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NUCLEATION SITE INSTABILITY IN NUCLEATE BOILING

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INTRODUCTION

THE INITIATION of boiling from a heated solid surface has been normally treated in terms of a critical radius of nucleation site [1, 2] and the preparation of boiling surfaces has normally been thought of in terms of roughness. The significance of nucleation site depth has been mooted by Marto and Rohsenow [3] as a result of their studies of pool boiling of liquid sodium. They observed small scale irregularities in the surface temperature of their boiler and occasional large temperature cycles coincident with evidence that boiling had been suppressed. The small scale temperature oscillations were ascribed to the effects of microlayer evaporation during nucleate boiling—that is the temperature dips are due to the periodic evaporation of a thin film of liquid under the base of a growing bubble [4–6]. These oscillations were then said to cause periodic partial condensation of the vapour inside the nucleation cavity so that liquid enters it until it is re-evaporated by the applied heat flux. Occasional non-boiling from a previously active vapour producing site is explained by suggesting that the slug of liquid could penetrate to the bottom of the cavity and snuff out the vapour nucleus before sufficient heat had been received through the cavity walls to prevent complete condensation of all of the vapour. Considerable superheat would then be necessary to re-initiate boiling from that cavity. The only direct experimental evidence for this phenomenon is that of Wei and Preckshot [7] who have shown that in nucleate boiling from a 10^{-3} m. diameter glass capillary nucleation site a residual pocket of vapour remains in the site after a bubble has departed.

The work described in this paper uses an artificial glass cavity so that the motion, if any, of the fluid within the cavity could be studied by high speed photography in order to confirm or refute the fundamental assertions of the Marto and Rohsenow model.

It may be as well to list some of the mechanisms which could drive a liquid plug into a vapour nucleation site.

(1) Condensation due to microlayer evaporation.
(2) Condensation on the incoming relatively cold liquid in the wake of departing bubble. This would be intensified in the case of sub-cooled boiling.
(3) Reaction to the transient pressure increase which accompanies the departure of a bubble from a surface [8].
(4) In sub-cooled boiling reaction to the very large pressure pulses (up to 1000 atm) caused by the collapse of vapour bubbles [9].

EXPERIMENTAL

A sketch of the apparatus is given in Fig. 1. It comprises a constant temperature tank controlled by a contact thermometer and associated relay unit and heating element, a glass capillary test cavity and a 3000 ft/s camera focused through a plane viewing window provided on the thermostat. The test site is shown in more detail in Fig. 2. It consists of a 2×10^{-3} m O.D. $\times$ 10^{-4} m I.D. glass capillary of 0·02 m depth around which a helical spiral of 5×10^{-5} m platinum wire is wound. Platinum leads ($1{\cdot}3 \times 10^{-4}$ m dia.) are welded to this element. This heater unit is then inserted in a thick walled glass tube $8{\cdot}4 \times 10^{-3}$ m O.D. $\times$ $2{\cdot}2 \times 10^{-3}$ m I.D. which is then fused down to completely embed the platinum winding. The top face was polished to remove any potential rogue sites.

Experiments were conducted on degassed, de-ionized water which was maintained at any given saturation condition from 20°C to 100°C in the thermostat. For sub-cooled experiments some air is admitted to the tank just prior to a run. Once boiling had been initiated from the capillary the power to the winding could be greatly reduced without suppressing the boiling. At steady heat fluxes the boiling was steady and no changes in nucleation with time due to permanent gas in the nucleation site were observed indicating the adequacy of the degassing procedure. During the short duration of a run the control heater was turned off to prevent disturbances across the viewing field.

RESULTS AND DISCUSSION

The results are given in Table 1 showing fifteen runs with conditions varying from 3×10^2 W/m^2 to $4{\cdot}3 \times 10^4$ W/m^2 at pressures from 20 mm to 760 mm and subcoolings to 21°C.

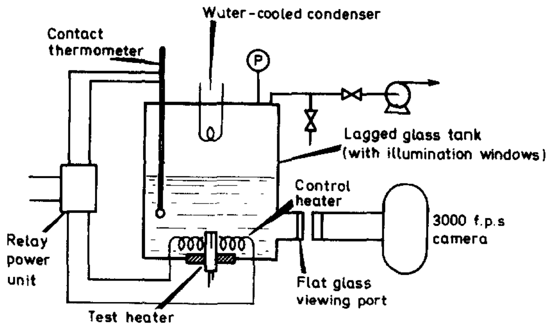

FIG. 1. Diagram of apparatus.

