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TECHNICAL REPORT

A REVIEW OF CRITERIA FOR PREDICTING INCIPIENT NUCLEATION IN LIQUID METALS AND ORDINARY FLUIDS

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FOREWORD

The work described in this report was performed by Mechanical Technology Incorporated under NASA Contract NASw-1705. The overall objective of this contract was to develop a comprehensive dynamical theory of forced-convection boiling in liquid metals. This report covers the first aspect of this study; namely, the evaluation and formulation of criteria for predicting conditions for incipient nucleation in liquid metals and also in ordinary fluids.

The work was done under the technical management of Mr. S. V. Manson, NASA Headquarters, Nuclear Power Systems.

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INTRODUCTION

The combination of excellent thermal conductivity, high vaporization temperature and moderate vapor pressure possessed by alkali metals makes them very attractive for use as working fluids for Rankine cycle space power systems. Consequently, considerable effort has been devoted recently toward development of once-through alkali metal boilers in which the liquid metal enters subcooled, is vaporized and departs as saturated or superheated vapor. Much of the work to date has concentrated on boilers for potassium and sodium, and considerable attention has been paid to the problem of achieving stability of operation of such boilers.

A number of traditional instability mechanisms for boiling flow have been recognized for some time, e.g. "Ledinegg Excursions" and liquid metal boilers are subject to these instabilities as well as are water boilers. The problem of the stability of liquid metal boilers, however, is further complicated by the fact that liquid metals can exhibit very large degrees of superheating before inception of boiling. This makes dynamic analysis of boiling liquid metal flow quite difficult because one can no longer assume that the flow is in thermodynamic equilibrium. Moreover, the superheating of liquid metals appear to give rise to a unique type of flow instability associated with drastic flow regime changes in the boiling channel. This instability is of the following nature.

When power input to the heated length of a liquid metal boiler is steadily increased from zero, a point is reached when the flow temperature at the exit of the heated length reaches saturation temperature. Due to the tendency of liquid metals to superheat in the liquid phase, further increase in power often does not result in inception of boiling, but rather leads to the condition that superheated flow exits from the heated length. As power is further increased, however, a point is reached where the degree of superheat, ΔT_s, at the exit is sufficiently large such that nucleation of vapor bubbles will occur and boiling will commence. The boiling will then tend to propagate upstream into superheated liquid, causing a sudden change of flow regimes and resulting in undesirable rapid temperature fluctuations in the boiling channel. The vapor liquid interface then can (a) reach a stable position, (b) oscillate within a finite zone, or (c) be swept back out of the boilder to reenter later as superheating again accumulates. The latter two modes are, of course, deemed unstable and are to be avoided if possible. Which mode occurs is governed by the thermo-hydraulic characteristics of the boiler and its associated flow loop.

Because of the technological importance of liquid metal boilers an analytical program was undertaken at M.T.I. under NASA contract Number NASw-1705 directed toward obtaining solutions for the thermo-hydraulic liquid metal boiler stability problem. The crux of this study is the problem of the non-equilibrium behavior of liquid metal flows. Therefore the first phase of this program is concerned with developing dynamic models for predicting the net rate of vapor formation in various two phase flow regimes in non-equilibrium boiling flows.

This present report is concerned with the first aspect of our study, namely that of establishing criteria for predicting the incipient nucleation for all liquids, with special emphasis on alkali metals. The report consists of a critical evaluation of both presently available experimental work in the field and existing theoretical models for predicting incipient nucleation.

Since the study of liquid-metal boiling phenomena is in a rapidly developing state, many aspects of the incipient nucleation of such fluids have not been satisfactorily resolved. Thus, this report reflects the current state of the art with regard to the understanding and prediction of incipient nucleation and does not pretend to provide final answers to all questions concerning this phenomenon. Nontheless, it is believed that enough information has now been obtained on nucleation that an engineer can make an approximate estimation of the amount of superheat required for nucleation given data about the past temperature history of the boiler in question. Moreover, the parametric effect of most system variables on superheat is now at least qualitatively understood.

GENERAL DISCUSSION OF PROBLEM

It is well to begin by defining explicitly what is meant by the superheat required for incipient nucleation. Given a liquid at pressure P there will be a corresponding saturation temperature T_s. To initiate boiling in this liquid, it is necessary to heat the liquid locally to a temperature $T_{inc} > T_s$. The discrepency between T_{inc} and T_s, denoted as $\Delta T_{inc} \equiv T_{inc} - T_s$, is the superheat required for incipient nucleation.

It is recognized that nucleation of vapor bubbles requires the existence of some vapor or gas-filled void of finite size in contact with the liquid to be vaporized. This is so because to initiate a vapor bubble of vanishingly small initial radius would require an infinitely large vapor pressure to overcome the surface tension forces. The pressure P_b inside a spherical bubble required to balance surface tension is given by

$$P_b = P + \frac{2\sigma}{r} \tag{1}$$

where σ is the surface tension of the liquid and r is the radius of the bubble. The pressure P_b inside the bubble can be comprised of the partial pressure of non-condensible gas, which we shall denote as P_g and partial pressure of the vapor P_v i.e.

$$P_b = P_g + P_v \tag{2}$$

combining Equation (1) and (2) we obtain

$$P_v = P - P_g + \frac{2\sigma}{r} \tag{3}$$

The Clausius-Clapeyron equation gives the following relationship between the saturation vapor pressure and liquid temperature

$$\frac{dP_s}{dT_s} = \frac{\lambda}{T(v_v - v_\ell)} \tag{4}$$

where λ is the latent heat of vaporization at temperature T, v_v is the saturated vapor specific volume, and v_ℓ is the saturated liquid specific volume at temperature T. Noting that dP_s/dT_s remains approximately constant with moderate variations in temperature, we can write for the saturation vapor pressure corresponding to T_{inc}

$$P_{inc} \simeq P + \frac{(T_{inc} - T_s)\lambda}{T_s\,(v_v - v_\ell)} \qquad (5)^*$$

or

$$T_{inc} = T_s + \frac{(P_{inc} - P)T_s\,(v_v - v_\ell)}{\lambda} \qquad (6)^*$$

From Eq. (3), the excess vapor pressure required to balance the surface tension of a bubble is

$$P_{inc} - P = \frac{2\sigma}{r} - P_g \qquad (7)$$

From (6) and (7) we obtain

$$\Delta T_{inc} = T_{inc} - T_s = \left(\frac{2\sigma}{r} - P_g\right) \frac{(v_v - v_\ell)\,T_s}{\lambda} \qquad (8)$$

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* An improved formula would be obtained by substituting $1/2(T_{inc} + T_s)$ instead of T_s for T in the right-hand side of Eq. (4). Then the formula for superheat would become

$$T_{inc} = \frac{T_s + \dfrac{(P_{inc} - P)T_s\,(v_v - v_\ell)}{2\lambda}}{1 - \dfrac{(P_{inc} - P)(v_v - v_\ell)}{2\lambda}}$$

The improved accuracy would be quite significant as $(T_{inc} - T_s)/T_s$ approaches $0\{1\}$. However, in current literature, the less accurate formula, Eq. (6) is commonly accepted.

which is the expression giving the superheat necessary to initiate bubble growth. In using this equation as a criterion for incipient nucleation, it is conservative to neglect the effect of non-condensible gas. Our criterion for the superheat required for incipient nucleation then becomes the well known expression

$$\Delta T_{inc} = \frac{2\sigma}{r} \frac{(v_v - v_\ell)}{\lambda} T_s \tag{9}$$

Equation (9) is a fundamental condition which must be satisfied or exceeded locally at some instant or at some point in the liquid if a vapor bubble is to begin growing from the nucleation radius r. This is true for all types of boiling situations i.e. for pool boiling as well as forced convection boiling, and to all fluids. However, for fluids such as water in which the temperature gradients near heated surfaces may become quite steep, it is difficult to know at which point near the heated surface Eq. (9) should be applied. This leads to an apparent relationship between wall superheat required for incipient nucleation and heat flux. In addition, pressure fluctuations associated with turbulent flow may make it difficult to determine the appropriate pressure at which to evaluate ΔT_{inc}, thus leading to the apparent effect of flow rate on incipient superheat in liquid metals discussed in the next section. In short, then, to apply Eq. (9) to predict the superheat necessary to initiate boiling requires knowledge of the following variables.

1. First, one must determine the maximum radius r_c of cavity available as a nucleation site.

2. Secondly, one must know the temporal and spatial variation of liquid temperature and liquid pressure in the vicinity of the nucleation cavity.

In the case of liquid metals, because of their excellent thermal conductivity, the liquid temperature in the vicinity of a heated surface does not vary significantly from the wall temperature over a distance on the order of the size of nucleation bubbles. Hence, the most important variable governing the superheat required for incipient nucleation is the size of cavity available for nucleation. In a later section there will be described various analytical models for predicting incipient boiling superheat in liquid metals which all seek to establish the maximum nucleation cavity size as a function of the pressure-temperature history of the nucleating surface.

In the case of normal fluids, such as water, temperature gradients in the liquid can be quite steep in the vicinity of the heated surface. It is then possible that although the wall temperature is hot enough to satisfy Eq. (9), vapor bubble growth may not occur due to the fact that one bubble diameter away from the heating surface, the liquid temperature may be well below the T_{inc} required to satisfy Eq. (9). In view of this, Hsu and Graham (Ref. 1) have suggested as a criterion for incipient nucleation in water and similar fluids that a bubble will grow from a nucleation site if and only if the temperature at a distance y from the wall equal to the bubble height, is greater than the T_{inc} required by Eq. (9) with $r = y$. This criterion presupposes that cavities of a size necessary for initiation of bubble growth are readily available, and it is the thickness of the thermal layer which controls the incipient nucleation wall superheat. This supposition appears to be valid for water, and in a later section there will be described various analytical extensions and modifications of the Hsu-Graham model for predicting incipient nucleation in water and other non-metallic fluids.

Although the key elements in the mechanism of nucleation may be qualitatively understood, the state of the art with respect to being able to quantitatively predict the superheat required for incipient nucleation is still in a fairly rudimentary state. This is particularly so for liquid metals, which exhibit very large degrees of superheat and for which there exists, at present, relatively little experimental data. In the next section is presented a critical survey of existing experimental investigations of boiling superheat for alkali liquid metals. An attempt is made to assess the influence of various parameters such as heat flux, flow velocity etc. on superheat.

SURVEY OF EXPERIMENTAL INVESTIGATIONS OF BOILING AND INCIPIENT NUCLEATION SUPERHEAT FOR ALKALI LIQUID METALS

There is a scarcity of experimental data on the boiling of alkali liquid metals. This is partly due to the fact that interest in boiling-metal systems (e.g. the SNAP and LMFB reactor) has risen only in recent years, and partly due to the difficulties associated with high-temperature experiments involving liquid metals. It is therefore not surprising that: (a) the number of reported investigations is small, (b) these are mostly of recent origin (i.e. within the last 6 years), (c) many of the investigations are of a preliminary scoping nature and only a few are detailed parameter studies, (d) there is wide scatter in the reported results, and (e) the general concepts of the fundamentals of the phenonmena are in a state of flux, reflecting rapidly increasing understanding as a result of the many investigations currently in progress.

This section of the report presents a critical summary of the status of experimental work in the field of boiling liquid metals. Attention is limited to the boiling inception superheat* problem, and only studies with the alkali metals (K, Na, etc.) are reviewed. While complete coverage of the literature is not implied, this summary does encompass the major pertinent experimental investigations reported to date. One should note, however, that in a rapidly developing field such as this, a critical summary can only represent the current state of the art and that periodic up-datings will be required to reflect new findings.

A. Summaries of Experimental Investigations

A total of twenty-one reported investigations were deemed to be pertinent and these are listed in the bibliography, Refs. 2 through 22. Table I gives a concise description of each investigation with regard to:

1. the test fluid,
2. the experimental system,

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* "Superheat" is here taken to be $\Delta T_{inc} = T_w - T_s$, where T_w is the wall temperature on the bubble nucleating surface.

3. the pressure range of the experiments,
4. magnitudes of the superheats measured,
5. major variables investigated, and
6. results and relevant comments.

It is worthwhile at this point to differentiate between the superheat associated with initial bubble nucleation (incipient boiling) and the superheat associated with steady boiling. The first is a measure of the maximum temperature (above saturation temperature) attained by the nucleation site prior to bubble inception. The latter is a measure of the time-averaged temperature of a heating surface over a number of bubble nucleation-growth-and-departure cycles. The first, denoted as "incipient ΔT_{inc}", is generally greater than the second, denoted as "boiling superheat". Of the twenty-one references reviewed here, four give data on boiling superheat, twelve give data only on incipient ΔT_{inc}, and five give data on both. The present interest is primarily in incipient superheat; therefore, those seventeen reports with data on incipient ΔT_{inc} are summarized below in slightly more detail.

The earliest of these investigations was the work of Edwards and Hoffman (Refs. 2, 3). Their experiments, using Na and K as the test fluids, were performed in small, natural convection loops having a boiler in one vertical leg and a condenser in the other vertical leg. Operating with the loop partially filled, pulsation flow was obtained due to periodic bursts of vaporization in the heated boiler. Cycle frequency was low, of the order of 1-2 cycles per minute. It is therefore reasonable to assume that incipient nucleation was required for each renewed burst of vaporization. Temperature at the boiler showed corresponding cycling, reading a maximum value just prior to each burst of vaporization. The authors calculated their incipient superheat, ΔT_{inc}, as the difference between this maximum boiler temperature and the saturation temperature at the condenser. These investigations were directed solely at the effects of (a) boiling pressure (or T_s) and (b) surface roughness (including artificial cavities) of the heated wall. Some typical results are reproduced in Figure 1. The points represent incipient ΔT_{inc} measured for K with a boiler surface which had drill holes of 0.003 inch radius. The curves represent theoretical superheats for nucleation with critical radius, r_c, calculated by the basic Laplace equation (sometimes referred to as the Gibb's equation):

$$\Delta P = P_v + P_g - P = \frac{2\sigma}{r_c} \tag{10}$$

$$\Delta T_{inc} = T_{inc} \text{ (at } P_v) - T_s \text{ (at } P) \tag{11}$$

where σ = surface tension of the liquid. It is seen that the measured superheats are generally higher than predicted for r_c taken equal to the drill hole radius.

Marto and Rohsenow (Ref. 6) obtained data for pool-boiling of Na from heated flat plates. Helium cover gas was present in the vapor space above the Na pool during the experiments. Results are presented in the classical form of boiling curves, showing heat flux plotted against wall superheat. The authors note that "the incipience, or onset, of nucleate boiling [in a typical run] does not occur until a superheat of 135°F is reached even though the stable nucleate boiling data have a superheat of only 33°F." Five different surface finishes on the boiling plate were tested: (a) mirror finish plate, (b) lapped finish plate, (c) mirror finish plate with artificial porous welds, (d) sintered porous nickel plate, and (e) mirror finish plate with artificial re-entrant cavities. The highest incipient ΔT_{inc} was reported for a mirror finish plate and the lowest incipient ΔT_{inc} for a re-entrant cavity plate.

In subsequent experiments, Shai and Rohsenow (Refs. 10, 11) used the same apparatus and obtained additional data for Na in pool-boiling on surfaces having a single artificial cavity. Traces were obtained of the fluctuating temperature in the wall (near the cavity), in the Na liquid, and in the vapor space. From this, the authors determined bubble cycle periods for stable nucleate boiling. The same temperature instrumentation also gave measurements of the maximum superheat reached by the wall prior to the change from natural convection heat transfer to nucleate boiling. This can be interpreted to give incipient boiling ΔT_{inc}. Typically, these incipient superheats were of the order of 100° to 150°F.

Holtz and Singer (Refs. 4, 5) measured incipient boiling superheats for Na contained in cylindrical vessels heated from the outside. Argon was used as cover gas over the Na pool. In each run, their procedure was to first adjust the argon pressure, then to raise the heat flux in a step-change to some prescribed value. The Na undergoes transient heating with rapidly increasing temperatures until the onset of incipient nucleation. Thermocouples in the Na pool and in the heated wall measured the fluid and wall superheats, (which differed by no more than 5°F in these experiments). The authors report three important observations. First, as is now commonly found, ΔT_{inc} was noted to decrease with increasing boiling pressure (i.e. system pressure at moment of nucleation). Second, the results indicated that for a given boiling pressure and heat flux, ΔT_{inc} increased for increasing maximum-previous pressure (pre-boiling history effect). Third, the authors also report that their measured ΔT_{inc} increased with increasing heat flux. Their experiments were at relatively low heat fluxes (8,000 to 20,000 $Btu/Hr.Ft^2$) and the authors note that this heat-flux effect may diminish at higher fluxes.

Petukhov, Kovalev, and Zhukov (Ref. 9) experimented with boiling from a heated horizontal rod submerged in a Na pool. In contrast to the studies reviewed above, these tests were made with essentially no inert gas in the vapor space. The authors report that the boiling of Na was characterized by large fluctuations in temperatures of the heater surface. They correctly attributed this to the instability of nucleation sites requiring periodic renewed bubble inceptions, accompanied by temperatures fluctuating between saturation value and some characteristic superheat value. Petukhov et al interpret this phenomenon in terms of <u>larger</u> critical nuclei radii for Na than for ordinary fluids (at the same superheat value). The generally accepted current interpretation is exactly the opposite -- namely that Na tends to flood the larger nucleation sites so that only sites with <u>small</u> critical radii are available, thus requiring higher superheats (per Equation 11). Petukhov et al also report an interesting test, wherein incipient boiling was initiated by a sudden decrease of system pressure (by cooling of the vapor space), rather than by the more usual method of raising system temperatures. The results are reproduced in Figure 2, which shows the sudden decrease of Na temperature from a superheat of $\approx 150°C$ to $\approx 10°$ as boiling inception occurred.

Pinchera et al (Ref. 18) report experiments with two different rod heaters in Na pools contained in cylindrical capsules. The first heater had thermocouples placed in grooves in the heater surface. Very low superheats ($\approx 10°C$) are reported for this heater, possibly due to the efficient nucleation sites provided by the thermocouple grooves. The second test heater did not have such grooves and the authors do report measuring superheats up to $\approx 90°C$ for this heater. However, there was extreme scatter in the data, as indicated by the results replotted in Figure 3. For example, at a saturation temperature of 780°C, the measured ΔT_{inc} varied from $\approx 5°$ to $\approx 70°C$.

LeGonidec et al (Ref. 16) measured superheats required for incipient nucleation in stagnant Na contained in a long pipe, with argon cover gas in the vapor space. Direct Joule heating of the pipe and Na was utilized to raise Na temperature from a starting value of $\approx 500°C$ until the occurence of vaporization. As pointed out by the authors, there was again wide scatter in the data, with measured ΔT_{inc} varying from about 20° to 200°C. This would correspond to nuclei with critical radii of 1 to 10 microns. The authors also note that both the number of occurences of superheating and the magnitude of ΔT_{inc} increased with time.

Smidt et al (Ref. 19) performed capsule experiments with stagnant Na pool wherein incipient nucleation was brought about by slow decompression at essentially isothermal conditions. The data, obtained over a boiling pressure range of 1 to 15 psia, show good precision. ΔT_{inc} are reported in the range of 100° to 500°F, corresponding to critical radii of 1 to 3 microns. These particular experiments were performed with "as-received" surface finish on the capsule wall. Further experiments with artificial cavities are mentioned but results were not included in this report.

