

## ON THE EXISTENCE OF TWO 'TRANSITION' BOILING CURVES

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**Abstract**—The idea that there are two 'transition' boiling curves accessible to a given liquid boiling on a given surface, is advanced. A variety of saturated, subcooled, pool, and flow boiling data are shown to be consistent with, and explainable in terms of, the idea. Some of the data are hitherto unpublished results. The two boiling curves are extensions of the nucleate and film boiling curves, and they are related to nucleate and film boiling phenomenologically.

### NOMENCLATURE

$c_p$ ,	specific heat at constant pressure;
$h_{fg}$ ,	latent heat of vaporization;
$Ja$ ,	Jakob number, $\rho_l c_p (T_{\text{liquid}} - T_{\text{sat}}) / \rho_g h_{fg}$ ;
$j$ ,	probability of nucleation in a molecular collision;
$T$ ,	temperature;
$\Delta T$ ,	$T_w - T_{\text{sat}}$ ;
$q$ ,	heat flux.

### Subscripts

w,	wall;
sat,	saturation;
hn,	homogeneous nucleation;
liquid,	liquid bulk;
max,	peak nucleate boiling $q$ ;
min,	minimum film boiling $q$ .

### INTRODUCTION

TRADITION has it that the heat flux,  $q$ , is a single valued function of the liquid superheat,  $\Delta T$ , during boiling—particularly during saturated pool boiling. However, a great accumulation of evidence forces us to the conviction that there are two boiling curves that typically relate to one another as shown in Fig. 1. These curves change in different ways as system variables are altered. Together they form the various continuous representations that have been advanced as 'the boiling curve'.

Nukiyama's independent  $q$  experiments [1] required that he terminate his nucleate and film boiling curves at the extreme heat fluxes,  $q_{\text{max}}$  and  $q_{\text{min}}$ . He speculated that these extrema would be connected by a single line element if  $\Delta T$  could be varied independently. Three years later, Drew and Mueller [2] obtained a few data that suggested Nukiyama was correct, and the notion of a single boiling curve was solidified.

The objective of this paper is to show how the massive intervening accumulation of data suggests that there are, in fact, two  $q$  vs  $\Delta T$  relationships available to

a given boiled liquid on a given surface. We shall also show how the two curves serve to explain some of the seemingly anomalous behavior we have witnessed in the past.

### THE TWO-CURVE PHYSICAL MODEL

We first present our conceptual model without rationalization or justification. We then offer the evidence for the model.

The two curves in Fig. 1 are simply labeled *nucleate* and *film* boiling. As the heat flux is increased, in the conventional nucleate boiling regime, to a value beyond the hydrodynamic peak,  $q_{\text{max}}$ , the collapse of the vapor escape path will be catastrophic. On the other hand, if  $\Delta T$  is increased independently, the vapor removal path is observed to change in a continuous manner. Therefore the 'jets-and-columns' mechanism should not disappear all at once.

There will instead be an increase in the number of nucleation sites and an increased tendency to separate the liquid from the surface, just beyond the peak of the curve. As the surface grows hotter, the duration of liquid contact will be reduced. When liquid moves into a dry patch, heavy nucleation will tend to blow it away quickly. The hydrodynamic 'jets-and-columns' mechanism is still admissible because the vapor production is below the critical value, but the disruptive situation at the surface leads more and more to oscillating liquid contact—to batchwise explosions of vapor into the liquid bulk.

The film boiling curve is also extended (to the left) beyond its conventional hydrodynamic limit. The minimum heat flux in this curve,  $q_{\text{min}}$ , is the value at which vapor is no longer generated rapidly enough to keep the film from falling into the heater. When  $q$  is varied independently and reduced below  $q_{\text{min}}$ , film boiling collapses catastrophically into nucleate boiling. But when  $\Delta T$  is independently reduced beyond the minimum, change is almost imperceptible as long as the system continues to change along the film boiling

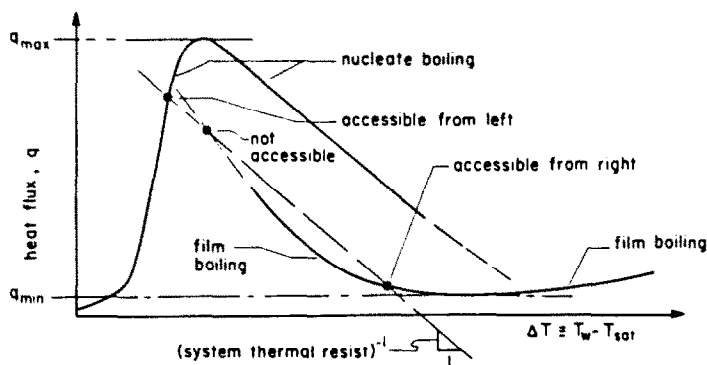


FIG. 1. The two boiling curves. The 'transition region' denotes all states between the local maximum and the local minimum—wherever they occur.

curve. There is some liquid-solid contact to the left of the minimum, and even the slightest contact will lead to substantial increases in the rate of the generation of vapor. Thus  $q$  begins to rise. The basic film boiling process is preserved in this region; however, it is increasingly augmented by instances of liquid-solid contact.

