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BY

Peter Griffith*

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December 1, 1958

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION
CAMBRIDGE 39, MASSACHUSETTS

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Abstract

Nucleation from a single cavity has been studied indicating that cavity geometry is important in two ways. The mouth diameter determines the superheat needed to initiate boiling and its shape determines its stability once boiling has begun. Contact angle is shown to be important in bubble nucleation primarily through its effect on cavity stability. Contact angle measurements made on "clean" and paraffin coated stainless steel surfaces with water show that the contact angle varies between 20° and 110° for temperatures from 20° to 170° C. On the basis of single cavity nucleation theory, it is proposed to characterize the gross nucleation properties of a given surface for all fluids under all conditions with a single group having the dimensions of length. Finally, it is shown experimentally that this characterization is adequate by boiling water, methanol and ethanol different copper surfaces finished with 3/0 emery, and showing that the number of active centers per unit area is a function of this variable alone.

The Role of Surface Conditions in Nucleate Boiling

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INTRODUCTION

In the past, many attempts have been made to correlate nucleate boiling heat flux versus temperature difference data on the basis of fluid properties alone. It has not been found possible to do this as the condition of the surface of the heater has been found, experimentally, to have a pronounced effect on both the slope and position of the nucleate boiling curve. In correlations this difficulty has been circumvented by choosing the best constant value for the slope for the boiling curve and determining the best value for a coefficient from one or more experiments. In doing this, there has been little appreciation of what surface conditions were important and how they manifested themselves through the slope and position of the boiling curve.

Corty and Faust (1) made gross measurements of heat flux wall superheat and the number of nucleation sites per? unit area for surfaces of various roughness. The experiments showed roughness was important but did not indicate how one should take cognizance of it in predicting the performance of a given surface in boiling. Other experimenters have varied contact angle with surface active agents and with various oils on the surface. There was an obvious effect, but the magnitude of the effect was quite unpredictable. Bankhoff (2, 3, 4) has examined the mechanism of bubble nucleation in some detail and has arrived at the conclusion that in boiling, bubbles originate from pre-existing vapor pockets in cavities on the surface. He also indicates the role of contact angle and cavity geometry. Westwater (5) has examined a boiling surface under a microscope and has observed that, in general, the bubbles do originate from cavities or large scratches on the surface. His observations verify qualitatively the deductions of Bankhoff.

In general, it can be said the surface conditions can affect the boiling process in two ways; either through altering the bubble shape and size at departure, and their frequency or through their effects on the wall superheat needed to initiate the growth of a bubble. It does not appear that there are very significant differences between engineering surfaces in so far as departure size or shape of the bubble is concerned. However, it does appear that the surface conditions can have a profound effect on the nucleation characteristics of the surface. It is on this second effect that attention will be focused in this work. In particular, two related problems will be considered. What are the conditions leading to the nucleation of a single bubble, and what surface and fluid properties must be specified in order that the gross nucleation characteristics of the surface will be determined.

Nucleation from a Single Cavity

The discussion of bubble nucleation from a single cavity will begin by considering an idealized conical cavity under equilibrium conditions; then, the effect of cavity geometry and contact angle will be considered. Finally, representative values of the contact angle will be presented.

1. The Conical Cavity

Imagine a concial cavity, such as is illustrated in Figure 1, with a bubble already in it. Let us further assume to begin that the contact angle between the liquid and solid is 90°. A plot of the bubble radius of curvature versus the bubble volume is as shown in Figure 1. The peculiar shape of the curve with its minimum and maximum exists because when the bubble arrives at the lip of the cavity, its radius of curvature begins to decrease with increasing bubble volume. Finally, when the bubble projects beyond the cavity with the shape of a hemisphere any further increase in volume results in an increase in the radius of curvature of the bubble. This minimum radius of curvature is called the critical radius r* and has a value equal to the radius of the cavity at its mouth. It is this radius which determines what the wall superheat is that is needed to initiate the growth of a bubble. For a wide range of cavity geometries and contact angles, this is the only dimension that need be specified to determine the superheat needed to initiate the growth of a bubble. The question of the range of cavity geometries and contact angles for which this is true will be considered later.

The radius of curvature at a curved interface, which is segment of a sphere, and the liquid superheat at equilibrium can be related as follows.

$$\Delta p = \frac{2\sigma}{r} \qquad (1)$$

Δp is the pressure difference between the inside and the outside of the bubble. When the bubble is at equilibrium the pressure inside the bubble and the temperature of the vapor and the liquid must correspond to those which exist at equilibrium across a plane interface. That is, the vapor must be at the saturation temperature corresponding to its pressure and the liquid must be at the same temperature. The liquid is therefore superheated. The excess temperature in the liquid can be related to the excess pressure in the bubble through the Clausius-Clapyron relation. This relation in difference form is as follows:

$$\frac{\Delta p}{(T_w - T_s)} = \frac{h_{fg}}{Tv_{fg}} \qquad (2)$$

When Δp is eliminated between equations (1) and (2), a relationship between liquid superheat and interface radius of curvature is obtained which is as follows

$$r = \frac{2\sigma T_w v_{fg}}{h_{fg}(T_w - T_s)} \qquad (3)$$

When the critical radius is substituted in equation (3) the temperature difference becomes the critical temperature difference. This is the minimum temperature difference which is needed to start the bubble growing from a cavity with a mouth radius r^*.

2. Cavity Size and Number, and the Wall Superheat

With the above straightforward theory, it was felt that a simple experiment on a specially prepared surface would be sufficient to show the relation between the wall superheat and the heat flux. In particular, if there were a number of identical cavities on the surface, one might expect that portion of the boiling curve would be vertical. This is because a very small increase in temperature would be sufficient to activate another cavity thereby substantially increasing the heat flux.

Furthermore, one would expect that the wall superheat measured in
such an experiment would be directly related, through equation (3), to
the cavity size on the surface.

In order to test this hypothesis, a boiling surface was prepared
by polishing a copper heater, about one inch in diameter, with emery
paper and then pricking it with a sharpened gramaphone needle to give
37 holes of uniform size and shape which were evenly spaced on the
surface. In order to help maintain nucleation from these sites, the
entire surface was washed with a paraffin carbon tetra-chloride solution
which left a thin film of paraffin on the surface. The method of surface
preparation and the experimental apparatus are described in greater de-
tail in Appendix A. A similar surface was prepared in exactly the same
way except that no cavities were placed on the surface; that is, there
were only the cavities left by the emery cloth on the second surface.
The boiling curves obtained from these two surfaces are compared in
Figure 2.

A number of observations can be made from the results of this
experiment. First, the curve for the surface with the cavities lies
to the left of the other one until a relatively large heat flux is
attained as is to be expected. Secondly, the slope is large, 7 or so,
but the line is definitely not vertical. This is not quite as expected.
Lastly, the wall superheats are of the order of 20° F. This is un-
expected.

