EFFECT OF ORIENTATION OF A FLAT HEATING SURFACE ON NUCLEATE BOILING HEAT TRANSFER

Thesis by

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ABSTRACT

The object of this experimental investigation was to obtain some information on the effect of the orientation of a heating surface on boiling heat transfer and particularly on the "burnout point". This was achieved by electrically heating a chromax strip that was cemented to some refractory backing so as to limit the heat transfer to one surface of the strip. The heating unit could be rotated about the longitudinal axis, thus allowing tests to be carried out with the surface of the strip oriented upwards, downwards, and vertically. The experiments were performed in a pool of subcooled isopropyl alcohol at three bulk temperatures. The results were presented in a graphical form with the heat transfer per unit area as a function of the difference between the strip surface and the bulk fluid temperatures. The curves obtained with the strip facing upwards or in a vertical position were qualitatively similar to the characteristic boiling curve while the curve for the downward facing strip resembled one commonly associated with free convection without boiling. With the bulk temperature at $80^{\circ}F$, for example, the burnout heat flux for the strip facing upwards was found to be 0.31 Btu/in^2-sec, while that for a downward facing strip was 0.062 Btu/in^2-sec. These results indicate the necessity of considering the orientation of heating elements in the design of heat transfer equipment which is to operate in the nucleate boiling region.

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I INTRODUCTION

Boiling heat transfer is defined as the heat transfer from a surface to a liquid under such conditions that the surface temperature is sufficient to create a vapour phase (Ref. 1). The existence of this type of heat transfer has been recognized for a long time, and many experimental and theoretical studies have been carried out in this field. The applications of this work have been manifold and include the operation of nuclear power plants and the cooling of rocket motors.

Many of the experimental investigations have been concerned with free convective heat transfer from electrically heated wires (Ref. 2,3), tubes (Ref. 4,5), and flat surfaces (Ref. 6,7). These have served as heating elements submerged in a stationary pool of liquid. Typical results of such investigations are presented in Fig. 1 in the form of a curve showing the heat transfer rate versus the difference between the fluid bulk temperature and the temperature of the heating surface. The results for most of these arrangements are qualitatively very similar and show the following characteristics. The portion of the curve AB corresponds to the usual convective heat transfer without boiling. As the surface temperature increases beyond the point B (slightly above the liquid boiling point), the heat transfer increases sharply with further increase in the surface temperature. Visual observations have shown that at Point B, small bubbles appear on the heating surface. These bubbles may grow and collapse without leaving the surface, or they may detach from the surface depending on the bulk temperature and the amount of air dissolved in the liquid. As the temperature of the surface is increased, more and more bubbles appear. The part of the curve BC is referred to as the nucleate boiling region because the vapour bubbles are believed to originate from nuclei on the heating surface. This type of boiling continues until further increase in the wall temperature results in the decrease of heat transfer to the point D where the trend is reversed. The portion CD represents an unstable regime and if the heating rate is controlled as it is for electrical heating, the temperature jumps from point C to point F as the heating rate is increased. In many cases, the point F corresponds to a higher temperature than the melting point of the heating element and hence the heater burns out. The point C is therefore often called the "burnout point" although actual destruction of the heating element may not occur, depending on the particular material of the element and properties of the fluid. The determination of the "burnout point" is of great importance to the design of heat transfer equipment because it specifies the maximum heat transfer rate which can be obtained without incurring a sudden and often destructive rise in temperature.

Recently, particular attention has been paid to the orientation of the heating surface and experiments have been performed with flat surfaces facing upwards (Ref. 6) and downwards (Ref. 7). Ishigai and co-authors (Ref. 7) made some experimental studies by heating the top of a copper rod whose bottom end was immersed in a pool of water and served as the heating surface. The copper rod was surrounded by a refractory material forming a common flat surface at the bottom end. Two rods were used in this series of experiments with 25 mm and 50 mm diameters, respectively. The ratios of the rod diameter (d) to the diameter of the refractory (D) were 0.125, 0.25, and 0.50. The curve obtained by plotting the heat flux against the temperature difference was found to be in many ways similar to that obtainable from electrically heated wires although the insulating material surrounding the heating surfaces tended to decrease the burnout point values. For example, the value of burnout heat flux for a diameter ratio of $d/D = 0.25$ ($d = 25$ mm) was found to be only about 22% of the value which, by extrapolation, was obtained for a diameter ratio $d/D = 1$.

The present experiments were conducted in order to obtain further information on the effect of orientation of the heating surface on the heat transfer performance. In order to be able to obtain a very direct comparison, the experimental apparatus was designed so that the same heating surface could be tested in various positions with respect to the gravitational field without altering any of the other test conditions. This was achieved by using a strip which was cemented to a refractory surface and which could be oriented in any direction. It was hoped that the results might also give a feel for the importance of the magnitude of the gravitational field itself on this type of heat transfer.

II EXPERIMENTAL INSTALLATION

The fluid selected for the present experiments was isopropyl alcohol. This selection was made because the heat transfer characteristics and boiling point of this fluid are such that the so-called "burnout point" may be reached without actually destroying the heating surface. In addition, there exists some prior information on boiling heat transfer in this fluid. The fact that no attempts were made to remove the air dissolved in the alcohol may be justified by two reasons: first, in most actual applications the liquid would be air-saturated, and hence data for aerated liquids would be of practical significance; secondly, the main purpose of the experiment was to obtain comparative results for various geometrical positions of the strip, and therefore the air content in the alcohol was not considered to critically affect this relative performance.

The alcohol was contained in a 7-1/2 inches in diameter by 4 inches high glass vessel with a plexiglass top at atmospheric pressure. To obtain an elevated alcohol temperature, the vessel was placed in a water bath heated by two immersion heaters. For the low alcohol temperature, the container was placed in an ice bath. A mercury-in-glass thermometer for bulk temperature measurement was placed at the same level as the strip but at a distance of 2-1/2 inches from it.

In order to limit the heat transfer from the strip to only one side, it became necessary to cement the strip to some insulating material. This was tried using various cements that should retain their adhesive properties up to a temperature of about $300^{\circ}F$. However, in the first few attempts the strip expanded and sheared off from the cement, thus introducing a second heat transfer surface as the heating progressed. To eliminate this problem, a second design was tried in which one end of the strip (not cemented this time) was loaded with a compression spring. It became apparent, however, that an electrical contact, loose enough to allow the sliding of the strip on expansion, was poor and caused erratic variations in the electrical resistance. In addition, the heat transfer from the lower strip surface was still not fully eliminated. A further method of installation was finally attempted, in which the test element consisting of a 0.001 inch thick chromax strip was cemented to a 1/16 inch thick piece of bakelite as shown in Fig. 2. The cement used was Stycast 2662 with catalyst No. 14 and the assembly was cured at 212°F for 3 hours. This cement is designed to retain satisfactory adhesive properties for temperatures up to 500°F.

After cleaning the strip and bakelite with methyl-ethyl-ketone, a layer of the cement was applied to the bakelite and the strip laid on. A slightly curved metal fixture, Fig. 3, was clamped onto the bakelite piece and held there during the curing process. This metal fixture was designed so that it came into contact with the strip and the non-cemented part of the bakelite only. When the cement was cured and the metal fixture removed, the bakelite piece straightened out elastically leaving the strip in tension. The strip would relieve, but not fully remove, the tension on expansion during the heating process. This tension served to insure intimate contact between the strip and its backing, and so this design was actually successful in preventing the breakage of the bond between the metal strip and the plastic backing. The bakelite was then bolted to two copper contacts which fitted into the threaded rods, Fig. 4. The strip could then be rotated to face any desired direction. Figure 5 shows the strip facing upwards, downwards, and in a vertical position.

Chromax was chosen as the heating strip material for its low coefficient of linear expansion ($8.78 \times 10^{-6}/^{\circ}F$) which remains essentially constant in the 68°F - 932°F range, and for its suitable resistance coefficient (2.0×10^{-4} ohm/ohm-°F). The low coefficient of expansion minimizes the shearing forces on heating, and the temperature coefficient of electrical resistance is sufficiently high to allow reasonably accurate temperature measurements. Chromax also possesses a relatively high melting point (2516 ^{o}F) and a satisfactory tensile strength of 1.5×10^{5} psi at $68^{o}F$. This high melting point allowed the strip temperature to reach the burnout point and even jump to the film boiling branch of the temperature versus heat transfer curve without causing actual destruction.

In order to measure the strip temperature, the strip itself was made to be one of the legs of a Wheatstone bridge. A diagram of the circuit is shown in Fig. 6 with the test section labeled R_2. The resistances R_1, R_3 and R_4 were made of long manganin wire wrapped around sheets of plexiglass and immersed in distilled water at room temperature. Because of manganin's very low temperature coefficient of resistance (8.3×10^{-6} ohm/ohm-^{o}F) and the relatively high surface area of these resistances compared to that of the strip, the electric resistances of these three resistors were maintained at essentially constant values. The resistance R_5 was a 1000 ohm variable resistor (helipot) in parallel with R_1 for balancing the bridge before each run. The total resistance R_6 consisted of a series of three separate resistors (ranges: 0-15, 0-25, 0-100 ohms) to allow the desired variation in the current input. A 1.5 volt dry cell in series with a 12 ohm resistor (R_7) was used for bridge balancing only. Direct current was chosen so as to avoid any A.C. frequency interference with bubble generation.

The strip temperature was derived from the unbalance in the bridge caused by the change in the strip resistance. The voltage unbalance was measured with a Hewlett-Packard D.C. Micro-Volt-Ammeter, while the input current was measured with a Weston D.C. Ammeter (ranges: 0-3, 0-15, 0-30 amperes). The resistance values of the bridge resistors R_1, R_3, and R_4 were determined accurately by means of an ESI impedance bridge prior to their installation in the test unit.

The above method of measurement does, of course, yield average values of the temperature for the entire strip. This value is, however, sufficient or even preferable for the present investigation as it eliminates spurious local temperature readings which might be caused, for example, by local surface conditions.

The use of thermocouples for the measurement of strip temperatures was not pursued because of the difficulties expected in placing the thermocouples in such a position that reliable readings could be obtained while at the same time maintaining electrical insulation from the strip.

III PROCEDURE

The experiments were performed at three bulk temperatures, namely 42°F, 80°F (room temperature), and 150°F. For each of these temperatures, runs were made with the strip facing upwards, downwards, and in a vertical position. The results are presented in Figs. 7 through 15 in which the heat transfer rate per unit area is shown as a function of the difference between the strip temperature and the temperature of the alcohol. The extent to which the curves shown in Figs. 7, 8 and 9 were found to be reproducible is shown in Figs. 10 through 14.

The bridge was balanced at the beginning of each run and the data taken at about 1.0 amp intervals for the vertical and 'up' positions, and at 0.5 amp intervals for the "down" position of the strip. In this manner, data were obtained in the free convection region as well as in the nucleate boiling region up to the "burnout point". Again, the "burnout point" was taken as the point of maximum heat transfer rate in the nucleate boiling region just before the temperature jump across to the film boiling regime. At each step the unbalance in the bridge and the corresponding current value were recorded and visual observations were made. In addition, several experiments were performed with nichrome wires without any inert backing for comparison purposes.

