STATE UNIVERSITY OF NEW YORK
AT STONY BROOK

COLLEGE OF
ENGINEERING

Report No. 36

ON LIQUID-SOLID CONTACT IN STABLE FILM BOILING

by

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APRIL 1965

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Introduction

There appear to be some questions remaining concerning the existence of liquid-solid contact in the "stable" film boiling regime of heat transfer. The purpose of the present note is to present experimental evidence of the existence of such contacts as well as some of the effects on heat transfer phenomena which result.

Experience has shown that liquid-solid contact can be achieved at stable film boiling temperatures by any means which will induce surface roughness elements to tickle the liquid-vapor interface. Observed methods include increasing surface roughness until contact is achieved; setting the interface into motion normal to the surface such that periodic contact is forced; subcooling the bulk liquid (or establishing forced convection or both) to thin the gas layer at constant surface roughness until contact results; and the use of external fields such as electrostatic fields or pressure fields to force the liquid into contact with the surface.

Evidence of momentary liquid-solid contacts at temperatures well above the normal transition temperature was reported in 1960 by Bradfield, Barkdoll, and Byrne [1]. These were quenching experiments with varying magnitudes of subcooling. At about the same time, Berenson [2] published the results of a steady state investigation of effects of surface roughness on heat flux in the transition range with saturated liquids. With these experiments as background, Bankoff and Mehra [3] constructed a theory for enhanced heat flux due to surface roughness based on plausible physical assumptions concerning partial liquid-solid contact in the transition boiling regime. The result was an expression for heat flux from the solid surface to the liquid per contact given as

$$q = 2kt_i \left(\frac{\tau_c}{\pi \alpha}\right)^{1/2} \tag{1}$$

where k is the liquid thermal conductivity, t_i is the liquid-solid interface temperature, α is the liquid thermal diffusivity and τ_c is the time of liquid-solid contact. This time was tentatively evaluated by comparison with frequency data in the transition boiling range [4, 5].

The present observations show that such contacts need not be limited to the transition boiling regime and they provide additional information as to different types and durations of contact possible. The data is taken from droplet film boiling studies at constant surface temperature and from quenching studies.

Discussion of Experimental Studies

Film boiling droplet studies have the advantage of providing direct photographic access to the gas-liquid interface and so are useful for furnishing visual evidence of liquid-solid contact. Figure 1 is a frame from a high speed motion picture and shows stable droplet film boiling in the absence of liquid-solid contact. Depicted is a 0.150 inch distilled water droplet film boiling above a pure copper plate (k = 235 Btu/ft in $^{\circ}$F) at a plate temperature of 580°F. The copper surface was chromed to a mirror finish so that the reflection of the droplet in the surface can be seen. The two vertical lines superimposed on the film represent a timing mark (left) and a voltage difference imposed across the gas layer (between the interface and the plate). In Figure 1 the potential gradient is zero*.

Figure 2 shows a water droplet film boiling on a rough aluminum plate. The liquid-solid contact can be clearly seen in the areas indicated by white arrows. The mean surface temperature is 650°F; the ambient pressure is atmospheric; the r. m. s. surface roughness is approximately 70 microinches. Occasional mesa-like roughness of the order of a thousandth of an inch above the mean roughness height were observed. Figures 2a), b), and c) were printed from the same strip of motion picture film. The total lapsed time from a) to c) is 3 1/2 milliseconds. The liquid filaments attaching the droplet to the surface are evidently connected to the aluminum plate at a locally highly cooled spot on the surface.

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* Potential gradients as high as 50,000 volts/inch (based on a gas film thickness of 0.001 inches) were applied without the occurrence of arcing. Beyond 60,000 volts/inch, breakdown of the gas dielectric occurred.

The transient character of the attachments is also illustrated by Figure 2. Contact filaments migrated from point to point beneath this droplet during 155 milliseconds of film selected for analysis (and containing Figures 2); nevertheless, complete disengagement never occurred. Figures a), b), c) are typical examples of the types of attachments which were observed on a rough surface although multiplets of each type were common. The migrations and attachment configuration changes appeared to be random in character although a certain preference for large roughnesses as attachment sites could be discerned as would be expected. The distorted appearance of the droplets in Figure 2 is due to the presence of capillary waves on the droplet surface. The absence of a regular frequency of contact in connection with this phenomenon will make it difficult to analyze by the approach of Reference[3]

It was found that the addition of solid particles (such as grit) on the surface or in the liquid can also promote the behaviour just described. The character of contact was found to vary with the degree of roughness added. With purer water and a smoother surface, the contact area first decreases and then contact becomes intermittent. Figure 3 is an oscilloscopic trace showing the variation of capacitance across the gas film as a result of roughness induced surface waves. Intermittent shorting occurred when contact between liquid and solid was established. The shorts are indicated by spikes extending below the base line of the regular waves on the trace. In Figure 3, the sweep speed is 0.010 second/cm so that the entire sweep occupies 1/10 second. It was possible to eliminate completely both the liquid-solid contact and the droplet surface waviness by returning to a heating surface of mirror finish and using commercial grade distilled water.

