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THE EFFECT OF POWER TRANSIENTS ON THE PEAK HEAT FLUX

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Abstract—An experimental investigation of the effect of power transients on the peak heat flux has been conducted for external flow of water normal to cylindrical test elements. Two sets of tests were run: The first set, using steps and one minus negative exponentials in the test element voltage, show that if a power transient is applied to a test element when air is present on its surface the transient peak heat flux may be as low as 25 per cent of the corresponding steady state flux; In the second set of tests surface temperature measurements indicate that for steps in power the tube wall temperature variation during the approach to steady state conditions is close to that predicted for transient conduction from the element.

NOMENCLATURE

a, thermocouple transfer function constant;
c, thermocouple transfer function constant;
$G(s)$, thermocouple transfer function;
$\dot{q}''$, heat flux;
t, temperature;
$\bar{T}(s)$, Laplace transformed temperature;
V, voltage.

Greek symbols
τ, wall thickness, time constant;
θ, time;
κ, thermal conductivity of water.

Subscripts
f, final;
0, initial;
p, peak;
ss, steady state;
$t.c.$, thermocouple;
$wall$, tube wall.

INTRODUCTION

SINCE most engineering applications of the boiling process involve steady state phenomena in which only small, slow changes in the heat flux are involved, most studies of the peak heat flux have investigated steady state conditions and relatively few have considered the effects of transients on the peak heat flux. The present tests give information regarding two transient areas: (1) the effect of power transients on the peak heat flux, and (2) the transient temperature variation following a step in test element power.

Transient peak heat flux tests. In the design of a boiling water nuclear reactor it is important to know how power transients affect the peak heat flux, and it is towards an understanding of this phenomenon that the present study is directed. For example, if the transient peak heat flux is significantly lower than the steady state flux, reactor designs based on steady state values could prove inadequate in the case of unexpected power excursions. Indeed, previous investigations [1–5] have indicated that in some situations when power is suddenly applied to a

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test element, the element may have a much lower peak flux than the corresponding steady state value for the same element. For instance, Jordan [3], in studying subcooled boiling of water in an electrically heated annulus, observed a peak heat flux of only 36 per cent of the corresponding steady state value when a rapid power transient was applied to the test section.

Some research has been performed in experimental boiling reactors to determine the effects of transient power surges on reactor performances. These tests (Borax [6], Spert [7], Kewb [8]) have shown that prompt critical power transients in water moderated reactors are, under most conditions, inherently safe because of the interaction of the boiling process and the neutron diffusion and absorption processes. The tests [6–8] focused attention on the overall reactor performance, while the present study is an attempt to obtain further understanding of the transient boiling process and to explain the low transient peak heat fluxes which have been observed [1–5].

Investigations of the effect of transients on the peak heat flux which were not conducted in reactors are those by Cole [9] who applied large steps in voltage to his test elements and Howell and Bell [10] who studied the effect of decaying pressure transients on the peak heat flux.

Transient temperature measurement tests. In a transient boiling study which was not concerned with the peak heat flux, Rosenthal and Miller [11] applied exponentially increasing power transients (periods of 5–75 ms) to vertical strips of aluminium and platinum in both subcooled and saturated water. In an investigation to extend and improve on the results of Rosenthal and Miller, Johnson, *et al.* [5], applied exponential (5–80 ms period) power pulses to both horizontal and vertical ribbons immersed in water. Other pertinent transient boiling studies are those by Graham [12] who applied steps in voltage to horizontal strips, and Lurie and Johnson [13] who applied steps in power to vertical ribbons.

EXPERIMENTAL APPARATUS AND PROCEDURE

These experiments were performed for external, vertically upward flow of water normal to electrically heated, horizontal tubes. The heat transfer loop used has been described previously [14, 15]. The test section, in which the elements were horizontally mounted, was a 1·2 × 8 in. rectangular section 32 in. long. The water was demineralized and deaerated, flowing at a free stream velocity of 3·3 ft/s (corrected for blockage) at atmospheric pressure and a subcooling of approximately 3°F for almost all tests. Test elements were as drawn 0·375 in. outside diameter, 2–6 in. long, 10 and 1·75 mil wall thickness stainless steel tubes which were wiped with oil, degreased with acetone, washed with detergent and rinsed in water before being tested. It was determined that the cleaning procedure had only a minor effect on the experimental results. Two sets of tests, using two different power supply circuits were run.

Transient peak heat flux tests. The first set, run to determine the effect of power transients on the peak heat flux, obtained power from a d.c. motor-generator. Power transients for the constant resistance elements were of the form,

$$V(\theta) = V_0 + V_f(1 - e^{-\theta/\tau})$$

with a time constant (τ) of roughly 0·1 sec, V_0 less than 1 per cent of V_f, and the final transient voltage (V_f) a variable quantity which could be preset at any desired value. These tests were run with both 10 and 1·75 mil wall thickness elements.

The procedure in these tests was, after the desired water conditions had been reached, to clean the elements, place them in the water, and to age the test elements by slowly increasing the test element power to a high heat flux value and leaving the power at this setting for the desired length of time (ageing period). The test element power was then decreased to zero, the element was allowed to reach equilibrium with the water, and a transient test to the desired final transient heat flux was run—these tests are designated as aged element tests. In some cases, the elements were not aged in this manner but transient tests were run after the elements had been in the water (with no power applied to them) for the desired length of time (soaking time)—these tests are designated as unaged element tests. The final test element voltage and current were measured with a digital voltmeter or, in cases where the elements melted (the peak heat flux had been reached), from the preset values of voltage and current. In cases where the peak heat flux was obtained, it was generally reached within 30 s of the start of the transient. For all other tests the test element power was left at the final transient value for approximately five minutes or more to see if the peak heat flux had been reached. The criterion used to determine if the peak heat flux had been reached was a visual observation of the overheating of the tube characterized by a reddish glow. In all cases burnout initiated near the 180° position (downstream) on the tube.

