SOME EXPERIMENTS IN

NUCLEATE BOILING HEAT TRANSFER

Thesis by

Chester Wright Gates, Jr.

Lieutenant Commander, United States Navy

In Partial Fulfillment of the Requirements

for the Degree of

Aeronautical Engineer

California Institute of Technology

Pasadena, California

1954

ACKNOWLEDGEMENTS

ABSTRACT

The present series of experiments was designed to provide additional information on the mechanism of bubble formation in boiling liquids. In particular, knowing that a pre-pressurization treatment raises the boiling temperature of a body of water markedly, it was desired to determine the effect of such treatment on boiling from a metal heating surface immersed in the water.

A 0.010" nichrome wire was immersed in a vessel of water, the entire assembly having been cleaned, and subjected to a pressure of 15000 psi for periods of time in excess of 15 minutes. The pressure was reduced to atmospheric and the wire heated to burnout by electric current. It was concluded that the effect of the treatment on the maximum heat transfer was small and equivalent to degassing the water.

A second series of experiments was conducted in which the temperature of the wire at the onset of boiling in pre-pressurized water was measured. These experiments indicated that the wire reached a temperature considerably in excess of normal nucleation temperatures, dropping to normal at the instant of nucleation. This effect could be explained in terms of the theory which postulates bubble formation from pre-existing gas or vapor nuclei.

TABLE OF CONTENTS

I. INTRODUCTION

The development, in recent years, of nuclear reactors, high temperature rockets, and high capacity boilers has emphasized the advantages of utilizing higher rates of heat transfer than are possible with normal metal to liquid conduction and convection. A typical curve of "boiling heat transfer rate" as a function of heating surface or "wall" temperature is shown in Fig. 1. It consists of four rather well defined regions characterized by different surface phenomena. In the first, heat transfer is largely by convection and no vapor is formed; in the second, bubbles are formed and considerable agitation takes place; in the third, the bubbles coalesce to form unstable masses of vapor blanket which interfere with heat transfer from wall to liquid; and, in the fourth, heat transfer is by means of conduction through a stable vapor film or blanket. The "burnout" point is so named because in order to reach a higher heat flux the temperature of the heating wire or wall must "jump" to a point on the complete film boiling portion where the temperature is normally above the melting point of the metal; therefore the wire or wall "burns out". The values indicated on the curve are representative of those obtainable with a liquid bulk temperature $50^{\circ}F$ below saturation temperature and flow velocity of 5 feet per second in distilled degassed water (Ref. 1). Increasing either the temperature difference or the velocity raises the heat flux. Fig. 1 illustrates the high rates attainable in boiling heat transfer; in order to use these rates safely, it would be desirable to be able to predict burnout as a function of liquid properties and flow parameters. Attempts to derive

correlations of this sort have, so far, not been successful; and it is felt that further understanding of the phenomena is required before the burnout point can be predicted satisfactorily.

The problem of boiling heat transfer falls into three phases: first, "nucleation" or the formation of bubbles; second, the growth and collapse cycle of the bubbles; and third, the mechanism of actual heat transfer. The present investigation is concerned with the first of these, the nucleation process.

Where a cavity exists in a liquid, the pressure inside differs from the pressure outside because of the surface tension. If the cavity is spherical the relation for the pressures is:

$$P_i = P_o + 2\,\sigma/r \tag{1}$$

where P_i = pressure inside the cavity,

P_o = static pressure of the surrounding liquid,

σ = surface tension (force per unit length),

r = radius of the bubble.

The cavity is filled with vapor (and possibly gas originally dissolved in the liquid); and the pressure is approximately equal to the vapor pressure at the temperature of the surrounding liquid. On first examination of Eq. (1) it seems impossible for a vapor bubble to form inside a body of liquid. The bubble would have initially an infinitesimally small radius, therefore the surface tension forces would be infinitely large and could not be overcome by the vapor pressure.

To explain the observed phenomena of bubble formation, two hypotheses are generally offered. According to the first, any normally

treated liquid contains a large number of small cavities, consisting
of masses of vapor or gas, stabilized on solid impurities of low
wettability as indicated in Fig. 2. The impurities are necessary for
the existence of the cavities, because vapor bubbles in a liquid are
unstable and even gas bubbles dissolve in a few seconds unless the
liquid is saturated with dissolved gas (Ref. 2). Small crevices in the
walls of the vessel containing the liquid or in any heating surfaces
immersed in the liquid may, of course, also serve as stabilization
points. Upon heating, the vapor or gas in the cavity will expand and
a part may separate from the solid, forming a bubble in the liquid.
The pressure inside this newly formed bubble will be very nearly equal
to the vapor pressure corresponding to the temperature of the sur-
rounding liquid. If this pressure is sufficient to overcome the surface
tension and the static pressure of its surroundings (Eq. (1)) the bubble
will grow, otherwise it will collapse. In distilled degassed water at
atmospheric pressure bubble formation has been observed to occur at
approximately $240^{\circ}F$ (Ref. 1, e.g.). According to Eq. (1) the bubble
must, for a value of surface tension (σ) of 70 dynes per cm, have had
a diameter of the order of 10^{-4} inches.

The second explanation of the occurrence of bubbles within a
liquid is based on the concept of thermal fluctuations. There is a
certain probability that cavities will be created inside a liquid because
of the random motion of the molecules. To explain the observed
phenomena, cavities of the order of 10^{-4} inches are required. It can
be shown (Ref. 1) that the probability of creating a cavity of this size
inside a liquid is practically non-existent. This mechanism cannot,

therefore, explain bubble formation inside a liquid. But its effective-
ness in creating bubbles at a heating surface cannot be as easily
dismissed. The properties of the surface material may be such that
the energy to create a cavity at the surface could be considerably less
than that required to form a bubble inside the liquid. The probability
of forming a bubble at the surface could then be relatively high, and
this mechanism could be important in the formation of such bubbles.
Present information on surface energies is not sufficient to compute
the probability of bubble formation; and the importance of this
mechanism for boiling cannot be determined at this time.

II. THE PROBLEM

Several experiments have shown that, in pre-pressurized water samples, it is possible to reach temperatures in excess of $400^{\circ}F$ before boiling occurs. Experiments of this type have been conducted by groups at the University of California at Los Angeles (Ref. 3), by the Hydrodynamics Laboratory at the California Institute of Technology (Ref. 4), and by others. Water samples were first subjected to pressure of over 5000 psi for more than 15 minutes; the pressure was then reduced to one atmosphere, and the water was heated. Essentially similar results were obtained with distilled, tap, or degassed water. It is, however, necessary to subject the container to a careful cleaning procedure in order to avoid nucleation spots on the surface. The results can be explained by the theory of gaseous or vapor nuclei. Upon pressurization a portion of the vapor or gas in each cavity is forced into solution, leaving a smaller nucleus which requires a higher temperature in order to produce a bubble capable of growing.

The present series of experiments was designed to indicate whether this effect persisted in the presence of a metallic heating surface, in particular to determine if the pre-pressurization had any effect on the burnout point since this is the point of main engineering concern. If no appreciable effect was observed, some possible causes were to be examined, and a closer study of the conditions at the onset of nucleation (Fig. 1) was to be conducted. These results were to be examined in the light of the theory which postulates cavity formation by thermal fluctuations, keeping in mind the existence of still other possible nucleation sources, e.g., electrolytic action. It was to examine these aspects that the second series of experiments was undertaken, to measure heating surface temperature in the vicinity of the nucleation point.

III. APPARATUS

A. Burnout Heat Flux Measurements

In order to obtain information on the effect of pre-pressurization on burnout heat flux, it was necessary to measure the heating current at the instant of burnout as well as the liquid bulk temperature. The latter was taken with standard precision mercury thermometers. Current measuring apparatus is shown schematically in Fig. 3a and described in detail below.

1. Heat Transfer Bottle

A considerable amount of unpublished data on maximum heat flux versus liquid bulk temperature was available from experiments by Sabersky (Ref. 5) working with nichrome and stainless steel heating wires in water and various other liquids. In order to use these results as a basis of comparison, 0.010" nichrome wire approximately 1" long was also chosen as the heating surface for the present series of experiments. As in the previous experiments, the wire was to be heated by means of direct current available in the building. During the experiments the wire, held by two electrodes or terminal rods, was submerged in the test liquid contained in a glass vessel (Fig. 4). It was desired to design the assembly, consisting of vessel, electrodes, and heating wire, so that the entire unit could be subjected to pressurization. The size of the vessel was therefore limited to approximately 2" diameter by the size of the pressurizing cylinder available at the Hydrodynamics Laboratory, California Institute of Technology. An effort was made to eliminate all extraneous sources of nucleation. Since ordinary rubber

was suspected of supplying many water-borne nucleation particles, it was avoided in the design; and the terminal rods were mounted in the male half of a 55-50 glass seal, the female half forming the bottom of the bottle. Originally a glass-metal seal was formed where the terminal posts entered the bottle, using 1/8" Kovar* rods. Kovar is an alloy (54 percent iron, 29 percent nickel, 17 percent cobalt, 0.3 percent manganese), the coefficient of thermal expansion of which closely approximates that of a special pyrex over a wide range of temperature. However the seal cracked in pressurizing; and, in subsequent bottles, latex rubber tubing was used to seal the terminal rods into the glass bottle. The reservoir, which was necessary to allow for the volume reduction of the water in the bottle during pressurization, was also made of latex, a material which is wetted by water in the same manner as glass. Several bottles broke during the experiments for various reasons: binding of the seal as a result of evacuating, heating, and compression cycles, crushing due to marginal reservoir space, and ordinary accidents. The final design of the bottle is shown in Fig. 4. It involved 3/16" stainless steel terminal rods and approximately two feet of tubing reservoir space attached in such a manner that bubbles, entrapped in the filling process, could be drawn from the bottle into the tube and evacuated. This allowed filling the bottle with degassed water in the manner illustrated (Fig. 4).