One would expect from the size of the cavities on the surface that
the wall superheat would be constant at about 3° F., instead of the 20°
observed. There appear to be several possible explanations for this
result. Either the cavities are not the nucleating centers or, the
mean surface temperature is not the one seen by the cavity or, some
other process determines whether a cavity will nucleate such as the
rate at which the interface travels down the cavity. That is the
nucleation properties of a cavity are determined by properties other
than those appearing in equation 3. In the next section the first of
these questions will be considered in connection with the stability of
cavities as nucleation centers. Then, in the succeeding sections,
experiments will be described which show what properties are important
in determining the nucleation characteristics of a cavity and finally
of a surface.

3. Stability of Various Cavities as Nucleation Centers

In the preceding discussion of the nucleation characteristics of a single cavity, it was assumed that the contact angle was 90° and the cavity was conical. In general, conditions different from these will not affect the temperature at which a cavity will nucleate but will affect its stability as a nucleation site. Let us consider the effect of contact angle variations and of cavity geometry.

The minimum radius of curvature or the maximum on the temperature-volume plot of Figure 1 is determined by both the diameter of the cavity mouth and the contact angle. In the case when the contact angle lies within the following limits the maximum on the reciprocal radius versus volume plot and consequently the r* and nucleation superheat is constant. These limits are

$$\theta < \beta < 90°$$ (4)

For the surface liquid combination for which Equation (4) is true the critical radius of curvature will always be equal to cavity mouth radius. If β is less than θ, no maximum will exist, while if is greater than 90°, the wall superheat needed to initiate boiling from the cavity will be reduced. The most stable cavities will be those that have large contact angles within them as the minimum on Figure 1 will be lower so that a lower temperature will be needed to deactivate the cavity.

If the cavity is of the re-entrant type, it will be very stable indeed. This can be seen in Figure 3 for which a plot reciprocal radius-volume similar to that of Figure 1 is developed. When the radius of curvature becomes negative, it means the liquid must actually be subcooled in order to deactivate a cavity. Such a cavity very likely serves as the nucleation site for the initiation of boiling.

4. Contact Angle

A large number of measurements have been made at low temperature of the contact angle between various surfaces and liquids. Careful measurements on clean, smooth, metal surfaces, metal oxide surfaces and metal sulfide surfaces, all show that the equilibrium contact angle is 0°. However, engineering surfaces are never clean or smooth, and, in the case of boiling, equilibrium is never attained. The foregoing effects all tend to make the contact angle greater than 0°.

Someone who has never made measurements of the contact angle cannot appreciate what minute quantities of a material are needed to contaminate a surface. A clean, dry metal surface held in air for more than an instant will pick up minute droplets of oil that completely alter its properties. Furthermore, no solvent used to wash the surface will remove the last traces of any contaminant on the metal. In fact, the only reliable way to form a clean metal surface is to grind it under water and keep it there.

Because no contact angle measurements exist for water at elevated temperatures, and representative values were not available for engineering "clean" surfaces, some contact angle measurements have been made as part of this program. The apparatus and technique used to make these measurements are described in Appendix B. Briefly, however, the tilting plate method was used in which the angle between the plate and the free surface of the liquid was adjusted until the liquid surface came into the plate without curvature. The angle between the plate and the liquid was then measured photographically. The contact angle for a surface contaminated with paraffin was measured along with those for a so-called "clean" surface. These measurements are presented in Figures 4 and 5.

As can be seen, the paraffin-coated surface gives fairly reproducible results while the scatter for the "clean" surface is large; β generally lies below the values for surface contaminated with paraffin. One could say from these measurements that any cavities with cone angles less than 30° would probably be effective as nucleation sites. With this information, let us continue with a consideration of the experimental determination of the truth of this theory.

Experimental Determination of the Nucleation Properties of Single Cavities

A series of experiments reported in reference (6) have been run to
determine whether the foregoing theory indeed is correct. In particular,
it was desired to determine first whether the nucleation mechanism
embodied in equation (3) was correct and second, whether a single dimension
was sufficient to specify the nucleation properties of such a cavity and
last, whether such a cavity is reasonably stable.

An apparatus was constructed which is described in detail in Appendix
C. This apparatus allowed one to maintain a liquid at any moderate tempera-
ture and at any pressure equal to or less than atmospheric pressure. It was
possible to immerse in this liquid a surface on which a cavity of known
geometry existed and to adjust the pressure and temperature of the liquid
until boiling from the cavity just ceased. The pressure and temperature
corresponding to this condition would be recorded and the corresponding
superheat could be calculated. In performing the experiments in this way,
essentially equilibrium conditions would exist in the test vessel, and the
temperature of the surface would be uniform and known.

A number of experimental determinations were made and these are presented
in Figures 6, 7, and 8. The liquid superheats appropriate for these cavities
are calculated from equation (3) assuming that the radius of the mouth of the
cavity is the minimum radius of curvature. The conditions under which these
experimental measurements were made were fixed by balancing the errors in
temperature measurement, which are large for large cavities, with the errors in
cavity size measurements, which are large for small cavities. Therefore,
cavities approximately 2×10^{-3} inches in diameter were used. In varying the
system pressure as was done in these experiments, variation was obtained in
all terms of equation (3), though not independently.

Once the cavity size and surface treatment were decided upon and the
specimen prepared, it was immersed in hot water and heating began.
This was continued until the air in the cavity and water was driven out,
which was about 1/2 hour for conical cavities and 2 hours for the reservoir

cavity. Then the rate of heating was decreased and bath and water temperature allowed to drop until the rate of bubble formation decreased to a low value, generally from 1 per 0.2 sec to 1 per 5 sec. This temperature was then recorded. The rate of boiling from the cavity could be increased by increasing the temperature or decreasing the pressure.

In running, some difficulty was experienced from the nucleation of bubbles from "rogue" nucleation sites (that is, sites which were not those prepared). To avoid this, it was necessary to keep the surfaces both clean and smooth. In addition to this difficulty, it can be seen there is a certain amount of scatter in the data, particularly for clean surfaces. It is felt this is due primarily to the difficulties associated with the temperature measurement and in maintaining a slow, steady rate of bubble formation from a cavity.

The stability of a cavity was found to be quite sensitive to the way in which the boiling was started. If the water was degassed before starting, it was found to be impossible to initiate boiling from the desired spots. Apparently, the degassed water dissolved all the gas from the cavity before boiling began so that the cavity filled with liquid and was no longer active. Also, it was found to be easier to maintain boiling and get reproducible readings from the paraffin treated cavity than the "clean" ones. This is to be expected when one considers the importance of contact angle on the stability of a cavity.

It was found to be possible to deactivate a cavity which was boiling by increasing the pressure suddenly. This occurred when the pressure increase was sufficient to make the water in the tube the equivalent of several degrees sub-cooled. If the pressure was decreased again, boiling would not start from the cavity at its characteristic activating superheat. Apparently the cavity became filled with liquid. In principal, this is the reason for the difference between the boiling curves for increasing and decreasing heat flux.

