EXPERIMENTS IN NUCLEATE BOILING HEAT TRANSFER

Thesis by

Roy Stribling Cornwell

Lieutenant Commander, United States Navy

In Partial Fulfillment of the Requirements

For the Degree of

Aeronautical Engineer

California Institute of Technology

Pasadena, California

1955

ACKNOWLEDGEMENTS

Professor R. H. Sabersky directed and encouraged the project in all its phases and his guidance is deeply appreciated. Dr. A. J. Ellis gave many helpful suggestions during the construction of the apparatus and throughout the test program. His assistance saved the author a great deal of time and made for a more accurate test apparatus. Mr. S. P. Sutera assisted in making tests and his aid was greatly appreciated.

ABSTRACT

The present series of experiments were undertaken in order to provide additional information on the effects of different heating surface materials on boiling heat transfer. Three different materials were used in conjunction with three different fluids.

Wires of platinum, tungsten and iron were chosen for the heating surface materials. All wires were approximately 0.010 inches in diameter and two inches long. The fluids used were methyl alcohol, carbon tetrachloride and iso-octane. Measurements of wire temperature and heat flux were made with the wire immersed in the fluid and heated electrically.

The results indicated that there was no major effect of the heating surface material on either the burnout heat flux or on the temperature of the nucleate boiling region. These findings are, of course, limited to the wire-fluid combinations tested as well as to the range of experimental conditions investigated.

TABLE OF CONTENTS

I. INTRODUCTION

Boiling heat transfer is defined as heat transfer from a surface to a liquid when the temperature of the liquid adjacent to the surface is sufficiently high to cause boiling. The bulk temperature of the liquid may be at or below its saturation temperature.

A typical boiling heat transfer curve is shown in Fig. 1, where the heat transfer rate, q/A (Btu/in^2 sec.) is plotted against the temperature of the heating surface, T (°C). In the region A to B, heat is transferred by convection. At point B, with the surface temperature somewhat above the boiling point of the fluid, bubbles of vapor begin to form on the heating surface. Depending on the fluid and the temperature, some of these bubbles grow and collapse in the manner described by Ref. 1, and some detach from the heating surface and rise into the fluid. As the surface temperature is increased, the frequency of bubble formation increases. Eventually some of the bubbles coalesce and form a partial vapor blanket over the heating surface. Because of the relatively poor conductivity of the vapor, the bubbles tend to act as insulation and a further increase in surface temperature actually tends to lower the heat transfer rate. A maximum is reached at point C. If higher heat transfer rates are required, the surface temperature has to be raised to a value above E. Since for some combinations of metals and fluids this temperature is above the melting temperature of the metal, point C is generally called the burnout point.

In the region between C and D large masses of vapor are formed by the coalesence of individual bubbles. These large vapor masses detach and rise, resulting in an essentially unstable condition at the heating surface and considerable agitation in the fluid. Beyond the minimum at point

D. a stable vapor film forms at the surface.

The region from A to B is generally known as the convection region, that from B to C as the nucleate boiling region, that from C to D as the partial film boiling region, and the region beyond D as the complete film boiling region.

In engineering design, the burnout point is of importance as it often represents a practical limit to the amount of heat that can be transferred from a surface. The present study is concerned with the nucleate boiling regime and in particular with the location of the burnout point and with the temperature at which nucleate boiling heat transfer begins. A considerable volume of data has been accumulated on water and several other fluids, notably alcohol. The heating surface was usually a wire suspended in the fluid or a metal tube with the fluid flowing either on the inside or the outside of the tube. (Refs. 1,2,3,4,5)

A question that has however, received relatively little attention concerns the possible effect of different wire materials on the nucleate boiling region and the burnout point for various fluids. It has so far been generally thoughtthat the location of the nucleate boiling region, as well as the burnout point, are not significantly influenced by the wire material. Some influence of the wire material on the burnout point has, however, been recorded (Ref. 2) and it seems desirable to give more attention to this aspect.

A further question to be examined is that concerning the relation of the temperature at the start of nucleate boiling to the normal fluid boiling point. Here again it has usually been assumed that the temperature at the start of nucleate boiling is close to the normal boiling point of the fluid. However, additional experience with different heating surfaces and fluids is required to substantiate this assumption.

The present series of tests were undertaken to examine the effect of different heating surface material on the burnout point and on the nucleation temperature in different fluids. It is hoped that the results may help to form conclusions on the effects of heating surface material on boiling heat transfer. A larger body of such information than is now available will be necessary before it will be possible to derive any general correlation between the burnout point and the parameters of the fluid and the flow field.

II. OUTLINE OF THE PROBLEM

In order to carry out the proposed series of tests, it was decided to use as a heating surface an electrically heated wire suspended horizontally in the test fluid. The electrical power input to this wire could then be easily measured and the heat transfer rate at the surface of the wire computed directly. By choosing the wire diameter sufficiently large, the wire curvature has only a small effect on the nucleation (Ref. 4). On the other hand, the diameter compared to the length of the wire was sufficiently small so that no serious end effects were to be expected. Calculations have been carried out to show that the temperature distribution through an electrically heated wire of small diameter is sufficiently uniform to allow the assumption of constant temperature throughout the wire (Ref. 4).

The heating surface materials chosen for the series of tests were platinum, tungsten and iron. Methyl alcohol (CH_3OH), Carbon tetrachloride (CCl_4) and isooctane (2-2-4 trimethyl pentane $(CH_3)_3CCH_2CH(CH_3)_2$) were selected for the test fluids. The heating surface materials were obtainable in wire form with a high degree of purity and the necessary physical constants were easily obtainable. The fluids chosen also consisted of a single chemical component and the necessary physical constants, particularly the boiling points, were again accurately known. Table I lists the physical properties of the fluids. No attempt was made to treat the fluids by degassing, pressurization or similar methods, as in practice they are normally encountered untreated, and in the present series of tests it was desired to investigate phenomena as they might occur in engineering applications.

Each heating surface material was tested in all the fluids and at two different bulk temperatures of the liquid. Normal room temperature of approximately 22°C. and a bulk temperature slightly below the saturation temperature were selected. Three or more runs were made at each condition with each wire, so that a total of about seventy-five runs were performed.

Each heating surface material was obtained in one continuous length, and the test wires used were cut from these. Since both resistivity and temperature coefficient of resistivity are strongly affected by composition, this procedure assured that all wires nominally of the same material actually had very nearly the same composition.

III. DESCRIPTION OF APPARATUS

The measurement presenting the most difficulty in the present series of tests was that of determining the wire temperature, and the design of the apparatus was largely dictated by the method chosen. Two methods of temperature measurement were considered: first, the possibility of using a thermocouple attached to the wire, and secondly, the possibility of using the wire itself as a resistance thermometer. The first method was rejected because it was surmised that the presence of a thermocouple at the heating surface might furnish extraneous nucleation points and thus influence the results. The second method was chosen as it left the heating surface unobstructed. The surface temperature and the resultant heat flux could then be calculated from relatively simple electrical measurements.

In order to measure the resistance change with temperature of the test wire, the wire was installed as one leg of a Wheatstone bridge as shown in Fig. 2. The change in resistance with temperature could then be determined by measuring the unbalance of the bridge and computing the temperature and the heat transfer rate by the methods shown in Appendices A and B.

The major difficulty encountered in the construction of the fixed legs of the bridge was dissipation of the heat caused by the rather large currents necessary to give an adequate heat flux in the test wire. In order that these fixed leg resistances remain constant, they were constructed of 0.0285 inch diameter manganin wire which has a temperature coefficient of practically zero (± 0.000006 / °C, Refs. 6 and 7) in the temperature range being considered. To further reduce any possible resistance changes in the fixed legs, each leg was constructed as a parallel circuit as shown in Fig. 2, with each resistance thus being required to carry only half of the leg current. In this way the surface area available for heat dissipation was increased. To dissipate the heat generated, the fixed legs were suspended in a cooling fluid. Water was rejected as a coolant as in several experimental attempts changes in conductivity were observed to influence the magnitude of the fixed leg resistance. Transformer oil was finally used as a coolant and proved very satisfactory. All connecting wires were of No. 12 copper wire.

For flexibility of operation of the bridge with test wires of different materials and different resistances, it was necessary to construct one of the control resistances of this bridge so that it could be adjusted. A manganin slide wire resistance in parallel with a manganin resistance constructed like the other permanent legs was used for this variable leg and both wires were placed in containers of transformer oil.

The current was varied by means of a one hundred ohm, fifty step, high capacity rheostat shown in Fig. 2. A ballast resistor also shown in Fig. 2 was connected in series with the rheostat. This ballast resistor operated in the nucleate boiling range in a container of distilled water.

A Leeds and Northrop "Speedomax" self balancing potentiometer was used to measure the bridge unbalance as shown in Fig. 2. Decade boxes were used to furnish a large resistance (9000Ω) and the potentiometer was used across a portion of this large resistance, measuring millivolts by the voltage divider principle.

The second measurement to be taken was that of the current in the test wire. This current was determined by means of a Weston Electric DC milliammeter, type D-55049 equipped with shunts to give ranges of five, ten, twenty and fifty amperes. The Calibration Laboratory at the California Institute of Technology calibrated the instrument.

All resistances were checked with a Rubicon portable Wheatstone bridge. A group of measurements were made over an extended period of time with the resistance being measured in the fluid in which it operated during the tests. These resistance measurements were found to change by not more than one per cent over a period of several weeks and as a result, only one value of each resistance was used in all calculations.

The bulk temperature of the test fluid was measured by a standard mercury thermometer suspended in the fluid.

The wire of platinum, tungsten or iron was clamped between the brass plates shown in Fig. 3, which were fastened to "Kovar"* rods. These rods were used in a previous experiment, although no special requirements were placed on the electrode material by the present series of tests. The brass plates gave a negligible contact resistance and did not appear to react chemically with the test fluid with one exception. Carbon tetrachloride reacted in the presence of the red hot wire and produced appreciable carbon deposits as well as another deposit presumed to be cuprous chloride. Since tests in the full film boiling regime were not necessary for the present investigation, this phenomenon was not objectionable. No burnouts were observed at the contacts at any time so the method of fastening the wire appeared to be fully satisfactory. The terminals and rods that were in contact with the test fluid were periodically cleaned with a ten per cent hydrochloric acid solution.

---

* Westinghouse trade name.

IV. TEST PROCEDURE

The test fluid was placed in a beaker and allowed to settle from the initial pouring. The test wire was cut, placed in the clamps, and then installed in the beaker. The wire was then connected to the bridge circuit as shown in Figs. 2 and 3. The power was turned on with all of the resistance of the rheostat in the circuit, thus producing a very small initial current. With this small current flowing through the bridge, the slide wire resistance was adjusted to initially balance the bridge. The rheostat resistance was then reduced by steps; at each step the magnitude of the current in the test leg was recorded from the ammeter and bridge unbalance was obtained by reading the potentiometer.

At the instant of nucleation, the potentiometer would usually move abruptly from the instantaneous value to a lower one, indicating a sudden drop in temperature. This type of temperature overshoot prior to actual boiling has been observed previously in specially treated water (Ref. 3) and in ethyl alcohol (Ref. 5). It was quite frequently obtained in the untreated fluids used in the present experiments. When the bulk temperature of the fluid was near saturation, bubble formation over the entire wire length appeared at the instant of nucleation. When the bulk temperature of the fluid was near room temperature, the rate of bubble formation did not seem as uniform over the length of the wire, at least as far as could be judged by visual observation. The ammeter reading remained essentially constant during the nucleation process in both cases.

Readings were taken as the rheostat resistance was reduced to the point where the power in the wire became sufficient to cause "burnout". At this point, the ammeter would reach a maximum and then drop, and a quite accurate reading could be obtained by careful observation. The potentiometer reading increased suddenly at this point, indicative of a rapid rise in wire temperature.

For the tungsten and the platinum wire, the so called "burnout" point did not correspond to actual fracture of the wire. The wire came to an equilibrium temperature in the full film boiling region. This temperature was sufficiently high to cause the wire to glow visibly. The iron wire, however, always broke upon reaching the "burnout" point.

In some cases, readings were actually taken in the complete film boiling region. This was done in the same manner as in the nucleate boiling range, with the voltage divider for the potentiometer set at a different ratio. The return curve follows a different route, but could be traced accurately all the way back to the original temperature.

As a part of the testing program, the temperature coefficient of resistivity (α, /°C) of the wires used was determined and the results were compared with the values given in various handbooks (Refs. 6,7). These tests were considered necessary as very small composition changes can have appreciable effects on this coefficient and it was considered undesirable to use handbook values without this experimental check. Curves of resistivity, ρ (microhm - cm), versus temperature were constructed (Fig. 4) and used for all computations of the wire surface temperature.

The change in the resistivity with temperature has to be taken into account in computing the heat flux value (q/A, Btu/in.^{2} sec.). It was therefore necessary to determine the temperature at each point, to find the corresponding resistivity and then obtain the heat flux from the equation:

$$q/A = \frac{I^2 \rho}{6610} \qquad \text{(Appendix A)}$$

The change in temperature was computed from the equation:

$$\Delta T = \Delta R / R_i \alpha \qquad \text{(Appendix B)}$$

The temperature coefficient of resistivity, α, was considered constant in the temperature regime encountered in the present series of tests.

The measurements necessary for the determination of ρ and α were taken by placing a test wire of each material in a beaker of alcohol, using the same wire holders as for the other tests. A very low current was used in the test bridge to get a reading of bridge unbalance. Then the fluid was heated to a higher temperature and the bridge unbalance was again read from the potentiometer. From the difference in bridge unbalance and from the value of the current the change of wire resistance with temperature could be computed, and consequently the temperature coefficient of resistivity of each wire material could be determined.

For tungsten, the value of α obtained was 0.00424/°C. This value agrees closely with that of $\alpha_{18°C} = 0.0045/°C$, which is listed in Ref. 6. Values of ρ for tungsten are listed in the same reference as follows:

Temperature °C	Resistivity ρ, microhm-cm.
17	5.65
117	8.06
217	10.56
317	13.23

Computing α from this data a value of $\alpha = 0.00435/°C$ was obtained. This value of α was used for computations and Fig. 4 was constructed from this data.

For platinum, the experimental value of α was 0.00348/°C. Ref. 7 lists α as 0.00354/°C and Ref. 6 gives the values of α shown below.

Temperature °C	Resistivity ρ, microhm-cm.
0	10.96
100	14.85
400	26.0

Computing α from this data gives a value of 0.00354/°C. This last value of α was used in all computations.

For iron, the experimental value of α was 0.005/°C. which agrees with that given by Ref. 6 for a temperature of 20°C. Since no consistent handbook data could be found for ρ versus temperature, the experimentally determined values of the resistance at 20°C. and of α were used to construct Fig. 4. As an initial value, the data given in Ref. 6 for $\rho_{20^\circ C} = 10 \times 10^{-6}$ microhm-cm was used, which checked closely with the experimental value.

Results of the calibration tests and a comparison with reference data are tabulated in Table II with an error estimate also shown.

Before proceeding further, it may be helpful to estimate the accuracy of the temperature and heat flux rates obtainable from the present test installation. First the resistances of the bridge had to be determined. These measurements were, as previously stated, obtained with a Rubicon portable Wheatstone bridge and the error in this measurement was considered less than one-half of one per cent.

The mercury thermometer used for temperature measurement was presumed accurate within the reading error of 0.2°C, resulting in negligible error.