The reader will note that we have not used the term 'transition boiling', and we suggest that region ought to be viewed as an extension of either film boiling or nucleate boiling. Drew and Mueller simply identified the region as a part of the film boiling regime and did not use the word 'transition'. Later such terms as 'partial' or 'unstable' film boiling were first introduced, and then dropped, in favor of the term 'transition' that did not commit anyone to a hypothetical mechanism. For the sake of clarity we shall speak of transitional nucleate, and transitional film boiling to distinguish the two curves.

We now turn our attention to two aspects of verification of the mechanism: Observations of the two mechanisms, and demonstration of ways in which given systems elect one or the other of the two processes.

#### SOME OBSERVATIONS IN SATURATED POOL BOILING

The classical photos of transition boiling on tubes given us by Westwater and Santangelo [3] have been widely reproduced. They are interesting because they clearly display both mechanisms in the transition region. Their Fig. 5, showing high- $q$  'transition' boiling at  $\Delta T$  only a little beyond the peak, reveals a vapor removal mechanism that clearly consists of jets such as those that collapse when  $q \gtrsim q_{max}$ . Their Fig. 7, showing low- $q$  'transition' boiling, at  $\Delta T$  about 3/4 of the value giving  $q_{min}$ , is indistinguishable from film boiling. They also provide a photograph for a state between these two pictures. It shows a completely blanketed, but very ragged, surface in what could be film boiling with a lot of local contact. The problem

with these photographs is that they can only approximately be related to a boiling curve for lack of actual surface temperature data.

We turn next to Berenson's 'infinite' flat plate data [4], which include surface temperature data and represent very close control of a variety of surface conditions. Figure 2 shows data for six of Berenson's surfaces on linear  $q$  vs  $\Delta T$  coordinates.

Berenson's system for regulating  $\Delta T$  independently had an important weakness that was brought to light in other systems by Stefan and Kovlev and by Grassman and Ziegler during the latter 1960s (see discussion by Hesse [5]). Berenson heated the lower side of a copper block, which was heavily finned, with condensing steam. He boiled more volatile fluids on the top of the block. The block placed a thermal resistance equal to (block thickness/conductivity) =  $0.000860 \text{ ft}^2 \text{ h}^\circ\text{F Btu}^{-1}$ , or  $0.0001514 \text{ m}^2 \text{ }^\circ\text{C W}^{-1}$ , between the condensing steam and the surface. Accordingly, if the line:

$$q = \frac{(T_{\text{cond steam}} - T_{\text{sat}}) - \Delta T}{0.00086} \quad (1)$$

expressed in the units of Btu, ft, h, and  $^\circ\text{F}$ , should happen to intersect the boiling curve in more than one point, then only one point can be reached in an experiment. If the system is initially in film boiling, then reduction of the condensing steam temperature will only allow one to observe the lowest curve that can be reached along a line of negative slope equal to (conductivity/block thickness). If one starts with the system in nucleate boiling then he can only reach the highest curve that such a line intersects.

Figure 2 shows three cases (Berenson's Runs No. 2, 3 and 4) where certain states are inaccessible, and one more case (Run No. 25) where some states might have been inaccessible. Runs No. 2, 3 and 4 do not reveal anything about the existence of the two 'transition' boiling curves hypothesis although they dramatize a basic limitation of Berenson's system. The reader should note that we avoid Berenson's use of logarithmic coordinates in reproducing these results.