All the above experiments were with stagnant liquid-metals. In the past two years, a few reports have been published of tests in flowing systems. Grass, Kotlowski, and Spiller (Ref. 15), report superheat measurements in tubular test sections under stagnant, natural-convective flow, and forced-convective flow conditions. Direct Joule heating of the tubular test sections was used, with heated lengths of 2 cm. to 200 cm. The authors note that there is wide scatter in the measured superheats, with a "Gaussian" type of distribution about a mean ΔT_{inc} value for each operating condition. These qualitative conclusions are reported:

1. ΔT_{inc} increased with better purification of the liquid metal prior to the tests;
2. K appeared to have a greater tendency to superheat than Na;
3. ΔT_{inc} are generally lower in forced or natural convection than in stagnant conditions.

Pinchera et al (Ref. 17) describe experiments with Na boiling under both stagnant and forced-flow conditions. Superheats at boiling inception were determined during imposed power transients on vertical rod heaters. In stagnant Na with 30-40 ppm oxygen content the superheats (as measured in the liquid) were in the range of 100° to 300°F. Contrary to the usual experience, these data show little effect of boiling pressure (i.e. T_s). The results reported for Na in forced-convective flow are very interesting in that they show a strong influence of velocity. The measured superheats (based on temperature of the heated wall), decreased sharply from a maximum value of ≈ 170°F at 0.4 m/sec velocity, to a maximum value of only ≈ 18°F at 1.6 m/sec velocity.

Logan et al (Ref. 13) experimented with Na in forced-convective flow past heated rods. Boiling inception was obtained by (a) increasing-power transient or (b) decreasing-pressure transient. The authors report large scatter in the measured incipient-boiling superheats, but that some trends were discernible from the behavior of the maximum superheats. In short, their investigation found the maximum ΔT_{inc} to

(a) decrease with increasing boiling pressure

(b) increase with increasing heat flux

In a later report (Ref. 20), these investigators also report that the mean superheat values, for a given set of operating conditions, decreased with increasing flow velocity.

Chen (Ref. 12) obtained measurements of the superheat required to initiate boiling in potassium, at a constant flow velocity of ≈ 0.2 ft/sec. The experiments were performed in a high temperature, forced-convective loop, using a radiantly heated tubular test section. At desired boiling pressure, incipient vaporization was obtained by small incremental increases in heat flux at the test section, with a minimum waiting period of 15 minutes at steady state conditions between successive increases. This slower procedure appeared to give more reproducible ΔT_{inc} data (less scatter) than procedures using rapid power, temperature, or pressure transients. Emphasis in these experiments were on the effect of preboiling deactivation conditions.

In a more recent study (Ref. 21), Chen investigated the effect of turbulent flow on incipient-boiling superheat. For a given deactivation condition and constant boiling pressure, Chen measured ΔT_{inc} at various flow rates. The results clearly showed superheats decreasing with increasing flow rate. A theoretical explanation was proposed, based on the effect of turbulence on pressure fluctuations at the wall.

B. Evidence of Parametric Dependences

For understanding of a phenomenon as complicated as incipient vaporization, one must rely heavily on well documented experimental evidence showing its functional dependence on the various governing parameters. Unfortunately, many of the experimental investigations of incipient-boiling superheat to date were not sufficiently well controlled or documented to isolate such functional dependence. Nevertheless, an attempt is made here to indicate, at least qualitatively, some of the parametric dependences that appear to affect incipient-boiling superheats of alkali liquid metals.

1. Boiling pressure

The parametric effect most clearly defined at this time is that of the system boiling pressure (i.e. the local pressure or saturation temperature) at the nucleation site. There is almost unanimous agreement among the available experimental results that ΔT_{inc} for incipient boiling decreases with increasing pressure. Figure 4 shows a composite plot of data from three different investigations. It is seen that the superheats measured for both K and Na definitely decrease as the system pressure is increased, other factors being constant. This parametric dependence is in agreement with the behavior predicted by the fundamental Laplace equation (1), which when combined with the Clausius-Clapeyron equation gives (neglecting V_L in Eq. (9))

$$\Delta T_{inc} \simeq \frac{2\sigma T_s}{\lambda \rho_v r} \tag{12}$$

where

λ = latent heat of vaporization

ρ_v = vapor density

T_s = saturation temperature at local pressure

The variation of ΔT_{inc} with saturation temperature (at constant critical radius) is then,

$$\frac{d\Delta T_{inc}}{dT_s} \simeq \left[\frac{\sigma}{\lambda \rho_v} + T_s \frac{\partial}{\partial T_s} \left(\frac{\sigma}{\lambda \rho_v}\right)\right] \frac{2}{r} \tag{13}$$

Examination of the physical properties tables shows that the right hand side of this equation is negative for the alkali liquid metals, thus indicating that ΔT_{inc} should indeed decrease as T_s (or boiling pressure) is increased.

2. Surface finish

It is generally accepted that bubble nucleation likely occurs at unflooded cavities on the boiling surface. It follows then, that surfaces of rough finish, or ones with artificial cavities, are more likely to have potential nucleation sites than polished surfaces. Stated another way, one expects that polished surfaces would have unflooded cavities of smaller dimensions than rough surfaces. Assuming that the critical radius for nucleation (r_c) is proportional to the cavity dimension, Equation (1) would then predict that rough surfaces (or ones with artificial cavities) would require smaller nucleation superheats, all other factors being equal.

The experimental results of Edwards and Hoffman (Ref. 2) appear to verify this reasoning. Some of their data on incipient boiling of K are reproduced in Figure 5. ΔT_{inc} is plotted against boiling temperature T_s, showing the range of results obtained on (a) "as received" surface and (b) surface with 0.006" diameter artificial cavities. It is seen that the latter rougher surface, with artificial cavities, did require substantially less superheat to initiate boiling.

This "roughness effect" may sometimes be tempered by other considerations. Chen (Refs. 12 and 28), Holtz and Singer (Ref. 22) and others have pointed out that for sufficiently rough surfaces, where there exists a multitude of nucleation cavities, the limiting criterion would likely be the degree of flooding in the cavities rather than the availability of cavities itself.

3. Dissolved gas content

The Laplace equation, written in the form of Equation (1), recognizes that the required pressure excess within the bubble nucleus is made up of a vapor pressure contribution (P_v) and a gas partial-pressure contribution (P_g). All factors being equal, a smaller vapor pressure would be required to cause incipient nucleation if the gas content in the liquid metal was increased (higher P_g). One thus expects incipient-boiling superheats to decrease as dissolved-gas concentration increases. To our knowledge, there has been no experimental study to date (with alkali metals) that can either verify or disprove this expected behavior. Carefully documented experiments to quantitatively measure the effects of gas content are needed.

4. Heat flux

The effect of heat flux is also not yet determined. Holtz and Singer (Ref. 4) reported that incipient ΔT_{inc} apparently increased slightly as heat flux increased. Their experiment, however, only covered a small range of heat flux, with all data being taken at $Q/A < 20{,}000$ Btu/Hr.Ft^2. In subsequent reports

(Ref. 22), these authors state that this seeming effect of heat-flux may actually have been caused by changing gas contents, brought about by diffusion during the duration of the tests. LeGonidec et al (Ref. 16), also attempted to determine the effect of heat flux but reported that, from their results, "the heating power seemed to be an unimportant parameter". This apparent unimportance of heat flux on incipient-nucleation superheat at least partly confirms the contention that the thermal criterion (Ref. 1) of nucleation, applicable for ordinary fluids, is usually not the limiting criterion for liquid metals.

5. Preboiling deactivation

Both Holtz (Ref. 5) and Chen (Ref. 12) have proposed that, in the case of alkali metals, it is often the preboiling pressure-temperature condition that determines the critical cavity size for nucleation, (r_c). It is the degree of cavity flooding (deactivation) caused by the preboiling history, wherein subcooled liquid may be forced into potential nucleation sites, that determines r_c and hence the superheat required to cause bubble nucleation. Experimental results from the few investigations where deactivation conditions have been controlled and documented appear to verify this effect (Refs. 4, 12, 22). Figure 6 shows results obtained with K (Ref. 12) boiling at 16 psia, after deactivation of the heating surface at 1180°F and various pressures. It is seen that increasing deactivation pressure (at constant deactivation temperature) reduces the critical nucleus radius and leads to higher incipient superheats. The same effect is obtained for decreasing deactivation temperature at constant deactivation pressure.

6. Flow rate

Recent experimental results (Refs. 13, 17, 21) obtained with flowing liquid metals have indicated a definite flow (a velocity) effect on incipient boiling ΔT_{inc}. Figure 7 shows data from Refs. 17 and 21 wherein ΔT_{inc} is given as a function of flow velocity, all other variables being essentially constant. It is seen that increasing flow rate sharply reduces the superheat required for nucleation. While there are only these few data available at this time, the measured effect of flow rate is so clearly evident that one can be fairly confident of the validity of this parametric effect. Chen (Ref. 21) has proposed a tentative theory, based on fluctuating pressures associated with turbulent flow, as a possible explanation for this "velocity" effect.

ANALYTICAL MODELS FOR PREDICTION OF LEVEL OF SUPERHEAT REQUIRED FOR INCIPIENT BOILING

As noted in an earlier section, there are conceptually two key quantities to be determined if one is to be able to predict the degree of wall superheat or bulk superheat required for incipient nucleation. One is the maximum radius of bubble nucleus available for nucleation and the second is the temporal and spatial variation of temperature and pressure in the liquid in which boiling is to be initiated. Both of these quantities are very difficult to determine; the first because of the irregular statistical nature of nucleation cavity availability and the second because, in turbulent flows, it is not possible to predict the exact time and space variations of pressure and temperature. Nonetheless, some reasonable analytical models have been developed for predicting boiling superheat and these will be reviewed below.

First let us consider the problem of predicting cavity size available for nucleation. This is particularly relevant to incipient nucleation in alkali metals, since the very high superheats obtained in these fluids seems to be due to the tendency of alkali metals to flood larger available cavities, the degree of superheat then being determined by the size of the largest cavity left unflooded.

One of the first analytical models developed to treat the flooding of nucleation sites by alkali metals is the "equivalent" cavity model proposed by Holtz. (Ref. 23). In essence, Holtz considered cavities of arbitrary irregular shapes such as those depicted in Figures 8 and 9. The flooding or non-flooding of such cavities depends upon the minimum radius within such cavities, the surface tension of the liquid, (i.e. its ability to wet the cavity interior), the shape of the cavity and the pressure and temperature of the liquid. In Figure 8 is shown a case of wetting liquid entering cavities. In this case, for the cavity shape shown, surface tension forces will tend to draw the liquid into the cavity. The liquid-gas interface will temporarily stabilize at the radius r' where the pressure $P_b' = P_g' + P_v'$ in the cavity balances and liquid pressure plus surface tension forces, i.e.,

$$P_g' + P_v' = P' + \frac{2\sigma}{r'} \qquad (14)$$

Since, during filling, the liquid will be below saturation temperature, the vapor pressure P_v will be less than P, and the presence of non-condensible gas (partial pressure P_g) is necessary in order to avoid flooding of the cavity. However, according to Holtz, one may expect that in liquid-metal systems all entrapped non-condensible gases will be removed from surface cavities by thermal diffusion. Hence, if the liquid metal wets the inner surface of the cavities, the cavity will be ultimately flooded no matter what its size* and will not be able to serve as a nucleation site.

In view of the above conclusion, Holtz postulates that there must be a certain number of surface cavities which do not become wetted by liquid metal during the fill process. Such a situation is depicted in Figure 9. Although alkali liquid metals do definitely tend to wet metal surfaces, the non-wettibility of certain cavities could be argued on the basis of impurities e.g. oxide layers.

In the case of a non-wetting fill process we have (neglecting non-condensible gases)

$$P'_v + \frac{2\sigma}{r'} = P' \tag{15}$$

and the cavity may remain unflooded provided the minimum radius of the cavity, r_m, is sufficiently small to satisfy the inequality

$$P'_v + \frac{2\sigma}{r_m} > P' \tag{16}$$

Now, if the cavity remained unwetted up to and including the point of incipient nucleation, then no superheat would be required to expel the vapor bubble from the cavity. This is because, as saturation temperature is approached and P_v approaches P, surface tension forces would aid rather than oppose expulsion of the bubble. In order to explain the degree of superheating observed in liquid metals, Holtz offers the supposition that although the liquid metal does not wet during filling, it will begin to wet as it begins to withdraw from the cavity,

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*Unless it is a reentrant cavity, which will be discussed later.

and the bubble curvature will reverse its direction as shown in Figure 9. With liquid wetting, the pressure relationship between P_v and P will be

$$P_v = P + \frac{2\sigma}{r_c} \tag{17}$$

i.e. superheat will be required to expel the bubble from the cavity.

Holtz's non-wetting - wetting model may be considered to be plausible if one considers the fact that although the liquid metal may not wet upon entry into a cavity, the cavity surface that has been in contact with the liquid metal can become altered due to dissolving of impurities so that the liquid metal can wet upon withdrawal.

The degree of superheat required for incipient nucleation according to Holtz's model is obtained by solving Equation (15) for $r' = r_c$, using the maximum value for $P'-P'_v$ that has occurred in the history of the last filling of the system. Large values of $P' - P'_v$ are produced by system pressures much greater than saturation pressure or, equivalentally, by system temperatures much lower than saturation temperature. The maximum value of the difference between system pressure and saturation vapor pressure that occurs in the pre-boiling history of a boiler is refered to as deactivation pressure while the maximum difference between saturation temperature and system temperature is referred to as deactivation temperature.

Holtz's model has been modified by Chen (Ref. 12) by considering a conical shape for cavities and taking the effect of undissolved gas into account. The undissolved gas has a strong effect in resisting the penetration of liquid into cavities especially under severe deactivation conditions. Chen's model retains the same supposition as Holtz's model that liquid does not wet as it penetrates a cavity but does wet as it withdraws.

Chen obtains the following expression for ΔP_{inc}, the excess pressure inside the bubble required for incipient boiling*.

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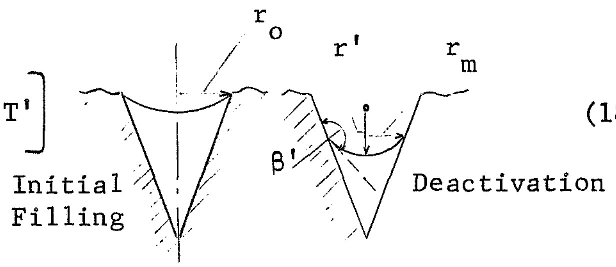
* As we shall see, a very nearly equivalent expression is obtained for ΔP_{inc} using a re-entrant cavity model.

$$\Delta P_{inc} = \frac{\sigma}{\sigma'}(P' - P'_v) - \frac{G_o}{r_m^3}\left[T + \frac{\sigma}{\sigma'}T'\right] \qquad (18)$$



where r_m is the conical radius at the depth of maximum liquid penetration into the cavity and $G_o = P_{go} r_o^3/T_o$ is a measure of the content of non-condensible gas trapped in the cavity (a quantity to be determined empirically). The primed quantities in this equation are the system temperature, pressure, vapor pressure, and surface tension measured at the most severe condition of deactivation experienced by the boiler in its pre-boiling history. Non-primed quantities are measured at conditions corresponding to inception of boiling.

The degree of superheat for incipient boiling corresponding to ΔP_{inc} can be obtained from the Clausius-Claperyon equation (Equation (4)) or from a vapor pressure vs. temperature curve. Values of superheat obtained from Chen's analysis will be discussed later in this section.

The Holtz-Chen model for predicting superheat in liquid metals has been given further refinement by Dwyer (Ref. 24) by considering that

(a) the quantity of inert gas present in an active cavity may decrease in time by being carried away by boiling and

(b) the effective cavity radius at inception of boiling can be different than the minimum interface radius established during deactivation.

Incorporation of these refinements permit one to obtain excellent agreement between measured and predicted superheats. Also, and more importantly, these concepts shed additional light on the various physical mechanisms at play in the determination of superheat required for incipient boiling. For example, the concept of loss of inert gas leads to an explanation of a heat flux effect on superheat. Unfortunately, although both the refinements introduced by Dwyer are physically reasonable, it is difficult if not impossible to arrive at a purely theoretical prediction either of the loss of inert gas with boiling or of the ratio of effective nucleation cavity radius to the minimum deactivation cavity radius. Hence, both refinements introduce additional empirical parameters into the incipient superheat calculations.

The conceptual difficulty in the Holtz-Chen-Dwyer model for incipient superheat of having to assume that liquid metals do not wet cavities during deactivation but do wet at the point of incipient boiling can be avoided by considering cavities of the re-entrant type. The concept of a re-entrant cavity has been previously proposed by a number of investigators to explain various aspects of nucleate boiling (see, for example, Ref. 6 by Marto and Rosenhow).

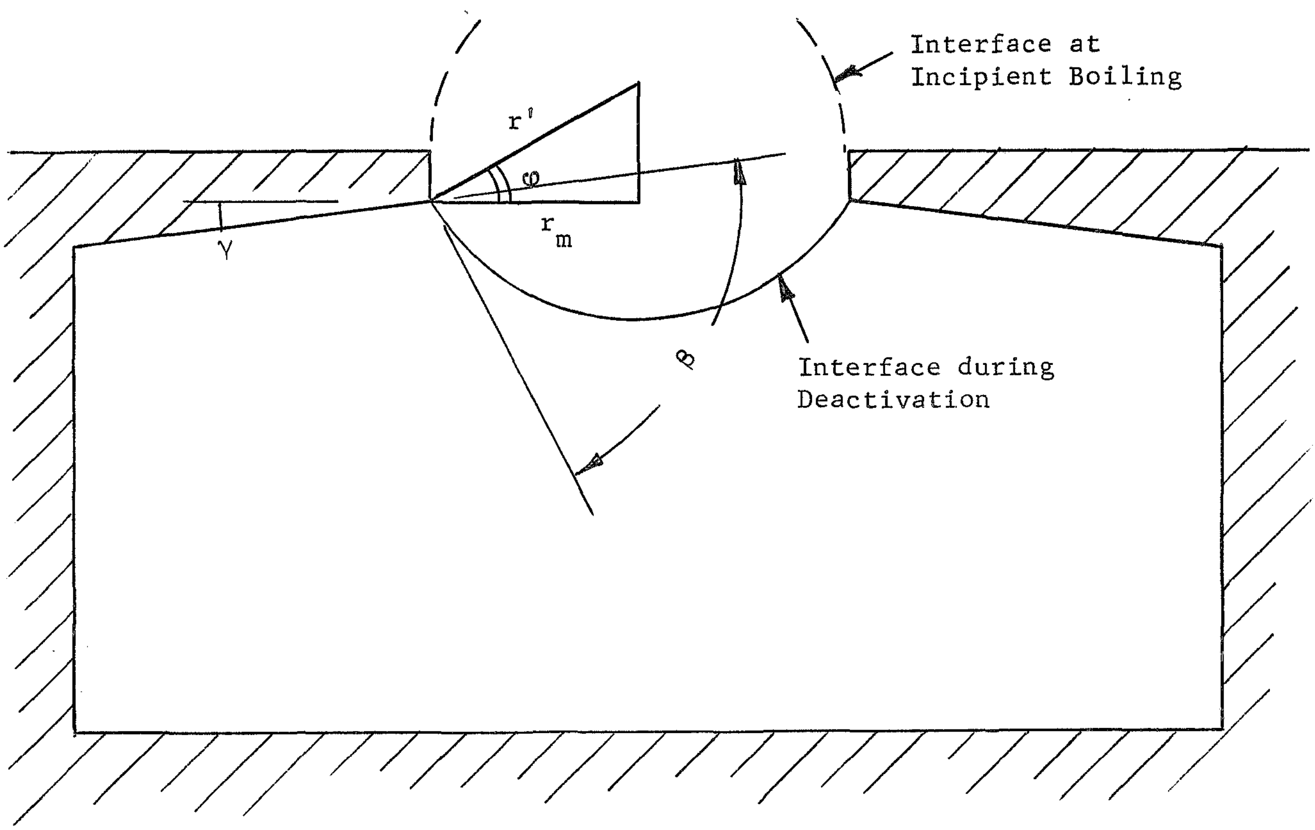


Figure 10

The above sketch of a re-entrant cavity is idealized in that the corners at the mouth of the cavity are assumed to be sharp. The cavity is also assumed to be rotationally symmetric. Suppose that liquid metal does bridge at the cavity mouth so that the cavity is not flooded during filling*. Now, if the liquid is subcooled, the interface will recede into the cavity and have a radius of curvature r'. Note that the surface tension force is in the direction to resist flooding. Let β be the wetting angle. Then

$$r' = \frac{r_m}{\cos \varphi} \tag{19}$$

where r_m = minimum radius of cavity opening

$$\varphi = 90^\circ - (\beta - \gamma)$$

It is interesting to see that a re-entrant cavity can remain unflooded even for a wetting fluid such as liquid alkali metals. For other types of cavities, the liquid has to be assumed non-wetting in order for a non-reentrant cavity to have a chance to remain unflooded.