Reading errors on the potentiometer were negligible and a calibration of the instrument with a standard cell showed no detectable deviations. Therefore, these errors were considered negligible compared with the other inaccuracies of the apparatus. The principal limitation on the accuracy of the ammeter was the accuracy with which the dial of the ammeter could be read. This reading error is estimated to be two parts in two hundred, or one per cent of the full scale reading.

Taking into account the foregoing experimental errors and considering the small discrepancies between the listed and the measured value of ρ, the values of ρ were considered to be accurate within two per cent. The temperature coefficients of resistivity, α, were similarly estimated to be accurate within 3 percent.

The wire dimensions were checked by micrometer and scale. Lengths were accurate to better than one per cent. The diameter of the platinum and tungsten wires was found to be 0.010 ± .0002 inches. The diameter of the iron wire ranged from 0.0091 inches to 0.0089 inches, with the average value of 0.009 inches being used in all calculations.

Summing the possible errors, it is estimated that the temperature determinations are accurate to ± 5°C. and the heat flux values to ± 7%.

V. PRESENTATION AND DISCUSSION OF DATA

The results of the experiments are presented in a series of graphs of heat transfer rates (q/A in Btu/in.^{2} sec.) versus wall temperature (T, degrees Centigrade). Two representative graphs, Figs. 5 and 6, are shown for discussion purposes. Detail graphs for each wire-fluid combination are shown in Figs. 7 through 24. From the data for the iron-methyl alcohol combination in Figs. 9 and 12, Fig. 5 was prepared. Only the center curves of Figs. 9 and 12 are reproduced. One of the curves in Fig. 5 corresponds to a fluid bulk temperature of 22°C. (room temperature) and the other to a fluid bulk temperature of 63°C., which is only 2°C. below the saturation temperature. The curves in Fig. 5 will be discussed in detail, as they are quite typical of the results obtained with other wires and fluids.

In Fig. 5, point A indicates the beginning of the run for a fluid bulk temperature of 22°C. Upon heating, the portion of the curve from A to B was first obtained, which region corresponds to heat transfer by free convection. In this region no bubble formation was observed, except possibly the occurrence of an occasional air bubble.

At point B, bubbles would form spontaneously and in great quantity over most of the wire concurrent with an abrupt temperature decrease, as indicated by a sharp drop in the potentiometer reading. Upon further heating, the steep portion, CD, of the curve typical for nucleate boiling heat transfer was obtained. The portion of the free convection curve AB which lies at a temperature above that of point C corresponds to the temperature overshoot which has been observed previously by several investigators (Refs. 3,5). The phenomenon of this overshoot has been explained (Ref. 3) by assuming that, under certain conditions, there will exist only relatively small nucleation cavities in the neighborhood of the heating surface. Relatively high temperatures will then be required to overcome the surface tension of the cavities and to initiate bubble formation. Once the generation of large bubbles has started, the heating surface has thereby been exposed to large masses of vapor, and it is believed that large nucleation cavities will have been created. These large cavities will then make further boiling possible at lower temperatures. With the present series of fluids and heating surface materials, the overshoot occurred frequently and without any special preparation of the fluid. The temperature overshoot is of interest in studying certain aspects of the problem of bubble formation. For engineering applications, however, the portion of the curve AB which corresponds to the overshoot is expected to be of only minor importance. The temperatures in the fully developed nucleate boiling region, on the other hand, were to be investigated as a part of this study. As the temperature range of the nucleate boiling region was small, it was sufficient to give a typical value representative of this range. The temperature determined by the intersection of the free convection curve with the extrapolation of the nucleate boiling curve (point C' on Fig. 5) was taken as this typical value. Point C' corresponds to the beginning of the nucleate boiling region in cases in which there is no temperature overshoot, and in the following the temperature corresponding to point C' will be called the "nucleation temperature".

As the heat transfer was increased beyond that corresponding to point C , the rate of bubble production seemed to increase steadily with correspondingly greater agitation of the fluid. As point D was approached "burnout" occurred as indicated by a sudden and drastic change in wire temperature. In the cases of platinum and tungsten, the wire glowed but would usually not melt. Readings could actually be taken in the high temperature full film boiling range. The iron wire, however, always melted at the burnout heat flux.

A similar set of data was obtained with the initial fluid bulk temperature near the saturation temperature. The results correspond to the right hand curve in Fig. 5. The type of curve obtained and the phenomena observed were the same for the experiments at the elevated bulk temperature as for those at the lower bulk temperature. The nucleate boiling region in this case was consistently at surface temperatures higher than those determined in the tests at low bulk temperatures. The burnout points were all lower than those at low bulk temperatures as was expected in view of the available experience in boiling heat transfer.

The principal questions to be investigated in the present series of experiments were the effects of wire material on the burnout point and on the temperature in the nucleate boiling region. These effects may be studied by examining the data shown in Figs. 7 through 24.

The burnout point will be considered first. The data shows that there was a variation in the burnout point for a given fluid and bulk temperature for successive tests with the same wire material. These variations were generally within 5 - 10%. This variation was probably due in part to experimental error, and in part possibly to slight differences in the surface conditions and composition of the wires. The differences in the burnout points obtained with the three wire materials respectively, were of the same order as the scatter of the results obtained from several tests with a single material. From the results of the present series of tests, therefore, no definite effect of the wire material on the burnout point was detected. The average values of the burnout point for methyl alcohol were:

Fluid Bulk Temperature	Average $(q/A)_{max}$ Btu/in^2 sec			Average q/A for all wires	Greatest Deviation from Average %
	Platinum	Tungsten	Iron		
22°C	1.210	1.453	1.295	1.319	10.17
63°C	0.519	0.542	0.551	0.537	3.35

The corresponding data for octane was:

Fluid Bulk Temperature	Average $(q/A)_{max}$ Btu/in^2 sec			Average q/A for all wires	Greatest Deviation from Average %
	Platinum	Tungsten	Iron		
22°C	0.580	0.653	0.567	0.6	8.83
74°C	0.460	0.483	0.434	0.459	5.45

The data for carbon tetrachloride was:

Fluid Bulk Temperature	Average $(q/A)_{max}$ Btu/in^2 sec			Average q/A for all wires	Greatest Deviation from Average %
	Platinum	Tungsten	Iron		
22°C	0.557	0.650	0.753	0.654	15.75
73°C	0.282	0.276	0.267	0.275	2.91

The second question to be studied was that concerning the temperature in the nucleate boiling region. The temperature at the beginning of this region (point C') will be taken as the significant temperature as was mentioned before. Again the differences in the experimental values for successive tests with the same wire materialwere of the same order as the differences obtained with different wire materials. For the combinations of wires and fluids tested no dependence of the nucleation temperature on the wire material could be determined.

The actual data obtained is shown below.

Nucleation Temperatures, °C

Wire	Platinum		Tungsten		Iron		Boiling Point °C
Fluid Temp.	Room	Sat	Room	Sat	Room	Sat	
Alcohol	95	110	93	118	75	87	64
Octane	96	130	120	125	88	122	98
Carbon Tetrachloride	85	90	80	91	80	97	76

In all cases the nucleation temperature was closely related to the boiling point. The widest variation was observed for a platinum wire in octane at a bulk temperature of 76°C., in which the nucleate boiling region was at a temperature 32°C. above the normal boiling point of 98°C.

It can be seen that in most cases the temperature of the nucleation region was higher when the bulk temperature of the fluid was near saturation than when the bulk temperature was low. The reason for this behavior can not be fully explained from available data. It is possible that these differences are attributable to the difference in air content of the fluid at the two temperatures. In each case, the liquid was probably saturated with air, and therefore contained more air at the low bulk temperature than at the high one. The fluid which would flow from the main body of the liquid into the neighborhood of the wire would thus have had to give off more gas when the bulk temperature was low. Gas bubble formation must therefore be expected to occur more readily in the former case than in the latter.

In the case of octane, the nucleation region for one series of runs at low bulk temperature was at a temperature which is actually below the normal saturation point. This could possibly also be explained on the basis of gas bubble formation as was discussed above.

In a few cases, measurements were extended into the full film boiling region and the data thus obtained is presented in Fig. 6. Path ABCD was followed as previously described with the test wire becoming incandescent between points D and E. With the same rheostat setting, equilibrium was reached at point E, with full film boiling being quickly established. As described in the introduction, a fairly stable vapor film was assumed to form at the wire surface; however, large quantities of vapor detached from this layer and rose to the surface. This boiling effect was continuous over the length of the wire and resulted in great agitation of the fluid.

By increasing the current, the portion of the curve from E to F was obtained. As the current was increased the wire became visibly hotter and greater agitation of the fluid took place. Reducing the current resulted in the portion of the curve from F to G.

Near point G, agitation of the fluid and the rate of bubble production decreased greatly. When point G was reached, nucleate rather than film boiling appeared to be fairly well established and the path to H was followed without any changes in current being made. From H, the path followed the increasing flux curve very closely, bypassing the temperature overshoot.

Data were not taken in the full film boiling regime for all wire fluid combinations as only the nucleate boiling range and the burnout point were of primary interest for this study.

VI. CONCLUSIONS

It was the purpose of the present series of tests to determine the effect of the material of the heating surface on the burnout point and on nucleation temperature for nucleate boiling heat transfer. The heating surface materials used were platinum, tungsten, and iron wires and the test fluids were methyl alcohol, carbon tetrachloride, and iso-octane. The experiments carried out were described in section IV and the results were presented in section V.

The results show that the burnout point as well as the nucleation point for each combination of fluid and wire material are subject to a certain scatter. For the burnout the range of this scatter was approximately five to ten per cent of the average value. This scatter is explainable in part by errors inherent in the use of the test equipment. In part, however, it is believed to be due to slight variations in the surface condition of the wire, in the composition of the wire, and possibly to small changes in the impurity and dissolved air content of the various fluid samples. Variations in burnout heat flux obtained with different wires in the same fluid were of the same order as the variations obtained in successive runs with the same wire material. Within the accuracy of the tests, the burnout point may be said to be independent of the wire material.

As a second item, the temperature in the nucleate boiling region was to be investigated. As the temperature change throughout this region is small, it was sufficient to give a single characteristic value for the whole range. The nucleation temperature (illustrated by point C' in Fig. 5) was selected as this characteristic value. The nucleation temperature for a given wire-liquid combination at fixed bulk temperature, was again subject to rather wide variations (± $10^oC.$). Again this was attributed in part to slight variations in the characteristics of the wire and the fluid. The differences in nucleation temperature for different wire materials were not significantly wider than the differences in nucleation temperature obtained from several tests with the same wire material. The results, therefore, do not show any effect of the wire material on the nucleation point.

The largest deviation of the nucleation temperature from the normal boiling point was observed for a platinum wire in iso-octane at a bulk temperature of 76^oC. In that case the nucleation temperature exceeded the normal boiling point by 32^oC. Such temperature differences may be of importance in some heat transfer equipment. In many applications however, particularly in the design of cooling systems, the assumption that nucleate boiling takes place approximately at the normal saturation temperature may be adequate.

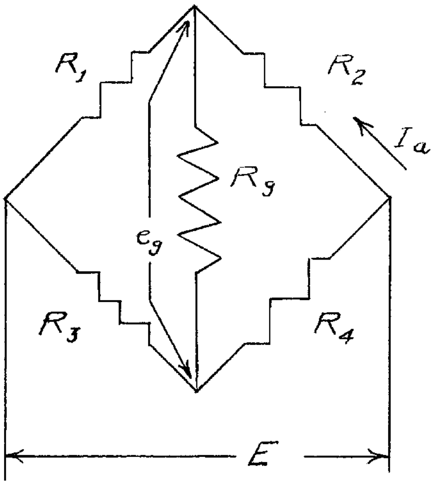
It was further observed that for each wire-fluid combination the nucleation temperature increased with the bulk temperature. No complete explanation for this behavior was found, but it was believed that this effect could be caused by changes in the air content of the liquid. (See section V.)

On the basis of the available results it may be concluded that the wire material has no major effect on either the magnitude of the burnout flux or on the temperature in the nucleate boiling region. This conclusion is of course limited to the surface materials and the fluids used in the present series of tests as well as to the range of experimental conditions investigated. Further tests will have to be conducted before it will be possible to make a more general statement on the effect of surface material on boiling heat transfer.

APPENDIX A

Computation of Temperature Difference

Ref. 2 shows a derivation for the change in resistance in one leg (ΔR) causing unbalance of a Wheatstone bridge.



In the diagram above, R_2 is the leg with the changing resistance and I_a is the current in this leg. The bridge unbalance is the potential difference across R_g, the voltage e_g. The change in resistance, provided the resistance R_g is large compared to the others (9000 Ω to 0.2 Ω in this case) is:

$$\Delta R = \frac{2 e_g}{I_a} \left\{ 1 - \frac{e_g [R_3 (R_1 + R_2^\circ) + (R_3 + R_4)(R_4 + R_2^\circ)]}{I_a D^\circ} \right\}$$

In this equation D° is the determinant of coefficients from the basic matrix of current and potential equations.

$$D^\circ = R_1 R_2^\circ R_3 + R_2^\circ R_3 R_4 + R_3 R_4 R_1 + R_4 R_1 R_2^\circ$$

The change in temperature of the heating wire from that at balance is given by the equation:

$$\Delta T = \Delta R / R_1 \alpha$$

where $R_i = \rho_i L/A$ the initial resistance of the wire

L = wire length

A = wire cross sectional area

α = temperature coefficient of resistivity of the wire material over the temperature range ΔT

The bridge was constructed with the following values of the various resistances.

$R_1 = R_2^0$

R_2^0 Platinum $= 0.106$ ohm

Tungsten $= 0.064$ ohm

Iron $= 0.131$ ohm

$R_3 = 0.244$ ohm

$R_4 = 0.242$ ohm

The values for ΔR were computed from the equations:

Platinum $$\Delta R = \frac{2e_g}{I_a}\left(1 - 12.3\,\frac{e_g}{I_a}\right)$$

Tungsten $$\Delta R = \frac{2e_g}{I_a}\left(1 - 18.84\,\frac{e_g}{I_a}\right)$$

Iron $$\Delta R = \frac{2e_g}{I_a}\left(1 - 10.3\,\frac{e_g}{I_a}\right)$$

APPENDIX B

Computation of Heat Flux

Heat energy dissipated by the wire may be equated to electrical energy absorbed.

$$q/A\ (\text{Btu/in}^2\ \text{sec})\ S\ (\text{in}^2) = I^2R\ (\text{watts}) \times \frac{550\ \text{ft lbs/sec HP}}{778\ \text{ft lbs/Btu}\ 746\ \text{watts/HP}}$$

Substitute for S in terms of L, length in inches, d, diameter in inches. Substitute for R the expression ρ L/A with ρ in microhm-cm. and A in square inches

$$q/A = \frac{I^2\rho L}{d^2/4} \times \frac{550}{778 \times 746} \times \frac{1}{\pi dL} \times \frac{1}{2.54} \times 10^{-6}$$

$$q/A = I^2\rho\ /\ 6.61 \times 10^9 \times d^3$$

For the platinum and tungsten wires, d = 0.010 inches

$$q/A = I^2\rho\ /\ 6610 \qquad (\text{Btu/in}^2\text{sec})$$

For the iron wire, d = 0.009 inches

$$q/A = I^2\rho\ /\ 4815 \qquad (\text{Btu/in}^2\text{sec})$$

After computation of the temperature by the method shown in Appendix A, the value of ρ at this temperature may be found on Fig. 4. Then q/A can be computed for the point.