Transient temperature measurement tests. The second set of tests was run to determine the transient temperature and heat flux variation following a step in power applied to a test element. Power steps were obtained from a 12 V wet cell in series with a variable resistance. One test element (1·75 mil wall thickness) with a fast response thermocouple welded to the inside wall was used in this set of tests. The thermocouple, made from 1 mil diameter Chromel–Constantan wires, was located on the downstream side of the test element (at the 160° position) for all tests. The thermocouple output was amplified and recorded on a high speed oscillograph record using a light beam galvanometer. To correct for the difference between the tube wall and the thermocouple temperatures, the thermocouple was calibrated for its transient response using the Laplace transform technique [16, 17] to obtain the thermocouple transfer function $G(s)$, where,

$$G(s) = \frac{T_{t.c.}(s)}{T_{wall}(s)} = \frac{a}{s + c}.$$

Six calibration tests of the thermocouple gave a time constant (a = c) of 2·32 ms for this thermocouple. The thermocouple was also calibrated for direct current voltage pickup using the current reversal technique.

The procedure used in these tests was to clean the element, age it for approximately 4 hr at a high heat flux value, decrease the power to zero and then record the resultant transient thermocouple response for a series of individual power steps to the test element (decreasing power to zero and allowing the test element to reach equilibrium with the water after each step in power). The transient thermocouple response, $t_{t.c.}(\theta)$, was then fit to a polynomial on a Burroughs B5500 digital computer in a least squares manner, the thermocouple transfer function was applied to this polynomial and a new polynomial obtained which represented the transient tube temperature as a function of time. The thermocouple temperature polynomials were ninth order or less, with the first three terms specified, and were fit to approximately 20 data points $(t_{t.c.}, \theta)$ in almost all cases. This procedure was followed for each individual test. The individual test results are given in [18], while the present paper gives only the average results of all tests to the same final heat flux.

EXPERIMENTAL RESULTS

Steady state peak heat flux values. Before performing the transient tests the steady state peak heat fluxes were determined using the procedure described by Vliet and Leppert [15] with the motor-generator set as the power supply. Seven tests on the 10 mil wall thickness elements gave an average value of $6{\cdot}55 \times 10^5$ Btu/ft^{2}h with a standard deviation of 4·9 per cent. Three tests with the 1·75 mil wall thickness elements gave values of 3·09, 3·37, and $3{\cdot}64 \times 10^5$ Btu/ft^{2}h for an average of $3{\cdot}37 \times 10^5$ Btu/ft^{2}h.

Transient peak heat flux tests. The experimental results from the 10 mil wall thickness elements show that: (1) the transient peak heat flux is the same as the steady state peak heat flux for elements which have been aged sufficiently, whereas for elements which have not been aged the transient peak heat flux can be as low as 25 per cent of the steady state value; (2) air is present on the surface of unaged elements and is not present on elements aged long enough to prevent low transient peak heat fluxes; and (3) the transient nucleation pattern is altered significantly by the presence of air on an element surface.

The results of the aged element peak heat flux tests are shown in Fig. 1 where the final transient heat flux is plotted vs. the total time the elements have been aged at a heat flux higher than approximately 40 per cent of the steady state heat flux (at this flux there appears to be dense, uniform nucleation of bubbles over the entire test element surface). Two sets of test results are

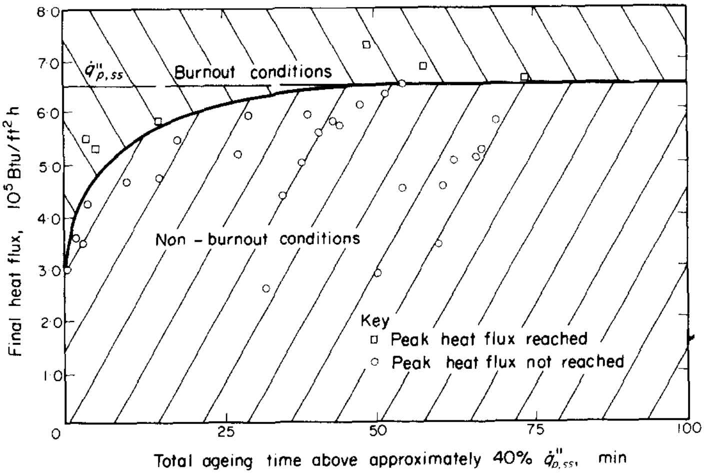


FIG. 1. The effect of ageing time on the transient peak heat flux.