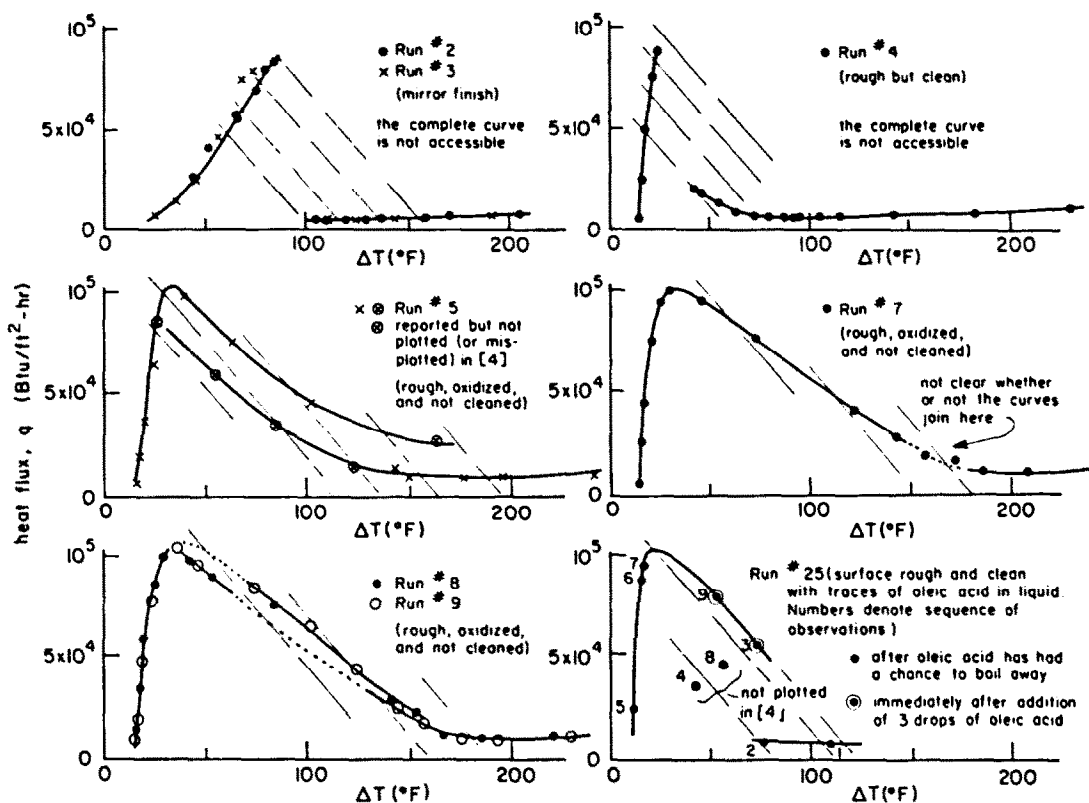


FIG. 2. Berenson's boiling runs for *n*-pentane on copper. Solid lines are our fair curves. Dotted lines are our extrapolations. Dashed lines are for equation (1).

Run No. 5 (which is plotted from Berenson's data tables, as are all of these curves) reveals five data points that were omitted or misplotted in his figures. When we include these points, the two boiling curves are clearly revealed. The data in Run No. 7 appear to lie on a single curve; however, they show a slight misalignment near the minimum. Berenson reports uncertainties of only 200–1000 Btu ft<sup>-2</sup> h<sup>-1</sup> °F in all of his careful measurements and his data align within this uncertainty in most cases. Thus such misalignment could reveal a separation between two distinct neighboring curves. Runs No. 8 and 9 provide independent observations that reveal somewhat greater misalignment, hence we believe that two 'transition' curves are revealed in these cases.

Berenson was puzzled by discontinuous changes of  $q$  in the transition curve for dirty, oxidized surfaces. He isolated the effects of cleanliness and oxidation by running a test, Run No. 22, with an oxidized surface that had been cleaned immediately before testing. He compared Run No. 22 to Runs No. 16, 17 and 23, all of which were for clean, unoxidized surfaces and saw no effect of oxidation on the boiling curve. Berenson concluded that oxide does not affect the boiling curve as long as the oxide thickness is thin enough that the thermal characteristics of the surface are those of the pure base metal. This was the case for his experiments.

Finally, Run No. 25 is particularly revealing. Beren-

son added a few drops of oleic acid (a wetting agent) to the liquid from time to time. It would boil off and more would be required. Two points in Run No. 25 were obtained immediately after the oleic acid was added and they fall distinctly high—in what must have been transitional nucleate boiling. Two data lay far below, on what we believe was the transitional film boiling curve.

The importance of Run No. 25 is, as Berenson noted, that it brings to light the great sensitivity of  $q$  to wetting, in the transitional region. Indeed, we see that the upper or nucleate boiling curve can *only* be sustained in the transitional region when the surface is dirty or when there is a surfactant in the liquid. Berenson argued that wetting lifted the transition boiling curve. We believe that the mechanism of boiling on the upper curve is transitional nucleate boiling which can only occur when there is wetting.

Figure 3 shows how the photos suggest that wetting action is responsible for selecting one or the other of the curves. In a really clean pentane-copper system the contact angle is a small positive value, but in an unclean system Berenson found that it would go to zero, so that wetting *had to* accompany contact. In this connection, Lienhard's [6] original photographs of the 'transition' boiling of acetone on an oxidized copper cylinder clearly reveal upper boiling curve behavior.