APPENDIX C

Sample Computation

Wire : Platinum

Fluid : Methyl Alcohol

Fluid Bulk Temperature 24°C

Voltage Divider Ratio 50

Ammeter Ratio 20

Bridge Zero at 0.05 MV

Readings : Ammeter; I = 170

Potentiometer; MV= 0.76

Ammeter reading times ammeter ratio $\frac{20 \text{ X } 170}{1000}$ = 3.4 amps

Correct MV reading by subtracting initial setting of potentiometer 0.76 - 0.05 = 0.71 MV

Multiply corrected MV by voltage divider ratio and convert to volts $\frac{0.71}{1000}$ X 50 = 0.0355 v

$$\Delta T = \frac{\Delta R}{R_i \alpha} = \frac{2 e_g}{I_a R_i \alpha}\left(1 - 12.3 \frac{e_g}{I_a}\right) = \frac{2 \times 0.0355}{3.4 \times 0.106 \times 0.00354}\left(1 - 12.3 \frac{0.0355}{3.4}\right)$$

T = 49.1 °C

$T = \Delta T + T_i = 49.1 + 24.0 = 73.1$ °C

Read ρ from Fig. 4 for each temperature: ρ = 13.8 microhm-cm

Compute q/A

$$q/A = \frac{I^2 \rho}{6610} = \frac{(3.4)^2 \times 13.8}{6610}$$

$$= 0.0242 \text{ Btu/in}^2 \text{ sec}$$

REFERENCES

1. Ellion, M.E., "A Study of the Mechanism of Boiling Heat Transfer", Thesis, Calif. Inst. of Tech., 1953.
2. Farber, E.A. and Scorah, R.L., "Heat Transfer to Water Boiling Under Pressure", Trans. ASME, Vol. 70 1948.
3. Gates, C.W., "Some Experiments in Nucleate Boiling Heat Transfer", Thesis, Calif. Inst. of Tech., 1954.
4. Sabersky, R.H., Div. of Engr., Calif. Inst. of Tech., private communication.
5. Van Camp, W.M., St. Clair, C.R., "Boiling from Wires with Emphasis on Transition Phenomena", ASME Paper No. 54-F-33.
6. Hodgman, C.D., et al, Handbook of Chemistry and Physics, 31st Edition, Chemical Rubber Publishing Co., Cleveland, Ohio, 1949.
7. Metals Handbook, American Society for Metals, Cleveland, Ohio, 1948.
8. Washburn, E.W., et al, International Critical Tables, First Edition, McGraw - Hill Book Co., Inc. 1928.

TABLE I

Properties of Test Fluids

Fluid	Synonyms	Chemical Formula	Mol. Wgt.	Density g/ml	Boiling pt °C
Methyl Alcohol	Methanol	CH_3OH	32.04	0.79609	64.65
Iso-octane	2,2,4-tri-methyl-pentane	$(CH_3)_2\ CCH_2-CH(CH_3)_2$	114.23	0.6918	99.3
Carbon Tetra-chloride	Tetra-chloro-methane	$CC\ell_4$	153.84	1.595	76.0

Fluid	Thermal Conductivity cal/sec cm °C	Electrical Conductivity $ohm^{-1}\ cm^{-1}$	Viscosity cp.	Surface Tension dynes/cm
Methyl Alcohol	0.000498	58×10^{-7} (20°C)	0.597 (20°C)	22.6 (20°C)
Iso-octane	0.000375 (n-octane)	$< 1 \times 10^{-13}$	0.542 (20°C) (n-octane)	21.8 (20°C) (n-octane)
Carbon Tetra-chloride	0.000263	4×10^{-18}	0.969 (20°C)	26.8 (20°C)

Sources: Refs. 6, 8.

TABLE II

Comparison of Handbook and Experimental Values of Temperature Coefficient of Resistivity, α (/°C)

Material	α , /°C			
	From Slope of ρ vs. T curve	Average Experimental values	Handbook (Ref.)	Deviation Between Exp. values and (Ref.)
Platinum	0.00354	0.00348	0.0036 (Ref. 5)	3.4 %
Tungsten	0.00435	0.00424	0.0045 (Ref. 4)	6.1 %
Iron	0.005	0.005	0.005 (Ref. 4)	0 %