The development of a satisfactory method of securing the heating wire to the rods also required considerable attention. Combinations of set screws and washers, used in early bottles, caused burnouts at

---

* Westinghouse trade name.

the point of fastening. This was taken as an indication of high contact resistance; and results involving such burnouts could not be counted as reliable. Every effort was made to avoid the introduction of additional metals into the circuit; but the only satisfactory arrangements involved clamping the wire between grooved brass plates (Fig. 4).

2. Power Source

The power source consisted of a 120 volt DC generator available in the building. The current was limited to 25 amps by the circuit breakers. The current was supplied to the test wire through a "ballast" resistor and a 100 ohm, 50 step, high capacity rheostat as illustrated in the circuit diagram (Fig. 3a). The ballast resistor consisted of 0.015" nichrome wire, hand-wound on a wooden core. Side taps were provided to allow the resistance to be varied as necessary to make use of the fine-control end of the rheostat. The entire resistor was submerged in water and operated in the nucleate boiling range. In this way, it was possible to dissipate large quantities of power through a small resistor. All connections between units were made with number 14 copper wire. 110 volt alternating current was used for a number of burnout tests. The results were not significantly different from those obtained with direct current; and the type of current was, therefore, not believed to be a major factor.

3. Instrumentation

Current measurements were made by means of a Weston Electric DC milliammeter, type D-55049, with shunts to give it ranges of 5, 10, 20, and 50 amperes. It was calibrated by comparison with the standard

ammeter of the Calibration Laboratory, California Institute of Technology. Current was converted to heat flux by the formula

$$q/A = I^2/K \tag{2}$$

where K is a function of heating wire dimensions and resistivity of the material (Appendix A).

When A.C. power was used current was measured by a Weston A.C. ammeter, model 155, 0-25 amp. scale, which had also been calibrated.

4. Pressurization Tank

As illustrated (Fig. 5), the pressurization tank consisted of a hydraulic differential piston and cylinder constructed by personnel of the Hydrodynamics Laboratory, California Institute of Technology. Pressure was indicated by an extensometer which measured the stretch of the cylinder. The extensometer has been calibrated against an accurate Bourdon gage.

B. Nucleation Temperature Measurement

1. Heat Transfer Bottle

The bottle used in this series of experiments was the final modification illustrated in Fig. 4 and described in Section III A 1.

2. Power Source

The power source was identical to that described in Section III A 2.

3. Instrumentation

To obtain an indication of heating surface temperature, two methods were considered: first, to measure the change in electrical resistance of the wire with temperature; and second, to measure the voltage output of a thermocouple welded to the heating wire. It was felt, however, that the thermocouple weld might introduce extraneous nucleation sources. The resistance method was therefore chosen. For this purpose, a Wheatstone bridge circuit was built with the heating wire forming the unknown resistance. The remaining resistances were made of 0.042" manganin wire, capable of carrying the necessary current (Fig. 3b). Though the resistance of manganin does not change appreciably with temperature, the resistances were immersed in low conductivity water as a further precaution. Since sensitivity is a maximum when the resistances of the bridge legs are equal, fixed resistances of approximately one ohm were chosen. The third leg was adjusted to balance the resistance of the test wire assembly before each run.

The galvanometer used in the first tests was a Weston Electric millivoltmeter of 1 ohm resistance calibrated to read 25 millivolts (or milliamps). The unbalance method of resistance determination was used, i.e., all control resistances were left unchanged, and changes in the resistance of the heating wire were determined from the deflection of the galvanometer. The relation between change in wire temperature and this galvanometer deflection can be shown (Appendix B) to be:

$$\Delta T = k_1 \ (i_g/I_a) \ (1 - k_2 \ i_g/I_a) \qquad (3)$$

Where k_1 = function of heating wire parameters and bridge components,

i_g = galvanometer current ,

I_a = heating current, and

k_2 = function of bridge components .

For the final measurements a Brown Electronik model 156X15V self-balancing potentiometer was obtained. This instrument, graduated to 5 millivolts by hundredths, was found to be more suitable than the galvanometer described above. A relation between temperature change and deflection similar to that above was calculated (Appendix B).

IV. DETERMINATION OF BURNOUT HEAT FLUX

A. Test Procedure

Each pressurization test was preceded by thorough and repeated immersion of the entire bottle, including wire, electrodes, and reservoir tube, in a laboratory cleaning solution of concentrated sulphuric acid saturated with sodium dichromate. The acid treatment was followed by several rinses, first in tap water, then in distilled water. Filling was then accomplished either by the stopcock and aspirator technique illustrated (Fig. 4) or by simple immersion in water contained in a porcelain pan similarly cleaned. The distilled water used was the multiple-filtered type obtained from the Controlled Atmosphere Launching Tank of the Hydrodynamics Laboratory.

The bottle and reservoir tube, and later the bottle with filler neck simply open, were placed in a seamless cellulose tubing* bag full of distilled water to prevent impure water from entering the bottle during pressurization. The bag was then placed in the tank (Fig. 5), the tank sealed, and the pressure raised to approximately 15000 psi. At the end of periods ranging from 15 minutes to several hours, the pressure was slowly reduced to atmospheric, and the bottle taken out. The test bottle was connected into the heating circuit (Fig. 3a); and the current was gradually increased until the wire burned out. Approximately 10 minutes normally elapsed from depressurization to burnout. On two occasions, however, more than 24 hours elapsed without change in results. The

---

* Visking Corp., Chicago, Illinois.

burnout heat flux was calculated from burnout current by means of Eq. (2).

The temperature of the bulk liquid was measured approximately one inch above the wire immediately after burnout. Although the thermometer was accurate to 0.1°, temperature of the water varied over a degree in the vicinity of the measurement so readings were taken to the nearest $^{\circ}F$.

B. Presentation of Results

A series of burnouts of Q.010" nichrome wire were conducted in both distilled and tap water (Table I). The results are shown in Fig. 6 together with curves drawn from unpublished similar experiments by Sabersky (Ref. 5). In these experiments the temperature difference acts as "driving potential" for heat flux; therefore, as the temperature of bulk liquid is decreased (or, alternately, as the temperature difference is increased) the maximum heat flux increases. Bulk temperature was varied by heating the water in the bottle over an electric hot plate. The series of burnouts in pre-pressurized water (Table II) indicated that pre-pressurization had only a small effect on the maximum heat flux. This is of engineering significance, since one may conclude that, if even such extreme treatment has little influence, the burnout point must not be very sensitive to the treatment and purity of the water. The burnouts in pre-pressurized water do seem to correspond to those previously obtained in degassed water. This could be explained by assuming that any gas nuclei present in the liquid must have been driven into solution during the pressurization.

The scatter of experimental points, particularly in the premature burnouts, may possibly be attributed to local hot spots caused by gas bubbles stabilized on the wire. Either degassing or pre-pressurizing decreased the scatter.

Before describing the next set of experiments an estimate will be made of the accuracy of some of the principal measurements involved in determining the burnout points. Variation in measurement of bulk temperature is largely a matter of thermometer positioning; and every effort was made to keep the position consistent. The major source of error in determination of heat flux was that due to reading the ammeter, the least reading of which was 1 percent full scale on the DC ammeter, 2 percent on the AC ammeter. The commonly tabulated value of resistivity of annealed nichrome (112 microhm/inch) was used in these computations though several experimental determinations indicated a value approximately 2 to 4 percent higher for the wire (page 17). Neglecting the last effect, the maximum possible error of the burnout heat flux measurement was estimated to be approximately 6 percent.

In an attempt to explain why pre-pressurization had so little effect on burnout heat flux, further attention was directed toward measuring the heating surface temperature at the start of nucleation.