During deactivation the interface equilibrium equation can be written as

$$P' - (P_v' + P_g') = \frac{2\sigma'}{r'} \tag{20}$$

The partial pressure of inert gas is included. Those cavities which cannot develop enough surface tension force to balance the pressure difference will be flooded; this can be caused by either one of the following:

1) r_m too large

2) $\cos \varphi$ too small

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*The analysis presented below follows that presented by Dougherty in Ref. 29.

Given a rough surface with complete range of re-entrant cavities with various values of r_m and β, and given any particular deactivation condition (particular value for r'), that cavity which would remain unflooded and require least superheat to subsequently nucleate would be the one with $r_m = r'$ i.e. with $\cos \varphi = 1$. Since these cavities will control the superheat required for inception of boiling, we can set $\cos \varphi = 1$ in our analysis.

Typically, the size of a re-entrant cavity is much larger than its opening. Therefore, the volume of the vapor phase inside the cavity does not change appreciably during the deactivation period. For a constant volume process, the partial pressure of the inert gas at inception of boiling is

$$P_g = \frac{T}{T'} P'_g \tag{21}$$

And, the bubble equilibrium equation at inception of boiling becomes

$$P_v + \frac{T}{T'} P'_g = P + \frac{2\sigma}{r_c} \tag{22}$$

Using $r_c = \alpha r'$* and Equation (20), we have

$$P_v = P + \frac{\sigma}{\alpha\sigma'} \left[P' - (P'_v + P'_g) \right] - \frac{T}{T'} P'_g \tag{23}$$

which is the same equation as obtained by Chen (Eq. 18) except that he has expressed P'_g as $G_o T'/r_m^3$ and also Eq. (23) contains the factor α.

Knowing P_v we can determine the corresponding temperature either by using a saturation table or the Clapeyron equation, from which the incipient boiling superheat

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*The factor α is included here to permit one to consider that the inception radius r_c may be different from the minimum deactivation radius r'. This concept was suggested by Dwyer, Ref. (24).

can be calculated. In Figures 11 and 12, the incipient boiling superheat calculated from the re-entrant cavity model is plotted against deactivation subcooling at deactivation pressures of 16 and 25 psia respectively. The boiling pressure of potassium is 16 psia. Chen's experimental data and analytical curve are also shown for comparison. In Figure 11, it can be seen that the experimental data show very little effect of deactivation subcooling in contrast to the analytical curves which show a steady increase in incipient boiling superheat with deactivation subcooling. In regard to this, Chen's model shows slightly better agreement with the data in Figure 11 than does the re-entrant cavity model with $\alpha = 1$. The fact that Chen's analytical curve tends to become more nearly constant at high values of deactivation subcooling is due to the effect of non-condensible gas in a conical cavity. In such a cavity, as deactivation pressure increases, the interface advances toward the apex and compression takes place. On the other hand, no appreciable compression can take place in a re-entrant cavity. This is why in Figures 11 and 12 the present model with $\alpha = 1$ predicts higher superheat than Chen's model especially under severe deactivation condition (large $T_s' - T'$ or large P').

In Figure 12, the experimental data for incipient boiling superheat show a more pronounced increase with deactivation subcooling than they do in Figure 11 although the effect is still slight. In Figure 12, the re-entrant cavity model with $\alpha = 1.5$ seems to give the best overall fit with the data. This suggest that the empirical coefficient α might tend to increase with boiling pressure, a hypothesis which could be checked by future experiments.

From the experimental data reported by Chen, it is seen that when the deactivation subcooling approaches zero the superheat appears to remain at a certain value different from zero whereas both the re-entrant analytical model and Chen's conical model predict that the superheat should approach zero with the deactivation subcooling. This discrepancy can be improved if one can assume that there is a critical cavity size $(r_o)_{crit}$, such that all cavities with $r_o > (r_o)_{crit}$ are entirely flooded even at minimum deactivation. The $(r_o)_{crit}$ is apparently a function of the liquid surface tension, wall and liquid temperatures, pressure during filling operation and filling velocity. Once $(r_o)_{crit}$ is known, Equation

(22) can be used to determine a minimum P_v or a minimum superheat required for incipient boiling even at zero deactivation. This minimum superheat is shown in Figures 11 and 12 as horizontal lines.

The difficulty associated with the above assumption of $(r_o)_{crit}$ is that it is difficult to justify physically. Certainly it is true that for cavities above some critical size, fluids could not bridge the cavity due to instability of the liquid surface, however, this critical size would be much larger than 1-2 $\times 10^{-4}$ inch which is the range of values for $(r_o)_{crit}$ required for the data in Figures 11 through 12. A possible explanation for such a value of $(r_o)_{crit}$ may be in an extension of Holtz's hypothesis that liquid metals do not wet cavities during penetration. Perhaps this could be modified to say that cavities below a certain critical radius tend not to be wetted during deactivation but all those above this size are wetted and hence become flooded. In any case, at present, the value of $(r_o)_{crit}$ may be viewed simply as an additional empirical constant.

All of the cavity flooding models discussed above have two essential features in common, namely that surface tension acts to prevent flooding of cavities and acts to resist growth of vapor bubbles. The models simply differ in the manner in which they offer plausible mechanisms by which this comes about i.e., by the hypothesis of non-wetting and then wetting, or by a re-entrant geometry. The key element in all models is that by assuming that surface tension resists flooding, one can arrive at a radius for unflooded cavities which is dependent on the pressure temperature history of the fluid, and hence arrive at a superheat required for incipient nucleation which is also dependent on pressure-temperature history. The fact that the predicted superheats agree rather well with experimental data suggests the basic correctness of this nucleation concept although postulated details of the mechanisms by which cavities remain unflooded during deactivation may still remain open to question.

Whereas, in liquid metals, the degree of superheat required for incipient nucleation is governed principally by the maximum radius of unflooded cavities, in more conventional fluids, such as water, temperature distributions near heated surfaces play a controlling role in the superheat required for nucleation. As noted in an earlier section, one of the most generally accepted concepts for analyzing the role of temperature distribution in controlling superheat is the concept proposed by Hsu and Graham (Ref. 1) which considers that bubbles will grow from a nucleation site if the temperature of the fluid at a distance from the wall equal to the bubble height is greater than the superheat required for bubble equilibrium against surface tension force (the superheat given by Eq. (9)). This concept was employed by Hsu (Ref. 25) in conjunction with an analysis of transient temperature profiles in order to predict the size range of active nucleation cavities on a heating surface. Bergles and Rohsenow (Ref. 26) have extended Hsu's and Graham's model to develop a graphical technique for predicting the inception of boiling in water. From their graphical calculations they obtained the following design equation for predicting the relationship between wall superheat $T_w - T_s$ and heat flux q at the point of incipient boiling

$$q = 15.60 \quad P^{1.156} \, (T_w - T_s)^{2.30/P^{0.0234}} \qquad (24)$$

More recently, Davis and Anderson (Ref. 27) have extended and modified these and other existing analyses of incipient boiling superheats to develop purely analytical expressions for the inception of nucleate boiling in forced convection flow. The Davis and Anderson mathematical model involves the following assumptions.

1. The bubble nucleus, which develops at a surface cavity, has the shape of a truncated sphere.

2. Equilibrium theory can be used to predict the superheat required to satisfy a force balance on the bubble.

3. A bubble nucleus will grow if the temperature of the fluid at a distance from the wall equal to the bubble height is greater than the superheat required for bubble equilibrium.

4. The bubble nucleus does not alter the temperature profile in the fluid surrounding it.

The temperature profile in the thermal layer along the wall in which the vapor bubbles begin to grow from nucleation size is assumed to be linear i.e.

$$T(y) = T_w - qy/K_L \tag{25}$$

This assumption is quite valid because the bubble nuclei are all sufficiently small that they lie within the laminar sublayer where heat transport occurs by conduction through the liquid.

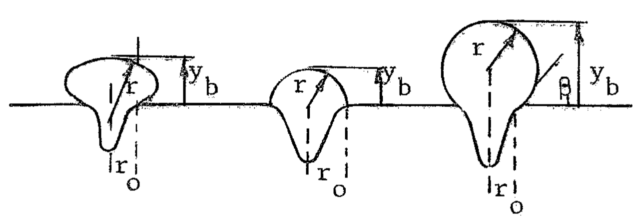
By combining the Clausius-Clapeyron equation (Eq. (4)), the ideal gas law $\rho_v = P/RT$ and the Gibbs equation for the over-pressure required to maintain a bubble against surface tension force (Eq. 1). Davis and Anderson obtained the following equation for the superheat required to satisfy the force balance on the bubble (see assumption 2)

$$T_B - T_s = \frac{RT_B T_s}{\lambda} \ln \left(1 + \frac{2\sigma}{rP_s}\right) \tag{26}$$

The bubble radius r is related to the height y_b of the bubble above the heated surface by the expression

$$y_b = r\,(1 + \cos\beta) = C_1 r \tag{27}$$

where β is the contact angle indicated in the sketch below



I. $y_b < r$ II. $y_b = r = r_o$ III. $y_b > r$

Fig. 13 Possible Bubble Models

Applying assumption 3, we find that the minimum superheat required to initiate bubble growth will occur when the curve for T_b as a function of y_b given by Eqs. (26) and (27) is tangent to the line for T(y) given by Eq. (25). This condition is illustrated in Fig. 14, reproduced from Reference 12. By analytically determining the condition of tangency, Davis and Anderson obtain the following expressions for the wall superheat required for incipient nucleation

$$y' = \frac{C_1 \sigma}{P} + \sqrt{\left(\frac{C_1 \sigma}{P}\right)^2 + \frac{2 C_1 K_L \sigma T_s}{\lambda \rho_v q_i}} \tag{28}$$

$$T_w - T_s = \frac{\frac{RT_s^2}{\lambda} \ln\left(1 + \frac{2\sigma C_1}{P_s y'}\right)}{1 - \frac{RT_s}{\lambda} \ln\left(1 + \frac{2\sigma C_1}{P_s y'}\right)} + \frac{q_i y'}{K_L} \tag{29}$$

For systems at moderate to higher pressures ($P \geq 25$ psia) or for low surface tension, the following simplified relation between q_i and $T_w - T_s$ is obtained.

$$q_i = \frac{K_L \lambda \rho_v}{8 C_1 \sigma T_s} (T_w - T_s)^2 \tag{30}$$

It is interesting to compare the values of wall superheat for incipient boiling predicted by Eq. (30) above with the values predicted by, say, Chen's model for liquid metal incipient boiling superheats (Eq. 18). An important point to be stressed here is that, in theory, it is necessary that both criteria be satisfied for inception of boiling to occur. The fact that we say that Eq. (30) pertains to water while Eq. (18) pertains to liquid metal merely reflects the fact that the temperature distribution criterion is usually the more stringent one for water and is, hence, the controlling criterion for this fluid while for liquid metals, due to high conductivity, the cavity suppression criterion is the more stringent one.

In Figure 15 are shown curves of wall superheat at incipient boiling as predicted by Davis and Anderson's analysis and also values predicted by Chen's criterion with $P_{go} r_o^3/r_m^3 = 13$ and with $P_{go} = 0$ (no account taken of effect of inert gas). In applying Chen's criterion, it is considered that the water is exposed to a pressure of 2.6 atmospheres at room temperature (75°F) as a deactivation condition prior to boiling. It is not known whether this is the deactivation condition actually experienced in the experiments, but it is a reasonable condition to presume might occur. The inert gas value of $P_{go} r_o^3 . r_n^3 = 13$ corresponds, for example, to there being gas at 0.2 psia in conical cavities after fill and degassing, and that the gas is subsequently compressed to a radius r_c which is 1/4 of the conical entrance radius r_o.

Also shown in Figure 15 are experimental values of the superheat at incipient boiling as determined by Bergles and Rohsenow. As can be seen, these values agree very well with values predicted by the Davis and Anderson model (The experimental values also agree well with Eq. (24) obtained by Bergles and Rohsenow). One can note that the simplified equation of Davis and Anderson (Eq. (30)) gives very nearly the same prediction as the more exact combination of Eq. (28) with Eq. (29).

The values of superheat predicted by Chen's model are independent of heat flux but are very dependent upon the amount of non-condensible gas assumed to be trapped in cavities. It is significant to note that with no gas trapped ($P_{go} = 0$) the predicted superheat is 44°F which is substantially above that measured at lower heat fluxes. On the other hand, consideration of there being a reasonable amount of non-condensible gas trapped reduces the predicted superheat to a very low level. Since it is difficult to know, in fact, exactly how much gas is trapped in a cavity, it is difficult to conclude from purely analytical considerations whether Chen's model is a controlling criterion for water or not. One must rely on experimental evidence, such as that shown in Figure 15, which indicates that for water it is not. From such data we infer, then, that there usually is enough non-condensible gas trapped in cavities of water systems that the controlling criterion for superheat is that based on consideration of wall temperature profile.

In all of the analytical models discussed in this section, it is tacitly assumed that the heating surfaces contain cavities in the size range required by the models. For commercial tubing, with "as received" surfaces, this is usually the case. However, if the heating surface is highly polished or finely plated or is a glass or ceramic material, the controlling factor for incipient boiling superheat may simply be the maximum size cavity existing in the heating surface. We have already seen in the previous section how changing the surface characteristics of tubing can alter the superheat required for nucleation (Fig. 5).

RECOMMENDED FORMULAE FOR USE IN PREDICTING INCIPIENT BOILING SUPERHEAT

Although many aspects of the problem of determining the superheat required for incipient boiling remain imperfectly understood or are beyond the reach of presently existing predictive capabilities, nonetheless, recommendations can be made as to the most generally usable and reliable criteria for predicting superheat that are presently available.

On the basis of the analytical and empirical information reviewed in the preceding two sections, it is concluded that incipient boiling superheat in "conventional" fluids, such as water, is controlled principally by the temperature gradients at the heated surface rather than by the flooding of cavitation sites. On the contrary, for liquid metals, incipient boiling superheat seems to be largely controlled by the flooding or non-flooding of available nucleation cavities during boiling "pre-history" (deactivation). Of criteria reviewed for predicting incipient boiling in conventional fluids, the authors prefer the thermal model developed by Davis and Anderson either in its more exact form as given by Eqs. (28) and (29) or in its more approximate form as given by Eq. (30) (valid for $P \geq 25$ psia).

For liquid metals, it is more difficult to recommend one particular criterion since existing experimental data is still too limited to establish any one of the criteria reviewed as being superior over the others. However, for reasons to be discussed below, the authors prefer either the Chen model or the re-entrant model for predicting incipient boiling superheat in liquid metals.

It is important to keep in mind that although different criteria are recommended, depending upon the class of fluids considered, the criteria are not mutually exclusive. That is, both criteria should be satisfied in order for boiling inception to occur, the criterion predicting the larger superheat for inception of boiling being the controlling one. In the case of liquid metals, a cavity flooding criterion inevitably turns out to be controlling rather than a thermal criterion although it is well to check the thermal (e.g. Davis-Anderson) criterion as well. In the case of normal fluids such as water, the situation is less clear, since the question of whether say, Chen's flooding model is controlling depends strongly upon the value selected for the non-condensible gas volume G_o (more will be said about this below). However, experimental evidence, such as that shown in Fig. 15, indicate that the thermal boundary layer considerations do control superheat in the case of such fluids. Hence, at present, it is simply recommended that the Davis-Anderson model be used for water and fluids of comparable heat transfer capability.

The Chen and Dwyer models for predicting incipient boiling superheat in liquid metals represent, essentially, successive refinements of an original model proposed by Holtz. Of these three, the authors prefer the Chen model for the following reasons: (1) The presence of non-condensible gas does definitely seem to be significant in reducing superheat, and Chen's model does permit taking account of this while Holtz's model did not include this effect. (2) Dwyer's refinements of the Holtz-Chen model, which take account of the decrease in non-condensible gas with time and also consider that the nucleation radius can be different from the minimum, are plausible and do permit one to achieve closer agreement between theory and experiment. However, these refinements introduce essentially two extra empirical factors to be determined, which makes the Dwyer model somewhat more unwieldy to employ than Chen's model.

The Chen model takes account of the effect of non-condensible gas through the assigning of a "reasonable" value for G_o in Eq. (18), G_o representing, essentially, the volume of non-condensible gas trapped in a typical cavity after the system is filled with liquid metal. It is, of course, impossible to predict analytically values for G_o and this quantity is best regarded therefore as an empirical constant. On the basis of the experiments conducted by Chen, reasonable values for G_o for liquid metals appears to be somewhere between 10^{-18} to 10^{-17} ft-lb/^oR. If one wishes to calculate a conservative upper limit for superheat, one can set $G_o = 0$. For water or normal fluids, proper values for G_o have not yet been experimentally established, however, this is not critical since the Chen criterion is not controlling for such systems (we may infer from this that G_o is reasonably large).

The re-entrant cavity model differs from the Holtz-Chen-Dwyer models in that it does not require that liquid metals not wet the heater tube during deactivation in order to maintain unflooded cavities. Hence, the re-entrant cavity model removes this conceptual difficulty associated with the Holtz-Chen-Dwyer model which many people may find unacceptable. The re-entrant cavity model does not take as full account of the effect of non-condensible gas as does the Chen or Dwyer models, but by considering that the nucleation radius for the re-entrant cavity may be larger than the minimum deactivation radius by some empirical factor α, as good if not better agreement with experimental data can be had with the re-entrant model as with Chen's model (see Fig. 12). In this regard, one should note that the non-condensible gas effect in Chen's model also requires determination of an empirical factor.

In short, then, either the Chen or re-entrant cavity models do a reasonable job of predicting the level of superheat required for inception of boiling in liquid metals. The choice of which to use rests with the reader. For that matter either the original Holtz model or the Dwyer model may appeal more to the reader and should not be discounted. Further experimental work will be required to demonstrate whether any of these models have any significant advantages over the others.

At present there is no analysis or established empirical correlation which will permit one to take account of the effect of flow rate of incipient boiling superheat for liquid metals although Chen (Ref. 22) has proposed a tentative theory which may be used as a guide for estimating the magnitude of this effect. Also the effect of heat flux on incipient boiling superheat of liquid metals has not been firmly established although the effect, if any, appears to be a minor one.

All the reviewed models for predicting incipient boiling superheat tacitly assume that nucleation cavities are available on the heating surface in the size range required by their respective criteria. Obviously if a surface does not contain such cavities, these criteria are not valid and the superheat will be controlled totally by the heated surface finish, i.e., by the maximum size of cavity present in the surface. There is much experimental evidence which shows that increasing surface roughness reduces incipient boiling superheat to some extent, but there is no means of predicting this effect. One can only note that the criteria presented in this section pertain, essentially to "as received" type finishes of commercial metal tubing and that for tubes with very highly polished surfaces, e.g. glass tubes, these criteria may not apply and that for artifically roughened or prepared surfaces, superheats will probably be lower than those predicted by these criteria.