FIGURE 1

TYPICAL BOILING HEAT TRANSFER CURVE

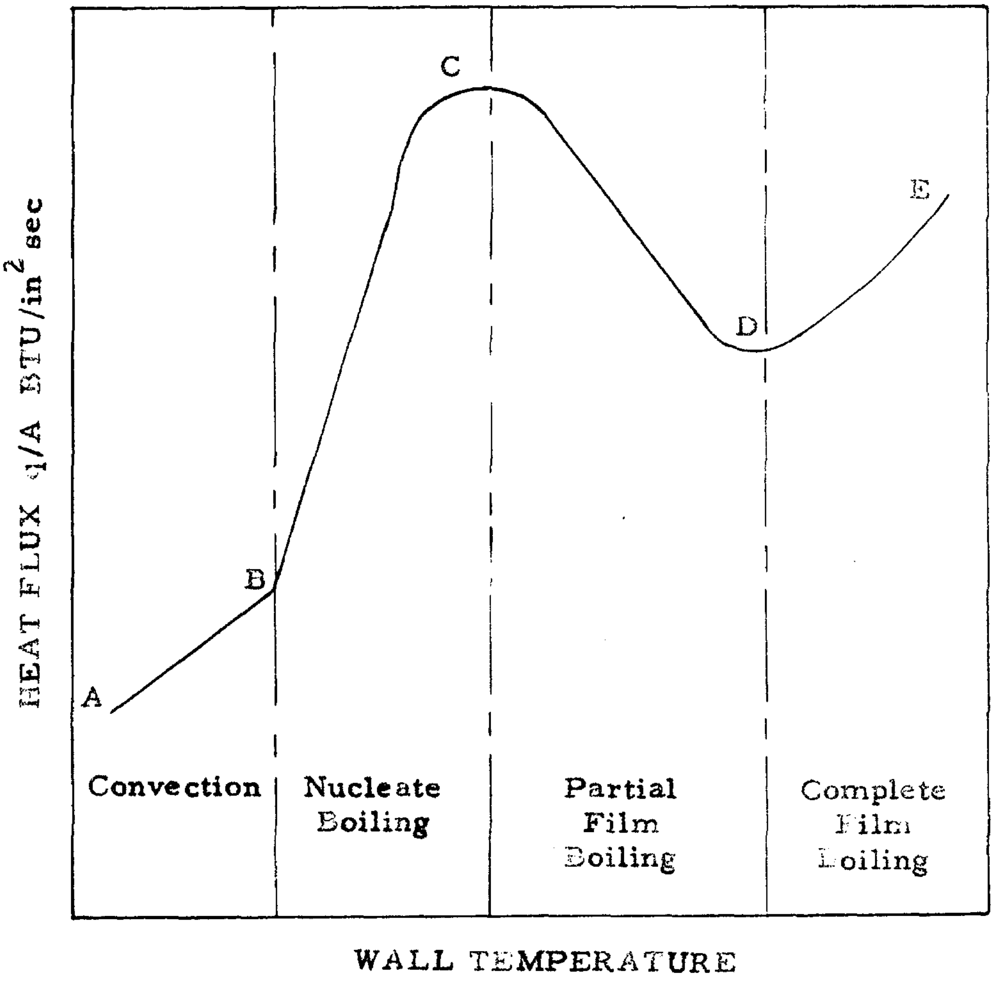


FIGURE 2

TEST BRIDGE

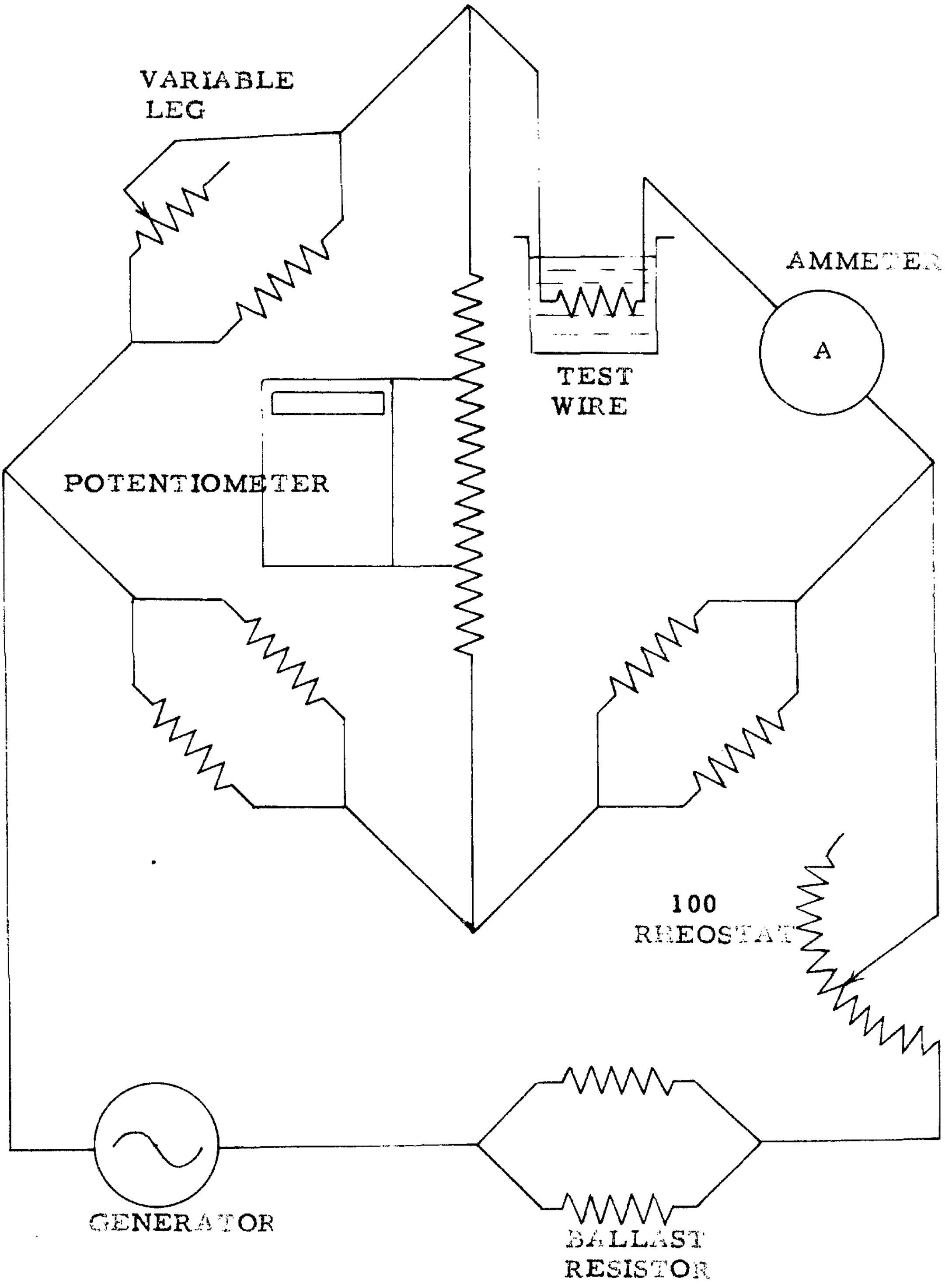


FIGURE 3

TEST WIRE HOLDER

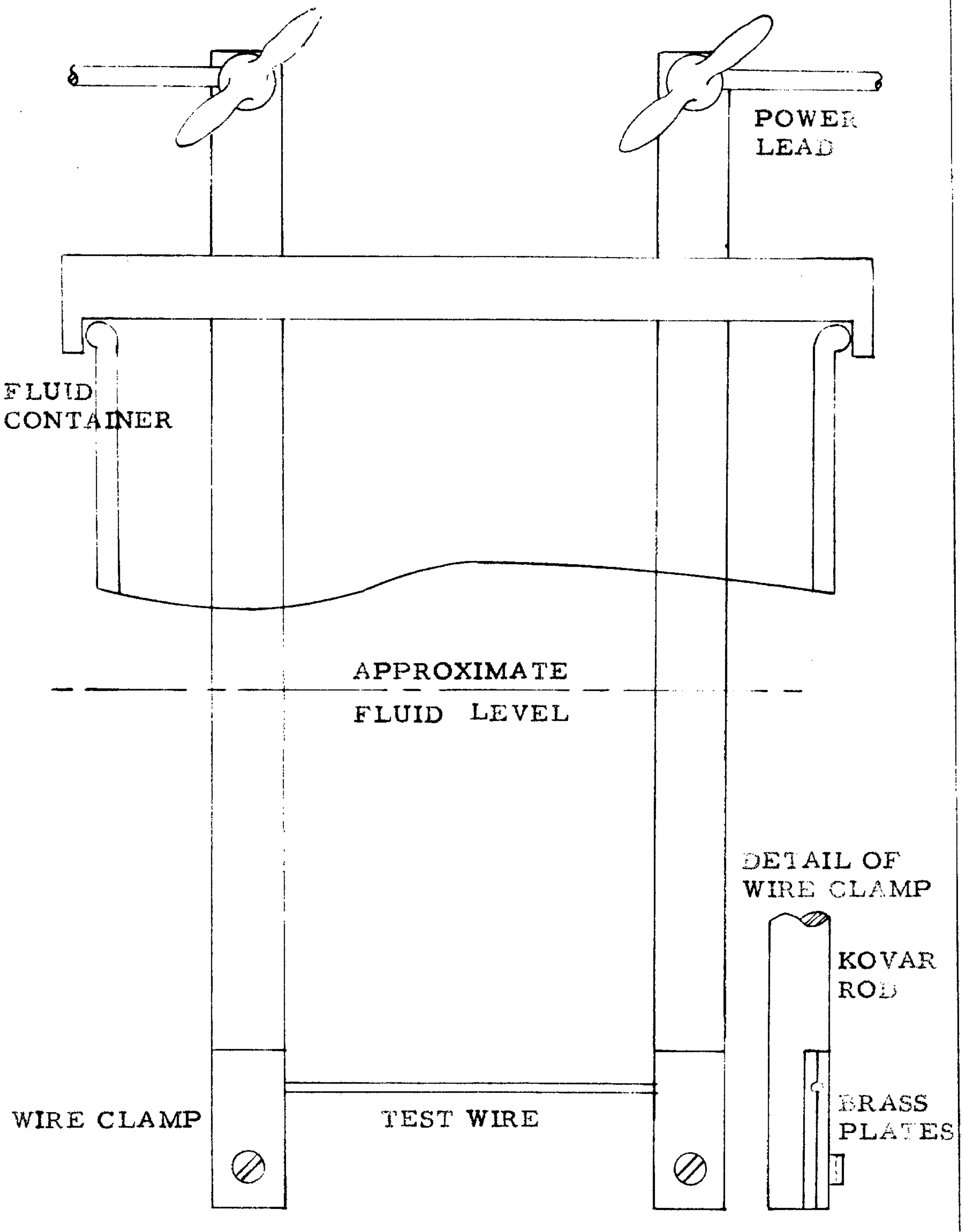


FIGURE 4

RESISTIVITY vs. TEMPERATURE

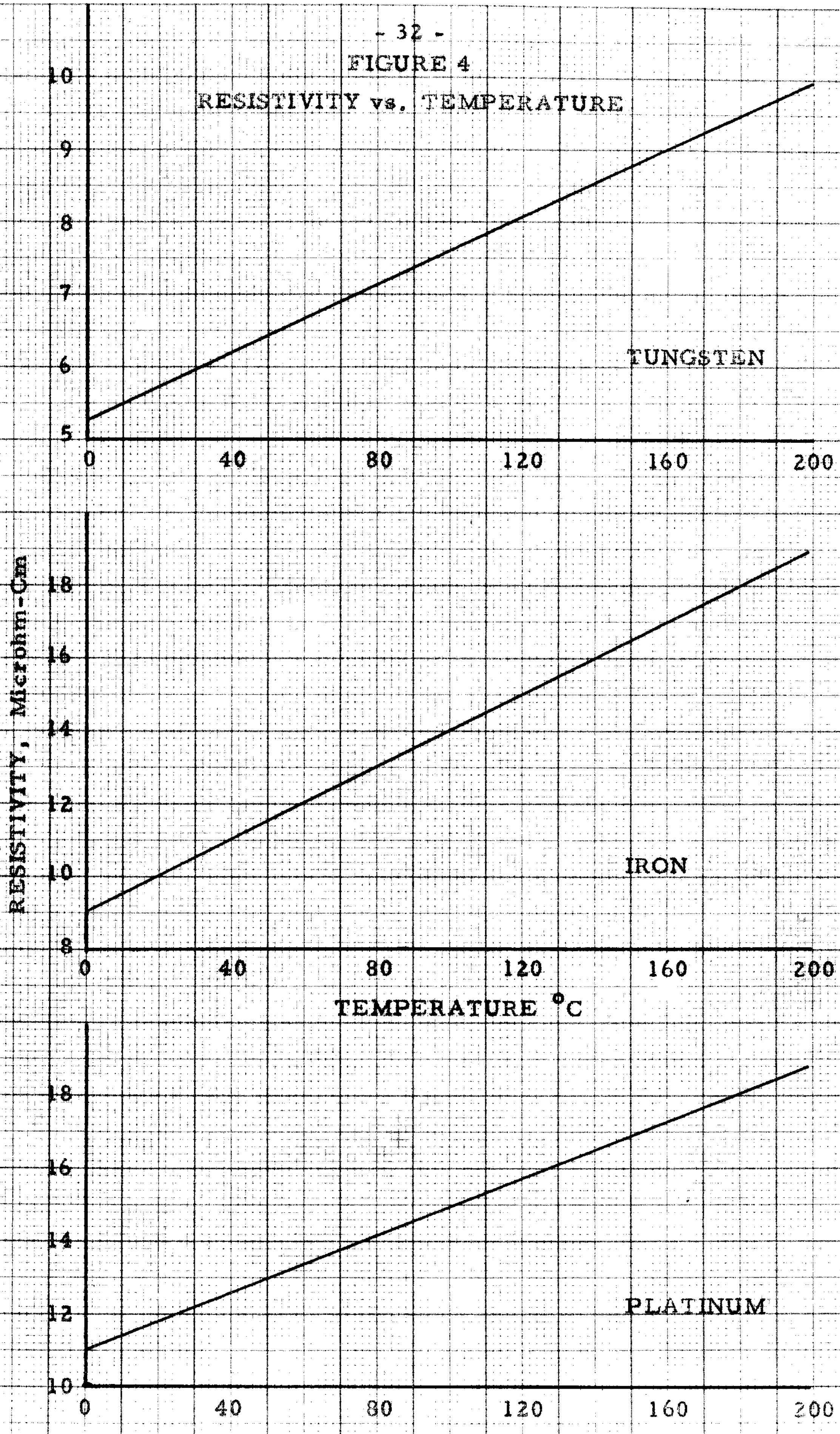


FIGURE 5

HEAT FLUX vs. WALL TEMPERATURE
Wire: Iron
Fluid: Methyl Alcohol
Bulk Temp.: $22^{\circ}C$ and $62^{\circ}C$