V. DETERMINATION OF NUCLEATION TEMPERATURE

A. Test Procedure

Preparation of the bottle and pressurization were the same as described in Section IV A. The bottle was then connected as one leg of the Wheatstone bridge described in Section III B. Change in resistance of the wire with temperature was indicated by unbalance of the galvanometer, balanced initially by adjusting the length of the resistance R_1. When using the Brown millivoltmeter two decade boxes adjusted to total 10,000 ohms were placed across the bridge with the millivoltmeter reading the potential drop across one (Fig. 3b). The ratio of this decade box resistance to the total 10,000 ohms then related the millivoltmeter reading to total bridge unbalance (e_g). Change in temperature was calculated from Eq. (3), page 10. As indicated in the following section, it was discovered that in the pressurized state the wire reached a temperature considerably above normal nucleation temperature before nucleation commenced; thereupon the temperature dropped rapidly to normal.

B. Presentation of Results

A series of experiments were conducted in which the temperature of the heating wire at the beginning of nucleation was determined. The first two (Appendix C), using nichrome wire in distilled water, indicated that an appreciable temperature drop occurred at the instant of nucleation (clearly defined by the sharp buzzing sound caused by bubble agitation).

The instrumentation was then improved by replacing the milli-ammeter with a self-balancing potentiometer to indicate potential unbalance of the circuit. Platinum was used as the heating wire in two experiments to take advantage of its higher thermal coefficient of resistivity. Tap water was used as the test liquid in these two experiments; and the temperature drop was again noted. In the fourth and subsequent test runs, the unbalance as recorded by the millivoltmeter was tabulated as a function of heating current. Converted to temperature change and heat flux by means of Eq. (3b) and Eq. (2) respectively, these were plotted in Figs. 7, 8, and 9. In order to establish an absolute value for the temperature in question, it was assumed that the steady state temperature after nucleation was equal to the normal value observed in degassed water, approximately 240° (Ref. 1). The initial temperature of the bulk liquid was, in each case, essentially room temperature. With the above assumption, the onset of boiling caused by a platinum heating wire in tap water was apparently delayed by pre-pressurization until the wire temperature reached approximately $310^{\circ}F$. Test runs using a nichrome heating wire in distilled water are plotted in Fig. 8 and indicate a nucleation temperature of approximately $290^{\circ}F$.

It must be mentioned that it was sometimes difficult to reproduce the temperature excess noted above. Several attempts to reproduce this effect using nichrome and tap water, e.g., yielded essentially negative results (Fig. 9). Observation of the nucleation pattern (Appendix C) indicated two possible explanations; first, that the wire was insufficiently cleaned, thereby leaving points at which the

pressurization had no effect; second, that the production of hydrogen

bubbles, observed at the cathode in this nichrome-tap water series,

caused a breakdown of the pressurization effect in the vicinity of the

negative terminal. A thorough investigation of these effects was not

completed; however, the former has been noted in connection with

glass as well as other materials (Ref. 4), while the latter could be

explained by the greater potential drop across the nichrome wire

coupled with the high conductivity of tap water. The conductivity of

the tap water was approximately five times that of the distilled filtered

water used; this, in turn, had a conductivity approximately five times

that of the low conductivity water in use by the Chemistry Department,

California Institute of Technology.

In the use of Eq. (3) it became necessary to know, to reasonable

accuracy, the physical constants of the wire material; resistivity at

$20^{\circ}C$ (ρ_{20}); and average thermal coefficient of resistivity over the

appropriate temperature range, approximately $20-150^{\circ}C$ (α_{20-150}).

The former was checked for both nichrome and platinum by measuring

the potential drop in millivolts across a length of wire immersed in

low conductivity water and carrying approximately 5 ma current. The

measured value for nichrome wire (116 microhm-cm to an estimated

$\pm$ 3 percent) corresponds closely to the standard tabulated value of 112,

(Ref. 6), the difference possibly being due to the wire-drawing effect.

The measured value for the platinum wire used (11.2 microhm-cm

$\pm$ 2 percent) apparently corresponds to tabulated values for platinum

type B, 10.8 microhm-cm (Ref. 6). The temperature coefficient of

resistivity of platinum (approximately α_{0-100}), measured by means

of the test Wheatstone bridge circuit at low current input for wires
alternately immersed in freezing and boiling water, checked closely
(0. 0034 $\pm$ 2 percent) the tabulated value of 0. 0036°C^{-1}, (Ref. 6), again
possibly reflecting the effect of wire drawing. The experimentally
determined thermal coefficient for nichrome was considerably lower
than the tabulated value of 0.0017°C^{-1} (Ref. 6). However, the value of
the coefficient is small, and an exact determination was beyond the
accuracy of readily available instruments. For this reason, the tabu-
lated values were used in the computations. It should be pointed out
that these values lead to lower computed temperature differences which
are therefore conservative in that they probably indicate temperature
excesses smaller than the actual ones.

Before leaving the subject of possible errors a brief discussion
of the other sources of experimental error in determining the tempera-
ture effect will be presented.

1. The measurement of the ratio of fixed resistances (R_4/R_3) in
the computation of Eq. (3) (Appendix B). This involved the steady state
reading of current (5 ma $\pm$ .05, or 1 percent), and potential
(5 mv $\pm$ .01, or 0.2 percent); therefore the possible error of the four
separate readings was less than 2.5 percent.

2. The determination of e_g/I_a, which involves a reading error
similar to that above and, in addition, an error due to the instantaneous
character of the highest potential reading, just at the instant of nucleation.
The ballast resistance was adjusted to give current steps approximately
equal to the last reading error (.05 amps, or $\pm$ 1 percent). However,
the corresponding potential jumps were on the order of 0. 10 mv, giving

a possible error of 2 percent (5 $\pm$ 0.10). The total possible error

from this source is then approximately 3 percent.

3. The physical dimensions of the wire. Length of the wire

(assuming contact actually made at the lip of the clamps) was deter-

mined to approximately 1/32" or $\pm$ 3 percent of the nominal 1" length

of heating wire. No attempt was made to check the cross sectional

area or volume of the wire, the dimensions as given by the manufacturer

being presumed accurate to 1 percent.

The estimated maximum error indicated for each determination

of temperature drop (Appendix C) includes the effect of these last three

items; but does not presume any inaccuracy in the tabulated values of

physical constants. As indicated above, the use of these values is

probably conservative. In any case the discovery that a temperature

drop does occur is the fact of major importance; this result is discussed

in the next section. The use of a wire whose diameter was small

compared to its length minimized the effect of temperature distribution

due to conduction.

VI. CONCLUSIONS

Measurements of the burnout heat flux in water pre-pressurized to 15000 psi for longer than 15 minutes indicated that the pre-pressurization produced only an effect equivalent to degassing of the water. It was therefore concluded that the burnout point, which is the point of major engineering concern in boiling heat transfer, could not be greatly increased by such treatment.

In the second series of experiments it was determined that, under certain conditions, pre-pressurization delayed nucleation until the heating surface reached a temperature considerably in excess of its temperature at normal nucleation. At the instant of nucleation the temperature dropped to normal.

A qualitative explanation of this behavior may be deduced from the theory which postulates bubble formation from pre-existing gas or vapor nuclei. As mentioned in Section I, it may be assumed that small masses of gas or vapor are stabilized on solid impurities of low wettability or in crevices of the heating surface (Fig. 2). As the temperature increases the vapor or gas will expand. Portions may be forced out of the crevices; and, if they are sufficiently large, the surface tension forces may be overcome, and the resulting bubbles expand. If the liquid is subjected to high pressures, some of the vapor in the cavities will condense, and some of the gas will be forced into solution. Upon release of the pressure, the remaining nuclei, or cavities, will contain smaller masses of gas or vapor than the original nuclei. A higher temperature will be required to initiate boiling in a liquid treated

in such a way. Once boiling has begun, however, and once the surface has again been exposed to vapor masses, the larger cavities will reform. Further boiling will then occur at the normal temperature.

The observed excess in nucleation temperature, on the other hand, seems difficult to explain on the basis of the theory of thermal fluctuations. The described treatment, while involving pressures large compared to the vapor pressure and static pressure of the liquid, should have little effect on the molecular forces and inter-facial energies. Thus, the quantities influencing the probability of creating a nucleus due to thermal fluctuations should not be affected.

It was therefore concluded that the theory of bubble formation from nuclei stabilized on solid particles offered a better explanation of the observed phenomena than did the theory of bubble formation as a result of thermal fluctuation.

