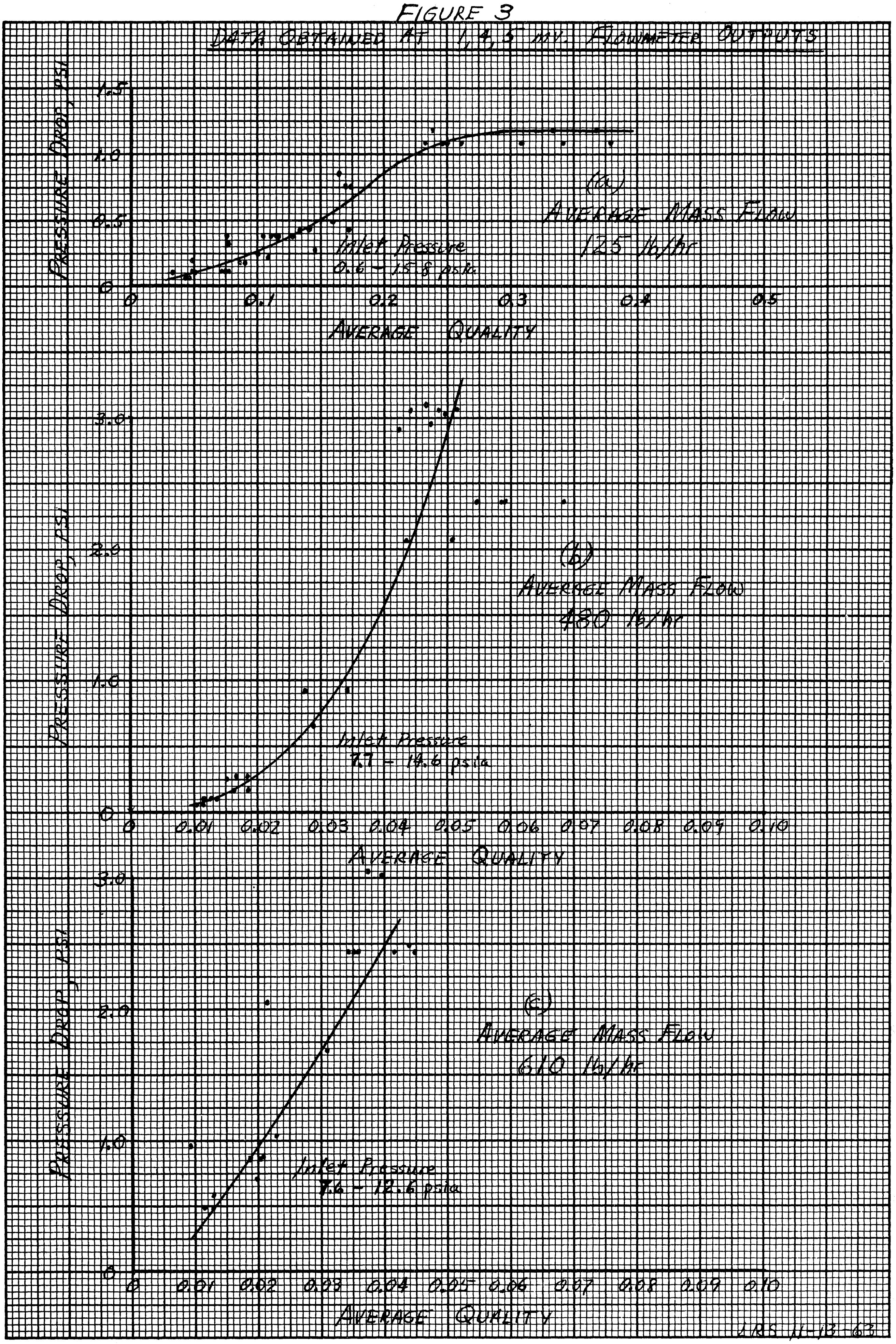


FIGURE 2. TEMPERATURE DIFFERENCE VS. PRESSURE AT CONSTANT HEAT FLUX

FIGURE 3


DATA OBTAINED AT 1, 4, 5 MV. FLOWMETER OUTPUTS
PRESSURE DROP, PSI
1.5
1.0
0.5
0
0
0.1
0.2
0.3
0.4
0.5
AVERAGE QUALITY
(a)
AVERAGE MASS FLOW
125 lb/hr
Inlet Pressure
0.6 - 15.8 psia
PRESSURE DROP, PSI
3.0
2.0
1.0
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
AVERAGE QUALITY
(b)
AVERAGE MASS FLOW
480 lb/hr
Inlet Pressure
7.7 - 14.6 psia
PRESSURE DROP, PSI
3.0
2.0
1.0
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
AVERAGE QUALITY
(c)
AVERAGE MASS FLOW
610 lb/hr
Inlet Pressure
7.6 - 12.6 psia
LRS 11-13-63