Even with a mirror smooth surface, however, contact can be achieved by driving the interface against the surface. Bouncing droplets provide one manifestation of this phenomenon. Figures 4 show the result of such a motion with a 1/10th inch diameter water droplet on a mirror smooth chromium heated surface. The surface temperature is 600^{o}F. Shorting of the oscilloscope trace can clearly be seen in Figure 4a). Due to the location of the auxilliary lens which superimposes the oscillograph trace on the motion picture film, the corresponding photograph is five frames displaced. The frame corresponding to the trace of Figure 4a) is shown as 4b). The attachment of the droplet to the heating surface can be clearly seen. Study of the simultaneous motion pictures and oscillograph traces shows that, over many cycles, the contact is strongly correlated with the nearest approach of the interface to the heating surface. Thus, although some irregularity of the droplet motion exists, liquid-solid contact is nearly periodic where bouncing droplets are concerned. This would seem to make it particularly adaptable to the type of analysis given in Reference [3].

This type of momentary contact was reported earlier[1] in a different context; namely, in connection with the quenching of the smooth chrome plated copper sphere (shown in Figure 5) in subcooled water.

However, the contact was intermittent rather than periodic and thirty or forty degrees of subcooling were required to produce the effect*. The effect of subcooling at constant surface temperature in the case of stable film boiling over a submerged surface is to thin the vapor layer and to suppress interface waves. Motion picture studies showed that as the subcooling is increased, the normally wavy interface (which characterizes laminar quenching) gradually changed in appearance and became glassy smooth. Frequently associated with this glassy appearance is an oscillation of the entire interface normal to the heated surface. On a completely submerged spherical object this takes the form of a rhythmic expansion and contraction of the interface as a spherical shell. Further increasing the subcooling results in intermittent and momentary contact between the liquid and solid surface as a result of the oscillation. This is apparently of very substantial area because for a very smooth heating surface as in Figure 5, the resulting hydrodynamic disturbance can be detected by quite loud "bumping" sounds associated with the phenomenon. These hydrodynamic disturbances are presumed to result from flash evaporation of the liquid as it contacts a large area of the surface.

Increasing surface roughness actually tends to prevent this bumping phenomenon, at least for a chrome plated copper surface such as that

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* Due to the small volume, the droplets were at approximately saturation temperature.

described in the preceding paragraph. With the addition of roughness, the bumping or intermittent contact is apparently replaced by a gradually increasing liquid-solid contact area. Figure 6 is typical of the gradual increase of surface contact which was measured in quenching a chrome plated copper hemisphere-cylinder of varying surface roughness (between 68 and 200 rms μ inches over area immersed). Such a curve results from measurements of electrical current flow from the bulk liquid to the metal surface by way of liquid-solid contacts. The driving potential was less than 10 volts d.c. The origin (time zero) corresponds to 1000°F and the nucleate boiling region is marked by the region of decreasing contact area (due to the onset of bubble formation) before final extinction. For rough estimates, the temperature can be assumed to decrease linearly with time between time zero and onset of transition. The area ratio curve is deduced from knowledge of the resistance characteristics of the quenching bath and the immersed area of the test piece. The curve clearly shows that liquid-solid contact did not occur until the temperature had dropped to roughly half the temperature at immersion. This points to the possible existence of a critical ratio of roughness characteristic to gas layer thickness as criterion for the onset of liquid-solid contact. There is not enough experimental evidence at present to justify a general theory for heat flow enhancement by continuous partial liquid-solid contact. However, it can be reasoned on physical grounds that heat flow enhancement should be describable in terms of the following dimensionless variables:

$$\frac{Nu_T}{Nu} = f \left[\frac{Pr}{Pr_\ell}, \left(\frac{c_p(t-t_{sat})}{c_{p_2}(t_{sat}-t_\ell)} \right), \frac{A_c}{A} \right] \tag{3}$$

where A_c area in contact with liquid;

A total area immersed.

Geometrical and quenching considerations suggest that the liquid-solid contact area can be described in terms of surface roughness by

$$\frac{A_c}{A} = g \left[\left(1 - \frac{\delta_o}{\epsilon_{max}} \right)^2, \frac{h_c \, \epsilon_{max}}{k} \right] \tag{4}$$

where ϵ_{max} is a maximum roughness element ;

δ_o is the stable film boiling gas layer thickness;

h_c is a heat transfer coefficient between liquid contacting element and bulk liquid;

k is the roughness element thermal conductivity.

As is indicated in its definition, ϵ_{max} should be based on a maximum (or possibly a mean maximum) roughness rather than the r. m. s. surface roughness standards. Additional experiments such as that which produced Figure 6 but instrumented additionally for heat flow are required to further define equations (3) and (4).