These tests showed that the theory of bubble nucleation embodied in equation (3) is substantially correct and that the specification of a single dimension for characterizing a nucleation site is sufficient. They showed that conical cavities are not stable for much subcooling and un-wetted cavities are more stable than wetted cavities. They showed importance of air on the initiation of boiling. Finally, they showed that the most likely explanation for the difference between the expected 3°F wall superheat and the observed 20°F in the experiments of figure 2 is that the surface is a lot cooler in the vicinity of a cavity than elsewhere.

The Specification of the Nucleation Properties of Boiling Surfaces

It remains to apply the above findings to the specification of a real boiling surface. The questions that must be answered are as follows. What measurements must be made in order to determine the nucleation characteristics of a surface, and what important variables must be fixed in order to fix the nucleation characteristics? In this section a series of experiments will be described which will indicate what must be specified in order to fix the nucleation properties of a surface, then the importance of the as yet un-tested variables will be discussed.

The experiments performed on the nucleation of single bubbles showed that a single dimension might be sufficient to characterize a cavity. The nucleation characteristics of a surface would be fixed if the size distribution of cavities on the surface were known. Equation (3) allows us to interpret the size of the cavity in terms of a wall superheat and fluid properties. Therefore, one might hope that though the mean surface temperature is a poor measure of the temperature at a cavity, for a given surface material and method of surface treatment, there would be a single value for the number of active cavities for a given value of the wall superheat and fluid properties. That is, if this theory applies to a real boiling surface, then a plot of the number of active spots per unit area, n/A, as a function of radius ought to be invariant even though the type of fluid or its pressure were altered. Thus for surfaces of the same material treated in the same way,

a single curve should result when n/A is plotted versus $\dfrac{2\sigma T_{vfg}}{h_{fg}(T_w-T_s)}$.
The second term has dimensions of radius and comes from equation (3).

To test this, an apparatus was constructed which allowed simultaneous measurements of surface temperature and heat flux and also allowed one to photograph the surfaces during boiling. The liquid temperature was kept low so the bubbles did not leave the surface and an unobscured view of the surface was possible. The number of bubbles on the surface could then be counted for photographs. The apparatus and test procedure are described in greater detail in Appendix D.

The results for four different copper surfaces treated the same way, on which water was boiled twice along with methanol and ethanol are shown in Figure 9. The surface was "clean" and finished dry with 3/0 emergy paper. The three fluids yield quite different n/A vs T_w-T_s curves though the two surfaces on which water was boiled give very similar results. When these points are plotted versus the group on right hand side of equation (3) (figure 10) it can be seen that all fluids fall on about the same curve. In so far as the properties not in equation (3) for alcohol and water are not the same, it can be said they have no effect on the gross nucleation properties of the surface-liquid combination.

Since the mean surface temperature has been shown experimentally to be not directly related to the temperature a cavity sees, one might expect that the thermal properties of the surface material might play a role. This question is now under study.

Conclusions

1. Nucleation occurs from pre-existing gas-filled cavities on the surface.

2. A single dimension in general is sufficient to characterize such an active cavity.

3. The wall superheat at which such a cavity will become active is fixed by surface tension and other known fluid properties.

4. The mean surface temperature is not a good indication of the temperature felt by an active cavity.

5. For surfaces made of the same material and treated in the same way, a single plot of the number of cavities versus cavity mouth radius can be developed which is appropriate to apply to a variety of fluids at various pressures.

Remaining Work

It still remains to test the importance of surface material thermal properties. Also, more detailed experiments will have to be performed which will directly relate the wall superheat and number of active sites to the heat flux from the surface. In this way the nucleation properties of the surface can be tied to the enthalpy transport per bubble.

List of Symbols

h_{fg} — latent heat of vaporization

T_s — absolute temperature of saturation

T_w — absolute temperature of wall

r — radius of curvature of bubble

v_{fg} — specific volume change on vaporization

n/A — number of active spots per unit area

β — contact angle measured through the liquid

σ — surface tension

Subscript

$*$ — critical condition corresponding to the hemispherical bubble at the mouth of the cavity also equal to cavity mouth radius

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APPENDIX A

Apparatus and Experimental Procedure Used to Obtain Heat Flux vs.
Wall Superheat Curves for Specially Prepared Surfaces

The heater and vessel are shown in cross-section in Figure 11. The
heat is supplied by three 120W Chromelux electrical heaters imbedded in
a copper collector section. The heat is then passed through a straight
conductor to the surface on which boiling is taking place. Three copper-
constantan thermocouples are imbedded in the straight conductor section
and the readings from these extrapolated to give the surface temperature.
These measurements can also be used to give the heat flux.

The surface is prepared by polishing it with 2/0 emery paper until no
scratches remain which are larger than those due to the emery itself.
One of the runs was made after the surface had been washed with a carbon
tetrachloride-paraffin solution without any further treatment. This left
a very thin layer of paraffin over the entire surface. The other run was
made on a surface that was washed with the same solution and pricked with
the punch described below, so that it had 37 evenly spaced cavities
2.7×10^{-3} inches in diameter at the mouth on equilateral triangles. The
sides of each triangle were 1/8" long. The holes were punched with a prick
which was made as follows. A steel gramaphone needle was sharpened to an
18° cone angle with an alabaster honing stone. The radius of curvature of
the tip was approximately 10^{-4} inches. This needle was placed in a nylon
holder that had a stop on it that prevented the needle from penetrating
the copper for any more than a certain predetermined distance. The needle
was held in this holder with a small setscrew. The depth of penetration
and shape of the cavity could then be determined from the shape of the
needle that made it and the diameter of the mouth of the cavity.

APPENDIX B

Description of the Apparatus and Method of Measuring the Contact Angle
(Naotsugu Isshiki Masugi)

It was desired to obtain values of the contact angle for water on engineering surfaces at temperatures for which boiling data was being taken. This necessitated building a device which maintained a given temperature and pressure while allowing one to observe the contact angle on a surface. Therefore, to obtain the correct conditions of temperature and pressure, a small boiler, illustrated in Figure 12a, was constructed. The various parts are described in the caption to the figure.

The test section was immersed in the liquid in the boiler on the line of sight between the two windows shown in the illustration. Two methods were tried to give the desired liquid-vapor-surface contact angles, the bubble method and tilting plate method. The bubble method while freer of contamination difficulties was found to be unsatisfactory because the bubble would not hold its size for any length of time. At elevated pressure, a bubble of pure vapor was formed which grew and collapsed with very slight changes in the water temperature. Air bubbles would not have given this difficulty, but the contact angles would probably not have been the ones that could exist between water and its vapor. For this reason, the tilting plate method was turned to.

