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A STUDY OF NUCLEATE BOILING NEAR THE PEAK HEAT FLUX THROUGH MEASUREMENT OF TRANSIENT SURFACE TEMPERATURE

CHI-LIANG YU and RUSSELL B. MESLER
University of Kansas, Department of Chemical and Petroleum Engineering,
Lawrence, KS 66044, U.S.A.

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Abstract—Measurements of transient surface temperature during nucleate boiling of water at high heat fluxes support the view of many investigators that a liquid film, herein called the macrolayer, exists beneath an agglomeration of vapor bubbles and is paramount in transferring heat. The macrolayer repeatedly dries out and reforms. Upon reforming, the surface temperature drops repeatedly for brief periods. This is apparently caused by microlayer evaporation beneath bubbles growing in the macrolayer. Sometimes, a brief quench precedes ebullition. Evaporation from the macrolayer just before it evaporates completely cools the surface effectively and evidence of nucleation then is absent.

NOMENCLATURE

c,	specific heat [W/kg deg];
k,	thermal conductivity [W/m deg];
q/A,	heat flux [W/m^2];
t,	time [s];
T,	temperature [°C];
x,	distance [m];

Greek symbols

α,	thermal diffusivity [m^2/s];
δ,	liquid film thickness [m];
λ,	latent heat of vaporization [J/kg];
ρ,	density [kg/m^3].

Subscripts

I,	body I;
II,	body II;
L,	liquid;
0,	initial;
sat,	saturated;
w,	wall.

INTRODUCTION

NUCLEATE boiling is an important means of transferring heat. It is also the subject of continuing research efforts because it is a very complicated phenomenon and there is still no general agreement on the details of just how nucleate boiling actually accomplishes the transfer of heat.

There has been much discussion of the mechanism of heat transfer during nucleate boiling. Jakob [6] proposed that the role of the bubbles was to stir the liquid and promote convective heat transfer. More recently, there has been convincing work by Rallis and Jawurek [18] that, especially at higher heat fluxes, a greater part of the vapor is generated right on the surface than had been previously thought. This is usually called latent heat transport. Zuber [21] has suggested that at low heat fluxes, heat transfer was by convection whereas at high heat fluxes, it was primarily by latent heat transport. Just how the vapor is generated at the surface at high heat flux is not yet clear.

Transient surface temperature measurements have previously provided important tests of various hypotheses, but such measurements have mostly been at low heat fluxes. There is even more of a need to understand nucleate boiling at high heat fluxes than at low. This study was undertaken to measure transient surface temperature near the peak heat flux.

BACKGROUND

At high heat fluxes during nucleate boiling, a conglomeration of vapor bubbles covers the surface and obscures the details of what is occurring. Still, if nucleate boiling is to be understood, one must know what is happening. Kirby and Westwater [9] reported in 1965 on a study in which they overcame the difficulty by photographing nucleate boiling through a transparent surface upon which boiling was occurring. They studied boiling of carbon tetrachloride. Above 50% of the peak heat flux, they began to observe the appearance of what they classified as Type III bubbles. Type III bubbles appeared to be bubbles growing within bubbles. They stated "their real importance is that they point out the existence of a liquid film under large vapor patches." Type III bubbles had lives of less than 1.5 ms. The bubbles would "suddenly burst leaving only a small wake as a clue to its disappearance."

Type III bubbles sometimes were followed immediately by the appearance of a dry spot on the heater surface. The dry spots sometimes grew in size and neighboring ones would merge. The typical life of a dry spot was about 10 ms. Near the peak heat flux, the dry spots were common and coalescences of dry spots were common also. Kirby and Westwater surmised that dry spots in the film presumably signal the approach of the peak heat flux.

Ishigai and Kuno [5] in 1966 reported on a study in which they boiled water on the outside surface of a vertical steam heated tube. They studied boiling from nucleate boiling through the peak heat flux and into transition boiling. They instrumented the surface with a thermocouple which they recognized would not give as true an indication as they would wish. However, they still hoped to detect differences in the types of boiling. They also devised a probe to detect electrically when steam covered the surface. By simultaneously recording the thermocouple and probe signals, they showed that the surface temperature rose when the probe indicated that steam covered the surface.

Ishigai and Kuno concluded that in the high heat flux region of nucleate boiling, a water film always stays on the boiling surface even when the surface is seemingly covered entirely with bubbles. When the heat flux is increased, the water film occasionally evaporates completely as an indication of the approach to the peak heat flux. At first this complete drying happens infrequently. As the surface temperature rises, the probability of complete drying increases gradually. This, they proposed, accounts for the shape of the boiling characteristic curve which is smooth and continuous through the peak heat flux into transition boiling.

Katto and Yokoya [7] reported in 1968 on a study in which they boiled water at high heat fluxes near the peak. They studied boiling on a copper surface 10 mm in diameter with a transparent optical system 2 mm above. They simultaneously photographed both a side view of the boiling and a plan view of the surface through the optical system. Large vapor bubbles would periodically fill the space between the surface and optical system. They observed that a liquid film remains on the surface the whole cycle when the surface temperature was not too high. Ebullition was observed in the liquid film. At higher surface temperatures, when the peak flux was approached, dry spots sometimes appeared and grew in the liquid film. They claimed that the peak heat flux occurs because of a balance between the consumption of the liquid film on the heated surface and the supply of liquid through the intermittent removal of vapor masses. They surmised that the thickness of liquid film near the peak heat flux was 0.1 mm when initially formed. They also claimed that if more liquid is supplied to the liquid film by any means, the peak heat flux is increased. In summarizing part of their results, they concluded that nucleate boiling at high heat fluxes is characterized by nucleate boiling within a liquid film on the heated surface and its production of vapor.

Iida and Kobayasi [4] reported in 1969 the results of a study of the distribution of void fraction above a horizontal heating surface in pool boiling of water. They devised a probe which enabled them to detect the presence of liquid at the tip of the probe. They found evidence that a thin liquid-rich layer existed on the surface during nucleate boiling at a relatively high heat flux. The evidence suggested to them that nucleate boiling under such conditions was governed by the liquid-rich layer. They mentioned an average thickness for the layer near the peak heat flux as 0.2 mm.

The liquid film on the surface reported by these several investigators will be termed the macrolayer in the rest of this paper. This will permit a clear distinction to be made between the macrolayer and what has come to be known as the microlayer. The microlayer is the liquid film which is formed between a bubble and the surface when an individual bubble grows on a surface during nucleate boiling. Figure 1 illustrates both the microlayer and macrolayer.

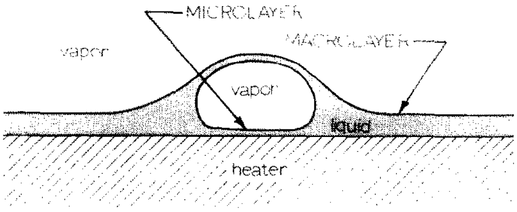

FIG. 1. Illustration of the microlayer and macrolayer.

The unique characteristic of the microlayer is that it removes heat from the surface underneath the bubble at an extremely fast rate by its rapid evaporation. Its rapid evaporation is promoted by its thickness of only 1–10 μm and the fact that it is formed rapidly on a hot surface. Its small thickness can produce a large temperature gradient through the microlayer if the surface is a material with better thermal properties than the liquid.

