A study into the interaction between nucleation sites in boiling heat transfer
by Francis Edwin Keller

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Chemical Engineering
Montana State University

Abstract:
Interest in the field of boiling heat transfer has brought about increased interest into the problems of what is going on at each individual site during nucleation and what, if any, interactions exist between sites. This research project was designed to investigate both individual sites and the interactions between sites when more than one exist.

The research was divided into two parts. • The first part consisted of a mathematical prediction involving idealized systems. The second part consisted of reproducing experimentally the idealized systems in the laboratory and of verifying or refuting the predictions.

. The study involved single sites of various sizes, two sites of equal size at various distances apart, two sites of different sizes at various distances apart, three sites of equal size on the vertices of an equilateral triangle at various distances apart, and three sites of equal size in a line at various distances apart. The heat transfer during nucleation was obtained for temperature excesses ranging from five to twenty-five degrees Fahrenheit.

The mathematical prediction scheme predicted a heat transfer during nucleation as compared with the' experimental value that was generally within the inaccuracies of the measuring equipment for all of the cases under study.

A STUDY INTO THE INTERACTION BETWEEN NUCLEATION
SITES IN BOILING HEAT TRANSFER

by

FRANCIS E. KELLER

A thesis submitted to the Graduate Faculty in partial
fulfillment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Chemical Engineering

Approved:

Lloyd Berg
Head, Major Department

Robert L. Nickelson
Chairman, Examining Committee

Louis D. Smith
Dean, Graduate Division

MONTANA STATE COLLEGE
Bozeman, Montana

December, 1963

ACKNOWLEDGMENT

I wish to thank the staff of the Chemical Engineering Department of Montana State College for their advice and assistance during the course of this research project. Special thanks are due to Dr. Robert L. Nickelson, under whose direction this research program was carried out.

The financial support of the Montana State College Engineering Experiment Station is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Interest in the field of boiling heat transfer has brought about increased interest into the problems of what is going on at each individual site during nucleation and what, if any, interactions exist between sites. This research project was designed to investigate both individual sites and the interactions between sites when more than one exist.

The research was divided into two parts. The first part consisted of a mathematical prediction involving idealized systems. The second part consisted of reproducing experimentally the idealized systems in the laboratory and of verifying or refuting the predictions.

The study involved single sites of various sizes, two sites of equal size at various distances apart, two sites of different sizes at various distances apart, three sites of equal size on the vertices of an equilateral triangle at various distances apart, and three sites of equal size in a line at various distances apart. The heat transfer during nucleation was obtained for temperature excesses ranging from five to twenty-five degrees Fahrenheit.

The mathematical prediction scheme predicted a heat transfer during nucleation as compared with the experimental value that was generally within the inaccuracies of the measuring equipment for all of the cases under study.

INTRODUCTION

One of the earliest fundamental studies into the phenomenon of boiling heat transfer was that of Nukiyama in 1934 (21). In this study he immersed an electrically heated horizontal wire into water; this is similar to many of the methods in use today.

Almost all liquids have the same boiling curves (see Figure 1) as those described by Nukiyama. As the heating surface is heated to a temperature (T_W) that is above the saturation temperature of the liquid (T_S), heat is transferred to the liquid by the process of natural convection. This region is that which has been designated as Region I of Figure 1. As the temperature difference, $T_W - T_S$ (also called the temperature excess given by T_X), increases, boiling starts at discrete sites on the hot surface. This type of boiling is known as "nucleate boiling" and is designated as Region II of Figure 1. The maximum point of the nucleate boiling region has been given the name 'burnout point'. The reason for this is that a low melting point electrically heated wire, when used as a boiling surface, will melt (or burnout) when these conditions are obtained. Region III of Figure 1 is known as the transition boiling region and can be characterized by decreasing heat flux with increasing temperature excess, by an unstable vapor blanket forming over the heating surface, and by no solid-liquid contact. As the temperature excess is increased, the vapor blanket stabilizes and the heat flux again increases with increasing temperature excess. This region is Region IV of Figure 1 and is known as the region of full film boiling.

A number of mechanisms have been proposed (10, 26, 27) to explain the high heat fluxes obtained in boiling. One theory is that the bubble growth and release induces a form of micro-convection in the laminar sub-layer. This theory assumes a temperature difference equal to the difference between the temperature of the heating medium and the measured liquid temperature controls rather than the temperature excess described previously. The primary argument against this theory comes from experimental work which indicates that the heat flux is dependent on the temperature excess and for a given temperature excess the heat flux remains essentially constant regardless of the subcooling of the liquid (19). Another proposed mechanism is that which assumes a simple latent heat transfer by the bubbles. Forster and Grief (9) and Gunther and Krieth (15) have performed calculations and have some experimental evidence to disprove this approach. A third proposed mechanism is that of vapor liquid exchange between the expanding bubble and the liquid and a subsequent pushing of the hot liquid into the fluid bulk. This mechanism fails because it is impossible to estimate the true interchange. Moore and Mesler (30) measured temperature drops on the heat transfer surface in a boiling water system with a special thermocouple which measured the temperature of a small area and had a microsecond response time. They observed, by using an oscilloscope, temperature drops of 20-30 degrees Fahrenheit in approximately two milliseconds. They then calculated the heat removed by the temperature drops and compared that to the actual heat flux. From this they proposed the theory that the large heat fluxes in boiling came from vaporization of a microlayer, 78-89 microinches thick in this investigation, of liquid at the base of the bubble. The theory developed by Moore and Mesler seems to best predict macroscopic boiling of all proposed mechanisms.

These mechanisms do not explain how bubbles themselves form. As implied by the term "nucleate boiling", the process is one of nucleation. Nuclei have been assumed to be: cavities and scratches on the boiling surface, regions of poor adhesion of liquid to heating surface, solids suspended in the liquid, ionic species in the liquid, grain boundaries, and other contaminants on the surface or at the interface. Bankoff (1, 2) concluded from theoretical considerations that bubbles probably form from pre-existing vapor or gas bubbles trapped in the cavities or the grooves on the solid surface. Microphotographs taken by Clark, Strenge, and Westwater (6) confirm Bankoff's theory. Corty and Foust (7) investigated the effect of surface roughness on boiling heat transfer rates from nickel to n-pentane. The nickel surfaces were polished with different grits; it was found that the rougher the polish, the higher the heat flux was for a given temperature excess. Jakob (17) showed this same characteristic with water as his boiling liquid.

Once the make-up of a site had been decided upon, a question arose as to when is a site an active site and when is it an inactive site. In an attempt to explain this, Gaertner and Westwater (13) performed a number of experiments which showed that some sites were active for every value of temperature excess studied, and some only became activated at higher and higher temperature excesses. Hsu (16) has made a study which seems to explain the work of Gaertner and Westwater. Hsu's conclusions are presented in graphical form in which an envelope of radius versus temperature excess is shown. This shows the maximum and the minimum size a site can have and still support boiling.

The mechanisms explained above have all been based on experimental work wherein the number, the location, and the size of the nuclei are random. To overcome this limitation, both experimental and theoretical studies have been made to try to explain just what is going on at an individual nucleating site. These works can be broken down into sub headings as:

Breakoff Bubble Diameter: Fritz (11) has assumed the boiling of a non-isothermal liquid on an infinite heating surface and has developed an expression which relates breakoff bubbles to the contact angle at bubble breakoff and to the temperature excess.

Zuber (28) assumed an isothermal liquid heated by a semi-infinite heating surface and developed an expression which relates the breakoff bubble diameter directly to the temperature excess.

Stanizewski (24) assumed a liquid having a uniform temperature gradient in it heated by a surface having a similar gradient in it and developed an expression similar to that of Fritz in that it was related to the contact angle; however, it was also related to the velocity of the wall of the bubble.

Various other authors (4, 8, 14) have developed similar expressions using slightly different assumptions.

Siegel and Keshock (23) studied these various approaches and showed that each method will probably predict the size of the bubble to be smaller than it really is in practice.

<u>Time to Attain Breakoff Bubble Diameter</u>: Fritz and Ende (12), Pleset and Zwick (22), Forster and Zuber (10), and Zuber (29) have studied the relation of bubble diameter with time of growth. Their expressions show that the diameter should vary directly with the square root of time. The expressions are all very similar with the only real difference being in the constants. This difference results from the assumed heating surface in each case which is: Fritz and Ende used a non-isothermal heating surface, Pleset and Zwick used an isothermal heating surface, Forster and Zuber used an isothermal heating surface, and Zuber used a non-isothermal heating surface.

<u>Energy Released as the Bubble Breaks Off</u>: Some of the most extensive work performed on the formation of bubbles and their subsequent collapse has been in the field of underwater explosions. One of the best presentations of this work is that of Lamb (18).

Gunther and Krieth (15) studied the collapse of a bubble which formed on a hot heating surface and encountered a subcooled liquid immediately after breakoff. From this they predicted the energy transfer during collapse.

Birkhoff and Zarantonello (5) developed an expression for the "nucleation energy" which they used to predict the liquid tensile strength.

Other authors have followed either the explosion growth and decay or the collapse into a subcooled liquid.

This research problem has concerned itself with sites, locations, and numbers which are known. It has become necessary to try to understand if and/or how one site can affect a neighboring site. Therefore, the problem of damping an energy wave has become important. Lamb (18) in an article shows that if velocity distribution is known in the direction of travel as well as other fluid properties, a viscous damping can be predicted. However, Stoker (24) has looked at the problem differently and has developed a relationship relating energy depletion as a wave moves a distance of one wavelength with the wavelength. His relation requires knowledge only of initial or arithmetically averaged conditions.

RESEARCH OBJECTIVES

The research was conducted primarily to develop a mathematical technique wherein the heat transfer during nucleation of a water system, where the bulk of the water was at saturation, could be predicted if the number of active boiling sites, the location of the boiling sites, and the size of the boiling sites were known. The specific predictions to be made were:

A. Heat transfer during nucleation as a function of temperature excess for one boiling site and this to be calculated for a number of different site sizes.

B. Heat transfer during nucleation as a function of temperature excess and distance between sites for two sites which were equal in size.

C. Heat transfer during nucleation as a function of temperature excess and distance between sites for two sites which were unequal in size.

D. Heat transfer during nucleation as a function of temperature excess and distance between sites for three sites which were equal in size.

The secondary purpose of the study was to develop and to use a laboratory device which could duplicate the number of sites, their locations, and their sizes used in the mathematical predictions. Item D was to be carried out in two different ways. In the first, the three sites were to be located at the vertices of an equilateral triangle and in the second the three sites were to be located in one straight line.

MATHEMATICAL PREDICTION

Since the system being studied has an isothermal temperature distribution in the boiling fluid and the bubbles which form are assumed to be spherical, the choice of equations to predict boiling energy, breakoff bubble diameter, etc., is limited to a few equations. Also, the choice for predicting maximum bubble size is limited because there was no attempt made to measure the contact angle at bubble breakoff because of the intricate equipment required. The equations used for predicting are:

Breakoff Bubble Diameter: In developing his relationship, Zuber assumed an isothermal boiling fluid and a semi-infinite heating surface which had a constant temperature across the surface. For these reasons this approach was chosen, and the equation used is:

$$D_d = \left[\frac{6 \sigma_{lv}}{g(\rho_L - \rho_V)} \quad \frac{K \cdot T_x}{Q/A} \right]^{1/3} \qquad (I)$$

Time to Attain Breakoff Bubble Diameter: Pleset and Zwick developed their equation using the same assumptions decided upon in this study. The equation which they developed and which is being used is:

$$D = \left(\frac{3}{\pi}\right)^{1/2} \frac{4 K T_x (\theta)^{1/2}}{L \rho_v \mathcal{D}^{1/2}} \qquad (II)$$

Energy Released as the Bubble Breaks Off: Since most of the work which has been performed on isothermal liquids has been performed in studying underwater demolitions, the work which Lamb shows in his book is closest to that of this study. The equation used for this study is given by Lamb as:

$$E_B = \frac{4}{3} \pi P(R^3_{max} - R^3) \qquad \text{(III)}$$

Where P refers to that pressure which would be exerted if the liquid were at the temperature of the heating source, in this study the saturation temperature of water plus the temperature excess; and R refers to a bubble radius to which the large bubble collapses, and is dependent upon the temperature of the liquid which is the saturation temperature of water at an atmospheric pressure of 640 mm Hg for this study.

