An Experimental Investigation of the Inherent Uncertainty in Pool Boiling Critical Heat Fluxes to Saturated Water

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The inherent uncertainty of the critical heat flux in saturated pool boiling has been inconclusively debated for some time. In an effort to ascertain this uncertainty a series of 234 tests was conducted at atmospheric pressure with saturated water outside horizontal, a.c. heated, 0.234-in. O.D., A-nickel tubes in an open 6 $\times$ 6 $\times$ 9-in. deep pool. Approximately fifty tests were conducted with each of four test sections which were protected from physical burnout by a detector circuit which terminated the applied current before the wall temperature exceeded approximately 450°F. The maximum relative uncertainty in the derived values of critical heat flux was ±3%.

For all the tests the minimum, average, and maximum critical fluxes were 0.201 $\times$ 10^6, 0.436 $\times$ 10^6, and 0.596 $\times$ 10^6 B.t.u./hr. sq. ft., respectively, and the average critical wall superheat was 41°F. The surface roughness of the test sections remained essentially unchanged during the program. The data show that there is an inherent uncertainty or scatter band in the critical heat flux under conditions of minimum surface variability, and that solely hydrodynamic theories of burnout do not fully represent the phenomenon, since surface condition can constitute a significant influence.

It is of both theoretical and practical interest to determine whether the nucleate-to-film-boiling transition, or critical heat flux, is characterized by exact values. The position that an inherent uncertainty exists has been taken by Kutateladze (*1*) and by Zuber and Tribus (*2*), whose hydrodynamic instability theory of burnout predicts a ±14% scatter about the mean value of ϕ_c with saturated pool boiling.

It has often been observed that a significant scatter seems to characterize critical heat flux measurements, and three sets of recently acquired data appear to support the inherent randomness contention. Morozov's data (*3*) show a maximum variation about the mean at a given pressure of ~±11%, the steady state data of Howell and Bell (*4*) scatter ±19% (vs. ±6% cited experimental error), and the results of Lienhard and Schrock (*5*) varied ±10 to 15% (vs. ±3% stated experimental error). The small heat capacity of the 1-mil thick heater strip used in reference *4* doubtless gave rise to larger variations in ϕ_c than would characterize a thicker heater.

Data scatter often seems to be smaller in forced convection burnout tests than in pool boiling. The better reproducibility experienced with forced coolant flow accords with the author's superposition method of critical flux prediction (*6*), which shows that when a large nonrandom convective contribution is added to a small boiling contribution to the total heat flux at burnout, any randomness characterizing the latter is attenuated.

Part of the problem in the assessment of inherent uncertainty in ϕ_c hinges upon the elusive effect of the heater surface condition (aside from roughness changes). Vliet and Leppert (*7*) for example showed that their critical flux results were, at ~5 ft./sec. and 30°F. subcooling for water flowing normal to a heated cylinder, a function of total boiling time. Critical fluxes determined after 1½ to 2 hr. of prior boiling were sometimes as much as 50 to 60% larger than those obtained with an unaged heater surface. Zenkevich and co-workers (*8*) observed a similar effect with a tube bundle cooled by an axial flow of water at ~200 atm. abs. They state that the first few transitions of boiling regime were low compared with those obtained subsequently, and that only after several transitions did ϕ_c attain a steady value. They further found that preliminary heating of the bundle to a high wall superheat at high pressure gave, at once, a steady value of ϕ_c. These studies indicate that a nonhydrodynamic factor, probably associated with a small change in the surface condition related to its wettability by the coolant, can play an important role in determining the level of a particular critical heat flux and therefore the scatter characteristic of a large data population. The masking effect of surface variability on the inherent scatter in the critical heat flux must therefore be taken into consideration.