IV VISUAL OBSERVATIONS

Considering first the experiments conducted at a bulk temperature of 80°F and for the heating strip facing upwards, the following observations were made. No bubbles were visible until the temperature difference between the strip and the alcohol reached about 60°F, which corresponds to a strip temperature of 140°F. At this temperature, a few (usually between 2 and 4) small bubbles of the order of 1/32 inch in diameter appeared. These bubbles were frequently seen to move along the length of the strip at an approximate speed of one inch per second, a motion which is ascribed to possible small charges at the bubble surface. This relatively slow motion, however, is believed to be of secondary importance in regard to the heat transfer. The bubbles eventually detached and rose to the surface with negligible changes in size. These bubbles are believed to contain a large amount of air for two reasons: first, the strip surface temperature was only at approximately 140°F, which is well below the boiling point of isopropyl alcohol (180°F at atmospheric pressure). Secondly, when the bubbles did detach, they would rise to the surface without a significant change in size. Had the contents of these bubbles been pure vapour, then, condensation should have taken place resulting in the collapse of the bubbles prior to their reaching the surface. Further increase in the current increased the size of the bubbles and decreased their motion along the strip. They also detached from the surface at a faster rate. When the surface temperature was near the boiling point, the bubbles were so numerous that their longitudinal motion ceased completely and they formed a rather stationary array on the surface. As the surface temperature exceeded the boiling point by about 20^{o}F, a hissing sound was heard which was attributed to the collapse of vapour bubbles and was taken as an indication that true boiling was in progress. It is at this point also that the curve of heat transfer rate versus temperature difference (e.g., see Fig. 7) shows a definite increase in slope which indicates the start of a new mechanism of heat transfer. Further increase in current increased the rate of formation and detachment of bubbles, and the strip temperature rose gradually. This trend continued until the strip suddenly began to glow at one or two points indicating that the burnout point had been reached and that the heat transfer mechanism had changed from nucleate to film boiling.

When the strip faced downwards, the bubble activity was much different from that described above. Small bubbles containing a large amount of air started to grow, but instead of detaching they merged to form even larger ones until there existed about five gas-vapour masses covering most of the strip and a portion of the bakelite backing. Additional small bubbles generated elsewhere along the strip also joined the large ones. The surface temperature increased rapidly with little increase in the current. Finally, the bubbles grew sufficiently large compared to the width of the backing so that they escaped around the sides. When this occurred, the temperature of the strip decreased because cooler liquid was replacing the bubbles. This bubble escape took place at intervals of about fifteen seconds. This rate was slow enough for the fluctuation in the strip temperature to be followed by the instruments. This formation, growth, and escape continued accompanied by temperature fluctuations until the burnout point was reached.

Finally, in this series of experiments the strip was placed in a vertical position. The general behavior as well as the results obtained for this position were very similar to those for the case where the strip faced upwards. The bubble activity started at about the same strip surface temperature (140°F). The small bubbles on the strip surface had no longitudinal motion. Rather they were swept off by convection currents and were soon replaced by newer ones generated from the same spots. Further increase in the heating rate increased the bubble activity and the number of generating points which seemed to be more or less equally spaced along the strip length. As the heat flux increased the bubble spacing became narrower with the result that the strip was almost covered with streams of rising bubbles. The flow picture remained this way until the burnout point was reached. Temperature readings were steady throughout.

For the elevated bulk temperature of 150^{o}F, the bubble activity was quite similar to that for room temperature. The activity, however, appeared to be more intense, that is, the growth, collapse or detachment was more rapid. Boiling with the associated hissing sound was, of course, reached for smaller temperature differentials, as the bulk temperature was now closer to the boiling point.

Finally, for the experiments conducted at the lowest alcohol temperature (42^{o}F), bubble formation did not start until the temperature differential reached about 110^{o}F, but this again corresponds to a strip temperature of about 150^{o}F. The flow appeared to be quite similar to that at room temperature, except that the bubble cycle was slower and the bubbles appeared quite "sluggish". Whereas at the higher bulk temperature bubbles escaped freely from the strip surface, this time the rate of detachment was very low even for increased heat flux. The bubbles after reaching a certain size almost seemed to "stick" to the strip. This same condition persisted until "burnout", at which time the strip started to glow at all the places where the bubbles were located. Figure 9 indicates the low burnout point obtained, much lower than had been expected. It is guessed that a combination of the changes in fluid properties such as surface tension and viscosity, and to a greater extent, gas solubility were responsible for the behavior of the gas-vapour bubbles at this temperature. There was very little change in the maximum heat transfer rate even when an attempt was made to brush off the bubbles.

The bubble behavior for the strip facing downwards was quite similar to that of the corresponding position at room temperature. Again, the bubble activity was slower, and the burnout heat flux was only slightly higher than that for the alcohol temperature of 80°F.

Boiling activity with the strip in a vertical position was comparable to that for the "up" position. The bubbles seemed to leave the strip surface somewhat more readily than in the latter case, aided probably by the convection currents which swept the surface more effectively in this position. The burnout point was slightly higher than that obtained in the "up" position.

V DISCUSSION OF RESULTS

The results are presented in graphical (Figs. 7 through 14) and tabular (Tables 1 through 6) form in the Appendix. These figures show heat transfer per unit area as a function of the difference between the temperature of the strip and the bulk temperature of the alcohol with the strip in the up, down, and vertical position, and at the three bulk fluid temperatures. Specifically, Figs. 7, 8, and 9 show the effect of strip orientation at the alcohol temperatures of 80°F, 150°F, and 42°F, respectively. Figures 10 through 14 give a comparative picture of the results obtained with different strips. Table 1 shows some of the "burnout point" values, while the data corresponding to Figs. 7, 8, 9, and 15 are tabulated in Tables 2 through 6.

Considering first the data at one bulk temperature, say 80°F (see Fig. 7), one immediately notices the strong effect of orientation of the strip on the heat transfer coefficient and on the burnout point values. It may be seen from Fig. 7 that for both the vertical and upward facing positions, the heat transfer rate after onset of boiling increases sharply with increasing strip temperatures, in a manner similar to that of the familiar boiling curves. On the other hand, the downward facing strip exhibits an entirely different behavior. There is very little change in the slope of the curve throughout the various regimes of heat transfer and the entire curve has the general appearance of one obtained in ordinary free convective heat transfer. Of major importance also is the decrease in burnout point which is obtained for the strip facing downwards compared to the value which is reached for the upward facing strip. This decrease in heat transfer and burnout point is probably caused by the inability of the convection currents to sweep away the bubbles that are being generated and, therefore, an insulating layer similar to that usually occurring in the film boiling region is formed at a relatively low temperature differential. The higher thermal resistance caused by this blanket reduces the dissipation of heat to the alcohol and hence the burnout point is reached at a much lower heat transfer rate than for the upward facing plate. In brief, when the strip is facing downward the formation of bubbles does not bring about any significant added agitation of the fluid at any time and no improvement in the heat transfer mechanism due to bubble motion is obtained. The shape of the curve reflects this fact, and the sudden rise of the heat flux versus temperature difference curve at the onset of nucleate boiling is missing.

It is pertinent at this point to note the results of an experimental investigation by Costello, Adams, and Clinton (Ref. 8). The authors found that in the case of semi-circular heaters rotating at high speed, the burnout heat flux for the inside surface (which corresponds to the strip facing upwards as the effective gravitation vector is pointing toward the heating surface) is higher than that for the outside surface. This is in agreement with the results presented here. By extrapolating these as well as the present results, one might guess that the burnout heat flux would also be lowered by the reduction of the gravitational force.

The burnout heat flux is usually lower for higher bulk temperatures because of the decreased temperature difference between the strip and the fluid which is needed to cause boiling. The results presented in Figs. 7 and 8 for the bulk temperatures of $80^{\circ}F$ and $150^{\circ}F$ agree with the above expectations. There is, however, a definite deviation from this trend for the experiments conducted at $42^{\circ}F$. Here, one might have expected that by lowering the bulk temperature, an increase in the burnout heat flux would result. Instead, the opposite was observed. This result is qualitatively explained by the fact that the bubble motion decreased significantly at this temperature and the bubbles showed a tendency to "stick" to the plate as was mentioned previously. This change in bubble behavior is ascribed principally to the fact that air is more soluble in the liquid at the low bulk temperature. The liquid at $42^{\circ}F$, therefore, may be assumed to contain a relatively large amount of air and when it is heated in the vicinity of the strip, it will be highly super-saturated with air. The bubbles will then contain a large fraction of gas and as a consequence they tend to be more stable on the heating surface. A similar behavior has been noted by a previous experimenter in connection with burnout points in aerated water (Ref. 9). The phenomenon is discussed in some detail in the cited reference.

It has to be realized that the results presented here apply to a particular strip with an insulating backing of a particular width. Undoubtedly, the results (especially for the strip facing down) would differ for varying geometries of the heating surface and the insulating backing because of change in flow patterns. This has been indicated by the results of Ishigai and co-authors (Ref. 7) who have conducted experiments for the heat transfer from a downward facing disc surrounded by insulating annuli of various sizes. Some of their results are presented in Table 1. The results showed that the higher the ratio of radius of the insulator to that of the heater, the lower the burnout point, as was pointed out in the introduction. The high (1.01 Btu/in^2-sec) burnout heat flux of nichrome wire (diameter 0.01 inch) in isopropyl alcohol at room temperature is indicated in Fig. 15 for comparison with the strip results. In this connection it should be recalled, however, that small wires generally yield much higher burnout point values than flat surfaces.

It is of further interest to compare the present results with the heat transfer rates that would be expected in normal free convection.

McAdams (Ref. 10) gives the following equation for calculating the heat transfer coefficient for a heated horizontal square plate facing upwards in the laminar range:

$$\frac{hL}{k_f} = 0.54 \left[\frac{L^3 \rho_f^2 g \beta_f \Delta T}{\mu_f^2} \left(\frac{\mu C_p}{k} \right)_f \right]^{0.25} \tag{1}$$

This equation is valid for free convective heat transfer without boiling and the fluid properties evaluated at the film temperature, i.e., the average of the fluid and heater temperature. Although the geometry for which this equation is written differs somewhat from the one of the present experiments, the results are believed to be suitable for comparison purposes. Calculations were made using this equation taking the strip width as the characteristic length, and the resulting curve is shown in Fig. 7. Comparison with the experimental curves shows close agreement in the pre-boiling region. The curve for the strip facing up begins to deviate markedly from the normal free convective curve as soon as boiling begins showing a sharp increase in the heat transfer rate. However, the curve obtained from the strip facing downwards maintains an almost constant slope throughout showing no improvement in heat transfer with boiling.

VI ERROR ANALYSIS

The two principal quantities that were to be determined in the present experiments were heat transfer per unit area (Q/A), and temperature difference (ΔT).

In the determination of heat transfer, the following equation was used:

$$\frac{Q}{A} = \frac{3413\, I_1^2 \gamma}{3.6 \times 10^6\, w} = \frac{3413}{3.6 \times 10^6} \frac{\gamma}{w} I_t^2 \left[\frac{R_3 + R_4}{R_1 + R_2 + R_3 + R_4} \right]^2 \qquad (2)$$

Differentiating this equation, one arrives at

$$\frac{d(Q/A)}{(Q/A)} = \frac{d\gamma}{\gamma} - \frac{dw}{w} + \frac{2dI_t}{I_t} + 2\left[\frac{dR_3 + dR_4}{R_3 + R_4} - \frac{dR_1 + dR_2 + dR_3 + dR_4}{R_1 + R_2 + R_3 + R_4} \right] \qquad (3)$$

The overall percentage error was obtained by summing up the absolute values of all of the quantities on the right hand side of equation 3. The numerical values of the strip resistivity and width were known to within ±5% and ±4%, respectively, while the error in the current sending was assessed at ±2% including the accuracy of the ammeter as well as a reading error. In addition, the ESI impedance bridge used for the measurements of resistances R_1, R_3, and R_4 had an error of 0.15% + 0.001 ohm. Substituting for the numerical values, one obtains

$$\frac{d(Q/A)}{(Q/A)} = 5 + 4 + 2(2) + 2\left[(.11 + .1) + .05 + .95 + .065 + .06\right] \mp 13.87 \quad (4)$$

Therefore, the absolute possible error in the determination of heat transfer was approximately ±14%. It should be emphasized that it would be most unlikely that all the errors would be in one direction, i.e., positive or negative at any given instance. It should also be noted that most of the possible errors considered above are essentially fixed, at least throughout a given series of experiments involving the same strip and bridge resistors. Essentially, the only source of error that leads to variations in consecutive experiments is due to the current measurements. This error is of the order of ±4%, and hence for a given experimental strip, the heat transfer results are expected to be reproducible to within ±4%. It is this variation that is of importance when determining, for example, differences in the results brought about by the orientation of the strip.