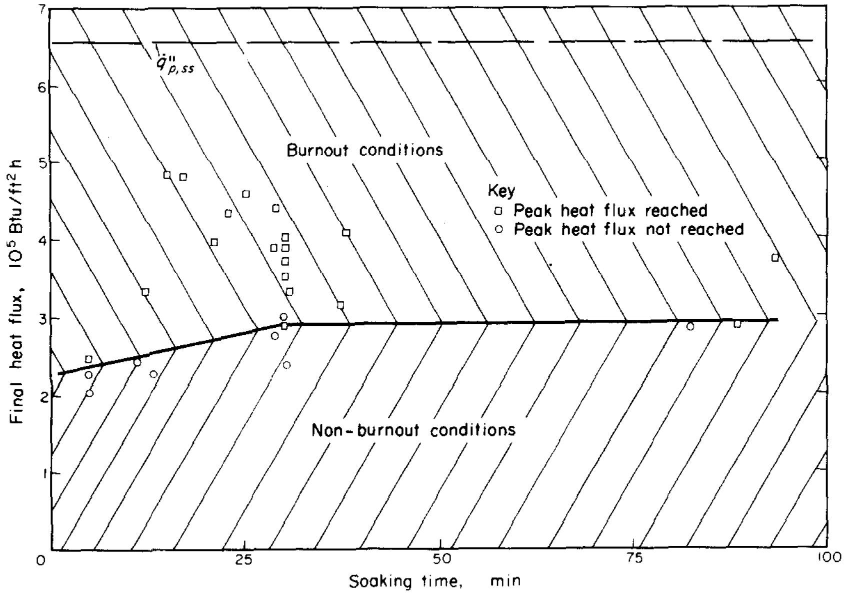
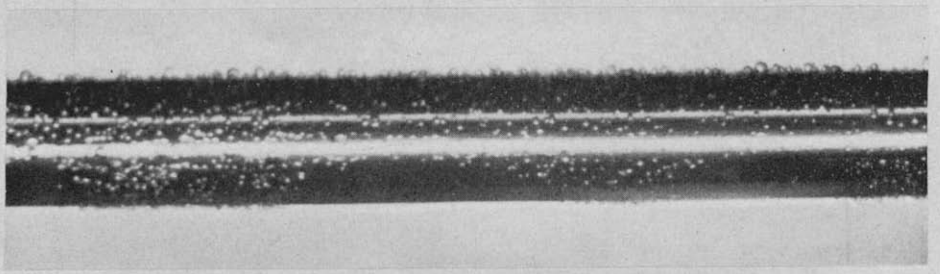
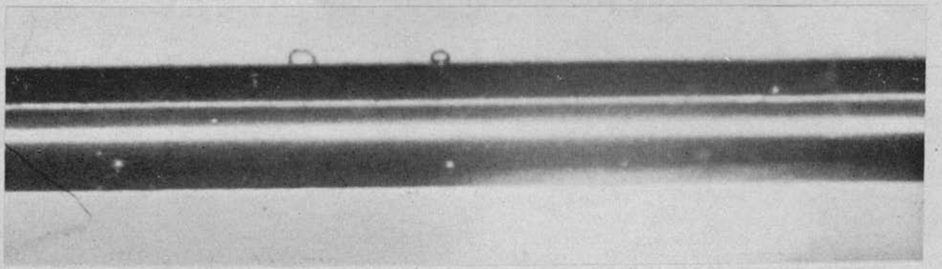


FIG. 2. The effect of soaking time on the transient peak heat flux.

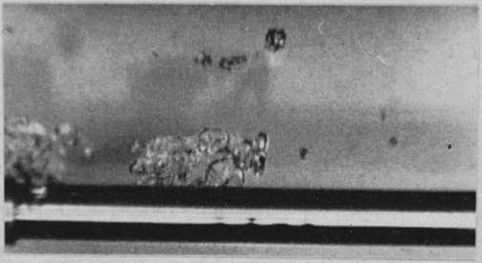


Unaged element

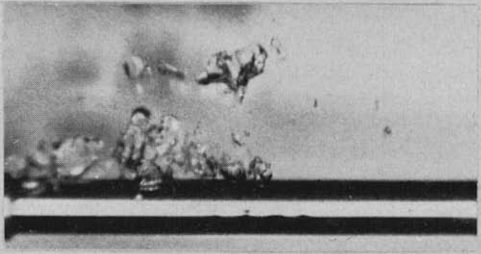


Aged element

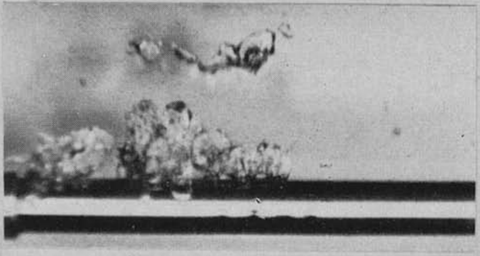
Fig. 3 Photographic comparison of unaged and aged element transient tests in subcooled water.