APPENDIX (A)

Computation of Heat Flux

Heat energy dissipated by the wire may be equated to electrical energy absorbed; thus:

$$q/A(Btu/in^2 sec) \ S(in^2) = I^2 R(watts) \ \frac{550}{(778)(746)} \quad \text{(conversion factors)}$$

Now for wire dimensions (L, d) in inches, resistivity (ρ) in microhm-cm, and $R = \rho L/A$:

$$q/A = \frac{I^2 \rho L}{\pi d^2/4} \ \frac{550}{(778)(746)} \ \frac{1}{\pi dL} \ \frac{1}{2.54}$$

$$= I^2 \rho / 6.61(10)^9 d^3$$

$$= I^2 \rho / 6610 \qquad \text{for } d = 0.010 \text{ in.}$$

$$= I^2 / 59 \qquad \text{for } \rho = 112 \text{ microhm-cm. (nichrome)}$$

Substituting these values into the previous equation reduces it to a quadratic in terms of ΔR, the change in resistance:

$$\Delta R^2 \left\{ I_a R_3 (R_1 + R_2^o + R_4) \right\} + \left\{ D^o i_g (R_2^o + R_4) + 2 R_g D^o i_g \right\}$$

$$+ \Delta R \left\{ D^o I_a + i_g R_g \left[R_3 (R_1 + R_2^o) + (R_3 + R_4)(R_4 + R_2^o) \right] \right\} = 0$$

This is of the form

(a) $\quad \Delta R^2 + (b_1 + b_2) \Delta R + (c_1 + c_2) = 0$

where

$$\Delta R = - \frac{(b_1 + b_2)}{2a} \pm \sqrt{\frac{(b_1 + b_2)^2}{4a^2} - \frac{(c_1 + c_2)}{a}}$$

In the present case the second term under the radical is much smaller than the first; and (b_2) is much smaller than (b_1). Approximating by binomial expansion:

$$\Delta R = \frac{c_1 + c_2}{b_1 + b_2} = \frac{(c_1 + c_2)(1 - b_2/b_1)}{b_1}$$

$$= \frac{(R_2^o + R_4 + R_g 2) i_g}{I_a} \left\{ 1 - \frac{i_g R_g \left[R_3 (R_1 + R_2^o) + (R_3 + R_4)(R_4 + R_2^o) \right]}{I_a D^o} \right\}$$

For the first circuit, that involving measurement of bridge unbalance by milliammeter, the constant terms may be evaluated in terms of the measured bridge components as follows:

$R_1 = R_2^o = 0.07$ ohm (platinum) ; 0.62 ohm (nichrome)

$R_3 = R_4 = 0.885$ ohm $\qquad ; R_g = 1.0$ ohm

$$D^o (\text{platinum}) = 0.118 \text{ ohm}^3$$

$$D^o (\text{nichrome}) = 1.65 \text{ ohm}^3$$

$\Delta R (\text{plat}) = 2.97 \, (i_g/I_a)(1 - 15.37 \, i_g/I_a)$

$\Delta R (\text{nich}) = 3.51 \, (i_g/I_a)(1 - 2.28 \, i_g/I_a)$

For the second circuit, that involving measurement of bridge unbalance by potentiometer (millivolts), (R_g) was of the order of 10,000 ohms and the equation reduced to:

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

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

$$\Delta T = \Delta R / R_i a$$

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

$$L = \text{length of the wire}$$

$$A = \text{cross-sectional area of the wire}$$

$$a = \text{temperature coefficient of resistivity of the wire material over the range } \Delta T.$$

Thus for temperature change in ^oF of a $.010$ inch wire between two states, neither of which are the balanced state, the equations are:

(circuit 1)
$$\Delta T \text{(plat)} = \frac{A}{\rho_i L a} \left[2.97 \frac{(i_{g2} - i_{g1})}{I_a} - 45.7 \frac{(i_{g2})^2 - (i_{g1})^2}{(I_a)^2} \right]$$

$$= \frac{11.68(10)^{-4}}{\rho_i L a} \left[\frac{\Delta i_g}{I_a} \right] \left[1 - 15.37 \frac{(i_{g1} + i_{g2})}{I_a} \right]$$

$$\Delta T \text{(nich)} = \frac{12.63(10)^{-4}}{\rho_i L a} \left[\frac{\Delta i_g}{I_a} \right] \left[1 - 2.28 \frac{(i_{g1} + i_{g2})}{I_a} \right]$$

(circuit 2)
$$\Delta T \text{(plat)} = \frac{7.19(10)^{-4}}{\rho_i L a} \left[\frac{\Delta e_g}{I_a} \right] \left[1 - 15.37 \frac{(e_{g1} + e_{g2})}{I_a} \right]$$

$$\Delta T \text{(nich)} = \frac{7.19(10)^{-4}}{\rho_i L a} \left[\frac{\Delta e_g}{I_a} \right] \left[1 - 2.28 \frac{(e_{g1} + e_{g2})}{I_a} \right]$$

APPENDIX (C)

Summary of Nucleation Temperature Measurements

(A) -- Nichrome heating wire (.010"); entire assembly thoroughly acid-cleaned; distilled water aspirated to reduce air content; pre-pressurized to 15000 psi for 30 minutes. Instantaneous galvanometer deflection from approximately 4.5 to -.5 milliamps at nucleation, (heating current approximately 5.5 amps); therefore (Eq. 3a):

$$\text{gross } \Delta T = 60^{\circ}F \ (\underline{+}25^{\circ}/o) \hspace{2cm} \text{(Fig. 8)}$$

(B) -- Nichrome; entire assembly thoroughly acid-cleaned; distilled water warmed to reduce air content; pre-pressurized to 15000 psi for 20 minutes. Instantaneous galvanometer deflection from 15 to 6.5 ma at 6.65 amps, therefore:

$$\text{gross } \Delta T = 85^{\circ}F \ (\underline{+}20^{\circ}/o) \hspace{2cm} \text{(Fig. 8)}$$

(C) -- Platinum heating wire (.010"); entire assembly thoroughly acid-cleaned; tap water at room temperature; pre-pressurized 2 hours at 15000 psi. Tested 48 hours later; Brown potentiometer deflection 4.15 to 2.35 mv instantaneously, steadying down on 2.45 in approximately 5 seconds (with potentiometer measuring 2/100 of Δe_g). Heating current 14.6 amps, therefore:

$$\text{net } \Delta T = 75^{\circ}F \ (\underline{+}10^{\circ}/o) \hspace{2cm} \text{(Fig. 7)}$$

(D) -- Platinum; bottle not even opened, merely repressurized to 15000 psi for 2 hours, tested 48 hours later. Recorded deflection versus heating current and plotted corresponding heat flux and

temperature.

$$\text{net } \Delta T = 79^\circ F \ (\pm 10^\circ/o) \hspace{2cm} \text{(Fig. 7)}$$

(E) -- Nichrome; acid-cleaned wire but not other parts of assembly; tap water; used the entire cellulose bag as reservoir, no latex tubing. Pressurized to 15000 psi for 2 hours; tested 18 hours later. Leak in cellulose bag allowed rusty sediment to enter bottle. Formation of a gas bubble on heating wire near negative terminal preceded oscillating nucleation at same spot.

$$\Delta T = 17^\circ F \ (\pm 10^\circ/o) \hspace{2cm} \text{(Fig. 9)}$$

(F) -- Nichrome (same wire); re-cleaned wire, used latex reservoir; tap water; pressurized to 15000 psi for 30 minutes, no sediment. Gas bubble and nucleation at same point on wire as in experiment (E). Temperature "jump" augmented by further gradual decline with increasing heat flux.

$$\text{total } \Delta T = 20^\circ F \ (\pm 10^\circ/o) \hspace{2cm} \text{(Fig. 9)}$$

(G) -- Nichrome; entire assembly thoroughly acid-cleaned; no latex reservoir; warmed tap water to reduce air content. Pressurized to 15000 psi for 30 minutes. Leak in bag allowed rust sediment to enter bottle again. No gas bubbles formed, but nucleation started at negative terminal again, then "jumped" to whole wire. Another temperature jump at higher heat flux accompanied by distinctly louder nucleation "buzz".

$$\text{total } \Delta T = 30^\circ F \ (\pm 10^\circ/o) \hspace{2cm} \text{(Fig. 9)}$$

(H) -- Nichrome; entire assembly thoroughly cleaned by successive
multiple rinsing in tri-chloro-ethylene, methanol, fresh acid-per-
manganate solution, tap water, and distilled water; distilled water
as test fluid. Pressurized to 15000 psi for 2 hours using only cellu-
lose bag, no latex tubing reservoir. Tested 18 hours later, small
amount of rusty sediment in bottle. Potentiometer deflection from
2.93 mv to 2.20 at instant of nucleation, steadying on 2.33 (poten-
tiometer measuring $1/10 \, \Delta e_g$). Heating current 6.05 amps. There-
fore:

$$\text{net } \Delta T = 40^{O}F \, (\pm 10^{O}/o) \qquad \qquad (\text{Fig. } 8)$$

REFERENCES

1. Ellion, M. E., A Study of the Mechanism of Boiling Heat Transfer, Thesis, Calif. Inst. of Tech., 1953

2. Epstein and Plesset, On the Stability of Gas Bubbles in Liquid-Gas Solutions, J. Chem. Phys., Vol. 18, No. 11, 1950

3. Final Report on Studies in Boiling Heat Transfer, AEC Research Contract No. AT-11-1-GEN-9, Dept. of Eng., Univ. of Calif., Los Angeles, March 1951.

4. Bonnamassa, F., Hydrodynamics Laboratory, Calif. Inst. of Tech., private communication

5. Sabersky, R. H., Div. of Eng., Calif. Inst. of Tech., private communication

6. Metals Handbook, Amer. Soc. for Metals, Cleveland, Ohio, 1948

TABLE I

BURNOUT HEAT FLUX

(untreated)

Column 1. Run number, from original data. Missing numbers

include those involving steel wire and other non-

pertinent data.