The difficulty with the tilting plate method is that the water surface is not renewed and as such is likely to become contaminated. Therefore, a small watertight chamber with glass ends was constructed which isolated the test water from the "boiler" water. For this apparatus, the boiler water simply provided the desired conditions of temperature and pressure. The test section is illustrated in Figure 12b and described in greater detail in the caption of that figure.

When running, the surface was prepared in the desired manner and the heat turned on. For points below 100°C., the total pressure was always 14.7 psia, (that is, the boiler and test section were open to the atmosphere). Above 100°C. the boiler was closed and boiled so that the air was driven off and the contact angle recorded characteristic of a pure vapor-water-metal system.

Readings were taken in the following manner. The temperature and pressure were recorded and the plate tilted so that the interface approached the plate without curvature. A picture was then taken. The camera used was a 35mm, shooting directly into the light so that a profile was obtained. The light was steady and the desired exposure obtained with the shutter on the camera. After developing, the film was projected in a microfilm viewer and the angles measured. Because the contact angle did not have single value, the tilt on the plate was usually not exactly right. When it was not, the angle between the tangent to the liquid surface at the triple interface and the metal surface was recorded.

In so far as there was no difficulty in reproducing the values for the paraffin coated surface, Figure 4, it can be said there was no effect from outside contamination on the readings. For the "clean" surface, the scatter and hysteresis is sufficiently large so that there is a likelihood that there is a certain variable amount of contamination on the water surface and on the metal surface which is affecting the results.

A great deal of difficulty was experienced while making these measurements in controlling the surface conditions in such a manner as to give reproducible readings. As these conditions are not usually very well controlled in boiling experiments, these values are probably representative of the ones that would exist during boiling. To the author's knowledge, these are the only contact angle measurements existing for high temperature water.

APPENDIX C

**Apparatus and Procedure Used to Test Nucleation Properties of
Single Cavities**

The overall experimental setup is shown in Figure 13 in which the
various parts are labelled on the drawing.

In a typical test run, the tube was first washed vigorously in hot
tap water followed by distilled water, and left empty. The test surface
was put in it after being lightly brushed with a paper towel, and then
the tube put into the oil bath, (which was being heated by the bunsen
burner). The cork assembly was put in place, the three thermocouple
tubes having been cleaned with a paper towel first. Meanwhile, distilled
water was being heated separately; when the thermocouples indicated a
temperature near boiling in the empty tube the hot (but not boiled),
distilled water was poured into it over the hot test surface. The tube
was removed to do this, to prevent water being splashed into the hot oil.
The thermocouples were again cleaned, the cork assembly put in place and
connected up to the rest of the apparatus and the test was under way at
atmospheric pressure.

Readings were taken at frequent intervals. Each comprised temperature
and pressure readings, with a note on the type of boiling in the tube.

Pressure readings were made up of the barometer reading (taken once),
the manometer reading, and the head of water above the cavity in the tube.

The purpose of the first part of each test was to boil off the air in
the water and cavity, and so vigorous heating was employed to give vigorous
boiling from the cavity. Originally, the air was boiled off the water
separately before the test began but when this was done the cavity could never
be activated at all. Apparently the air in the cavity must have diffused out
before the temperature rose high enough to provide enough vapor for stability.
Hence, the necessity found for keeping the cavity "primed" by air from the
water at the start of a test.

When slow boiling, and starting and stopping of boiling were required, the bunsen burner was removed and the rate of boiling left to drop. It slowed down very gradually because of the large bulk of the oil bath. As soon as boiling stopped completely, heating was resumed strongly to prevent the temperature dropping far enough to kill the cavity.

Atmospheric pressure in the test tube was assured by leaving the cork loose on the pressure reservoir. Atmospheric pressure readings were taken first, and then readings at diminishing pressure down to the lowest required; conditions at each stage were controlled with the faucet pump and the bunsen burner. Finally, the test tube was returned to atmospheric pressure by loosening the pressure reservoir cork again, and some readings taken with the cavity dead.

At shut-down, the surface was removed and had the water evaporated off it before being stored in air under a dust cover of paper. The tube was washed vigorously as at the start, and then filled with distilled water. The thermocouple tubes were cleaned again, and the whole cork assembly returned to the tube for storage until the next test.

The great emphasis on cleanliness was found to be necessary by experience, as very active "rogue" nucleation points were formed on the glass or other parts of the test surface if these precautions were not taken. Even when they were taken, there was sometimes trouble and in this case the only sure cure was to stop the test, clean the tube and everything in it, and start the test again from the beginning. However, sometimes they would stop of their own accord or be stopped by a slight drop in temperature.

Often the "rogue" point killed the cavity because it had the lower critical superheat ΔT^*, and so held the temperature down below that required by the cavity. When it did not kill the cavity (having a ΔT^* nearly the same), but only accompanied it, readings were still good as long as rates of boiling from the cavity not from the other, were noted. But the condition is undesirable.

APPENDIX D

Experimental Apparatus and Experimental Procedure Used to Obtain
Gross Nucleation Properties Data

The vessel and heater arrangement for this series of tests is
identical with those described in Appendix A. The surface was always
copper and always finished with 3/0 emery, with strokes in the same direction.

The pictures, from which the bubble counts were made, were taken
with a camera with the lens open all the time. The image on the
negative was just about the same size as the bubble being photographed.
The bubbles were stopped with an Edgerton micro-flash unit giving a shot
of light 2×10^{-6} seconds in duration. Four pictures were taken at each
setting and all were counted. The average result for the four pictures is
plotted on Figures 9 and 10. A number of small photographic difficulties
had to be overcome in order to obtain pictures that could be counted.

First, in order to have an unobscured view of the surface the bubbles
that were formed had to be condensed near the surface. This meant for the
water the temperature must be kept in the vicinity of 160°F. For methanol,
the temperature was about 89° and for ethanol about 102°F. If the tempera-
ture were lower, the bubbles became too small to see and if it were higher,
the view became obscured. The water temperature was controlled with a
cooling coil.

The light needed to take the pictures came in at an angle of 45° from
the surface and the picture was taken from directly above the surface.

For the ethanol and methanol the bubbles were very small so that the
temperature of the liquid had to be kept rather high in order that the
bubbles remain visible. This meant that the bubbles departed from the
surface and confused the picture slightly. However, with an "f" stop of
2.4 the depth of focus was so small that the departed bubbles were always
out of focus. For the alcohols, also, a convection current was set up by the

rising bubbles which disturbed the liquid surface. This also confused the pictures. However, when a petrie dish was floated on the surface this difficulty was overcome.

There was considerable nucleation about the soft gasket sealing the test section into place for the alcohol runs. This occurred so far from the section of interest, however, that it did not hurt the pictures or spoil the temperature measurements.

When counting the pictures, an area of interest was selected in the center of the test section 1/2" in diameter and only bubbles in this area were counted. It was found that the bubbles in a set of pictures did not always appear at the same place. The reason for this is probably that there was a pause between bubbles at a point so that the surface sometimes appeared bare at this point in a still picture. Thus, the number of bubbles counted was the time average for the surface. Probably more spots were active.