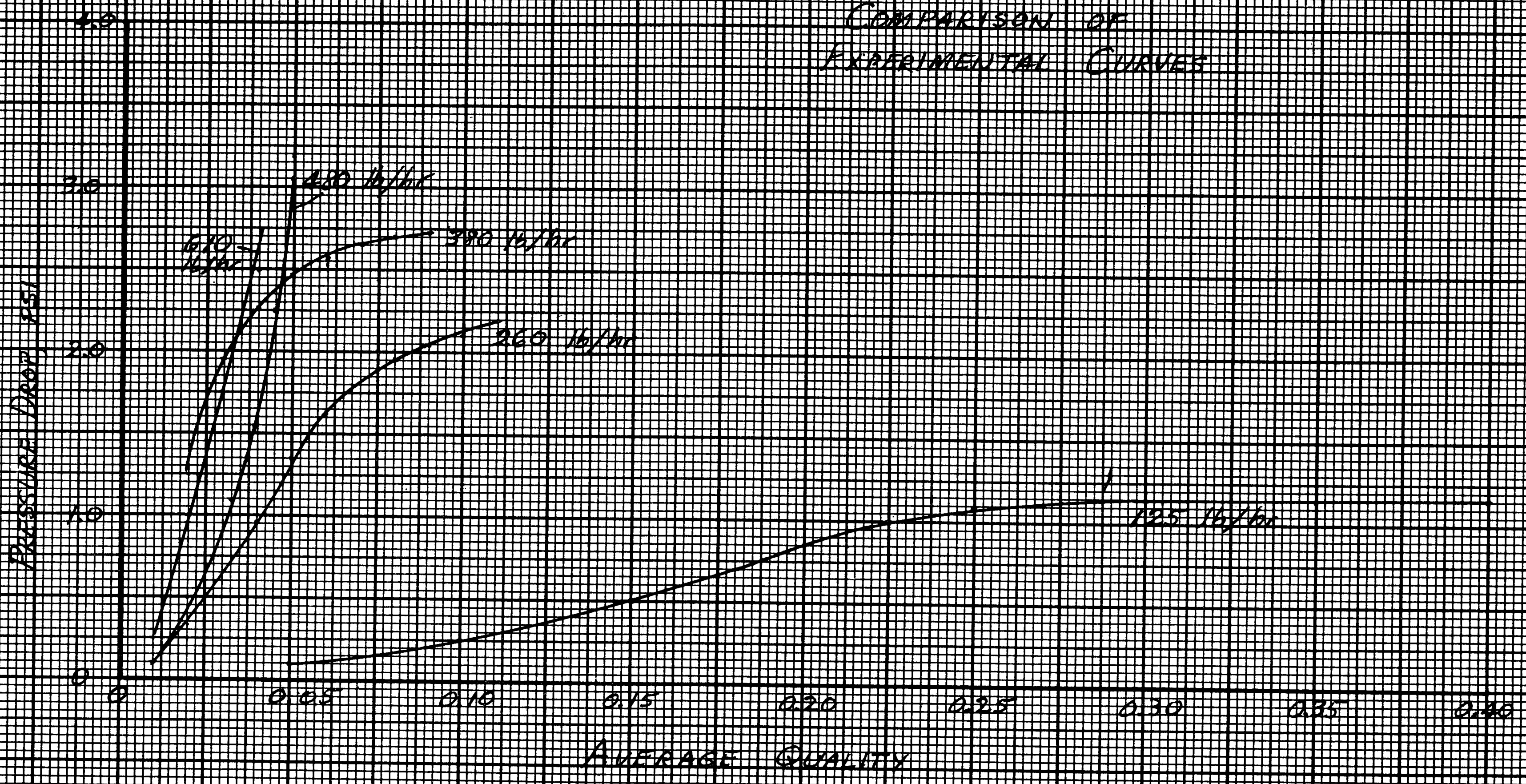


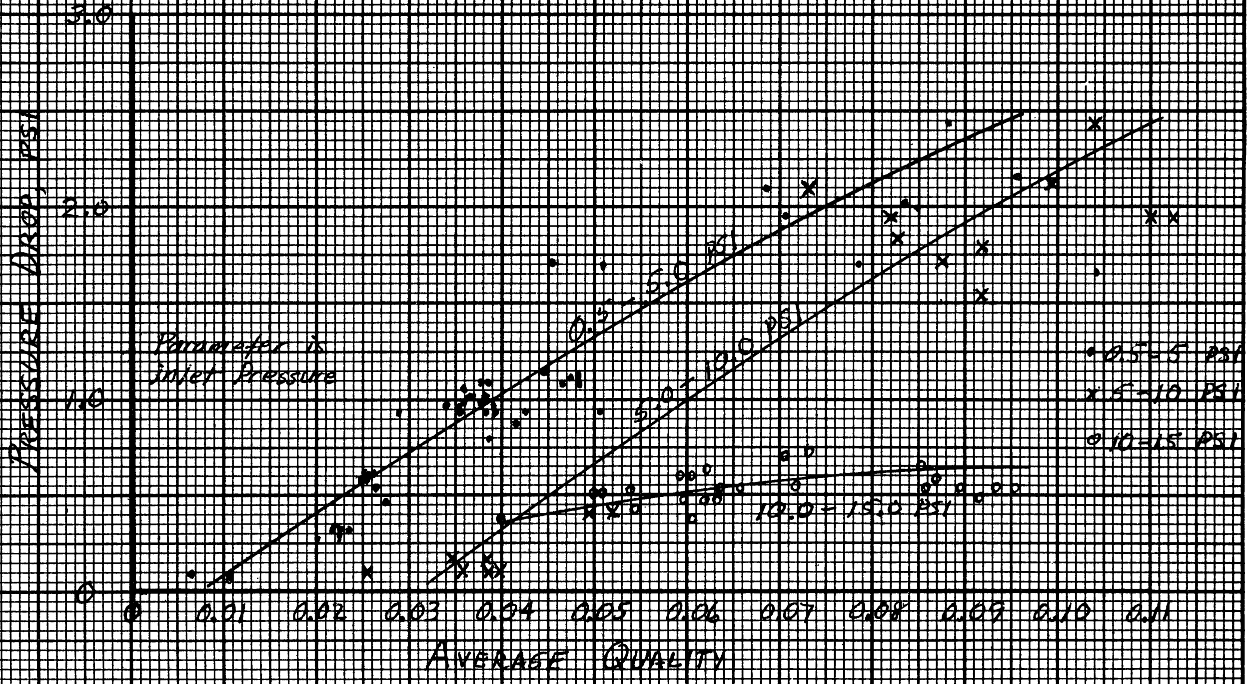
FIGURE 4

COMPARISON OF
EXPERIMENTAL CURVES

LRS 11-13-63

FIGURE 5

EFFECT OF INLET PRESSURE ON PRESSURE DROP FOR 260 LB/HR MASS FLOWS



Pressure Range PSIA	Vapor Density Range LB/FT^3
0.5 to 5.0	0.0013 to 0.01
5.0 to 10.0	0.01 to 0.02
10.0 to 15.0	0.02 to 0.03

