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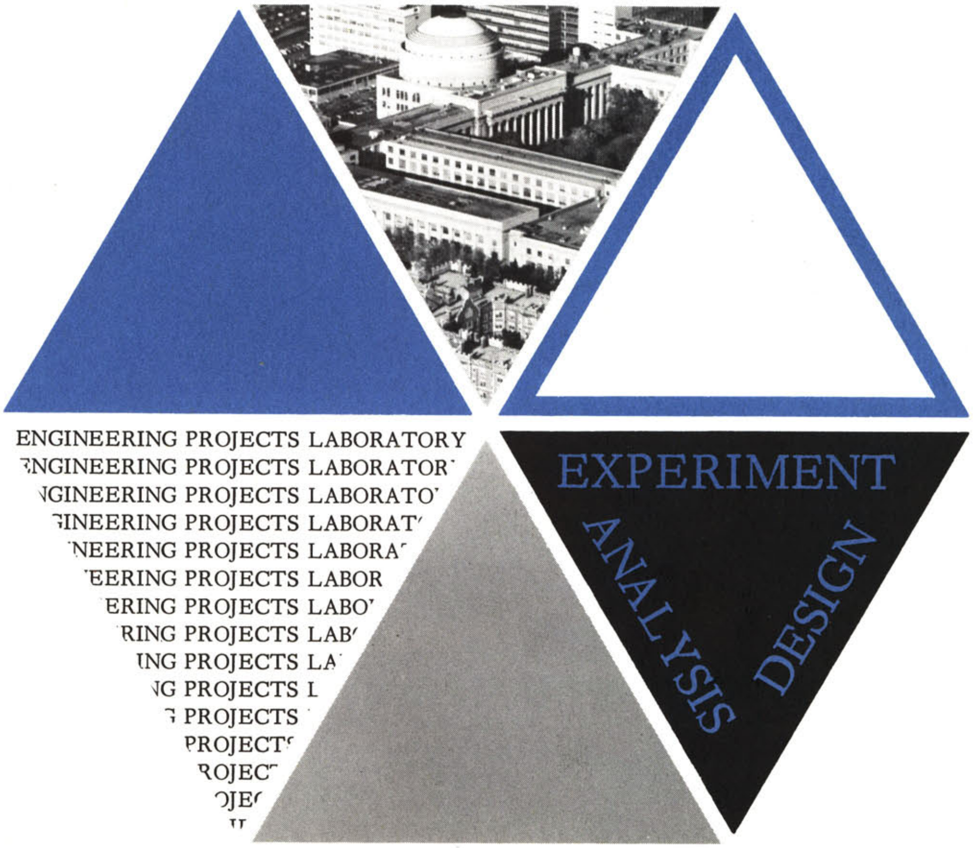

THE MECHANISM OF VOID FORMATION IN INITIALLY SUBCOOLED SYSTEMS

Peter Griffith*
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Abstract

When an initially subcooled, water filled system undergoes a transient in heat flux or pressure such that bubbles form, the most important variable which determines the volume of the resulting void is the number of bubbles that is formed. In this report the number of bubbles that are formed is shown to be a function of the surface micro-configuration, the contact angle and the history. A method of specifying the history is developed, experiments are run and the general correctness of the history specification is shown to be correct. Order of magnitude values of the limiting wall superheats as a function of the surface history and configuration are presented, but the reproducibility of the experiments is not found to be high.

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Introduction

A recurring problem in nuclear reactors is the response of the system to some sort of transient. An important facet of this problem is the question of what is the void-time relation for a specified transient in pressure or heat flux. It is this question to which this work is addressed.

If one looks closely at the problem of determining the void-time relation, it is clear that the problem reduces to that of determining the number of bubbles that form and their individual growth rates. Bubble growth rates have been much studied in the past few years and the growth process is welluunderstood (1), (2), (3). It is not clear, however, what determines the number of bubbles that form and it is this part of the question with which we are primarily concerned.

This is basically a nucleation problem so we shall begin this work by looking at the nature of the probable nucleation cites in initially subcooled systems. We shall then consider how one would specify the history of a surface from the viewpoint of the nucleation problem and finally present the results of some experiments which show how history affects the nucleation properties of the surface.

Prior Work

The prior work can be conveniently divided into the work in which a heat flux transient was imposed and that in which a pressure transient was imposed.

The work on flux transients includes references (4), (5), (6), (7) and (14). In references (4), (5), (6) and (14) an initially subcooled heated surface experiences a transient and its temperature increases to well over the temperature at which one would expect boiling to begin. The actual temperature difference at which boiling starts for all these experiments is found to be unpredictable. In reference (7) it is found that a boiling transient can be predicted if one knows the number of additional bubbles that will form as a result of the transient. In all these works the nucleation properties of the systems were unknown and essentially uncontrolled. In all these experiments reproducibility was found to be poor and prediction not possible.

Among the workers who have studied pressure transients, references (8), (9), and (10) should be mentioned. In reference (8) the amount of suspended matter was found to very substantially affect the amount of water blown out of a vessel when the pressure was suddenly dropped. In reference (9), pressure history was found to affect the tensile strength of a liquid but scatter in the results prevented anything but a qualitative conclusion as to the magnitude of these effects. Reference (10) reports some pressure-time and volume-time relationships though it was not found possible to make any predictions as to what the system responses would be. Nucleation properties were not measured or controlled.

Bubble Nucleation and History

It is an experimental fact that history plays a role in determining the number of bubbles that form in a pressure transient. Consider what shaking does to a can of beer or the results reported in reference (9). In this section we shall look into just what it is in the history that is important and develop a method of specifying this history.

It is now generally established that boiling takes place from cavities on the solid surface (11). With the contact angles referred to in reference (11), the only cavities that could be stable with sub-cooled liquid must be re-entrant. The simplest possible re-entrant cavity is illustrated in figure (1). Assuming rotational symmetry and contact angles less than 90° (as measured through the liquid) let us consider in some detail what determines the stability and nucleation properties of such a cavity.

From a mechanical force balance, the pressure difference between the inside and the outside of a bubble or drop must be equal to

$$P_c - P_\infty = \frac{2\sigma}{r} \tag{1}$$

The pressure inside the cavity is the sum of the partial pressure of the air "P_a" and that of the vapor P_s. P_s is a function of the surrounding temperature. If we substitute these two quantities in equation (1) and solve for the radius we end up with equation (2)

$$r = \frac{2\sigma}{P_a + P_s - P_\infty} \tag{2}$$

P_∞ is the pressure outside the cavity and r is the equilibrium radius of curvature which the interface will assume at any given temperature and pressure. Let us now turn our attention to the sequence of states the cavity of figure (1) passes through as the system is filled, heated, pressurized, de-pressurized, etc.

History starts when the surface was last absolutely dry. Normally the system is filled with a fluid at about room temperature with a certain concentration of air. Degassing may occur, but once the system is closed, the concentration of air in the system "x" remain fixed. Henry's law then allows us to calculate the partial pressure of the air for any system temperature. Henry's law from reference (12) is

$$P_a = K x \tag{3}$$

In general the constant K is a function of temperature. The value for P_a from equation (3) can be substituted into equation (2) along with the corresponding values of P_∞ and P_s and the equilibrium value of "r" evaluated.