Heat Transfer During Nucleation for One Site: Using the energy released as the bubble breaks off and the time to attain breakoff bubble diameter, the heat transfer during nucleation for one site can be calculated from:

$$Q_1 \doteq \frac{E_b}{J\,\theta} \qquad \text{(IV)}$$

Depletion of Wave Energy: A number of workers have studied the problem of the passage of a wave through a fluid and its subsequent depletion. Most of these studies generally involve assumptions of things such as an average velocity over an interval, and other similar items. One of the studies has eliminated these assumptions and has made it possible to calculate the energy depleted in a water wave at a distance of one wave length from the generating source. This is the equation developed in Stoker:

$$E_d = \frac{\pi}{4} \rho R_{max}^3 \quad m \lambda^2 \quad \cosh^2 mh$$

Besides the assumption of one wave length travel, Stoker's work assumes a wave which is travelling in a medium large enough so that the wave is linear in nature. Since this work has been concerned with a wave which moves away from a spherical generating source and since it has been concerned with sites no one wavelength apart, it was necessary to modify Stoker's equation to fit these. The two modifications are: First, a factor only involving that fraction of the shell of the expanding pressure wave which would contact another bubble and second, a factor allowing the calculation of the depletion at various distances travelled. The modified equation is:

$$E_d = \frac{\pi}{4} \rho R_{max}^3 \psi \phi \quad m \lambda^2 \cosh^2 mh \qquad (V)$$

Heat Transfer During Nucleation for More Than One Site: In calculating the combined energy required to cause boiling at two or more sites in a system, some additional assumptions have had to be made. These assumptions include one site predominating and influencing all other sites even if all sites are identical in size, no damping of the energy wave occurs at the water-heating surface interface, and the two previous assumptions of isothermal temperature distribution in the water and the formation of spherical bubbles only. In this calculation the predominant site will require the total amount of heat transfer during nucleation as calculated for one site at a given temperature excess. But the other site or sites will have their heat transfer during nucleation reduced by the amount of energy remaining in the wave at a distance equal to the lineal separation of the sites.

The resulting equation uses the results of the energy released as the bubble breaks off, the time to attain the breakoff bubble diameter, and the modified Stoker equation. The equation is:

$$Q_n = Q_1 + (N - 1)\left(\frac{E_b - E_R}{J \cdot \theta}\right)_x \qquad \text{(VI)}$$

which gives the heat transfer during nucleation of two or more sites when all of the sites are of the same size.

Using the work of Hsu, this idea was extended to the case of two non-equal size sites. This extension required that the breakoff bubble diameter, and the energy released as a bubble breaks off, had to be calculated for both sizes of sites. Once these values were known, it was possible to use the graph prepared by Hsu to predict the temperature excess required by each site before boiling would be initiated. Once these were known, the heat transfer during nucleation could be calculated using Equations V and VI.

EQUIPMENT AND EXPERIMENTAL CONSIDERATIONS

Equipment: In order to duplicate the mathematical predictions in the laboratory, it was necessary to obtain a material which could be used as a heating surface which had no nuclei of its own. One of the best materials for this was found to be mercury.

One serious problem presented itself in the use of mercury as the heating surface. The problem was that mercury "wets" very few materials. This non-wetting is serious in that the water moves around and under the mercury by capillary action when placed on top of it. A compromise had to be made in this case. The mercury was placed in a stainless steel container 6-1/2 inches in diameter and 7-1/2 inches in height, and an inner container of a tin-plated steel 4 inches in diameter and 6 inches in height which the mercury "wet" was used to maintain a water-mercury interface around which the water could not move.

To be able to maintain the mercury at some temperature excess above the saturation temperature of the water, the unit described above was placed inside of a Precision Scientific Company Number N-3 constant temperature bath. The temperature of the mercury was measured by three iron-constantan thermocouples located across the diameter of the mercury-water interface but not at the same depth, and entirely surrounded by mercury. Iron-constantan thermocouples were chosen because of their great resistance to corrosive attack under long-time exposure to mercury.

All runs were to be made with the heat transfer apparatus open to the atmosphere. At the altitude of Bozeman, Montana, this meant that the atmospheric pressure was approximately 640 mm Hg.

Since the mercury was to be heated to a predetermined temperature excess above the saturation temperature of the water by the constant temperature bath, and since boiling would lower the temperature of the mercury which, in turn, would stop the boiling, it was necessary to develop some heater which would maintain the temperature of the mercury at the predetermined value and allow boiling to be continuous. Therefore, a small D.C. heater made of nichrome resistance wire wound on a solid glass form and coated with Sauereisen Number 6 ceramic cement was prepared. This unit was immersed in the mercury and was so positioned that the heater was inside of the small tin-plated inner container. The lead wires to the heater were brought out through the annular space between the two containers.

A schematic diagram of the system is shown in Figure 2.

Since mercury has no boiling sites of its own, it was necessary to produce sites on its surface. Two schemes were studied for the production of these sites. One scheme involved using very fine metal wires just touching the surface of the mercury, and the other involved using glass capillary rod that was drawn to a very fine tip. Both methods seemed to work, but the drawn glass rod seemed better in that a finer, more uniform site could be made. Also, in case something went wrong with the site such as breaking, etc., the glass rod could be replaced more rapidly. The drawn end of the glass capillary rod was measured by use of a Bausch and

Lomb microbiological micrometer stage. The rods were held in place by clamps and were suspended so that they just touched the mercury surface.

Early work involved using glass rods which did not come down through the water, but rather touched the surface of the mercury from underneath. These rods had to be placed before the tin-plated container was set in place because they had to be led under the wall of this container and up through the annular space between this container and the stainless steel container. The difficulty with this method was that the sites were hard to place at exact separations. Also, work showed that the difference in heat transfer measured during nucleation for the top oriented site as compared with this bottom oriented site was less than five percent.

Power was supplied to the heater from a 6-volt, D.C. automotive battery. The power was controlled by the use of the circuit shown in Figure 3. This circuit contained a variable water-cooled rheostat which could lessen or increase the load to the small heater immersed in the mercury. The small heater was placed in parallel with two precision resistors. Two resistors were used so that the voltage drop across one of them could be kept within the range of a millivoltmeter. From this the total voltage drop across the precision resistors could be calculated from

$$V_t = \eta \; V \qquad \text{(VII)}$$

In a parallel circuit, the voltage drop is the same in each path, so the voltage drop across the heater was known. A shunt placed in the circuit allowed the measurement of the current flow. The power dissipated by the small heater to the mercury pool could then be calculated by the expression

$$W = I\ V \tag{VIII}$$

<u>Experimental</u>: Each experimental run was preceded by a cleanup of the equipment. These cleanups also included any materials which might come into contact with the mercury or the water, or which might be placed so that some contaminant could flake off.

The stainless steel and the mercury were cleaned by treatment with a three percent by weight solution of boiling citric acid for thirty minutes. The surfaces were then flushed with hot water for ten minutes and then with distilled water for ten minutes. The components were dried and covered with a thin plastic film to prevent re-contamination.

Demineralized water was to be used as the boiling fluid, but it also had to be deaerated by boiling. After the deaeration it was stored in a clean container (which had been cleaned in the same way the stainless steel was cleaned) and covered to prevent re-aeration.

All other items were cleaned by flushing with acetone, by drying, and by storing in thin polyethylene bags.

After cleaning, the equipment was assembled as shown in Figure 2 with the exception that the glass rods were not put into the system. The mercury depth was two inches and the water depth was one inch. The controller on the oil bath was set so that some predetermined value of temperature excess would be obtained in the mercury bath. The bath was then turned on and the system was allowed to reach steady-state.

After steady-state had been reached, as determined by continuous reading of the three thermocouple outputs, the glass rods were put into place. Very few bubbles were observed at the sites produced by the touching of the glass rod to the mercury surface; but, a slight depression in the temperature of the mercury was noted adjacent to the site.

The electrical circuit of Figure 3 was then turned on and the heater was activated. The power was increased until the temperature reading throughout the mercury again was at the predetermined temperature excess at which time continuous boiling occurred at each site (if all sites were of the same size) on the surface. After observing the boiling for a period of time, readings were taken of voltage drop and current flow through the heater. These two readings gave the power dissipated in watts which was then converted to heat transfer during nucleation by:

$$Q = \frac{W\,M}{J} \qquad \text{(IX)}$$

The experiments were carried out for the cases of:

A. One boiling site at various values of temperature excess; and it was repeated for numerous sites.

B. Two equal sized sites whose separation was varied from one-sixteenth inch to one inch at each temperature excess.

C. Two unequal size boiling sites whose separation was varied from one-sixteenth inch to one inch at each temperature excess.

D. Three equal sized sites placed at the vertices of an equilateral triangle whose separation was varied from one-sixteenth inch to one inch at each temperature excess.

E. Three equal sized sites placed in a straight line pattern whose separation was varied from one-sixteenth inch of one-half inch at each temperature excess.

RESULTS

Theoretical: Using the equations listed under Mathematical Prediction, calculations were made to develop the heat transfer during nucleation curves listed in Research Objectives.

Using Equation I, the breakoff bubble diameters were calculated for different temperature excesses. The results of the calculations are presented as Table I and are shown in Figure 4 as bubble diameter at breakoff as a function of temperature excess.

The time to attain breakoff bubble diameter was calculated from Equation II. The results of these calculations are presented in Table II and are presented as bubble diameter as a function of time with parameters of temperature excess in Figure 5.

From Equation III, it was possible to calculate the energy released as the bubble breaks off. The results are given in Table III and are shown as energy released as a function of temperature excess in Figure 6. The heat transfer during nucleation for an individual site was calculated from Equation IV and the results are given in Table IV and are shown as heat transfer during nucleation as a function of temperature excess in Figure 7.

The depletion of the energy in that portion of a wave which would be involved with another wave generator, as calculated from Equation V, is tabulated in Table V and is presented as energy depleted as a function of the distance away from the known point of origin with parameters of temperature excess in Figure 8.

Calculations were performed using Equation VI for N = 2 and N = 3. The sites, designated by the letter N, were assumed to be of the same size (in this case one mil in diameter). The results of the calculations are given as Table VI for N = 2 and as Table VII for N = 3, and are shown as Figure 9 for N = 2 and Figure 10 for N = 3. In Figures 9 and 10, the heat transfer during nucleation is plotted as a function of the distance between the sites with parameters of temperature excess.

Using the graph developed by Hsu, and assuming two unequal size sites (in this case one of one mil diameter and one of one-quarter mil diameter) calculations were made of heat transfer during nucleation versus the distance between the two sites at various values of temperature excess. These two sizes were chosen because of their threshold temperature excess for boiling. The one mil diameter site will begin to boil at a temperature excess of five degrees Fahrenheit and the one-quarter mil diameter site in the same system should begin to boil at fifteen degrees Fahrenheit temperature excess. The results of the calculations are given in Table VIII and are shown in Figure 11.

Experimental: The experimental data of current flow and voltage drop occurring in the D.C. heater which supplied the heat of boiling to the boiling sites was converted into power transferred in terms of watts dissipated by Equation VIII. This was then put in terms of Btu per hour by Equation IX.

Table IX and Figure 12 show the results of a number of runs which were performed on one site. Runs were made on sites which were one-quarter mil in diameter, one-half mil in diameter, and one mil in diameter. Many of these runs were repeated as much as five times. Because the heat transfer during nucleation was not changed by changing site size in the range noted, the data for two and three sites will be reported only as an averaged value of all experimental runs.

The averaged results of the experiments on two equal sized sites are given in Table VI and are shown as Figure 9 in which the heat transfer during nucleation is presented as a function of distance between boiling sites with parameters of temperature excess.

The results of the experiments on two unequal sized sites are given in Table VII and are shown as Figure 11 in which the heat transfer during nucleation is presented as a function of distance between boiling sites with parameters of temperature excess.

The results of the experiments on three equal sized sites located on the vertices of an equilateral triangle are given in Table VII and are shown as Figure 10 in which the heat transfer during nucleation is presented as a function of distance between boiling sites with parameters of temperature excess.

The results of the experiments on three equal sized sites located in a line are given in Table VII and are shown as Figure 10 in which the heat transfer during nucleation is presented as a function of distance between boiling sites with parameters of temperature excess.

DISCUSSION

First consider the situation where only one nucleating site exists on a heating surface. Generally, the only way that information has been obtained in the past on one site has been to experimentally study a real surface having random sites, locations, etc., and then predict a boiling heat flux for one site. One such result is shown by Becraft (3). These predictions, however, do not take into consideration the interaction of one site upon another and hence give a prediction for the heat flux of a statistical site and not a real one.