Quite a variation has been reported in the duration of cooling from microlayer evaporation. Times of 0.2–40 ms have been reported. The rapid cooling is terminated either when the microlayer dries up or when deeper liquid returns to the surface as when the bubble detaches. Longer duration cooling has been observed when bubbles continue to grow large and remain on the surface for a long time as frequently occurs when boiling at low pressures. Cooper and Lloyd [1] report cooling beneath a toluene bubble formed at 7 kPa for up to 40 ms. Foltz and Mesler [2] report a duration of 40 ms with water at 25 kPa. At atmospheric pressure, bubbles are usually on the surface a much shorter time. Hospeti and Mesler [3] reported on boiling water at atmospheric pressure and observed cooling of from 2.5 to 7.5 ms with the shorter times being more common. There was evidence of microlayer dry-out because while the bubbles still remained on the surface, the temperature beneath the bubbles rose. Bubbles usually remained on the surface 10–20 ms although one bubble stayed 90 ms.

The shortest duration cooling has only recently been reported by Mesler [14]. Cooling periods of as short as 0.2 ms were observed. Such short periods of cooling are the result of bubbles growing in a liquid film. As was observed by Kirby and Westwater, bubbles growing in a liquid film have a short life and can detach quickly. There was no evidence of dry-out.

Other investigations have been concerned with boiling in thin liquid films. Nishikawa *et al.* [16] varied the depth of water from 1 to 30 mm. They report improved boiling heat transfer with decreasing depths below 5 mm. Kusada and Nishikawa [12] extended the study to depths less than 1 mm where boiling became unsteady and the surface began to dry. The best heat transfer occurred when water still wet 70% of the area.

Kopchikov *et al.* [10] report that the peak heat flux is much greater when boiling with thin liquid films applied to the surface as a spray than during pool boiling. Water, ethanol, carbon tetrachloride and benzene were studied at pressures from 10 to 100 kPa.

Toda and Uchida [19] have reported achieving exceptionally high heat transfer rates to films of water 0.2–0.7 mm thick flowing over a surface at 2–10 ms. They report a jump phenomenon occurs at high heat fluxes in which the greater part of the liquid film jumps up over the heating surface due to vast amounts of vapor generated by vigorous boiling. Even so, the heating surface remains covered with a thin liquid film showing intense nucleate boiling. At still higher heat fluxes, part of the thin liquid film begins to dry up.

Two different theoretical approaches have been used to explain peak heat fluxes in nucleate boiling. The older theory considered the hydrodynamics of the flow of vapor outward against the inflow of liquid. This theory by Kutateladze [13] and Zuber [22] predicted the peak heat flux in pool boiling of saturated liquids in simple situations quite well. An implicit assumption was that any liquid which did get to the surface would remove heat.

Katto *et al.* [8] and Torikai and Akiyama [20] have shown that a new theory is necessary because there are several effects which are not dealt with by the older theory. The new theory considers a liquid film which is able effectively to cool the surface even though it does not continuously cover the entire surface. The newer theory can predict higher heat fluxes because it considers that in certain cases more liquid is supplied to the surface film than the hydrodynamics of the simpler situation would permit. Instances where the supply can be greater are where there are jets such as studied by Toda and Uchida [19], where there are sprays as studied by Kopchikov *et al.* [10] and where the liquid has a temperature below saturation as studied by Ponter and Haigh [17].

The object of this research was to measure transient surface temperature at heat fluxes near the peak to determine whether important deductions might then be possible concerning the behavior of the macrolayer and the microlayer.

EXPERIMENTAL APPARATUS

The apparatus was designed to permit high speed cinephotography and simultaneous measurement of transient surface temperature during nucleate boiling. The boiling surface was contained in a vessel with windows. A portion of the bottom of the vessel was raised to the level of the windows and the boiling surface was located at the center of the raised portion. This provided a good view of the boiling. The top of the vessel had holes for a condenser and for insertion of an immersion heater. Figure 2 shows a drawing of the arrangement.

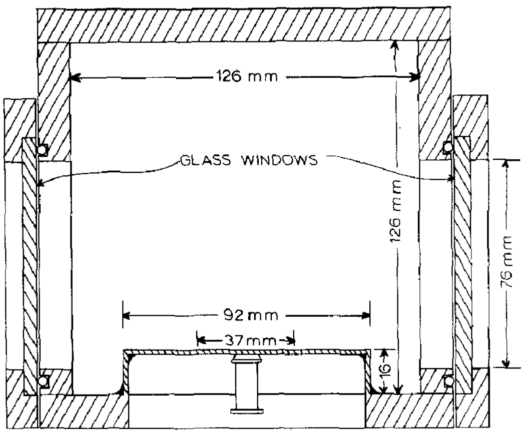

FIG. 2(a). The boiling vessel.

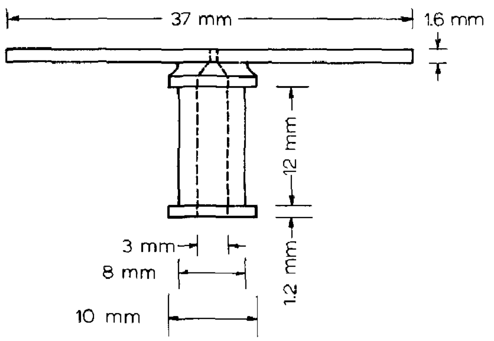

FIG. 2(b). Dimensions of the boiling surface.

Boiling occurred on a Chromel *P* disk 37 mm in diameter and 1.6 mm thick. Only a circular area 8 mm in diameter at the center was heated so that boiling would occur away from the influence of surface discontinuities. The transient surface thermocouple was located at the center of the disk.

The thermocouple was the same type as used by Moore and Mesler [15] and Hospeti and Mesler [3]. Its construction is described by Kovács and Mesler [11]. It consisted of 0.13 mm dia Alumel wire insulated with a thin coating of aluminum oxide and installed in a Chromel tube 0.71 mm O.D. Both the Chromel and Alumel were thermocouple alloys. The tube was drawn through a 0.64 mm hole in the Chromel disk and cut flush with the surface. Polishing produced an open circuit between the Alumel wire and the Chromel tube. The thermocouple junction was made by bridging the insulation with a scratch made with a needle. The surface was again polished. Heat was supplied electrically to a piece of copper beneath the center of the disk. A copper rod 8 mm in diameter by 16 mm long and with a 3 mm axial hole, but only 1.5 mm near the bottom, was silver soldered to the bottom of the Chromel disk before installation of the thermocouple as shown in Fig. 2. The hole through the copper was concentric with the hole through the Chromel disk. About 0.3 m of Nichrome wire was wound on mica around the copper rod. This was then covered with

Sauereisen No. 7 high temperature cement. Silicone rubber was placed over the thermocouple connections. Then, the region surrounding the copper was potted in high temperature cement.

The signal from the thermocouple was displayed on a Tektronix 531 oscilloscope with a 1A7 pre-amplifier. A small reference voltage was first subtracted from the thermocouple signal using the circuit in Fig. 3. This permitted amplification of signal variations about the reference for better viewing. It was still possible to determine DC voltages by adding the reference to the difference. The reference voltage was read with a laboratory potentiometer.

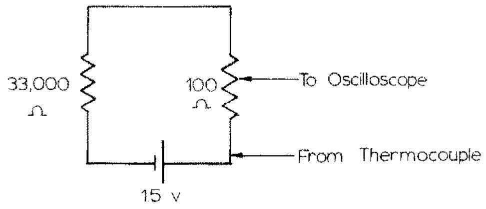

FIG. 3. Reference voltage source.