This has been done and in figures shown later, typical equilibrium radius against time curves are shown. These are figures 4a and 4b. Let us now consider what this means in terms of the re-entrant cavity illustrated in figure (1). For a contact angle less than 90° for the cavity illustrated, a stable position of the interface exists within the cavity as long as the curvature is negative and

$$|r_{c2}| < |r| . \tag{4a}$$

If the curvature is positive and

$$|r| < |r_{c1}| \tag{4b}$$

the bubble will nucleate. While for the negative radii of curvature if

$$|r| < |r_{c2}|$$

the re-entrant portion of the cavity will fill up with liquid and the cavity be deactivated. The meaning of this is as follows.

A cavity can only effectively serve as a nucleation cite if the history is such that it has not, at any time, been filled with liquid. Therefore, for any given wall superheat a cavity will nucleate only when the superheat is high enough or alternatively

$$r_{c1} > R_{uc} \tag{5}$$

and if for all times in its history when the curvature is negative

$$|r_{c2}| < |R_{LC}| . \tag{6}$$

In equation (5) R_{uc} is the value of "r" calculated from equation (2) for the existing conditions of temperature and pressure. In equation (6) R_{LC} is the minimum value of $|r|$ calculated from equation (2) at any time in the history of the surface when the curvature is negative There is a possibility of confusion in the evaluation of R_{LC} so it is appropriate to consider in a little greater detail what it means.

Referring back to figure (1), the interface can hang on the lower lip and have a variety of radii of curvature varying all the way from a negative curvature with an absolute magnitude of R_{LC} through negative and positive infinity right up to some positive value around r_{c1}. Equation (6) is meant to apply only while the interface is "droplike," that is, while the center of curvature is located in the liquid.

The main point of this section can now be stated succinctly as follows. No matter what the history of the surface is (beginning when it was last dry), a value for "r" and thus R_{LC} can be computed from equation (2). For the same values of R_{LC} but different detailed histories it is now stated that the nucleation properties of the surface will be the same. That is, at equal values of the pressure and surface temperature the same number of sites will be active when R_{LC} is the same.

This assertion must be tested experimentally as it rests on several assumptions. These assumptions are:

1. Contact angle effects are not important. Contact angle drift has been ignored and the contact angle and cavity geometry interaction in determining R_{LC} have been ignored. These interactions are difficult to delineate in general terms and depend in a complex way on the cavity geometry.

2. Cavity geometry can be greatly simplified. One can draw any number of possible cavity shapes. These shapes could have several re-entrant portions or necks. The performance of these cavities for different histories, in general will be different.

The experimental program will be described next and has as its general objective the determining of how important these assumptions are. Two sets of experiments were run. One set had the pressure-temperature history controlled for a test section in a tube which experienced a sudden pressure release at constant temperature at the end of the run. The other set was essentially a known heat flux transient at constant pressure. Each of these experiments will be described separately with their results then the combined conclusions will be drawn.

PRESSURE TRANSIENT TEST

A quick pressure release type of test apparatus was chosen because it offered the easiest control of the pressure and temperature history. Several apparatus were tried but all but the last, which is described here, suffered from pressure transients that were slow enough to affect the results. The heat flux transient apparatus was constructed to show that pressure and temperature transients were the same when compared on the proper basis, that is, the same value of R_{LC} and R_{UC}. Only a few runs were made on it.

The apparatus used in this investigation of transient void formation is pictured in figure (2). The test section is a medium-wall Pyrex tube of one half inch diameter and four feet length. This tube is mounted in a copper cylinder containing silicone oil to provide a uniform temperature. The top of the cylinder has been cut away for purposes of observing and recording the number of bubbles formed. At one end of the glass tube an aluminum membrane and knife assembly are mounted. This assembly has the purpose of providing for a quick pressure release.

The membrane is a relatively heavy gage aluminum foil, selected because it ruptures promptly when struck by the knife but it can also resist pressures up to 62 psig, which is the maximum pressure in this series of tests. Saran wrap and cellophane were other materials tested but rejected because of inadequate strength or too-slow rupture. The knife assembly is a tubular cylinder containing a spring driven knife for puncturing the membrane and a trigger for releasing the knife. The cylinder is vented to the atmosphere to insure that the pressure there will be one atmosphere when the membrane is pierced. On the opposite end of the test section there is a series of fittings, connections, valves and meters and gages. It is here that the apparatus is filled with water, pressurized and controlled. The pressure transducer was removed after completion of the dynamic response tests to be described later.

Procedure

It is important to this investigation that as many potential variables as possible be maintained constant or rendered unimportant to the final result. Toward this end a rigid test procedure is followed. It is described in detail below.

At the start of the test the particular pressure and temperature history is selected. This history is a variation of the typical history shown in figure (4) of this report. In each test the test surface is wiped clean and dry then allowed to sit on the table, exposed to the air, while the test section is swabbed out to remove all residue from the bubbles formed in the preceding test. The swabbing is done in the same manner that one would clean out a shotgun. As the swab is removed from the test section the apparatus is filled with water. The test surface is placed in the test section and after bleeding out all air pockets the system is closed. The variable portion of the surface history begins at this time. The pressure-temperature history specified at the beginning of the test is imposed upon the test surface. Two conditions of particular importance, the "lower critical radius" R_{LC} and the number of degrees of superheat (or equivalently an upper critical radius) are specified and produced Ordinarily the R_{LC} condition is imposed at the beginning of the history by producing the highest system pressure coincident with the lowest system temperature. As can be observed from equation (2), this produces the smallest equilibrium bubble radius which exists during the history. Subject to two restraints the pressure-temperature history can be varied in any desired manner. These restraints are that R_{LC} as established by the present history must be the smallest equilibrium radius which is produced and that the equilibrium radius as defined in equation (2) must not become infinite. The infinite radius criterion corresponds to an inversion of the bubble interface from inward curving to outward curving and might produce a bubble before the pressure was released. Spurious nucleation (from the glass) was eliminated by running tests without the metal surface present to see what superheat the glass could sustain. Subsequent tests with the metal surface present were run with the temperature maintained below this value.

With these restrictions in mind an arbitrary history of heating, cooling, increasing or relaxing pressure was imposed until the temperature approached the specified value of superheat. This superheat was established relative to the boiling point at one atmosphere pressure. (Later it will be shown that the pressure rarefaction reduces the system pressure momentarily to one atmosphere and that this criterion for superheat is valid.) As the system temperature approaches the desired value, the pressure is set according to the second restriction and the heating rate is slowed down to insure a uniform temperature throughout the test section. The air vent on the knife assembly and the valve on the pressure line are closed tightly to seal the system and the membrane is punctured. As the rarefaction wave travels across the test section, the active nuclei for which the cavity mouth radius-superheat condition is satisfied, grow into bubbles large enough to be visible. The growth rate is very fast with the size of the bubbles dependent upon the superheat and the number of bubbles formed. In the ideal test the bubbles either remain attached to the test surface or detach, rise to the top of the tube and rest there. The usual test, somewhat removed from the ideal, is discussed further in the paragraph - Experimental Results - Pressure Transient. The number of bubbles is then simply counted and the apparatus is cooled to room temperature, opened and cleaned as described at the beginning of the procedure.

At the beginning cf the program a series of tests was run to make sure that certain important conditions could be met in the operation of the apparatus. Each of these tests involved the basic procedure described above with variations designed to establish the desired result. The results of these tests are given in the paragraph - Experimental Results - Pressure Transient, with a brief description of the pertinent variation from the above procedure.