In calculating the temperature differential, the following equation was used:

$$\Delta T \mp \frac{\Delta V\left[R_1 + R_2 + R_3 + R_4\right]}{R_3 R_0 \alpha I_t} \quad (5)$$

Logarithmic differentiation of this equation leads to

$$\frac{d(\Delta T)}{\Delta T} = \frac{d(\Delta V)}{\Delta V} + \frac{dR_1 + dR_2 + dR_3 + dR_4}{R_1 + R_2 + R_3 + R_4} - \frac{dR_3}{R_3} - \frac{dR_0}{R_0} - \frac{d\alpha}{\alpha} - \frac{dI_t}{I_t} \quad (6)$$

The major source of error in determining this temperature differential lies, probably, in the resistance coefficient of temperature, α. A value obtained from the manufacturer's catalogue was used in the present calculations, and a plot of the strip resistance as a function of temperature from the same source is presented in Fig. 16. In the course of the present work a determination of α was made, and the results obtained agreed fairly well with the catalogue value. The percentage error was, nevertheless, estimated to be within about ±5%, and the maximum error in the voltage readings was ±3% of the full scale value. Therefore, the total percentage error is estimated at

$$\frac{d(\Delta T)}{\Delta T} = (3+1) + (.05 + .95 + .065 + .06) + .2 + .25 + 5 + 2 = 12.67\% \quad (7)$$

A calculation was also made (see Appendix) to determine the heat loss through the ends of the strip and the corresponding deviation from the average temperature of the strip. The heat loss was found to be less than 1% of the total heat transfer, and 96% of the strip length was shown to be at a temperature within 1% of the maximum. The error due to this temperature variation was, therefore, assessed at less than 2%. Therefore, the maximum possible absolute error in the temperature measurement was taken to be ±15%.

Again, not all of this total error affects the reproducibility of the results, but only that portion caused by the readings of the voltage unbalance and the current input. The reproducibility is therefore believed to be within ±6%, and as mentioned earlier, it is this value that is of importance in comparing the data obtained from a given strip.

One further aspect should be considered here. As was noted previously, large bubble aggregates would detach at intervals of approximately 15 seconds when the strip was in the downward facing position. This would cause the strip temperature to fluctuate with an amplitude of about ±14% of the temperature differential. Similar but much less extensive fluctuations amounting to only about ±3% also occurred when the strip was facing upwards. In plotting the various graphs, it was decided to take the average values of these temperature fluctuations.

VII CONCLUSION

The results presented here strongly suggest that in the gravitational field, free convective heat transfer in the nucleate boiling region and the burnout heat flux are very dependent on the orientation of the heating surface. For the configuration of the present test series, for example, the burnout heat flux at $80^{\circ}F$ bulk temperature was 0.31 Btu/in^2-sec for the heating strip facing up and only 0.062 Btu/in^2-sec for the strip facing downwards, other test conditions being identical. These results clearly emphasize the necessity for carefully considering the orientation of heater elements in the design of heat transfer equipment which is to operate in the nucleate boiling regime. On the basis of this sensitivity to orientation, one might also expect that changes in the strength of the gravitational field will have a significant effect on the burnout heat flux.

APPENDIX

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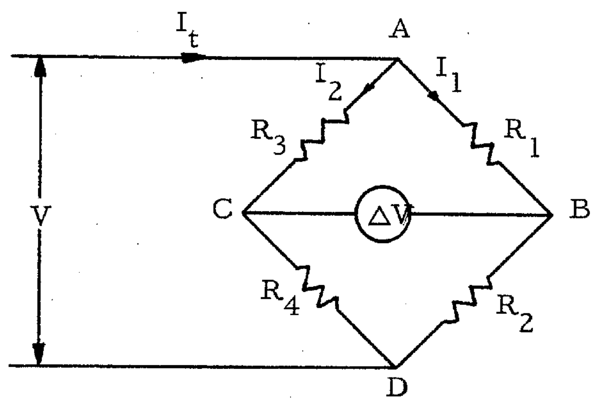
Nomenclature

A	strip surface area
C_p	specific heat at constant pressure
d	copper rod diameter
D	refracory outer diameter
g	acceleration due to gravity
h	heat transfer coefficient
I_1	electric current through test section
I_t	total electric current
k	thermal conductivity
L	characteristic length in equation 1
ℓ	half of the strip length
Q	heat transfer rate
R	electrical resistance
R_o	strip resistance corresponding to the bulk fluid temperature
T	temperature
T_o	bulk fluid temperature
ΔT	difference between the strip and bulk fluid temperatures
t	strip thickness
ΔV	voltage drop across the bridge
w	strip width
α	resistance coefficient of temperature
β	coefficient of volumetric expansion

γ	strip resistance per unit length
γ_o	strip resistance per unit length at bulk fluid temperature
ρ	density
μ	dynamic viscosity

Derivation of Temperature and Heat Transfer Equations



$R_1 = 1.165$ ohms

$R_2 = R_0(1+\alpha\Delta T)$

where $R_0 = 1.08$ ohms

$R_3 = 1.845$ ohms

$R_4 = 1.71$ ohms

At balance, $\frac{R_1}{R_2} = \frac{R_1}{R_0} = \frac{R_3}{R_4} = 1.08.$

Assuming that the current through the voltmeter is negligible at all times, then,

$$I_t = I_1 + I_2.$$

Therefore

$$I_1 = \frac{I_t(R_3 + R_4)}{R_1 + R_2 + R_3 + R_4}$$

$$\Delta V = V_C - V_B \quad \text{where } V_C = I_2R_3 \quad \text{and} \quad V_B = I_1R_1 .$$

Substituting for V_C and V_B and using the fact that $R_1R_4 = R_0R_3$, then

$$\Delta V = \frac{VR_3\ \Delta R}{(R_1+R_2)(R_3+R_4)} \qquad \text{where } \Delta R = R_2 - R_0.$$

Since $V = I_1(R_1+R_2)$ and $R_2 = R_0(1+\alpha\Delta T)$, then

$$\Delta T = \frac{\Delta V(R_1+R_2+R_3+R_4)}{R_0R_3I_t\alpha} \qquad (8)$$

The last equation may be rewritten as

$$\Delta T = \frac{\Delta V(R_1+R_0+R_3+R_4)}{R_0 R_3 I_t \alpha}\left[1 + \frac{R_0 \alpha \Delta T}{R_1+R_0+R_3+R_4}\right]$$

It may therefore be noted that by dropping the last term of this equation, the error thus introduced is less than $R_0\alpha / R_1+R_0+R_3+R_4$. Since $\alpha = 2.0 \times 10^{-4}$ ohm/ohm-^{o}F, it is clear that by assuming $R_2 = R_0$ for the temperature differential calculation, no significant error is introduced. Hence

$$\Delta T = \frac{\Delta V(R_1+R_0+R_3+R_4)}{R_0 R_3 I_t \alpha} \tag{9}$$

Therefore, by measuring I_t and ΔV, ΔT may be calculated.

<u>Heat Transfer:</u>

Heat transfer per unit area is given by

$$\frac{Q}{A} = \frac{I_1^2 R_2}{A} = \frac{I_1^2 \gamma}{w}$$

where γ is the resistance per unit length.

If Q/A is expressed in Btu/in^2-sec, then

$$1055\, Q/A = \frac{I_1^2 \gamma}{w} \tag{10}$$

But $\gamma = \gamma_o(1 + \alpha \Delta T)$ and $I_1 = \dfrac{I_t(R_3+R_4)}{R_1+R_2+R_3+R_4}$. Therefore,

$$Q/A = \left[\frac{I_t(R_3 + R_4)}{(R_1 + R_0(1+\alpha\Delta T) + R_3 + R_4)} \right]^2 \frac{\gamma_o(1+\alpha\Delta T)}{1055\ w}$$

Thus, the above equation may be approximated to:

$$Q/A = \left[\frac{I_t(R_3 + R_4)}{R_1 + R_0 + R_3 + R_4} \right]^2 \frac{\gamma_o}{1055\,w} \left[1 + \alpha\,\Delta T \left(1 - \frac{2R_0}{R_1 + R_0 + R_3 + R_4} \right) \right] \qquad (11)$$

Hence by measuring I_t and using the value of ΔT obtained earlier, Q/A may be calculated. The quantity $\alpha\Delta T(1-2R_0/R_1+R_0+R_3+R_4)$ amounts to about 3% of Q/A, and it was included in all calculations.

End Effects of the Strip

Taking a heat balance for a longitudinal segment of the strip Δx: heat generated is equal to the convective heat transfer to the alcohol, plus the conductive heat transfer along the strip to the ends. Symbolically,

$$\frac{dQ}{dx}\,\Delta x = h(T-T_o)w\Delta x + wtk\left[\frac{dT(x)}{dx} - \frac{dT}{dx}(x+\Delta x)\right] \qquad (12)$$

Rearranging the terms and taking the limit as $\Delta x \rightarrow 0$:

$$\frac{d^2T}{dx^2} = \frac{h}{kt}\left[(T-T_o) - \frac{1}{hw}\,\frac{dQ}{dx}\right] \qquad (13)$$

The boundary conditions are:

at $x = 0$, $\dfrac{kdT}{dx} = 0$ and

at $x = \ell$, $T = T_o$ where the strip length is 2ℓ.

Let $T-T_o - \dfrac{1}{hw}\,\dfrac{dQ}{dx} = \theta$ and $\dfrac{h}{kt} = a^2$. Equation 13 then reduces to

$$\frac{d^2\theta}{dx^2} = a^2\theta \qquad (14)$$

Solving this equation and applying the boundary condition, one finally arrives at:

$$T = T_o + \frac{1}{hw}\,\frac{dQ}{dx}\left[1 - \frac{\cosh ax}{\cosh a\ell}\right] \qquad (15)$$

Therefore the conductive heat transfer at the end of the strip is:

$$\frac{wt\,kdT}{dx}\Bigg|_{x=L} = \frac{kat}{h}\,\frac{dQ}{dx}\,\tanh a\ell \qquad (16)$$

Taking a point on the curve for the strip facing up:

$$Q/A = 0.25 \quad \text{Btu/in}^2\text{-sec}$$

$$\Delta T = 192^\circ F$$

Inserting the numerical values for the quantities in equation 16, it is found that the heat lost at one strip end is 1.3 Btu/hr. Since the 0.25 Btu/in^2-sec corresponds to 340 Btu/hr, then the percentage heat loss is:

$$\frac{2 \times 1.3}{340} = 0.76\% \quad .$$

Temperature Profile:

The maximum temperature is at the point x=0, i.e.,

$$T = T_o + \frac{1}{hw}\,\frac{dQ}{dx}\left(1 - \frac{1}{\cosh a\ell}\right) .$$

The last term is negligible. It would be of interest to find the numerical value of x where the temperature differential $T-T_o$ is 99% of $\frac{1}{hw}\frac{dQ}{dx}$. Solving the equation

$$0.99\,\frac{1}{hw}\,\frac{dQ}{dx} = \frac{1}{hw}\,\frac{dQ}{dx}\left[1 - \frac{\cosh ax}{\cosh a\ell}\right]$$

it is found that $x/\ell = 96\%$. Hence the error in the temperature calculated due to this variation is assessed to be 2%.