Representative curves of incipient boiling superheat, as calculated from Chen's criterion are shown in Figs. 16, 17 and 18 for liquid cesium and in Figs. 19, 20, and 21 for liquid potassium. Fig. 16 shows superheat as a function of deactivation subcooling for a boiling pressure of 40 psia and a deactivation pressure of $P' = 50$ psia. Deactivation subcooling is defined as the difference between T_s', the saturation temperature at P', and T', the minimum temperature to which the liquid is subjected at the pressure P'. Curves are shown for different values of G_o, the non-condensible gas parameter. It is interesting to note that for values of G_o large enough, increased deactivation subcooling can decrease rather than increase the superheat.

Fig. 17 shows the effect of deactivation pressure P' on incipient nucleation superheat for cesium at a deactivation subcooling of 100°F. The curve is for $G_o = 3 \times 10^{-17}$ in-lb/°R $= 0.25 \times 10^{-17}$ ft-lb/°R.

Fig. 18 shows the effect of system pressure on incipient nucleation superheat for constant deactivation pressure and temperature (i.e. constant critical radius r_c). As is predicted by Eq. (13), superheat decreases with system pressure.

Figs. 19, 20, and 21 are similar, respectively, to Figs. 16, 17 and 18 except they are for potassium rather than cesium.

Representative curves of incipient boiling superheat for water as calculated from Davis and Anderson's analysis, are shown in Fig. 22. The approximate Eq. (30) is used. Also shown is the semi-empirical correlation of Bergles and Rohsenow (Eq. (24)), which is seen to be in good agreement with the Davis and

Anderson analysis.

For water and other "normal" fluids, superheat is controlled by the temperature profile near the heated surface, and, hence, is dependent upon heat flux. Superheat does not appear to depend upon pre-boiling history i.e. upon deactivation temperature and history. With all fluids, however, superheat does depend upon system pressure, and this effect for water can readily be seen in Fig. 22. One can note, in particular, that the fractional change in superheat due to a given change in pressure is fairly constant and independent of the level of superheat. This observation may be used to extend the usefulness of the superheat curves presented for cesium and potassium. For example, the curves of superheat vs. deactivation subcooling shown in Fig. 16 are for a system pressure of 40 psia and a deactivation pressure of $P' = 50$ psia. From Fig. 18 we see that for fixed T' and P', the superheat decreases by about 20% as system pressure increases from 40 to 50 psia. Therefore, to use the curves in Fig. 18 for a system pressure of 50 psia with the same deactivation pressure of 50 psia, one would simply decrease the levels of the superheat curves in Fig. 18 uniformly by 20%.

In concluding this section, it should be stressed that because of the complex and statistical nature of incipient nucleation, the various criteria for predicting incipient boiling superheat recommended in this section can be expected to predict superheats accurately only <u>on the average</u>. Any particular single measurement of incipient boiling superheat may depart significantly from the predicted value, even in experiments where all pertinent variables are carefully controlled. To appreciate this one need only examine the scatter of data in, say, Chen's experiments (Figs. 11 and 12) which were designed specifically to obtain carefully controlled data on incipient boiling superheat. Although much improvement can be made in present capability of predicting superheats, it appears unlikely that it will ever be possible to predict this phenomenon consistently to any greater degree of precision than is represented by the above mentioned scatter in experimental measurements.

APPENDIX

PHOTOMICROGRAPH STUDY OF SURFACE CAVITIES

The major objective of this photomicrograph sutdy of surface cavities was to obtain information regarding size, shape and density of surface cavities which may become nucleation sites for liquid metal boiling. Stainless Steel SS347 tubing of commercial grade was used for this study. Both the extruded seamless tubing and the welded tubing were investigated for the purpose of determining any apparent influence of fabrication method on forming cavities.

Specimens for this study were prepared by the procedure enumerated below:

i) The outer surface of the tubing was chrome-plated.

ii) The tubing was cut transversely with a water-cooled wheel.

iii) The specimen was mounted in lucite.

iv) The specimen was polished by using metallographic techniques, i.e., first rough grind with 240, 400, 600 grits paper (water lubricated), then fine polsih with 3 micron, 1 micron and finally 0.05 micron Gamma micropolish (aluminum oxide).

v) The specimen was scanned under a microsope at the O.D. for various cavities.

Ten specimens were prepared from the welded tubing and an equal number of specimens were prepared from the seamless. Typical prints of photomicrographs taken at 750 X magnification are reproduced in Figures 23 and 24. Discernible pits are classified into five types diagrammatically shown in Table II. Clearly, Type II is the re-entrant type cavity. Discernible pits are those with an overall dimension in excess of 0.2 mil. They are, however, all less than 0.6 mil. A summary of the total number of discernible pits found is contained in Tables II and III for welded and seamless tubings respectively. All five type pits are present in both the welded tubing specimens and the seamless tubing specimens. The welded tubing specimens appear to have about twice the cavity population of the seamless tubing specimens.

NOMENCLATURE

C_1	$= 1 + \cos\theta$ (See Fig. 13)
G_o	$= P_{go}\, r_o^3/T_o$, Measure of non-condensible gas trapped in cavity (Eq. 18), ft-lb/^oR
K_L	Thermal conductivity of liquid, Btu/ft-^oF-sec.
P	Local liquid pressure, lb/ft^2
P_b	Pressure inside bubble, lb/ft^2
P_g	Partial pressure non-condensible gas, lb/ft^2
P_s	System saturation pressure, lb/ft^2
P_v	Vapor pressure, lb/ft^2
P_{inc}	Saturation vapor pressure corresponding to T_{inc}
P_{go}	Partial pressure of non-condensible gas at fill, lb/ft^2
ΔP_{inc}	$= P_b - P$, excess of bubble pressure over local liquid pressure required for inception of boiling, lb/ft^2
q	Heat flux, Btu/ft^2-sec.
q_i	Heat flux required for inception of boiling, Btu/ft^2-sec.
R	Gas constant, ft/^oF
r	Bubble radius, ft.
r'	Bubble radius at condition of maximum deactivation, ft.
r_c	Bubble radius at point of inception of boiling, ft.
r_m	Minimum radius of cavity, ft.
r_o	Radius at mouth of cavity, ft.
$(r_o)_{crit}$	Maximum cavity size which can remain unflooded, ft.
T	System temperature, ^oR
$T(y)$	Temperature distribution near heated surface, ^oR
T_{inc}	Local temperature required for inception of boiling, ^oR

NOMENCLATURE (continued)

T_o	Temperature of non-condensible gas at fill, °R
T_s	Saturation temperature corresponding to P
T_w	Wall temperature, °R
ΔT_{inc}	Superheat required for inception of boiling, °R
V_v	Specific volume of vapor at T_{inc}, ft^3/lb.
V_L	Specific volume of liquid at time, ft^3/lb.
y	Coordinate measuring distance from heated surface, ft.
y_b	Height of bubble tip from heated surface, ft.
α	$= r_c/r'$, ratio of boiling inception radius to deactivation radius
β	Wetting angle, radians
γ	Angle in re-entrant cavity (See Fig. 10), radians
λ	Latent heat of vaporization, Btu/lb or ft-lb/lb.
ρ_v	Density of vapor, lb/ft^3
σ	Surface tension, lb/ft.
φ	$= 90° - (\beta-\gamma)$ (See Fig. 10), radians

Superscripts

(')	Refers to quantities evaluated at condition of maximum deactivation

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FIGURES

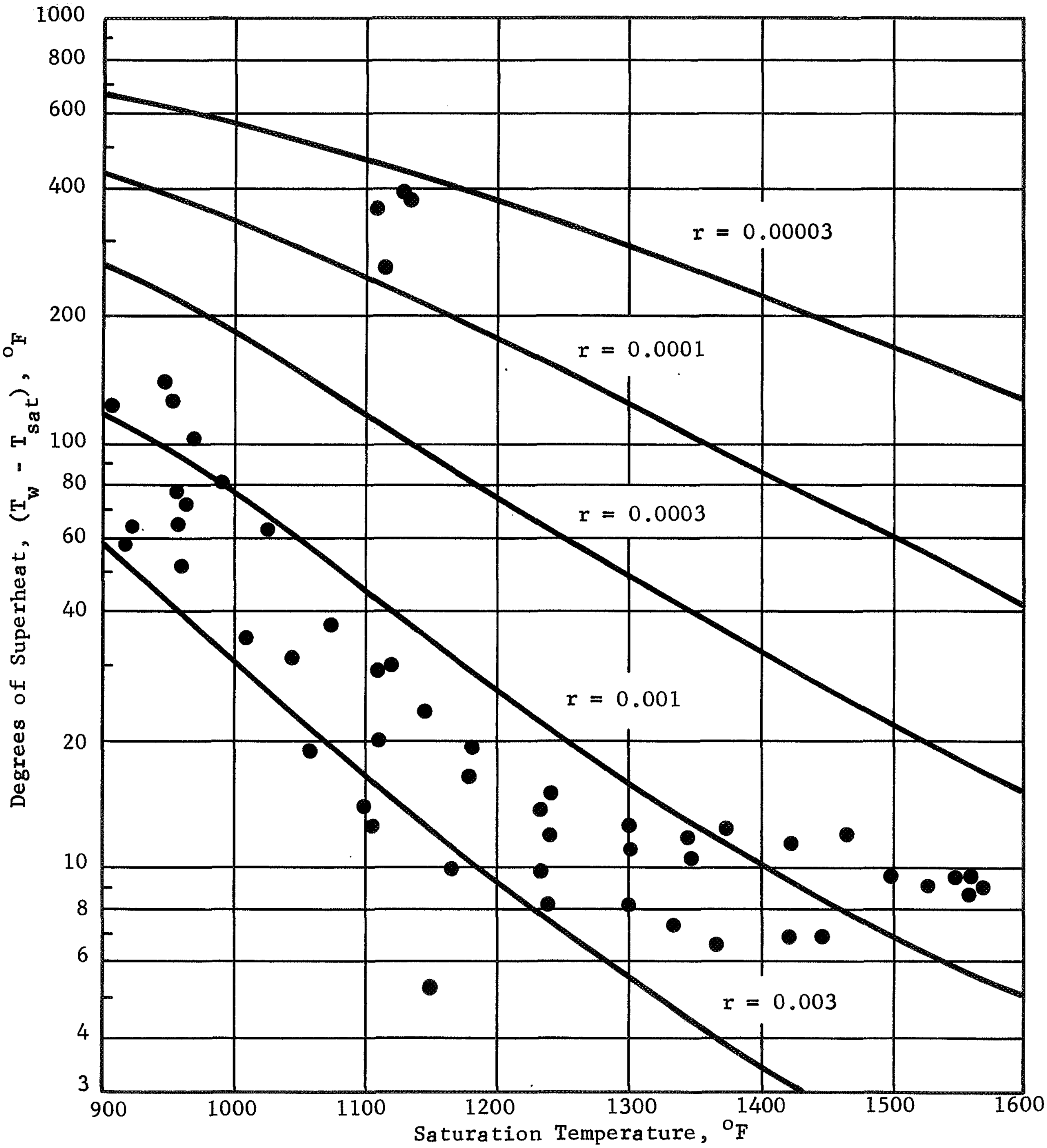


Fig. 1 Incipient Boiling of K on Surface with Artificial Drill Holes of 0.006" diam. (from Ref. 2)

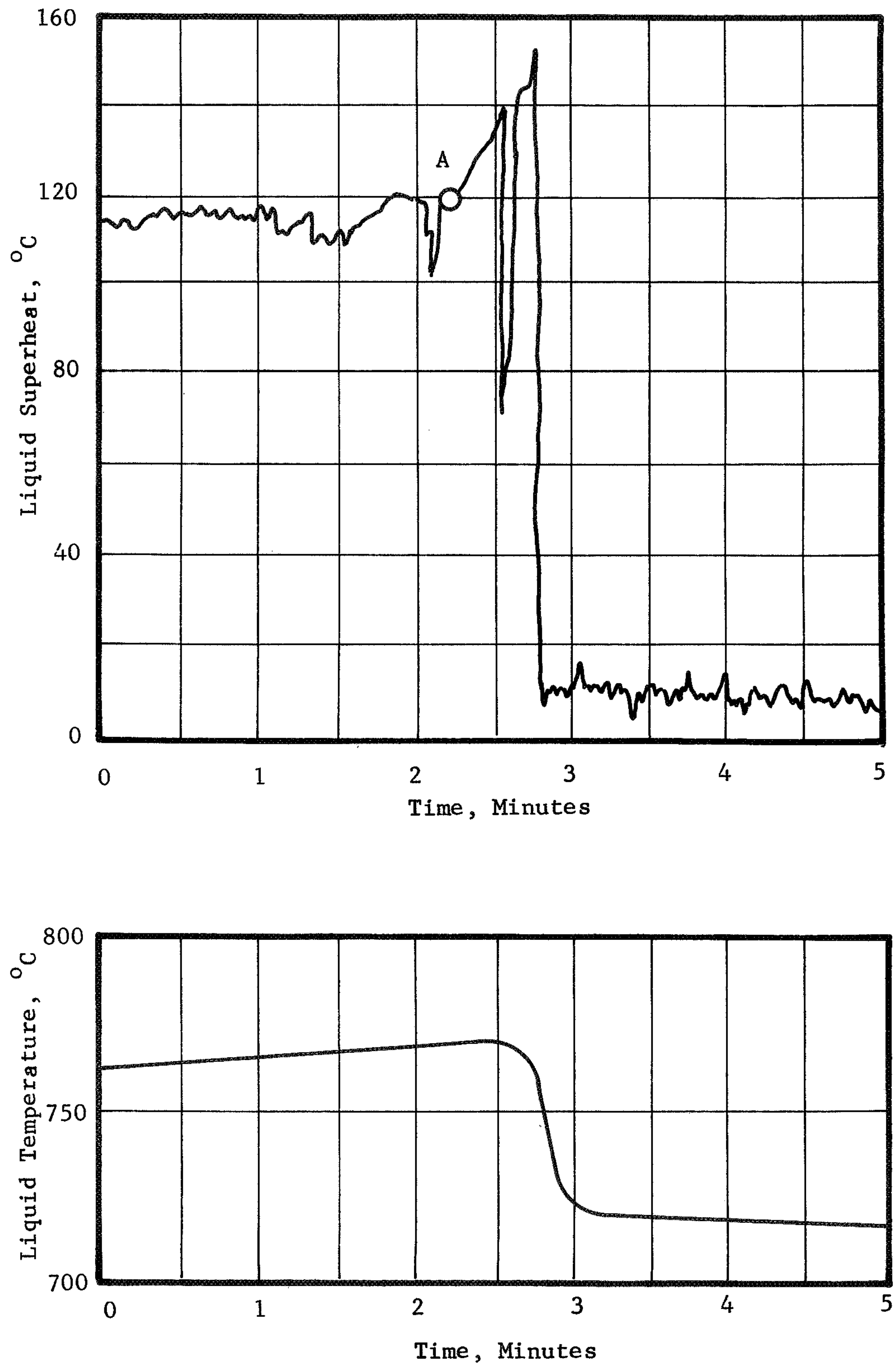


Fig. 2 Temperature Change in Na Pool upon Boiling Initiation. From Ref. 13.

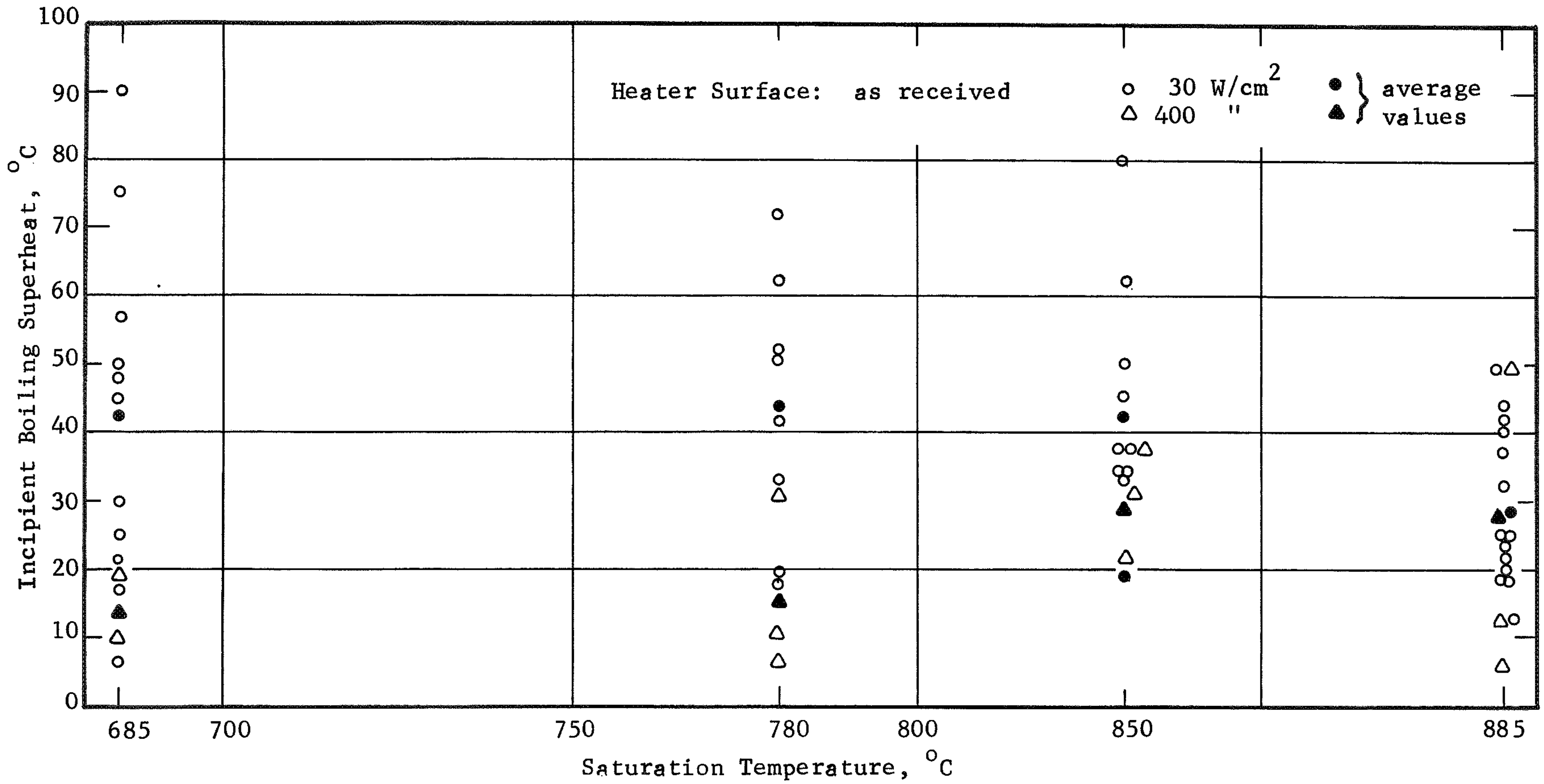


Fig. 3 Incipient Boiling of Na in Capsules. Rod Heaters of As-received Surface Finish. (from Ref. 18)