Sakurai and Shiotsu [7] followed up on a feedback

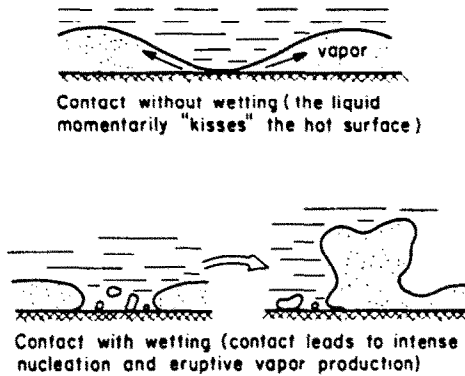


FIG. 3. Transitional boiling in the film region (above) and in the nucleate region (below).

control strategy invented by Peterson and Zaalouk [8] for studying transition boiling. Their data (see example in Fig. 4) reveal a hysteresis behavior in the transition region. They indicate that the upper 'transitional' boiling curve corresponds with the mechanism that we have described as transitional nucleate boiling. They also indicate that, at point B in Fig. 4, boiling suddenly breaks into patches of nontransitional nucleate and nontransitional film boiling that coexist on the wire.

We believe that point B is the point of intersection of the two 'transitional' boiling curves. Thus when  $\Delta T$  is reduced from a high value, three possible situations can exist at the return to point B: a mixture of two boiling modes, or pure transitional film boiling, or pure transitional nucleate boiling. Sakurai and Shiotsu do not say what the character of boiling is as  $\Delta T$  is reduced below the value at point B. However it must be one of two things:

- (1) A mixture of two boiling modes that both converge on point A, or
- (2) A single boiling mode that would converge on point A.

Either situation would require that a second transitional boiling curve exist. This curve is the transitional film boiling curve.

#### FACTORS DETERMINING THE SELECTION OF A TRANSITIONAL BOILING MODE

The preceding remarks are restricted to pool boiling in saturated or near-saturated liquids. In subcooled external flow-boiling configurations we observe that the transitional film and transitional nucleate boiling curves are separated much further from one another. We shall see that such situations dramatize the two curve idea and they raise the problem of selection of one curve or the other as a major practical issue.

#### Some transient quenching experiments

Quenching experiments yield boiling curves in which the surface temperature is the independent variable. All regimes of boiling are accessible to this naturally-occurring phenomenon. A natural selection of either the upper (transitional nucleate) curve or the lower (transitional film) curve thus results, as a body is quenched.

Observations from quenching experiments reveal jumps from one curve to the other. Stevens [9] provided very complete high-speed motion picture records for repeated quenches of silver spheres moving at  $1.52 \text{ m s}^{-1}$ , in water at various temperatures. These records made it possible to identify the actual transition boiling behavior reproducibly. Stevens observed what he called the 'transposion' during forced convection on a silver sphere. This was an almost instantaneous collapse of film boiling as the sphere cooled. Stevens also identified what he called '3-region boiling' in some cases. His high-speed photographs showed a ring-like transition to nucleate boiling that began at the forward stagnation point and moved around the sphere in a fraction of a second as cooling proceeded. As the transition ring moved, there remained a smoother-looking interface on the downstream surface of the sphere.

The coexistence of different boiling regimes that occur in certain instances suggest something akin to Shiotsu and Sakurai's averaged observations. However, these coexistences were only observed in some

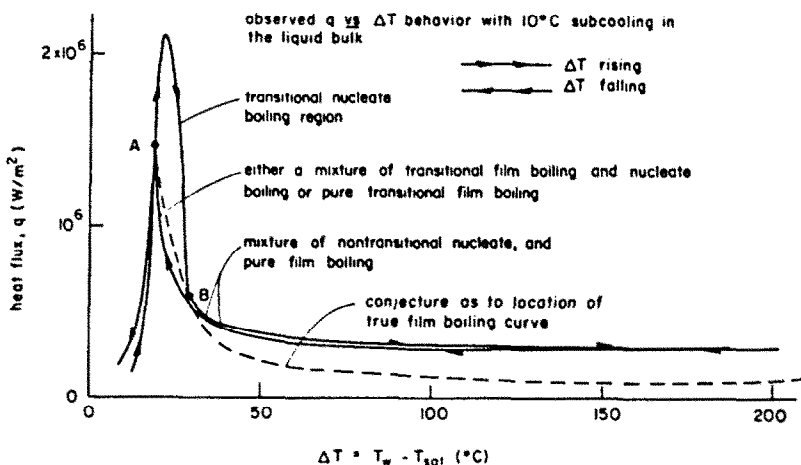


FIG. 4. Sakurai's and Shiotsu's [7] hysteresis loop.