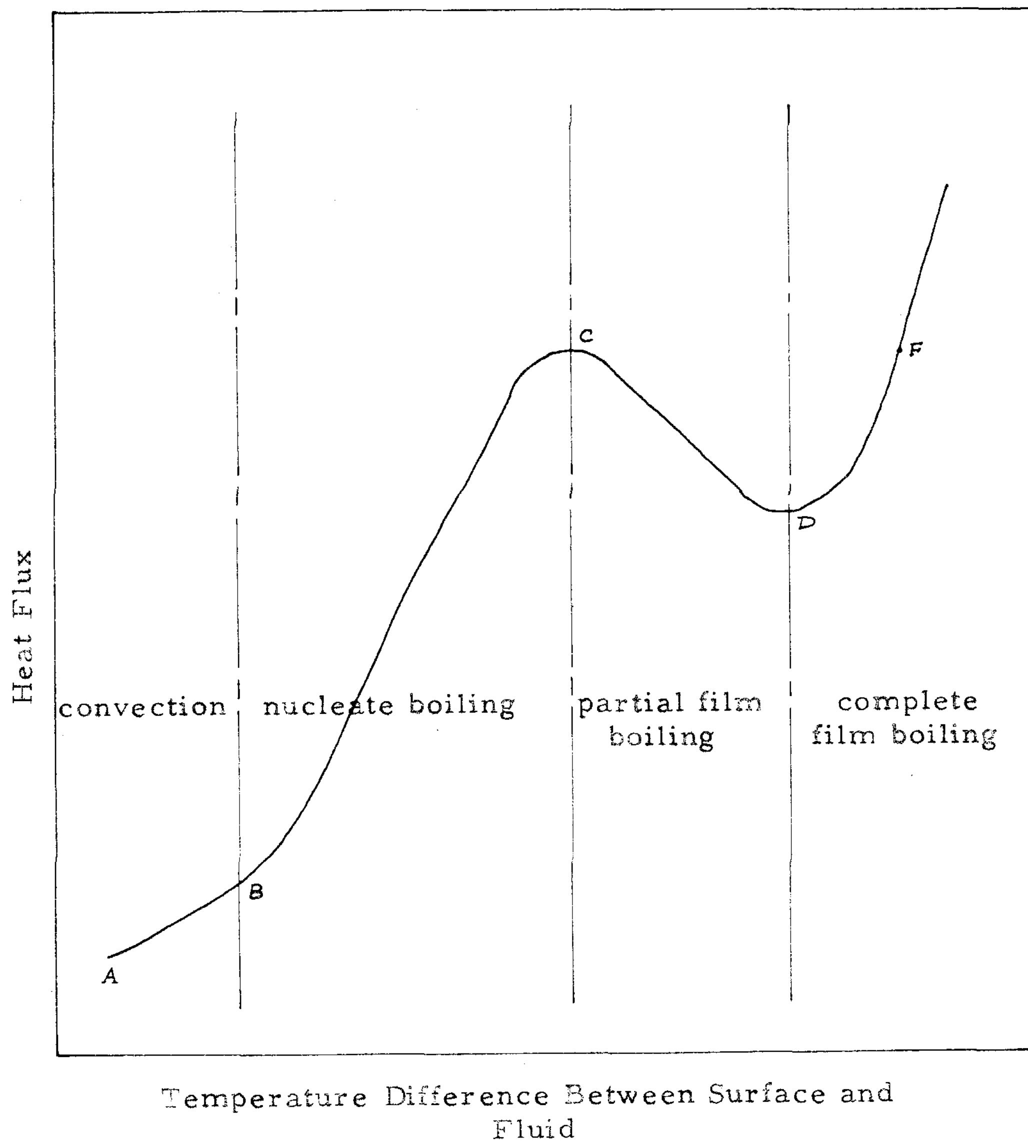


Fig. 1 Typical boiling heat transfer curve.

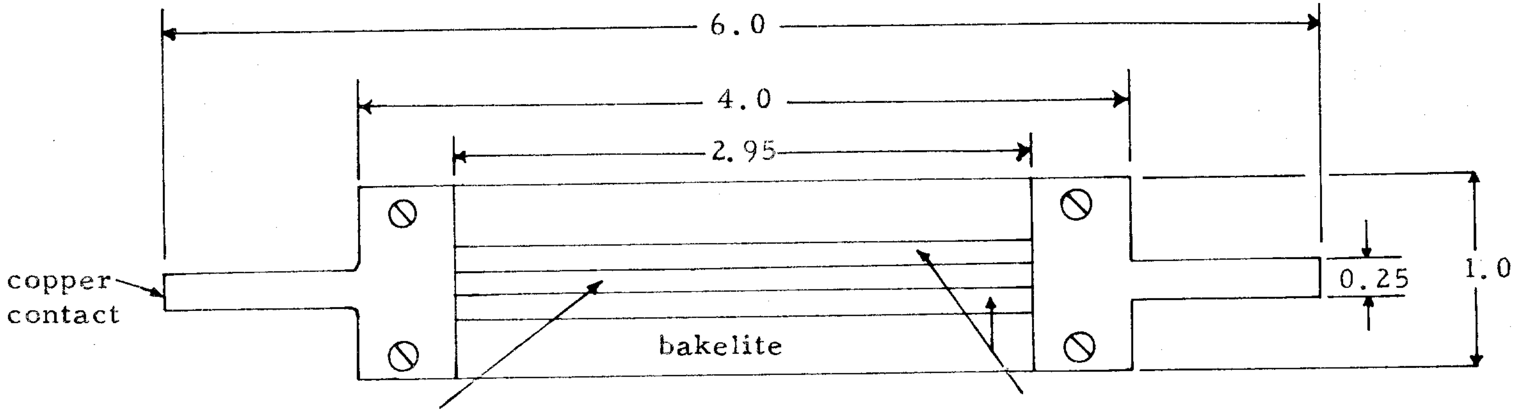


Fig. 2 Test section.

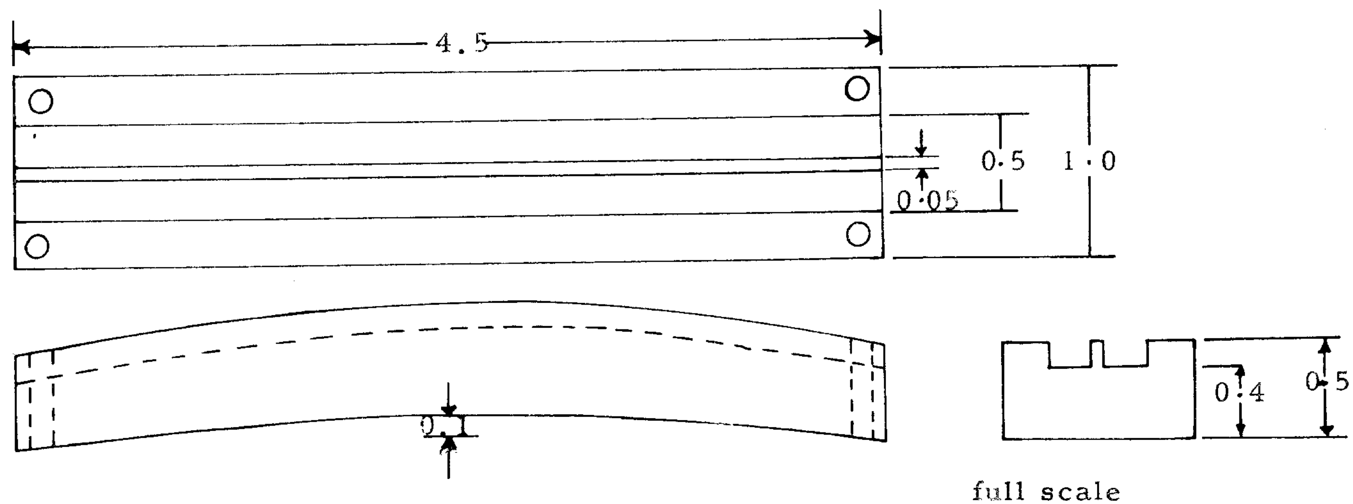


Fig. 3 Aluminum fixture.

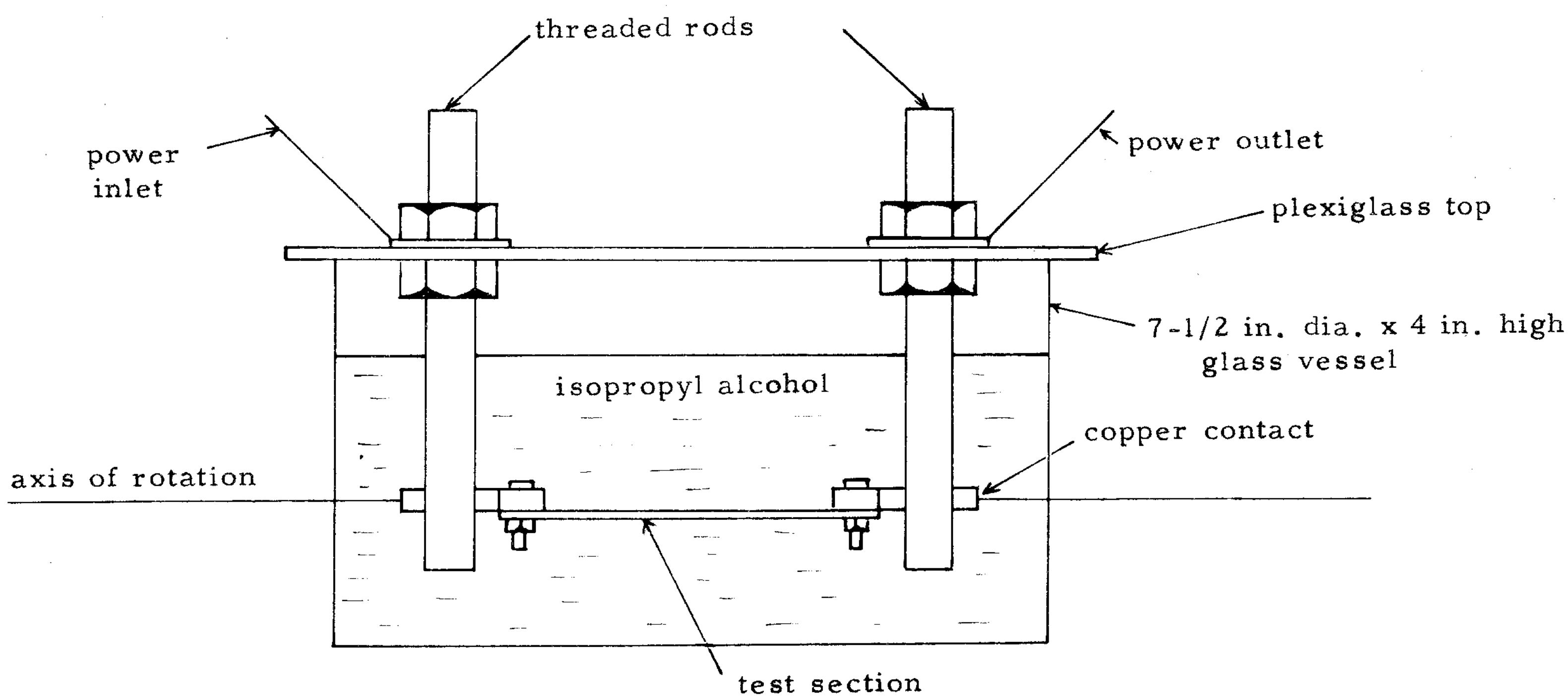


Fig. 4 Test section installation.