The penetrations listed were the deepest recorded over the 100 ft of film per run. Average maximum penetrations were perhaps half of these. Also listed are bubble departure diameters, bubble growth periods and bubble waiting periods. The heat fluxes given in the table are approximate steady fluxes computed by the method given in [10].

Figure 3 is taken from Run 4B which was a check run in which the capillary heater was switched on just prior to the camera in order to be able to distinguish between a water filled and a steam filled cavity. The dark area advancing up the capillary is the steam displacing the liquid from the site. To assist the reader the penetration is marked at the side of the photographs. Figure 4 shows typical behaviour from a sub-cooled case, Run 3. (Other examples are available

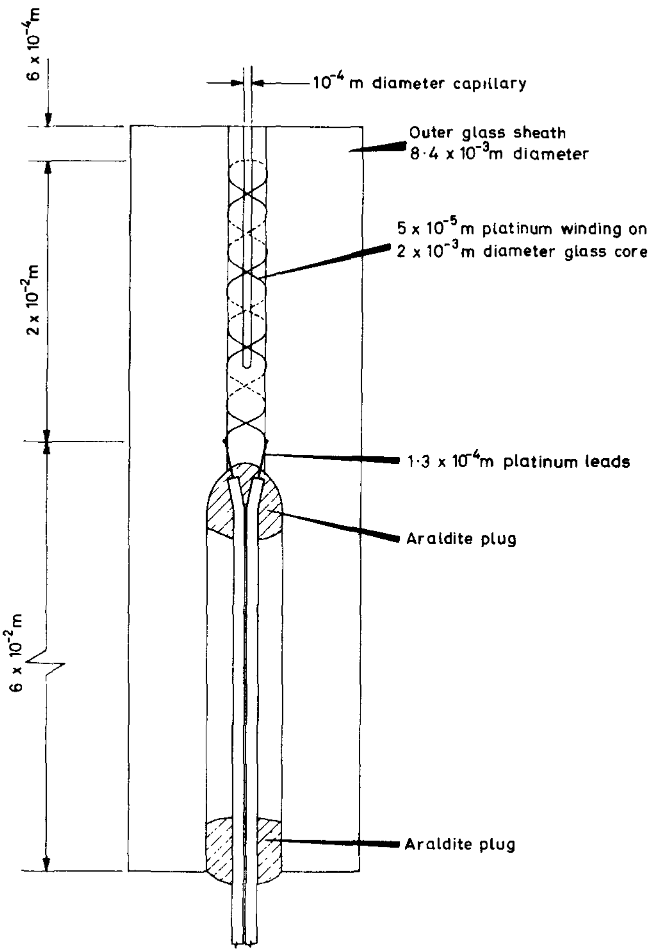

FIG. 2. Details of capillary test heater.