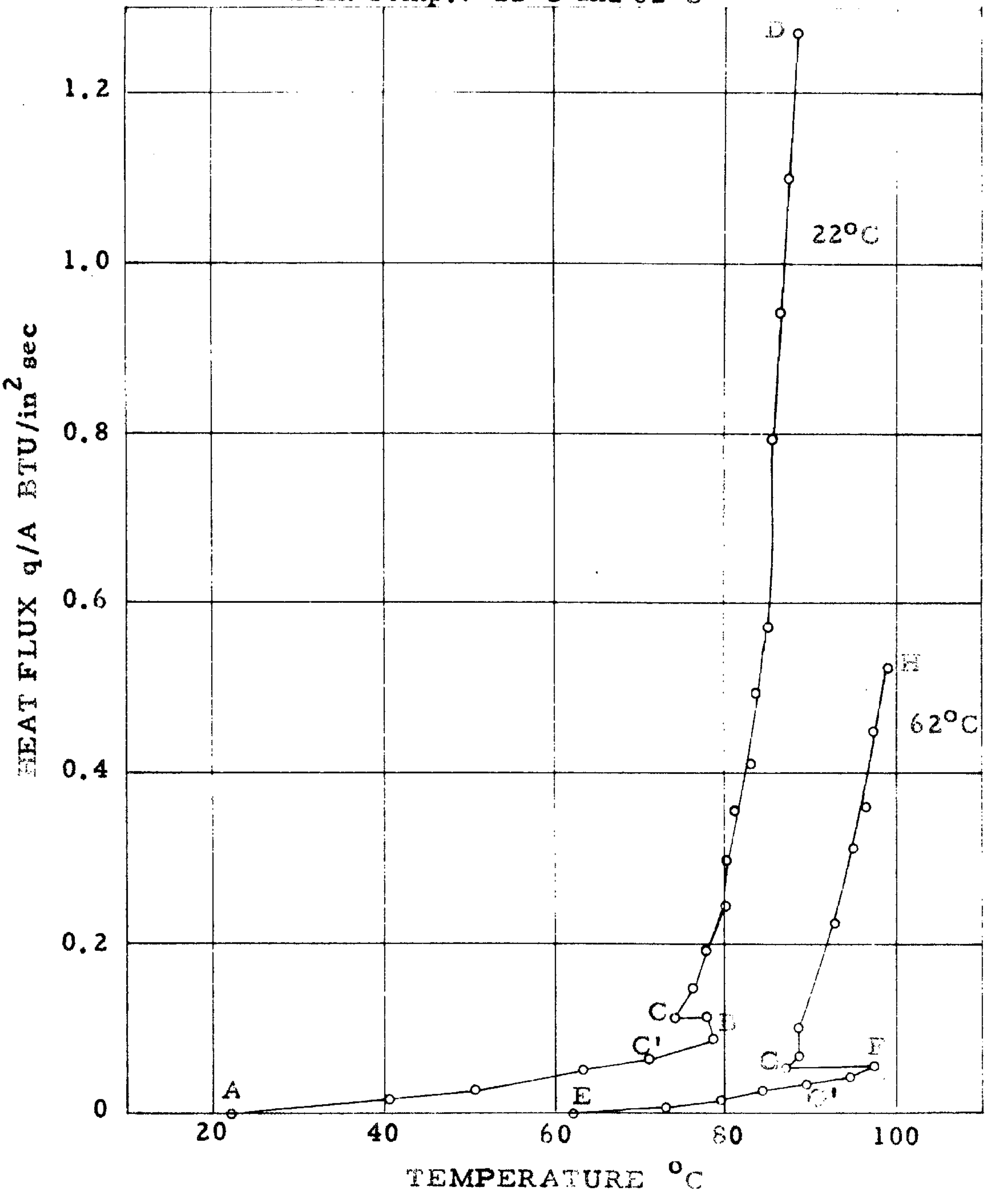


FIGURE 6

HEAT FLUX vs. WALL TEMPERATURE

Wire: Platinum
Fluid: Carbon Tetrachloride
Bulk Temperature: 22°C

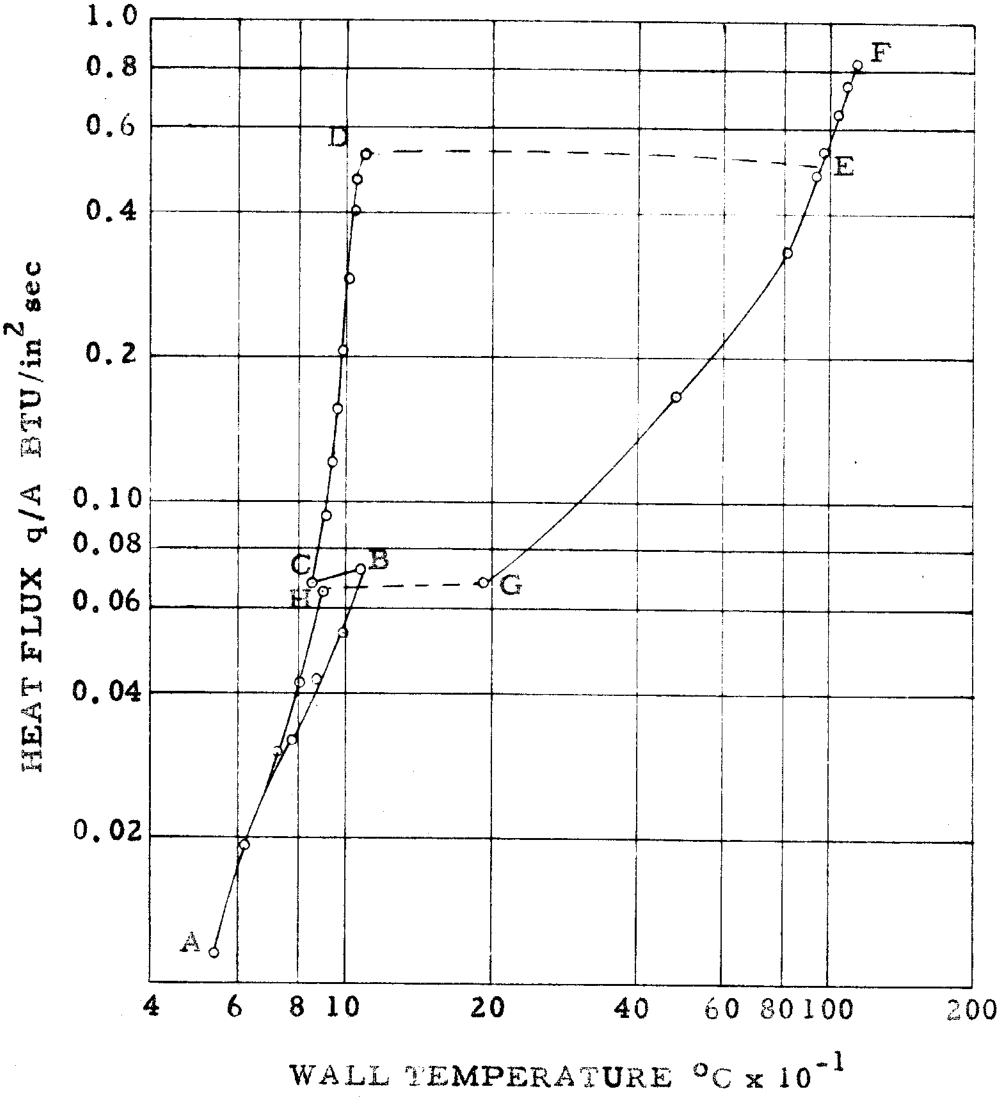


FIGURE 7

HEAT FLUX vs. WALL TEMPERATURE

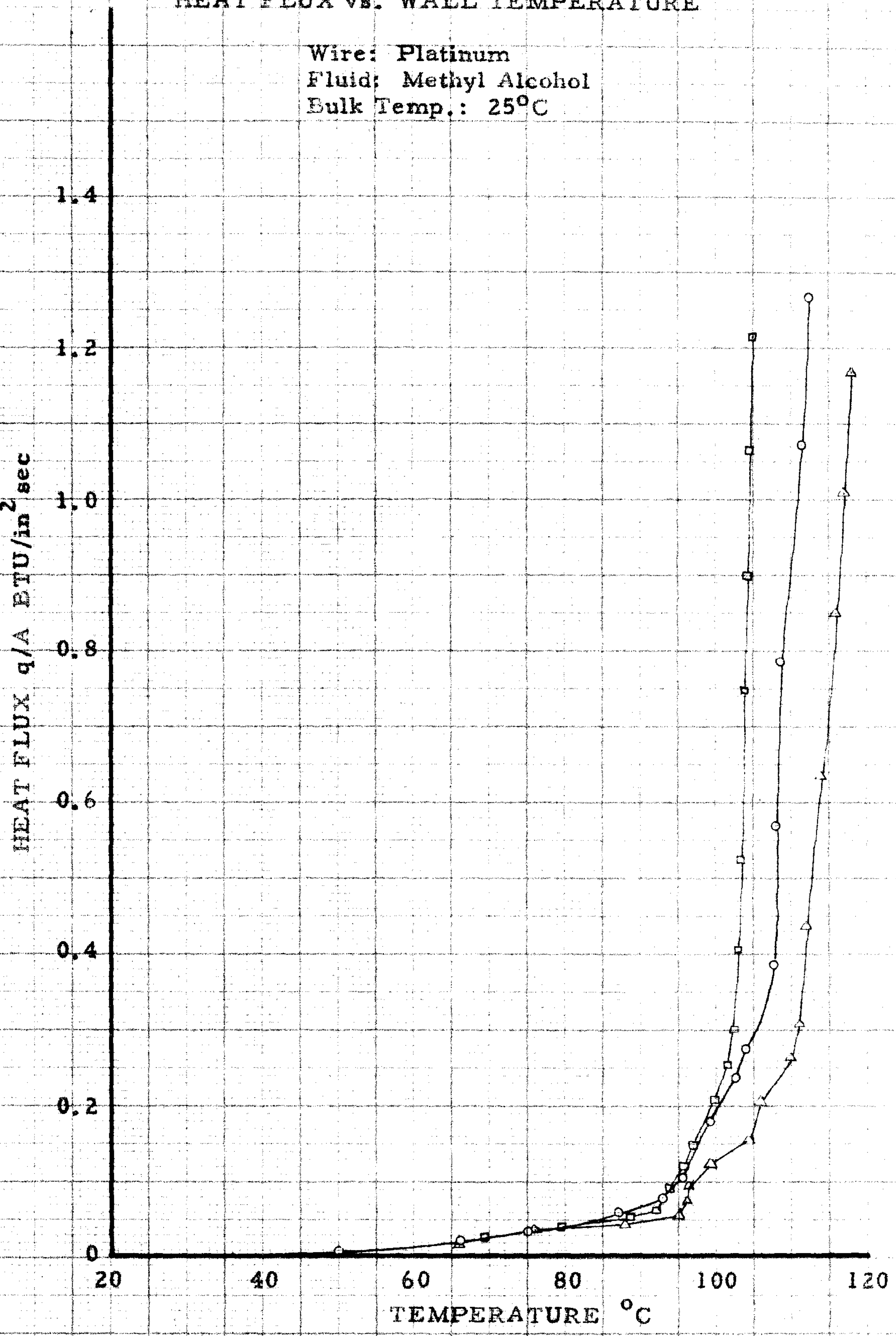


FIGURE 8

HEAT FLUX vs. WALL TEMPERATURE

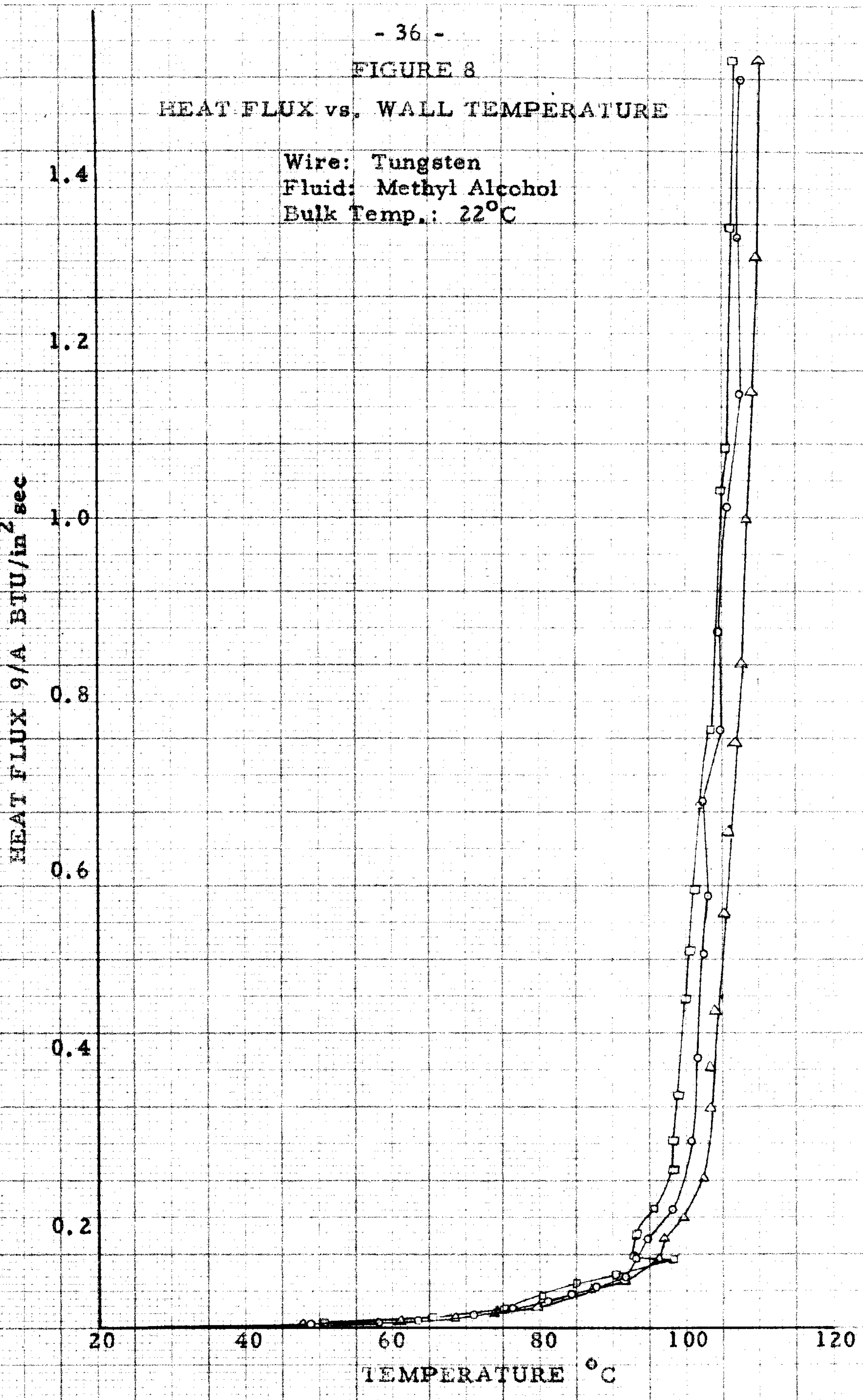


FIGURE 9

HEAT FLUX vs. WALL TEMPERATURE

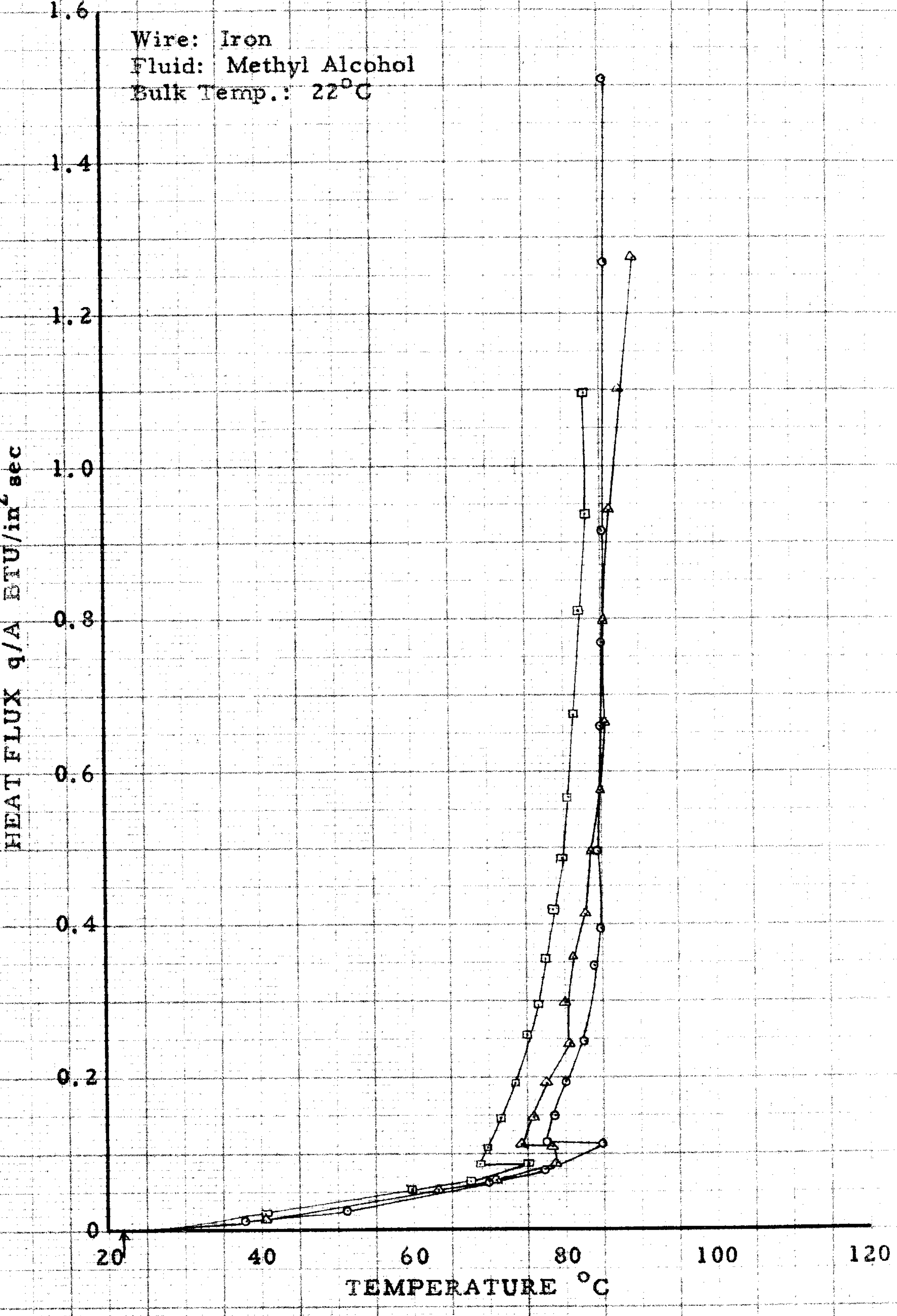


FIGURE 10

HEAT FLUX vs. WALL TEMPERATURE