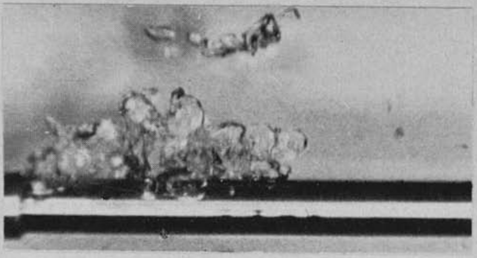
$\theta = 135$ ms



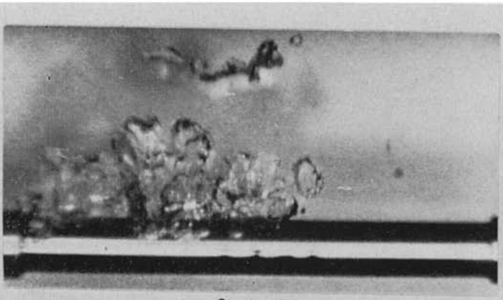
$\theta = 146$ ms



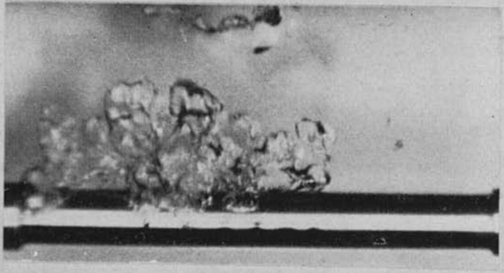
$\theta = 148$ ms



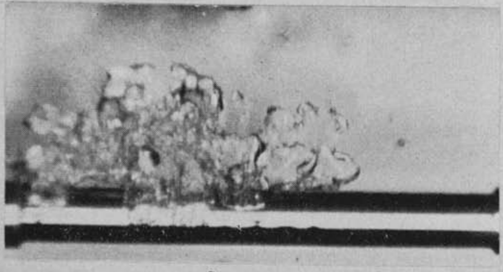
$\theta = 150$ ms



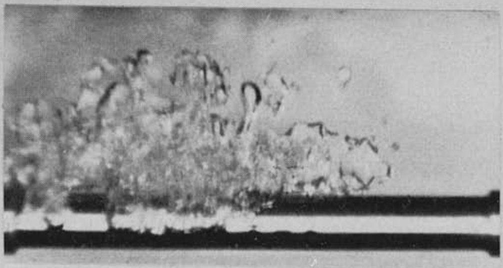
$\theta = 152$ ms



$\theta = 154$ ms



$\theta = 161$ ms



$\theta = 161$ ms

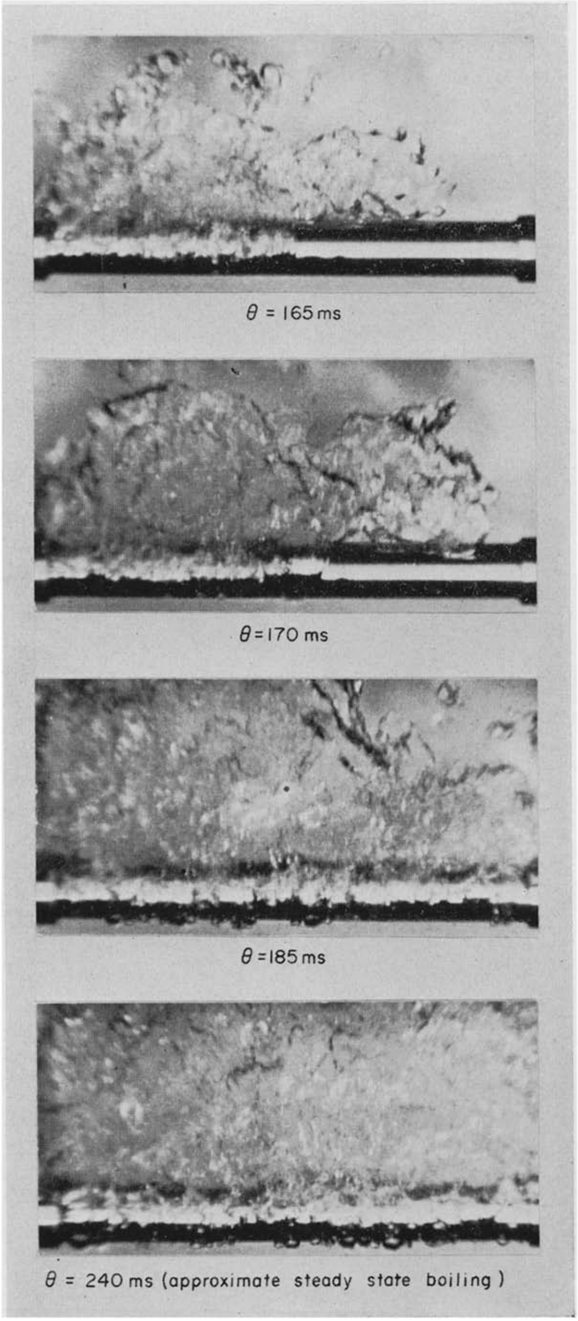
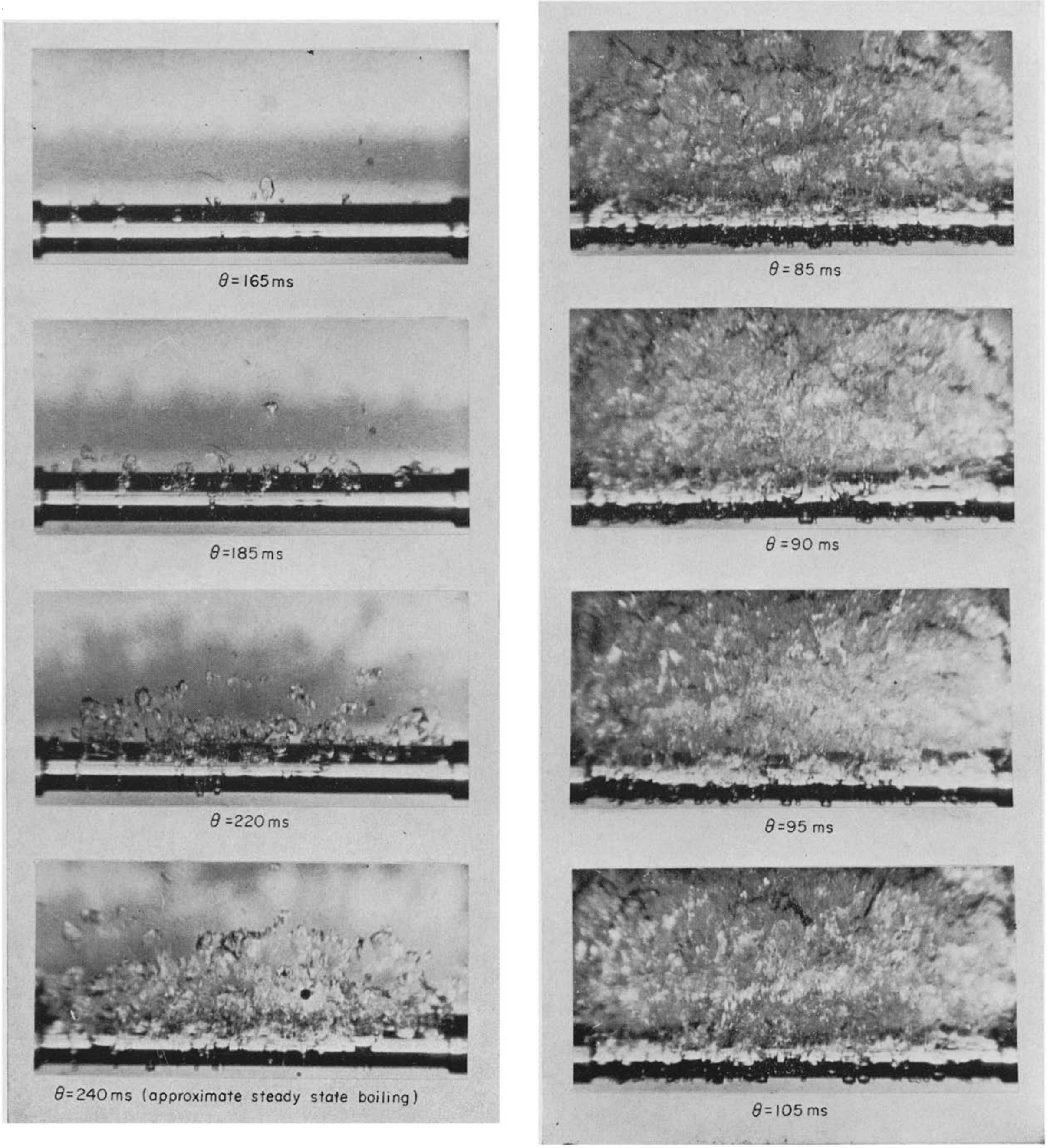