It was mentioned above that adding roughness to a metallic surface serves to reduce the tendency toward "bumping" instabilities. However, a dramatic exception occurs if the surface is porous and wetting, as is graphite. A description of this destructive phenomenon follows.

Many quenching experiments with graphite in subcooled water were performed by the writer as a result of curiosity concerning film boiling in the presence of a reacting surface (the water gas reaction in the case of graphite in water). For large subcooling, quite violent transitions took place at elevated surface temperatures. On two occasions the aquarium in which the experiments were conducted was destroyed by the resulting hydrodynamic disturbance. Figure 7 shows the appearance of a six inch long graphite cylinder before and after transition occurred. The model centroidal temperature was 1500°F and the bulk liquid temperature was 165°F. Figure 7a) shows stable subcooled film boiling. The tiny bubbles in the field are suspended in the bulk liquid in this case. Figure 7b) shows the appearance subsequent to extinction. A cloud of graphite particles can be seen in the vicinity of the model. This appearance was typical of the phenomenon. High speed motion pictures (2300 frames per second) showed that the transition from stable film boiling (Figure 7a)) to liquid-solid contact (Figure 7b)) occurred in less than one thousandth of a second. This phenomenon was sufficiently explosive to destroy the apparatus on two different occasions.

The graphite surface is rough, porous, and wetting. With these characteristics in mind, it was reasoned that the process begins by the occurrence of more or less uniform contact of the interface with the surface roughness elements during one of the rigid interface oscillations previously mentioned. Because of the surface cooling which

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results and since the surface is both wetting and porous, the liquid is drawn by surface tension and driven by inertia deep into the surface where intimate thermal contact with the primary heat source is established. As this occurs, an explosive evaporation takes place with the consequences just described.* Motion pictures of this phenomenon are available for loan should anyone be interested. Towing basin experiments with quenching showed the existence of these effects also in forced convection. Velocities as high as 30 feet per second were investigated. As might be expected (since the primary effect of forced convection is to thin the gas layer, all other conditions remaining constant), forced convection simply causes liquid-solid contact to occur at a higher body temperature than with free convection.

Summary and Conclusions

It has been established that liquid-solid contact exists in the "stable" film boiling regime. The contacts may be periodic (as in the case of bouncing droplets) or continuous when sufficient roughness exists.

For the case of bouncing droplets, it seems clear that the theory of Reference [3] is ideally suited because of the periodicity of contact. Adaptation requires only frequency studies of the droplets which can be easily done

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* It has also been suggested that thermal stresses at the surface may be responsible.

with the aid of motion pictures.

However, for droplets film boiling on rough surfaces and for film boiling on rough immersed surfaces, the contact is quasi-continuous (fluctuating about a mean) and a physical model is less clear. The foregoing observations suggest three parameters which are important in liquid-solid contact at stable film boiling temperatures: the subcooling parameter $\left[\frac{Pr}{Pr_{\ell}}\left(\frac{C_p \Delta t}{C_{p_{\ell}} \Delta t_{\ell}}\right)\right]$; the ratio of (maximum surface roughneww) to (gas layer thickness); and, a Biot modulus based on mean roughness element characteristic geometry $\left[\frac{h\,\epsilon_{max}}{k}\right]$. The first two regulate interface stability and onset of contact due to "tickling"; the third determines surface temperature relative to heating element "bulk" temperature in the presence of time dependent phenomena at the solid surface (i. e., local surface cooling). It should be possible to express an effective area ratio and resulting Nusselt number ratio in terms of these parameters to permit comparison of contact and zero contact cases.

It may become desirable to control heat flow by controlling liquid-solid contact in the stable film boiling regime. If so there appear to be at least three methods available for development: i) application of external pressure fields: ii) suction through heating elements; and, iii) use of electrostatic fields. The first method has been tentatively explored by Di Cico and Schoenhals [6] who showed that pressure pulsations enhance heat flow. The second method has been developed by Weyner and Bankoff [7]. The third method has been used by Markels and Durfee [8] in pool boiling and by the present author in droplet film boiling. In all these cases, it will be necessary to learn to avoid the destructive instabilities described above if stable operation is to be achieved at high surface temperatures.

Acknowledgement

This work was supported by the National Science Foundation under Grant Number G20191.

Nomenclature

A	surface area;
c_p	specific heat at constant pressure;
h	heat transfer coefficient;
k	thermal conductivity;
L	characteristic length
Nu	Nusselts number, hL/k;
Pr	Prandtl number, $c_p \mu / k$;
t	temperature;

Greek Symbols

α	thermal diffusivity;
δ	vapor layer thickness;
ϵ	roughness element characteristic dimension;
τ	time;
μ	dynamic viscosity;

Subscripts

c	contact;
i	liquid-solid interface;
ℓ	liquid;
o	steady state;
T	total.