A Fastax *WF 17* camera was used for cinephotography. This camera has dual lenses. This arrangement permits an oscilloscope streak to be superimposed on the bubble image. A Wollensak Fastax Control Unit controlled camera speed. Film speeds of 1500–4000 f/s were used. Timing line marks on the film were provided at 1000 Hz with a Milli-Mite Timing Light generator.

A three phase rectifier with variable voltage control and, at times, a heavy duty 12V battery in series provided DC current for heating. Current and voltage were measured to determine heat input. The maximum rating of the rectifier was 15V and 125A.

ANALYSIS OF HEAT TRANSFER

Evaporation of a thin liquid film on a solid surface has been modeled one dimensionally by several investigators studying microlayer evaporation. It is of interest here to extend such a model to consider the evaporation of the relatively thicker macrolayer. The model developed here is an extension of the one described by Foltz [2]. The model makes the following assumptions:

(i) Heat conduction is one dimensional.
(ii) The surface is on a semi-infinite solid.
(iii) The temperature varies linearly across the liquid film.
(iv) The heat flux across the liquid film is

$$\frac{q}{A} = \frac{k_L}{\delta}(T_W - T_{sat}). \qquad (1)$$

The heat-conduction equation is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (2)$$

with boundary conditions:

$$k_s \frac{\partial T}{\partial x} = \frac{k_L}{\delta}(T - T_{sat}) \quad \text{at } x = 0 \qquad (3)$$

$$-k_s \frac{\partial T}{\partial x} = \frac{q_0}{A} \quad \text{for large } x \qquad (4)$$

$$T(x,0) = T_{w0} - \frac{q_0}{A} k_s x \quad \text{for } x \geqslant 0. \qquad (5)$$

Equation (2) was solved by standard numerical techniques with a Fortran IV program on a Honeywell 635 computer. With an initial specification of film thickness and surface temperature, a new temperature distribution at the next time step is calculated. The instantaneous heat flux determined by equation (1) evaporates a small portion of the liquid during the time step.

$$\Delta\delta = \frac{q}{A}\frac{\Delta t}{\rho_L \lambda} \qquad (6)$$

reducing the thickness. The process is then repeated with new values of film thickness and surface temperature. When δ became less than 0.4 μm, it was necessary to extrapolate the heat flux with a third order polynomial instead of using equation (1) to avoid an erratic behavior caused by the δ in the denominator of equation (1).

The surface temperature calculated through the use of this model for an interesting case is shown in Fig. 4.

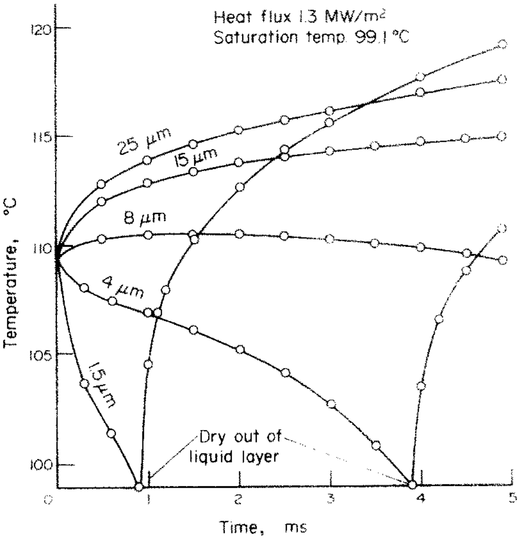

FIG. 4. Calculated surface temperatures beneath an evaporating liquid film.

The heat flux is 1.3 MW/m², the initial temperature 109.4°C. The initial film thickness is a parameter, varied between 1.5 and 25 μm. Saturation temperature is 99.1°C. For an initial thickness of 8 μm, the temperature is seen to remain relatively constant. For thicker films, it rises while for thinner films, the temperature falls until the film dries out. Following dry out, the temperature rises rapidly.

Shown in Fig. 5 is the predicted surface temperature for evaporation of a typical microlayer.

RESULTS AND DISCUSSION

The typical transient temperature behavior underneath a growing bubble observed in a preliminary

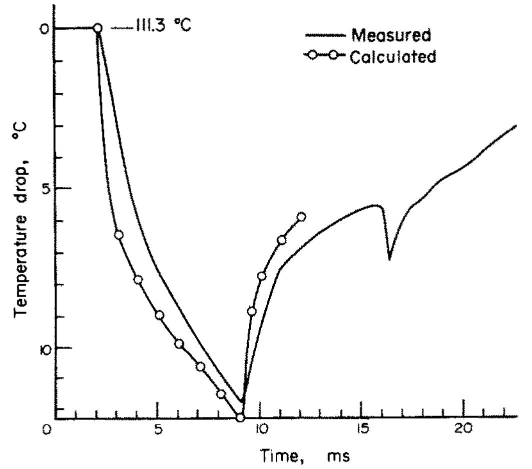

FIG. 5. Experimental and predicted surface temperatures beneath an evaporating microlayer.

phase of the study is shown in Fig. 5. The surface temperature drops suddenly when a bubble grows over the surface. The cooling is caused by evaporation of the microlayer formed as the bubble grows over the surface. Suddenly, after 7 ms, the surface temperature rises indicating the microlayer has completely vaporized since simultaneous cinephotography shows the bubble is still on the surface. The warming is interrupted briefly about 7 ms later at the instant when liquid returns to the surface as the bubble detaches. Liquid returning to the surface is able to cool the surface very little compared to cooling from microlayer evaporation. Sometimes bubbles leave the surface before the microlayer dries out. Shown for comparison in Fig. 5 is the surface temperature predicted using the model developed earlier and an initial microlayer thickness of 4 μm chosen to give the same dry out time.

The surface temperature at or near the peak heat flux exhibits a variety of patterns. At times, the behavior changes through a series of stages with no adjustments being made in the heat input. One such progression is shown in Fig. 6. The initial behavior is shown in (a). Short periods of higher temperature are next observed in (b). Higher temperatures then occur more often as in (c) until finally the higher temperatures persist (d), and it is necessary to reduce the rate of heat input to avoid an excessive temperature. The periods of higher temperature apparently indicate the surface around the thermocouple is dry. This general behavior seems to correspond with the reports of Ishigai and Kuno, Katto and Yokoya and Iida and Kobayasi regarding the tendency of the surface to dry near the peak heat flux.

At times, other interesting details of the surface temperature behavior near the peak heat flux can be observed. These can be seen in Fig. 7. At first, a drop in temperature of 5°C occurs in about 3 ms, followed by a rapid temperature rise to 25°C above saturation in 20 ms. A liquid film evaporated completely to provide the initial cooling. Then, a dry surface allowed the rise in temperature. Suddenly, there is a 5°C drop in temperature for 2–3 ms and then a sudden further drop of 15°C. The initial drop is apparently due to a liquid water quench. When two bodies with an initial temperature difference of ΔT are brought into perfect contact, the interface temperature change of the first can be calculated as [15]:

$$\Delta T_{\mathrm{I}} = \frac{(k\rho c)_{\mathrm{II}}^{1/2}}{(k\rho c)_{\mathrm{I}}^{1/2} + (k\rho c)_{\mathrm{II}}^{1/2}} \Delta T.$$

With values for Chromel and liquid water, this becomes for the Chromel:

$$\Delta T_{\mathrm{I}} = 0.17 \Delta T.$$

If the water that is quenching the surface is at the saturation temperature, then ΔT is 25°C and ΔT_{I} is 4°C. This is in reasonable agreement with the observed 5°C change. The surface temperature in Fig. 5 shows a quench when liquid returns as the bubble departs.