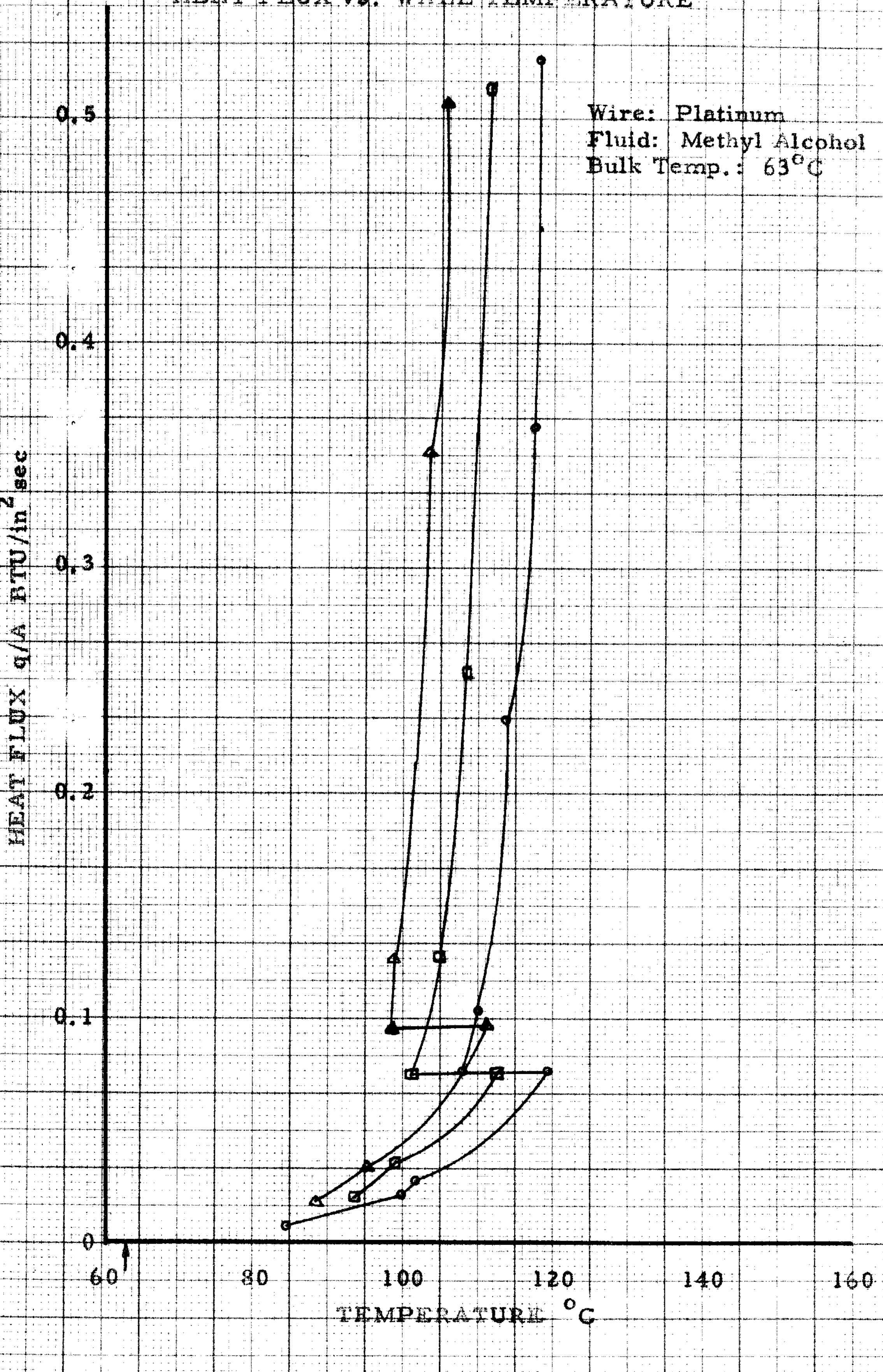


FIGURE 11

HEAT FLUX vs. WALL TEMPERATURE

Wire: Tungsten
Fluid: Methyl Alcohol
Bulk Temp.: 63°C

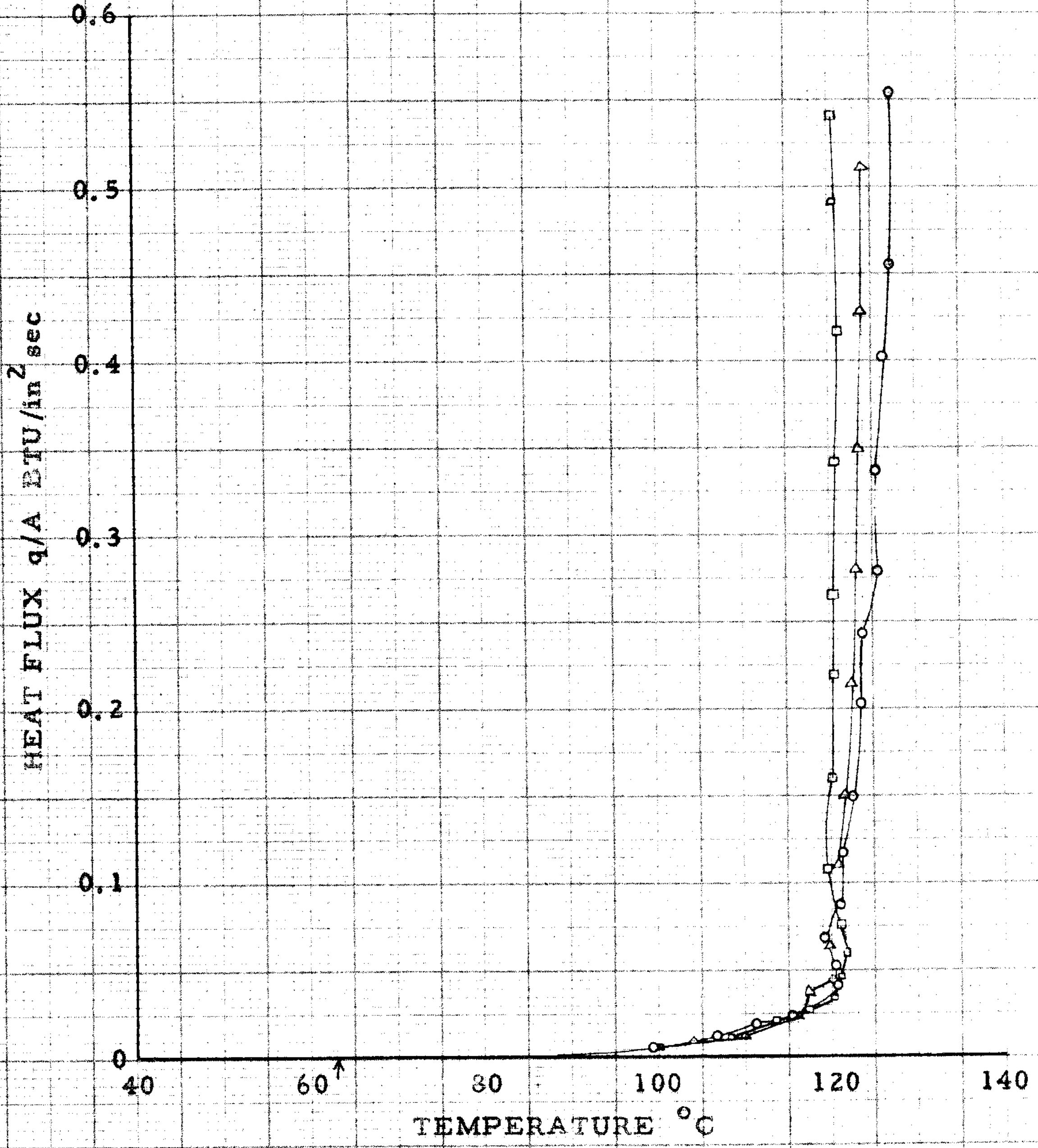


FIGURE 12

HEAT FLUX vs. WALL TEMPERATURE

Wire: Iron
Fluid: Methyl Alcohol
Bulk Temp.: 62°C

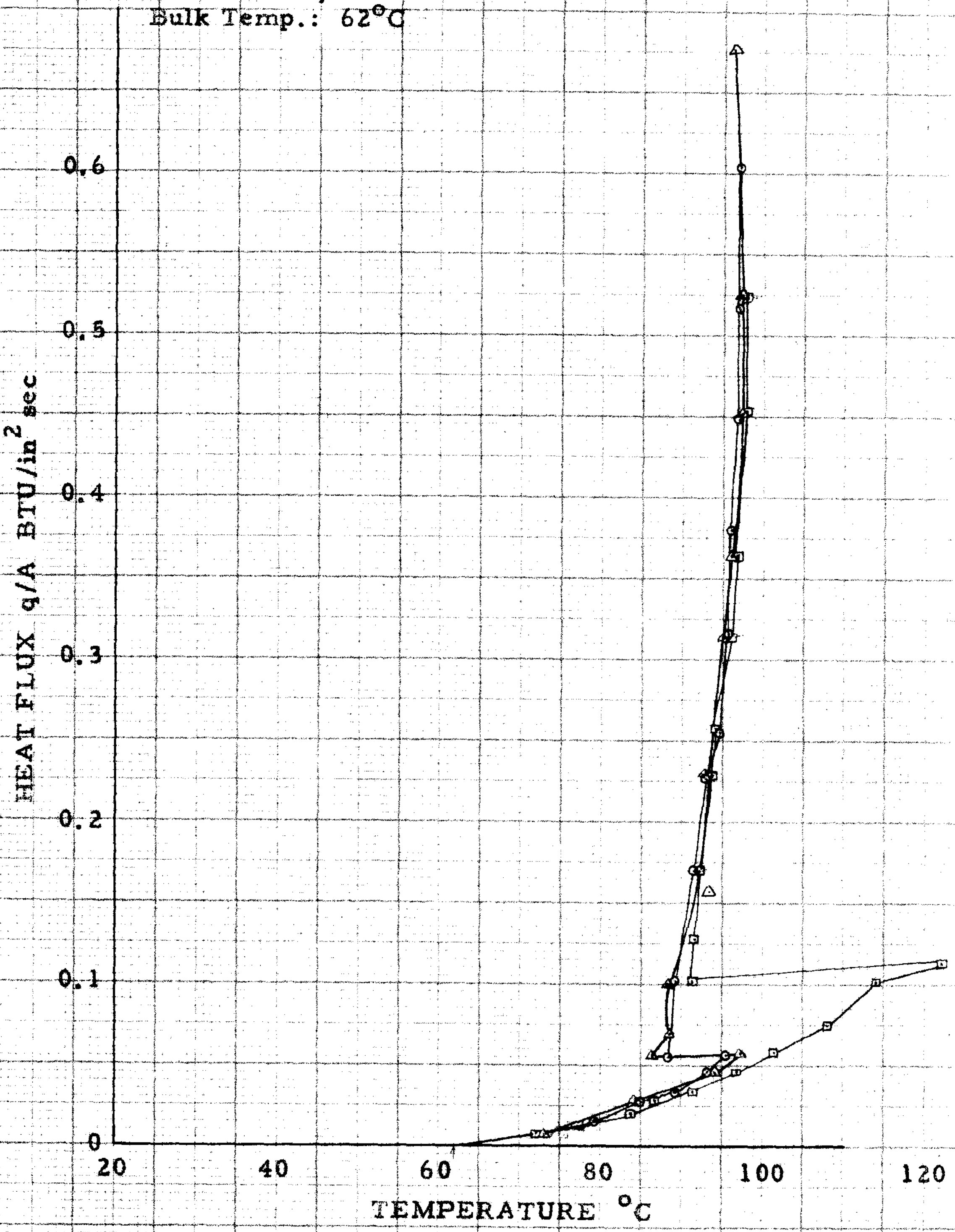


FIGURE 13

HEAT FLUX vs. WALL TEMPERATURE

Wire: Platinum
Fluid: Octane
Bulk Temp.: 25°C

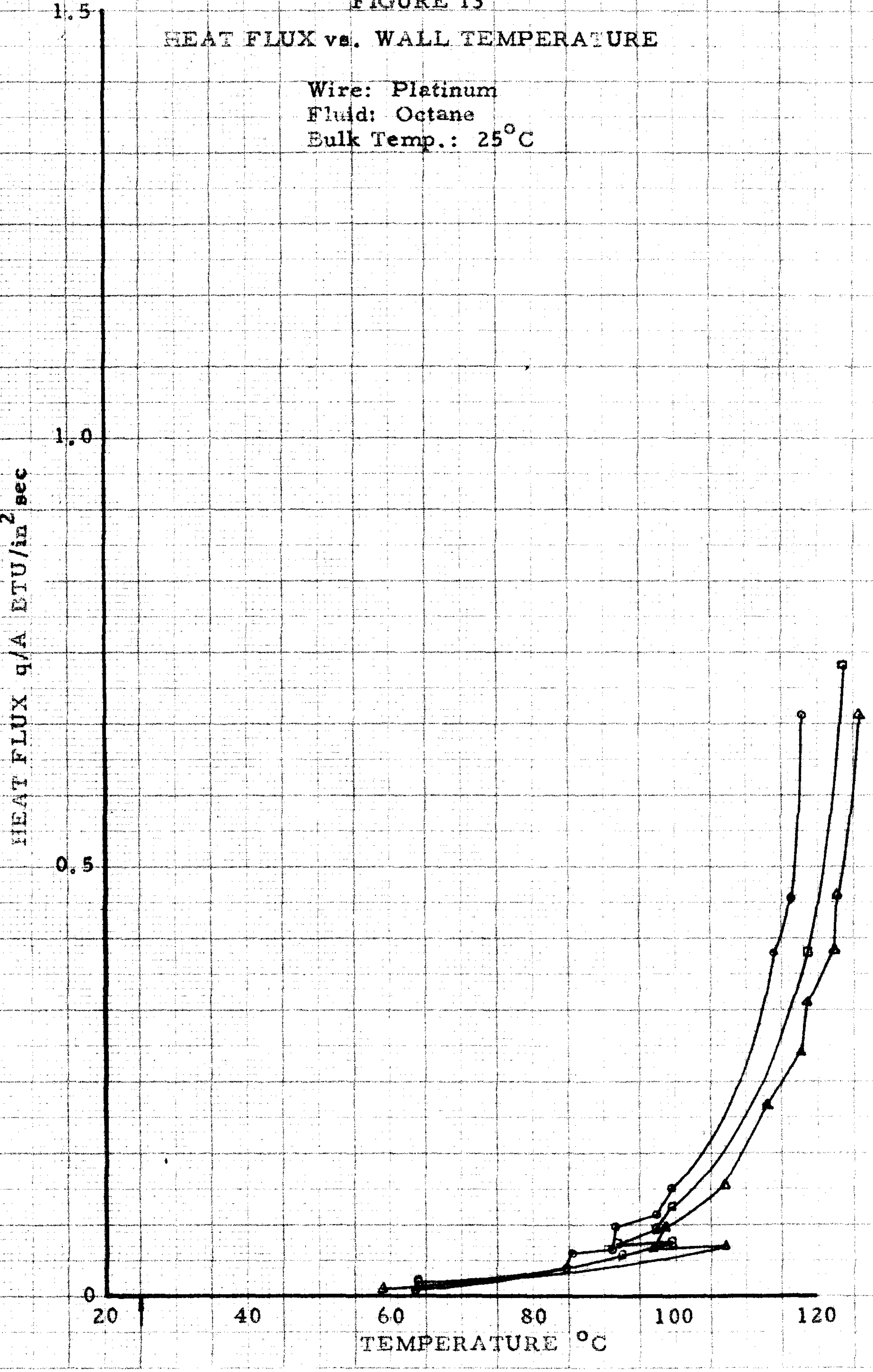


FIGURE 14

HEAT FLUX vs. WALL TEMPERATURE