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FIGURE 6

COMPARISON OF ISOTHERMAL DATA WITH VALUES PREDICTED BY LOCKHART-MARTINELLI METHOD

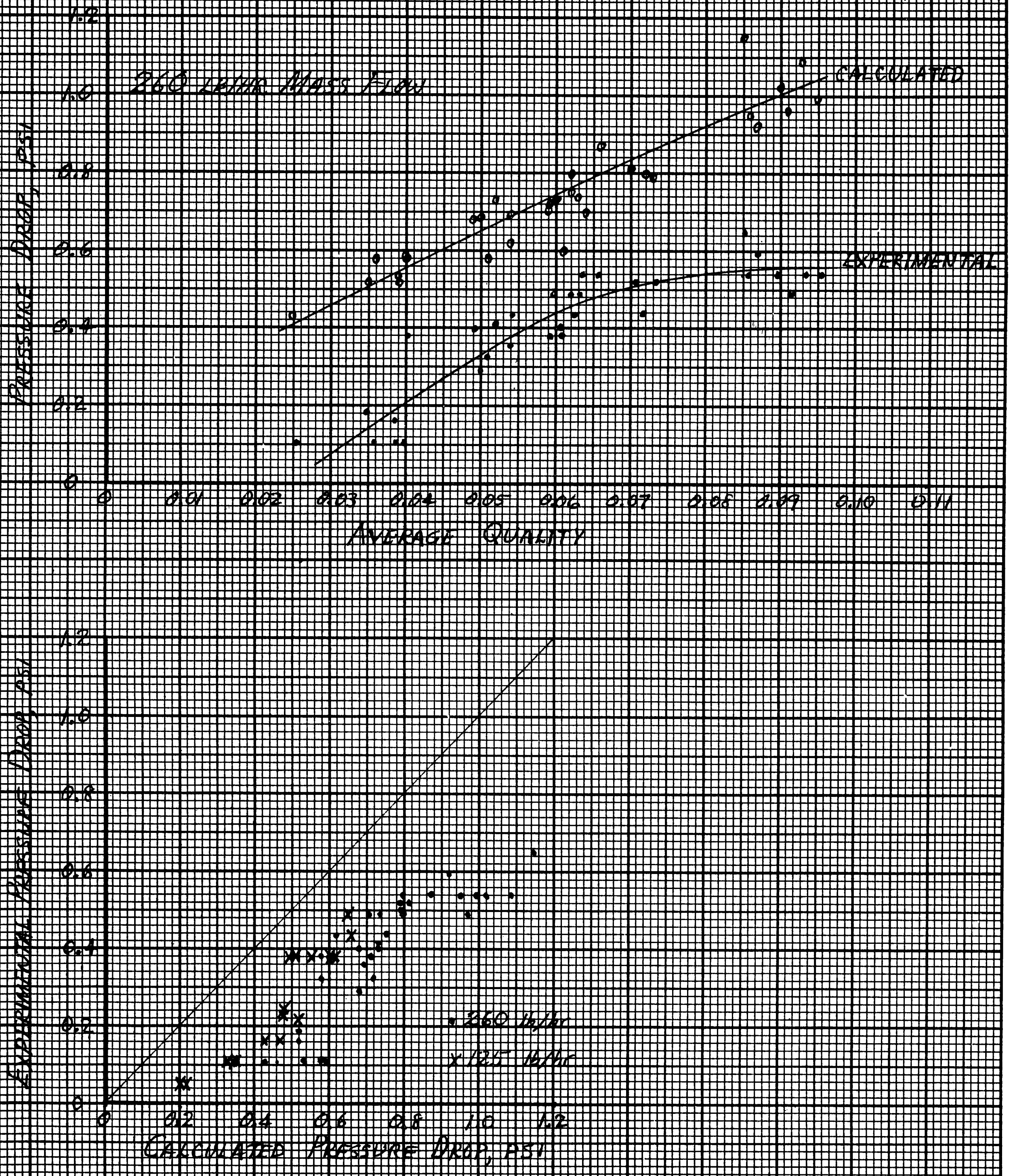

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TABLE I

Calibration of new set of micro-thermocouples

Standard	109	429	605	785	987	1179	1376	1574	1779	1767
Micro-TC A	111	438	610	788	987	1176	1369	1561	1760	1748*
B	111	438	611	790	986	1171	1382	1550	1694	1676*
C	111	437	610*	789	986	1168	1354	1526	1714	1685
D	111	436	610	790*	989*	1178	1369	1560	1756*	1742
E	111	437	610	791	990	1176	1364	1552	1728	1710
F	111	437	610	791	991	1178	1362	1546	1717	1691
G	111	435	609	790	990	1178	1368	1555	1736	1714
H	111	436	611	792	992	1180	1370	1560	1756	1742
Standard		422	602	786	991	1185	1380	1575	1776	1761

Recalibration of new set of micro-thermocouples

Standard	501	490	701	910	1111	1298	1501	1707	1506	1501
Micro-TC A	510	499	706	910	1105	1289	1488	1688	1492	1488
B	461	457	659	859	1050	1229	1424	1590	1392	1388
C	468	463	666	866	1060	1238	1435	1611	1425	1421
D	511	500	707	910	1106	1288	1484	1677	1480	1476
E	489	484	689	891	1086	1271	1466	1651	1457	1453
F	470	466	669	870	1062	1242	1436	1611	1424	1422
G	489	483	687	890	1085	1268	1461	1638	1438	1436
H	510	501	707	912	1107	1289	1486	1683	1484	1484
Standard	496	489	701	912	1113	1299	1503	1707	1502	1503

* Standard checked after this reading also.

Order of readings: Standard, micro-thermocouples, standard (plus any additional readings of the standard deemed necessary).

The tabulations are in degrees Fahrenheit and are the temperature in the tables corresponding to the actual emf's obtained.