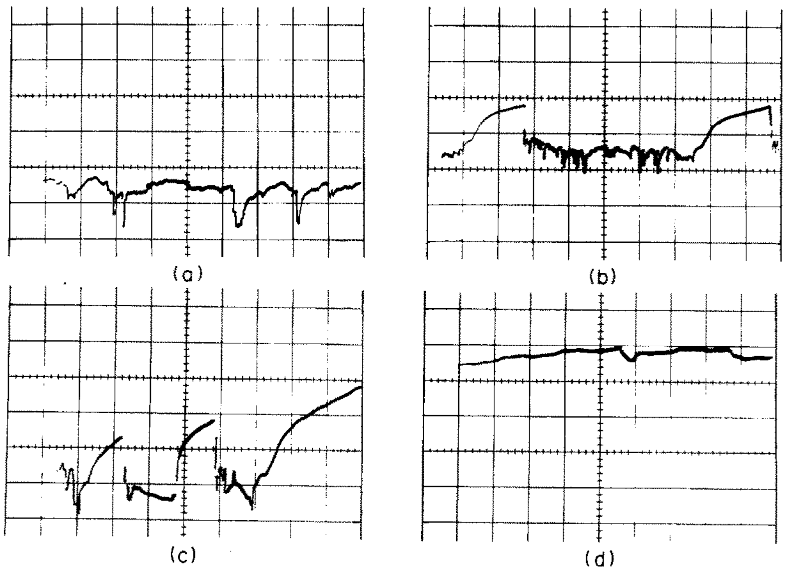

FIG. 6. Transient surface temperature at 1.4 MW/m^2.

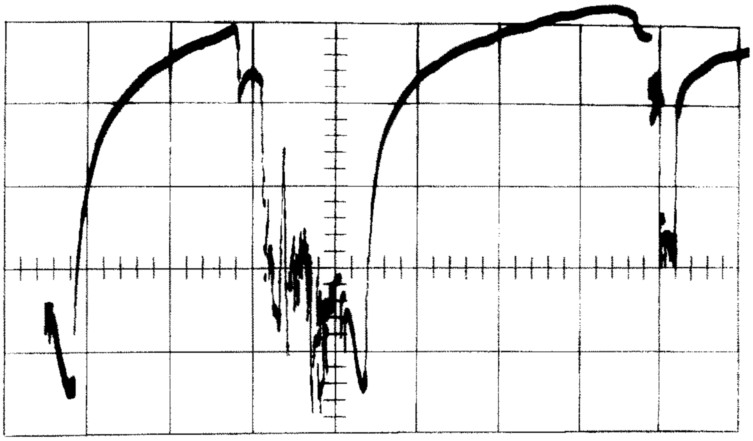

FIG. 7. Transient surface temperature at 1.3 MW/m^2.

The next 15°C drop in temperature is part of many repeated rapid changes in surface temperature. These rapid changes occur so fast that little detail can be seen because the oscilloscope sweep rate was not fast enough. Another technique proves useful in elucidating this behavior.

Following the rapid temperature fluctuations is a period of smooth temperature decline similar to the first. The temperature then repeats the cycle.

Streak photography of the oscilloscope using the Fastax camera proves useful in resolving the rapid temperature changes and in supporting the previous observations. The streak is superimposed on motion pictures of the bubbles. This technique greatly expands the time scale and still covers a much longer time. One hundred and ninety-two frames in 1.5 m of 16 mm film covering 112 ms are produced in Fig. 8. The heat flux was near the peak. This portion was chosen as representative of several rolls of film.

The white line down the scene is the oscilloscope record. Temperature decreases as the line moves to the right. Across the scene represents 28.5°C. The filming rate is 1705 f/s. Small white marks on the film are 1 ms timing marks.

The pictures show a scene 1.1 cm wide over the center of the disk where intense boiling is occurring. Although vapor can be seen leaving the surface, there is always vapor over the surface. The white lines representing the temperature in Fig. 8 have been traced to make them easier to see. These are reproduced in Fig. 9.

The rapid temperature changes are seen between frames 1 and 9 and between 48–74. These are seen to include short cooling periods of 0.1 to 0.5 ms duration. The cause of these short cooling periods was at first elusive. The short duration is a unique attribute which is predicted by just one of many hypotheses considered. That hypothesis is that the cooling is caused by microlayer evaporation beneath bubbles that are growing in a macrolayer. Kirby and Westwater [9] and Katto and Yokoya [7] have reported that bubbles do grow in the macrolayer. The duration of the cooling is short because the bubble life is short in a thin film. The liquid water that initially returns to the surface apparently forms a thin film or macrolayer. Mesler [14] has recently reported experimental support for the short duration cooling due to microlayer evaporation beneath bubbles growing in liquid films.

From 9 to 34, 74 to 95 and 128 to 143, the surface remains relatively cool and there are no short duration cooling periods. The absence of these suggests that the surface is covered with a macrolayer sufficiently thin that adequate cooling is provided by its evaporation without the surface temperature ever rising to the temperature necessary for nucleation. Thus, nucleation is suppressed. The abrupt increases in temperature at 34 and 143 apparently indicate the macrolayer has dried out at these times.

Following the abrupt rises at 34 and 143, the temperature continues to rise more slowly to 48 and 191. This behavior is consistent with the notion that the surface dried out at 34 and 143. The drops in temperature at 48 and 191 are apparently liquid water quenches as discussed previously.

From 45 to 128, a few short periods of cooling occur. Most of these are of about 0.1 ms duration but just before 128 there is one of 1.5 ms duration.

Two different modes of cooling can be distinguished in the preceding discussion. First, there is direct evaporation from the top of the macrolayer. Second, there is microlayer evaporation associated with bubble growth in the macrolayer.

From 9 to 34 and from 128 to 143 are periods of 15 and 8 ms respectively. During both these periods, the temperature passes through a maximum before exhibiting an abrupt jump when the macrolayer dries out. It is apparent that heat transfer from macrolayer evaporation exceeds the heat flux supplied since the temperature at dry out is the lowest. From 74 to 95, heat transfer from macrolayer evaporation must nearly balance the heat supplied since the temperature stays relatively constant.