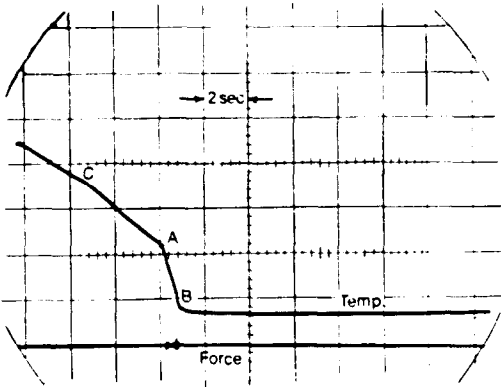


FIG. 5. Temperature-time trace for a 9.04 mm dia. silver sphere cooling in 82°C water.

cases. Let us consider some additional measurements. Figures 5 and 6 show previously unreported pool boiling data for a 9.04 mm dia. silver sphere in water with a thermocouple at its center. These data and additional high speed movies were obtained by the first author in the same apparatus as that used at the University of Houston by Henningson [10]. The oscilloscope traces in Figs. 5 and 6 reveal major 'jumps' in the heat flux for 82°C and 99°C water (see points A). There are also smaller jumps in heat flux at higher temperatures at points C. Points B on the traces represent the maximum temperature time slope, proportional to  $q_{max}$ . The photographs also show a force trace that reflects the rapidity of vapor volume change in the system. This signal emanates from a piezoelectric crystal upon which the liquid container is mounted. As oscillations in vapor volume surrounding the sphere occur, the center of gravity of the liquid is accelerated up or down. Henningson showed that various boiling regimes can be detected by this technique. Figure 7 shows the data from Figs. 5 and 6 reduced to boiling curves. Jumps in  $q$  occur in both the 99°C and 82°C water. Measurements were made in 27°C water, but the thermal characteristics of the sphere were not adequate to give good system response. Consequently, these data are not presented.

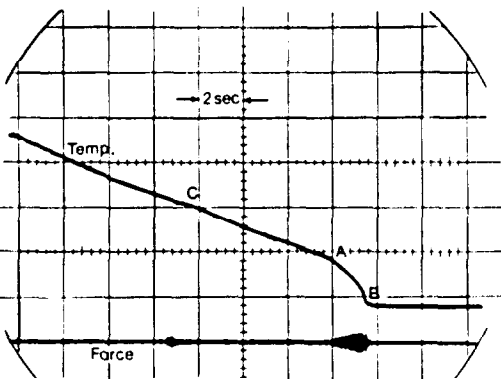


FIG. 6. Temperature-time trace for a 9.04 mm dia. silver sphere cooling in 99°C water.

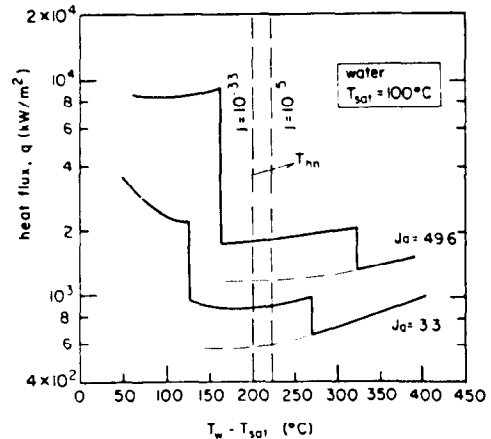


FIG. 7. Heat flux for saturated water at 1 atm. in pool boiling from a 9.04 mm dia. silver sphere.

Ungar and Eichhorn [11] have measured transient heat transfer from a 2.54 cm dia. copper sphere cooling in stationary and flowing methanol. Their temperature-time profiles closely resemble those reported in Figs. 5 and 6. Figure 8, which shows their subcooled pool boiling curves, also reveals rapid shifts in heat flux at or near the apparent minimum heat flux, followed by the maximum flux at a lower temperature.

#### The effect of subcooling

Subcooling has the effect of greatly increasing the nucleate transitional boiling heat flux and shifting the curve to the right. If any portion of that curve subtends surface temperatures far enough in excess of the maximum homogeneous nucleation temperature,  $T_{hn}$ , then that portion of the curve becomes inaccessible since liquid-solid contact becomes impossible.