In this work the idealized boiling system has been used and predictions have been made for the heat transfer during nucleation for one site in an ideal system and they have been checked out by experimentation. Figure 13 is a comparison between the theoretical heat transfer during nucleation and the average experimental heat transfer during nucleation. As was noted in the results, an average value can be used for the experimental case because the heat transfer during nucleation is almost constant for all site sizes at given temperature excess. As can be seen from the figure, most of the differences between the theoretical values and the averaged experimental values can be explained by the accuracy or rather inaccuracies of the measuring devices.

Those values of temperature excess where a difference occurs which is greater than the measuring errors are those temperature excesses where the bubble might not be allowed to grow to the calculated breakoff diameter due to the forming of another bubble before the first can break off.

No work was performed to experimentally determine rate of bubbling from a site so no prediction can be made concerning the lessening in breakoff bubble diameter; hence the lessening of breakoff energy. However, Günther and Krieth (15) have studied boiling photographically and show that bubble rate is a function of the temperature excess.

Second, consider those cases where more than one site, all of equal size, are present in a known pattern on a heating surface. Common sense tells one that as the sites are brought together, they should act as one site with each contributing a factor of 1/N of the heat transfer during nucleation. At infinite separation each site should contribute a quantity equal to the heat transfer during nucleation and the total heat should be N times that for one site. The range from no separating distance to infinite separating distance required some prediction scheme to show whether or not it would be possible to predict the curve as it travels from zero to infinite separation. Figures 9, 10, and 11 show that the prediction scheme given under Mathematical Prediction adequately fits the data obtained experimentally. However, the figures become quite unwieldy as more and more temperature excesses are added to the study.

After careful study of the data presented in Figures 9 and 10, it was decided that perhaps a better method of presenting the data, other than heat transfer during nucleation as various temperature excesses as a function of distance between sites, could be developed. After a number of trials and errors, one of the better comparisons was that of $(Q_n / N Q_1)$ x 100 percent as a function of the distance between sites. The reason that this ratio was finally chosen is that there was no longer any dependence on temperature excess. At any given distance between sites the ratio was almost the same for all temperature excesses. Results of the calculation of this ratio for the theoretical case are shown in Tables X for two sites and XI for three sites and are presented as Figures 14 for two sites and 15 for three sites. Results of the calculations of the ratio for the experimental work are shown as Tables X for two sites, XI both for three sites arranged on the vertices of a triangle and for three sites in a line and are shown graphically as Figure 14 for Table X and Figure 15 for Table XI.

As can be seen in Figures 14 and 15, the temperature excess is no longer a parameter even though a band of results are shown for the experimental work rather than one simple curve. This band is due to the measuring errors in the equipment, separation measuring errors, and the bubbling problem stated for the single site case. Also, at the larger separations the predicted curve no longer is within the band, but predicts a higher heat transfer during nucleation or in this case, a higher ratio.

To explain this deviation, first consider the situation where two sites are boiling. The deviation can be brought about in a number of ways. A few ways concern the errors caused through inaccuracies of the equipment used in measuring temperatures, site sizes, and site separations. Another possibility is that a small wave is generated in the mercury at the higher temperatures which forces the bubbles at the dependent sites to detach sooner than they really should. No wave was seen; however, the surface was viewed at an angle down through the water and a wave would have to be quite large before it could be seen.

Considering the situation of three sites on the vertices of an equilateral triangle, the deviation from the predicted value is greatest at the lesser separations and is less at the greater separations. The explanation for this seeming reversal in form is that as the sites are brought closer and closer together, the assumption that only one site predominates and the other two have no inter-relation is invalid. Since the energy level left in a wave is so great at the short distances travelled, and even though the wave travelling between the two dependent sites is being lessened by other wave fronts from the predominant site, there has to be an effect and this effect shows up as the larger difference. As the sites are placed further and further apart, the energy left in the wave passing between the two dependent sites becomes of lesser and lesser importance and the same reasoning as for the two sites takes over.

Considering the situation where there are three sites in a line and where one of the sites predominates (in this case the center site), the deviation from the expected values are brought about in the same manner in which the deviations exist for two sites. In this study the size of the equipment, the tin-plated inner container, made it impossible to study separations any greater than one-half of an inch because at greater separations the container wall interfered. Hence no conclusions can be drawn about any deviations at separations greater than one-half inch.

Thirdly, consider the case where two non-equal boiling sites are used. Common sense says that two nucleation sites not having the same diameter should not have the same threshold temperature excess at which boiling becomes initiated. Many researchers have also stated this, and Hsu (16) came up with a curve to predict the maximum radius and the minimum radius a site can have at a given temperature excess in order to bubble. In this work the two sites were one mil in diameter and one-quarter mil in diameter. Hsu states that the one mil site should boil at five degrees Fahrenheit temperature excess, the one-quarter mil site should boil at fifteen degrees Fahrenheit temperature excess when used together.

In predicting the heat transfer during nucleation for these two sites no prediction was made for the transition from one site to two site boiling. Figure 11 shows the prediction.

During the experimental work, it was found that the threshold for the smaller site was not the predicted fifteen degrees Fahrenheit temperature excess but really was about twelve degrees. However, the heat transfer during nucleation deviated from the curve for the one large site only at the largest separations used, one inch, as can be seen in Figure 11. When the sites are close together, the large site is so close that it does not cause a disturbance which can act as a nucleus for boiling which it can at the greater separations. As fifteen degrees Fahrenheit temperature excess, as predicted by Hsu, is approached, the heat transfer during nucleation curve takes on the values for two sites at the studied distances apart and above fifteen degrees temperature excess stable boiling exists at both sites. Figure 11 shows the comparison between the theoretically predicted heat transfer during nucleation and that obtained experimentally.

As in the previous cases the experimental curves were less than the theoretically predicted curves. Since there were two sites operating, the same possibilities exist for the difference as for the case of two equal sized sites.

CONCLUSIONS

The primary object of this research was the development of a mathematical scheme which would allow for the prediction of heat transfer during nucleation for idealized systems. The secondary objective was the setting up of the idealized system in the laboratory to test the prediction, the assumptions behind the prediction, and the ability to obtain such an idealized system in practice.

From the results of the experimental work for the equal sized sites, it appears that the assumptions which form the basis of the prediction scheme, are valid over the whole range of temperature excess and the whole range of distance between sites studied. However, there seems to be a region which can be called a "region of maximum validity" or "lesser error" involving the closer sites and the lower temperature excesses. However, on real surfaces the sites would be randomly scattered and would in all probability be close together, hence making any need for refinement to include anything outside of this region unnecessary at this time.

The results for two unequal sites seem to present a different conclusion than that drawn above. For this case there is no "region of maximum validity", but rather the difference between the theoretical and the experimental results tends to remain about the same for all temperature excesses at a given distance between sites. This tendency is due to the two sites not having either the same threshold temperature to initiate boiling or the same energy transferred at bubble breakoff to the boiling fluid.

Even though discrepancies exist between the predicted and the experimental results, the prediction scheme used throughout this work gives results which are within experimental accuracy for the system studied. However, it will probably not give good results for real heating surfaces unless the surfaces closely approximate the assumed surface.

SUGGESTIONS FOR FUTURE WORK

There are two possible areas of extension of the present work. The first area involves the extension of the work on the idealized system already used, and the second involves an attempt to extend the work to real boiling surfaces.

I. Idealized case.

A. Try to include frictional resistance by the mercury pool to the passage of a wave.

B. Try to study mercury surfaces to see if any waves are generated on it which could hinder or amplify the wave which is travelling in the water.

C. Extend the work to other boiling fluids.

II. Real case.

A. Extend the work so as to be able to predict the heat transfer during nucleation curve for a real surface. This might be done by a statistical study of the surface which would give an average size and an average separation. Then by knowing the number of sites, the heat transfer for the sites on the surface could be calculated from an expression similar to:

$$Q = \frac{N\, E_{b,\, ave.}}{J\, \theta_{ave.}} \qquad (X)$$

APPENDIX

NOMENCLATURE

A	Area of heat transfer, square feet
$\mathcal{D}$	Coefficient of diffusion of mass, ft^2 per hour
D	Diameter of bubble, ft.
D_d	Diameter of bubble at breakoff, ft.
E_b	Energy transferred to the fluid by the bubble at breakoff, ft-lbs.
E_d	Depletion of wave energy, ft-lbs.
E_r	Energy remaining in a wave, $= E_b - E_d$, ft-lbs.
g	Gravitational constant, (lb force)(ft) per (lb mass)$(hour)^2$
h	Depth of boiling fluid, ft.
I	Current flow, amperes
J	Constant to convert energy to heat terms, 778 ft-lbs per Btu
K	Coefficient of thermal conductivity, Btu per ft-°F-hr
L	Latent heat of vaporization, Btu per lb.
m	Wave number, ft^{-1}
M	Constant to convert watts to ft-lbs per hour, 2.655×10^3
N	Number of sites
P	Pressure, lbs per ft^2
Q	Heat transfer during nucleation, Btu per hour
Q_1	Heat of transfer during nucleation for one site, Btu per hour
Q_n	Heat transfer during nucleation for N sites, Btu per hour
R	Radius of the bubble, ft.
R_{max}	Radius of the bubble at breakoff, ft.
T_s	Saturation temperature of the boiling liquid, °F

T_W	Temperature of the heating surface, °F
T_x	Temperature excess, °F
V	Voltage drop, volts
W	Power dissipated, watts
x	Distance between sites, inches
ϕ	Factor for distances not equal to one wavelength
ψ	Factor for fractional viewing of one bubble by the other
λ	Wavelength, ft.
η	Factor relating voltage drop of one resistor to voltage drop for both resistors
Ω	Resistance, ohms
ρ	Density, lbs mass per cubic foot
ρ_L	Liquid density, lbs mass per cubic foot
ρ_V	Vapor density, lbs mass per cubic foot
σ_{LV}	Surface tension, lbs force per foot
θ	Time, hours

SAMPLE CALCULATIONS

<u>Prediction Scheme</u>: In the section on Mathematical Prediction a number of equations are presented which permit the calculation of the heat transfer during nucleation for one, two three, etc., sites. These sites can be any orientation, but one site must be predominant and must affect all other sites and there can be no interaction between these sites.

Sample calculations are presented for a temperature excess of 15 degrees Fahrenheit, with a water saturation temperature of 203 degrees Fahrenheit.

<u>Breakoff Bubble Diameter</u>:

$$D_d = \left[\frac{6 \sigma_{lv}}{g(\rho_l - \rho_v)} \frac{K\, T_x}{Q/A} \right]^{1/3}$$

At 218 degrees Fahrenheit

σ_{lv} = 0.1251 pounds force per foot

ρ_l = 59.2 pounds weight per cubic foot

ρ_v = 0.0416 pounds weight per cubic foot

K = 0.393 Btu per foot-hour-degree Fahrenheit

T_x = 15 degrees Fahrenheit

Q = 2 Btu per hour, for one site

A = πD_d^2 square feet, area of the bubble

$D_d = 3.17 \times 10^{-3}$ feet

Time to Attain Breakoff Bubble Diameter:

$$\Theta = \frac{D_d^2}{\left(\frac{3}{\pi}\right)\left(\frac{4\ K\ T_x}{L \rho_v (\alpha)^{1/2}}\right)^2}$$

$L = 966.4$ Btu per pound

$\alpha = 0.571 \times 10^{-3}$ square feet per hour

$\Theta = 1.8 \times 10^{-8}$ hours

Energy Released as the Bubble Breaks Off:

$$E_b = \frac{4}{3} \pi P (R_{max}^3 - R^3)$$

$P = 2380$ pounds per square foot

$R_{max} = 1.58 \times 10^{-3}$ feet

$R = 0.994 \times 10^{-3}$ feet, as determined from Lamb for the collapsed radius at this temperature

$E_b = 2.93 \times 10^{-5}$ foot-pounds

Heat Transfer During Nucleation for One Site:

$$Q = \frac{E_b}{J\ \Theta}$$

$Q = 2.09$ Btu per hour

Depletion of Wave Energy:

$$E_d = \frac{\pi}{A} \rho R_{max}^3 \psi \phi m \lambda^2 \cosh^2 m h$$

Using a distance between sites of one-quarter of an inch

λ = 0.0705 feet

h = 0.0833 feet

m = 74.1 reciprocal feet

ψ = 0.057 dimensionless

ϕ = 0.087 dimensionless

E_d = 1.93×10^{-5} foot-pounds

Calculation of ϕ and ψ Factors For Use in Depletion of Energy Equation:

Since Stoker has shown that the depletion of energy as a wave travels a distance of one wavelength is a function of the square of the distance, the factor for distances other than one wavelength must be of the same order. Hence:

$$\phi = \left(\frac{x}{12}\right)^2 \Big/ \lambda^2$$

Stoker was concerned with a spherical wave. In this study only a fraction of the wave from one source touched a second bubble. A study of a cone whose vertex was the predominant site and whose base was the diameter of a dependent site was made. The results of the study show that for separations greater than one-thirty-second (1/32) of an inch, and no greater than one inch, the relationship is:

$$\psi = \frac{(6 - 7x + 4x^2)}{6} \quad \frac{R_{max}}{(x/12)}$$

Heat Transfer During Nucleation for Two and Three Equi-Sized Sites:

$$Q_n = Q_1 + (n - 1) \left(\frac{E_b - E_r}{J . \theta} \right)_x$$

Using a separation of one-half an inch.