  2. Temperature of bulk liquid at burnout, $^\circ$F.

  3. Burnout heat flux, btu/in^2-sec.

  4. Power source, AC or DC.

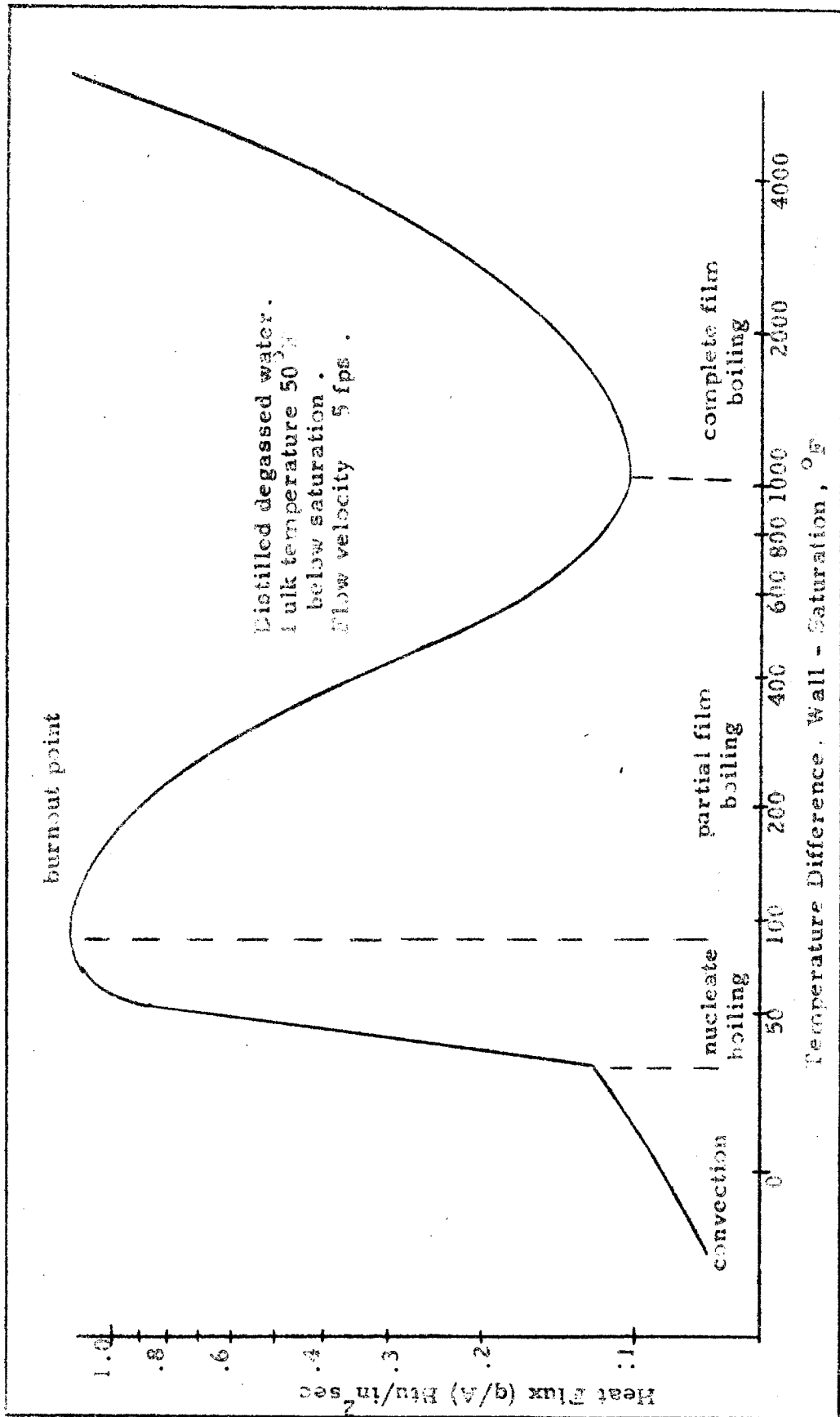 5. Location of burnout, center or end of wire, positive

or negative terminal for DC.

Nichrome-Distilled Water						Nichrome-Tap Water				
1	2	3	4	5		1	2	3	4	5
18	119	7.1	DC	-		2	162	3.1	DC	-
19	85	6.7	DC	-		3	169	3.1	DC	-
20	90	6.7	DC	-		11	140	5.5	DC	C
22	80	6.5	DC	C		12	97	7.0	DC	-
25	112	7.2	DC	-		13	108	7.0	DC	-
28	86	4.4	AC	E		14	115	4.5	DC	-
29	97	6.0	AC	E		15	130	4.7	DC	-
30	104	5.0	AC	E		16	148	4.3	DC	-
31	120	6.0	DC	-		17	160	3.7	DC	-
35	82	4.5	AC	E		32	90	6.1	AC	-
36	92	5.1	DC	-		33	112	5.7	AC	-
37	92	4.8	DC	-						
38	108	7.2	DC	-						
39	112	7.0	DC	-						
40	122	6.0	DC	-						
41	134	5.2	DC	-						
42	112	7.2	DC	-						
43	120	6.0	DC	-						
44	104	7.2	DC	C						
45	110	7.2	DC	C						

TABLE II

BURNOUT HEAT FLUX

(pre-pressurized)

Column 1 - 5. Same as Table I

6. Type of water, distilled or tap.

Nichrome -- pre-pressurized water					
1	*2*	*3*	*4*	*5*	*6*
10	122	7.85	DC	C	T
26	93	9.36	DC	-	D
27	92	8.82	DC	-	D
46	130	6.12	AC	C	D
47	152	4.74	AC	C	D
48	120	7.05	DC	C	D

BOILING HEAT TRANSFER

Fig. 1

Temperature Difference. Wall - Saturation, °F

Heat Flux (q/A) Btu/in²sec

Distilled degassed water.
Bulk temperature 50°F
below saturation.
Flow velocity 5 fps.

convection

nucleate
boiling

partial film
boiling

complete film
boiling

burnout point

bulk
liquid

meniscus

vapor or
gas nucleus

external
pressure (P_o)