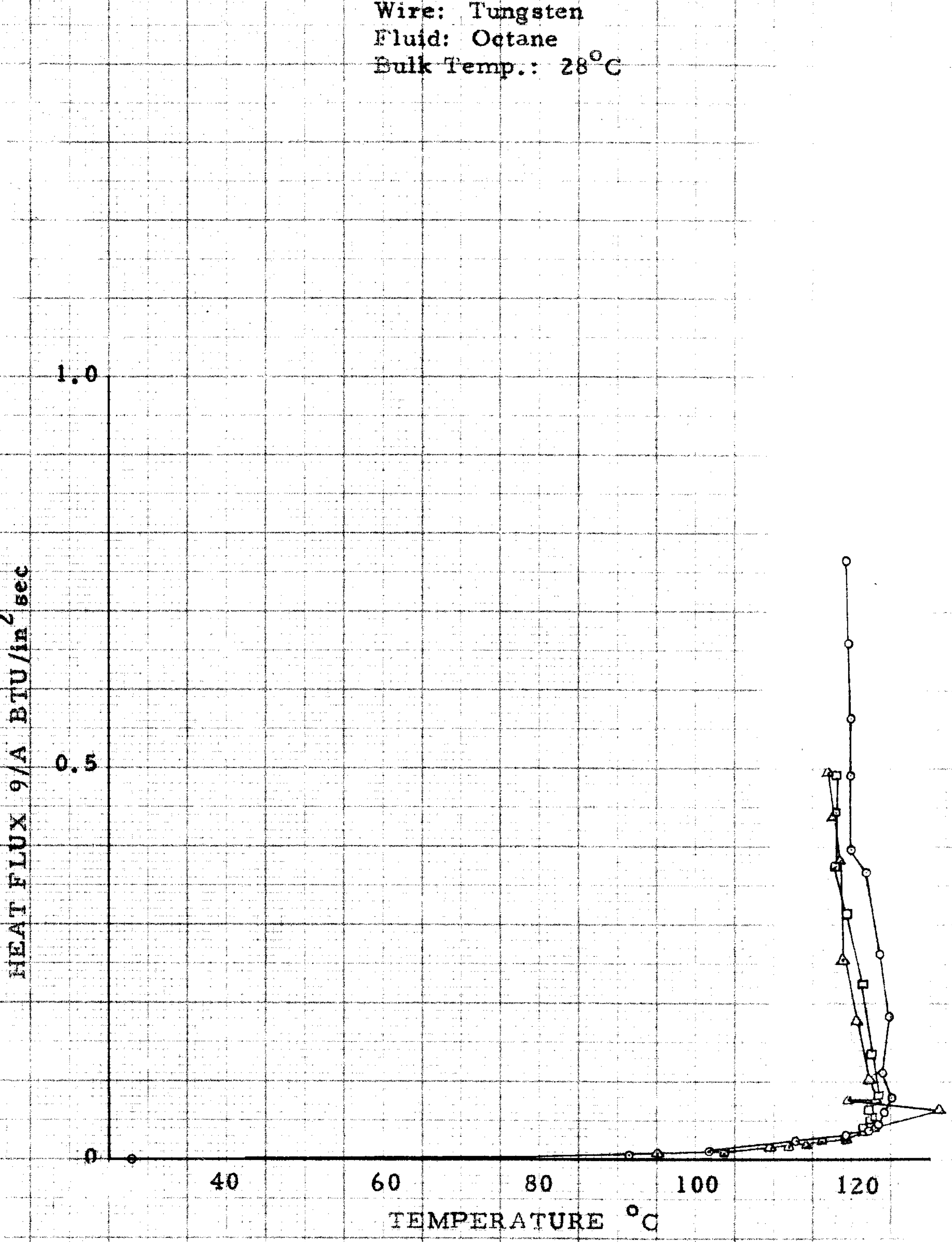


FIGURE 15

HEAT FLUX vs. WALL TEMPERATURE

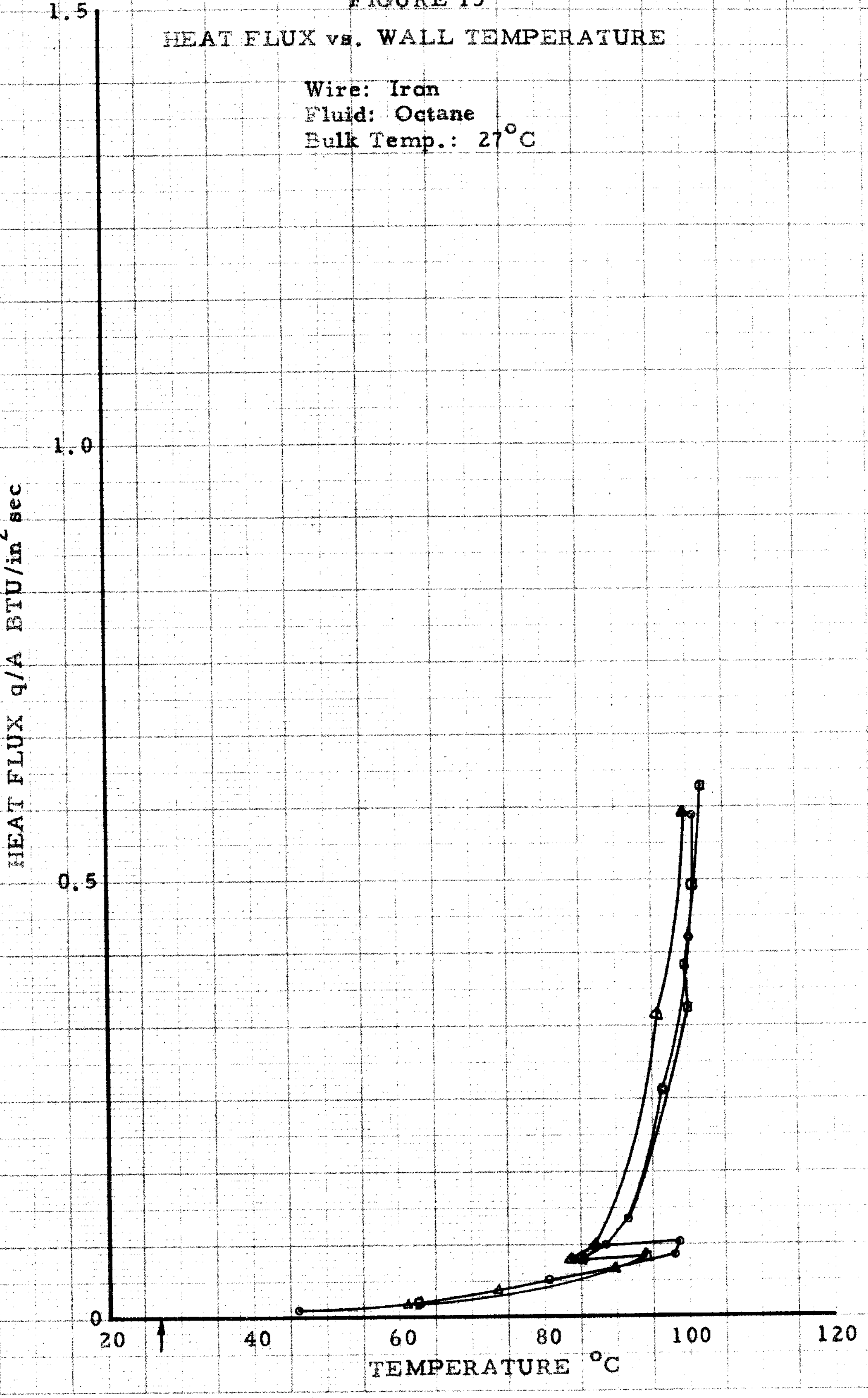


FIGURE 16

HEAT FLUX vs. WALL TEMPERATURE

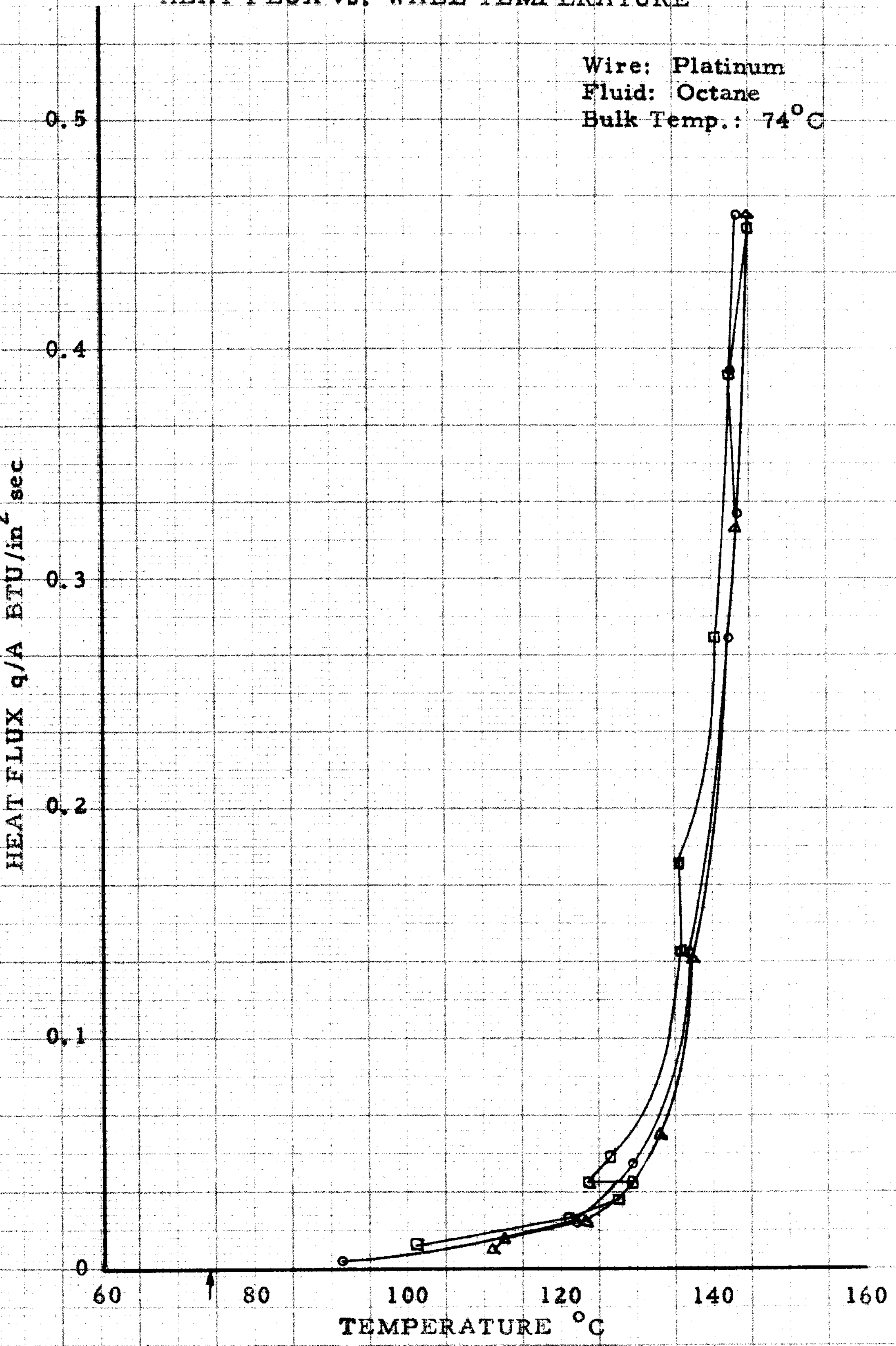


FIGURE 17

HEAT FLUX vs. WALL TEMPERATURE

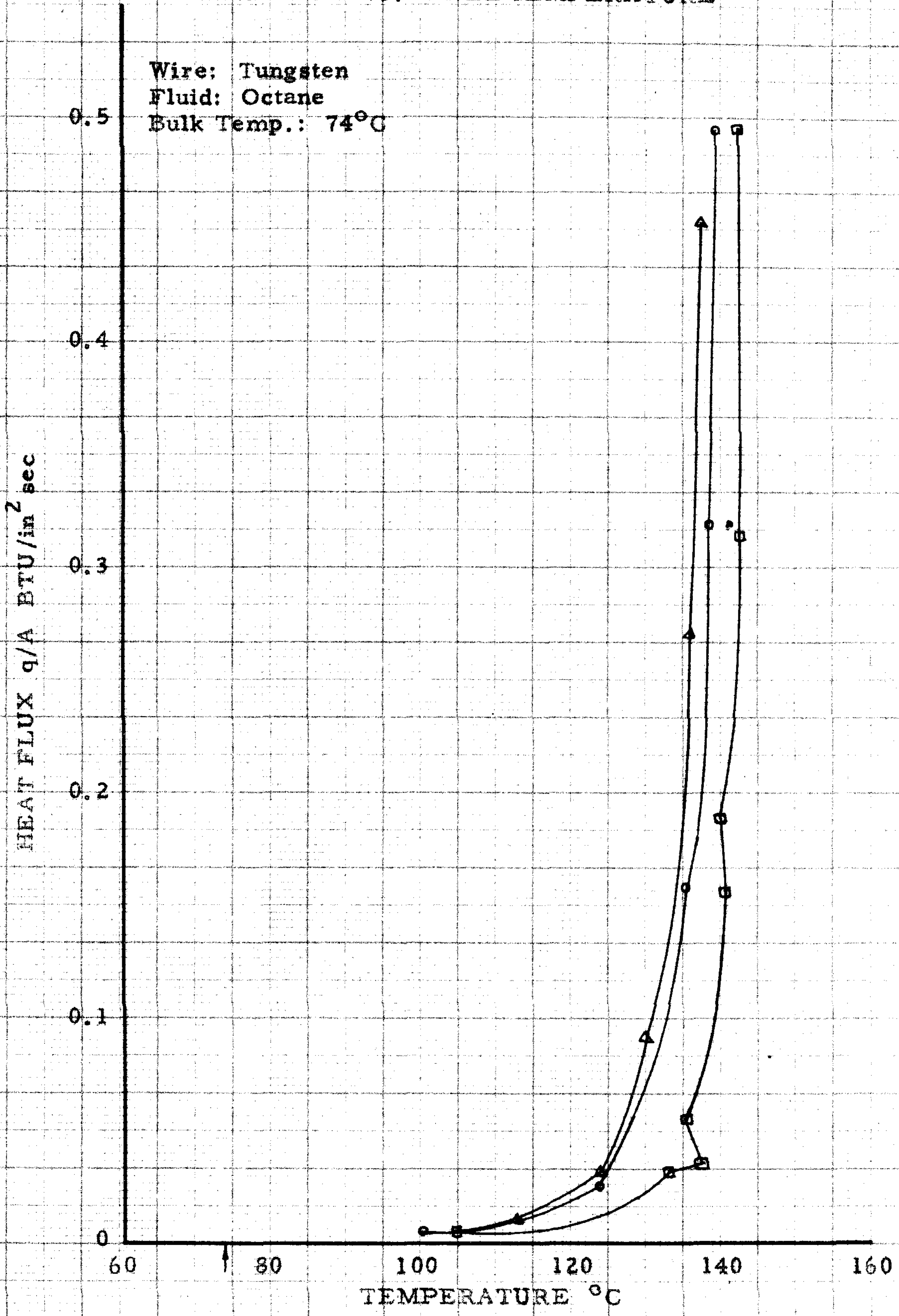


FIGURE 18

HEAT FLUX vs. WALL TEMPERATURE

Wire: Iron
Fluid: Octane
Bulk Temp.: 74°C

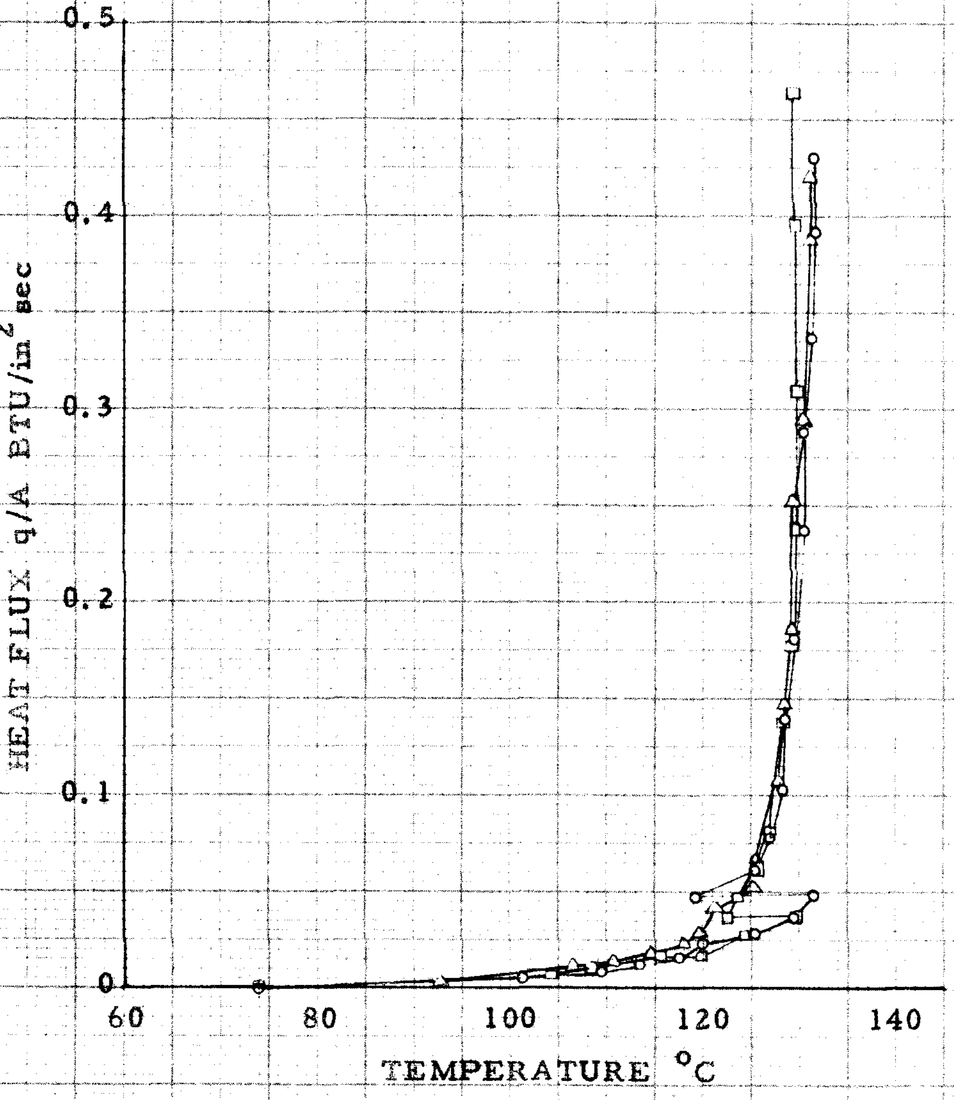


FIGURE 19
HEAT FLUX vs. WALL TEMPERATURE

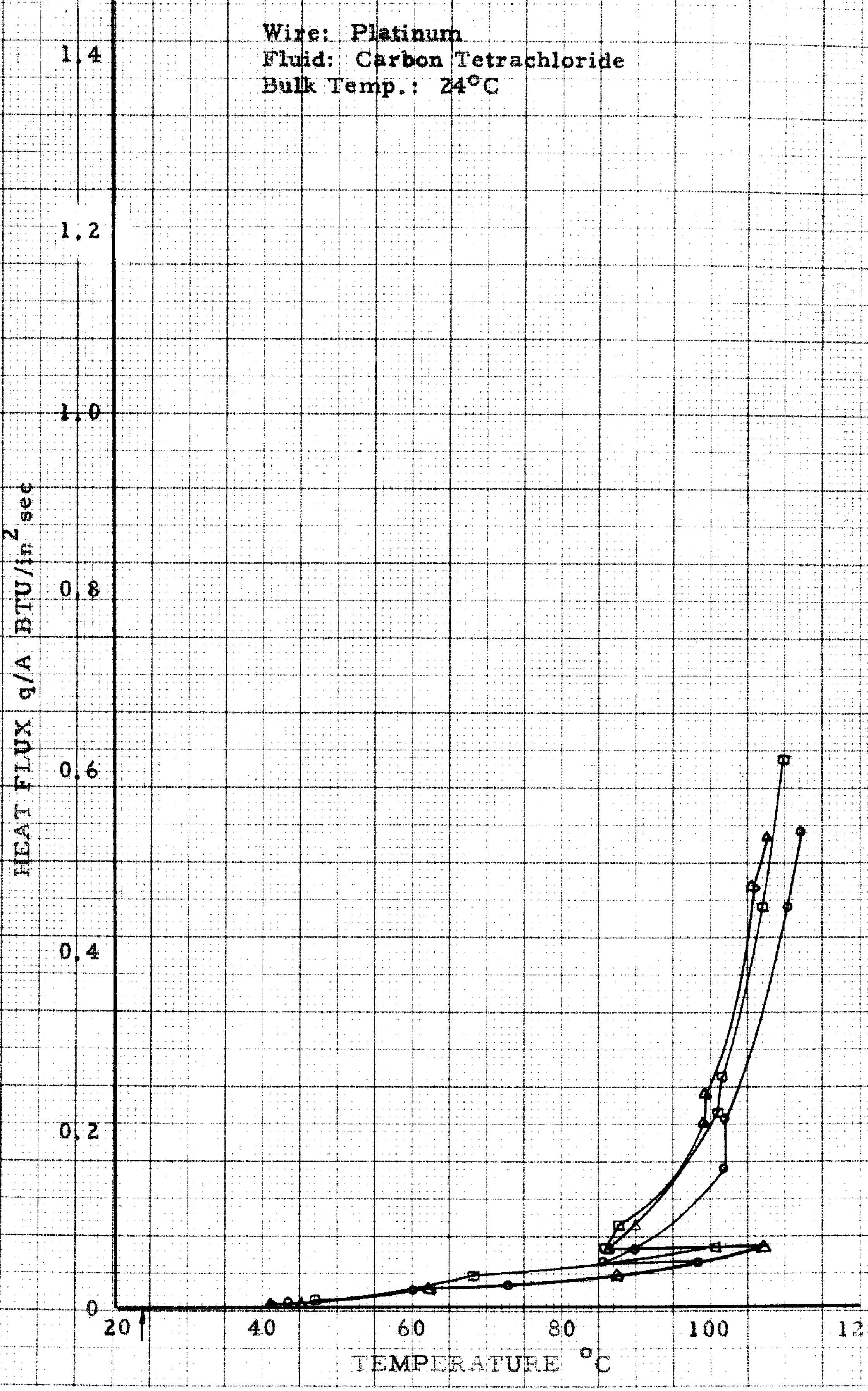