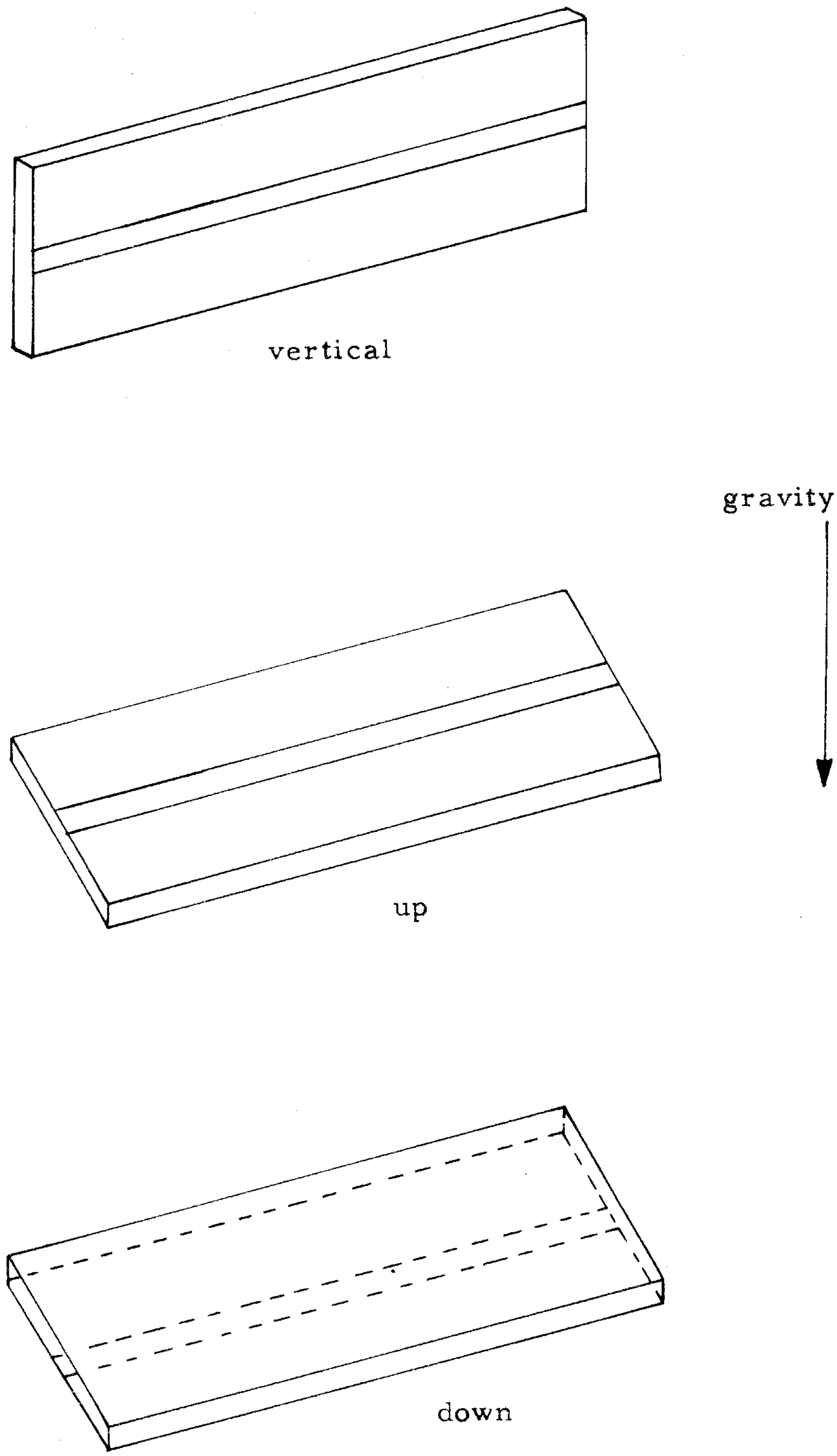


Fig. 5 The strip in various test positions.

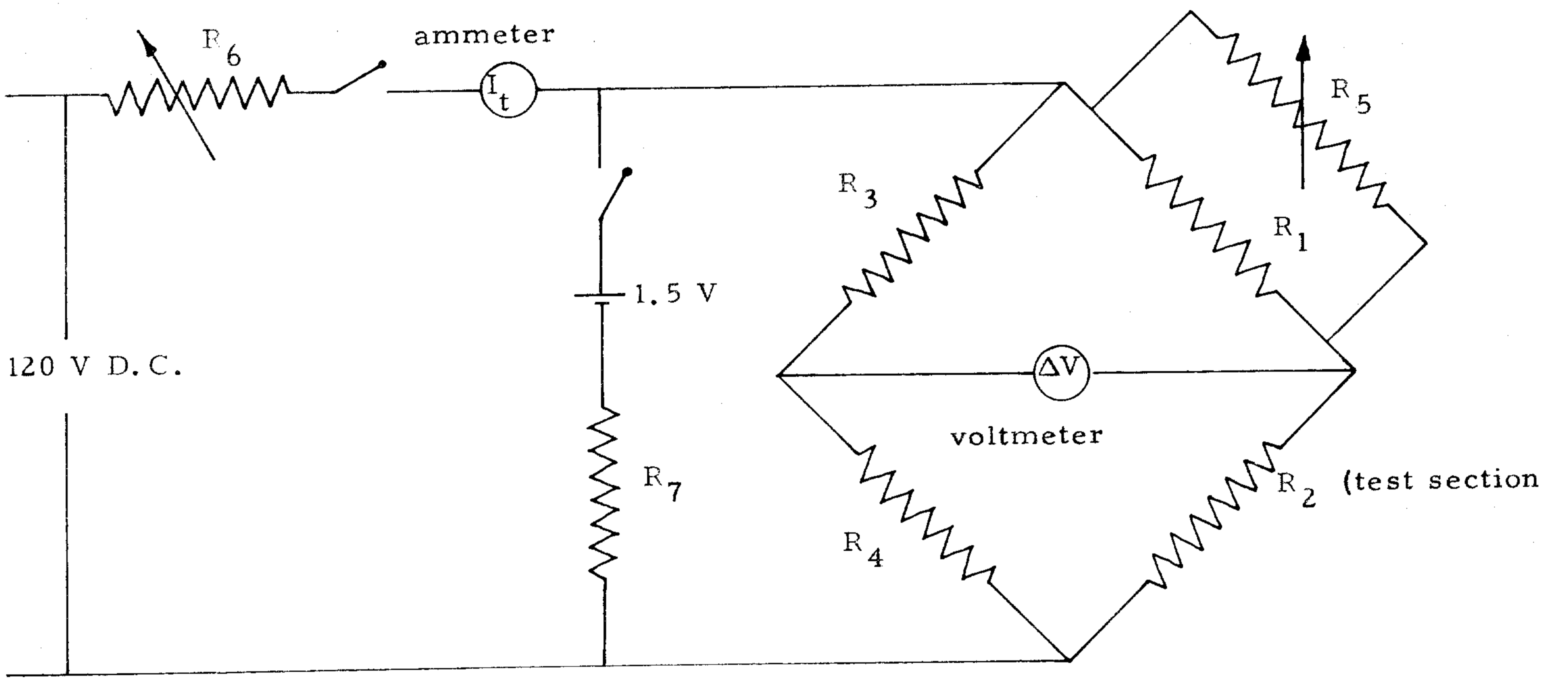


Fig. 6 Electrical circuit for heating and temperature measurement.

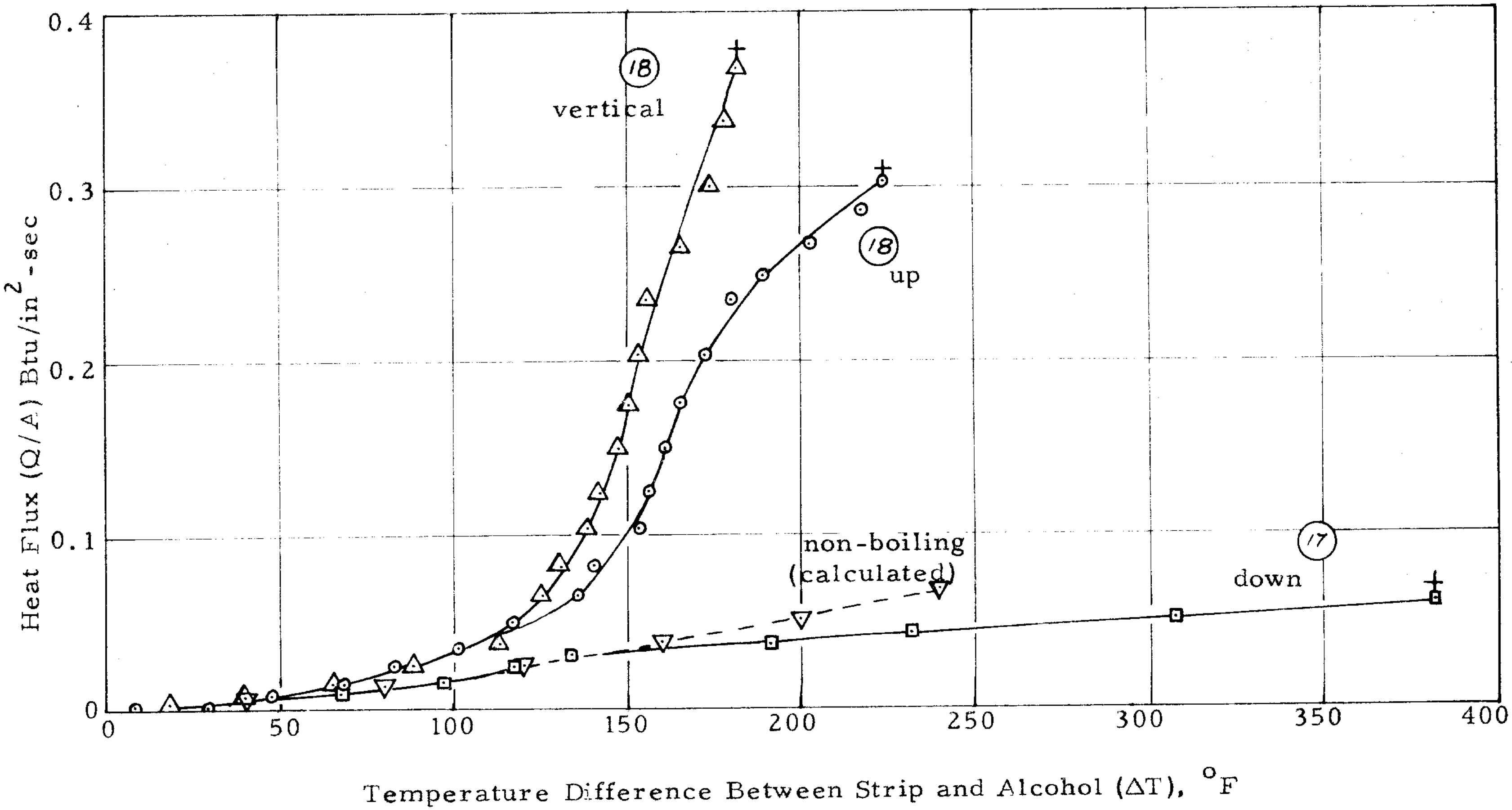


Fig. 7 Effect of strip orientation at alcohol temperature of 80°F.