Experimental Results - Pressure Transient

The first series of tests was run to determine the minimum pressure during the rarefaction wave and the duration of that minimum pressure. It is essential that the minimum pressure always reach one atmosphere so that the superheat can be established without recording a pressure trace for every test. In addition, it is desirable to control the superheat rather than compensate for it in producing uniform and reproducible results. In the first test the output from the pressure transducer, installed for these special tests, was put into an oscilloscope and photographed. The result is shown as Curve A in figure (3) of this report. It can be seen that the pressure decayed rather slowly to one atmosphere after a rapid but small initial rarefaction. The pressure decrease was thought to be due to rebound from the downstream end of the apparatus. To counteract this effect a delaying coil of fifty (50) feet length was added. The pressure response of the modified system is shown on Curve B in Figure 3. It can be seen that the pressure dropped rapidly to one (1) atmosphere then recovered somewhat and oscillated irregularly before settling down to a new equilibrium condition. No heat was added to the system, the entire process occurring at room temperature.

The test was repeated again, this time with heat added so that the temperature at the time of the membrane rupture was 212°F. The pressure fell rapidly as in the previous tests but never reached one (1) atmosphere. Three bubbles formed during the test (as a result of air) and it became necessary to examine whether these bubbles could produce the observed effect upon the rarefaction wave. The bubbles are known to grow quite rapidly and could generate an appreciable pressure wave as they emerged from their cavities.

To examine this problem a series of tests was run with slightly varied histories and different values of superheat (all referred to one (1) atmosphere pressure.) A typical result, Curve D of Figure 3 shows the influence of a large number of bubbles, (20 or more) as compared to Curve C, the results of the three bubble test. It is expected then that for large numbers of bubbles the results will be distorted by the effects of previously formed bubbles. There should result a heavier concentration of bubbles on the upstream end of the test surface. For small numbers of bubbles the effects from this phenomenon should be minimal. The program is aimed at small bubble populations so the effect should not be a major factor in the results.

Having established that the principal conditions of the tests were being met, the pressure transducer and oscilloscope were removed from the system to simplify operations.

In the paragraph, Experimental Methods - Pressure Transient, reference is made to the behavior of bubbles in an ideal test. The bubbles grow out of the cavities very rapidly, literally bursting from the surface. They rise to the top of the tube and rest there to be counted. In fact, the behavior of the bubbles is quite dependent upon the test conditions. The volume of the knife assembly must be filled after the membrane is broken and the bubbles will grow large enough to accomplish this and bring the system to an equilibrium pressure related to the temperature and the air present. The behavior of the bubbles will be as follows: for severe histories, very small R_{LC}, the number of bubbles will be small. The bubbles will grow very rapidly and to a large size, bursting out of the cavities and to the top of the test section. They agglomerate there at a rapid rate. It is necessary to count these bubbles by an estimation. The counting is similar to the reading exercises provided by the phrase cards in speed reading training. The skill at recording an image in the mind's eye from a vision of very short duration can be developed by practice. A mistake of one or two bubbles on a count of three or four introduces a considerable scatter percentage wise but the error should be no larger than this. As the superheat is increased the number of bubbles increases and both the size of bubbles and violence of the growth are reduced. In these cases the number of bubbles is easily counted as agglomeration is greatly reduced.

As the R_{LC} of the history is increased the number of bubbles is increased slightly and the counting difficulties are diminished until we arrive at a large R_{LC} and large superheat. In this case the number of bubbles becomes so large that the rarefaction wave is distorted and bubble agglomeration again increases. The approximate number of bubbles to which these practicing limits applied was approximately four (4) bubbles for the severe history and fifteen (15) to eighteen (18) bubbles for the mild history. No meaningful results could be achieved with the stainless steel rod for histories in which $R_{LC} > 4.0 \times 10^{-5}$ inch. For the case of $R_{LC} = 6.0 \times 10^{-5}$ inch there were uncountable numbers of bubbles for all the levels of superheat used in these tests. These limits were the limits of the test.

Experimental Results

The principal parameters tested in this program were the effects of R_{LC} and superheat (or R_{UC}) upon the number of bubbles formed during a sudden pressure drop and the effects of variations on the pressure-temperature history on the number of bubbles formed when R_{LC} and superheat were held constant. The results of the tests, shown on Figures 5, 6, and 7 of this report indicate that the bubble nucleation process has a considerable amount of randomness in it. The scatter here is about the same as that shown in reference (9) in spite of the precautions taken in the experiments.

Figure 5 is a summary of the experimental results on the number of bubbles formed as a function of history and the superheat. Within the scatter no effect of the details of the history could be seen. As expected the number of bubbles formed increases with superheat at the time of pressure release and increases for large values of R_{LC}. In Figure 5 each point represents one run. As can be seen there was considerable scatter for any given set of conditions. The lines are the average values. In general the details of the history are different for each of these runs.

Figure 6 shows the effect of surface finish on the nucleation properties of two wires finished as indicated in the text. As can be seen, the rough wire is much easier to nucleate. Clearly surface finish is an important parameter.

Figure 7 is the raw data for different times of being held at the top pressure. For times less than two minutes some effects are discernable but for longer times none are. In some cases the pressure was held for several hours. Apparently, the contact angle drift and gas diffusion processes which are relatively slow, all come to completion in the first two minutes. Figures 5, 6, and 7 summarize the results for the experiments run in the apparatus illustrated in Figure 2. Let us now turn our attention to the other experiment.

EXPERIMENTAL METHOD - HEAT FLUX TRANSIENT

Apparatus

It is the purpose of this series of experiments to examine the relationship between a pressure transient test and a heat flux transient test to determine if the pressure transient apparatus can be used to predict the results of a heat flux transient. All transients are combinations of these two, so these represent the limit. To this end an additional apparatus was assembled as described on Figure 7. The apparatus consists of two beakers, mounted concentrically in the manner of a double boiler. In the smaller beaker there is a float which supports the electrodes between which the test surface is suspended. The test wire is heated by battery. Timing of the transient is accomplished by oscilloscope and the bubble formation is recorded by high speed camera.

Procedure

Before performing the heat flux test a series of nucleation studies is performed on the test wires by the pressure transient method. In these tests it is important that the pressure-temperature history imposed upon the test surface be as nearly as possible identical to the pressure-temperature history for the heat flux transient. Specifically it was desired that R_{LC} be the same in both tests. By considering the effects of degassing, cooling and reheating of the test surface during a heat flux transient test a typical history was devised and imposed upon the pressure transient tests. The amount of superheat for each successive test was increased until the first bubbles were formed. The tests were then repeated with superheat varied in the range of the value of the first boiling so that reproducibility and the growth of more than one bubble could be predicted. This process establishes a nucleation characteristic for the test surface. The nucleation characteristic for each test surface to be used in the heat flux transient tests is predetermined in this manner.

With this information completed the same test surface is placed between the electrodes in the heat flux apparatus. Careful precautions are necessary to insure that the wire is as clean after soldering as it was when tested in the pressure transient apparatus. The beakers are filled with water and boiled vigorously for several hours. The wire, too, is heated to drive gases out of the cavities. After degassing, the float, a smooth plastic dish, is placed on the water surface in such a manner that no air bubbles remain. The system is cooled to room temperature and the water remains degassed since no free surface is exposed to air. All necessary electrical connections are made at this time, care being taken that the circuit be kept open. The electrical circuit is shown on Figure 8.