FIGURE 20

HEAT FLUX vs. WALL TEMPERATURE

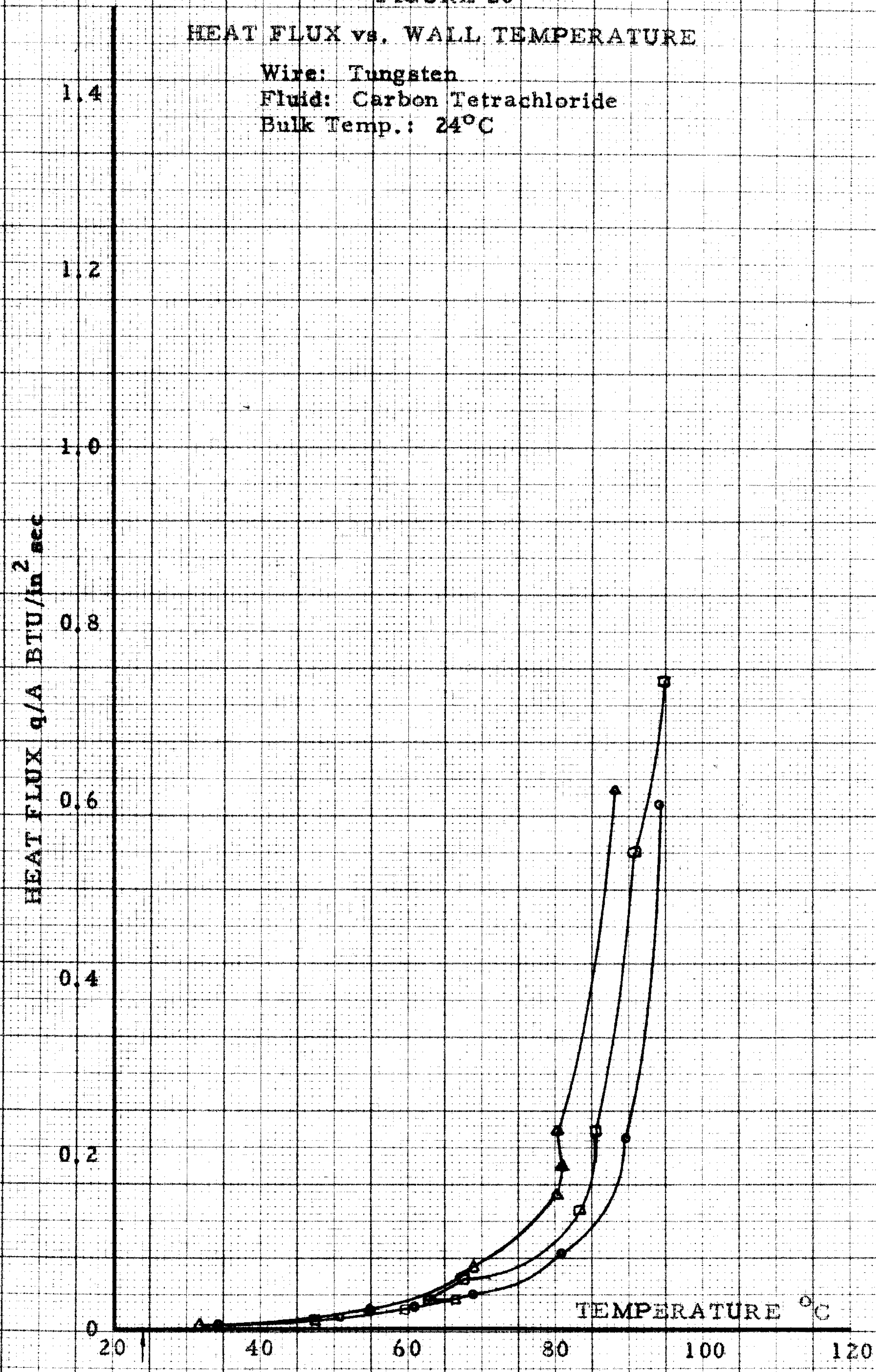
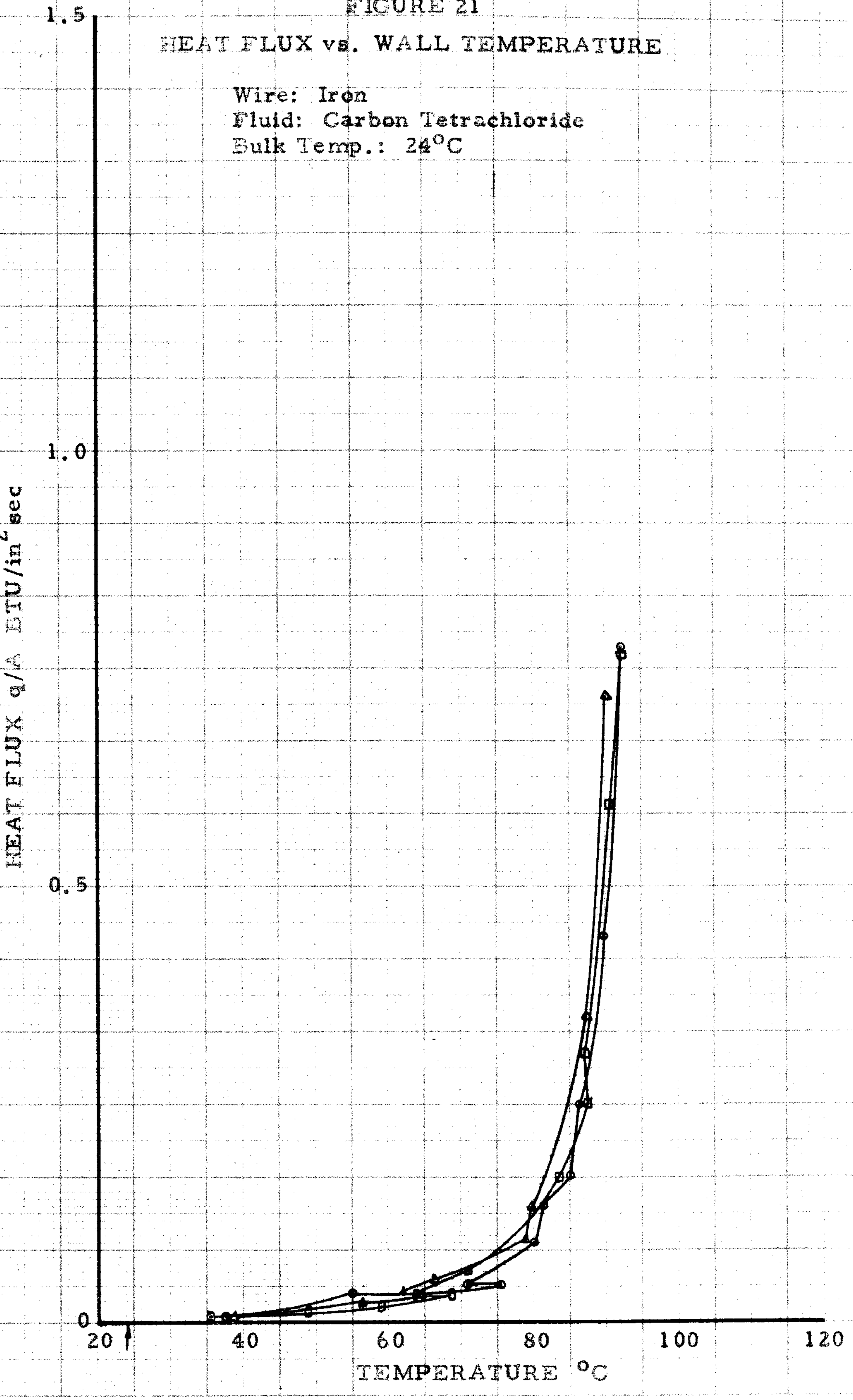


FIGURE 21

HEAT FLUX vs. WALL TEMPERATURE



Wire: Iron
Fluid: Carbon Tetrachloride
Bulk Temp.: 24°C

FIGURE 22

HEAT FLUX vs. WALL TEMPERATURE

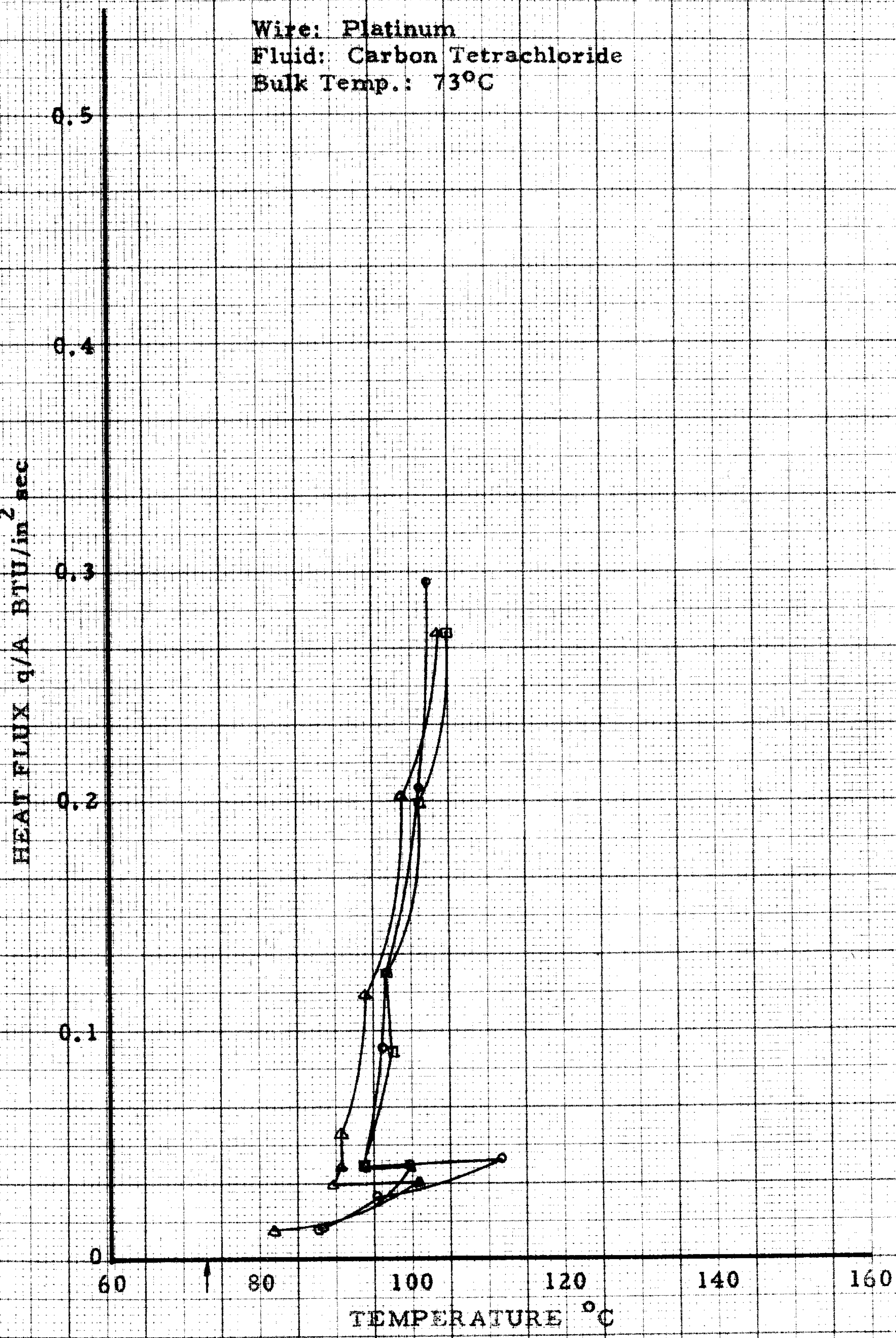
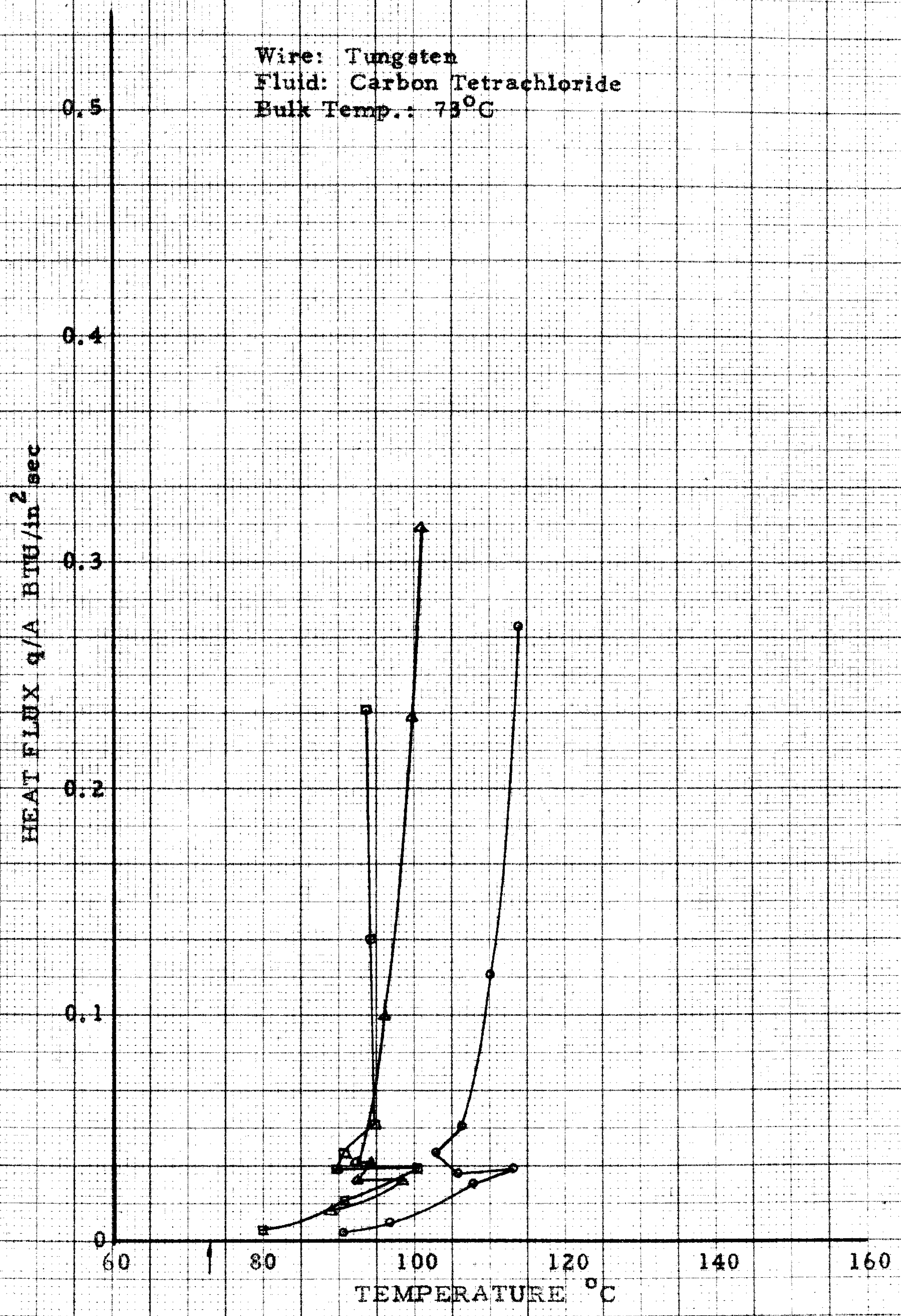


FIGURE 23

HEAT FLUX vs. WALL TEMPERATURE



Wire: Tungsten
Fluid: Carbon Tetrachloride
Bulk Temp.: 73°C

FIGURE 24

HEAT FLUX vs. WALL TEMPERATURE