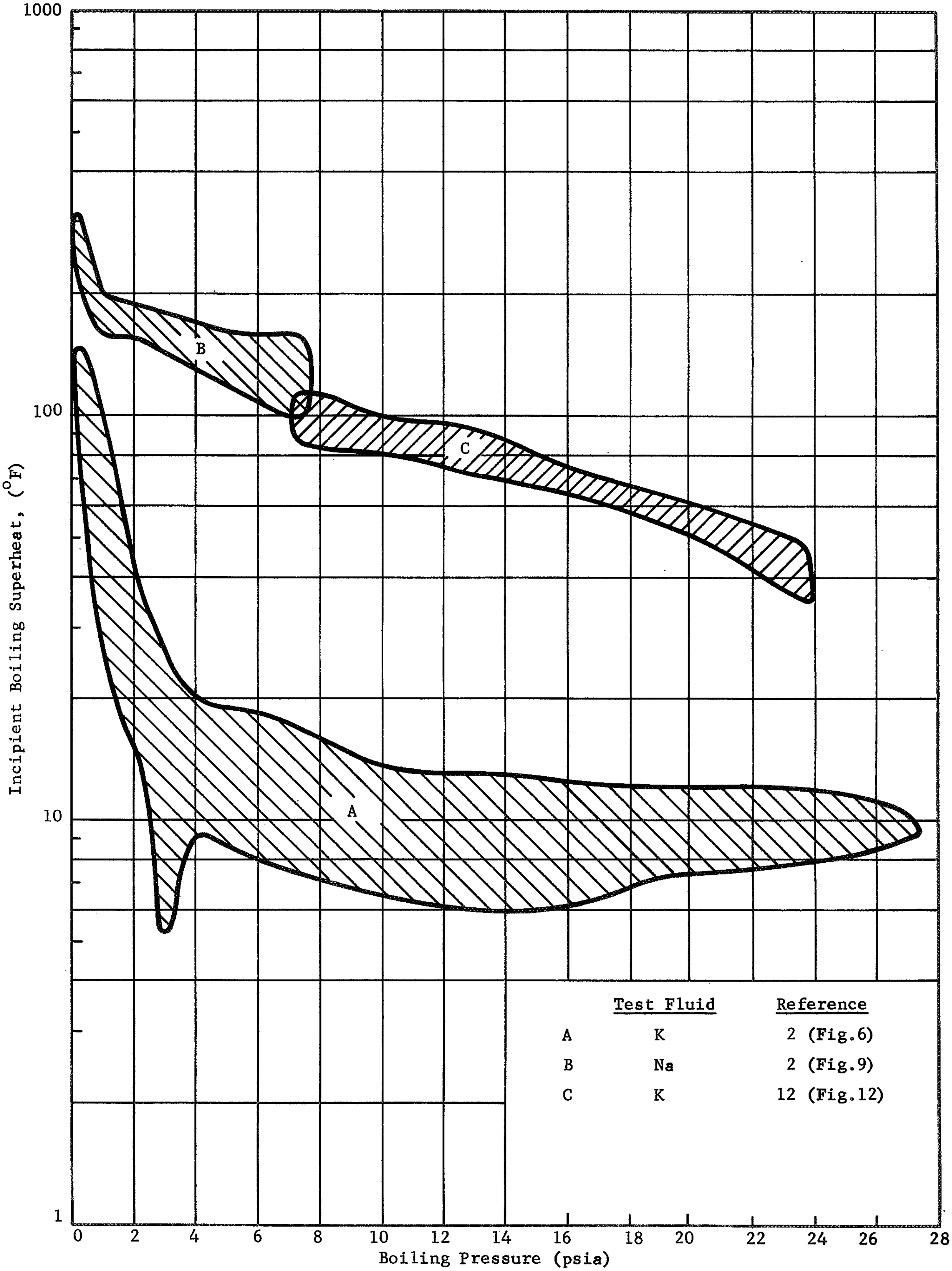


Fig. 4 Experimental Data on Effect of Boiling Pressure on Superheat

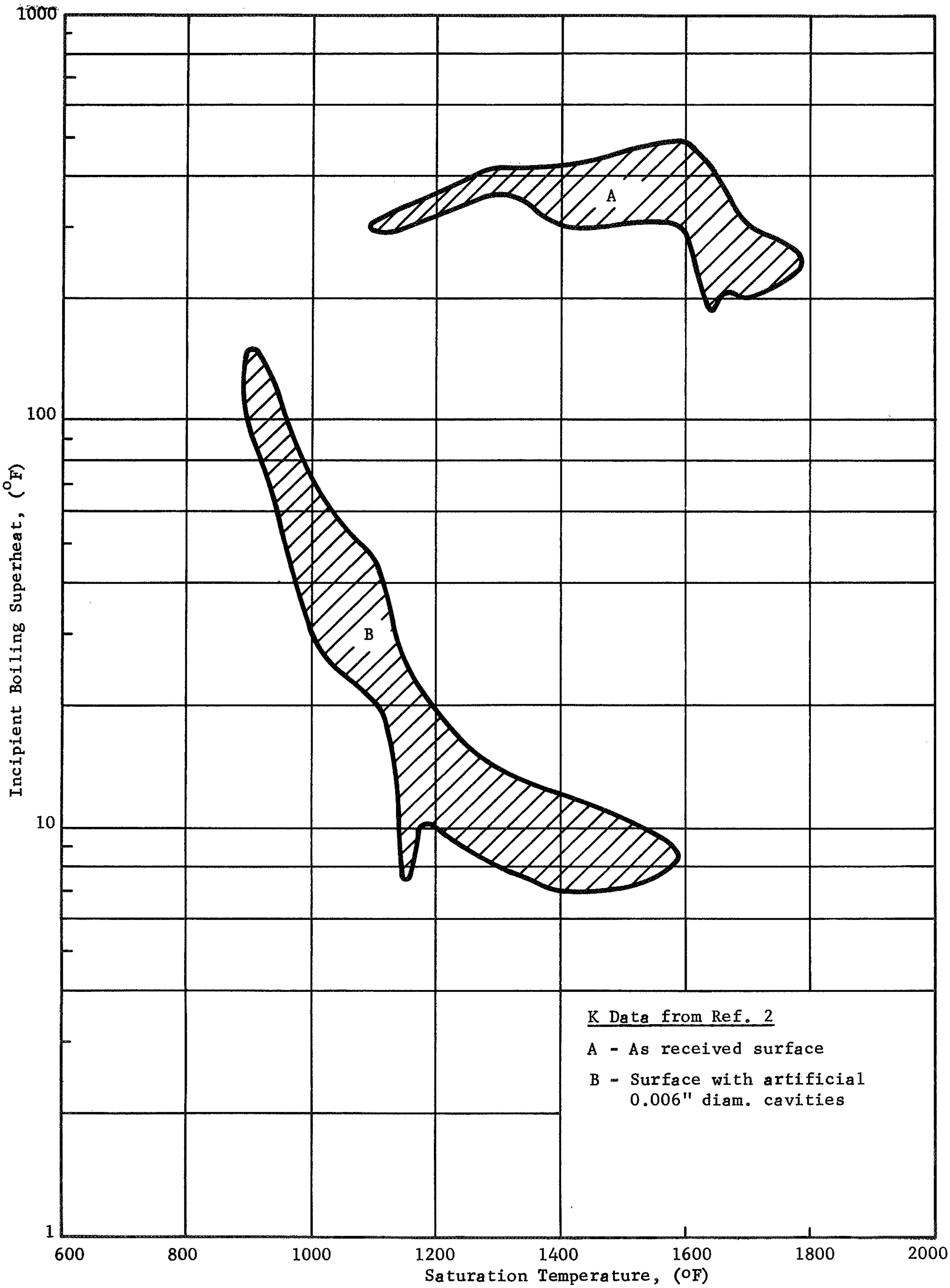


Fig. 5 Effect of Surface Roughness on Superheat

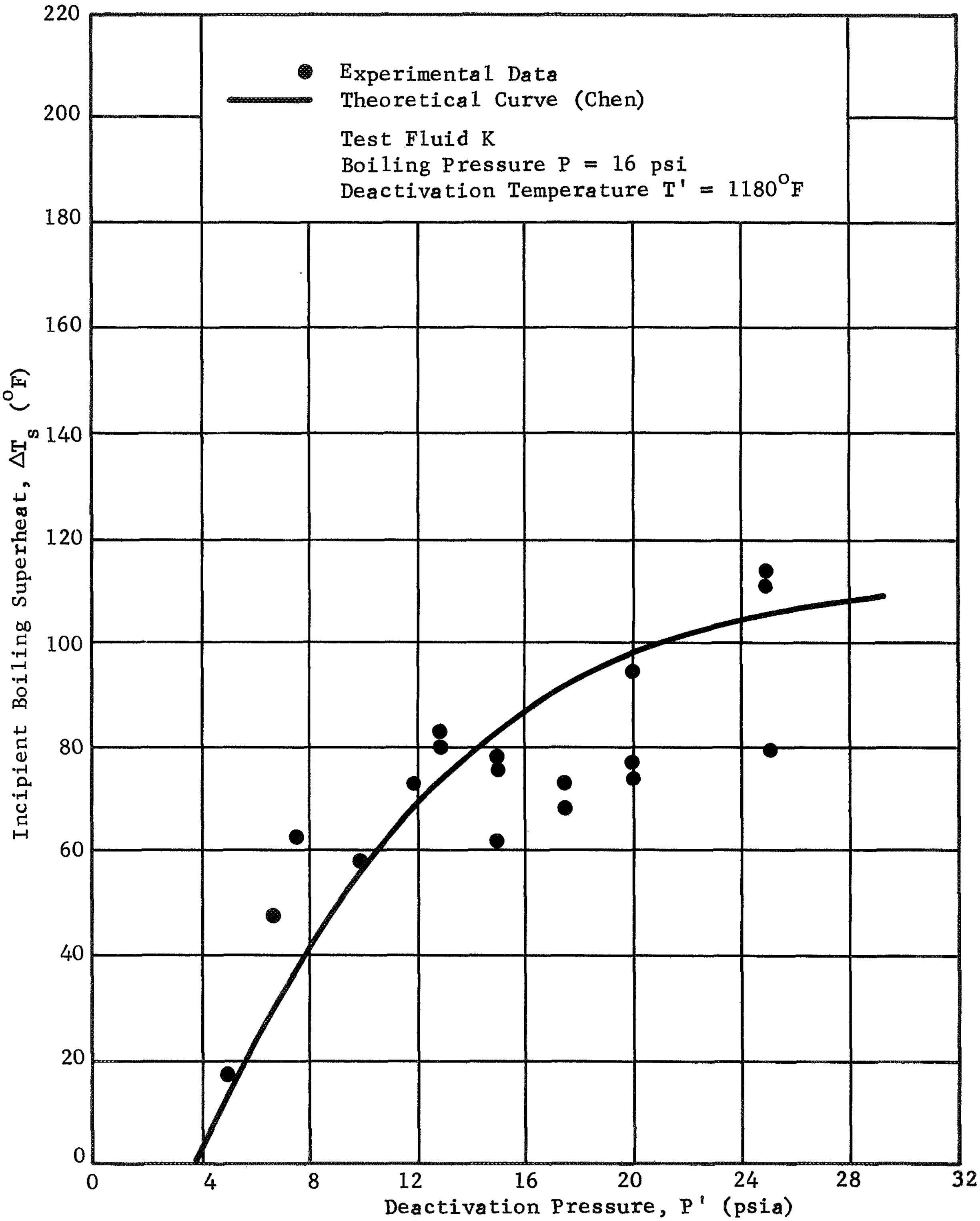


Fig. 6 Effect of Deactivation Condition on Superheat, ΔT_{inc}

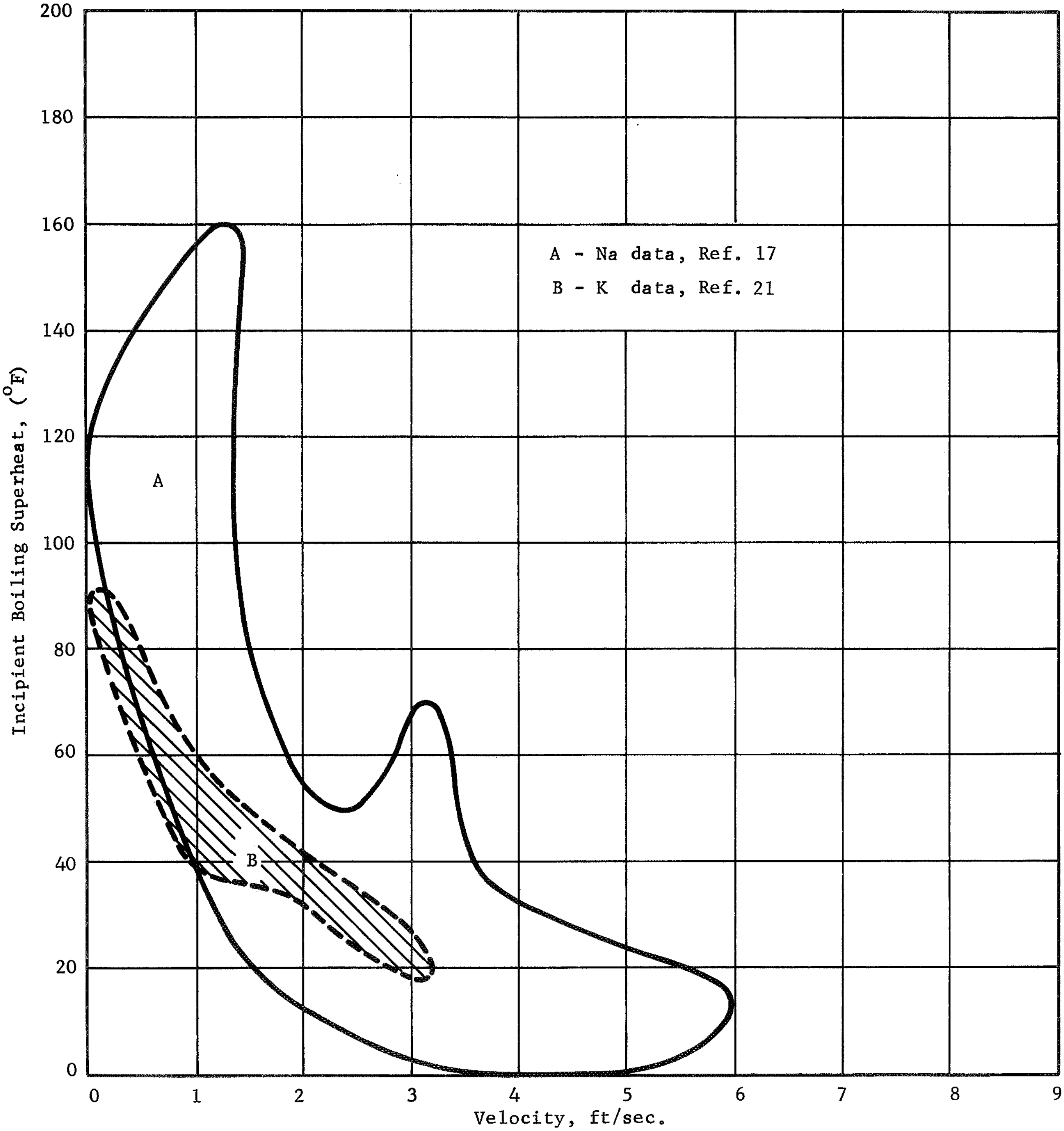


Fig. 7 Effect of Flow Rate on Superheat, ΔT_{inc}

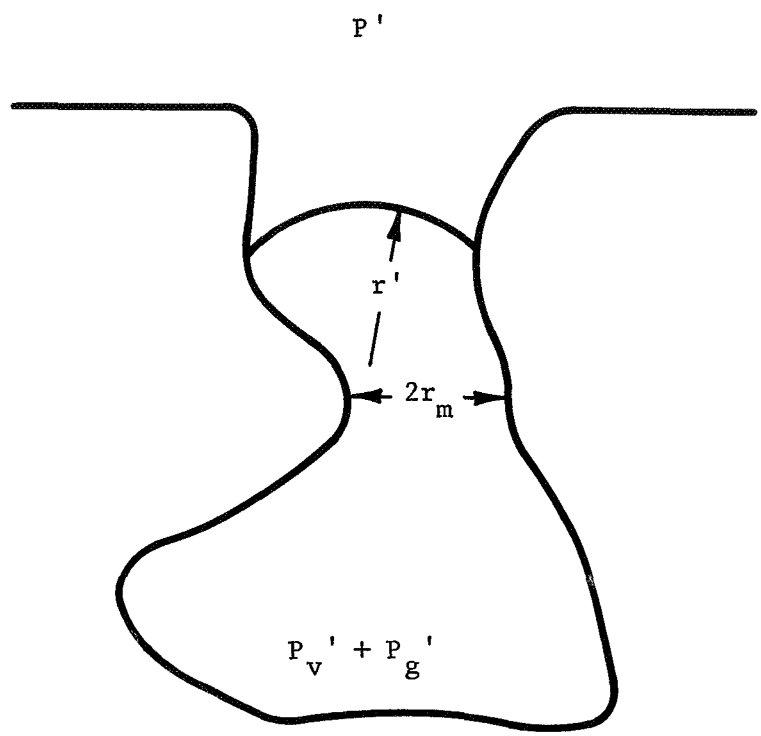


Fig. 8 Wetting Liquid Entering a Surface Cavity

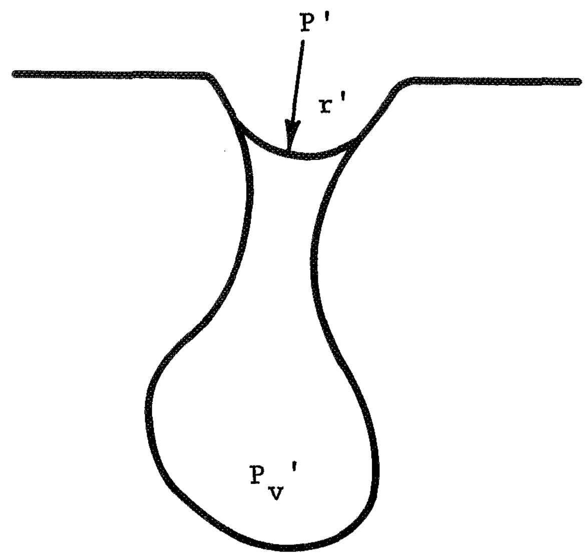


Fig. 9a   Non-wetting Liquid Entering a Surface Cavity

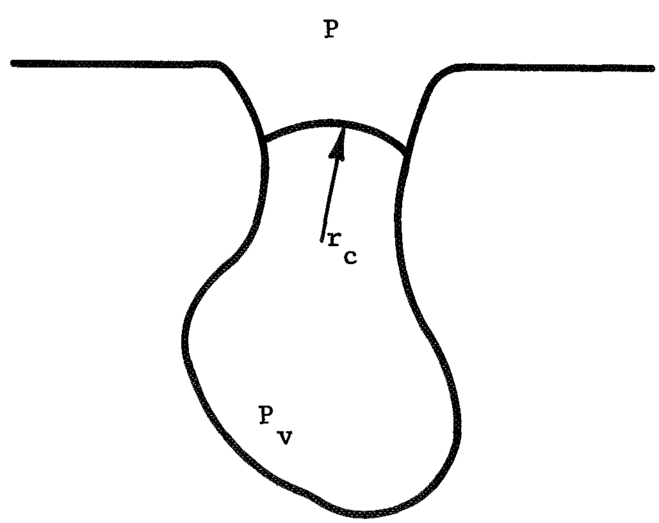