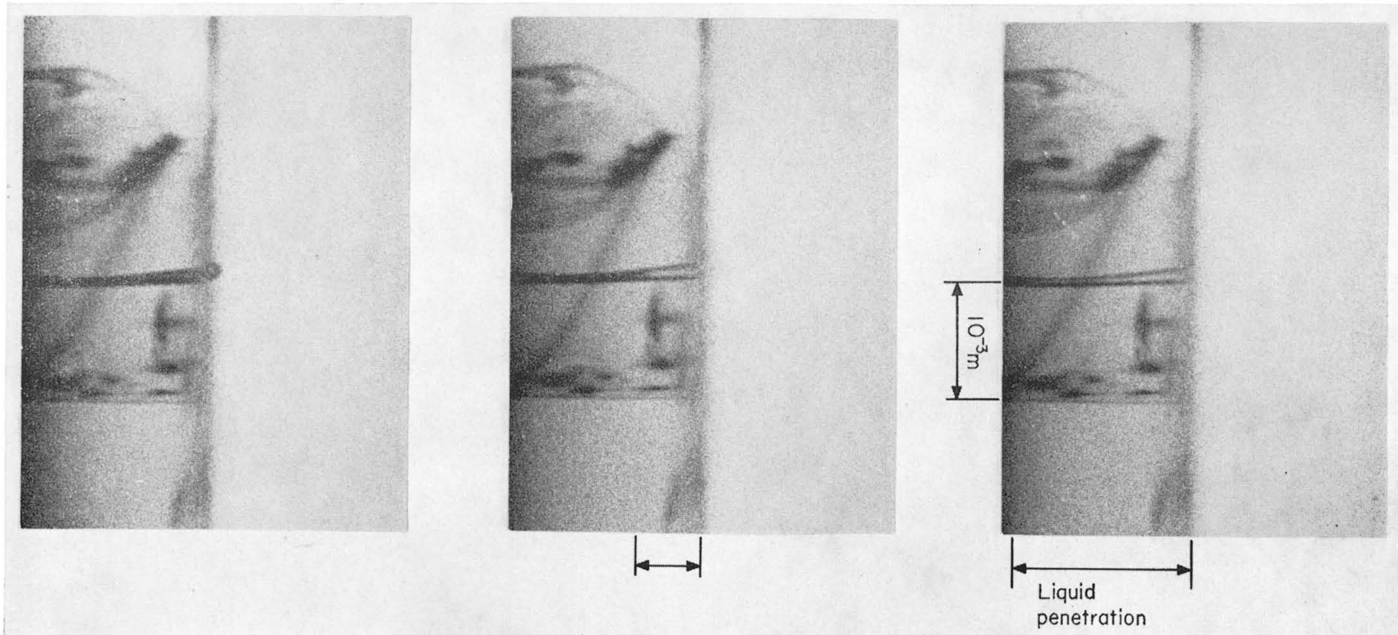

FIG. 3. Run 4B: appearance of cavity when filled with water and with steam

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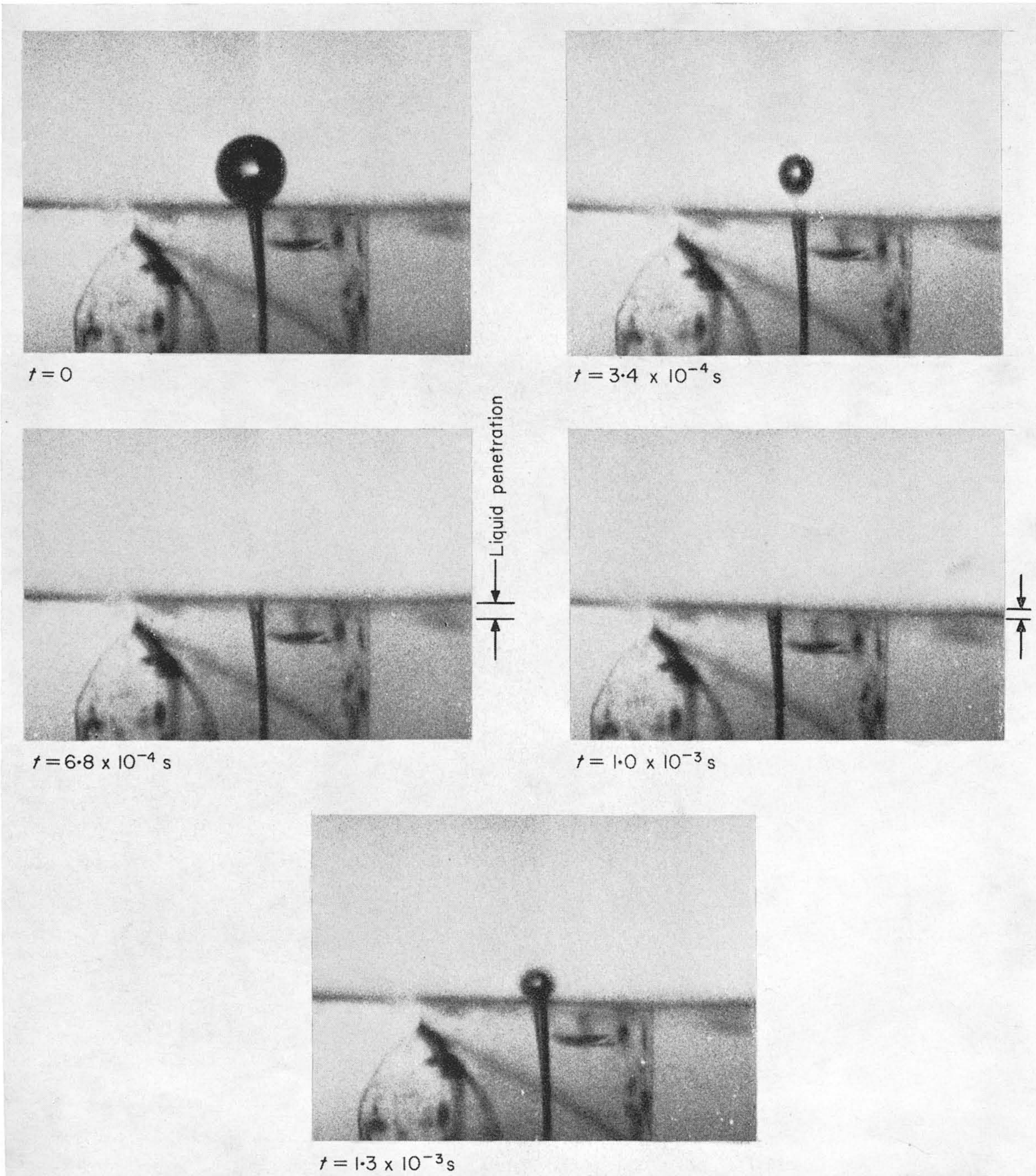

FIG. 4. Run 3: showing cavity penetration during sub-cooled boiling.