TABLE II

Check on micro-thermocouple drift at 1200°F

Time*		45m	1h 30m	3h 45m	6h 15m	7h 15m	45m	1h 30m	3h 45m	6h 15m	7h 15m
Standard		1205	1212	1248	1240	1238	Difference from standard				
Micro-TC	A	1201	1208	1242	1232	1230	-4	-4	-8	-8	-8
	B	1081	1092	1127	1118	1117	-124	-120	-121	-122	-121
	C	1121	1132	1167	1158	1156	-85	-80	-81	-82	-82
	D	1185	1192	1226	1216	1216	-21	-20	-22	-24	-22
	E	1148	1157	1194	1187	1185	-59	-54	-54	-52	-53
	F	1113	1123	1160	1151	1150	-94	-88	-88	-88	-88
	G	1129	1138	1175	1167	1166	-79	-73	-73	-72	-72
	H	1202	1206	1238	1229	1228	-6	-5	-10	-10	-10
Standard		1208	1211	1248	1239	1238					

Recheck on micro-thermocouple drift at 1200°F after cycling to 300°F once

Time		25m	50m	2h 40m	5h 25m	7h 40m	25m	50m	2h 40m	5h 25m	7h 40m
Standard		1201	1203	1211	1236	1247	Difference from standard				
Micro-TC	A	**									
	B	1070	1074	1089	1111	1121	-130	-129	-122	-125	-126
	C	1115	1119	1131	1154	1164	-86	-84	-80	-82	-83
	D	1183	1184	1190	1214	1223	-18	-19	-21	-22	-24
	E	1144	1148	1157	1181	1191	-58	-55	-54	-55	-55
	F	1108	1112	1124	1148	1157	-94	-91	-87	-88	-89
	G	1124	1129	1140	1163	1172	-78	-74	-71	-73	-74
	H	1189	1197	1202	1226	1234	-13	-6	-9	-10	-12
Standard		1202	1203	1211	1236	1246					

* h denotes hours; m denotes minutes.

** Open circuit due to broken lead wire connection.

The variation of furnace temperature between readings is a result of adjustments in the rheostat setting for the furnace to compensate for changing heat losses. The tabulations are in degrees Fahrenheit and are the temperatures in the tables corresponding to the actual emf's obtained.

TABLE III

Check on micro-thermocouple drift at 1800°F

Time	25m	3h 5m	4h 45m	5h 50m	7h	25m	3h 5m	4h 45m	5h 50m	7h
Standard	1774	1843	1830	1831	1831	Difference from standard				
Micro-TC A	*	*	1803	1801	1800			-27	-30	-31
B	1371	1640	1633	1634	1636	-403	-203	-197	-197	-195
C	1429	1724	1720	1723	1716	-345	-119	-110	-108	-115
D	1615	1766	1753	1752	1750	-159	-76	-77	-79	-81
E	1441	1732	1724	1728	1732	-333	-110	-106	-102	-99
F	1426	1685	1672	1670	1668	-348	-157	-158	-160	-163
G	1418	1701	1685	1724	1722	-356	-141	-145	-106	-108
H	1628	1802	1792	1791	1790	-146	-39	-38	-39	-40
Standard	1774	1841	1830	1830	1830					

* Open circuit due to broken lead wire connection.

Recheck on micro-thermocouple drift at 1800°F after cycling to 450°F once

Time	25m	45m	2h 40m	3h 40m	8h 15m	15h 40m	18h 15m
Standard	1805	1803	1782	1810	1833	1766	1771
Micro-TC A	*	*	1734	1761	1796	1674	1676
B	1583	1588	1580	1600	1639	1533	1537
C	1561	1533	1384	1368	1718	1045	1036
D	1708	1708	1687	1706	1825	1506	1250
E	1674	1678	1657	1679	1724	1533	1522
F	1606	1615	1600	1620	1658	1536	1526
G	1146	1312	1182	1163	1630	905	
H	1754	1755	1730	1755	1785	1691	1685
Standard	1802	1802	1782	1810	1832	1765	1771

Difference from standard

A	*	*	-48	-49	-37	-92	-95
B	-221	-215	-202	-210	-194	-232	-234
C	-273	-270	-398	-442	-115	-720	-735
D	-96	-95	-95	-104	-8	-259	-521
E	-129	-124	-125	-131	-108	-232	-249
F	-197	-187	-182	-190	-174	-229	-245
G	-657	-490	-600	-647	-202	-860	
H	-48	-47	-52	-65	-47	-74	-86