Fig. 9b   Liquid Wetting Surface Cavity when $P_v \geq P$

Figure 10 may be seen on page 21

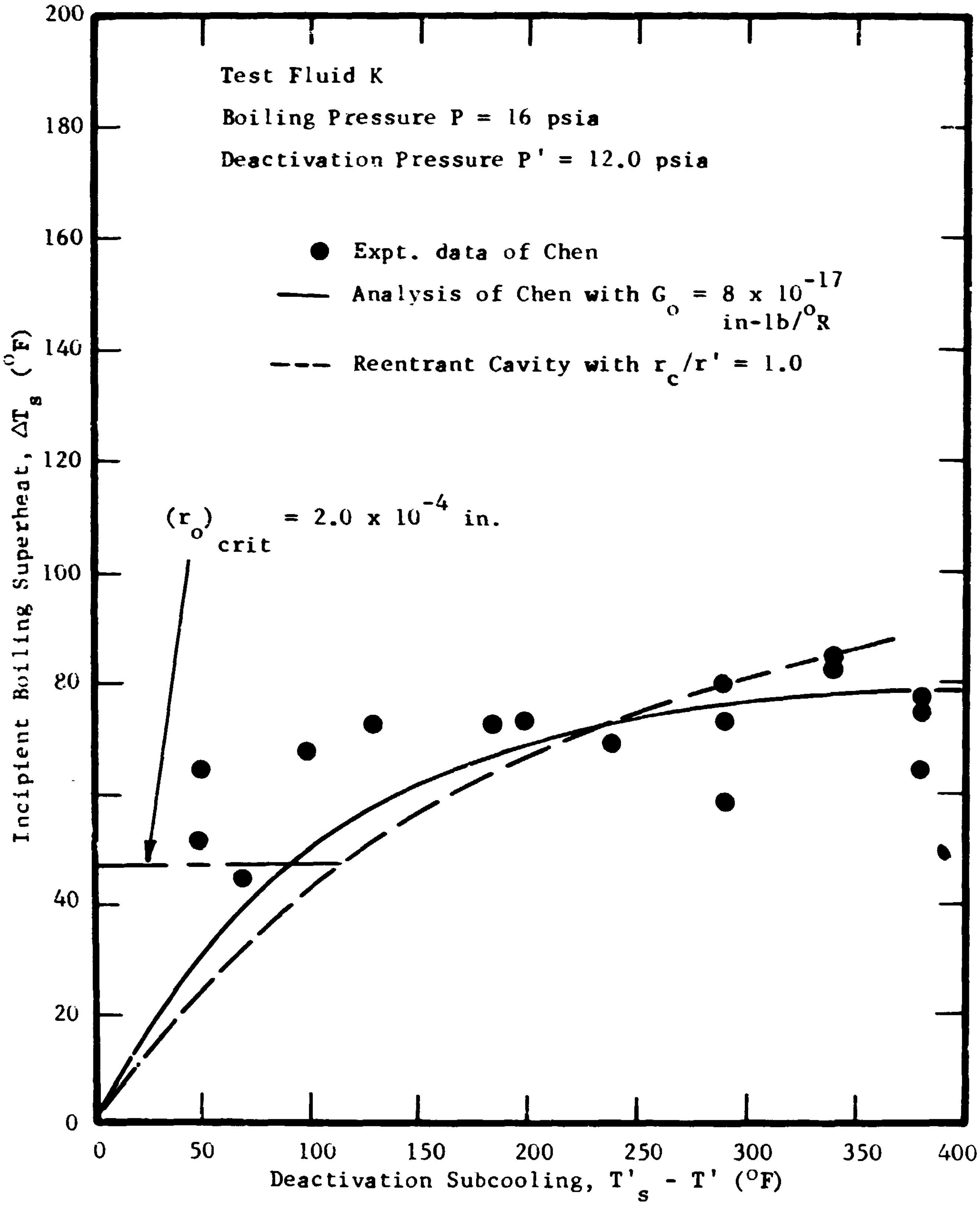


Fig. 11 Incipient-Boiling Superheats after Deactivations at 12 psia

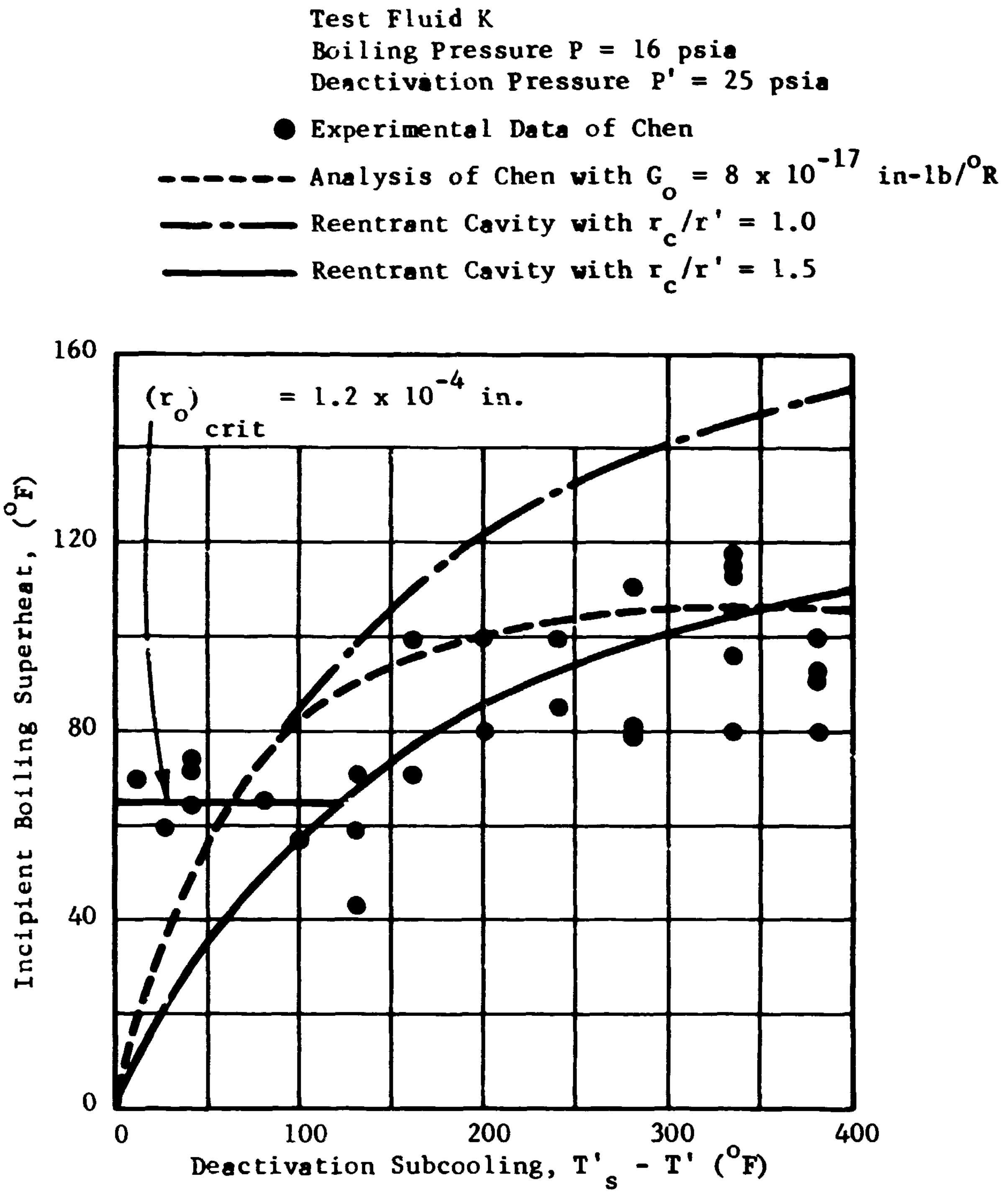


Fig. 12 Incipient-boiling Superheats After Deactivations at 25 psia

Figure 13 may be seen on page 27

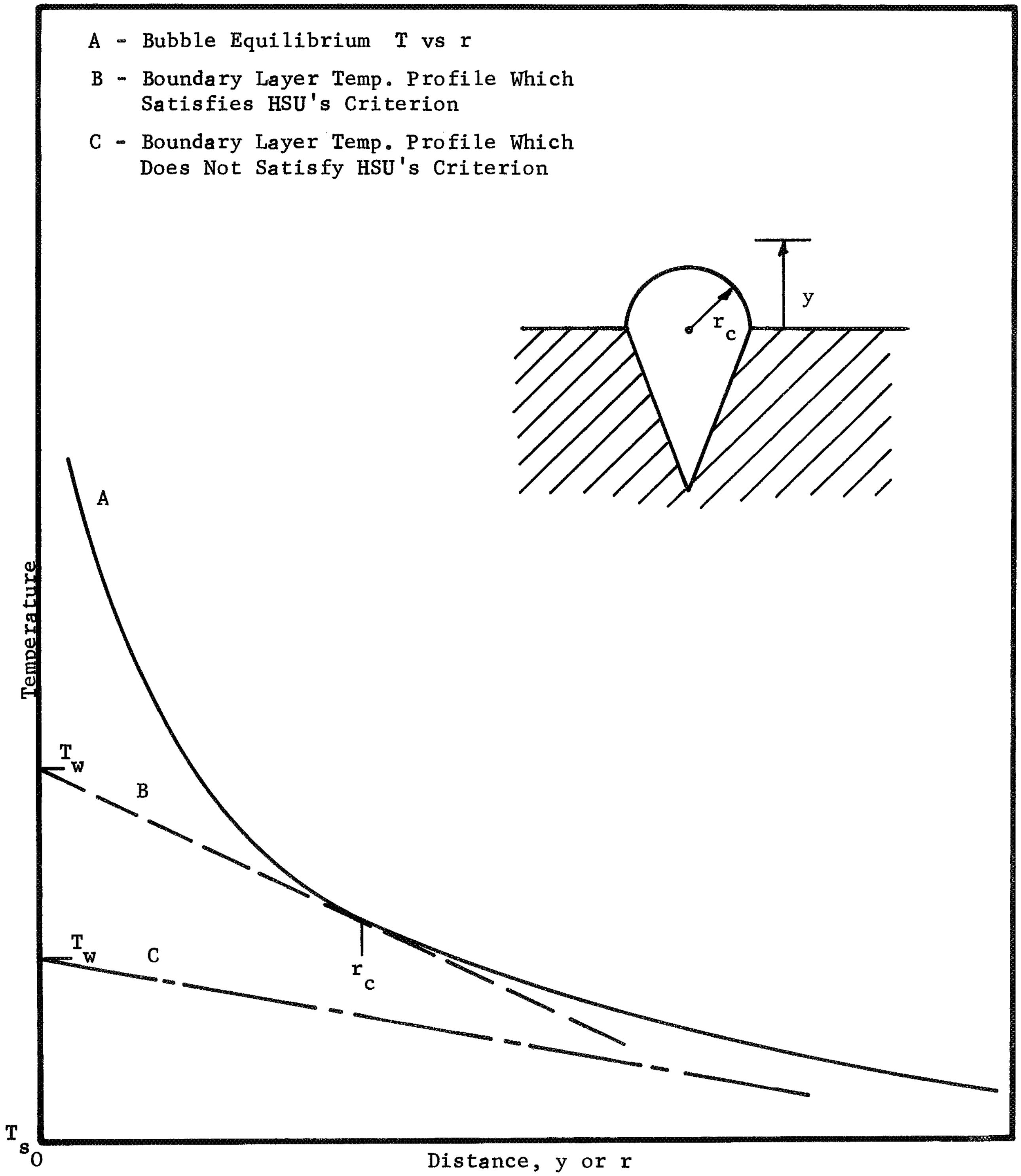


Fig. 14 Criterion for Bubble Nucleation in Ordinary Fluids (from Ref. 12)

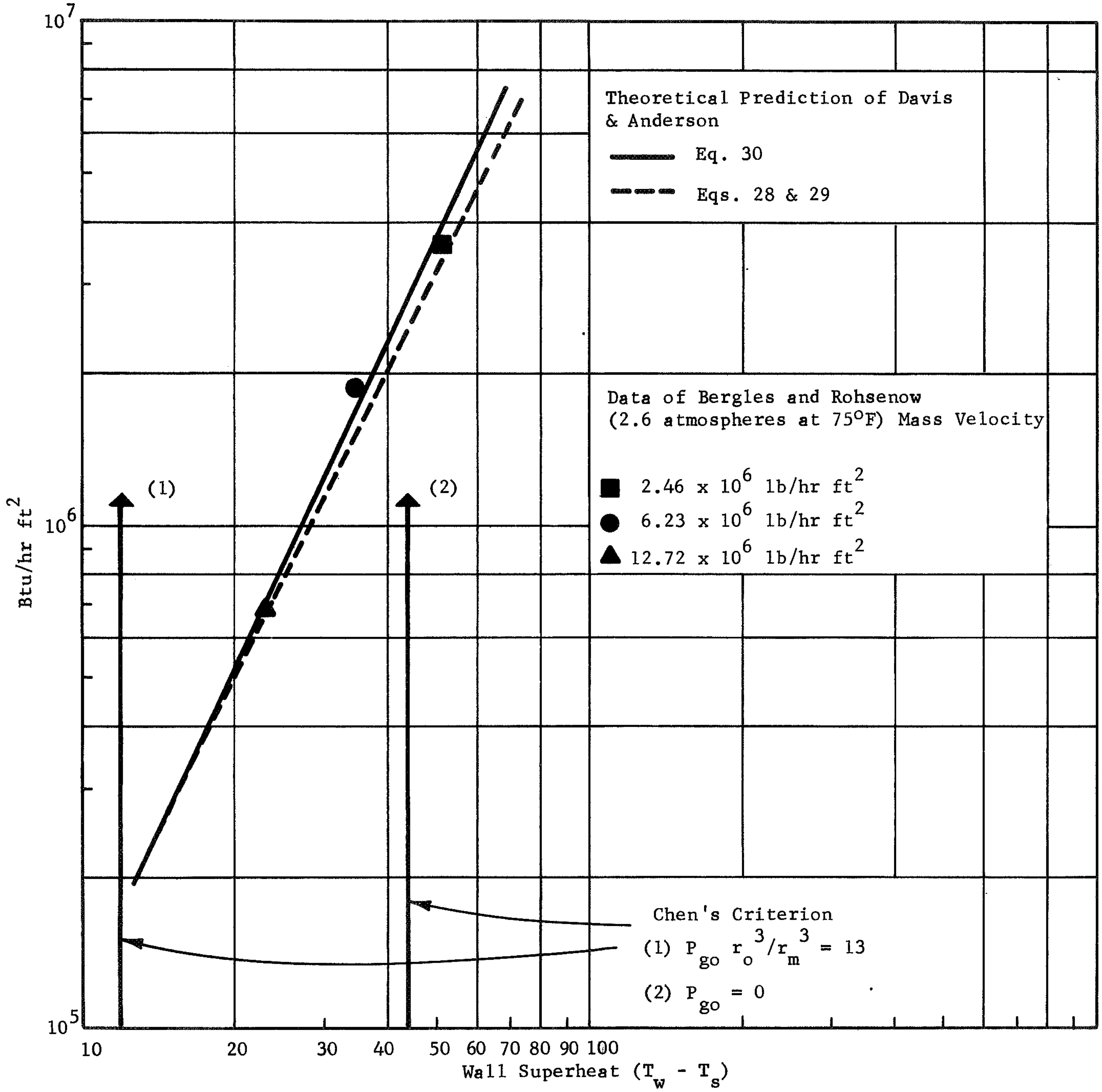


Fig. 15 Superheat Required for Incipient Nucleation in Water; Comparison of Data of Bergles and Rohsenow with Criteria of Davis and Anderson and of Chen