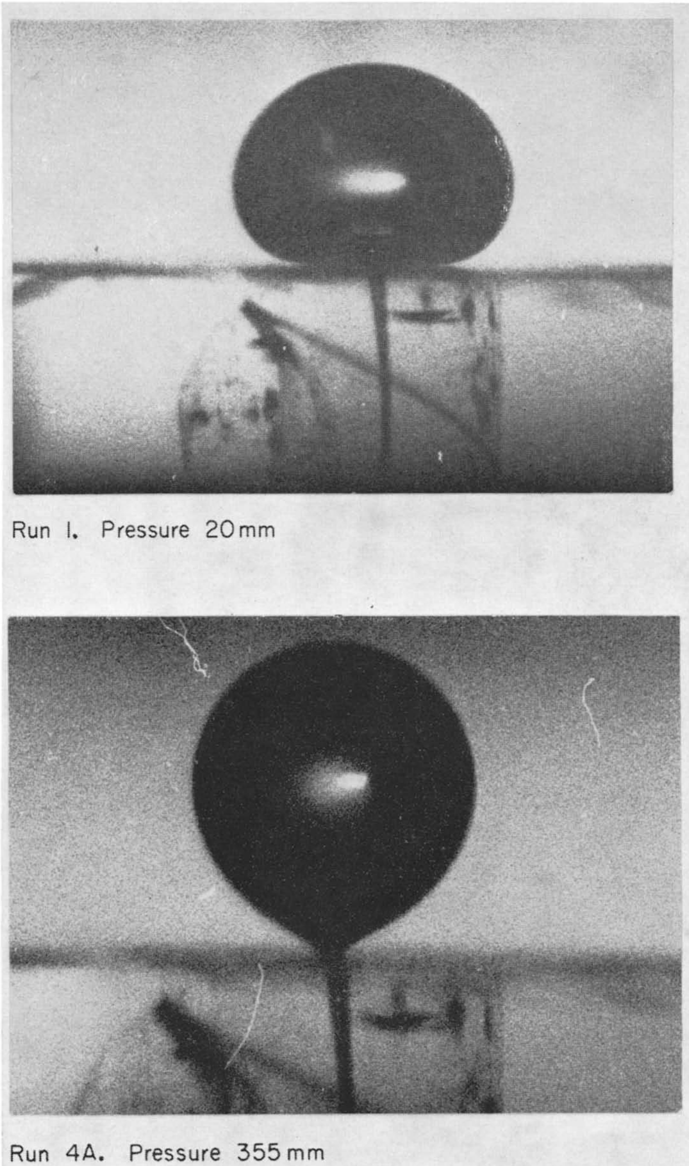

FIG. 5. A comparison between low and high pressure bubbles growing at the prepared nucleation site.