Fig. 5(a) Photographs of unaged element transient peak heat flux test. Water velocity 3·3 ft/s, subcooling 3°F, final/heat flux 2·75 × 10^5Btu/ft^{2}h. θ = time from start of transient



θ = 165 ms

θ = 185 ms

θ = 220 ms

θ = 240 ms (approximate steady state boiling)

θ = 85 ms

θ = 90 ms

θ = 95 ms

θ = 105 ms

Fig. 5(b) Photographs of aged element transient peak heat flux test.
Water velocity 3·3 ft/s, subcooling 3 °F, final/heat flux $2{\cdot}60 \times 10^5$ Btu/ft^{2}h. θ = time from start of transient.

presented in this figure: (1) those transient tests which reached the peak flux, and (2) those tests which did not reach the peak flux. The line dividing these two sets of tests on the graph represents the dividing line between the burnout and non-burnout final transient heat flux as a function of the ageing time of the test element. From this graph it appears that a test element must be aged at close to 40 per cent of the steady peak heat flux for approximately 40 minutes or longer if a low transient peak heat flux (burnout) is to be avoided.

The results of the tests on the instrumented test element as presented in Table 1 substantiate this result.

The results of the tests of unaged elements are shown in Fig. 2, where the final transient heat flux is plotted as a function of the time between the insertion of the test element in the test channel and the start of the transient power pulse (soaking time). For these unaged tests no boiling occurred on the tube surface between the time the element was placed in the water and the start of the transient power pulse. Again the figure is divided into two regions, the combinations of soaking time and final transient heat flux which (1) caused the peak heat flux to be reached and (2) did not result in the transient peak heat flux being reached. From these results it is seen that the unaged element transient peak flux is much lower than the steady state peak heat flux, and that it is only a weak function of the soaking time. For these 10 mil wall thickness elements the transient peak flux was as low as 37 per cent of the corresponding steady state peak heat flux when a test element was soaked

Table 1. Summary of transient temperature measurement tests

		Final transient heat flux		Time to reach steady state (ms)	
Test	Δt_{sub} (°F)	(10^5 Btu/ft^{2}h)	($\%_{o\dot{q}}{}''_{p,ss}$)	Individual	Average
1	3·7	0·71	21	33	
2	3·7	0·71	21	40	
3	3·5	0·71	21	90	48
4	3·3	0·71	21	38	
5	4·3	0·71	21	37	
6	4·3	0·74	22	50	
7	3·5	1·13	33	31	
8	3·7	1·11	33	32	32
9	3·9	1·11	33	34	
10	4·1	1·81	53	26	26
11	4·1	1·80	53	25	
12	3·7	2·12	63	17	
13	3·7	2·14	63	16	20
14	3·7	2·14	63	23	
15	3·7	2·14	63	23	
16	3·4	2·37	70	22	
17	3·3	2·37	70	16	17
18	3·3	2·39	70	14	
19	72·4	2·59	—	40	
20	72·4	2·62	—	34	37
21	72·4	2·62	—	38	

for only 5 min. This behavior is quite different than the behavior of the aged elements.

Unaged transient tests were also performed on some 1·75 mil wall thickness tubes, and the results of these tests [18] also show that the unaged transient peak heat flux is much lower than the corresponding steady state peak heat flux. In fact, for these thin walled elements the effect is even more pronounced since these elements burned out at heat fluxes as low as 25 per cent of the corresponding steady state peak flux, at heat fluxes where only a few nucleation sites were present on the tube surface.

To further examine the difference in behavior between the aged and unaged elements, high speed films of aged and unaged transient tests in subcooled water were taken. In order to distinguish between pure water vapour bubbles and bubbles containing air, these tests were performed in deaerated water at a temperature of 100°F. At this temperature pure bubbles which grew on the tube surface collapsed upon contacting the subcooled bulk liquid, while bubbles containing air did not completely collapse, but remained fixed on the tube surface unless carried away by buoyant or viscous drag forces.

One set of films was taken using a pool boiling tank. The distilled water was deaerated thoroughly by boiling for an extended period at 212°F. The water was then cooled to 100°F, the element inserted in the tank, soaked for 15 min, and a transient test run to a final heat flux value of $0{\cdot}94 \times 10^5$ Btu/ft^{2}h (unaged test). The element was allowed to continue boiling at this heat flux while the water temperature was brought to saturation and left there for 10 min. At this heat flux there appeared to be uniform boiling over the entire tube surface. The power was then turned off and the water cooled to 100°F, whereupon a second (aged) transient test was run to the same final power setting. Upon viewing the films of these runs it was seen (see Fig. 3) that the unaged surface rapidly became covered with small bubbles (0·003–0·025 in. dia.) which remained fixed on the tube surface. Although these bubbles grew and shrank, they never completely collapsed; they also remained fixed at their initial positions on the tube surface. Interspaced between these stable bubbles were several nucleation sites where vapor bubbles were observed to grow and collapse. On the other hand, in the film of the aged element test, none of the stable bubbles were attached to the surface. The only vapor present on the surface were the growing and collapsing bubbles at nucleation sites. Figure 3 presents photographs of these aged and unaged elements taken approximately one second after the start of the power transients. When steady state conditions were reached in the unaged test, there were approximately 1600 bubbles on the front half of the tube, while the aged surface had an average of twenty bubbles on the front tube surface at any instant.

A similar set of films, taken in the heat transfer loop with water at a temperature of 100°F and a velocity of 3·3 ft/s, to a final heat flux of $3{\cdot}5 \times 10^5$ Btu/ft^{2}h, showed air bubbles on the unaged element surface but no stable air bubbles present on the aged surface.