surface
tension $(2\sigma/r)$

internal
pressure (P_i)
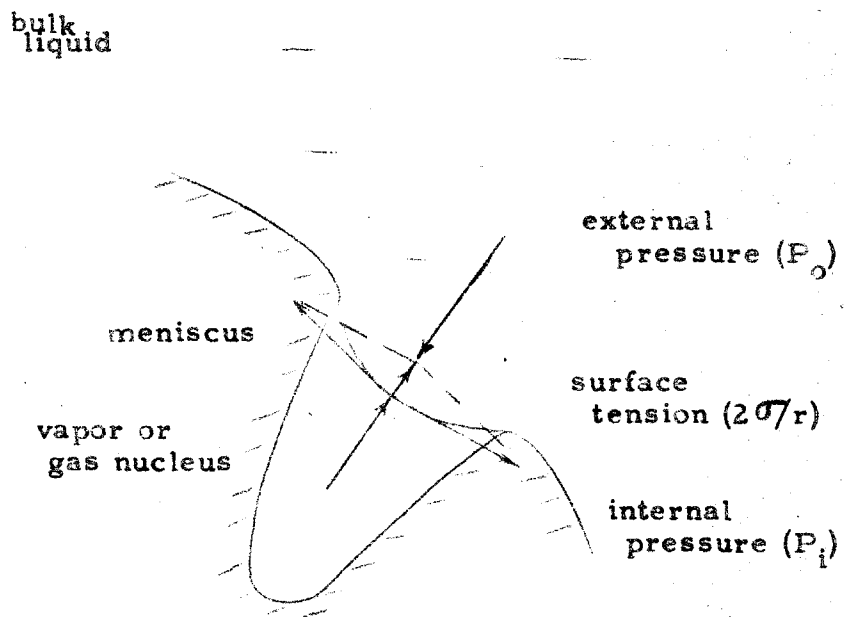
SURFACE STABILIZED NUCLEUS
Fig. 2
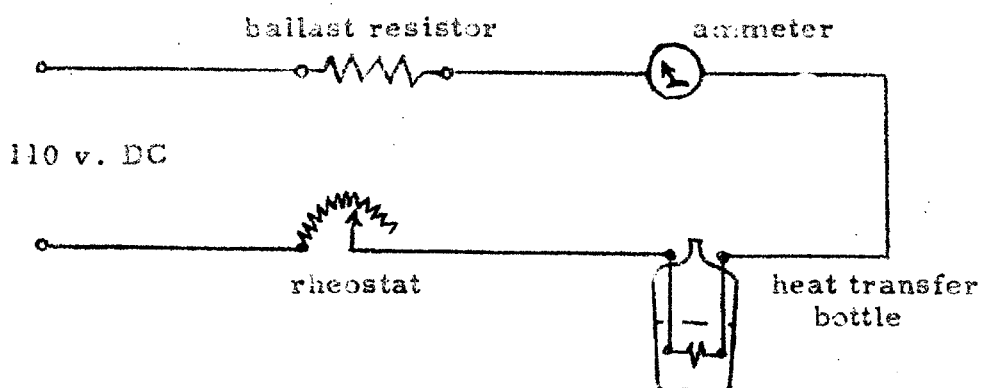
(a) Determination of burnout heat flux
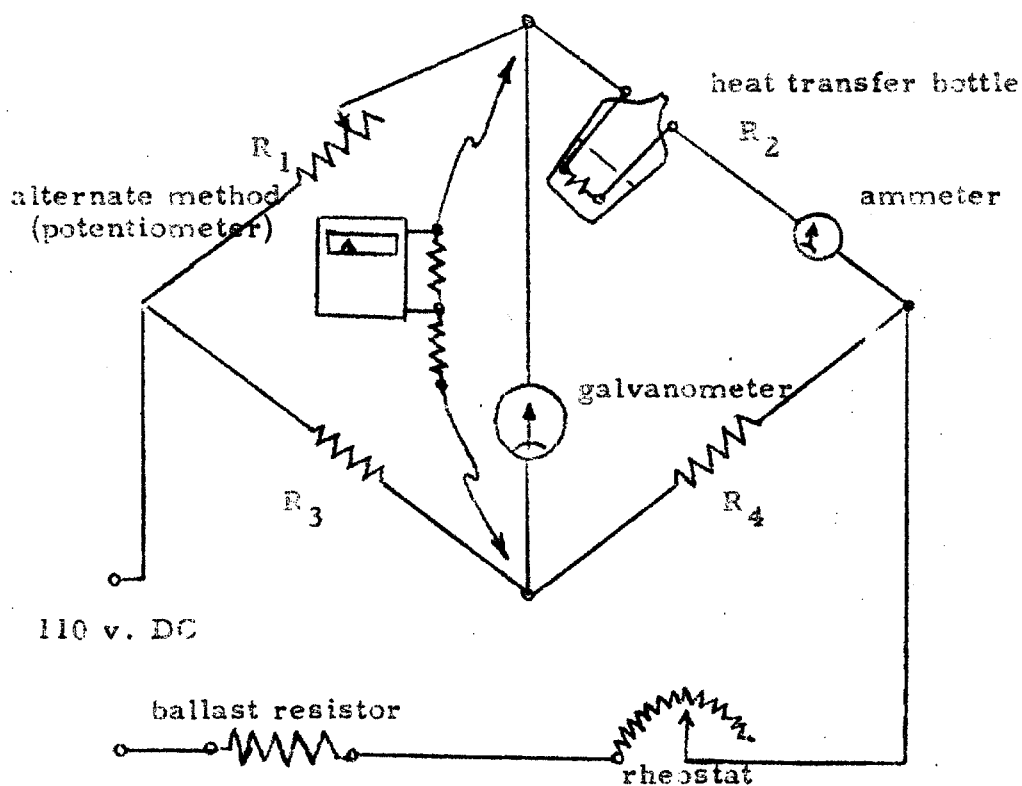
(b) Determination of nucleation temperature

SCHEMATIC CIRCUIT DIAGRAMS
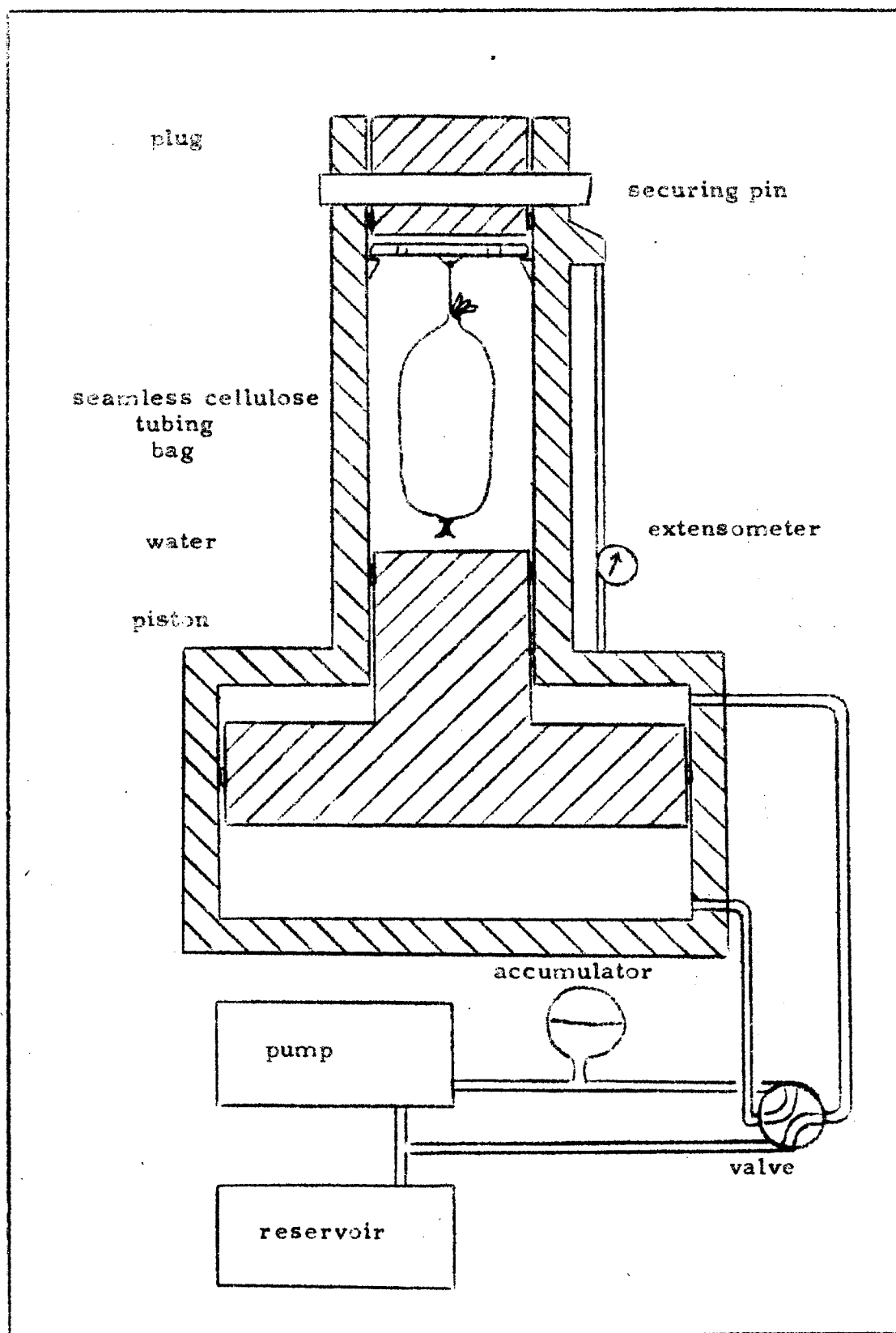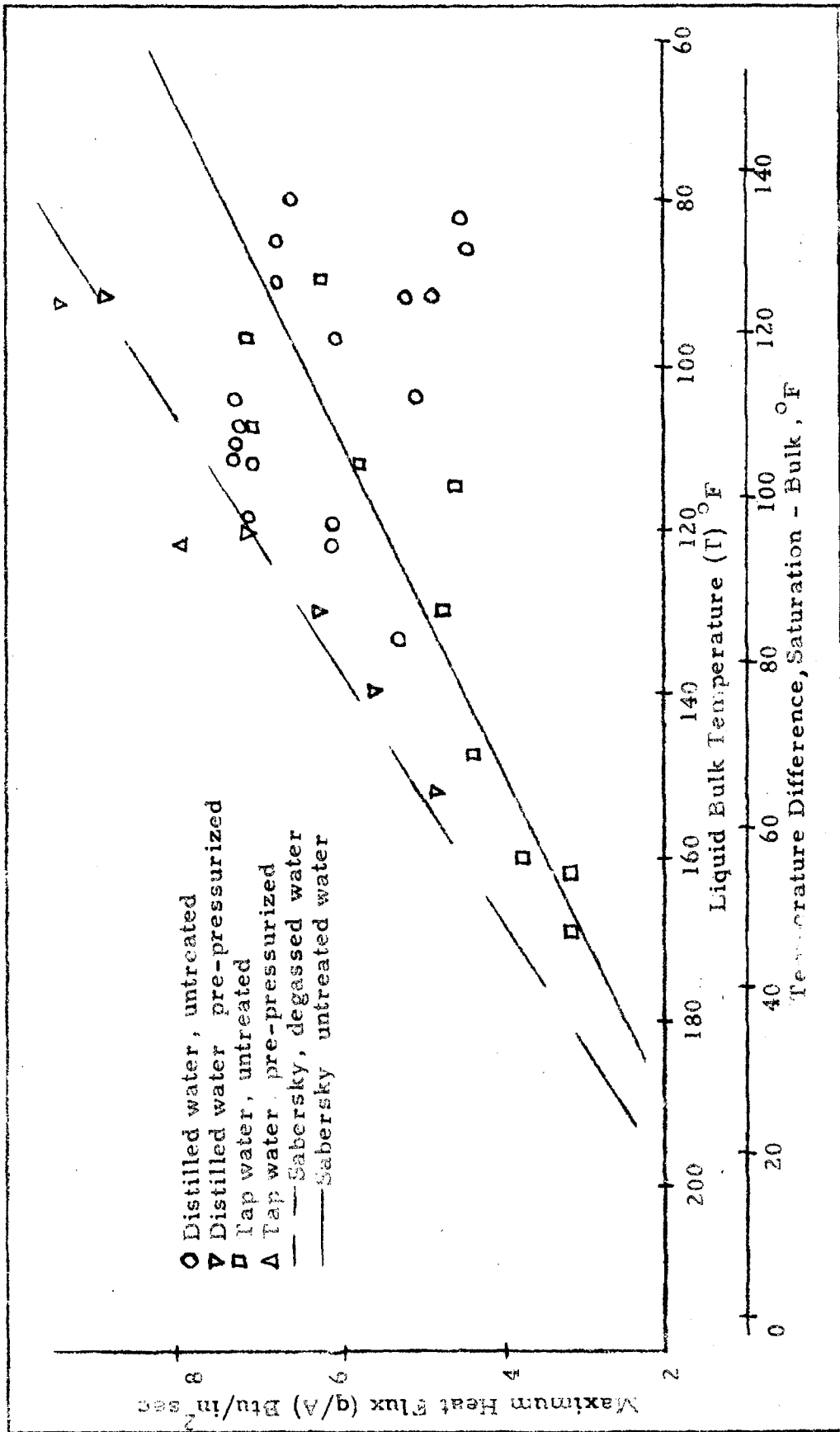Fig. 3