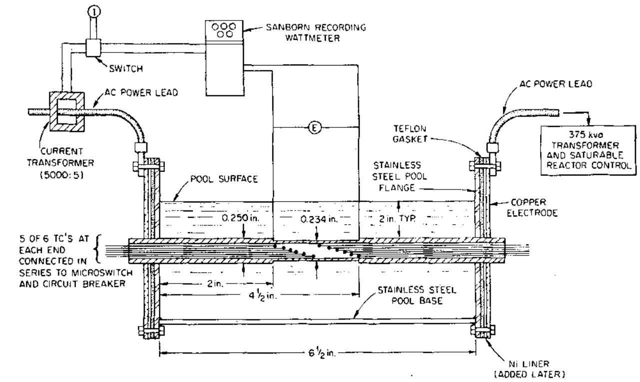
EXPERIMENTAL SYSTEM

The pool boiler measured nominally 6 $\times$ 6 $\times$ 9-in. deep. The horizontal A-nickel heater tube, heated by 60 cycles/sec. alternating current, was silver soldered across two insulated copper end plates which served as electrodes; the bottom and two sides were fabricated of welded 304 stainless steel plate and were flanged at the ends to receive the copper end plates. During early testing it became apparent that some electrochemical deposition of copper onto the test section was occurring, and a thin A-nickel sheet liner was placed inside the copper electrodes.

It was decided to conduct a number of tests with each of a few tubes rather than use a new tube for each test or a uniform treatment before each experiment, since even if the tubes were machined or treated macroscopically the same way each time, they would still differ microscopically.

Since the program called for a large number of tests to be made with each of several test sections, a burnout detector was essential, preliminary testing having shown that manual power interruption would not reliably prevent overheating or burnout of the test sections.

Successful burnout protection was achieved by machining 0.008 in. of the outside tube wall from a 2.5-in. length and spacing ten thermocouples within the zone of increased heat flux, as shown in Figure 1. The two thermopiles were each composed of five ceramic-insulated chromel/alumel 36-gauge thermocouples connected in series to give an additive emf output. The bare thermocouple beads in each bundle were uni-



TUBE	d_o(in.)	d_i(in.)	L_h(in.)	L_r(in.)	NOTES:
FIRST 6	0.250	0.180	6.5	4.0	— PRELIMINARY TESTING, TUBE O.D. NOT REDUCED
1,2,3,4,4a	0.234	0.180	6.5	2.5	— FOR FINAL TESTS AS SHOWN IN FIGURE

Fig. 1. Schematic pool boiler configuration.

formly spaced over a 1.25-in. length, and one bundle was inserted into the tube from each end to give a total monitored length, centered axially, of 2.5 in. The thermopile signal was recorded on a fast-response potentiometer provided with a microswitch making rolling contact with the edge of its slotted traversing disk. When the trip limit (which was adjustable) was reached, the microswitch dropped into the slot and actuated a fast-response circuit breaker which interrupted the current. A sixth thermocouple connected to a separate recording potentiometer was included in each bundle for independent measurement of the inside tube-wall temperature. The calculated ratio of heat fluxes from the reduced and unreduced wall sections was 1.307, and the boiling transition always initiated in the hot zone monitored by the thermopiles. The calculated thermal response of the reduced wall zone at a ϕ_c of 0.5×10^6 B.t.u./hr. sq. ft. was 1,010°F./sec. It is estimated that the maximum local overshoot of tube wall temperature experienced at the critical heat flux was 200°F., so that the metal temperature never exceeded ~450°F. Care was taken to insure that in every accepted test the recorded thermopile output had changed slope suddenly and was increasing at a very rapid rate before the microswitch was actuated. In the rare instances when this did not occur, the test was rejected and the recorder trip point was increased slightly before further tests were conducted.

The reduced reading of the heating current, along with the voltage across the reduced wall portion of the test section, constituted the input to a recording wattmeter. Both voltage and current could be independently measured by switching out the instrument, at which time the zero reading was checked. As shown in Figure 2 the trace changed slope suddenly when the boiling transition began. For consistency the critical flux was taken in all cases to be the point of intersection of the tangents to the two straight lines at each end of the break in the trace, as indicated by Figure 2.

The water charged to the pool had been distilled and deionized and gave readings of electrical resistivity and pH before charging of 1.55 to 2.00×10^6 ohm-cm. and 6.0, respectively. After the testing the resistivity of the pool water approximated 3×10^5 ohm-cm.

Before use the pool was degreased with trichloroethylene and washed with acetone. In approaching the critical flux the power input was increased smoothly at various rates, the effect of which will be discussed in a following section. The barometric pressure varied between 14.23 and 14.50 lb./sq.in.abs. (14.40 lb./sq.in.abs. average). Except during supplementary tests conducted to determine the effect of low liquid levels on the critical heat flux of a horizontal tube, the liquid level above the top of the tube at ϕ_c varied between 1.5 and 3.0 in., within which range the ϕ_c is independent of liquid level. Inside and outside tube diameters were measured at five stations for tube No. 4, and for the central portion the maximum variation in inside diameter, outside diameter, and wall thickness was ± 1 mil. During preliminary heating tests the pool water sometimes sloshed at right angles to the tube axis, and two clean glass baffle plates were positioned parallel to the tube axis and ~¼ in. above the quiescent liquid surface to prevent the motion.