The macrolayer thickness must evidently be determined by a balance between loss by evaporation and entrainment and gain by addition of liquid as might result from drop impingement. Since liquid additions cannot presently be directly observed or measured,

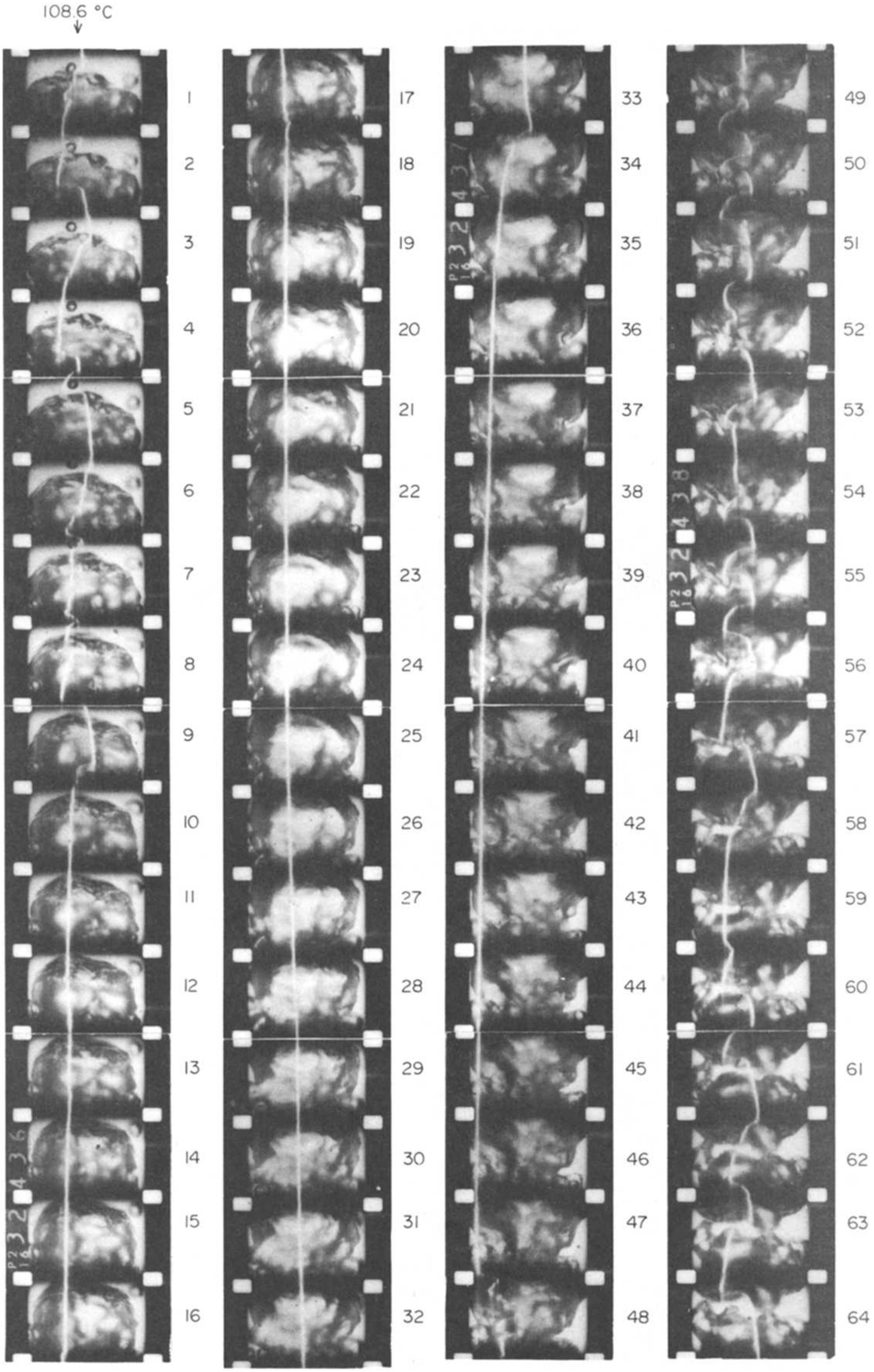

FIG. 8. Cinephotography of boiling at 1.3 MW/m^2 with simultaneous surface temperature indication superimposed. The continuous white line is the oscilloscope indication of the temperature which lags the bubble picture by 5 frames. Across the scene is 28°C and 1.1 cm. White marks on the right edge are ms timing marks. The picture rate is 1705 f/s.