+ burnout point

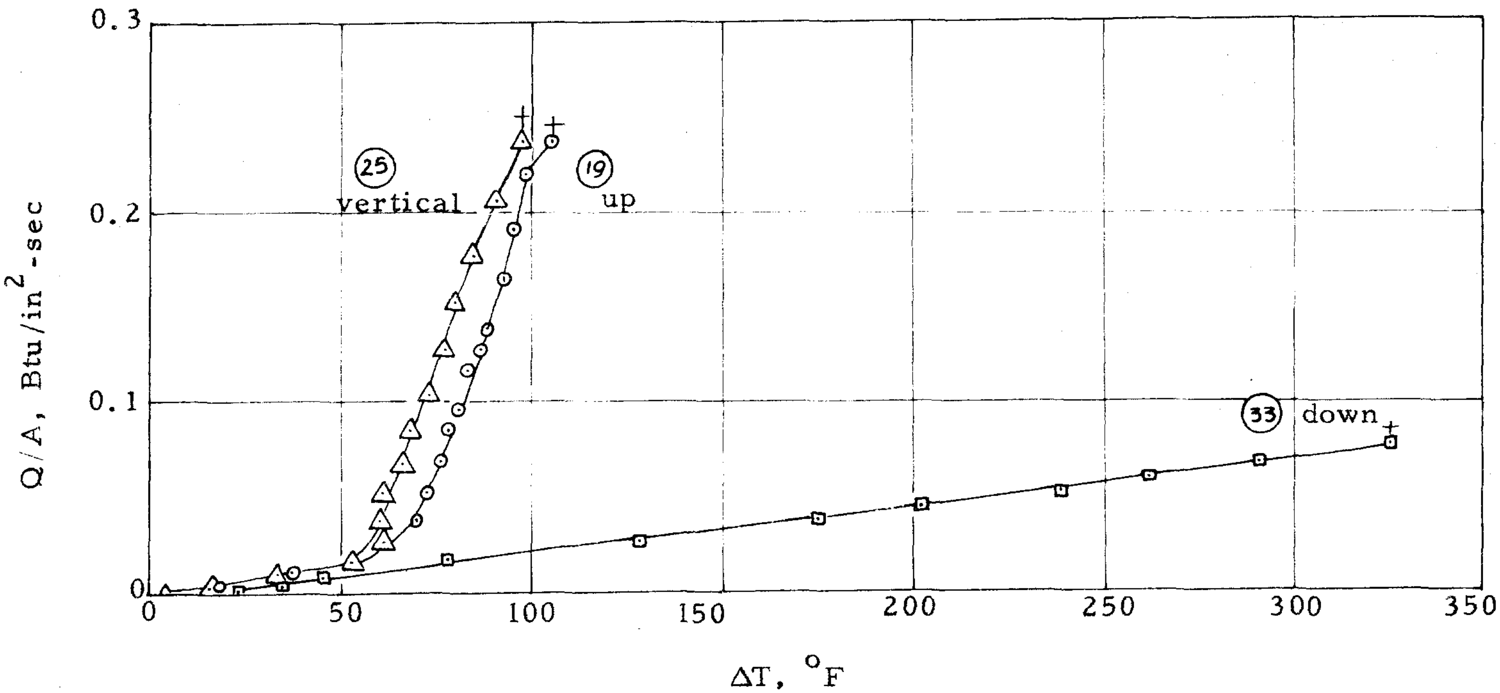


Fig. 8 Effect of strip orientation at alcohol temperature of 150°F.

+burnout point

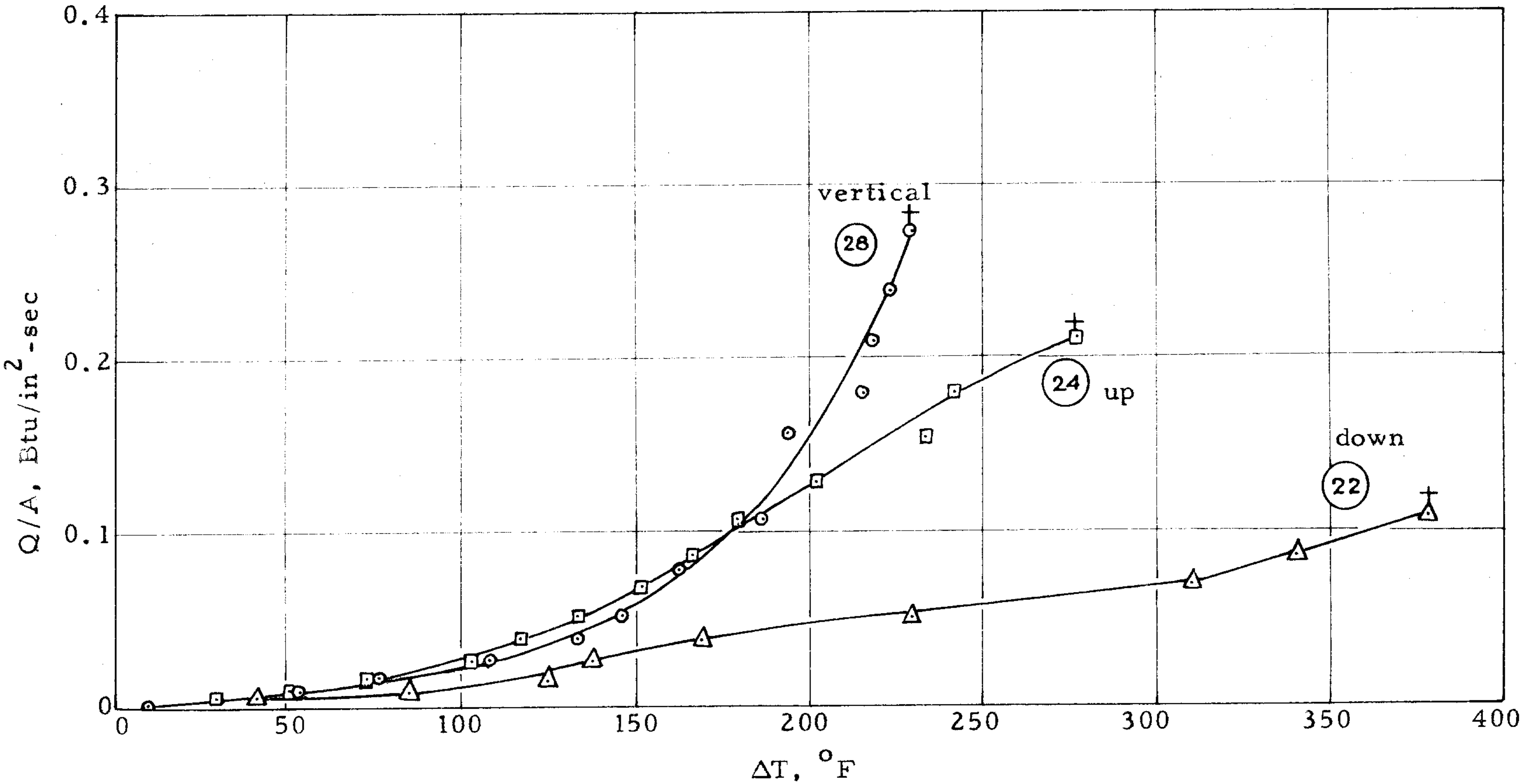


Fig. 9 Effect of strip orientation at alcohol temperature of 42°F.

+ burnout point

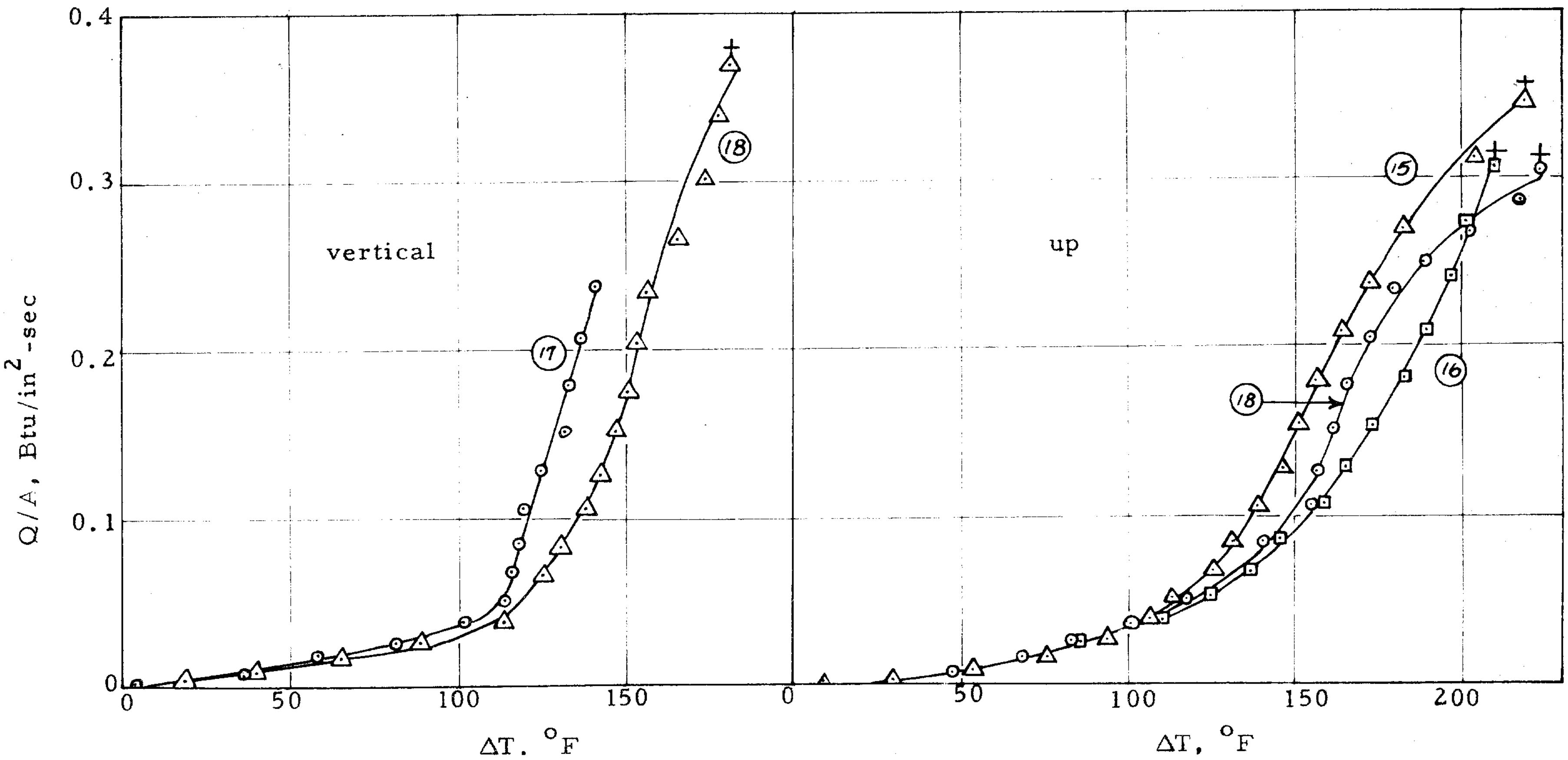


Fig. 10 Comparison of results from different strips. Alcohol at 80°F.