With the electrical connections made, the camera loaded and set and lighting prepared, the test apparatus is heated by Bunsen burner to the saturation temperature for the test liquid, in the case, water. The high speed camera is started so that it has time to pick up speed then the switch is closed to produce a step function in heat generation in the wire. The lens of the camera, the test wire and the face of the oscilloscope are aligned so that viewing of the wire and of the oscilloscope are simultaneous. The waiting period for the first bubble starts when the switch is closed. This instant is observed on the film by a shifting of the oscilloscope trace from 0 voltage to a finite voltage drop across the test wire. The voltage shift for the circuit (actually the circuit's transient response) occurs in one frame interval of the film so that the beginning of the waiting period is well defined. The growth of the bubbles from invisibly small to visibly large on the film strip is similarly very fast and occurs in an interval of time corresponding to one frame. The waiting period is measured by counting the number of frames consumed during the period. The film speed is determined by a timing flash on the border of the film. By counting the number of frames per second and dividing this number into the total number of frames consumed, the duration of the waiting period is measured.

After filming of the heat flux transient the apparatus is cooled to room temperature and the process is repeated exclusive of the degassing procedure. Degassing need be repeated only after the test surface is removed from the water or after changing the test surface.

Experimental Results - Flux Transient

The experimental procedures described above were performed upon two test wires of slightly different surface characteristics. The first wire is used in an as-drawn condition and is referred as the bright wire. The second wire was identical except that the surface was scratched and pitted by being rubbed in coarse, dry lapping compound. The nucleation characteristics for the two wires are shown on Figure 5.

Using the information above the mouth radius of the active cavities is determined. Next the transient temperature distribution at the surface is calculated. The calculation for the heat flux transient are outlined in the Appendix and the results are shown on Figure 10. The Bergles (13) incipient boiling criterion relates the cavity radius to the temperature distribution. By using the Bergles criterion and the cavity size distribution which was ascertained in the pressure transient test a temperature-distance condition is determined and marked on the calculated temperature field. The elapsed time intervals on the temperature distribution will predict the duration of the waiting period for a particular bubble. Limitations to the accuracy of this method will be the approximations which are required to calculate the temperature distribution and the reproducibility of the nucleation data from the pressure transient test. It is apparent from the pressure transient data on the stainless steel rod that this will be the limiting accuracy and the accuracy may be poor.

Pressure transient data for the test wires showed better reproducibility, however, especially in regards to the temperature at which the first bubble formed. Apparently a single, stable cavity was responsible for this. For each of the test wires the repeated tests agreed in a range of 5°F. Using this data predictions were made for four tests with the roughened wire and one test with the bright wire. The results for Tests 1, 2, and 5 agreed very well and are shown in Table I. For Tests 3 and 4, however, the results were quite unsatisfactory. The predicted waiting period was more than twice as long as the measured time. Close examination of the test surface showed that this discrepancy resulted from dirt which collected on the wire. A thin film of black substance was present on the wire providing spurious nucleation sites.

TABLE I

FLUX-TRANSIENT RESULTS

TEST NUMBER	WIRE	POWER	PREDICTED t_w	MEASURED t_w
1	Roughened	25.0 Watts	0.056 sec.	0.054 sec.
2	Roughened	25.0 Watts	0.056 sec.	0.055 sec.
5	Bright	23.04 Watts	0.212 sec.	0.258 sec.

A small mirror had been placed in the bottom of the test beaker to improve lighting of the test wire. The black backing of the mirror had apparently chipped and peeled off during the degassing process. Since the wire was electrically charged during the degassing process the dirt particles were attracted to the wire and stayed there. In subsequent degassings the electric current was run through the wire for a much shorter time to reduce the severity of this problem. The correlation between the predicted delay times from the pressure release experiment and those actually observed was quite good. It is not felt that any better correlation can be expected.

Conclusions

1. The number of bubbles that form in a pressure or heat flux transient is strongly affected by wall superheat and less strongly by history.

2. Within the experimental scatter the details of the pressure time history or the nature of the transient are not important so long as R_{LC} is kept constant.

3. The scatter is most likely tied to the geometric complexities of the cavities and the contact angle drift. It is apparently inherent in the nucleation processes and will appear in the most carefully controlled experiments on "as received surfaces" without any kind of promoter.

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K	Henry's Law constant of proportionality
P_a	Partial pressure of air
P_c	Total pressure in the cavity
P_s	Saturation pressure of the vapor
P_∞	Pressure in the body of the fluid
R_{uc}	Upper critical radius of curvature always positive
R_{LC}	Lower critical radius of curvature almost always negative
x	Concentration of air in water, units compatible with Henry's Law constant
r	Radius of curvature
r_{c1}	Radius of curvature of cavity mouth
r_{c2}	Radius of curvature of re-entrant portion
σ	Surface tension

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APPENDIX

CALCULATION OF TRANSIENT TEMPERATURE FIELD IN THE VICINITY OF A TEST WIRE

Assume that a one dimensional solution is satisfactory for this calculation. The differential equation for this case is:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a_t}\frac{\partial T}{\partial \tau}$$

The boundary conditions for the solution are:

$$T(\infty,\tau) = \frac{\partial T}{\partial x}(\infty,\tau) = \frac{\partial^2 T}{\partial x^2}(\infty,\tau) = 0$$

$$\frac{\partial T}{\partial \tau}(0,\tau) = \frac{q}{\pi r_0^2 \rho c_p} + \frac{2k}{r_0 \rho c_p}\frac{\partial T}{\partial x}(0,\tau)$$

The partial differential equation and its boundary condition are reduced to the finite difference equations:

$$T_{j,k} = \frac{T_{j-1,k-1} + T_{j+1,k-1}}{4} + \frac{T_{j,k-1}}{2}$$

and

$$T_{0,k} = \beta g + \frac{2g}{h}T_{1,k-1} + \left(1 - \frac{2g}{h}\right)T_{0,k-1}$$

where

$$\beta = \frac{q}{\pi k},$$

$$g = \Delta\theta = \frac{\Delta\tau\, a_t}{r_0^2},$$

and

$$h = \frac{\Delta x}{r_0}.$$

The solution for the transient temperature distribution is shown on Figure 10 of this report.

T = temperature difference = $t - t_{initial}$

x = Distance from wire surface

a_t = Thermal diffusivity

q = Heat generation rate per unit length

τ = Time

ρ = Density

k = Thermal conductivity

c_p = Specific heat

r_o = Radius of wire

CAPTIONS

Figure 1 Idealized re-entrant cavity.

Figure 2 Schematic of quick pressure release apparatus.

1. Air bleed
2. Air bleed
3. Pressure gage-Ashcroft 1850
4. Pressure line - 0-150 psig capacity
5. Water line
6. Delay coil - copper tube 1/2" O.D.
7. Pressure transducer - Dynisco Type 6025, 6 v., 0-300 psi connected to oscilloscope
8. Test section - glass tube 1/2" O.D. medium wall pyrex
9. Uniform temperature bath - silicone oil
10. Test surface
11. Membrane - aluminum foil
12. Knife assembly
13. Heater

Figure 3 Various pressure-time traces

A = Pressure-transient test for case of no delaying coil and no heat addition.
B = Case of no heat addition with delaying coil
C = Case of heat addition with delaying coil, 3 bubbles formed $T = 212^oF$
D = Case of heat addition with delaying coil, $T = 265^oF$, many large bubbles were formed.