Table 1

Run number	Power to winding [W]	Flux [W/m^2 × 10^{-4}]	Water temperature [°C]	Saturation temperature [°C]	Bubble waiting period [s]	Bubble growth period [s]	Average diameter of bubble at departure [m]	Maximum penetration [m]
1	2·32	1·0	22	22	$2·2 \times 10^{-1}$	$2·04 \times 10^{-2}$		$<5 \times 10^{-5}$
2	3·25	1·43	22	39	$2·5 \times 10^{-3}$	1×10^{-3}	$1·4 \times 10^{-3}$	$5·7 \times 10^{-4}$
2A	1·73	0·76	39	37·5	$7·7 \times 10^{-2}$	$1·4 \times 10^{-2}$		$<5 \times 10^{-5}$
3	3·85	1·65	39	60	$<5 \times 10^{-4}$	$3·8 \times 10^{-3}$	$1·7 \times 10^{-4}$	$1·3 \times 10^{-4}$
4A	0·24	0·07	82	80	$3·4 \times 10^{-3}$	$4·1 \times 10^{-3}$	$1·7 \times 10^{-4}$	$2·0 \times 10^{-4}$
5	4·55	1·92	82	100	$<5 \times 10^{-4}$	1×10^{-3}–9×10^{-3}	collapses	$1·3 \times 10^{-4}$
6	1·32	0·51	82	78	5×10^{-4}	$2·8 \times 10^{-3}$	$2·6 \times 10^{-3}$	$2·3 \times 10^{-4}$
6A	1·32	0·51	82	83	$<5 \times 10^{-4}$	3×10^{-3}–$1·4 \times 10^{-2}$	$1·3 \times 10^{-4}$	$2·0 \times 10^{-4}$
6B	1·32	0·51	82	88			stationary 10^{-3}	0
6C	2·43	0·91	82	93	$<5 \times 10^{-4}$	$1·2 \times 10^{-2}$	$8·3 \times 10^{-4}$	$<5 \times 10^{-5}$
6D	9·70	4·29	82	98	$<5 \times 10^{-4}$	$1·7 \times 10^{-2}$	$5·3 \times 10^{-4}$	$<5 \times 10^{-5}$
7	0·11	0·03	101	98·5	$4·1 \times 10^{-3}$	3×10^{-3}–2×10^{-2}	$1·1 \times 10^{-3}$	$5·1 \times 10^{-4}$
7A	0·97	0·36	101	98·5	2×10^{-3}	$9·8 \times 10^{-3}$	$1·4 \times 10^{-3}$	$1·8 \times 10^{-4}$
8	0·11	0·03	100	99	$1·9 \times 10^{-2}$	$2·4 \times 10^{-1}$	$1·4 \times 10^{-3}$	1×10^{-4}
8A	0·97	0·36	100	99	$1·6 \times 10^{-3}$	$8·3 \times 10^{-3}$	$1·6 \times 10^{-3}$	9×10^{-5}

[10]*.) A penetration of $\sim 10^{-4}$ m into the cavity was observed. In the case of saturated boiling the mechanism of bubble growth on the surface changed from inertia controlled at low pressures (Run 1) to surface tension controlled as the pressure increased to greater than 0·5 atm. This is particularly interesting as the low pressure bubbles spread out across the surface trapping a liquid microlayer under the bubble base, whilst the surface tension controlled bubbles remained spherical—see Fig. 5. From Table 1 the penetration in the case of Run 1 is very small indeed (if any at all occurred), but appreciable penetration does occur at the higher pressures (e.g. Run 4A). However, it is explicitly to the former case that the theory of Marto and Rohsenow [3] applies. It is suspected that either the bulk liquid which flows towards a nucleation site after a bubble departs is an important contributor to meniscus penetration (as the incoming relatively cold liquid will provide an excellent surface on to which the vapour in the cavity can condense) or, that the pressure rise in the wake of the departing bubble [9], is responsible for the penetration.

In Fig. 6 detailed motion of the meniscus from Run 2 is shown. This was one of the few cases in which the motion was slow enough to show this amount of detail. The qualitative agreement with the Marto and Rohsenow model is very good here since they postulate on entry profile proportional to $t^{\frac{1}{2}}$ and a linear time response for the liquid slug

* Higher quality resolution is available by inspecting the 16 mm silent movie from which these data are taken. A loan copy is available by writing to: Cockcroft Hall, A.E.R.E. Harwell, Berkshire, England quoting the author and title of this paper.

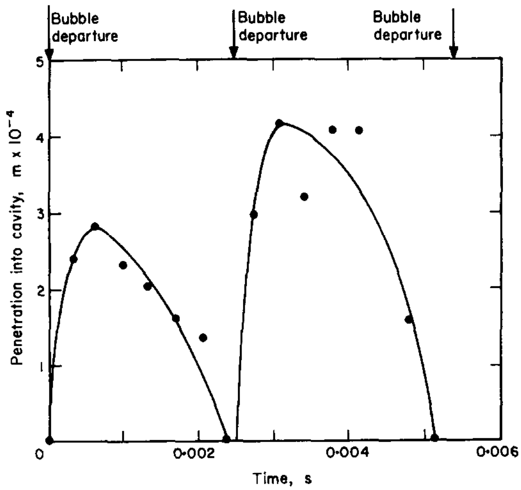

FIG. 6. Motion within nucleation site detected in Run 2.

to move out of the cavity. Unfortunately a quantitative comparison to this theory requires knowledge of the heat flux imparted to the bubble from the microlayer and the consequent temperature dip of the solid surfaces.

CONCLUSIONS

Nucleation site instability of the type suggested by Marto and Rohsenow [3] can occur in nucleate boiling. This may have serious consequences in suppressing boiling or alternatively allowing irregular and explosive boiling. The detailed mechanism of this phenomenon may not be solely dependent on microlayer evaporation at the base of a growing bubble but involve other mechanisms. More detailed study will be necessary to elucidate these specific mechanisms.

ACKNOWLEDGEMENT

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