Sites	Q_n
2	3.87 Btu per hour
3	5.63 Btu per hour

Heat Transfer During Nucleation for Two Non-Equal Size Sites:

The equation is the same used for equal sized sites, but from the work of Hsu the smaller site will begin to boil at a temperature excess of 15 degrees Fahrenheit. Therefore, using that temperature and a separation of one-half inch gives a heat transfer of 3.09 Btu per hour.

Experimental: In the experimental work the data taken was in terms of voltage drops across a shunt and across a precision resistor in parallel with the D.C. heater. Equations have been presented to show the calculations of the heat transfer during nucleation from the data.

Current Flow Through the Heater:

$$I = \frac{V}{\Omega}$$

V = 0.004 volts

Ω = 0.0113 ohms

I = 0.354 amps

Voltage Drop Across the Heater:

$V_t = \eta V$

η = 100, factor relating precision resistor voltage to D.C. heater voltage

V = 0.01661 volts, precision resistor voltage drop

V_t = 1.661 volts

Power Dissipated by the D.C. Heater:

$W = V\,I$

W = 0.585 watts

Heat Transfer During Nucleation for One Site:

$$Q = \frac{W\,M}{J}$$

Q = 1.845 Btu per hour

Heat Transfer During Nucleation for Two and Three Equi-Sized Sites:

For a separation of one-half an inch, the heat transfer is

Sites	W	Q_n
2	1.069	3.64 Btu per hour
3	1.550	5.28 Btu per hour, in a line
3	1.515	5.16 Btu per hour, on the vertices of an equilateral triangle

Heat Transfer During Nucleation for Two Non-Equal Size Sites:

For a separation of one-half an inch:

Power dissipated by the heater is 1.022 watts and the heat transfer is 3.49 Btu per hour.

Table I: Theoretical Breakoff Bubble Diameter

Temperature Excess, °F.	Breakoff Bubble Diameter, Ft.
5	0.00380
10	0.00346
15	0.00317
20	0.00298
25	0.00278

Table II: Theoretical Time to Attain Breakoff Bubble Diameter

Temperature Excess, °F	Time, Hours
5	12.65×10^{-8}
10	4.6×10^{-8}
15	1.8×10^{-8}
20	1.0×10^{-8}
25	0.544×10^{-8}

Table III: Theoretical Energy Transferred as the Bubble Breaks Off

Temperature Excess, °F	Energy, Foot-Pounds	Site Size, Mils Diameter
5	3.85×10^{-5}	1
5	3.86×10^{-5}	1/4
10	3.28×10^{-5}	1
10	3.30×10^{-5}	1/4
15	2.93×10^{-5}	1
15	2.94×10^{-5}	1/4
20	2.75×10^{-5}	1
20	2.76×10^{-5}	1/4
25	2.49×10^{-5}	1
25	2.50×10^{-5}	1/4

Table IV: Heat Transfer During Nucleation, One Site

Temperature Excess, °F	Theoretical Heat Transfer, Btu/Hr	Site Size, Mils Diameter
5	0.392	1
5	0.388	1/4
10	0.916	1
10	0.911	1/4
15	2.09	1
15	2.03	1/4
20	3.53	1
20	3.51	1/4
25	5.88	1
25	5.85	1/4

Table V: Depletion of Wave Energy

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Energy Depleted, Foot-Pounds
5	1	0.72×10^{-5}
5	2	1.43×10^{-5}
5	4	2.26×10^{-5}
5	8	2.97×10^{-5}
5	12	3.33×10^{-5}
5	16	3.47×10^{-5}
10	1	0.72×10^{-5}
10	2	1.44×10^{-5}
10	4	2.19×10^{-5}
10	8	2.78×10^{-5}
10	12	3.05×10^{-5}
10	16	3.18×10^{-5}
15	1	0.63×10^{-5}
15	2	1.21×10^{-5}
15	4	1.93×10^{-5}
15	8	2.48×10^{-5}
15	12	2.77×10^{-5}
15	16	2.89×10^{-5}

Table V (continued)

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Energy Depleted, Foot-Pounds
20	1	0.63×10^{-5}
20	2	1.13×10^{-5}
20	4	1.81×10^{-5}
20	8	2.36×10^{-5}
20	12	2.56×10^{-5}
20	16	2.61×10^{-5}
25	1	0.55×10^{-5}
25	2	0.99×10^{-5}
25	4	1.67×10^{-5}
25	8	2.17×10^{-5}
25	12	2.35×10^{-5}
25	16	2.38×10^{-5}

Table VI: Heat Transfer During Nucleation, Two Equi-Sized Sites

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Heat Transfer, Btu/Hr	Experimental Heat Transfer, Btu/Hr
5	1	0.47	0.480
5	2	0.549	0.545
5	4	0.639	0.621
5	8	0.718	0.684
5	12	0.756	0.714
5	16	0.771	0.73
10	1	1.12	1.108
10	2	1.32	1.255
10	4	1.53	1.44
10	8	1.695	1.581
10	12	1.77	1.651
10	16	1.805	1.69
15	1	2.53	2.52
15	2	2.95	2.90
15	4	3.46	3.30
15	8	3.87	3.64
15	12	4.06	3.80
15	16	4.14	3.86
20	1	4.34	4.11
20	2	4.97	4.74
20	4	5.86	5.40
20	8	6.56	5.99
20	12	6.80	6.20
20	16	6.88	6.30
25	1	7.17	6.39
25	2	8.23	7.37
25	4	9.81	8.47
25	8	11.0	9.26
25	12	11.41	9.61
25	16	11.51	9.76

Table VII: Heat Transfer During Nucleation, Three Equi-Sized Sites

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Heat Transfer, Btu/Hr	Experimental Heat Transfer on Vertices of Equilateral Triangle, Btu/Hr	Experimental Heat Transfer in a Line, Btu/Hr
5	1	0.541	0.492	0.531
5	2	0.694	0.601	0.671
5	4	0.878	0.765	0.845
5	8	1.032	0.972	0.995
5	12	1.118	1.06	---
5	16	1.156	1.089	---
10	1	1.32	1.135	1.245
10	2	1.775	1.375	1.555
10	4	2.145	1.75	1.92
10	8	2.40	2.21	2.26
10	12	2.625	2.40	---
10	16	2.70	2.47	---
15	1	2.99	2.64	2.88
15	2	3.82	3.18	3.72
15	4	4.83	4.08	4.50
15	8	5.63	5.16	5.28
15	12	6.05	5.64	---
15	16	6.21	5.76	---

Table VII (continued)

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Heat Transfer, Btu/Hr	Experimental Heat Transfer on Vertices of Equilateral Triangle, Btu/Hr	Experimental Heat Transfer in a Line, Btu/Hr
20	1	5.15	4.16	4.75
20	2	6.43	5.29	6.01
20	4	8.19	6.69	7.36
20	8	9.64	8.42	8.59
20	12	10.11	9.06	---
20	16	10.26	9.32	---
25	1	8.46	6.59	7.38
25	2	10.59	8.16	9.36
25	4	13.75	10.40	11.42
25	8	16.10	13.00	13.22
25	12	16.85	13.95	---
25	16	17.15	14.35	---

Table VIII: Heat Transfer During Nucleation, Two Non-Equal Sites

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Heat Transfer, Btu/Hr	Experimental Heat Transfer, Btu/Hr
5	all	0.390	0.386
10	all	0.913	0.865
12	1	---	1.31
12	2	---	1.31
12	4	---	1.31
12	8	---	1.31
12	12	---	1.315
12	16	---	1.324
14	1	---	1.76
14	2	---	1.76
14	4	---	1.76
14	8	---	1.87
14	12	---	2.05
14	16	---	2.15
15	1	2.145	---
15	2	2.40	---
15	4	2.74	---
15	8	3.09	---
15	12	3.74	---
15	16	3.83	---
16	1	---	2.61
16	2	---	3.53
16	4	---	3.93
16	8	---	4.10
16	12	---	4.30
16	16	---	4.36

Table VIII (continued)

Temperature Excess, °F	Distance Between Sites, Sixteenths of an Inch	Theoretical Heat Transfer, Btu/Hr	Experimental Heat Transfer, Btu/Hr
20	1	4.17	4.08
20	2	4.90	4.81
20	4	5.74	5.67
20	8	6.52	6.47
20	12	7.02	6.92
20	16	7.07	7.01
25	1	7.12	6.82
25	2	8.45	7.85
25	4	9.65	8.99
25	8	10.95	10.20
25	12	11.35	11.02
25	16	11.52	11.32

Table IX: Heat Transfer During Nucleation, One Experimental Site

Temperature Excess, °F	Heat Transfer, Btu/Hr	Site Size, Mils Diameter
5	0.384	1
5	0.388	1
5	0.386	1/2
5	0.390	1/2
5	0.388	1/4
5	0.381	1/4
10	0.879	1
10	0.872	1
10	0.877	1/2
10	0.869	1/2
10	0.855	1/4
10	0.868	1/4
15	2.00	1
15	2.05	1
15	2.03	1/2
15	1.98	1/2
15	2.02	1/4
15	1.97	1/4
20	3.25	1
20	3.19	1
20	3.26	1/2
20	3.21	1/2
20	3.22	1/4
20	3.22	1/4
25	4.99	1
25	4.97	1
25	4.91	1/2
25	4.96	1/2
25	4.90	1/4
25	4.93	1/4

Table X: Ratio of $(Q_n/NQ_1) \times 100$, Two Equi-Sized Sites

Distance Between Sites, Sixteenths of an Inch	Temperature Excess, °F	Theoretical Ratio	Experimental Ratio
1	5	60.5	62.5
1	10	60.5	63.0
1	15	60.5	63.5
1	20	60.5	64.0
1	25	60.5	64.0
2	5	70.5	71.0
2	10	70.5	72.0
2	15	70.5	72.5
2	20	70.5	73.0
2	25	70.5	74.0
4	5	83.0	81.0
4	10	83.0	82.0
4	15	83.0	82.5
4	20	83.0	84.0
4	25	83.0	85.0
8	5	92.5	89.0
8	10	92.5	90.5
8	15	92.5	91.5
8	20	92.5	92.0
8	25	92.5	93.0
12	5	97.5	93.0
12	10	97.5	94.0
12	15	97.5	94.5
12	20	97.5	95.5
12	25	97.5	96.5
16	5	99.0	95.0
16	10	99.0	96.0
16	15	99.0	96.5
16	20	99.0	97.0
16	25	99.0	98.0

Table XI: Ratio of $(Q_n/3Q_1) \times 100$, Three Equi-Sized Sites

Distance Between Sites, Sixteenths of an Inch	Temperature Excess, °F	Theoretical Ratio	Experimental Ratio: Vertices of an Equilateral Triangle	Experimental Ratio: In a Line
1	5	46.0	42.5	47.5
1	10	46.0	43.0	48.5
1	15	46.0	43.0	50.0
1	20	46.0	44.0	50.5
1	25	46.0	44.5	51.0
2	5	61.0	51.5	58.0
2	10	61.0	52.5	59.5
2	15	61.0	53.0	61.0
2	20	61.0	54.0	62.5
2	25	61.0	55.0	63.0
4	5	76.5	66.0	73.0
4	10	76.5	67.5	74.5
4	15	76.5	68.0	76.0
4	20	76.5	69.0	76.5
4	25	76.5	70.0	77.0
8	5	89.5	84.0	86.0
8	10	89.5	85.5	87.0
8	15	89.5	86.0	87.5
8	20	89.5	87.0	88.0
8	25	89.5	87.5	89.0
12	5	96.0	91.5	--
12	10	96.0	91.5	--
12	15	96.0	93.0	--
12	20	96.0	93.5	--
12	25	96.0	94.0	--