funnel

Filling
arrangement

stop cock

clamp

to aspirator

latex rubber tubing

power lead
terminals

glass
seal

3/16" stainless
steel rod

Clamp
detail
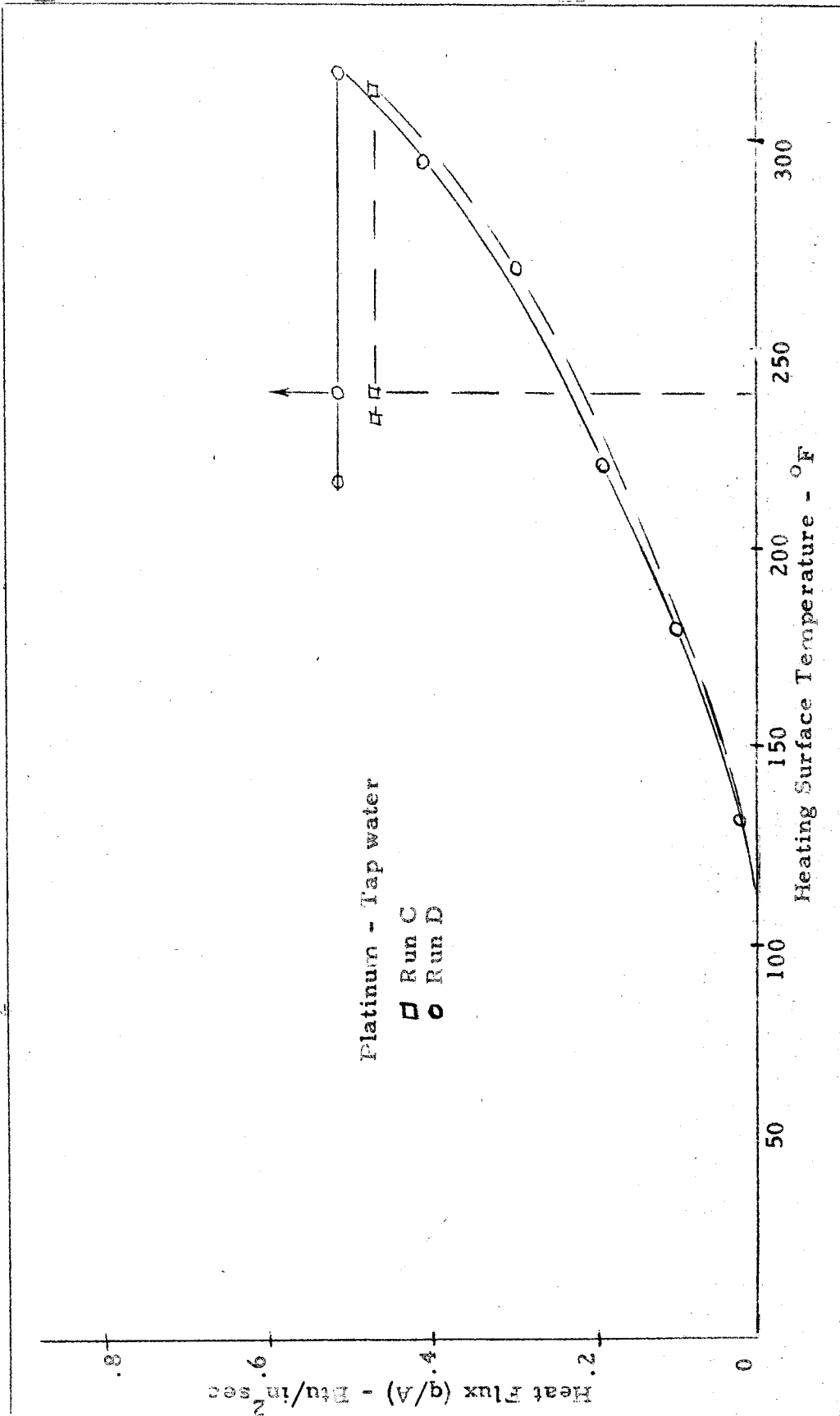
heating
wire

heating
wire

brass
clamps
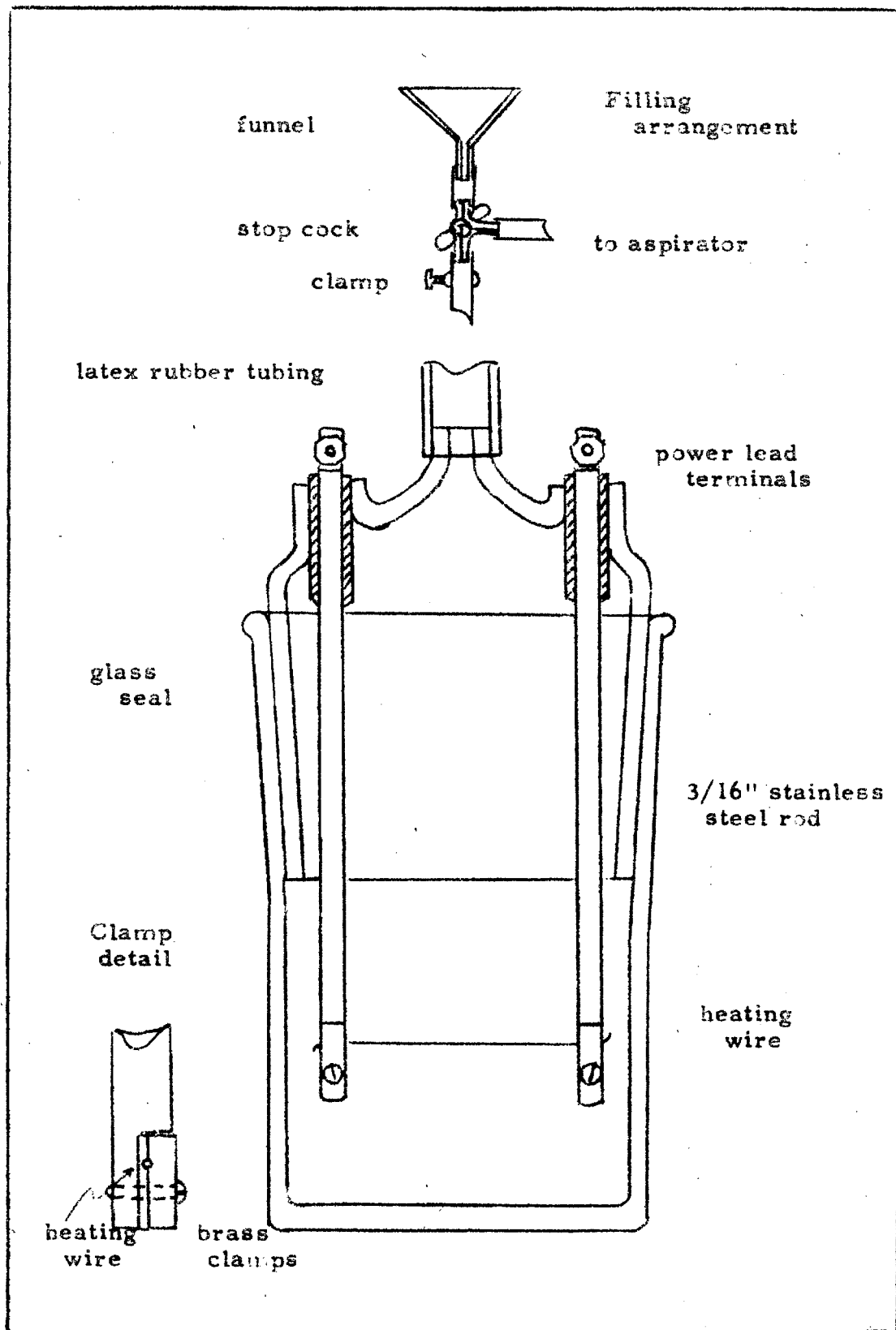
HEAT TRANSFER BOTTLE
Fig. 4