Lienhard and Karimi [12, 13] have shown that the spinodal line and the absolute limit of homogeneous nucleation are nearly the same in a liquid. This limit occurs where the probability of nucleation per mole-

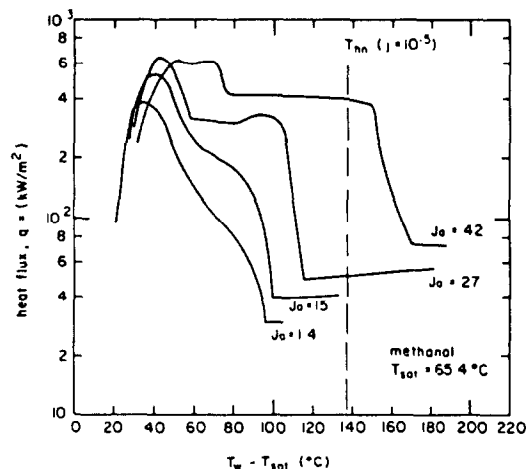


FIG. 8. Heat flux for saturated methanol at 1 atm. in pool boiling from a 2.54 cm dia. copper sphere [11].

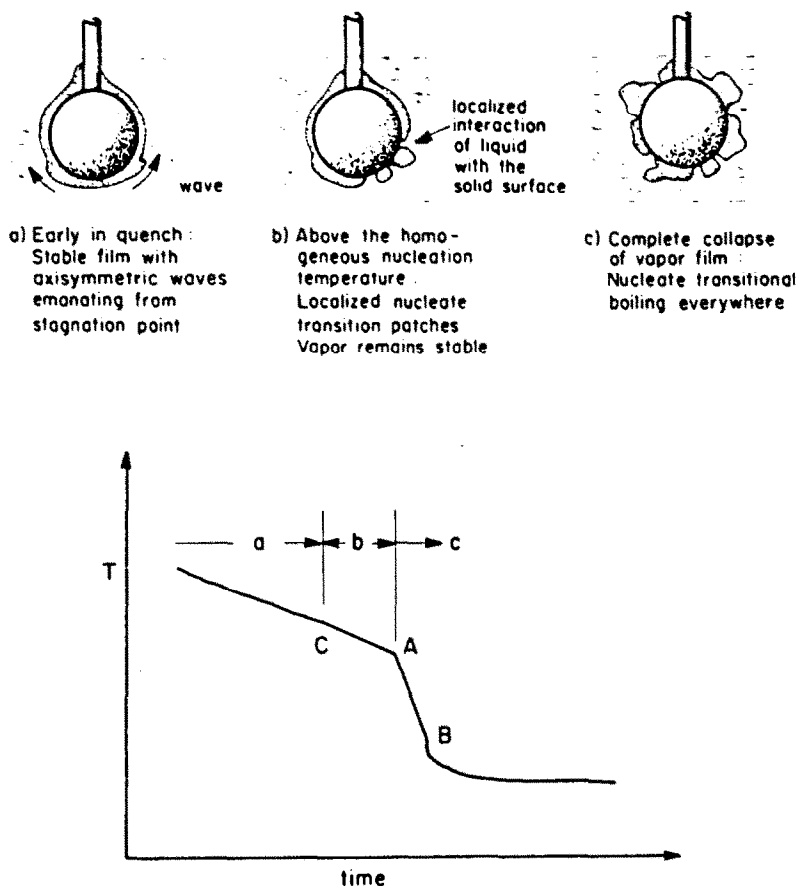


FIG. 9. Various stages of pool boiling behavior during the quenching of a sphere in a subcooled liquid.

cular collision,  $j$ , is on the order of  $10^{-5}$ . Clean systems normally nucleate when  $j$  lies between  $10^{-33}$  and  $10^{-13}$ . Following the method of Lienhard [12],  $T_{hn}$  values have been calculated and superimposed on Figs. 7 and 8.

High speed photographs of quenching of the 9.04 mm sphere reveal the process leading from film boiling to the upper boiling curve. Figure 9 uses sketches from frames of these movies to show what we see happening in this process. In the beginning stages of the quench, the film is stable, disturbed only by regular axisymmetric waves that originate at the lower stagnation point and move up around the sphere as shown in Fig. 9.

Our observations reveal that in these quenching situations, the system will follow the upper boiling curve if it can. When the measured sphere temperature is still above  $T_{hn}$ , the interfacial temperature that the subcooled liquid might reach on sudden contact will be less than  $T_{hn}$ . It then becomes possible for the mode of boiling to jump from film to transitional nucleate. Several factors can contribute to an interface temperature below  $T_{hn}$ . For one thing, the sudden contact of saturated liquid with a hot sphere will lead to small

drops in the interface temperature. More importantly, when the wavy liquid draws close—just before contact—there can be very high momentary heat removal from the sphere. The wavy interface can thus cause local temperature drops, even in a highly conducting sphere. Once momentary contact occurs in a wetting situation, nucleation will rapidly follow, with still greater local cooling.