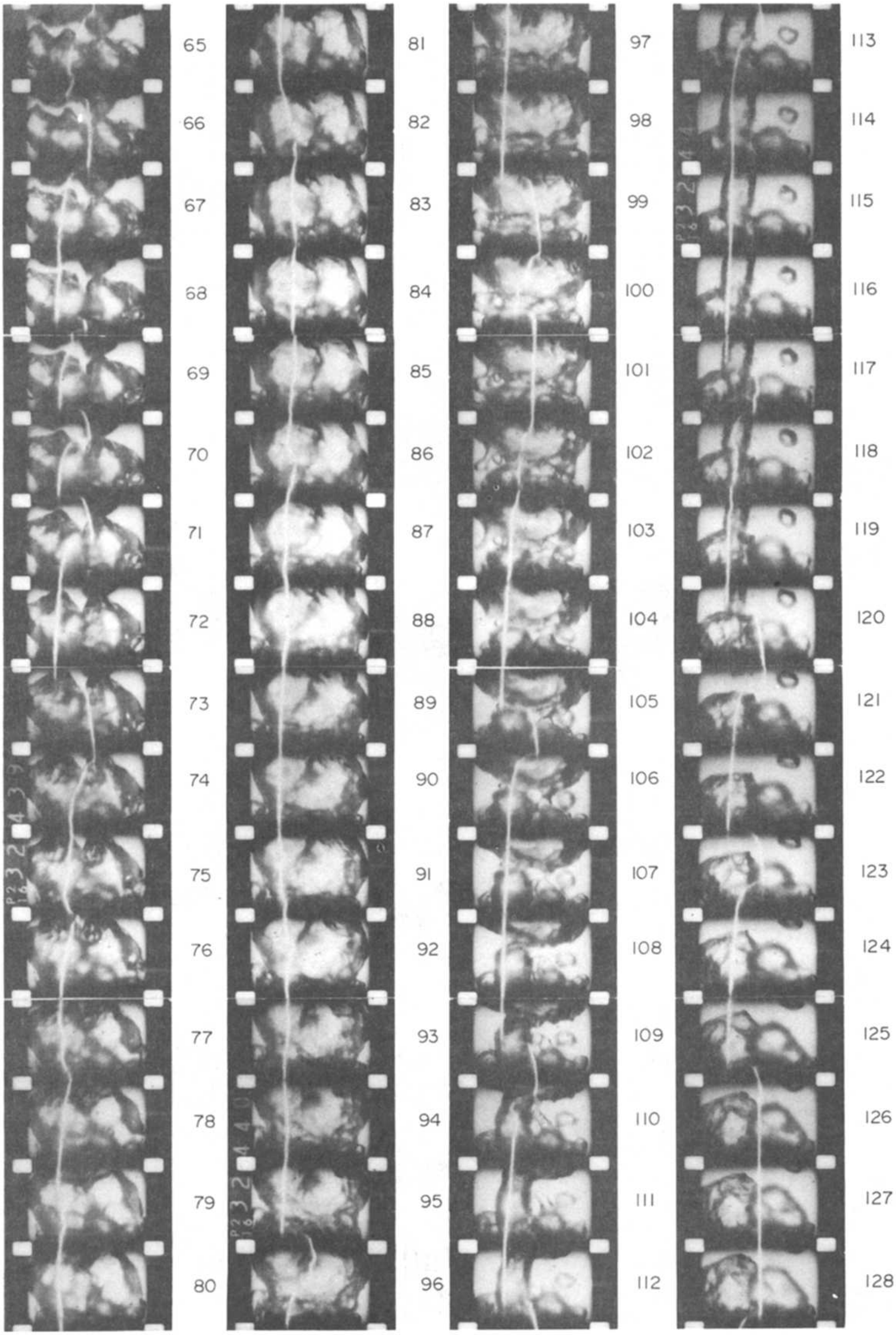

FIG. 8. *Continued.*

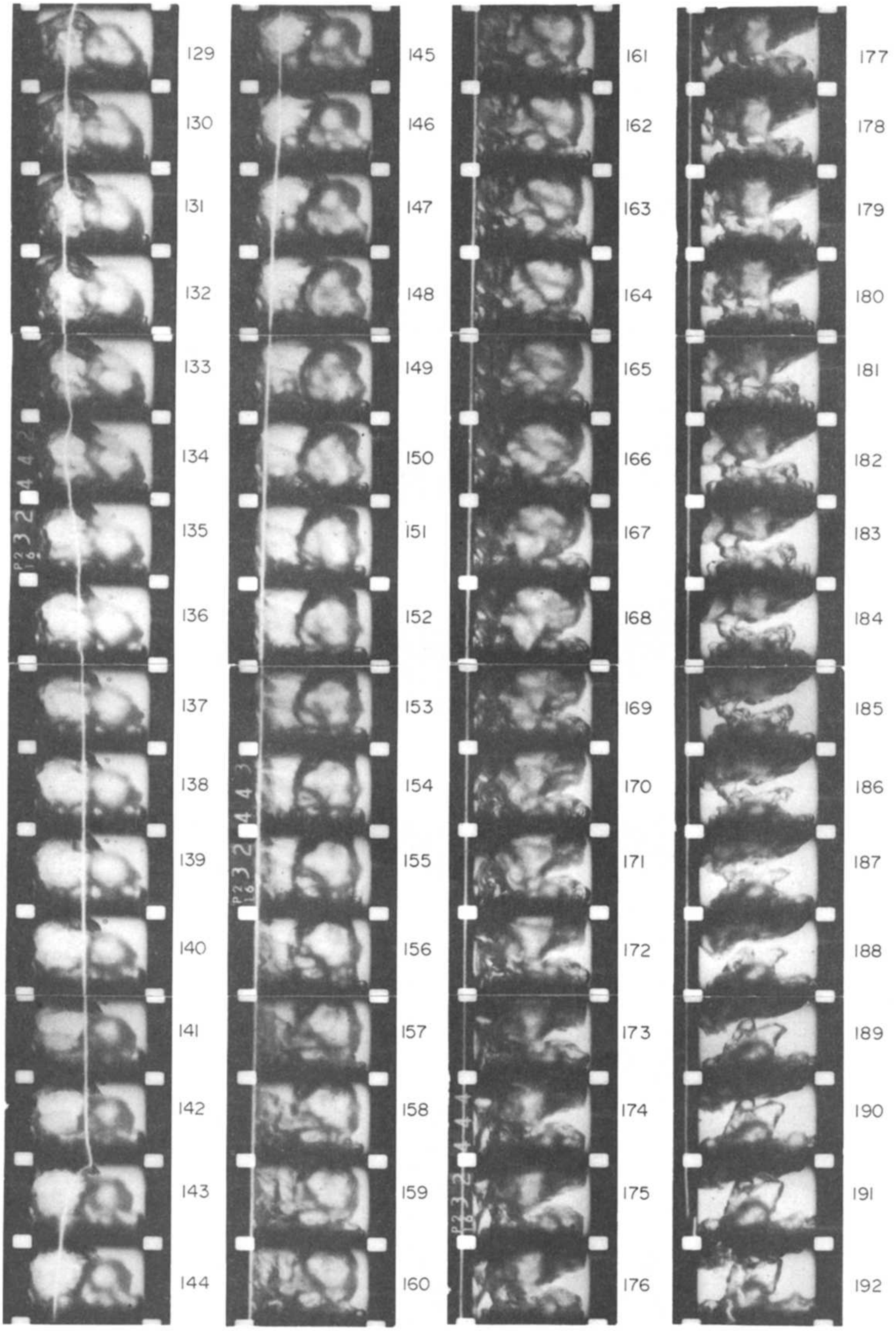

FIG. 8. *Continued.*

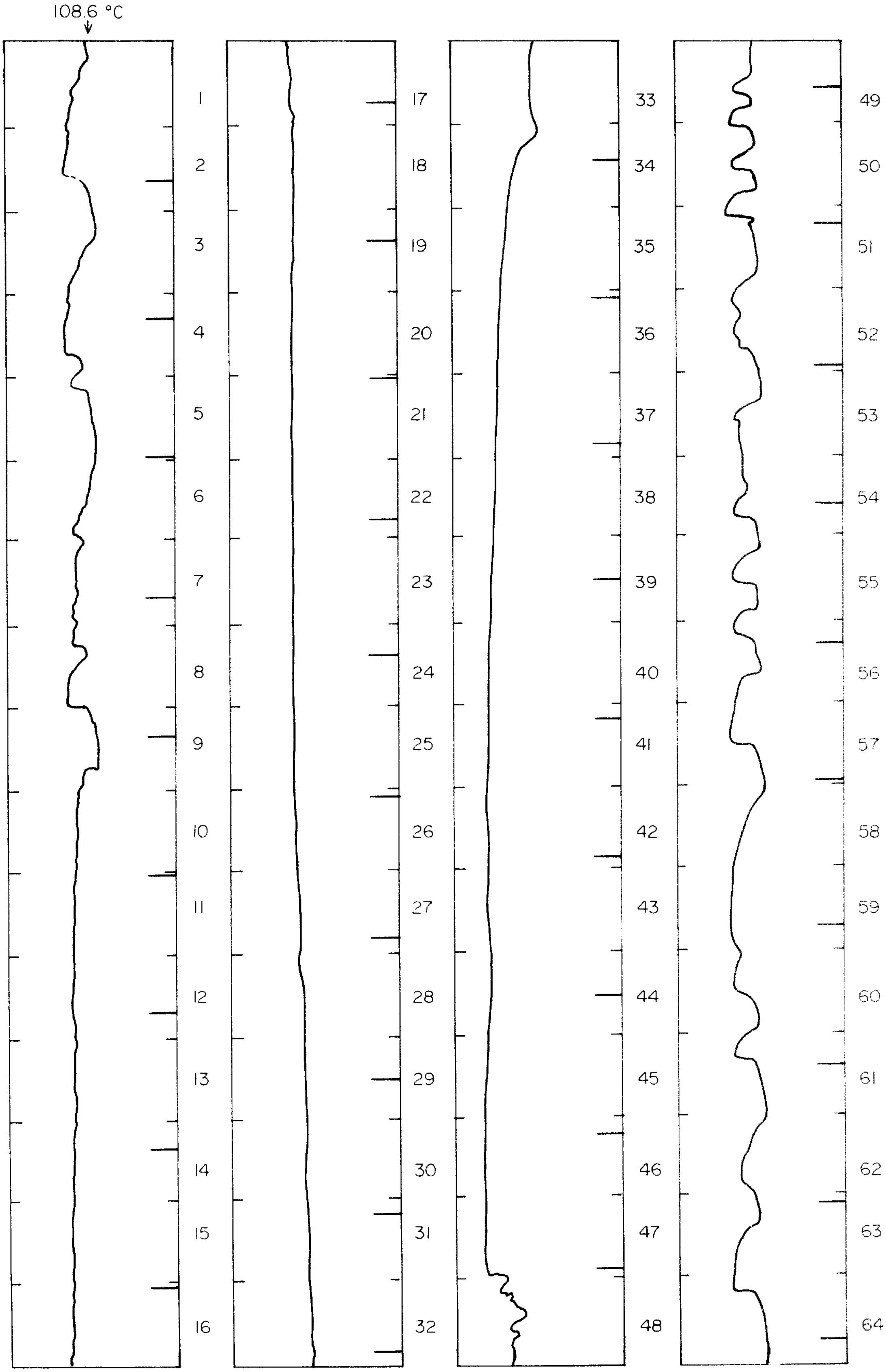

FIG. 9. Temperature indication traced from Fig. 8.