Figure 4 (a) Pressure temperature history.

Figure 4 (b) r history for the conditions of (a) solved from equation (2).

Figure 5 All the experimental results for different histories and superheats. Each point represents one run and the line represents the average condition for all of the runs at the same conditions.

Figure 6 Effect of surface finish on bubble nucleation.

Figure 7 Effect of time spent at high pressure on the nucleation properties of the surface. Time effects were not noticeable for periods greater than two minutes.

Figure 8 Schematic of the flux transient apparatus.

Figure 9 Flux transient circuit.

Figure 10 Transient temperatures around the wire illustrated in Figure 8, drawn to scale. Apparently the effect of the temperature gradient on the nucleation superheat is small for the cavity sizes of interest. The bubble is in an almost isothermal environment at almost the wire temperature at any instant.

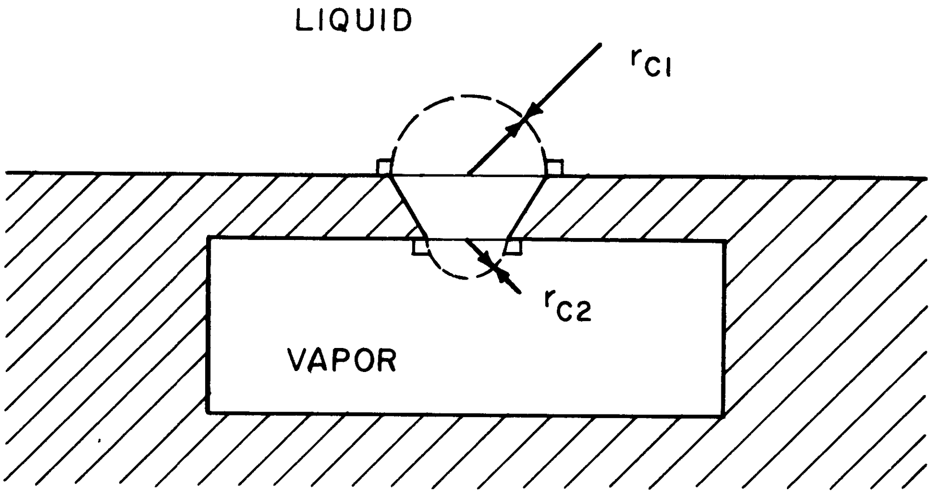


FIGURE 1

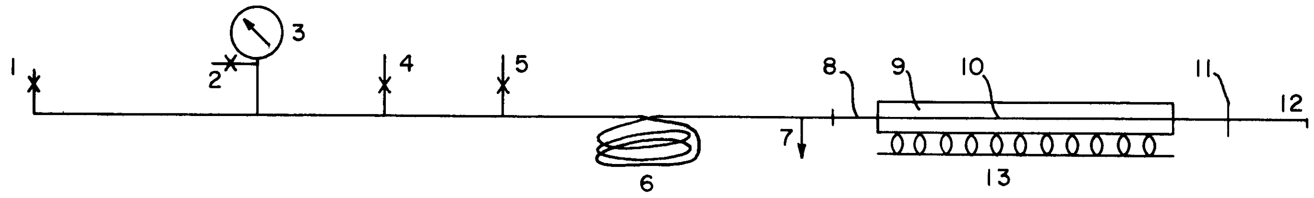


FIGURE 2

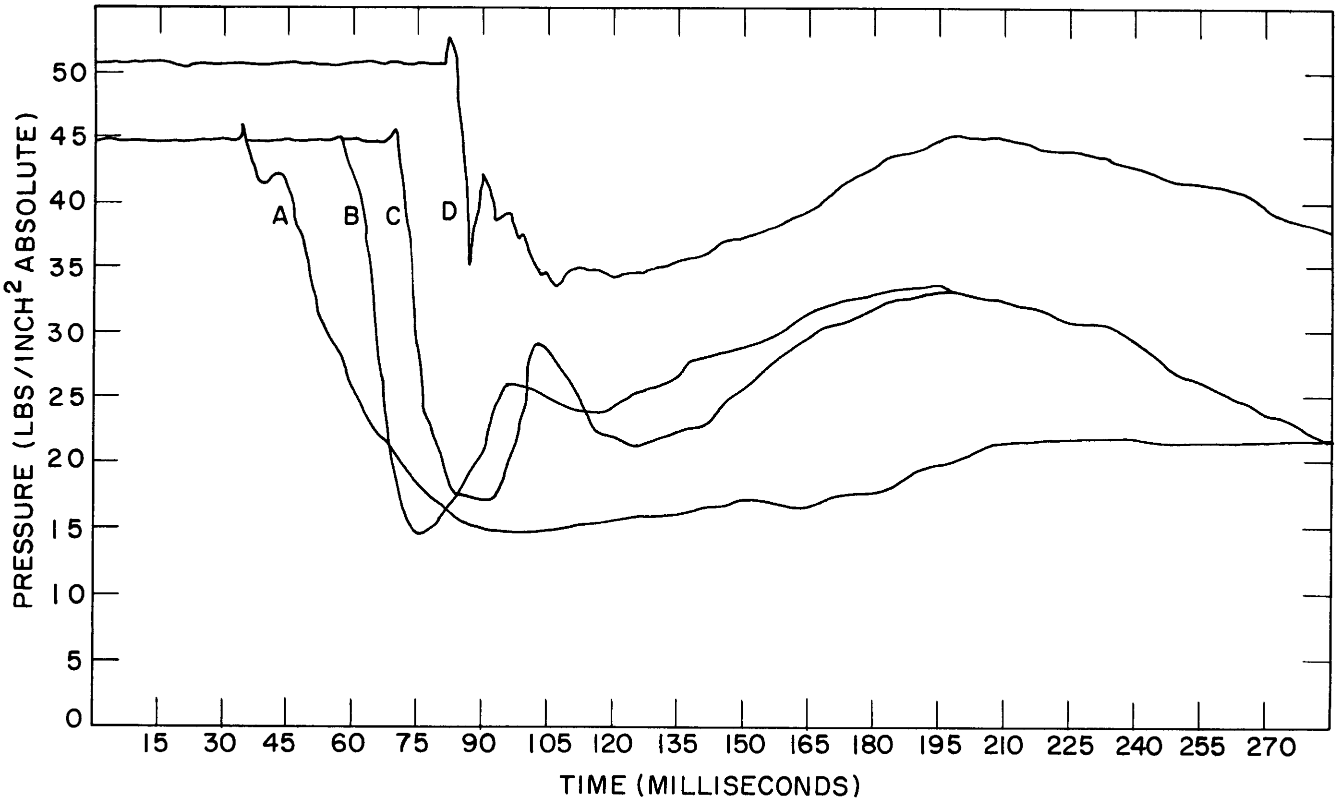


FIGURE 3

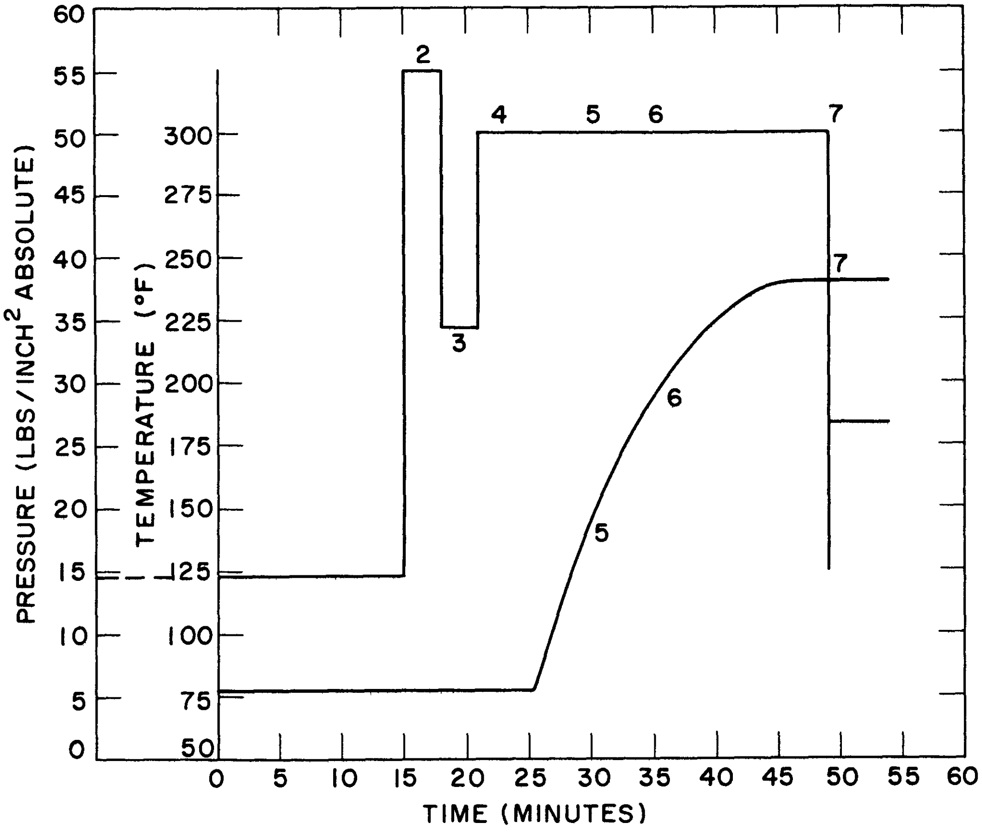


FIGURE 4a

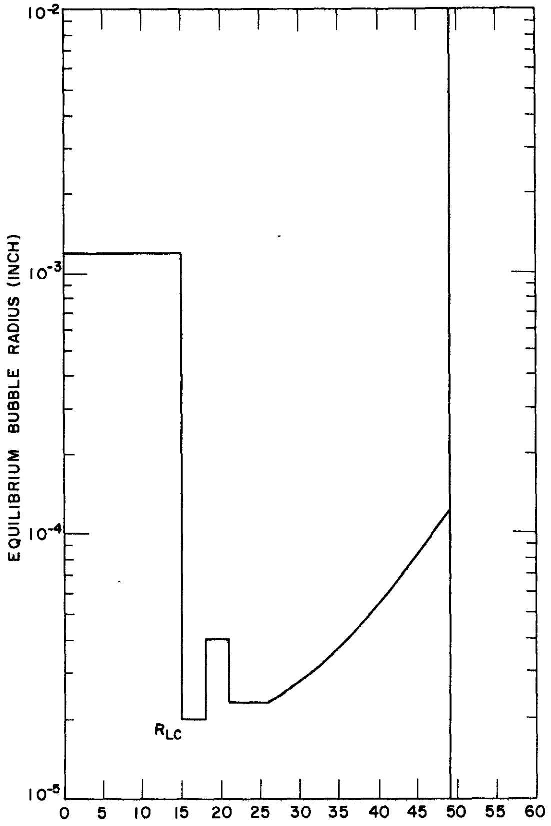
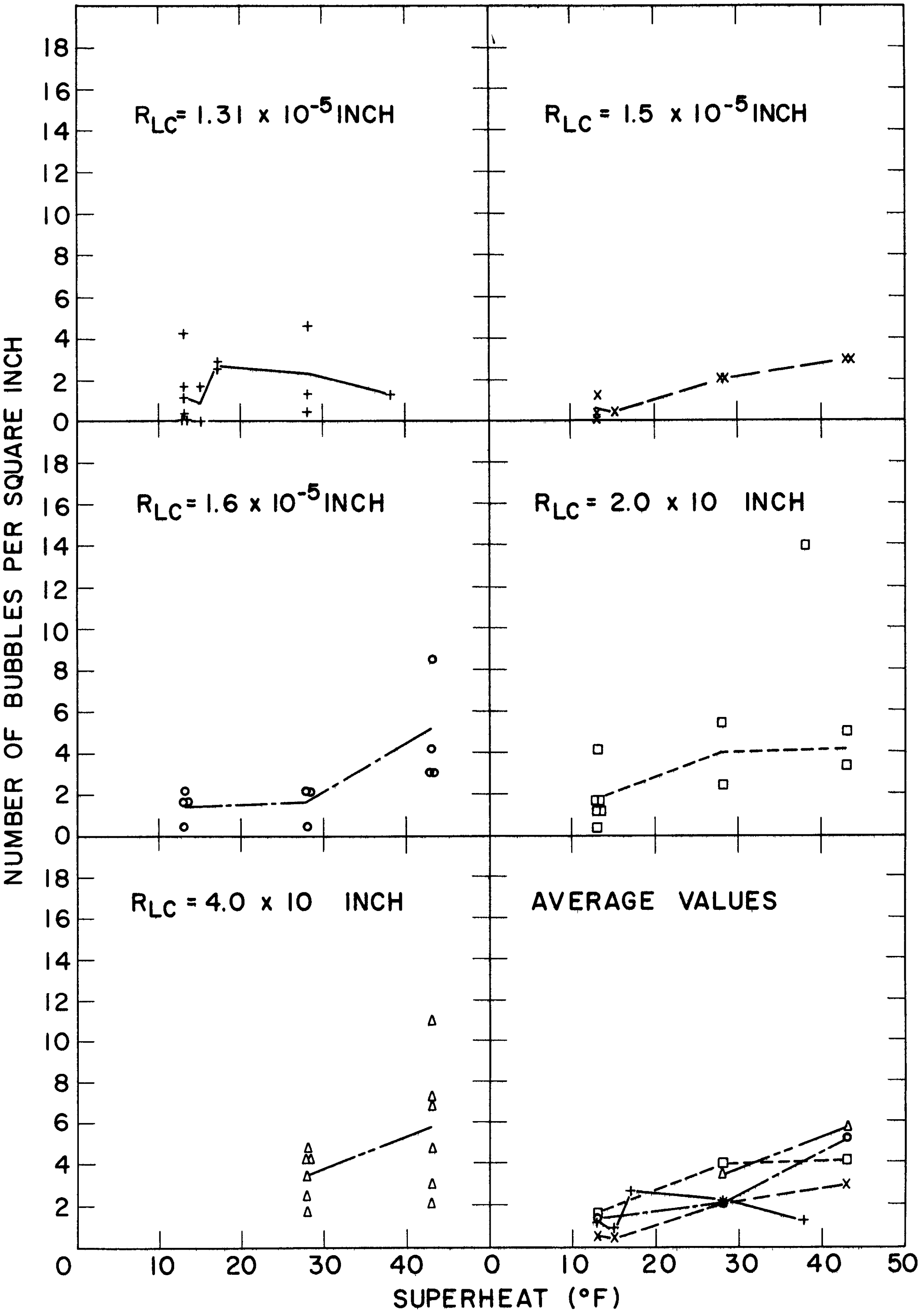