Table XI (continued)

Distance Between Sites, Sixteenths of an Inch	Temperature Excess, °F	Theoretical Ratio	Experimental Ratio: Vertices of an Equilateral Triangle	Experimental Ratio: In a Line
16	5	98.5	94.0	--
16	10	98.5	95.0	--
16	15	98.5	95.5	--
16	20	98.5	96.0	--
16	25	98.5	96.5	--

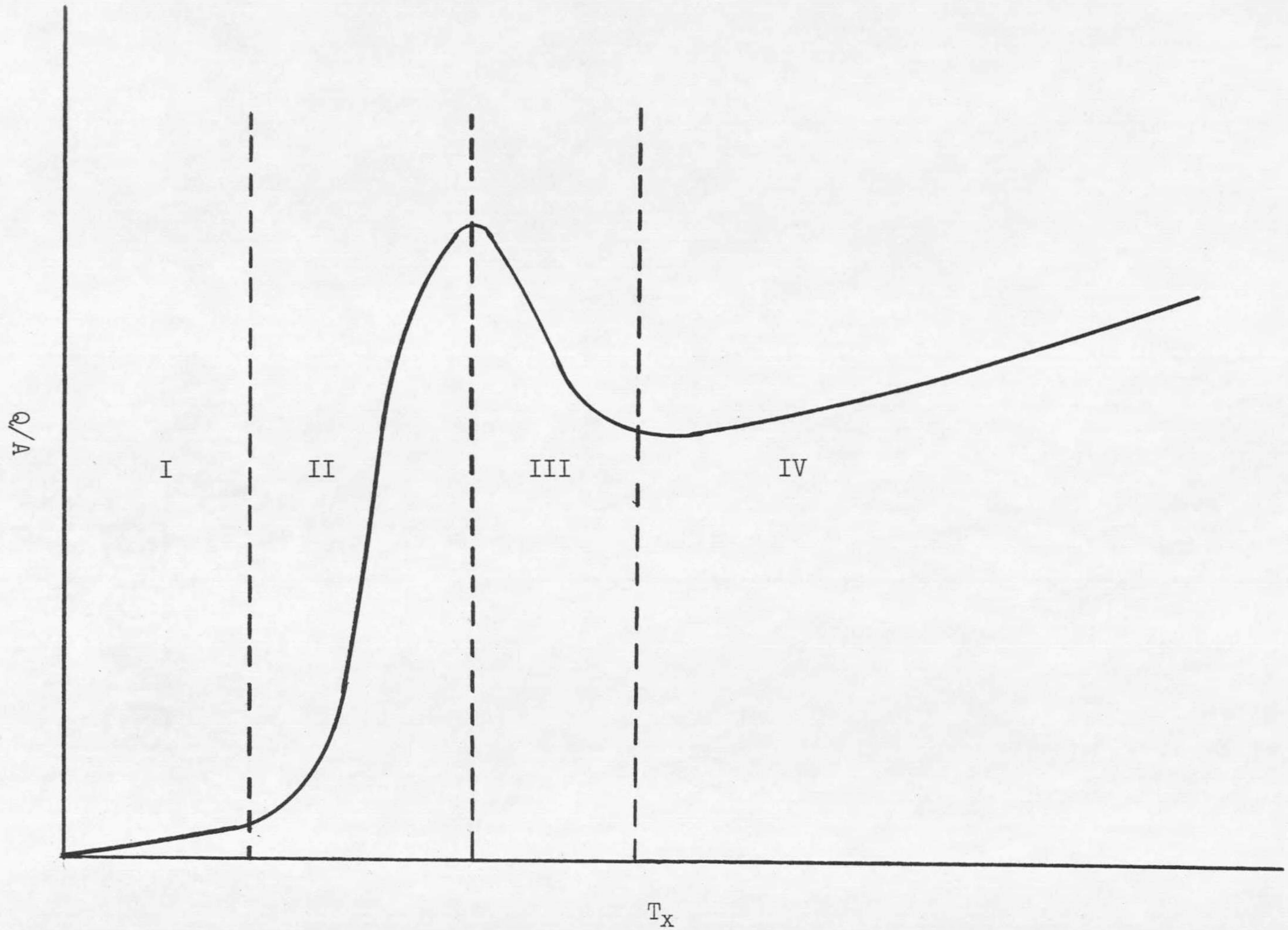

Figure 1. General Boiling Curve

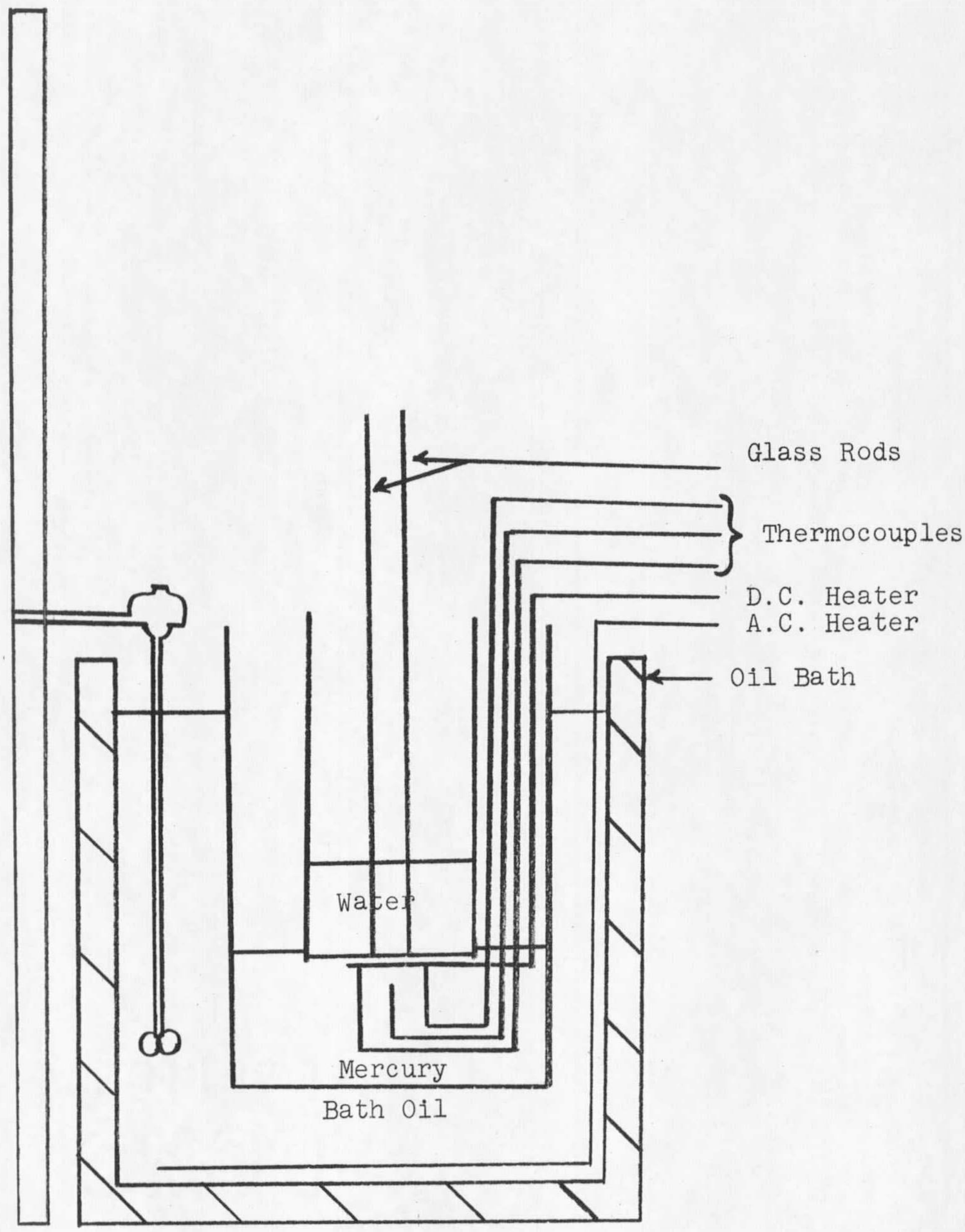