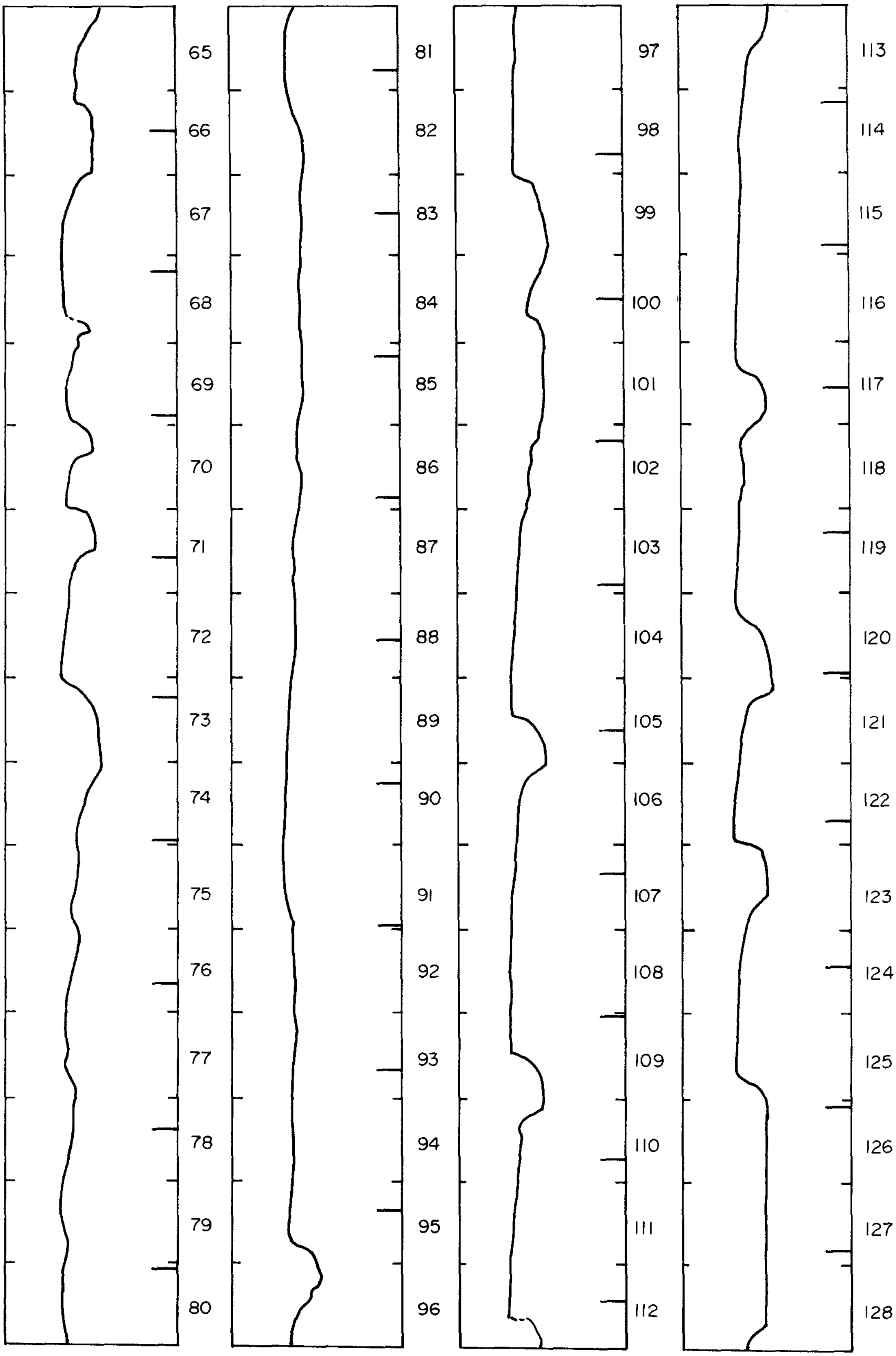

FIG. 9. *Continued.*

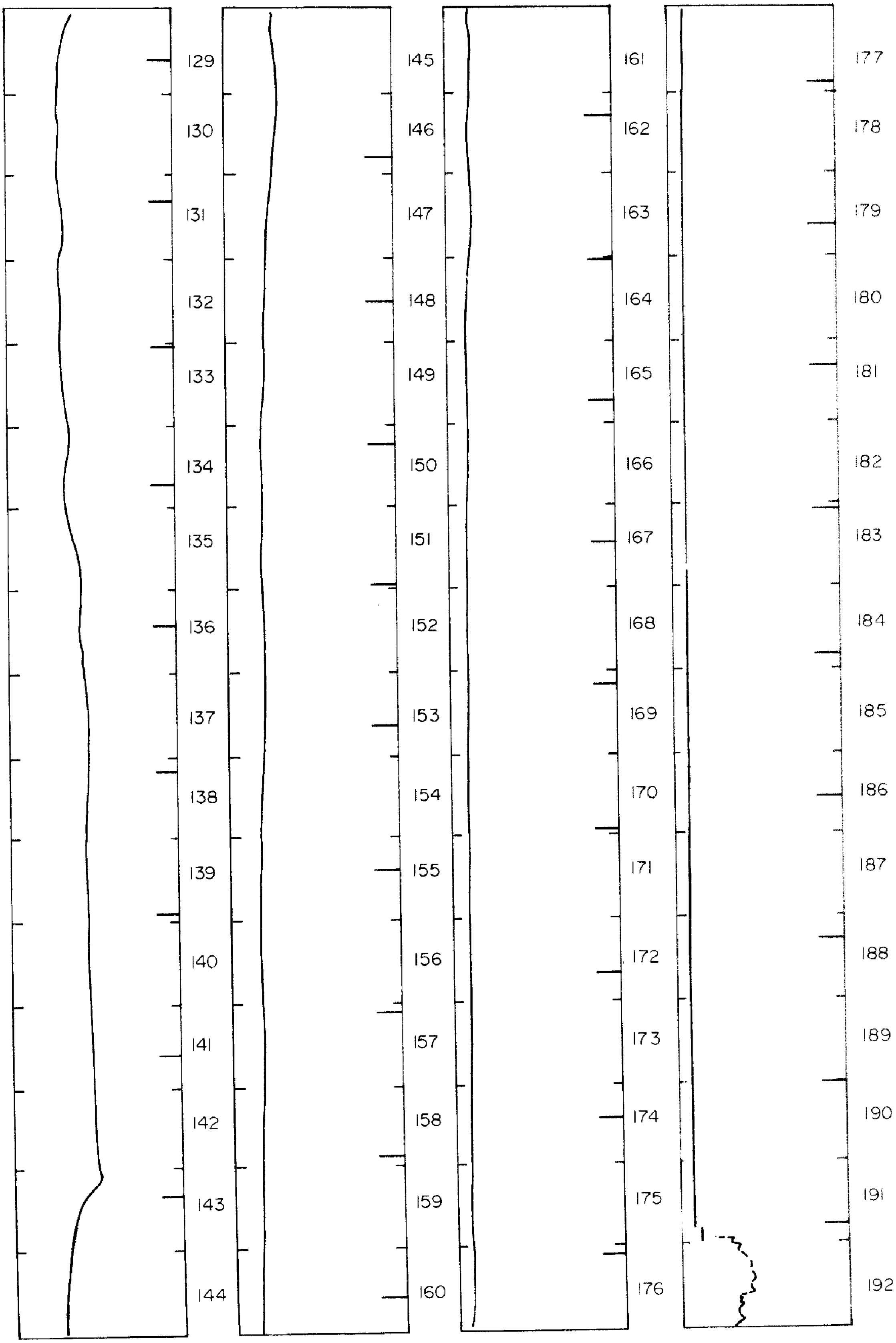

FIG. 9. *Continued.*

possibly the best that can be done is to infer them from the surface temperature beneath the film. An increase in film thickness would cause the surface temperature to rise and cause increased ebullition in the macrolayer.