FIGURE 4b



R_{LC} = 1.31 x 10^{-5} INCH
R_{LC} = 1.5 x 10^{-5} INCH
R_{LC} = 1.6 x 10^{-5} INCH
R_{LC} = 2.0 x 10 INCH
R_{LC} = 4.0 x 10 INCH
AVERAGE VALUES
NUMBER OF BUBBLES PER SQUARE INCH
SUPERHEAT (°F)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50

FIGURE 5

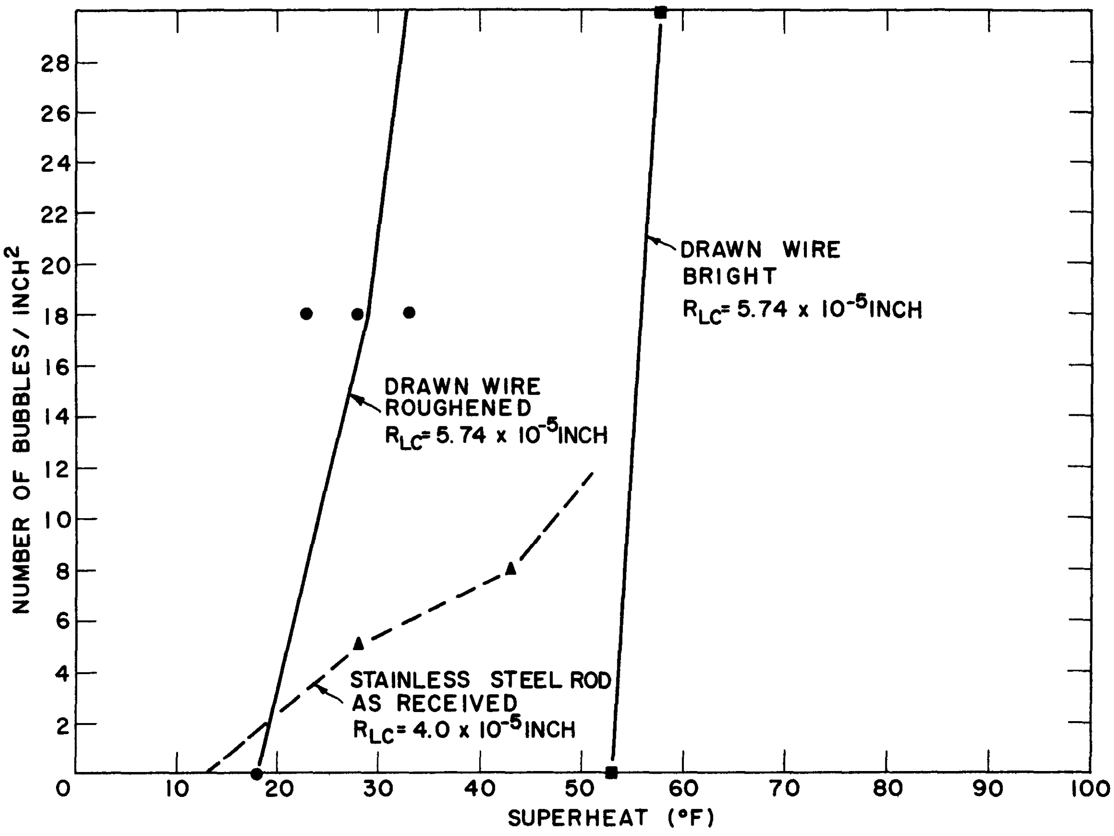


FIGURE 6 EXPERIMENTAL RESULTS SURFACE FINISH EFFECTS

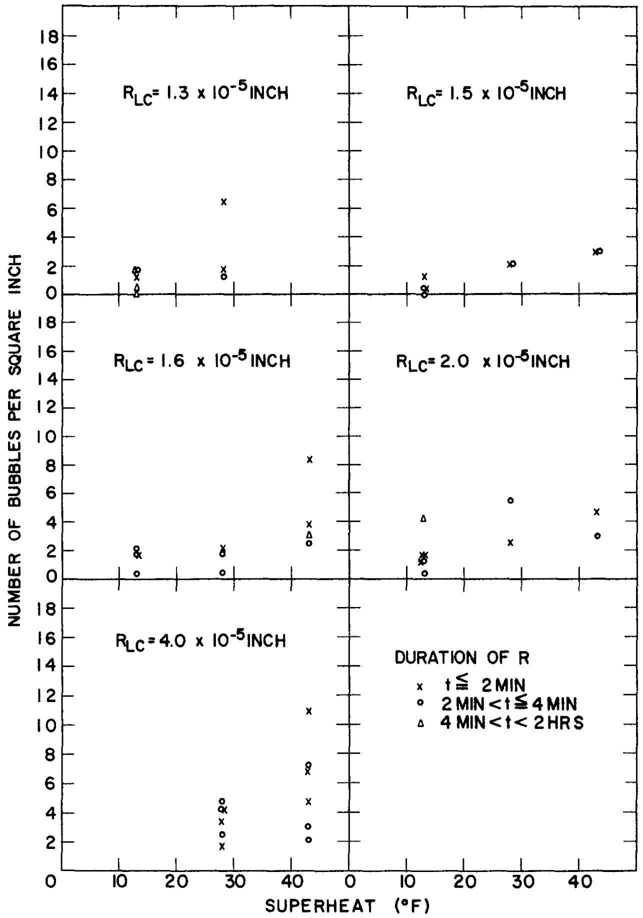
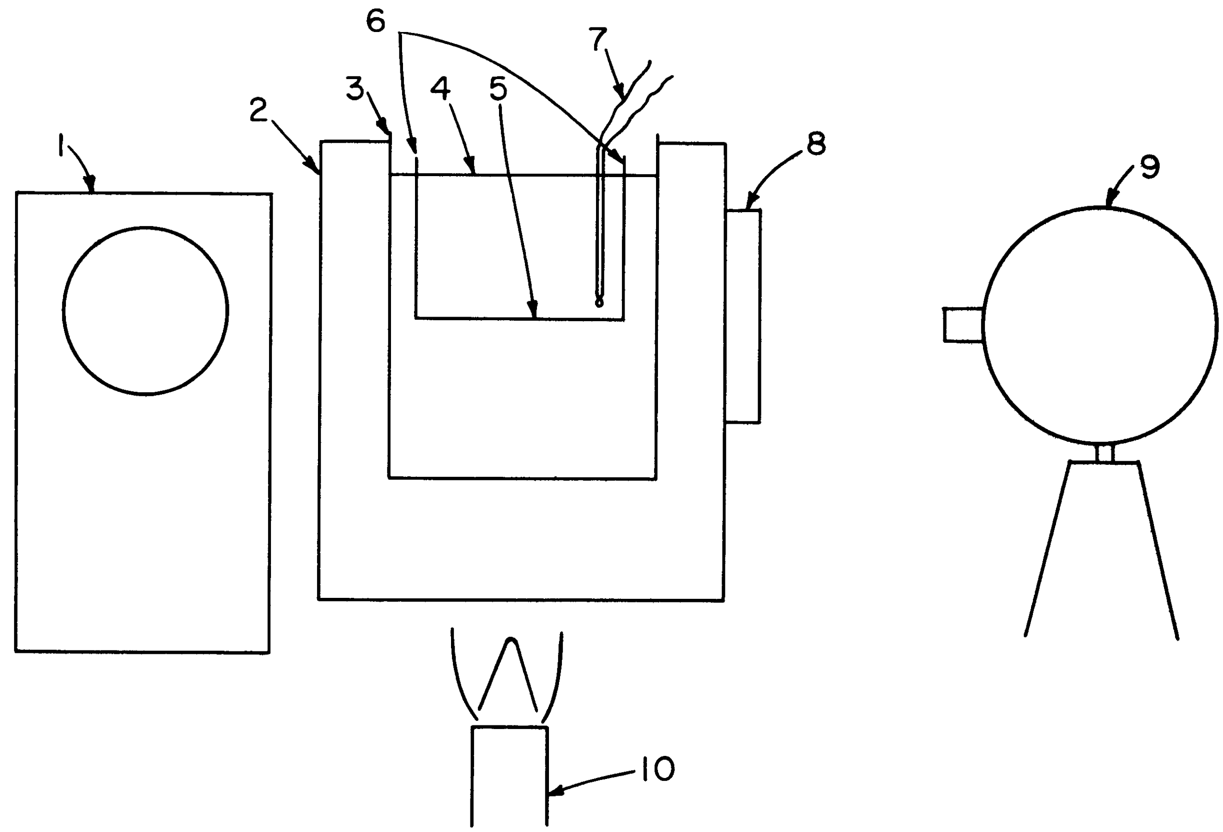