Figure 2. Simplified Diagram of Boiling Apparatus

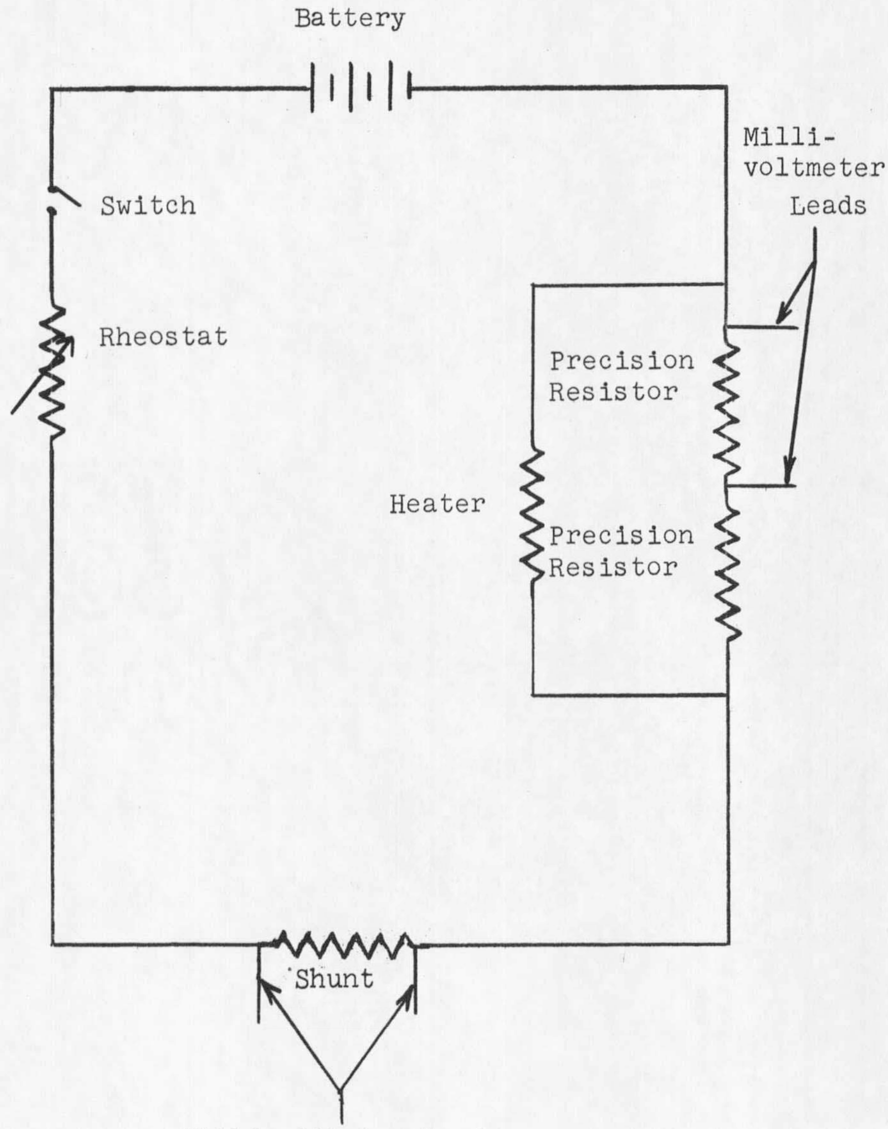

Figure 3. Simplified Diagram of Power Control Circuit

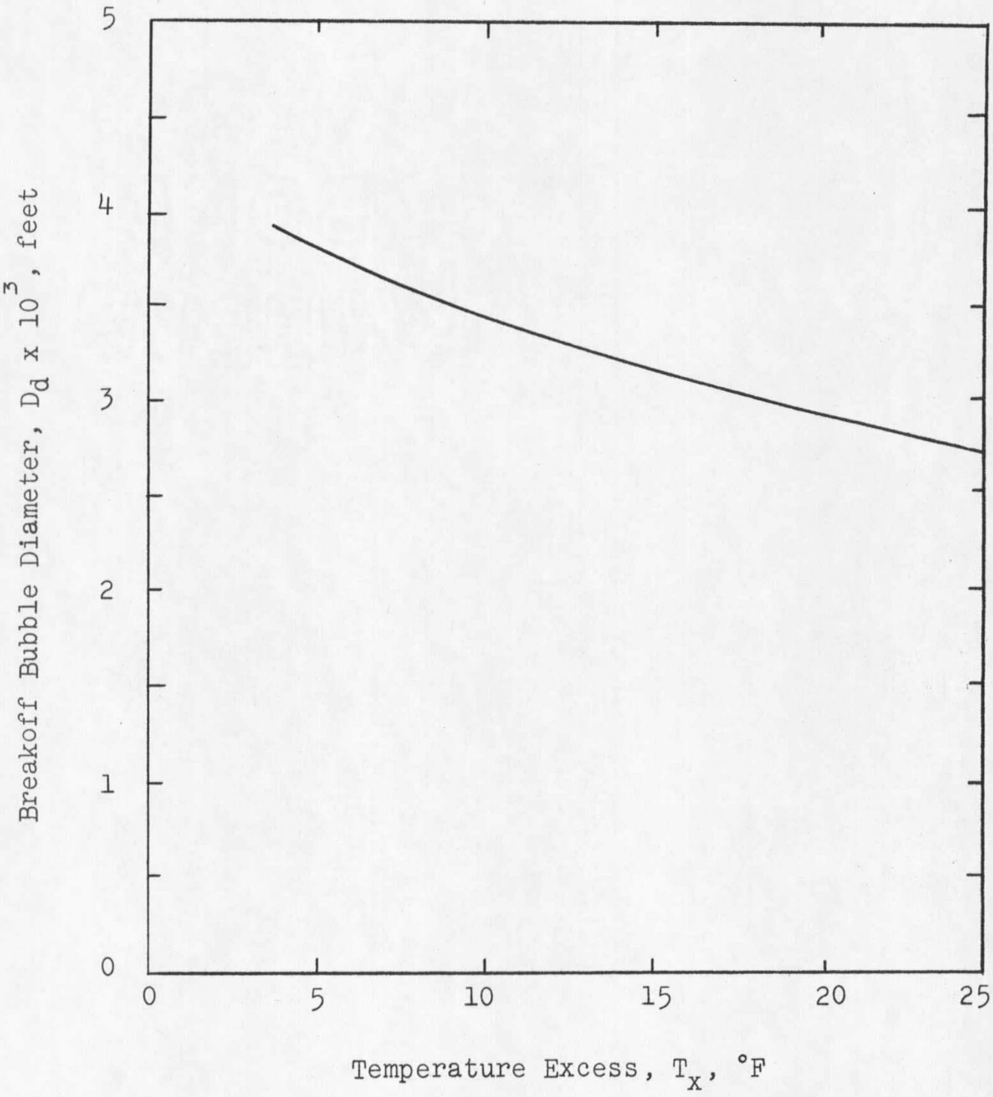

Figure 4. Theoretical Breakoff Bubble Diameter

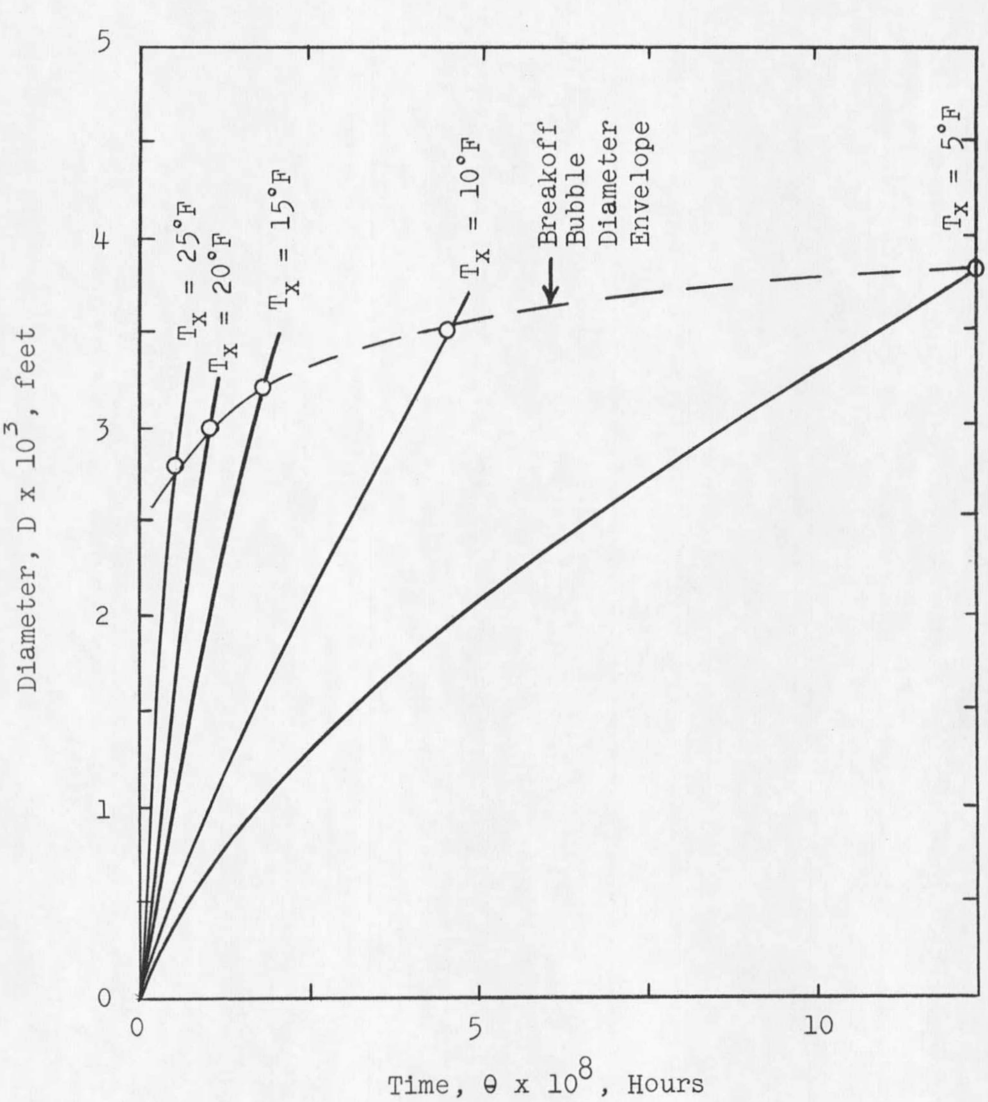

Figure 5. Theoretical Bubble Diameter At Any Time

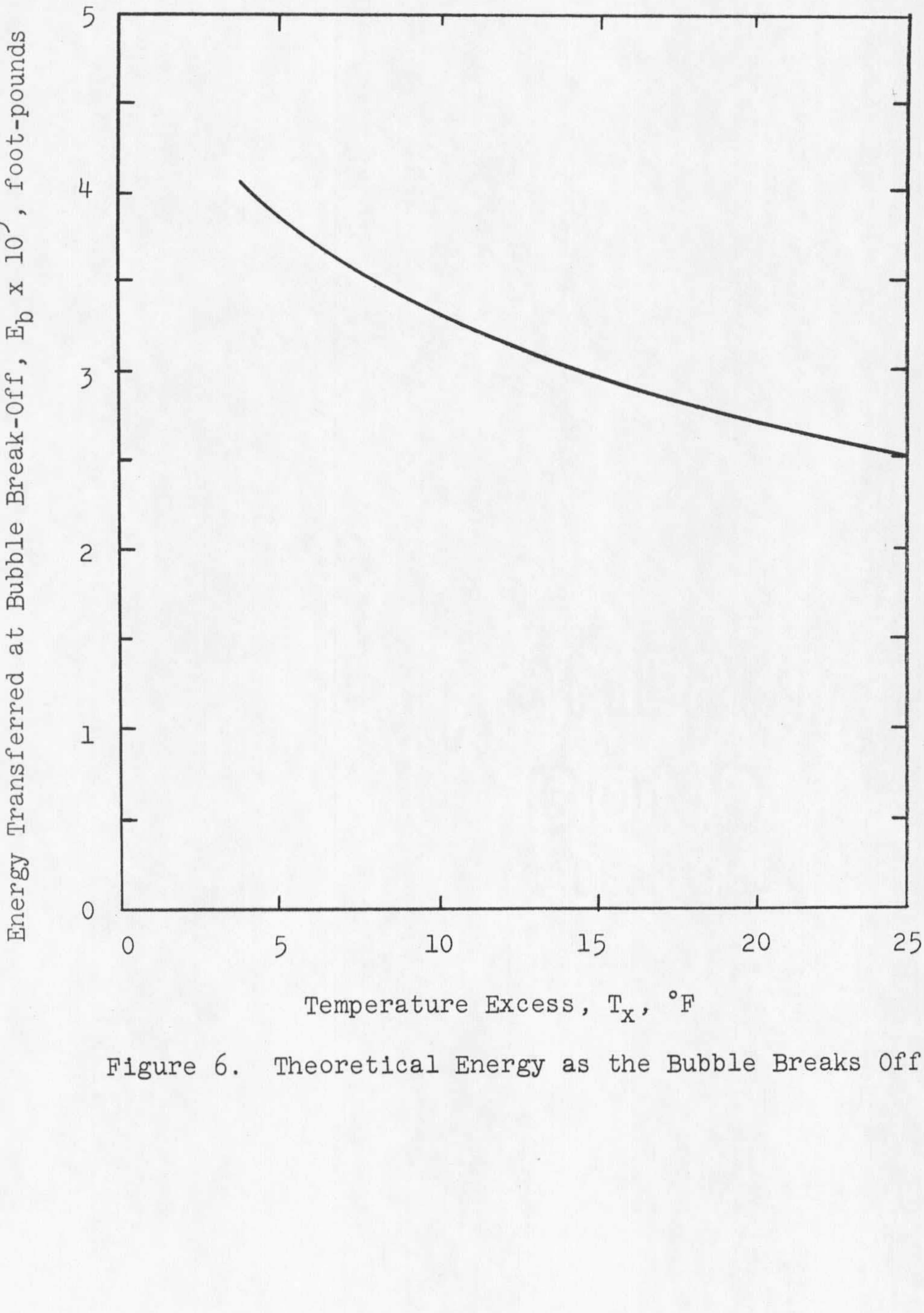