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List of Figures

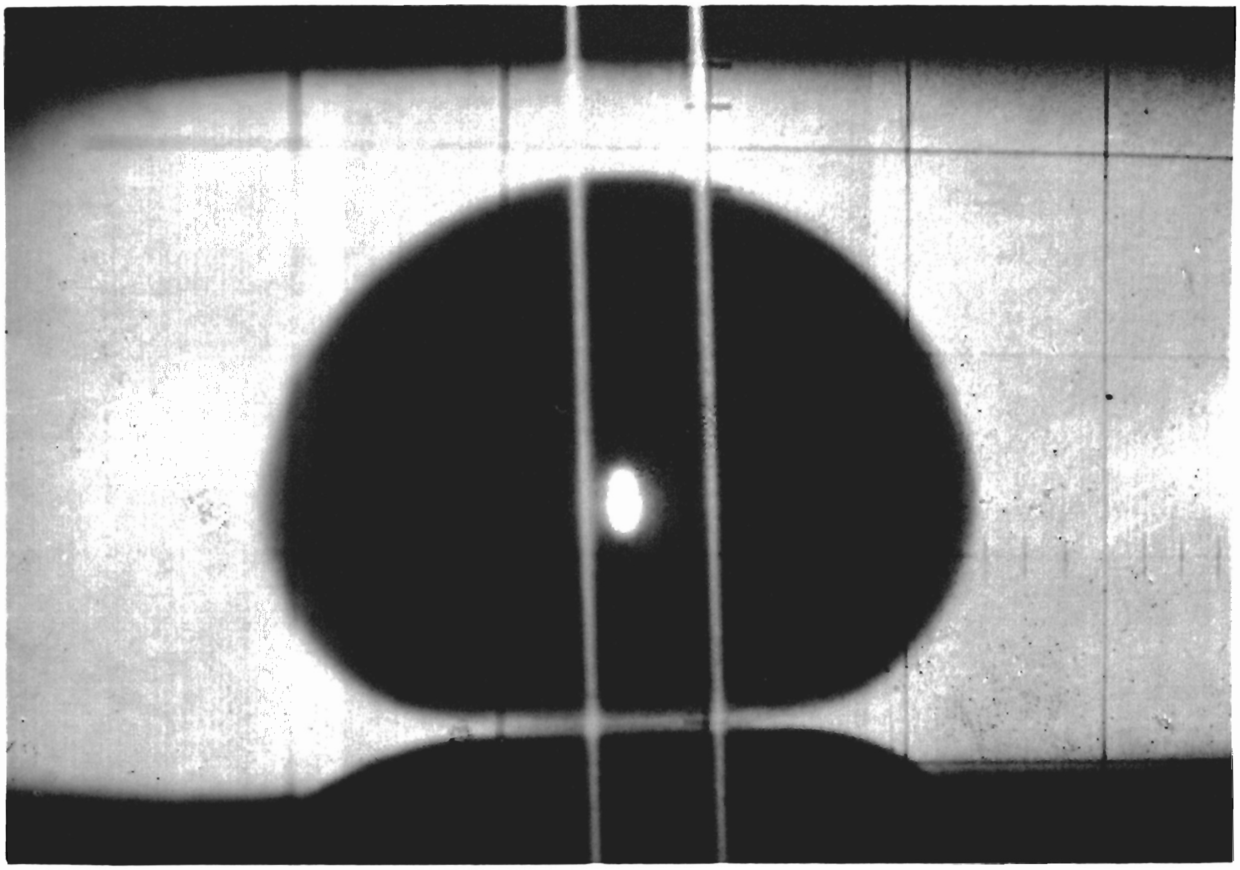
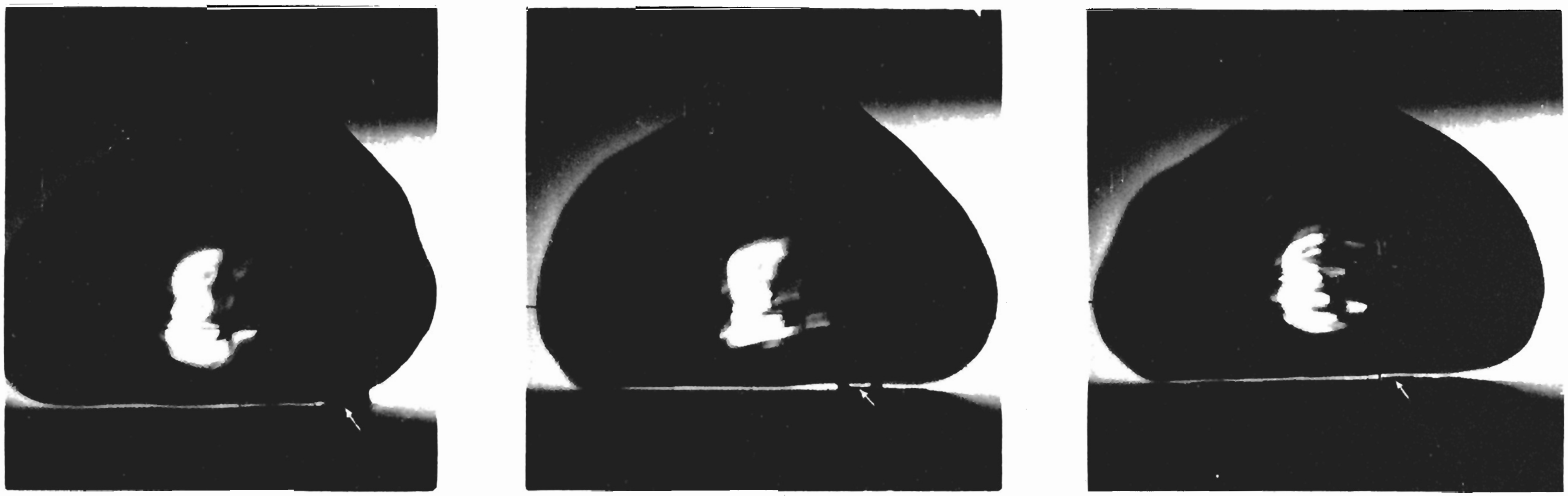