PRESSURIZING TANK
Fig. 5

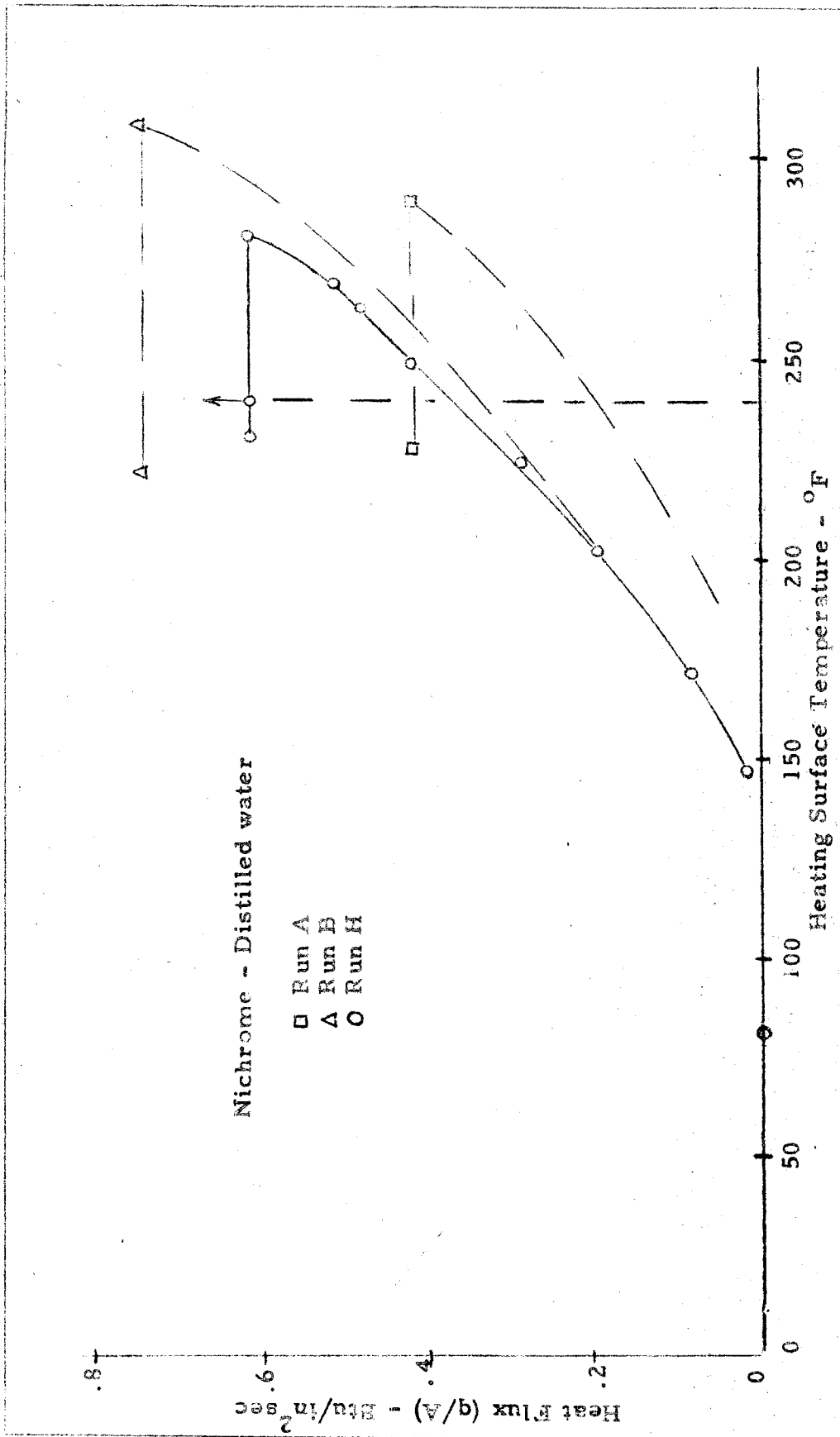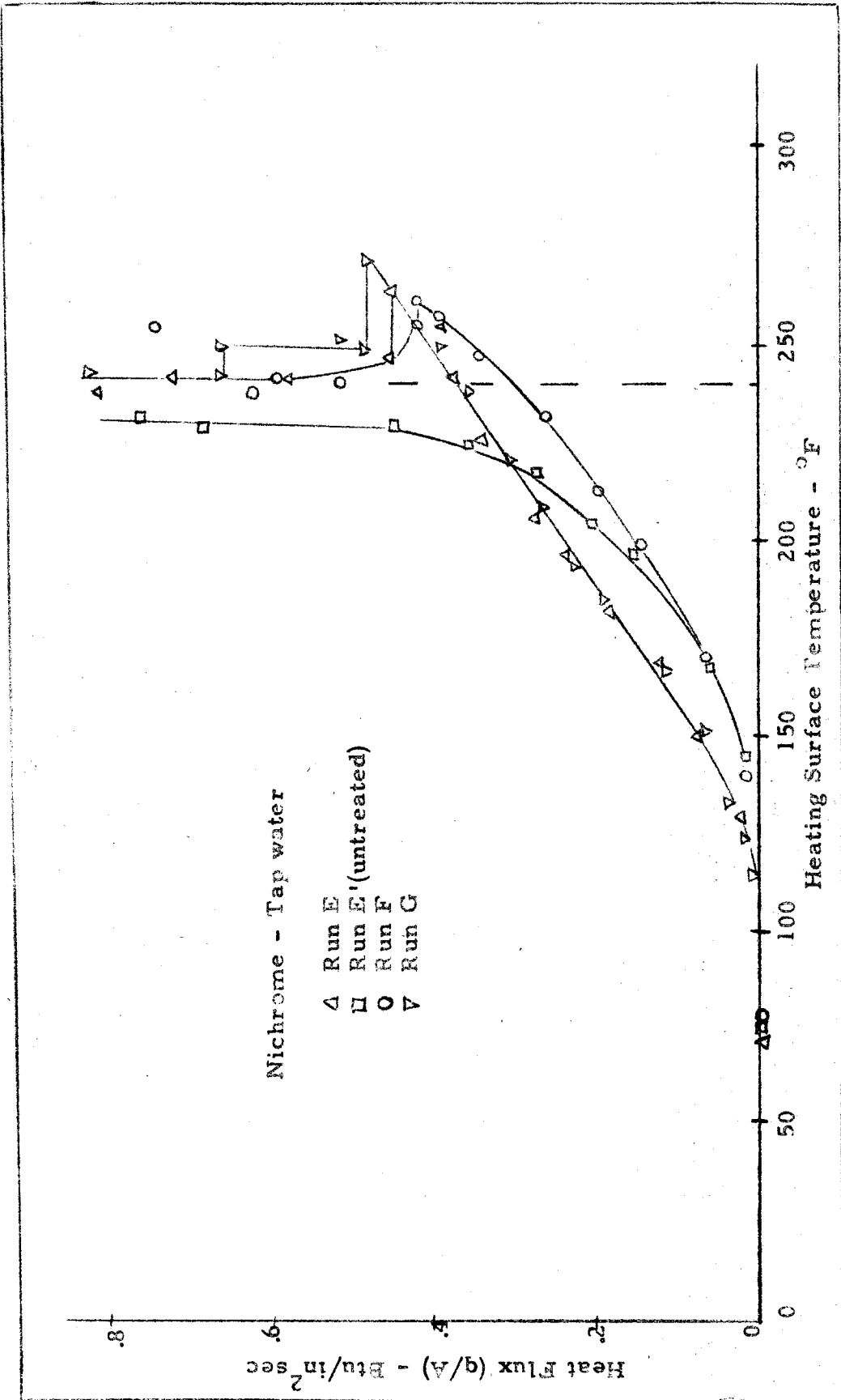BURNOUT HEAT FLUX MEASUREMENTS
Fig. 6

NUCLEATION TEMPERATURE MEASUREMENTS

Fig. 7

NUCLEATION TEMPERATURE MEASUREMENTS.
Fig.8

Nichrome - Tap water

△ Run E
◻ Run E'(untreated)
○ Run F
▽ Run G

NUCLEATION TEMPERATURE MEASUREMENTS
Fig. 9