Figure 6. Theoretical Energy as the Bubble Breaks Off

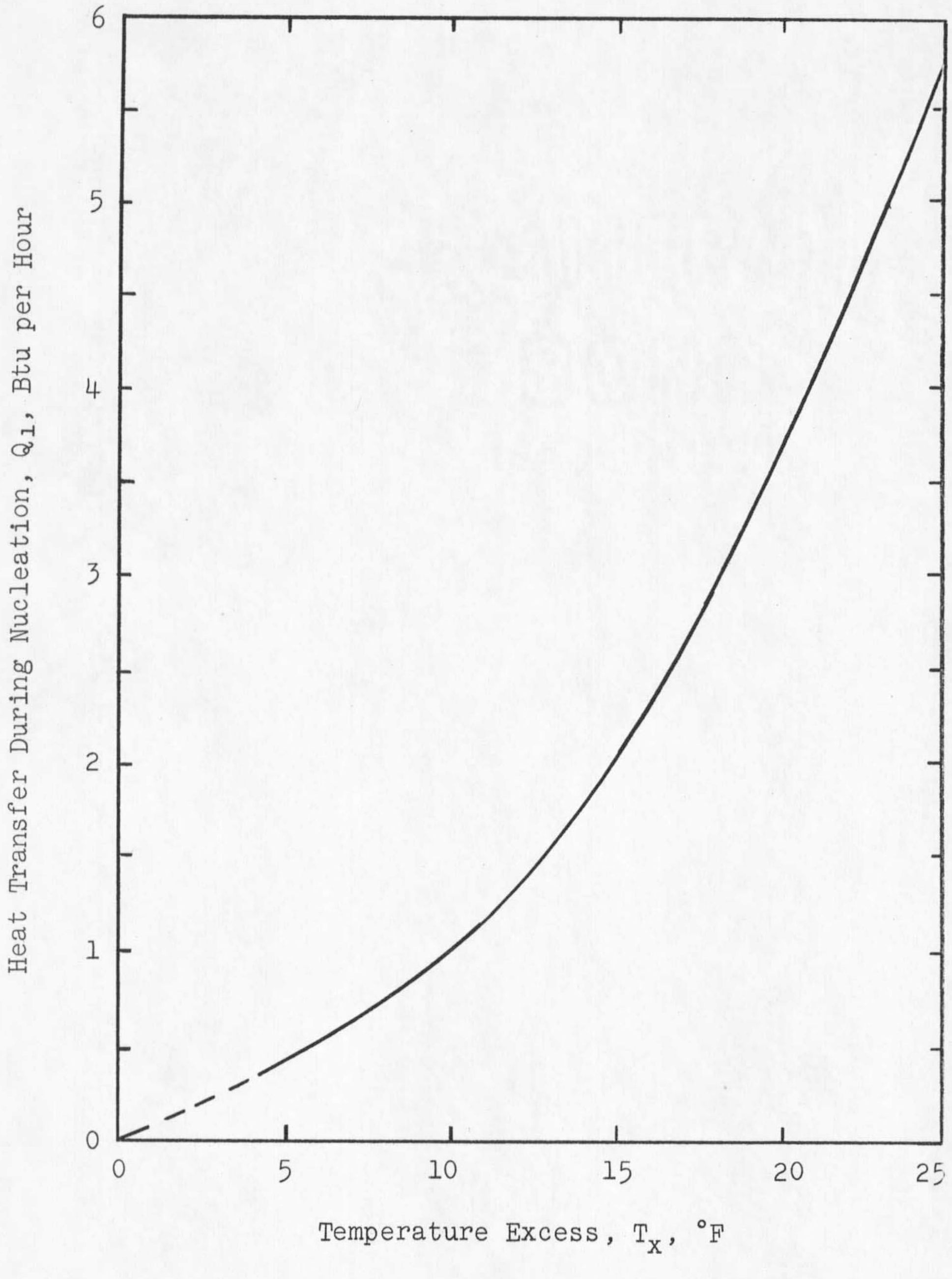

Figure 7. Theoretical Heat Transfer During Nucleation for One Site

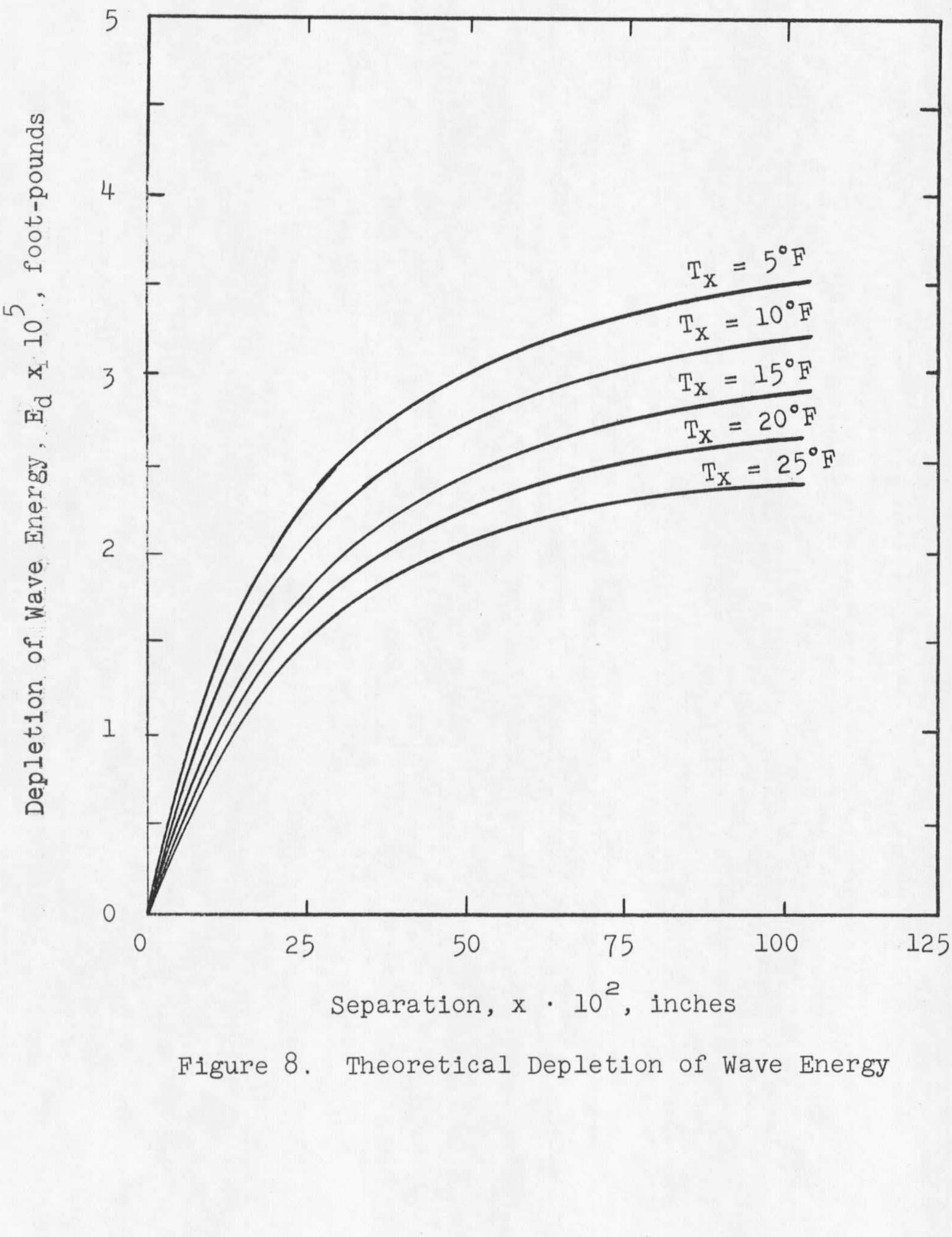

Figure 8. Theoretical Depletion of Wave Energy

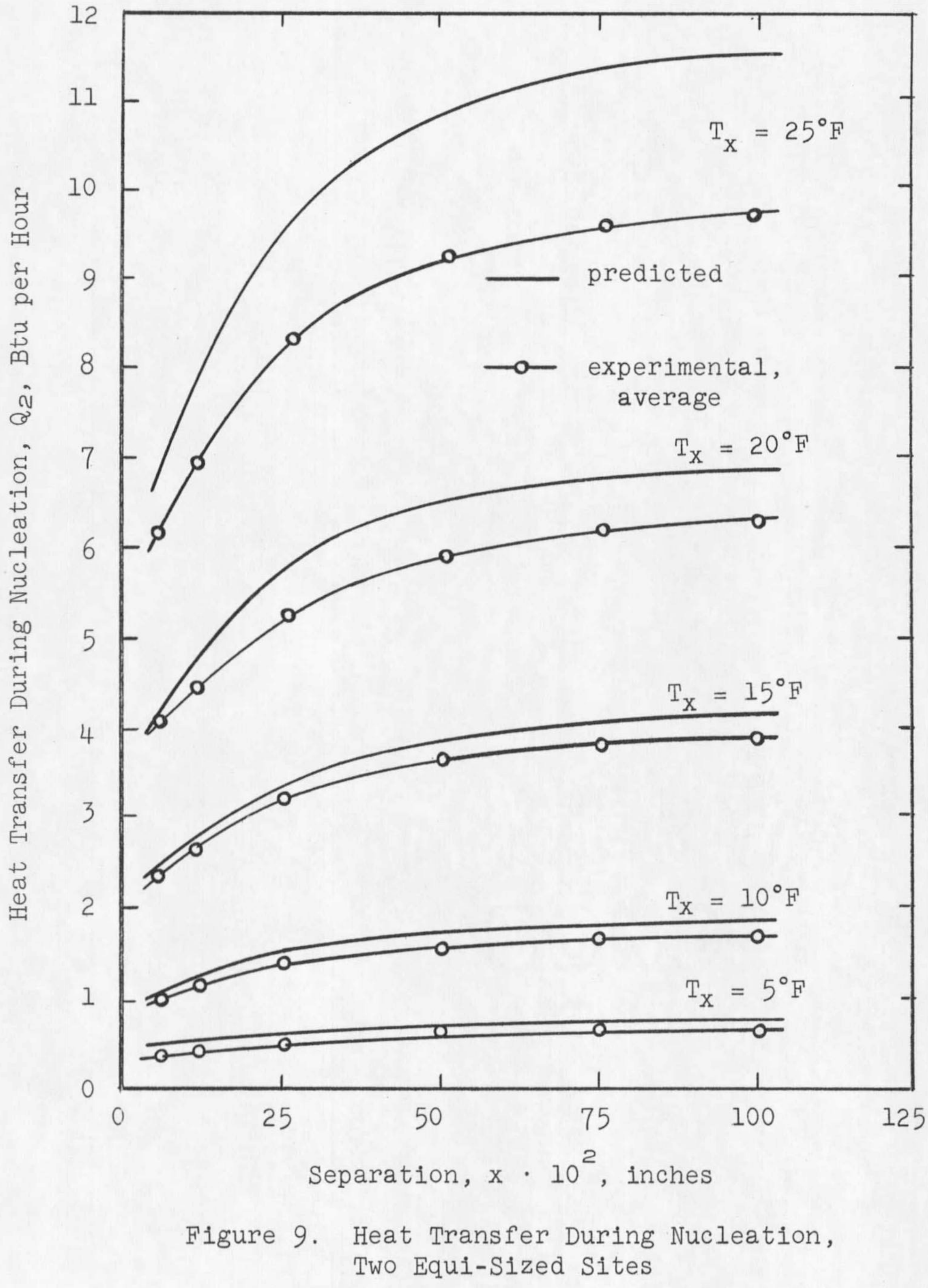

Figure 9. Heat Transfer During Nucleation, Two Equi-Sized Sites

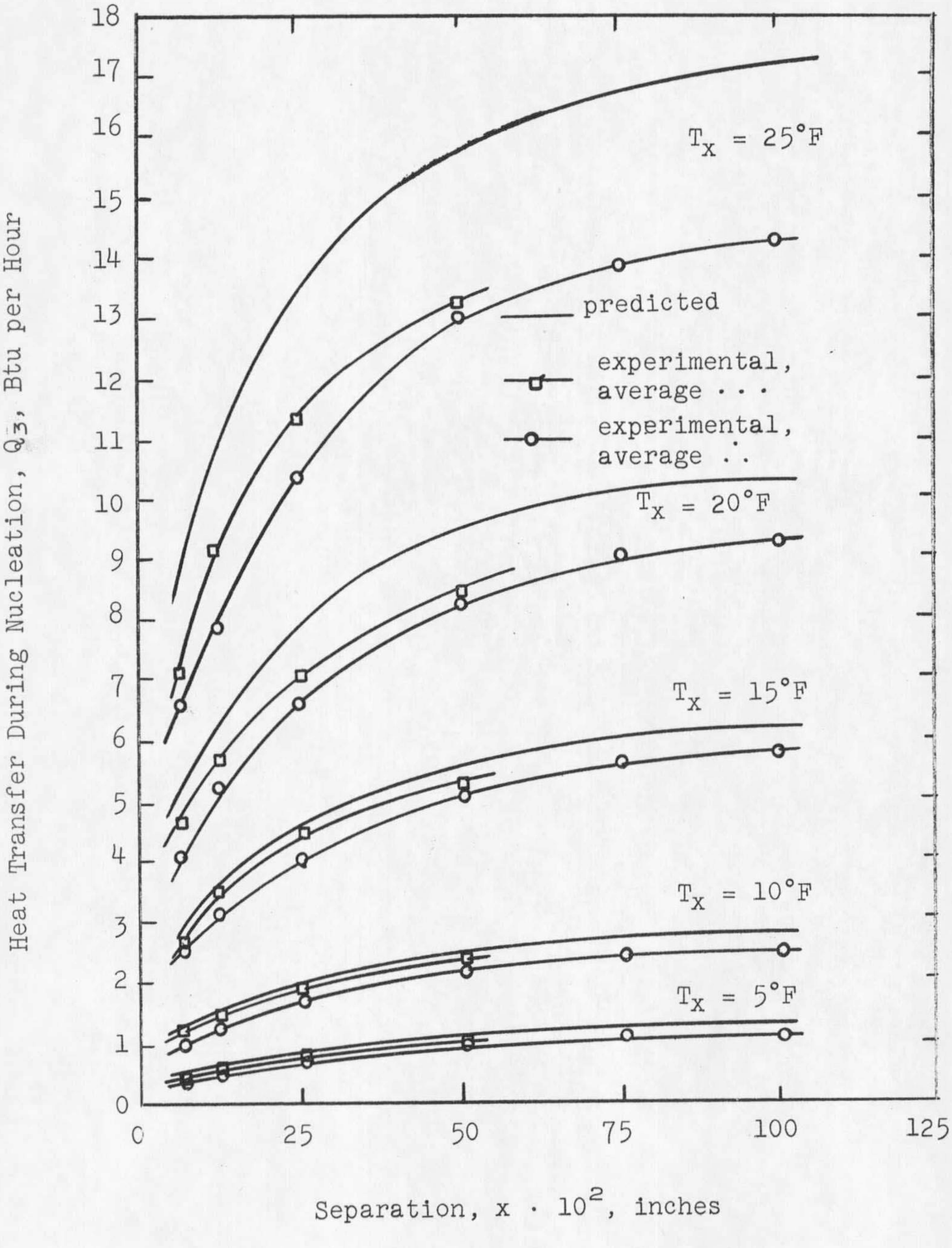