The thickness of the macrolayer when nucleation is suppressed may be examined in two ways. First, the heat input rate corresponds to a certain loss rate of macrolayer thickness, assuming no liquid deposition. The product of loss rate and time to evaporate provides an estimate of the initial thickness. At 1.3 MW/m^2, the loss rate is 0.6 mm/s. The durations of 9–34 and 128–143 are 15 and 8 ms giving thicknesses of 9 and 4.8 μm respectively. Another assessment of the thickness is possible by referring to Fig. 4 which was prepared for similar parameters. Figure 4 displays temperature behavior for 4 and 8 μm thick macrolayer evaporation which are similar to the observed behavior.

From 1 to 9 and 48 to 74 are periods of 5 and 16 ms, respectively, when there is much evidence of microlayer evaporation. The period from 49 to 74 was analyzed to estimate the heat transfer due to microlayer evaporation. In each cooling period, the surface was assumed to change to a constant lower temperature for the period. For the surface of a semi-infinite solid, the heat transfer per unit area may be calculated as [14]:

$$\frac{Q}{A} = \frac{2\Delta T k(t)^{1/2}}{(\pi\alpha)^{1/2}}.$$

There are 18 cooling periods with durations of from 0.13 to 0.57 ms during the 16 ms. The temperature drop is 9.7°C. The average heat flux was computed by summing the heat transfer per unit area for each cooling period and then dividing by 16 ms to give 1.9 MW/m^2. The average heat input is 1.3 MW/m^2. The estimated cooling rate is thus 46% greater.

Ebullition in the macrolayer begins again at 95. This continues for 20 ms. During this time, evaporation could occur from both microlayer and macrolayer evaporation. The average heat flux accounted for by microlayer evaporation and calculated in the same manner as before is 0.8 MW/m^2 compared to the heat input of 1.3 MW/m^2. Macrolayer evaporation could easily account for the difference.

CONCLUSIONS

The results of this investigation support the views of many recent investigators who report that the behavior of a liquid film or macrolayer on the surface is of utmost importance in nucleate boiling of water near the peak heat flux. The macrolayer is transient and frequently dries up completely. Transient temperature measurements indicate several new details which suggest the following understanding of macrolayer behavior: when liquid returns to the dry surface, it sometimes first quenches the surface for a very short time, a few ms or less. The cooling the surface exhibits during the quench is much less than that which follows. The surface temperature falls repeatedly for many short periods. These short cooling periods are only fractions of milliseconds and appear to be caused by microlayer evaporation beneath tiny bubbles whose life is short because they can readily escape from the thin macrolayer. More than the average heat input can be removed through this process. Ebullition ceases prior to dry out presumably because evaporation from such a thin macrolayer keeps the temperature low enough to suppress nucleation. When the surface is dry, the surface temperature increases, rapidly at first.

Both evaporation of the microlayer and macrolayer result in vapor generation at the surface. The existence of a liquid film on the surface is an indication that there is very little liquid near the surface and thus, little opportunity for liquid convection to carry much heat away from the surface. Conduction by vapor would be small. Thus, it appears that latent heat transport is responsible for nearly all of the heat transferred at heat fluxes near the peak heat flux.

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ETUDE DE L'EBULLITION NUCLEEE, PRES DU PIC DE FLUX THERMIQUE, A PARTIE DE LA MESURE DE LA TEMPERATURE VARIABLE DE SURFACE

Résumé—Des mesures de la température variable de la surface, pendant l'ébullition nucléée de l'eau aux flux thermiques élevés, sont en faveur de l'idée de plusieurs investigateurs selon laquelle un film liquide, appelé la macrocouche, existe sous une agglomération de bulles de vapeur et est responsable du transfert de chaleur. La macrocouche s'assèche et se reforme alternativement. Lors des réapparitions, la température de surface chute de façon répétée pendant de brèves périodes. Ceci est apparament causé par l'évaporation d'une microcouche sous les bulles en croissance dans la macrocouche. Parfois un refroidissement bref précède l'ébullition. L'évaporation de la macrocouche juste avant qu'elle s'évapore complètement, refroidit efficacement la surface et l'évidence de la nucléation est par suite absente.

EINE UNTERSUCHUNG DES BLASENSIEDENS IN DER NÄHE DER MAX. WÄRMESTROMDICHTE MIT HILFE DER MESSUNG DES INSTATIONÄREN TEMPERATURVERLAUFES IN DER OBERFLÄCHE

Zusammenfassung—Die Messung des instationären Verlaufes der Oberflächentemperatur während des Blasensiedens von Wasser bei hohen Wärmestromdichten unterstützt die Ansicht vieler Forscher, daß ein Flüssigkeitsfilm, hier Makroschicht genannt, unter einer Ansammlung von Dampfblasen existiert, und diese Schicht für den Wärmeübergang ausschlaggebend ist. Die Makroschicht trocknet wiederholt aus und bildet sich erneut. Bei der Ausbildung der Makroschicht fällt die Oberflächentemperatur jeweils für kurze Augenblicke ab. Dies ist offensichtlich durch die Verdampfung einer Mikroschicht unterhalb der in der Makroschicht wachsenden Blasen bedingt. Manchmal geht der Verdampfung ein kurzes Quenching voraus. Die Verdampfung der Makroschicht kurz vor deren Austrocknung kühlt die Oberfläche sehr wirksam und es tritt dann keine Blasenbildung ein.

ИССЛЕДОВАНИЕ ПУЗЫРЬКОВОГО КИПЕНИЯ В ОБЛАСТИ ПОЧТИ МАКСИМАЛЬНОГО ТЕПЛОВОГО ПОТОКА ПУТЕМ ИЗМЕРЕНИЯ НЕУСТАНОВИВШЕЙСЯ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ

Аннотация — Измерения неустановившейся температуры поверхности при пузырьковом кипении в области больших тепловых потоков говорят в пользу точки зрения многих исследователей о том, что под скоплением пузырьков существует жидкая пленка, называемая здесь макрослоем, которая вносит основной вклад в процесс переноса тепла. Время от времени макрослой частично высыхает и перестраивается. При его перестройке температура поверхности неоднократно падает на короткие периоды времени. Это, очевидно, связано с испарением микрослоя под пузырьками, растущими в макрослое. Иногда бурному кипению предшествует кратковременное затишье. Испарение из макрослоя непосредственно перед его полным исчезновением эффективно охлаждает поверхность, и тогда не остается никаких следов зарождения пузырьков.