Figure 1.



(a) (b) (c)

Figure 2.

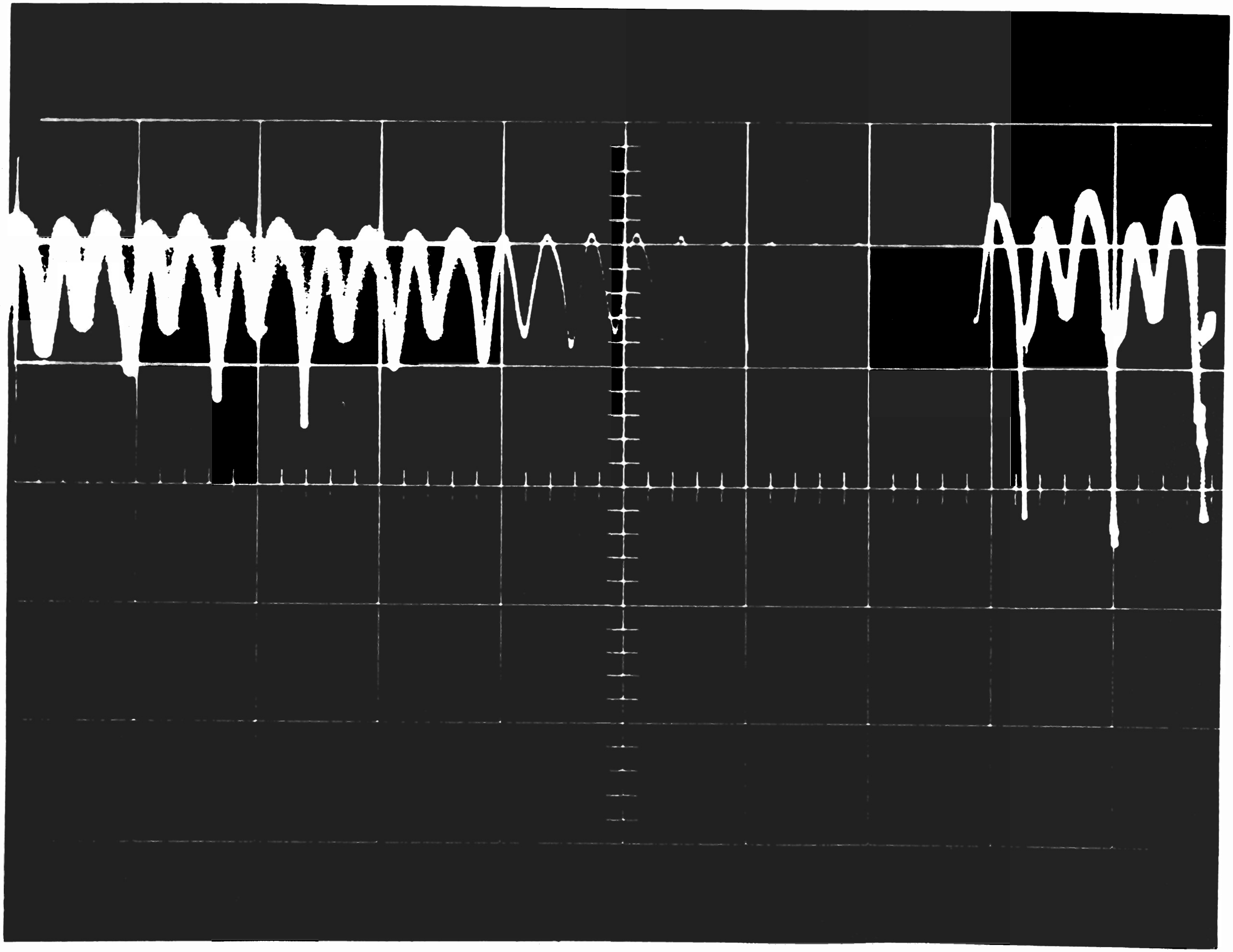
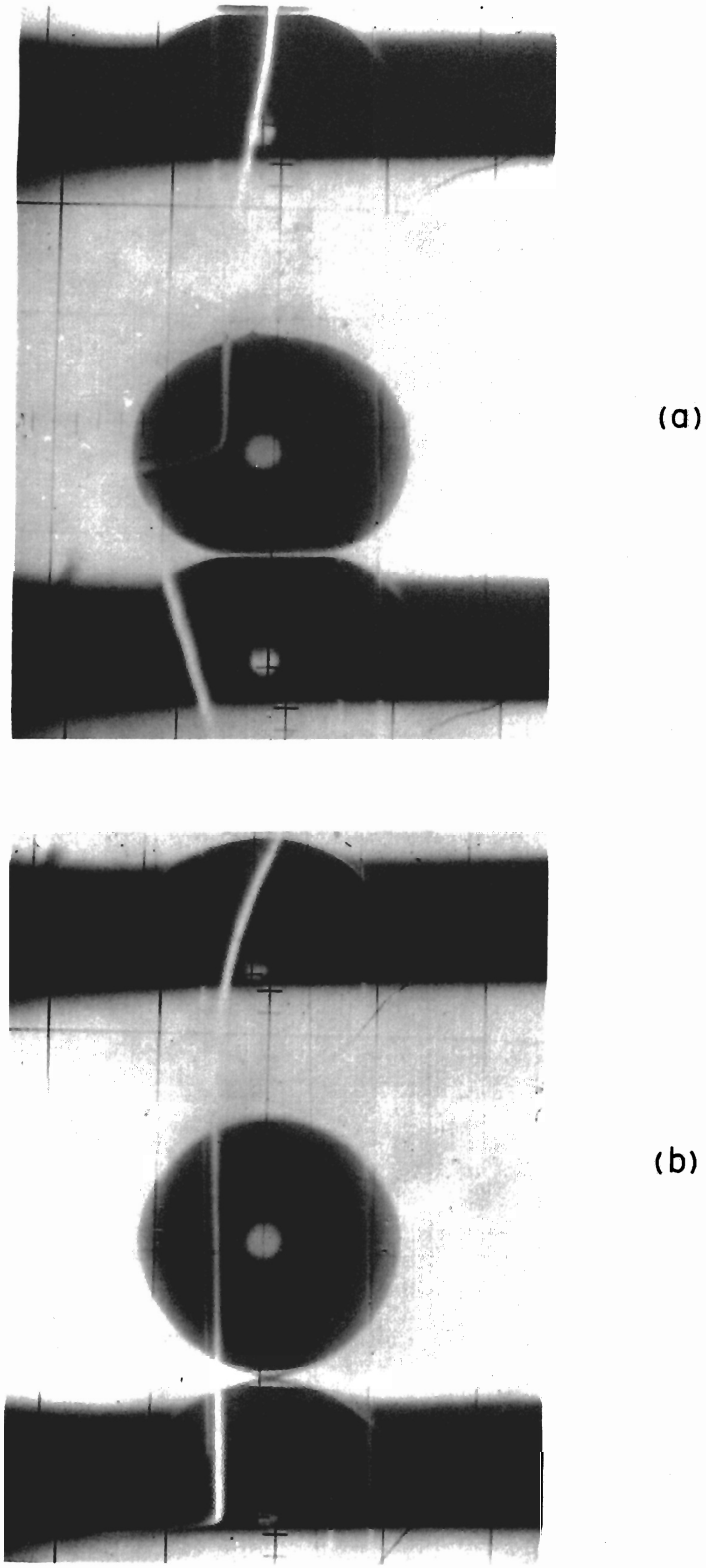