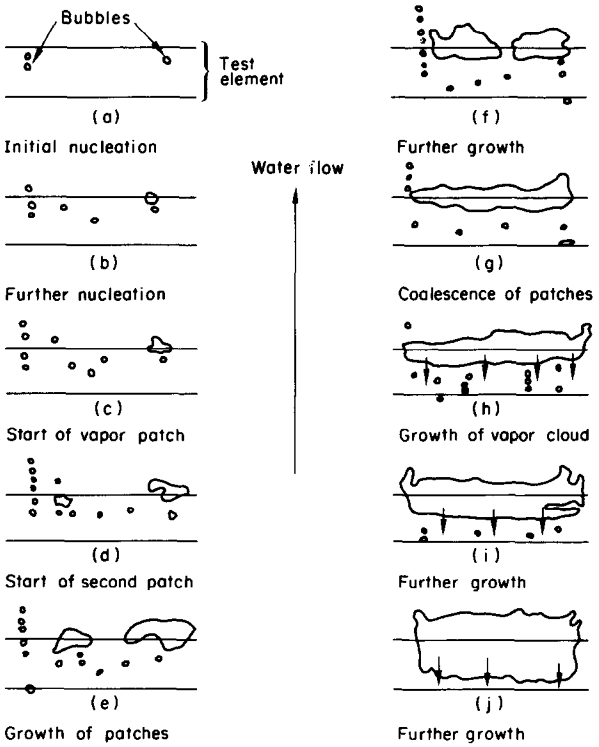
In the films of these unaged transients the air bubbles which covered the tube did not seem to originate from nucleation sites and remained fixed at those sites. Rather, during the first part of the transient, a large bubble would form at a site and grow into the subcooled bulk liquid. It would then start to collapse, and would break into several small bubbles which would attach themselves to the tube surface and remain there. The surface of the element was covered with these small bubbles after approximately 20 such larger bubbles had grown and collapsed. The larger bubbles which formed after the tube was covered with these small bubbles did not exhibit such spreading behavior.

These films demonstrate that air is present on the surface of the unaged elements and is not present on the aged element. This fact, combined with the results of the tests mentioned previously, leads to the conclusion that air on the surface of unaged elements is causing the low transient peak heat fluxes, and that ageing the elements by boiling from the surface for a sufficient length of time (40 min at a heat flux which results in uniform nucleation on the tube surface) eliminates this air.

To determine the manner in which the air affected the transient peak heat flux, films of aged and unaged transient peak heat flux tests at water subcoolings of 3°F were taken. These films show a marked difference in the manner of vapour formation on the two different surfaces (Fig. 4 and 5). In the case of power transients with an aged surface, vapor bubbles form at random points on the surface and are then swept along the tube by the flowing liquid until they depart from the tube rear. These vapor bubbles form at discrete nucleation points, and once a nucleation site is activated it continues to produce discrete bubbles. There is very little coalescing of the bubbles.

In contrast, the unaged surface initially forms discrete bubbles at several locations, and one or two of these bubbles, rather than being swept downstream by the liquid, continue to grow until they become patches of vapour on the surface. If the final transient heat flux is high enough, these patches then continue to grow, both up- and downstream and along the tube axis, until they form a cloud of vapor which in some cases covers and effectively insulates the entire rear half of the test element. The growth of one of these vapor clouds is sketched in Fig. 4, while Fig. 5 shows photographs of aged and unaged transient tests on an element to the same final heat flux value. Eventually, if the element does not burn out, the clouds are broken up and the nucleation pattern on the tube surface appears the same as the nucleation pattern on the aged element surface.

Transient temperature measurement tests. Tests



(a) Initial nucleation

(b) Further nucleation

(c) Start of vapor patch

(d) Start of second patch

(e) Growth of patches

(f) Further growth

(g) Coalescence of patches

(h) Growth of vapor cloud

(i) Further growth

(j) Further growth

FIG. 4. Schematic diagram of vapor cloud formation on an unaged element during a transient peak heat flux test.

with the instrumented test element were run at six different final transient heat flux settings with approximately four runs at each setting. The tests at the lowest heat flux settings were run for both aged and unaged conditions, while the remainder were all aged element tests run to determine the characteristics of the transient boiling process. Almost all were run at a water subcooling of approximately 3°F, but at the highest final transient flux tests were run at 72·4°F subcooling. All tests were made with a fluid velocity of 3·3 ft/s. The data are summarized in Table 1, which includes the approximate time taken for the test element to reach steady state conditions after the start of the transient power pulse, as determined by noting the time taken for the thermocouple temperature to reach approximate steady state conditions.

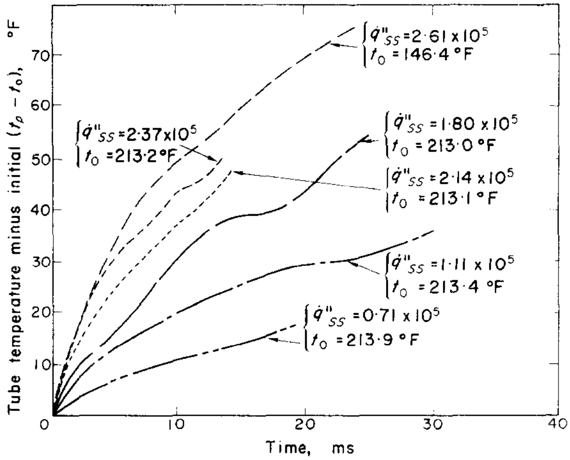


FIG. 6. Transient tube temperature variation caused by a step in energy generation rate—average results.

Figure 6 presents the average results of all runs to the same final heat flux value as curves of tube temperature minus initial tube temperature vs. time. The transient tube temperatures were calculated from the measured thermocouple temperatures as described previously. The difference in these temperatures was always less than 15°F, and for most of the tests was less than 10°F. The temperature difference between the inner and outer walls was calculated to be less than 2°F for all cases [18].