FIGURE 7 TIME EFFECTS IN NUCLEATION



1. OSCILLOSCOPE
2. WATER BATH
3. TEST BEAKER
4. PETRI DISH
5. TEST WIRE
6. ELECTRODES
7. THERMOCOUPLE
8. LENS
9. HIGH SPEED CAMERA
10. BUNSEN BURNER

FIGURE 8 FLUX TRANSIENT APPARATUS

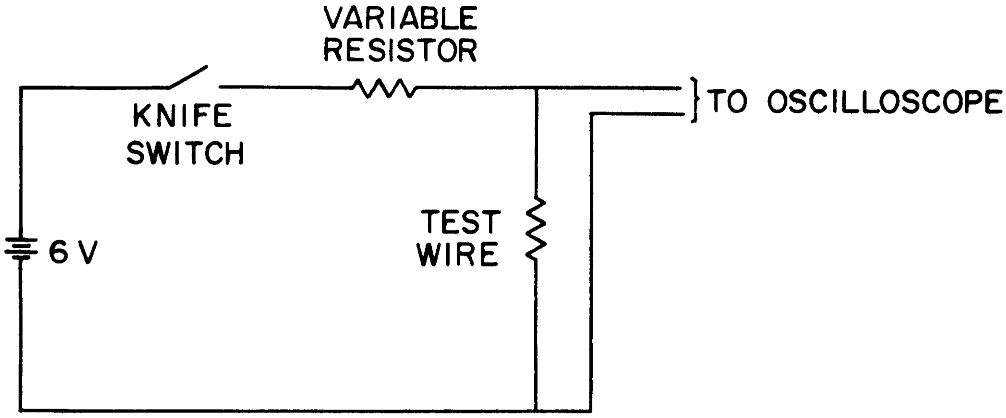


FIGURE 9 FLUX TRANSIENT CIRCUITRY

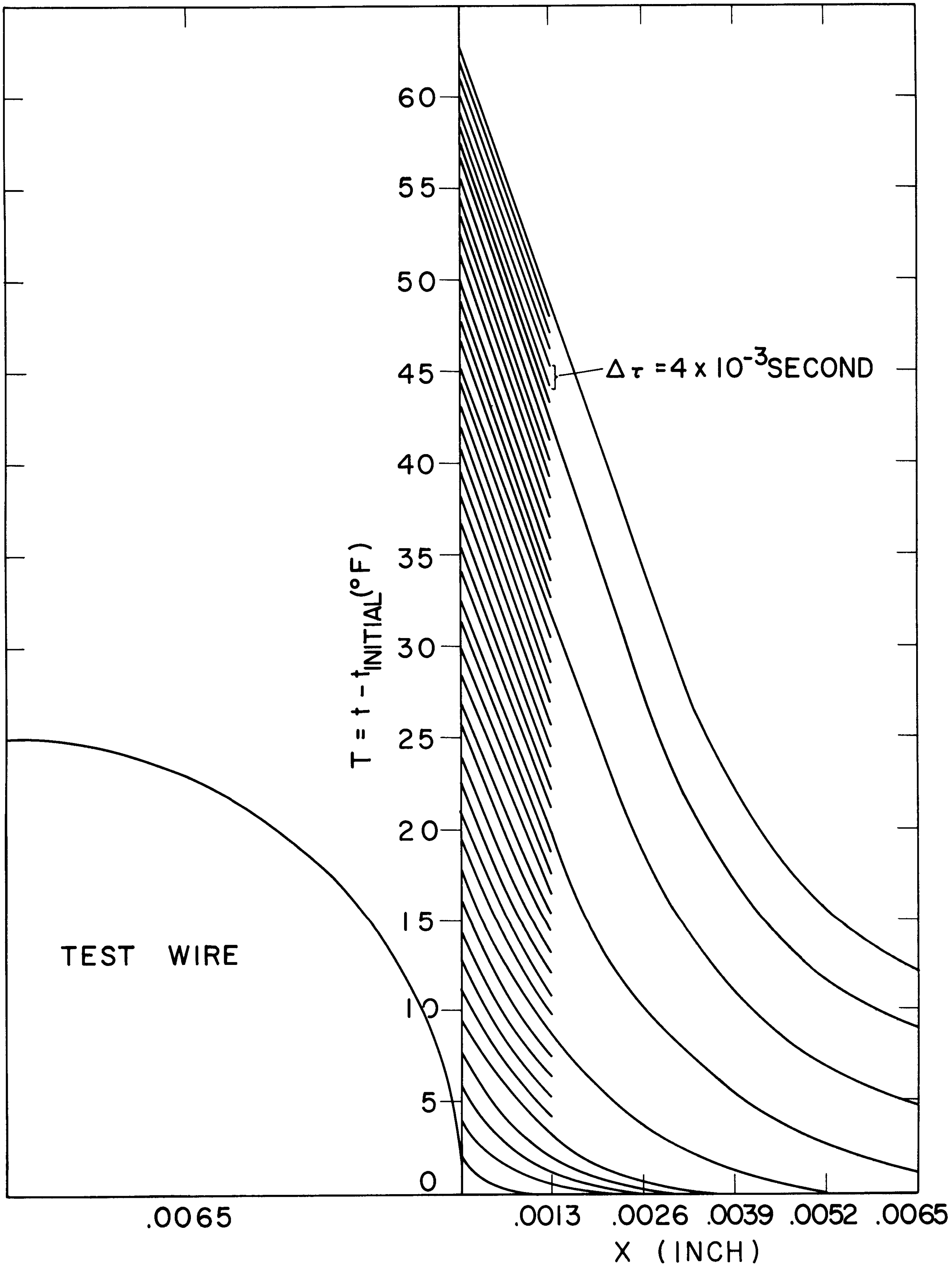


FIGURE 10 TRANSIENT TEMPERATURES