When starting up, the tank was filled with fluid and vigorous boiling was allowed to occur for about an hour. The cooling water was then turned on and the flux lowered to the desired value. Thus, the surface was degassed and the desired point always appraoched from a higher flux. Experience has shown that only this is the only way to obtain reproducable boiling data.

FIGURES

Figure 1   The conical cavity with a 90° contact angle. The r* is the
critical value and has associated with it the critical Δ T.
The shape of the temperature-volume curve is qualitatively
the same as the reciprocal r versus volume curve.

Figure 2   Boiling curves of water at one atmosphere and 90°C on paraffin
treated copper surfaces finished with 3/0 emery. The circles
are for points taken on the surface with the 37 cavities
described in the text and Appendix A. The crosses are for an
identical surface without these cavities.

Figure 3   The reservoir cavity contact angle 90°. Note that it is
possible to have temperatures below saturation without de-
activating this cavity.

Figure 4   Contact angles for water on stainless steel treated with paraffin.

Figure 5   Contact angles for water on "clean" stainless steel.

Figure 6   Measured nucleation superheats compared to the calculated. The
center line is the calculated value from equation (3). The other
lines are for an error of 1×10^{-4} inches in measuring the cavity
mouth diameter. D = .0019".
　　　⊡ steady stream of bubbles
　　　△ between 5/sec and 1 in 5 sec
　　　◇ slower than 1 in 5 sec
　　　✦ dead cavity
　　　○ stopping
　　　✕ starting

Figure 7   Different cavity. D = .018 clean surface. Symbols the same as
for Figure 6.

Figure 8   Reservoir cavity, D = .0016 for the top line and .0018 for the
bottom one. Symbols the same as for Figure 6.

Figure 9   Number of active spots per unit area versus wall superheat.
                Methanol on 3/0 finished copper
                ethanol on 3/0 finished copper
                water on 3/0 finished copper
                water.

Figure 10   Same data as Figure 9 plotted versus r* as calculated from
            equation (3).

Figure 11   Heater and tank assembly used to obtain data presented in
            Figures 2, 9, and 10.

   1) cooling coil copper
   2) brass tank with two glass sides
   3) neoprene washer
   4) brass nut to hold heater assembly in place
   5) heater assembly dimensioned as follows:
      - diameter in straight section, 1"
      - thickness of plate on top, .021"
      - distances of thermocouples from the underneath side
        of the plate, .22", .91", and 1.61".
   6) thermocouple hole
   7) chromolux heater, one of three
   8) top plate, .021" thick.

Figure 12a Schematic diagram of test boiler used to obtain contact angle
            measurements:
   1) pressure gage
   2) safety valve
   3) blow-off valve
   4) thermocouple
   5) stainless steel flanged cross used as boiler, 1' from
      flange to flange, 2-1/2" I.D.
   6) insulation
   7) 35mm camera
   8) drain valve
   9) window, glass o-ring sealed

10) 500 watt chromolux immersion heater

11) water level

12) light

13) variac

14) stainless steel flange

Figure 12b Test section for contact angle measurable:

1) flange cover

2) distilled water

3) tilting plate

4) water level in vessel

5) hose equalising pressure

6) frame, brass

7) barrel containing water and test plate with brass sides and glass ends. This barrel turns in its frame under the action of the mechanism which is screwed in and out of the flange.

Figure 13 Test set up used to obtain the nucleation superheats for single cavities. (Not to scale.)

Liquid   Vapor

(4)   L
      V
(*)
β = 90°   (1)
         (0)
          o
          r*
          r₁
          θ

(a)

$\frac{1}{r}$
$\frac{1}{r}^*$

(O) (1) (*) (4) Volume
(b)

FIGURE 1

$\frac{q}{A} \times 10^{-3}$ BTU/hr. ft.²

500

300

100
80

60

40

20

1
1   20   40   60 80 100
         (Tw − Ts) °F
FIGURE 2

(4)
(3)
(*)
β = 90°   θ   r*
          (1)   Liquid
          (B)   Vapor
γ
          (A)
          (O)

(a)

$\frac{1}{r}$

(O)(A) (B) (1)   (*)(3)   (4)   Volume

(b)
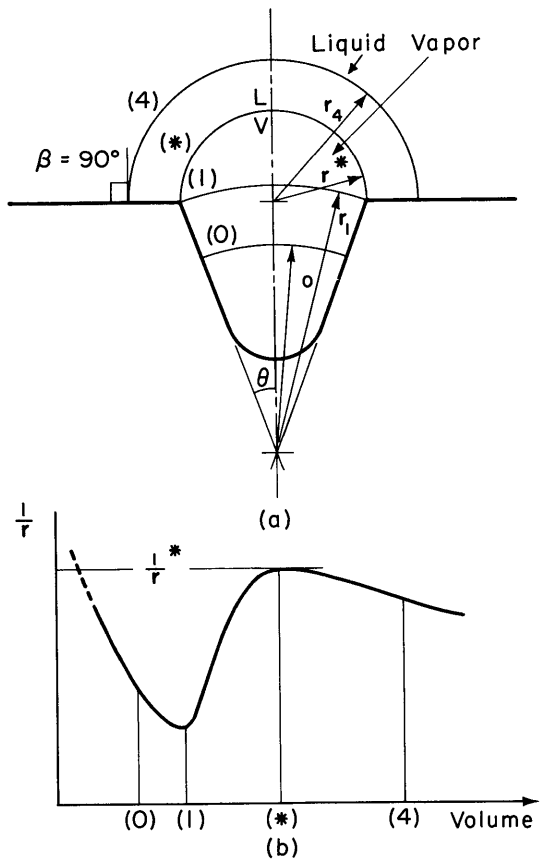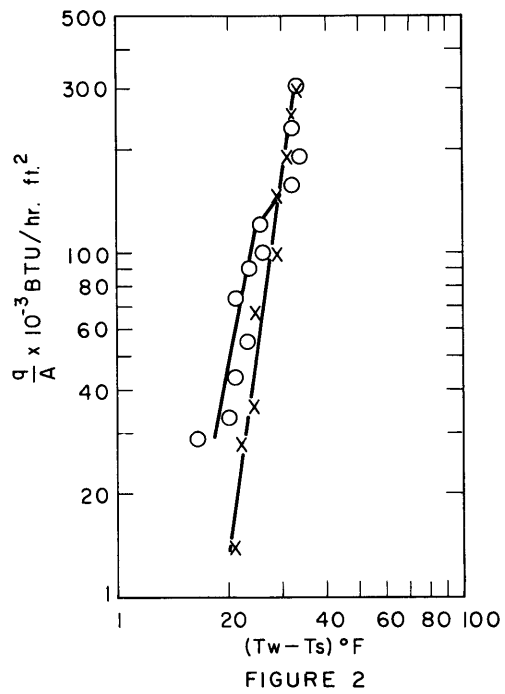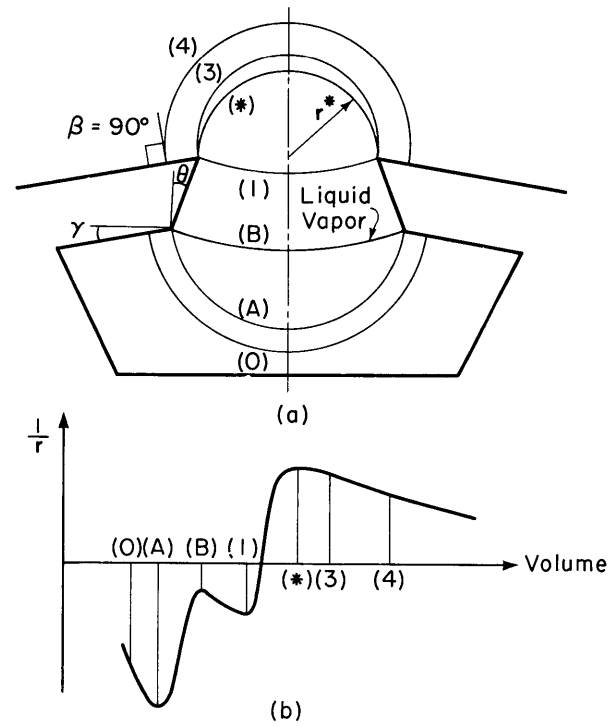
FIGURE 3