DISCUSSION

Transient peak heat flux tests. The results of the aged and unaged peak heat flux tests show that the transient peak heat flux is essentially the same as the corresponding steady state flux for an element which has been aged by boiling to eliminate a sufficient amount of air from the test element surface. Also, the aged element transient peak heat flux is unaffected by the transient speed, since both the step function power changes, the 0·1 s period negative exponential transients, and manually controlled power transients of periods up to two minutes (see [18]) displayed transient peak heat fluxes that were essentially the same as the steady state peak heat flux.

These results appear to conflict with those of Cole [9] who concluded, for steps in power applied to horizontal strips in water, that the peak heat flux increases as the amplitude of the power step increases. However, his tests were for steps in power to levels greater than the steady state peak heat flux, while the present tests were for power levels less than (or equal in some cases) the steady state peak heat flux. Thus, the nature of the two sets of experiments are quite different, which accounts for the difference in results.

Unaged elements displayed transient peak heat fluxes considerably lower than the corresponding steady state values. The unaged transient peak heat fluxes, which depended only weakly on the amount of time the element had soaked in the loop water (Fig. 2) displayed minimum values of approximately $2{\cdot}5 \times 10^5$ and $0{\cdot}85 \times 10^5$ Btu/ft^{2}h [18] for the 10 mil and the 1·75 mil wall thickness elements, respectively. These low values, 37 per cent and 25 per cent of the corresponding steady state peak heat fluxes for the thick and thin elements respectively, were caused by the presence of air on the test element surfaces. Two other possible explanations of the difference in behavior between the aged and unaged test elements were: (1) residual cleaning material on the unaged elements was causing the low transient peak heat fluxes and that ageing the elements removed these residual materials, or (2) aging the test elements altered the test element surface in such a manner (possibly by depositing material on the surface) that the low transient peak heat fluxes, which were inherent in the transient boiling process, were precluded. These possible explanations were discarded when the results of the present tests (see [18]) showed that the low transient peak heat fluxes for the unaged elements were unaffected by the cleaning procedure used, and that exposing an element to the atmosphere for a short period of time (as low as 1 hr) completely eliminated the effects of the ageing process as far as the transient peak heat flux was concerned.

The manner in which the air causes the vapor cloud to form is not known, but the films of the saturated transient tests shed light on the mechanism. In these tests (see Fig. 4 and 5) the vapor cloud seems to grow by causing surface nucleation sites to nucleate along the edge of the cloud. From this observation a model may be developed to explain how the cloud forms.

It is proposed that the surface of the tube is covered with small pits and scratches many of which are filled, for unaged tests, with air. Upon heating the tube in a transient test, the wall temperature increases rapidly until sites nucleate. If a site is on the rear of the test element, the bubble may remain attached to the test element surface causing the surface temperature to rise underneath the bubble (after the initial temperature drop), since the tube surface is insulated under the bubble. Conduction to the surrounding metal causes the test element surface around the bubble to rise and this causes the nucleation sites filled with air to nucleate, thus extending the vapor insulated portion of the test surface. This process extends the vapor cloud until either the test element reaches the peak heat flux at a position on the tube which has remained insulated during the cloud growth, or else the cloud collapses because (1) the transient conduction process can no longer nucleate the vapor filled cavities, or (2) the bulk fluid flow breaks up the cloud.

The presence of air affects this process in two ways. First, the air present in the surface cavities causes the cavities to nucleate at lower temperatures than if the air were not present (i.e. aged tests), and second the air in the bubbles decreases the rate of collapse when vapor contacts the slightly subcooled liquid—this increases the residence time (and size), of the bubbles on the surface and thus increases the temperature rise under the bubbles which increases the possibility of further nucleation.

Accepting the above explanation of the premature burnout process, it should be noted that the phenomenon is not limited to, or dependent upon, the transient process. It only shows up in transient studies since in steady state investigations the air is driven from the tube surface gradually at low heat fluxes and does not form the large, insulating cloud which causes burnout to occur.

Transient temperature measurement tests. The results of the transient tests with the fast response thermocouple welded to the inside wall of the test element are shown in Fig. 6 for the average of all of the tests to a given power level, and these average results are compared in Fig. 7 to the calculated values of the tube wall tempera-

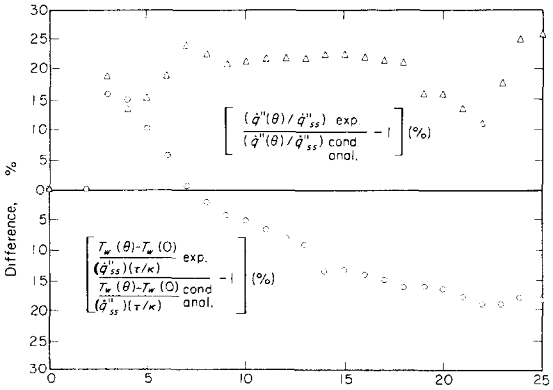


FIG. 7. Comparison of experimental transient heat flux and temperature variation with one dimensional conduction solution for a step in energy generation rate.

ture and heat flux vs. time for a step in power applied to an infinite slab of finite thickness assuming transient one dimensional conduction to the surrounding fluid [19]. The solution assumes that (1) the water is a semi-finite body and (2) the thermal resistance of the test element is negligible. The results are presented in terms of the deviation of the non-dimensionalized experimental temperature and heat flux from the analytical solutions.

Figure 7 indicates that transient conduction is the dominant mode of heat transfer during the transient boiling process rather than transient convection. In Fig. 7 it is seen that the average experimental results are within 25 per cent of the expected transient conduction results (a maximum difference in temperature of 10°F) for times up to 25 ms from the start of the transients. Lurie and Johnson [13], who measured the average test element temperature for steps in power applied to horizontal ribbons also concluded that transient conduction was the governing heat transfer mechanism. The conclusion that transient conduction is the governing heat transfer mechanism during the approach to steady state conditions does not agree with the results of Graham, who measured the transient temperature variation of 0·005 in. thick horizontal and vertical Chromel strips immersed in water and alcohol and subjected to steps in voltage [12]. Graham concluded that natural convection occurred in the early part of the transient. However, Graham measured strip temperatures with a thermocouple attached to the underside of the strip and did not correct the measured thermocouple temperatures to strip temperatures, nor did he correct for the temperature drop through his test element. These two corrections would bring his experimental results much closer to the calculated transient conduction temperature variation. In two studies involving exponential power increases. Rosenthal and Miller [11] and Johnson *et al.* [5] conclude that transient conduction is the governing heat transfer mechanism in the initial transient region.