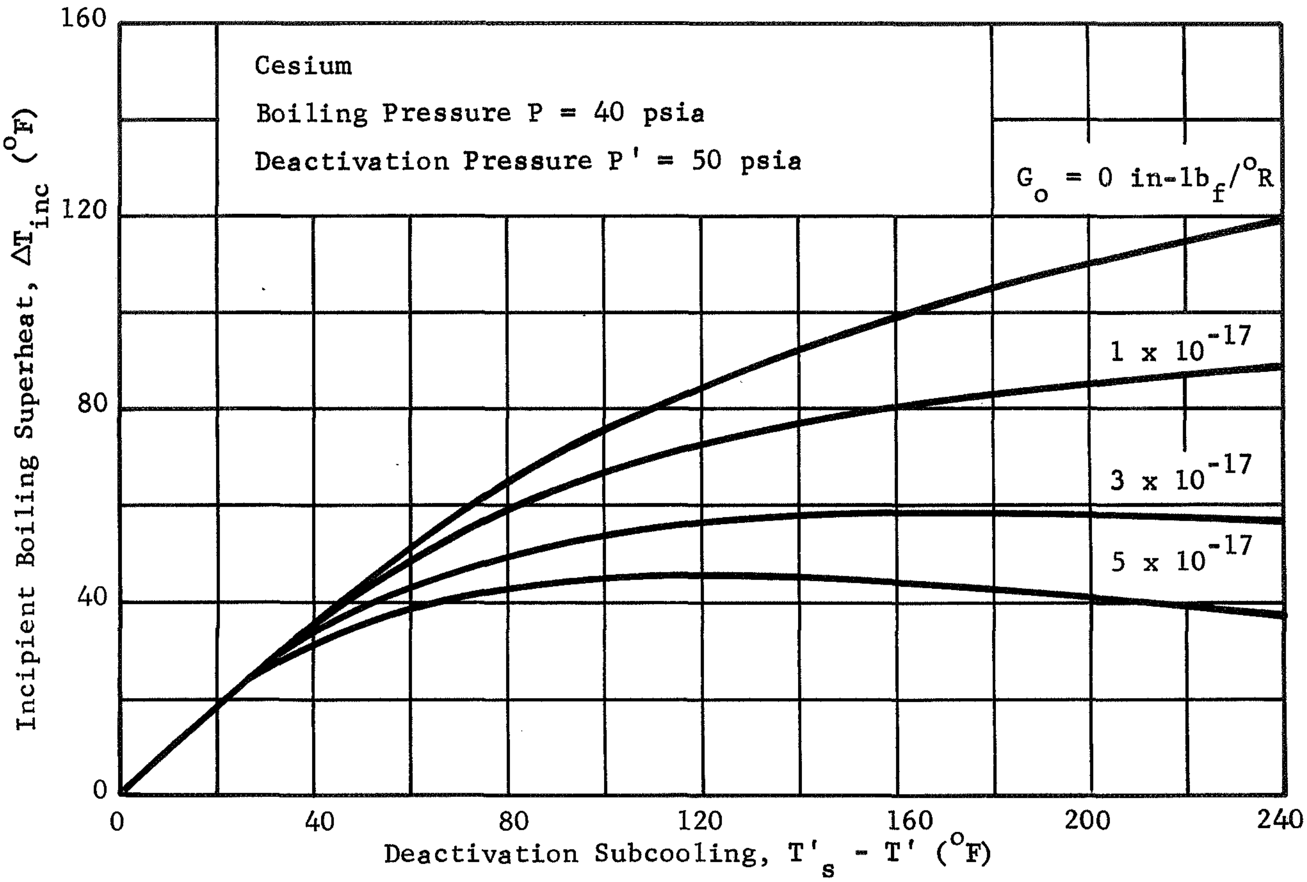


Fig. 16 Incipient Superheat vs Deactivation Subcooling for Cesium

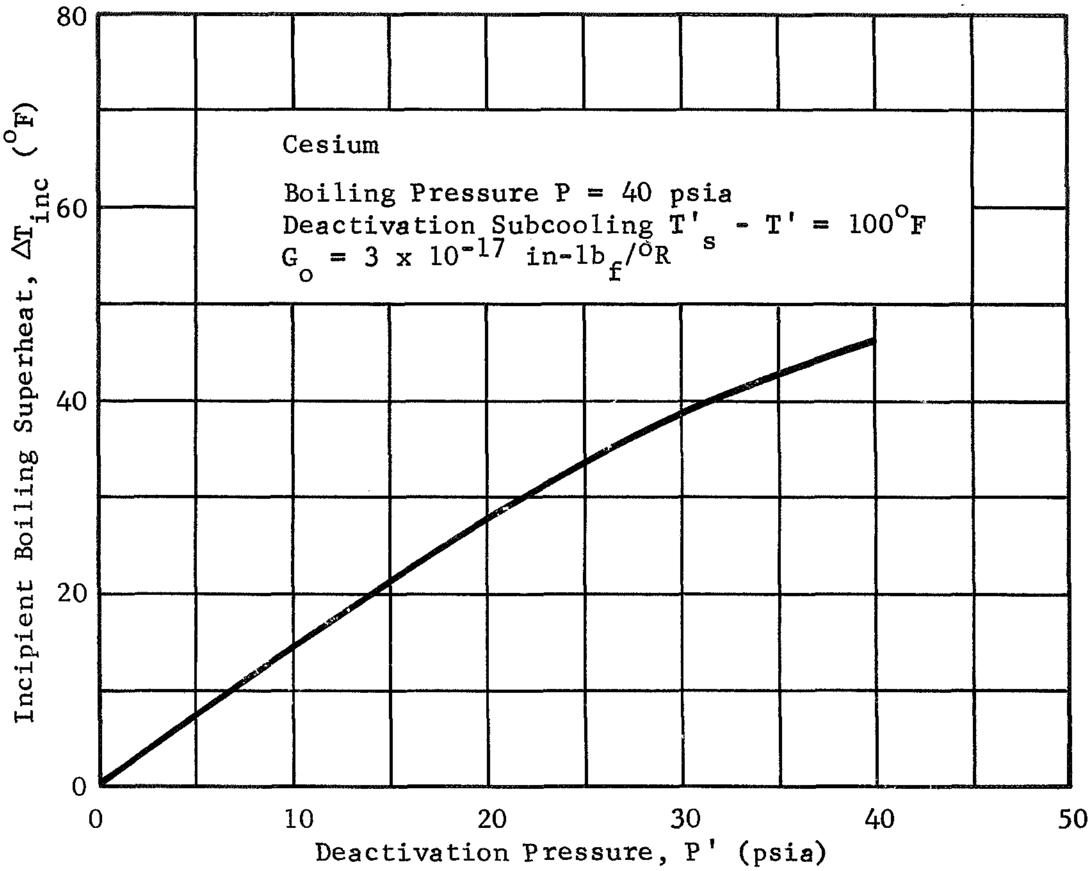


Fig. 17 Incipient Superheat vs Deactivation Pressure for Cesium

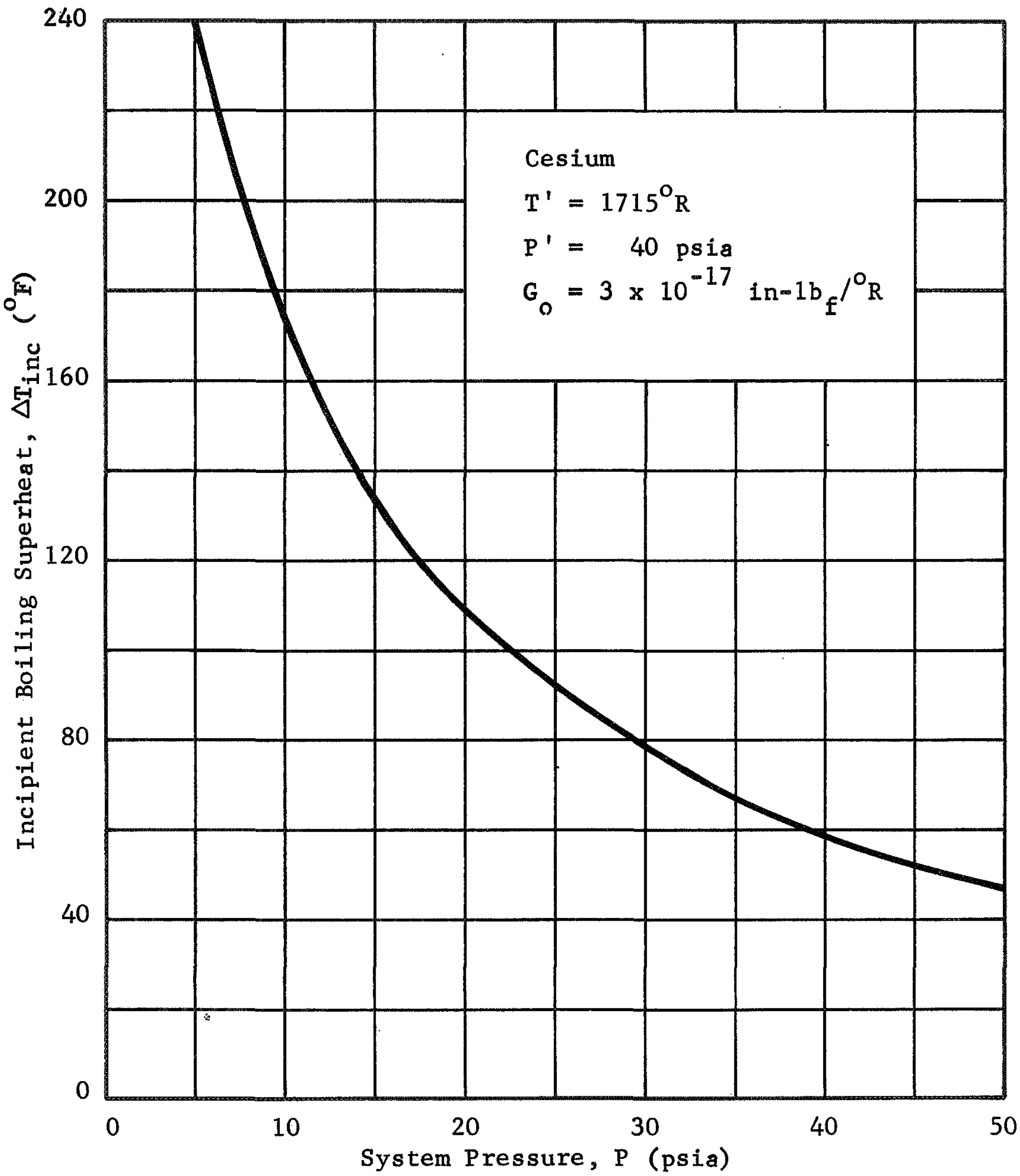


Fig. 18 Incipient Superheat vs System Pressure for Cesium

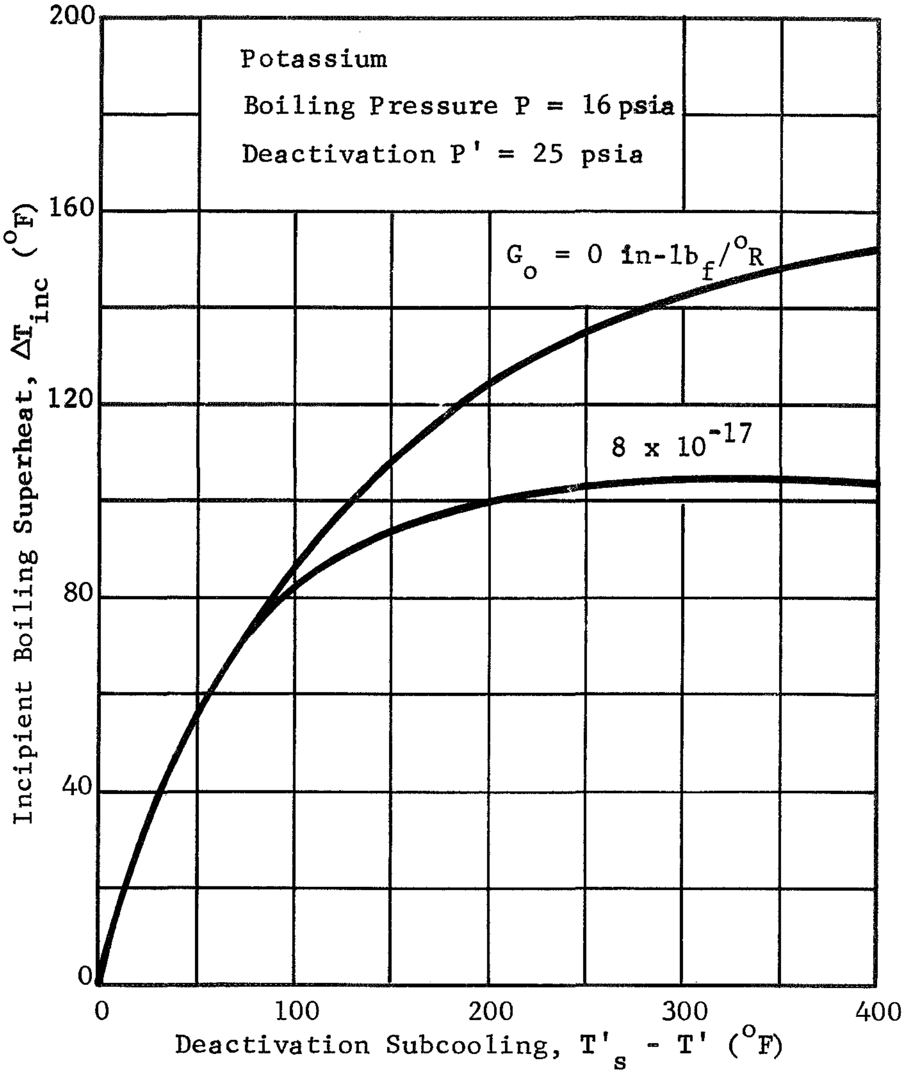


Fig. 19 Incipient Superheat vs Deactivation Subcooling for Potassium

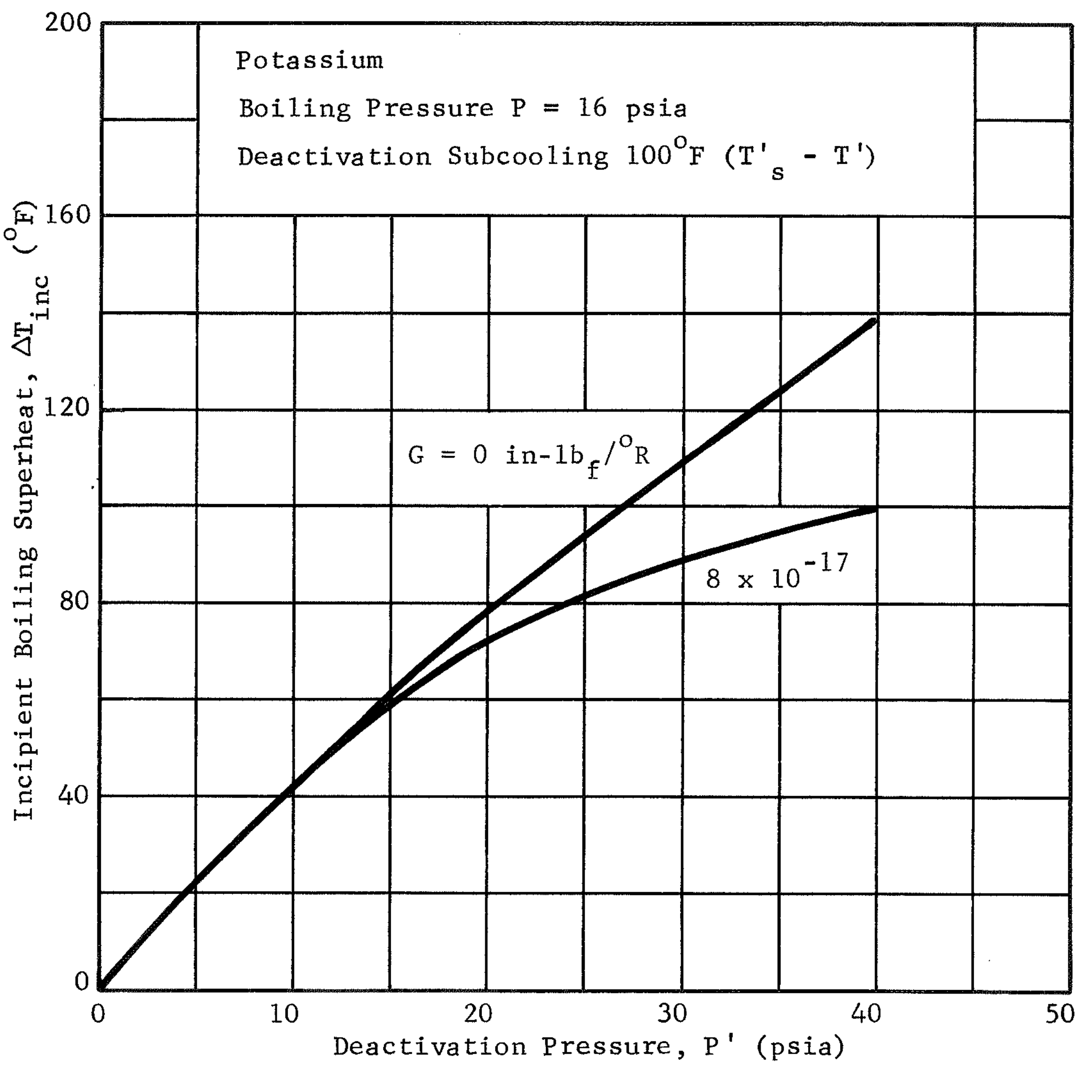


Fig. 20 Incipient Superheat vs Deactivation Pressure for Potassium

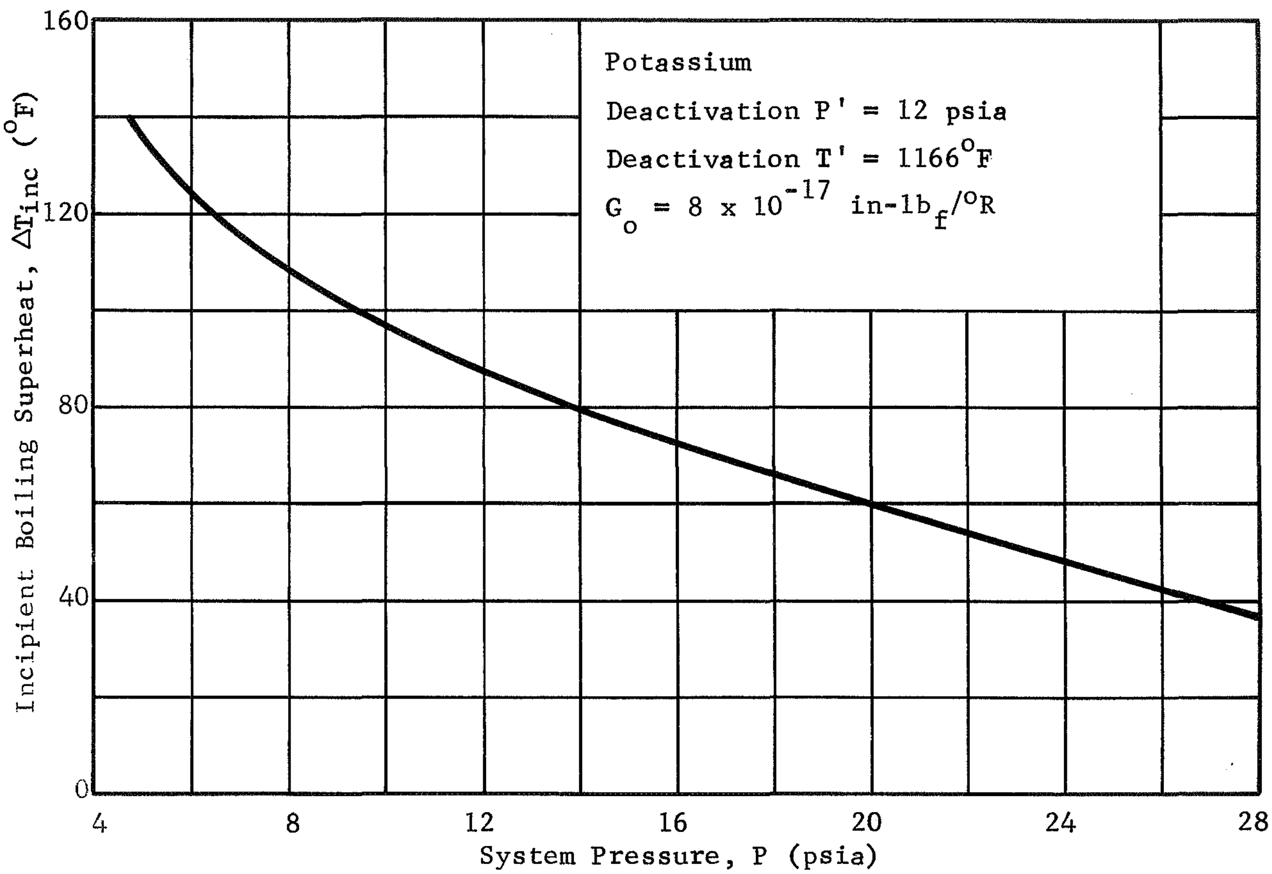


Fig. 21 Incipient Superheat vs System Pressure for Potassium

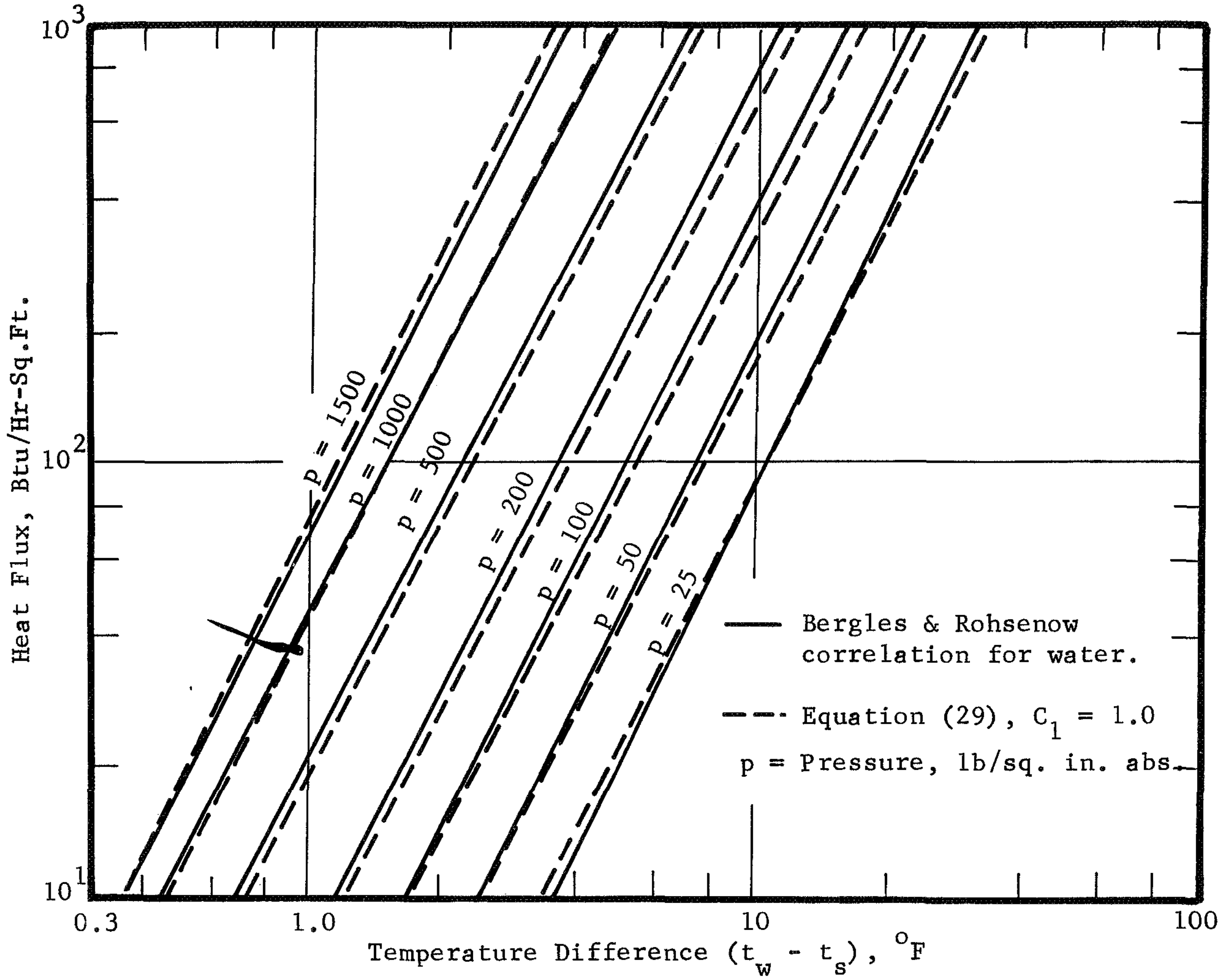


Fig. 22 Curves of Incipient Boiling Superheat vs. Heat Flux for Water

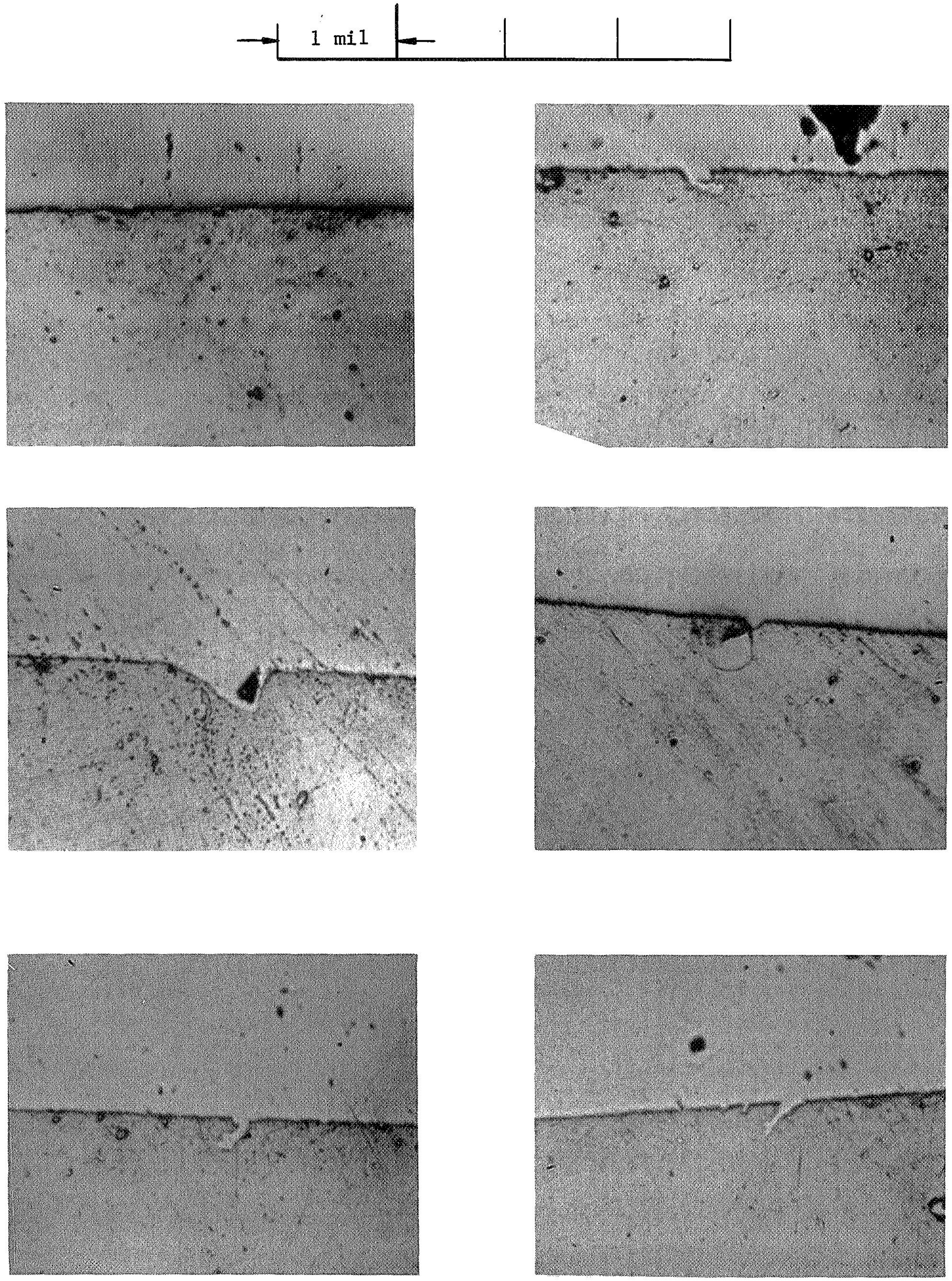


Fig. 23 Photomicrographs of Seamless Tubing Made of 347SS, with 3/8" O.D. and 35 mil. Wall Thickness.

Woff 18238

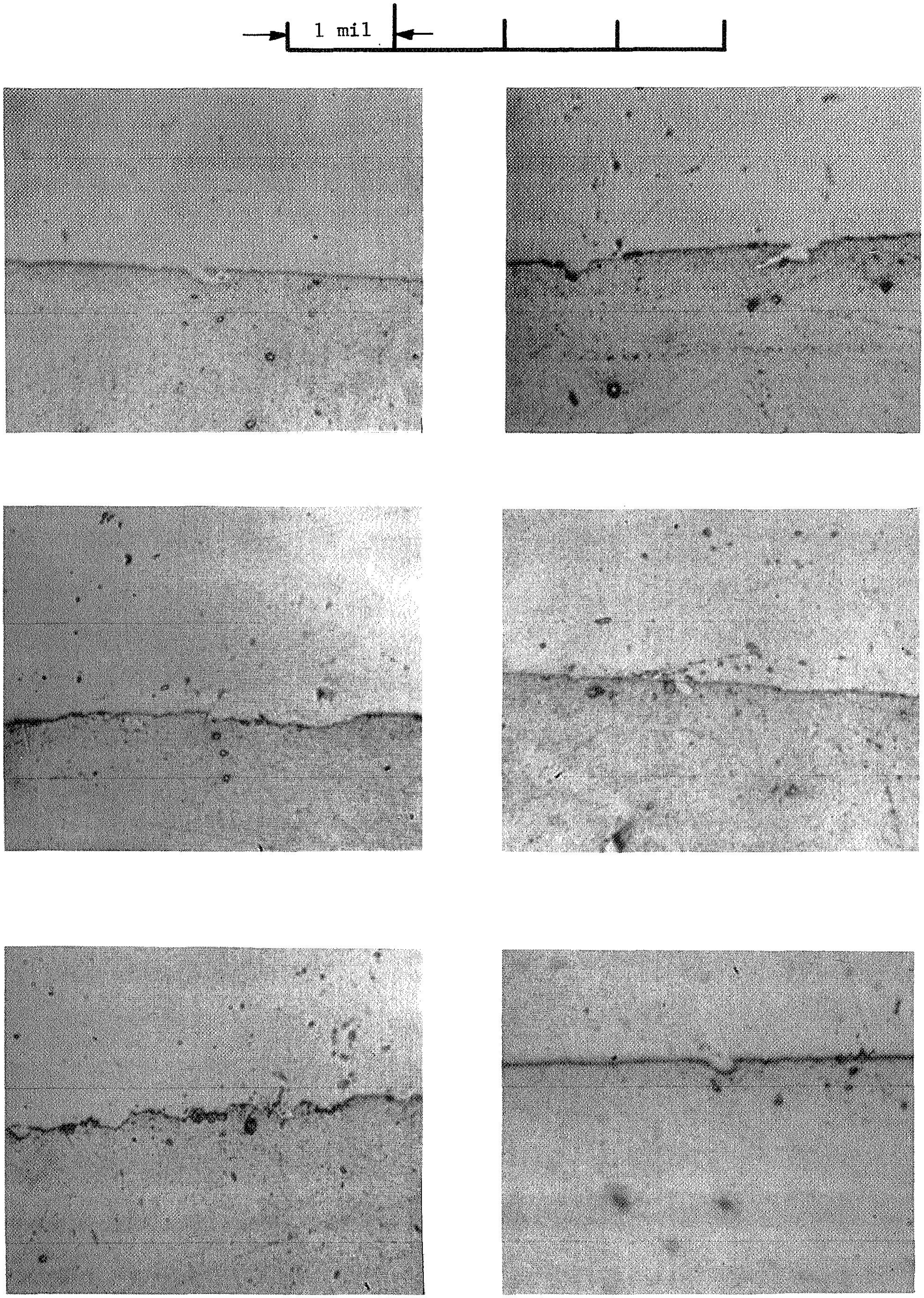


Fig. 24 Photomicrographs of Welded Tubing Made of 347 SS, with 3/8" O.D. and 35 mil. Wall Thickness

TABLES

TABLE I Summary of Experimental Investigations of Boiling a

EFERENCE	AUTHORS	TEST FLUIDS	SYSTEM	INCIPIENT ΔT_{inc} (^oF)	BOILING SUPERHEAT (^oF)	PRESSURE (PSIA)	VAR
2	Edwards and Hoffman	K Na	Natural convection loop		K: 2^o-500^o Na: 50^o-700^o	0.8-65	(1) (2)
3	Edwards and Hoffman	K	Natural convection loop	90^o-500^o	6^o-80^o	1-40	(1) (2)
4	Holtz and Singer	Na	Pool (in 2" diameter pipe)	40^o-280^o		0.2-15	(1) (2) (3) (4)
5	Holtz and Singer	Na	Pool (same as Reference 4)	40^o-300^o		0.2-15	sam
6	Marto and Rohsenow	Na	Pool-boiling off horizontal	20^o-130^o	2^o-60^o	1-8	(1) (2) (3)
7 8	Lurie and Noyes	Na	Pool and forced convection in		Pool: 20^o-60^o Forced-Convection 30^o-80^o	2-5	(1) (2) (3)
9	Petukhov, Kovalev,	Na	Pool boiling on horizontal rod	$\sim 30^o$-300^o		0.15-12	(1) (2)
10 11	Shae and Rohsenow	Na	Pool boiling off horizontal surface	Up to 150^oF	20^o-100^o	1-2	(1) (2) (3)

FOLDOUT FRAME #1

nd Incipient Nucleation Superheat for Alkali Liquid Metals

IABLES INVESTIGATED	RESULTS AND COMMENTS
Boiling pressure (T_s) Surface finish - artificial cavities	ΔT_{inc} measured under cyclic temperature fluctuations associated with periodic natural convection flow. Articifial cavities significantly reduced ΔT_{inc}.
Boiling pressure (T_s) Artificial re-entrant cavities	Incipient ΔT_{inc} measured under transient heat-up conditions. Incipient ΔT_{inc} are consistently greater than "stable" boiling superheat. Re-entrant cavities are about as effective in reducing ΔT_{inc} as cylindrical cavities of same size.
Boiling pressure (T_s) Heat flux (low level) Deactivation pressure Pressure pulses during boiling	ΔT_{inc} measured under tarnsient heat-up. Increasing pressure gives lower incipient ΔT_{inc} and greater probability for stable sustained boiling. In this low heat flux range ($< 20{,}000 \frac{Btu}{hr\text{-}ft^2}$) incipient ΔT_{inc} found to increase with increasing heat flux. Possibility of inadvertent nucleation at "rogue" sites outside of polished test zone - combining with transient heating to give seeming effect of heat flux on ΔT_{inc}.
e as Reference 4	Essentially the same study as Reference 4, but gives more plots of experimental results. Definite deactivation pressure affect, though measured ΔT_{inc} were very much lower (by factor of ~ 2 to ~ 50) than predicted by Holtz's "previous history" model. Same question of "rogue" sites as in Reference 4.
Boiling pressure Heat flux, up to $236{,}000 \frac{Btu}{hr\text{-}ft^2}$ Surface finish-artificial cavities, porous welds, etc.	Higher incipient ΔT_{inc} than stable-boiling superheat shown on standard boiling curve. Strong effect of surface finish. Noticeable hysteria or "history" effect.
Boiling pressure Bulk subcooling Heat flux	Primarily offer steady boiling and critical heat flux data. Pool boiling results for well superheat in fair agreement with Freta-Zuber correlation. Convective boiling, with bulk subcooling had incipient boiling essentially coincide with critical heat flux (at fluxes $\sim 10^6 \frac{Btu}{hr\text{-}ft^2}$.
Heat flux Boiling pressure	Primarily after pool boiling heat transfer data. Observed temperature fluctuations associated with periodic changes between natural convection heat transfer and bumping of boiling
Heat flux Artificial cavities Boiling pressure	Traces for a thermocouple near boiling surfaces showed temperature fluctuations of $\sim 80^oF$ for bumping boiling versus $\sim 10^oF$ for stable-boiling. Boiling superheat of $\sim 100^oF$ obtained with natural convection heat transfer at heat flux of $\sim 80{,}000$. This drops to $\sim 25^oF$ on start of bumping-boiling. Even during stable-boiling the boiling superheat from extrapolated temperature measured within solid was $\sim 30^oF$ less than boiling superheat corresponding to maximum surface temperature measured by "surface thermocouple" in temperature cycling.