Figure 3.


(a)

(b)

Figure 4.

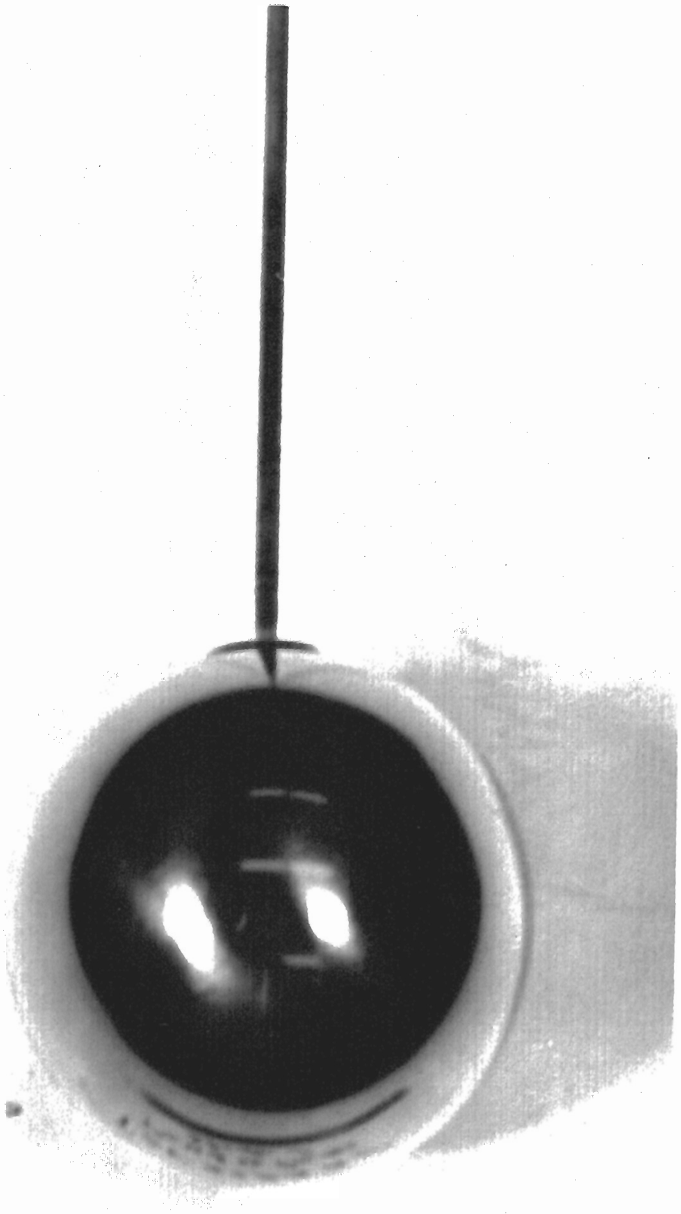


Figure 5.