The time required to reach steady state, as given in Table 1 for the present tests, also agrees well with the results of Lurie and Johnson, as shown in Fig. 8.

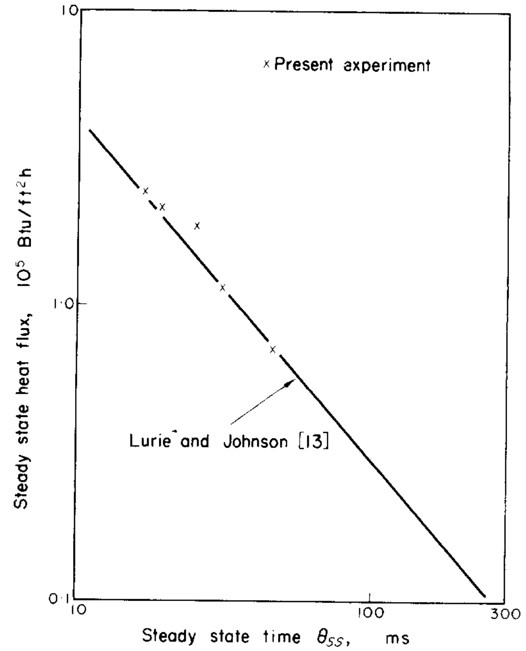


FIG. 8. Comparison of time required for thermocouple temperature to reach steady state with the results of Lurie and Johnson.

No significant difference between the aged and unaged element transient temperature versus time curves for these tests were observed. If the assumed model for the cause of the low unaged peak heat fluxes is correct, the transient temperature curves of the two types of tests should be the same up to the point where the vapor cloud forms on the unaged element. Because of the desire to save the instrumented test element, unaged tests were not run with this element at heat fluxes high enough to produce such a cloud.

Also, the steady state peak heat flux values of $3{\cdot}37 \times 10^5$ Btu/ft²h and $6{\cdot}55 \times 10^5$ Btu/ft²h as determined in the present investigation for the 1·75 and 10 mil wall thickness elements respectively agree well with the results of previous investigations [1, 2].

Last, it should be mentioned that no significant, consistent temperature overshoot (for the subcooled conditions) was observed in these tests as has been observed in others [5, 11, 12, 13]. The conclusions drawn from the present experimental results on this subject are tentative however because of the small number of tests and the local nature of the temperature measurements. Further discussion appears in [18].

CONCLUSIONS

For the peak heat flux tests:

(a) The transient peak heat flux is the same as the steady state peak heat flux for test elements which have been aged by boiling to remove enough of the air trapped on the test element surface. This result is independent of the test element wall thickness and the speed of the power transient.

(b) The transient peak heat flux for elements, regardless of thickness, which have not been aged is considerably lower than the steady state peak heat flux. These low unaged transient peak heat fluxes are caused by air on the test element surface.

For a step in power applied to the test elements, with temperature measured on the rear of the cylinder:

(a) The test element temperature variation is close to that predicted by transient conduction during the approach to steady state conditions.

(b) The time required to reach steady state is short, and decreases rapidly as the amplitude of the power step increases.

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Résumé—Une recherche expérimentale de l'effet des transitoires de puissance sur le flux de chaleur maximal a été conduite pour un écoulement extérieur d'eau normal aux éléments d'essai cylindriques. Deux groupes d'essais ont été effectués: le premier groupe, en appliquant à l'élément d'essai un voltage en échelons et en exponentielle décroissante, montre que si un transitoire de puissance est appliqué à un élément d'essai en présence d'air sur sa surface, le flux de chaleur transitoire maximal peut être aussi bas que 25 pour cent du flux de chaleur correspondant en régime permanent; dans le deuxième groupe d'essais, les mesures de température de surface indiquent que, pour des échelons de puissance, la variation de la température pariétale du tube pendant l'approche des conditions du régime permenent est voisine de celle prédite pour la conduction transitoire à partir de l'élément.

Zusammenfassung—Der Einfluss von Energiestössen auf den maximalen Wärmefluss an zylindrischen, von Wasser quer angeströmten Testkörpern, wurde experimentell untersucht. Zwei Versuchsreihen wurden durchgeführt: In der ersten wurde die Spannung im Versuchselement schrittweise und mit eins minus negativen Esponenten geändert. Dabei zeigte sich, dass ein Energiestoss auf das Testelement bei Vorhandensein von Luft an seiner Oberfläche, eine Abnahme des maximalen Wärmeflusses auf 25 Prozent des entsprechenden stationären Wärmeflusses bewirken kann. In der zweiten Versuchsreihe zeigen die Temperaturmessungen, dass bei schrittweiser Energieänderung die Änderung der Rohrwandtemperatur zu stationären Verhältnissen hin, ähnlich der für die instationäre Wärmeleitung vom Element vorhergesagten verläuft.

Аннотация—Проведено экспериментальное исследование влияния изменений мощности на максимальный тепловой поток при поперечном обтекании цилиндрических элементов потоком воды. Проделаны две серии опытов. В первой серии использовалось ступенчатое изменение напряжения в элементах и напряжение, изменяющееся по закону «единица минус отрицательная экспонента». Эти опыты показали, что, если изменения мощности, подведенной к элементу происходили при наличии воздуха на его поверхности, то максимальный тепловой поток мог быть на 25 % ниже соответствующего стационарного. Во второй серии опытов измерения температуры поверхности показали, что при скачкообразном изменении мощности поведение температуры стенки трубы при переходе к стационарному состоянию близко к расчетному, полученному для нестационарной теплопроводности элемента.