Figure 10. Heat Transfer During Nucleation, Three Equi-Sized Sites

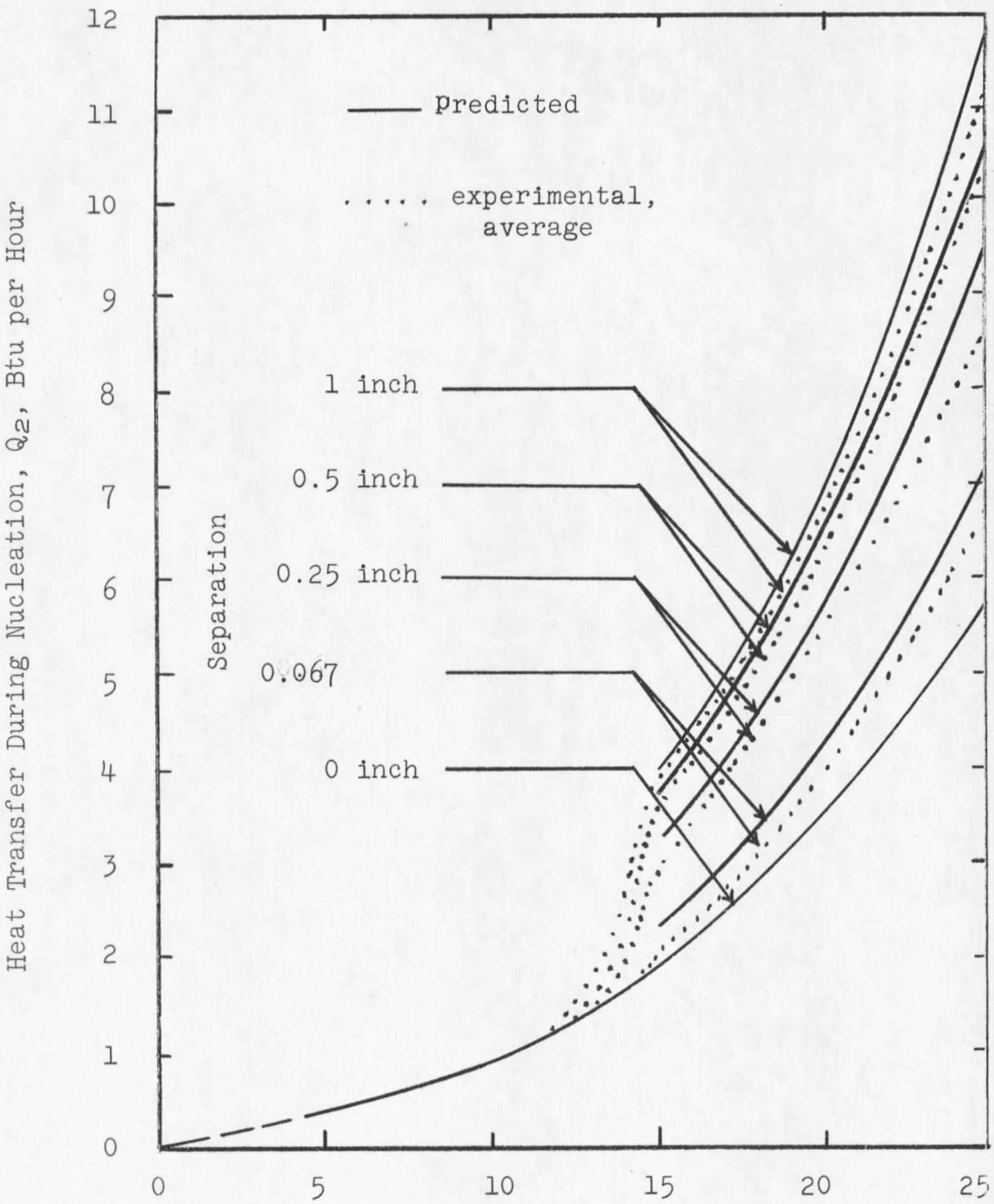

Figure 11. Comparison of Heat Transfer During Nucleation, Two Non-Equal Sized Sites

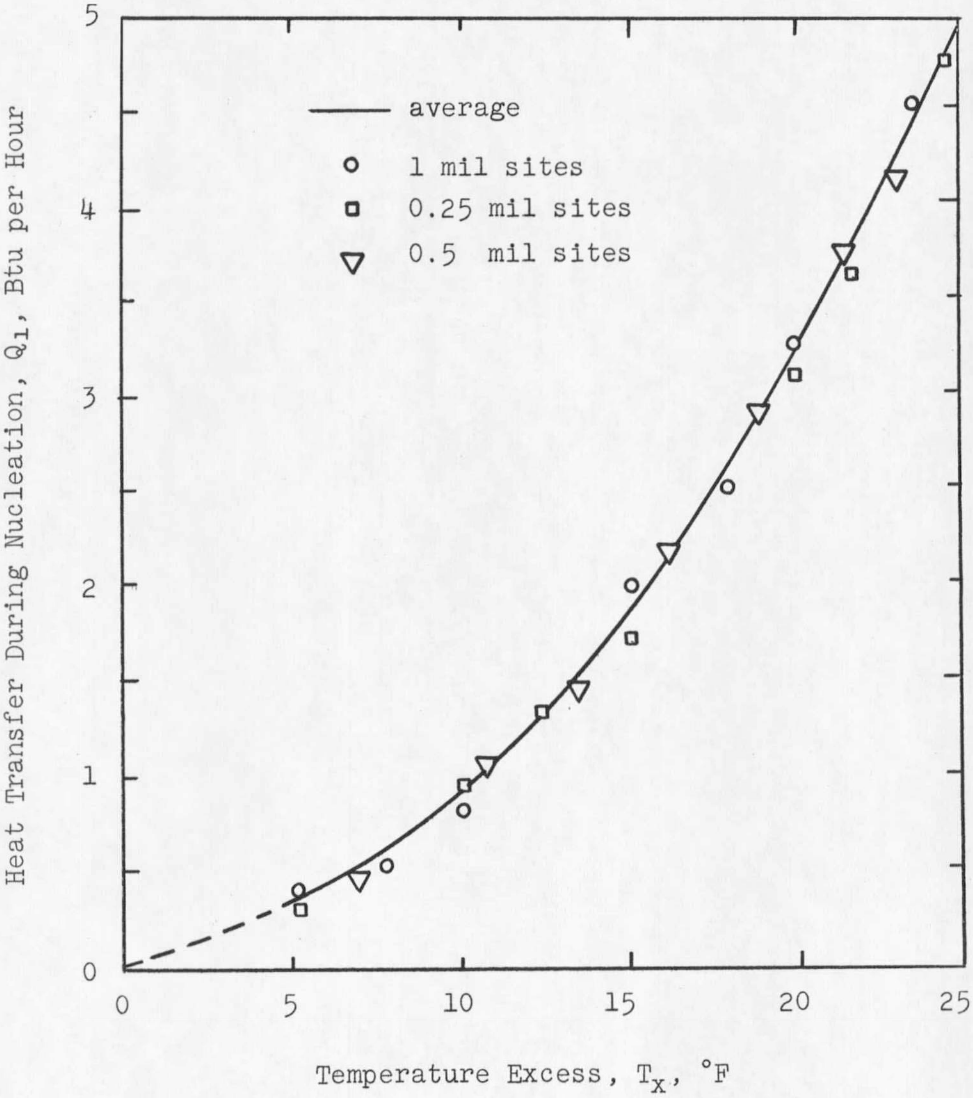

Figure 12. Experimental Heat Transfer During Nucleation, One Site

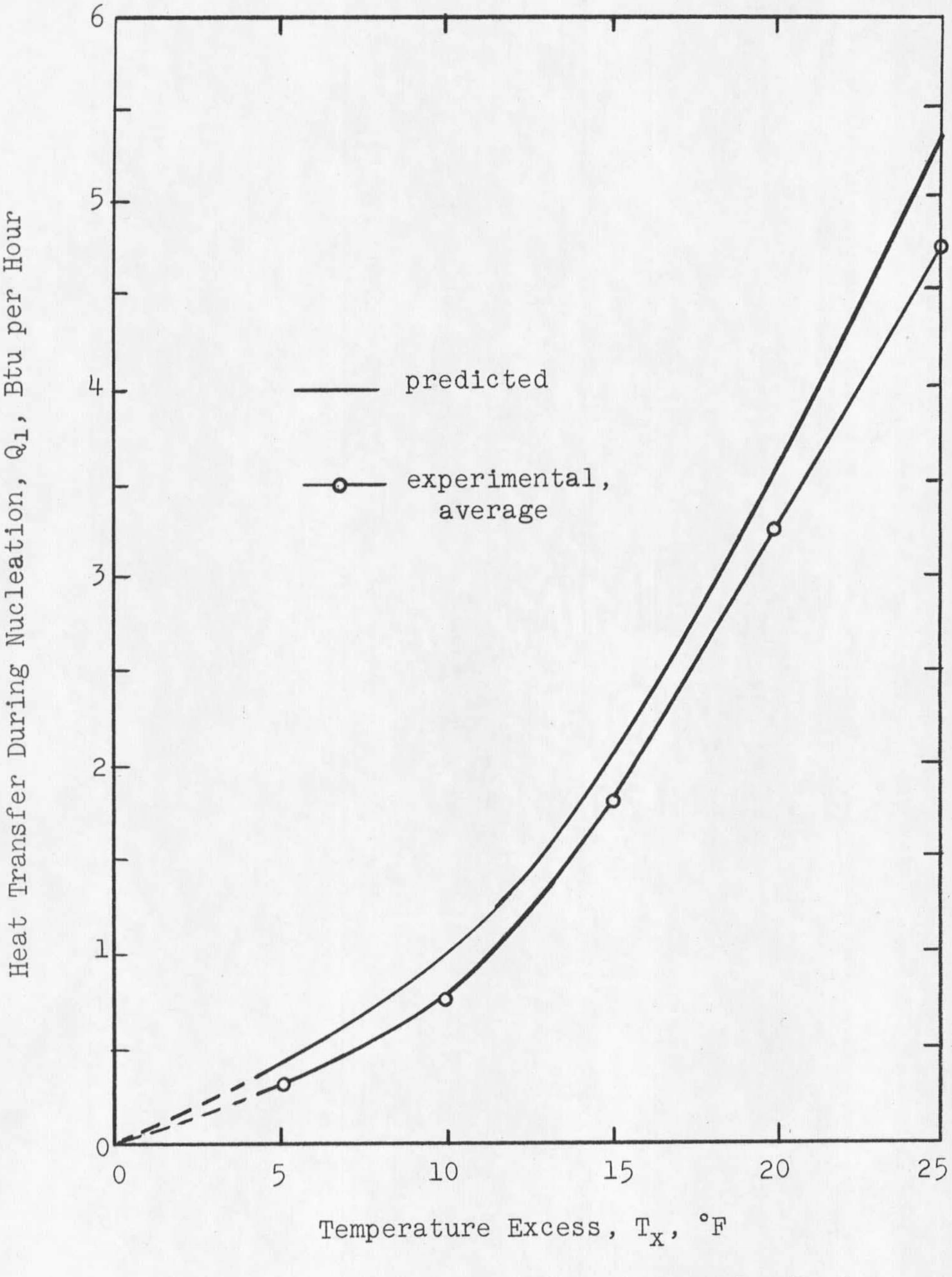

Figure 13. Comparison of Heat Transfer During Nucleation, One Site