+ burnout point

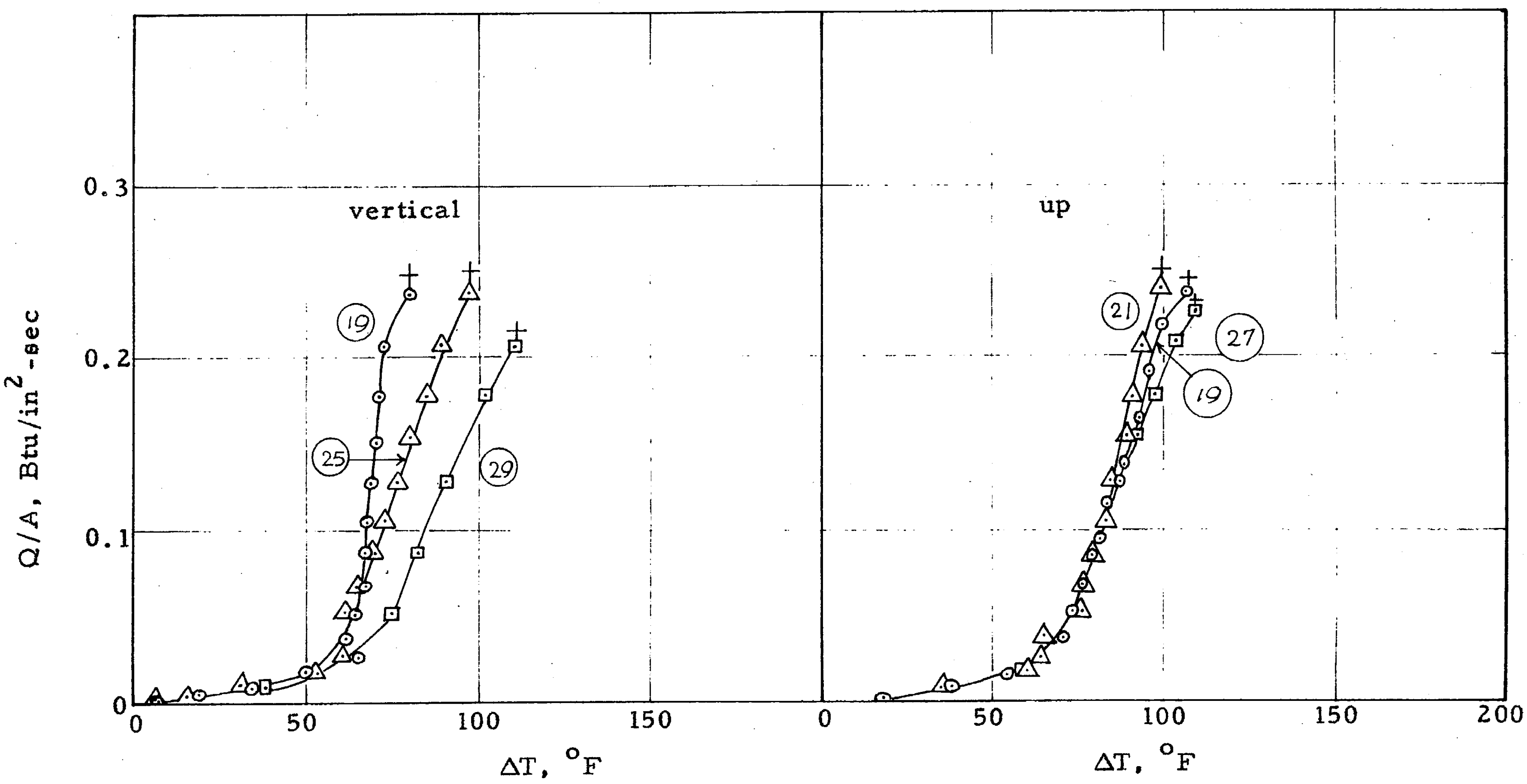


Fig. 11 Comparison of results from different strips. Alcohol at 150°F.

+ burnout point

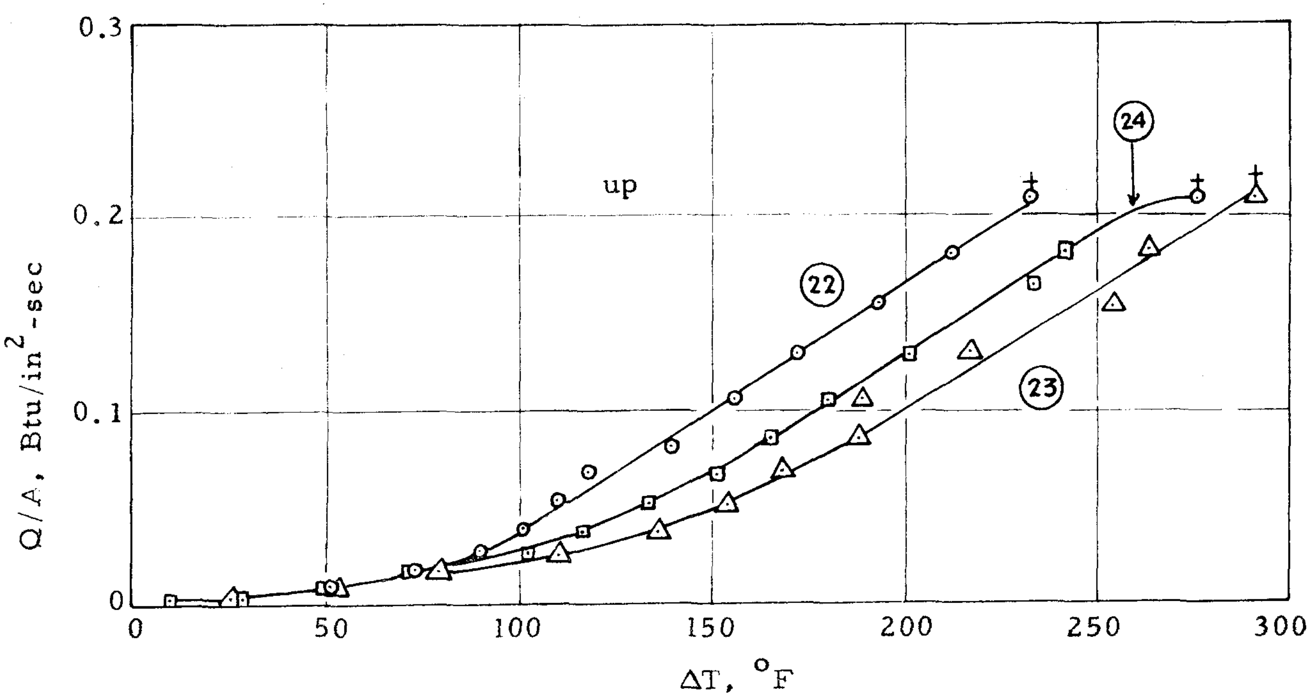


Fig. 12 Comparison of results from different strips. Alcohol at 42°F.

+ burnout point

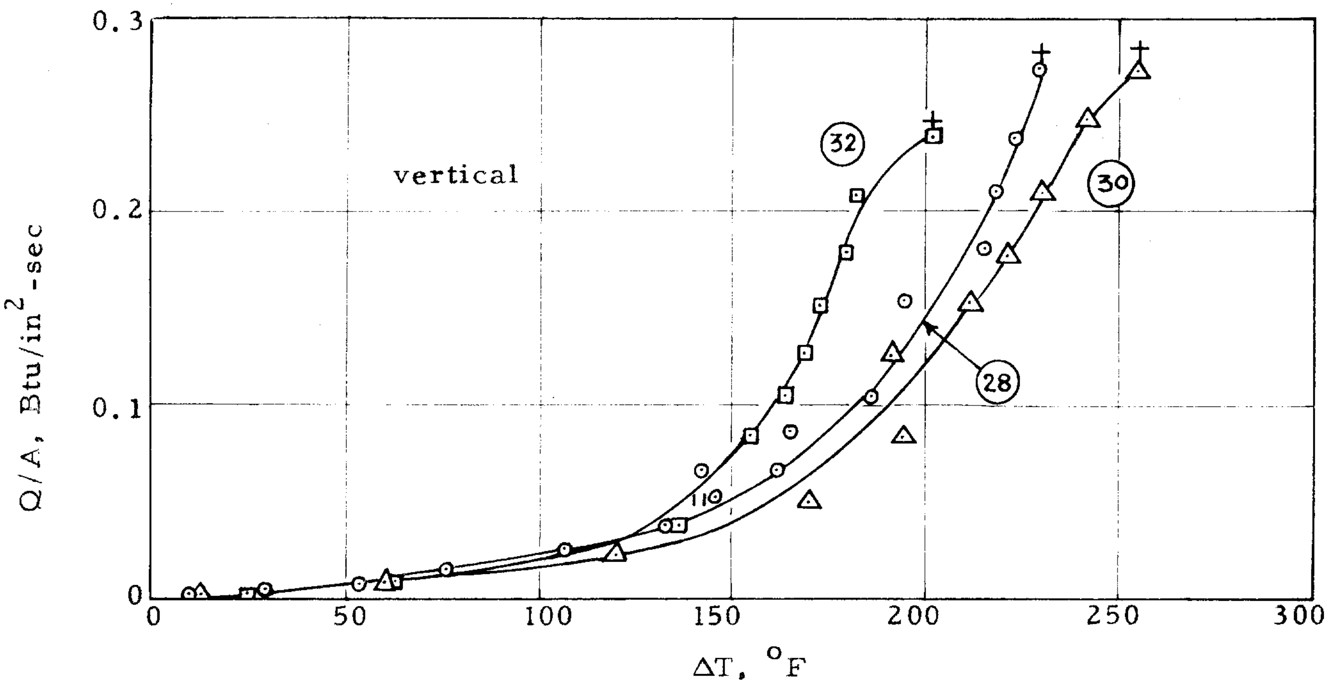


Fig. 13 Comparison of results from different strips. Alcohol at 42°F.

+burnout point

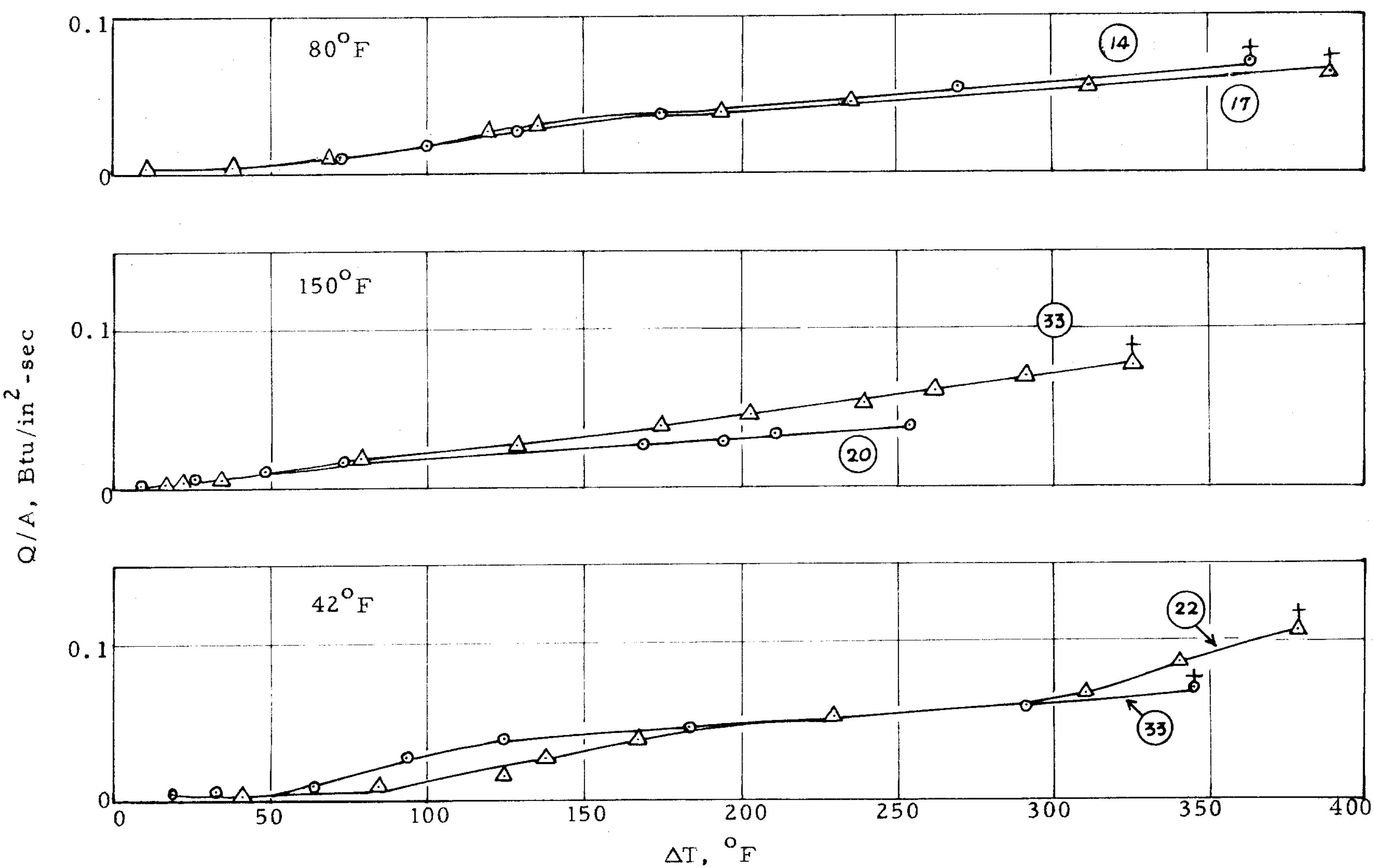


Fig. 14 Comparison of results from different downward-facing strips.