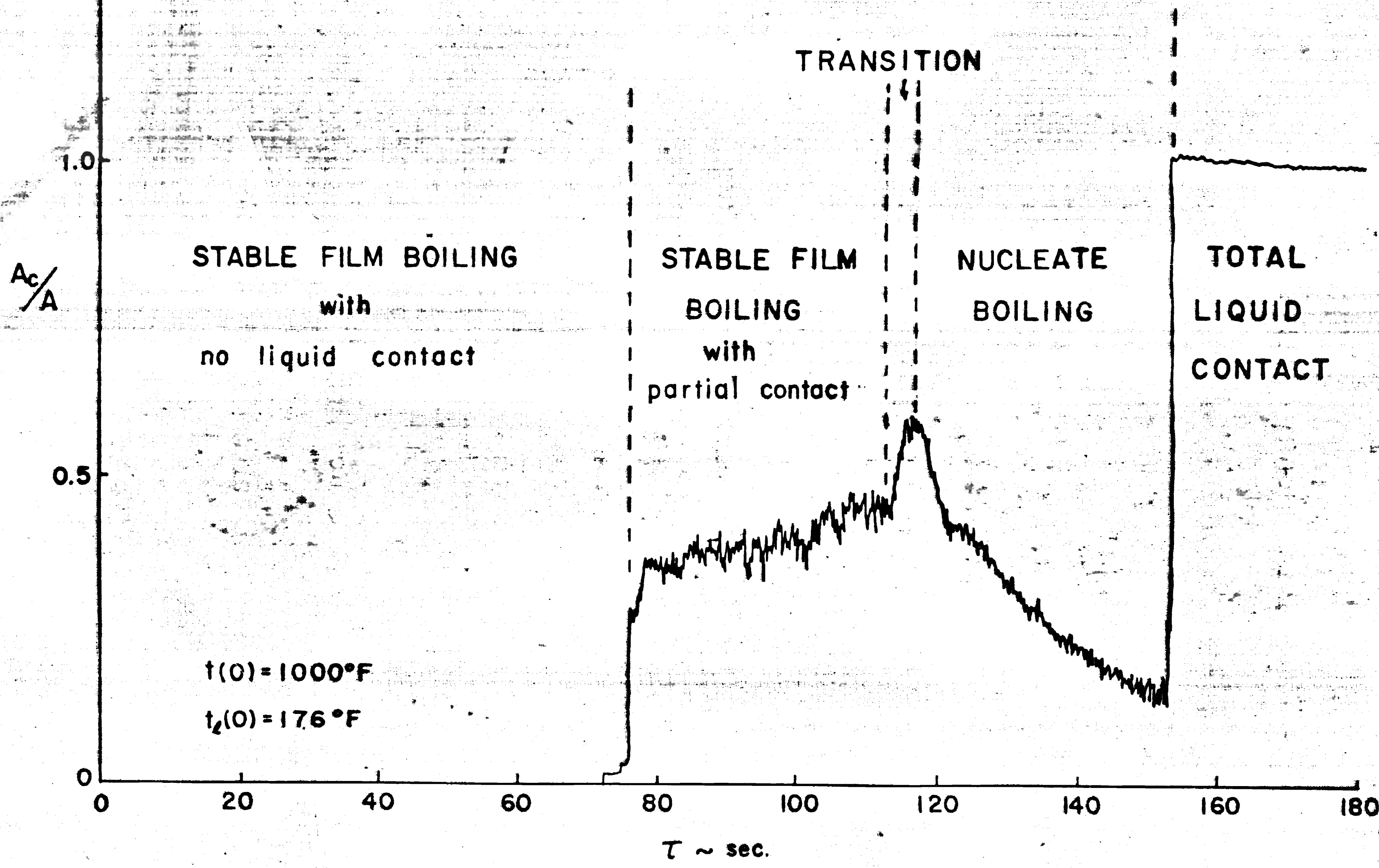

TRANSITION
1.0
0.5
0
A_c/A
STABLE FILM BOILING
with
no liquid contact
STABLE FILM
BOILING
with
partial contact
NUCLEATE
BOILING