FOLDOUT FRAME #2

TABLE I

FERENCE	AUTHORS	TEST FLUIDS	SYSTEM	INCIPIENT ΔT_{inc} (°F)	BOILING SUPERHEAT (°F)	PRESSURE (PSIA)	VARIA
12	Chen	K	Forced convection loop	17°-117°		8-24	(1) B (2) P c
13	Logan et.al.	Na	Forced convection loop	bulk ΔT_{inc} -14° to 100°		8-12	(1) H (2) B (3) F
14	Bond and Converse	K	Forced convection loop		mostly 50°		(1) B (2) H (3) F
15	Grass et.al.	K Na	Stagnant, natural convection and convection in tube	40°-1500°		1-7	(1) B (2) D (3) F
16	LeGonidec et.al.	Na	Stagnant pool in tube	40°-320°		1-20	(1) B (2) D (3) H
17	Pinchera et.al.	Na	Head rod in pool and forced convection	0°-300°		1.5-15	(1) B (2) F
18	Pinchera et.al.	Na	Capsule	10°-140°	12°-25°	1.7-15	(1) B (2) H (3) T v
19	Smidt et.al.	Na	Capsule	100°-500°		1-15	(1) B (2) N
20	Logan et.al.	Na	Forced convection loop	0°-140°			(1) F (2) S
21	Chen	K	Forced convection loop	10°-120°		24-8	(1) F (2) F (3) I
22	Holtz	Na	Pool	Up to 200°		15	(1) I (2) I (3) S (4) N

FOLDOUT FRAME #1

E I (Continued)

ARIABLES INVESTIGATED	RESULTS AND COMMENTS
1) Boiling pressure 2) Pre-boiling deactivation condition	Data indicated significant dependence of ΔT_{inc} for incipient vaporization on deactivation temperature, deactivation pressure, and boiling pressure boiling inception obtained after controlled deactivation by small incremental increases in heat flux (and fluid temperature). Flow maintained constant at $\sim$ 0.2 ft/sec.
1) Heat flux 2) Boiling pressure 3) Flow velocity	Large random scatter in measured ΔT_{inc}. The maximum bulk ΔT_{inc} seemed to increase with heat flux and to decrease with velocity.
1) Boiling pressure 2) Heat flux 3) Flow quality	T_s was taken to be that corresponding to exit pressure. Therefore, ΔT_{inc} actual, based on local true local T_s would be less than the reported values.
1) Boiling pressure 2) Duration of tests 3) Flowing versus	Heating by electric resistance in tube wall and in liquid metal, Large scatter in ΔT_{inc} results with a Goussian type of distribution about a most probably value of ΔT_{inc}, for a given set of conditions. Contrary to theory, found ΔT_{inc} higher for K than for Na. Flow conditions gives "slightly" lower ΔT_{inc} than stagnant conditions. Measured ΔT_{inc} increased with number of days of operating time.
1) Boiling pressure 2) Duration of operation 3) Heating power	Tests used transient heating by electrical resistance through tube. Almost 1 order of magnitude in scatter of data. ΔT_{inc} does show decrease with increasing pressure. Report ΔT_{inc} increase with duration of operation. No noticeable effect of heating power.
1) Boiling pressure 2) Flow velocity	Stagnant Na tests show ΔT_{inc} spread $\approx 100^{o}$-300^{o}, with no clear dependence on pressure. Flow ΔT_{inc} decreased from $\approx 170^{o}$F(max) to 18^{o}F(min) as velocity changed from 0.4 to 1.6 m/sec.
1) Boiling pressure 2) Heat flux 3) Transient heating versus steady boiling	Wide scatter for ΔT_{inc} obtained with transient heating; e.g. at T_s of 780^{o}C, ΔT_{inc} varied 10^{o}F to 100^{o}F. For steady boiling, at a given heat flux, boiling superheat decreased as T_s increased (up to 830^{o}C). The boiling curves show marked hysterisis due to incipient-boiling superheating.
(1) Boiling pressure (2) Na purity	Results in this report obtained by slowly decreasing pressure in the capsule. Data show good precision. ΔT_{inc} correspond to calculated cavity radii of 1-5μ.
(1) Flow velocity (2) Surface finish	For a given flow rate, ΔT_{inc} scattered about a mean value. The mean ΔT_{inc} decreased with increasing flow velocity.
(1) Flow rate (2) Boiling pressure (3) Deactivation condition	At any constant deactivation and boiling pressure, ΔT_{inc} showed definite parametric dependence on flow rate, decreasing with increasing flow. Theoretical explanation is proposed, based on turbulent pressure fluctuations.
(1) Deactivation condition (2) Boiling pressure (3) Surface roughness (4) Neutron flux	Verified the strong effect of deactivation history. Deactivation effect over-rides effect of gross variations in surface roughness. Earlier heat flux effect explained in terms of gas diffusion. Increased oxide concentration decreases ΔT_{inc}. No discernible effect from neutron (thermal level) flux.

FOLDOUT FRAME #2

TABLE II

Number of Pits at O.D.
0.5 in 347 SS Welded Tubing

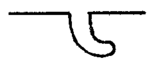
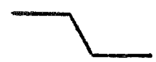
Pit Type / Specimen	I 	II 	III 	IV 	V 
1	29	0	3	8	1
2	22	1	6	3	3
3	17	1	7	3	5
4	30	3	3	5	11
5	36	2	1	12	4
6	34	5	3	18	5
7	24	5	4	8	7
8	26	2	5	12	3
9	32	0	4	9	6
10	36	3	5	8	2
Total	286	22	41	81	47
Average	28.6	2.2	4.1	8.1	4.7

TABLE III

Number of Pits at O.D.
0.5 in SS347 Seamless Tubing

Pit Type/ Specimen No.	I	II	III	IV	V
11	14	1	1	4	7
12	14	3	3	8	3
13	7	0	1	3	2
14	6	1	3	5	1
15	7	0	1	3	1
16	9	1	2	4	1
17	9	1	1	4	0
18	6	3	7	5	0
19	6	0	4	4	0
20	6	1	2	0	2
Total	84	11	25	40	17
Average	8.4	1.1	2.5	4.0	1.7