+burnout point

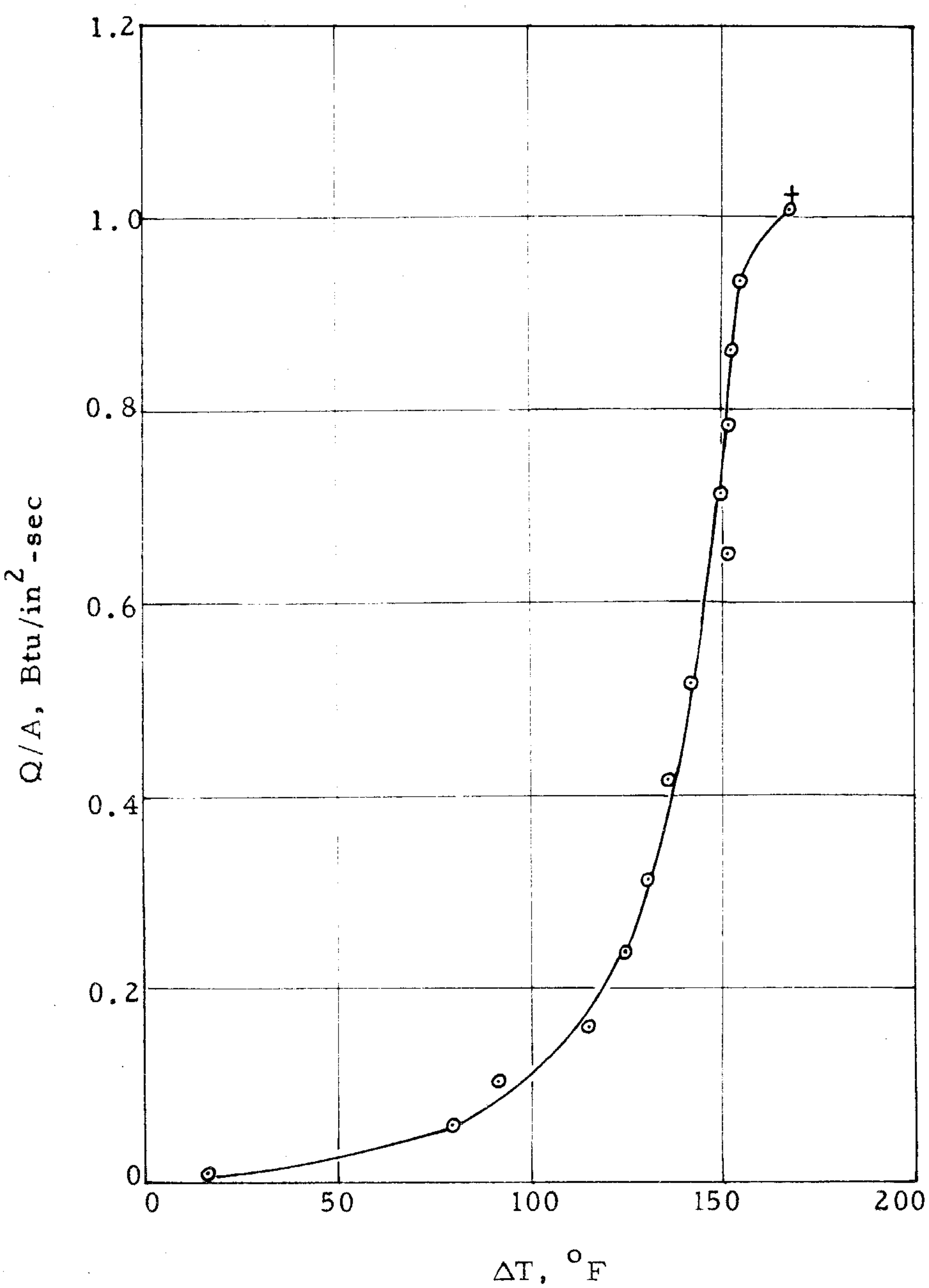


Fig. 15 Horizontal nichrome wire boiling curve. Alcohol at 80°F.

+ burnout point

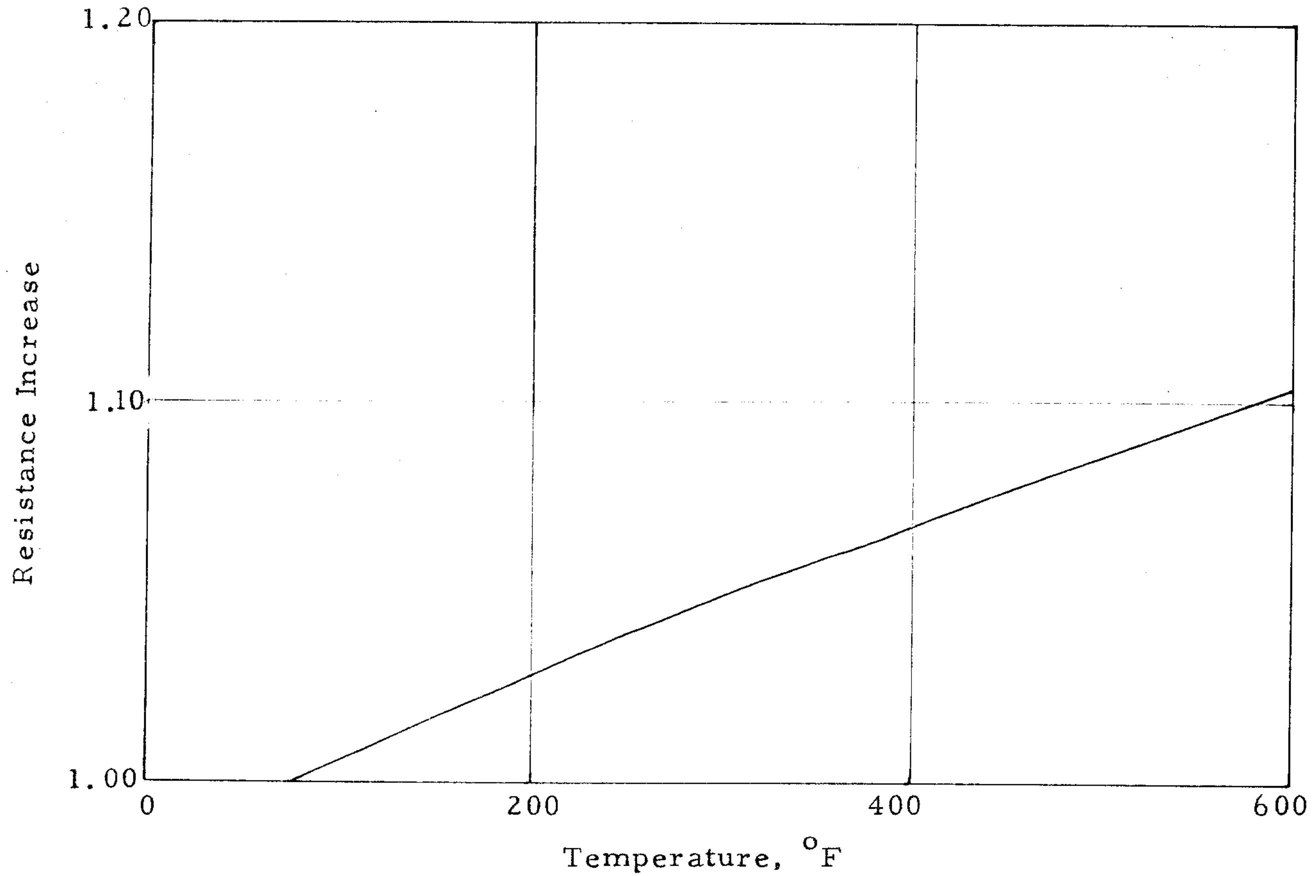


Fig. 16 Chromax strip resistance as a function of temperature (Ref. 15).

Table 1. Some Burnout Heat Flux Values

	$(Q/A)_{max}$-Btu/in^2-sec
Room Temp. - 80°F	
Vertical	0.374
Up	0.31
Down	0.062
Nichrome wire	1.01
Elevated Temp. - 150°F	
Vertical	0.237
Up	0.237
Down	0.078
Lowered Temp. - 42°F	
Vertical	0.274
Up	0.211
Down	0.104
Flat Surface Facing Down, d=25mm (Ref. 7)	
d/D = .125	0.148
d/D = .25	0.264
d/D = .50	0.602
d/D = 1.0	1.2
Tube in isopropyl alcohol (Ref. 5)	0.174

Table 2. Alcohol at 80°F

Run 18, Vertical		Run 18, Up		Run 17, Down	
ΔT °F	$Q/A \times 10^3$ Btu/in^2-sec	ΔT °F	$Q/A \times 10^3$ Btu/in^2-sec	ΔT °F	$Q/A \times 10^3$ Btu/in^2-sec
2	1	8	1	11	1
18	4	29	4	38	4
40	9	48.5	9	68	9
67	17	69	17	98	17
90	26	84.5	26	119	26
116	38	102	38	135	32
129	52	119	52	194	39
128	675	138	67.5	235	45
133	853	142	86	312	53
140	106	156	106	388	62*
144	128	159	129		
149	154	162.5	153		
153	179	168	180		
156	208	174.5	208		
159	239	181.5	239		
168	272	192	256		
176	307	205	273		
180	345	220	291		
184	375*	227	309*		

* "Burnout" point

Table 3. Alcohol at 80^{o}F, Calculated from eqn. 1

ΔT ^{o}F	$Q/A \times 10^3$ Btu/in^2-sec
40	5.7
80	14
120	24
160	38.5
200	52
240	69

Table 4. Alcohol at 150°F

Run 25, Vertical		Run 19, Up		Run 33, Down	
ΔT °F	Q/A x 10^3 Btu/in^2-sec	ΔT °F	Q/A x 10^3 Btu/in^2-sec	ΔT °F	Q/A x 10^3 Btu/in^2-sec
4	1	4	1	17	1
16	4.2	18	4.2	23.3	2.3
33	9.4	38	9.4	34	4.6
53	16.6	54.5	16.6	45	9.0
61	26	69	31.5	78	17.5
60.6	37.5	70	37.5	128	26
61.3	51	71.6	44.4	174.5	38
65.5	67	72.8	51.5	202	45
68	85	76.5	67	239	52.5
72.7	105	79.2	85	262	60.5
76.7	127	81.2	95	291	69
80	152.5	83.8	116	325	78*
85	178	87.2	127		
89.4	206	88.5	139		
97.5	237*	93.	164.5		
		96	191.5		
		99.3	220		
		106.7	237*		

* "Burnout" point

Table 5. Alcohol at 42^{o}F

Run 28, Vertical		Run 24, Up		Run 22, Down	
ΔT	Q/A x 10^3	ΔT	Q/A x 10^3	ΔT	Q/A x 10^3
^{o}F	Btu/in^2-sec	^{o}F	Btu/in^2-sec	^{o}F	Btu/in^2-sec
9	1	10	1	12	1
29	4.2	28.4	4.2	40	4.2
53.4	9.4	49.5	9.4	83.5	9.4
76.2	16.7	72	16.7	123.7	16.7
107.8	26	102	26	137	26
133.4	38	116.5	38	167.5	38
145.5	52	133	52	229	52
162	67.5	151	67.5	310	69
165	86	165	86	340	88
186	106	179	106	378	109*
192	154	201	129		
215	181	233	154.5		
218	210	241	181		
223	240	276	211*		
229	274*				

* "Burnout" point

Table 6. Nichrome Wire with Alcohol at 80°F

Run 7, Horizontal

ΔT, °F	Q/A x 10^3, Btu/in^2-sec
17.1	6.4
79.6	58
92	101.5
115	159
125.3	236
131	310
136	415
142.6	515
151.5	648
150	713
152	782
152.3	860
155.7	930
168.5	1006*

* "Burnout" point