The dynamics of such contact are quite complicated; but we are able to observe it clearly in the high speed movies. Momentary patches of transitional nucleate boiling start to appear on the sphere slightly above  $\Delta T = T_{hn} - T_{sat}$ , as is shown in Fig. 9. At low subcooling these patches are accompanied by the small point-C jumps. These are actually jumps to averages of film and nucleate transition heat fluxes.

At low subcooling these patches are clear cut and they endure. When the liquid is colder the patches are more numerous, they flicker on and off, and cause the average heat flux to rise in a more continuous fashion. In the less subcooled cases, the film boiling that remains over the larger portion of the sphere suddenly gives way to complete transitional nucleate boiling in the transposition jump at points A, as shown in Fig. 9.

Ungar's data show jumps in heat flux at all four subcoolings. If we nondimensionalize the subcooling with a modified Jakob number

$$Ja = \frac{\rho_l c_p (T_{\text{sat}} - T_{\text{liquid}})}{\rho_l h_{fg}}$$

then we get  $Ja = 42$  at his maximum level of subcooling in methanol (26.8°C), and  $Ja = 49.6$  at ours in water (18°C). The two sets of data are comparable at similar  $Ja$ 's, although the  $q$  vs  $\Delta T$  curves differ considerably in magnitude. At  $Ja = 42$  and 21, Ungar recorded smaller jumps in heat flux at temperatures higher than those encompassed by the curves in Fig. 8. Ungar [14] describes the behavior corresponding to the jumps as a 'momentary quivering' of the vapor shell prior to the breakdown of the film. This matches our visual impression of the momentary transitional nucleate boiling patches we saw at our points C.

It is our contention that the lowest measured fluxes for both of the systems represented by Figs. 7 and 8 do not necessarily represent true  $q_{\min}$  points. The dashed lines on Fig. 7 show the extensions of the film boiling curves that would probably occur if the rapid jumps in heat flux were not present. Similar extensions for Ungar's data are not provided since his data plots do not include the observed point C-type shifts that lead to averages of transitional film and transitional nucleate boiling behavior.

Stevens noted that transposition preceded his '3-region boiling'. Since the silver spheres were highly conducting and could not sustain large temperature differences, the '3-region' process is, in all probability, the movement of the peak heat flux around the surface from front to back. It represents a fairly continuous change of transitional nucleate boiling into conventional nucleate boiling, and should probably have been called '2-region boiling'.

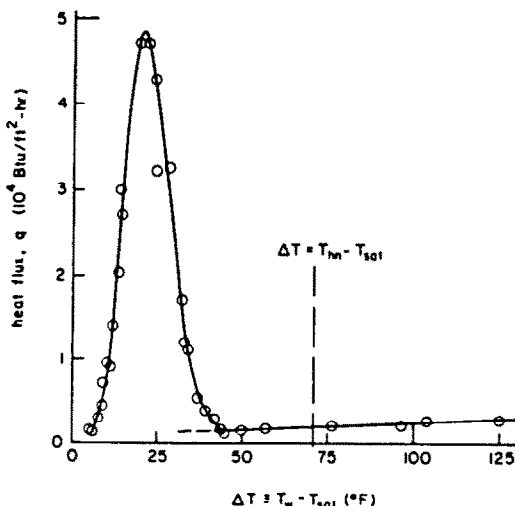


FIG. 10. Typical quench data for a 1 in. dia. copper sphere in saturated nitrogen at 1 atm. and normal gravity.

### The effect of velocity

Increased flow velocity affects the film and nucleate boiling curves in the same way as increased subcooling, but to a lesser extent. The effect of velocity is to move the  $q_{\min}$  point to a temperature higher than  $T_{hn}$ . This gives the same kind of behavior as is seen in a subcooled system. Most quenching data are for relatively low velocities so the effect is not made as prominent as it is by subcooling (Dhir and Purohit [15] likewise observed that the effect of subcooling on  $q_{\min}$  is much stronger than the effect of velocity).

### The location of the minimum flux

By now it is clear that  $q_{\min}$  may or may not be attainable in either a quench or steady-state experiment. Two independent sets of circumstances must be fulfilled if a system is to leave the film boiling curve and go to the transitional nucleate curve, at a temperature higher than that which gives the hydrodynamic limit dictated by the collapse of Taylor waves:

- (1)  $T_{hn}$  must be sufficiently higher than the temperature at  $q_{\min}$ , to permit the jump, and
- (2) The liquid must wet the heater.