FIGURE 4
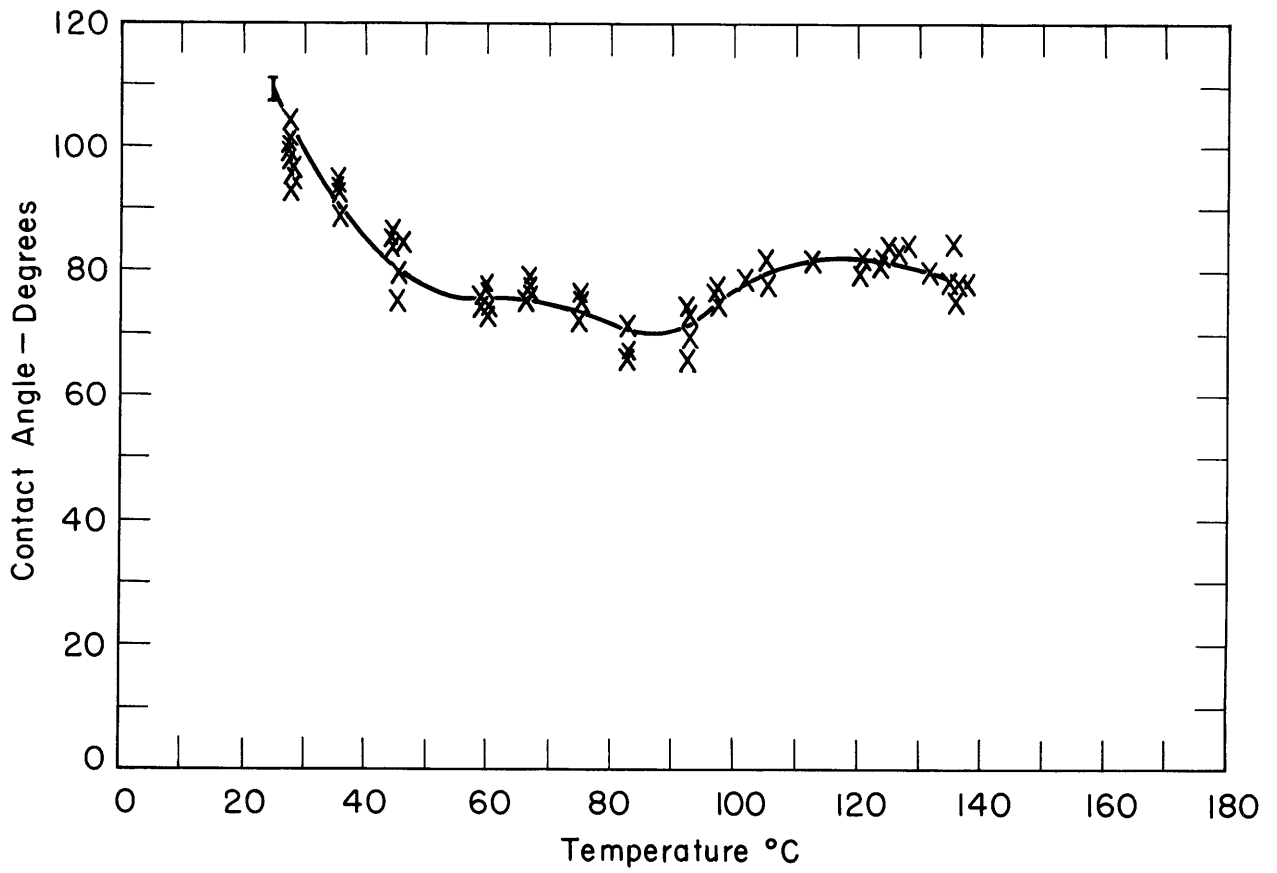
FIGURE 5
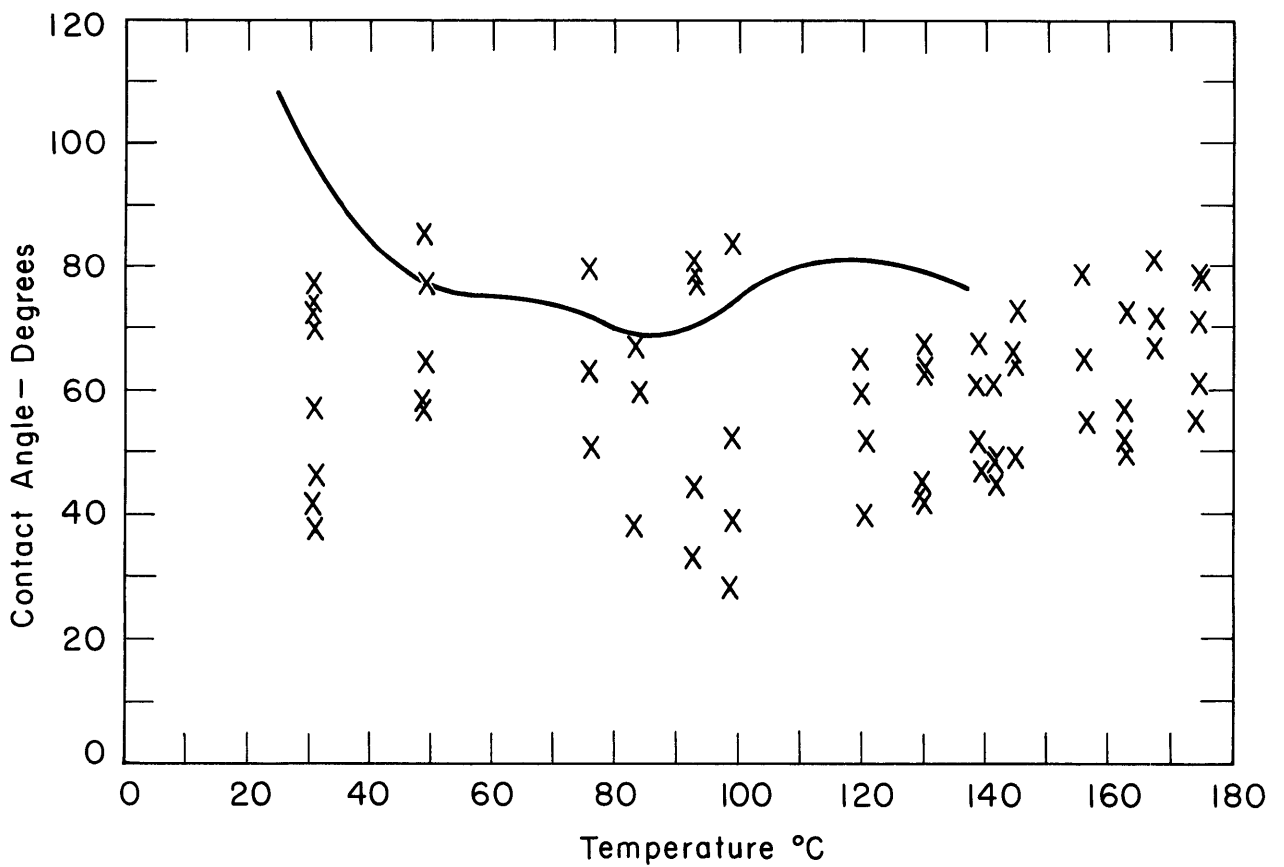
FIGURE 6
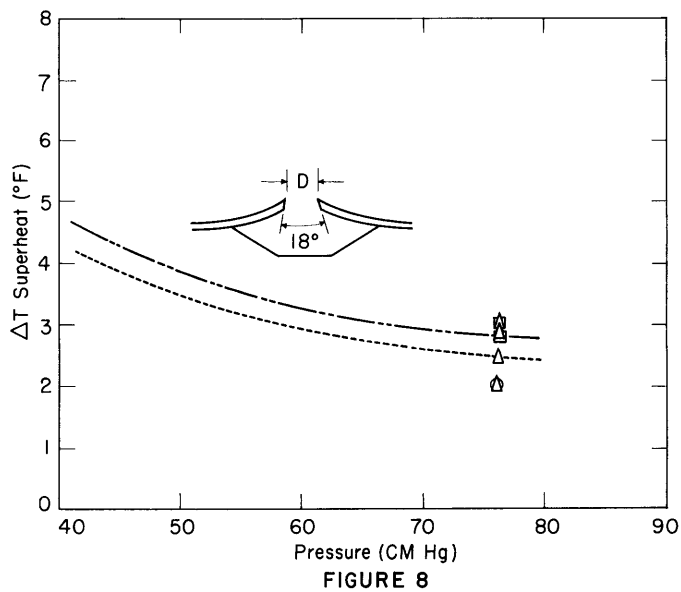