TOTAL
LIQUID
CONTACT
$t(0) = 1000°F$
$t_\ell(0) = 176°F$
0
20
40
60
80
100
120
140
160
180
τ ~ sec.

Figure 6.

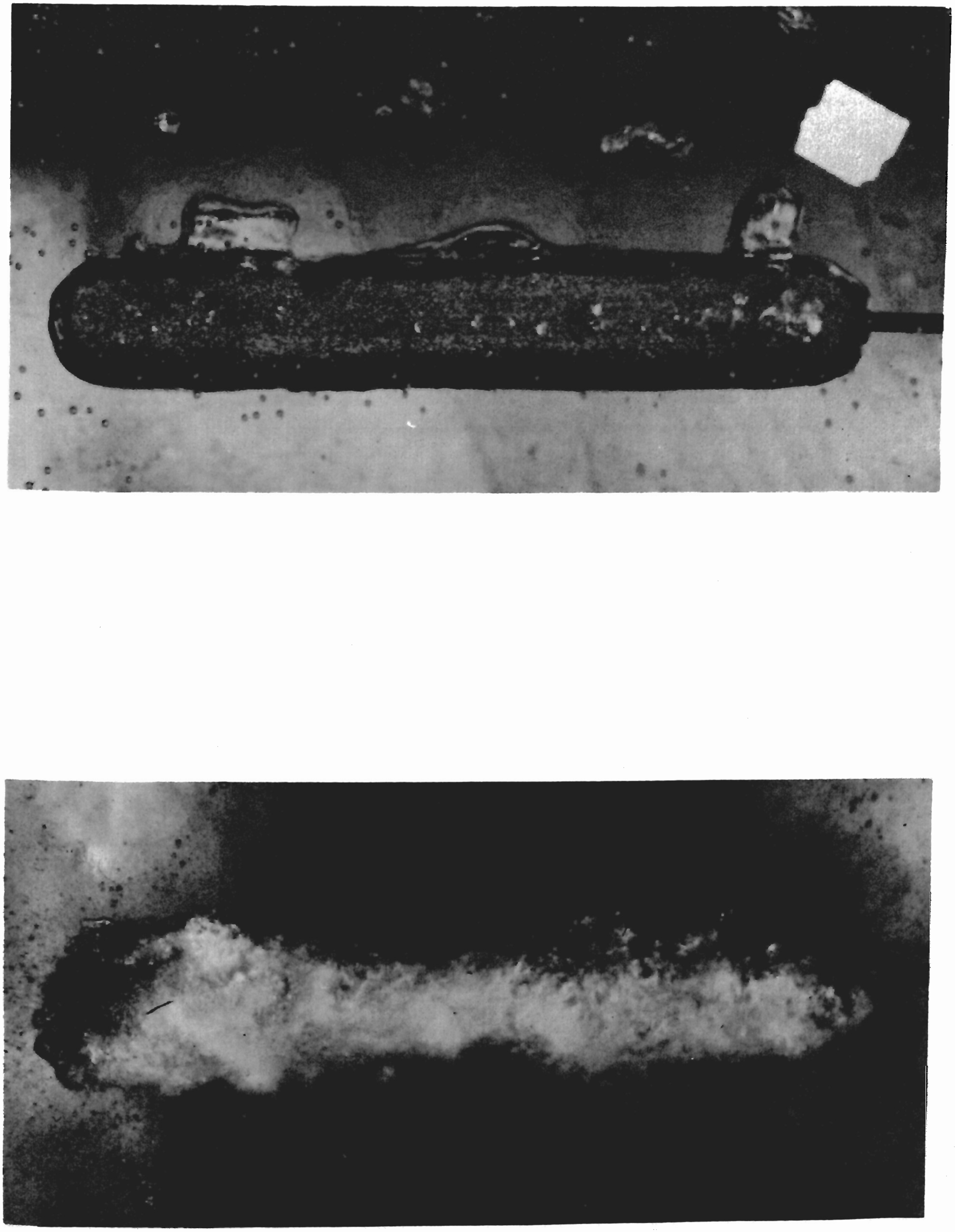


Figure 7.