Let us look at some circumstances in which these conditions are, or are not, met. Figure 10 shows the normal gravity quench of a 1 in. dia. copper sphere in nitrogen by Merte and Clark [16]. (Similar quenching behavior was reported by Veres and Florschütz [17] who used 0.938 in. dia. spheres in Freon 113.) We note that the data suggest a clear intersection above the hydrodynamic minimum. Berenson's Runs Nos. 2 and 3, shown in Fig. 2, also show this behavior. Both our data (Fig. 7) and Ungar's data (Fig. 8) suggest that jumps to transitional nucleate boiling occur (at least locally) before  $q_{\min}$  has been reached.

Thus the two 'transition' curve idea serves to explain why so many experiments (and quenching experiments in particular) fail to reach a plausible  $q_{\min}$  value. In the light of the two 'transition' boiling curve idea we see that apparent local maxima and minima, different from the hydrodynamic limits, might be reached. We propose to retain the terms  $q_{\min}$  and  $q_{\max}$  for the extrema defined by hydrodynamic instabilities.

Thus, if we move downward and to the left on the stable film boiling curve we will reach  $q_{\min}$  only if a jump to the transitional nucleate boiling curve is not triggered first. If a jump is triggered, it will define a pseudo- $q_{\min}$  point. The summary paper by Lienhard and Dhir [18] on the hydrodynamic minimum was therefore restricted, in its comparison with data, to very clean, other-than-quenching systems where such jumps did not occur.

By the same token, Berenson's data (Fig. 2, Run No. 5) suggest that by executing the transitional film boiling curve all the way back to conventional nucleate boiling, one might likewise encounter a pseudo- $q_{\max}$  point.

### CONCLUSIONS

- (1) There appear to be two possible  $q$  vs  $\Delta T$

relationships that a given liquid-heater configuration may obey, in what has been called the transition boiling regime.

(2) The heater-liquid interfacial chemistry is a very important determinant in selecting one curve or the other. Wetting is probably required to sustain the upper curve.

(3) Large discontinuous jumps in heat flux occur at constant  $\Delta T$ , from film to transitional nucleate boiling, in many systems as  $\Delta T$  is reduced independently.

(4) There is a serious need for additional measurements if two 'transition' curve behavior is to be incorporated into heat transfer design. These include:

- (a) Additional  $q(\Delta T)$  curves must be observed with good control of surface finish and chemistry.
- (b) Such curves must be accompanied with good photographic records. These must be used to diagnose physical mechanisms in the 'transitional' region.
- (c) Observations of contact angles must be made on hot surfaces, and during boiling.
- (d) The role of external disturbances in triggering jumps between the two curves, should be pursued.

(5) Steady state transitional experiments are vastly superior to quenching experiments, for revealing the character of transition boiling, since they introduce far fewer spurious complications. Steady experiments are difficult; nonetheless more are needed.

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#### SUR L'EXISTENCE DE DEUX COURBES D'EBULLITION "TRANSITOIRE"

**Résumé** — On avance l'idée qu'il y a deux courbes d'ébullition "transitoire" accessibles pour l'ébullition d'un liquide donné sur une certaine surface. Une variété de données sur l'ébullition saturée, sous-refroidie, en réservoir ou avec convection forcée est en accord avec — ou explicable par — cette idée. Quelques résultats sont inédits. Les deux courbes d'ébullition sont des extensions des courbes d'ébullition nucléée et en film, et elles sont reliées phénoménologiquement à ces deux mécanismes.

#### ZUR EXISTENZ ZWEIER "ÜBERGANGS"-SIEDEKURVEN

**Zusammenfassung** — Die Vorstellung, daß für eine vorgegebene Oberflächen-Flüssigkeits-Kombination zwei "Übergangs"-Siedekurven möglich sind, wird propagiert. Es wird gezeigt, daß eine Menge von Daten aus dem gesättigten, dem unterkühlten, dem Behälter- und dem Strömungs-Siedebereich mit der Vorstellung verträglich sind und mit ihr erklärt werden können. Einige dieser Daten sind bis heute nicht veröffentlicht. Die zwei Siedekurven sind Verlängerungen der Blasen- und der Film-Siedekurve und stehen auch zum Blasen- und Filmsieden in phänomenologischer Beziehung.



**О ПРЕДСТАВЛЕНИИ «ПЕРЕХОДНОГО» РЕЖИМА КИПЕНИЯ ДВУМЯ КРИВЫМИ**

**Аннотация** — Предложено новое описание «переходного» режима кипения жидкости на определенной поверхности. Показано, что большое число данных (в том числе и неопубликованных) по развитому кипению, кипению с недогревом, кипению в открытом объеме и при течении согласуется с таким подходом и могут быть объяснены на этой основе. Обе кривые являются продолжениями кривых пузырькового и пленочного кипения и феноменологически связаны с этими режимами.