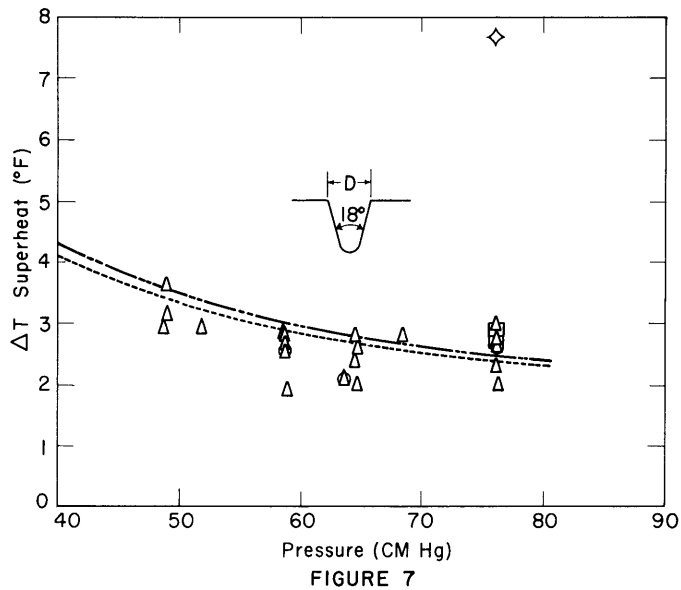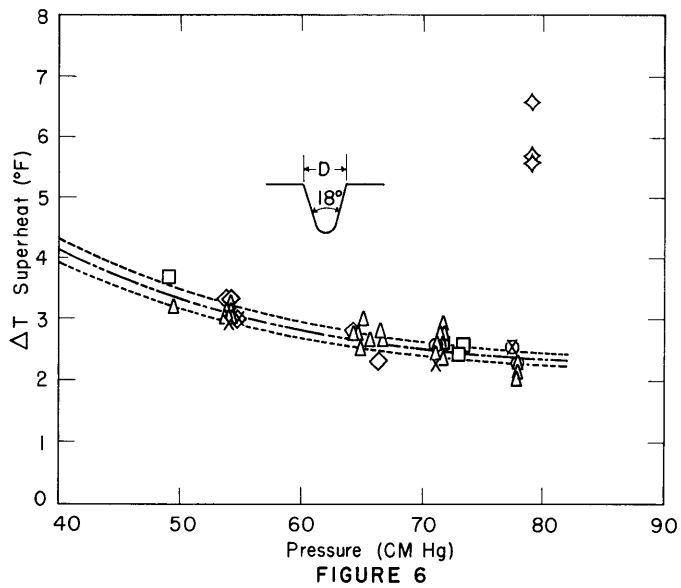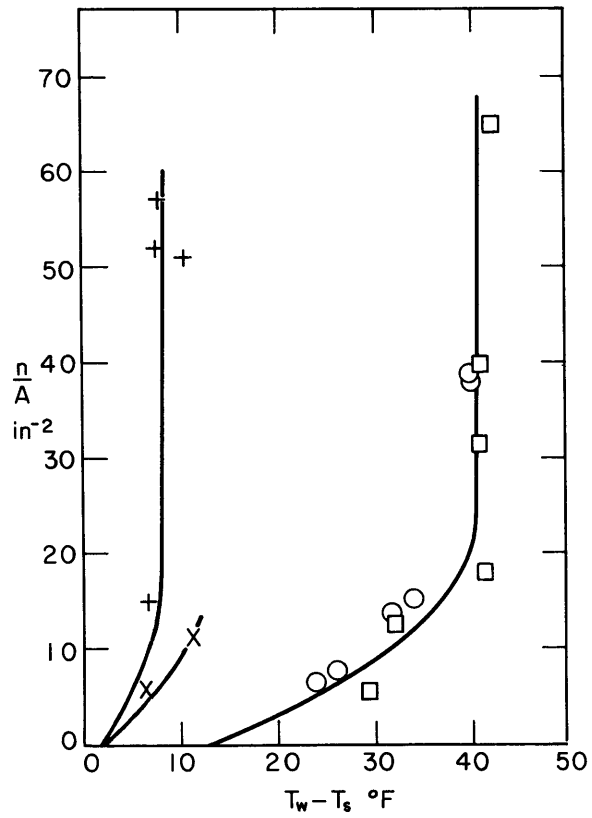
FIGURE 7

FIGURE 8

FIGURE 9
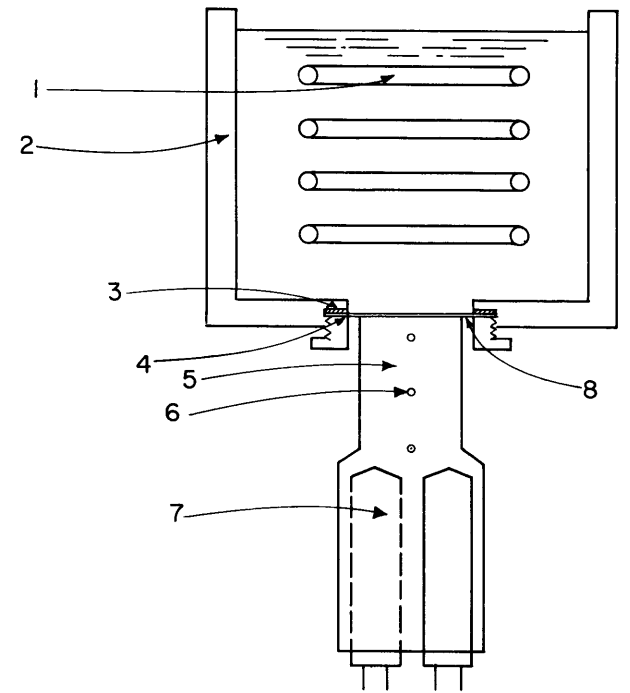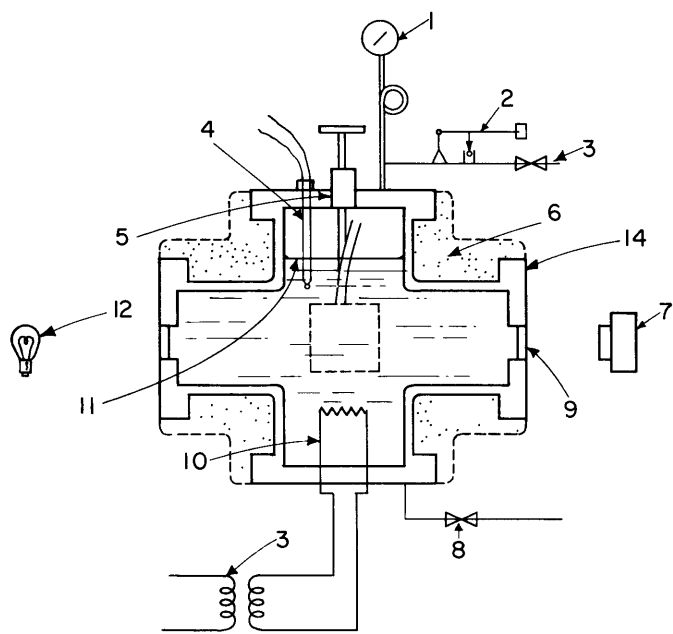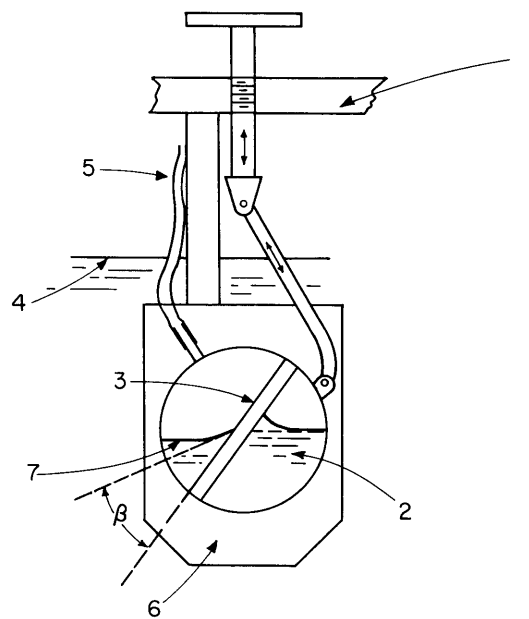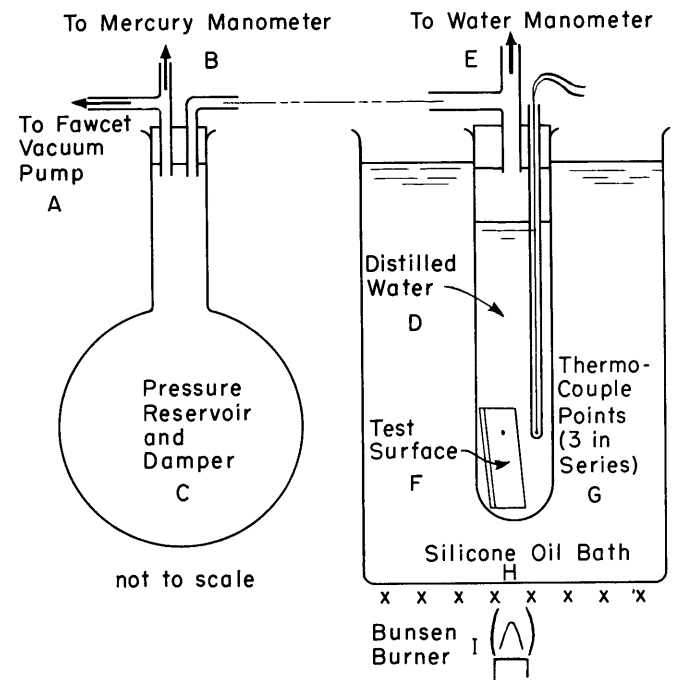
FIGURE 10

FIGURE II

FIGURE 12a

FIGURE 12b

To Mercury Manometer

To Water Manometer

B

E

To Fawcet
Vacuum
Pump
A

Pressure
Reservoir
and
Damper
C

not to scale

Distilled
Water
D

Test
Surface
F

Thermo-
Couple
Points
(3 in
Series)
G

Silicone Oil Bath
H

Bunsen
Burner I

FIGURE 13