The outside tube surface roughness was measured at six locations for each tube when its test program was completed. The overall average roughness varied between 13.5 and 17.0 μin. root-mean-square, and the average for the reduced wall zone alone varied between 12.5 and 15.8 μin. root-mean-square. For two tubes the surface roughnesses were also measured before testing, and the change which occurred during testing did not exceed 1 μin. root-mean-square in either case.

In order to avoid the low critical fluxes which both McAdams (*9*) and Adams (*10*) noted when successive transitions to film boiling follow one another quickly, several minutes were allowed to elapse between consecutive determinations. It is believed that the low critical fluxes which immediately follow a transition from film to nucleate boiling are caused by a temporary shortage of nucleating sites resulting from degassing of the heating surface during the relatively high-temperature excursion following attainment of the critical flux (*9, 10*).

DATA REDUCTION AND ESTIMATED ERRORS

The power input into the reduced wall portion of the test section was taken from the wattmeter trace, as shown by Figure 2. Calibration checks of the readings were made regularly throughout the test program with a separate voltmeter and ammeter, each of which were accurate to better than ±¾% full scale. The eighty-four tests, covering the full power range, gave average and maximum deviations relative to the initial calibration curve of ±0.74 and ±1.49%, respectively, which may be compared with claimed maximum deviations for the wattmeter of ~±1% (relative) and ±3% (absolute).

The estimated maximum inaccuracies in the measured surface area and in the current transformer stepdown ratio are ½% each. It is believed that the interpretation of the burnout point (Figure 2) involved a further maximum uncertainty of 1%. It is consequently thought that the maximum absolute and relative experimental uncertainties associated with the derived critical heat fluxes are ±5 and ±3%, respectively.

The effect of a.c. heating on the critical heat flux was estimated with the approximate solution of Bertolotti et al. (*11*), which may be expressed as

$$\frac{(\phi_c)_{ac}}{(\phi_c)_{dc}} = \frac{[1 + (2\,\omega\,\tau)^2]^{1/2}}{1 + [1 + (2\,\omega\,\tau)^2]^{1/2}} \tag{1}$$

wherein $\omega = 2\pi f$ and $\tau = cv/hs$. The ratio of critical heat fluxes calculated from Equation (1) for the average conditions of this study is 0.970. The absolute level of the critical fluxes was therefore reduced by ~3% by the a.c. heating, but the values of ϕ_c relative to one another should have been unaffected.

The temperature drop across the tube wall was calculated from

$$\Delta t_w = \frac{\phi_o\, r_o}{2\, k_m} \left[1 - \frac{4}{\left(\dfrac{r_o}{r_i} + 1 \right)^2} \right] \tag{2}$$

as derived by Massier (*12*) for thin-wall tubes (that is for $r_o/r_i \rightarrow 1$). Equation (2) is accurate within 1.7% for the conditions of this study (27-mil wall thickness). Comparison with the numerical zone type of solution of Stein and Gutstein (*13*), which takes into account the temperature dependencies of the thermal and electrical conductivities, shows that in the present case these variations are

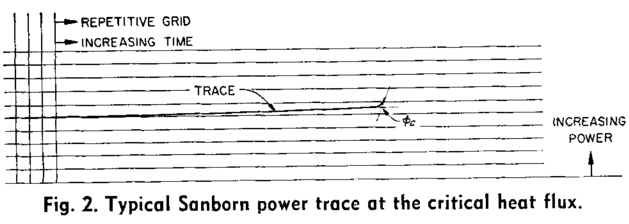


Fig. 2. Typical Sanborn power trace at the critical heat flux.

negligibly small. When one uses values for the thermal conductivity of A-nickel from reference *14*, Equation (2) gives wall temperature drops ranging from 6.5°F. at $\phi_c = 0.2 \times 10^6$ to 20.0°F. at $\phi_c = 0.6 \times 10^6$ B.t.u./hr. sq.ft.

The effect of a.c. heating on variations in the tube wall temperature was estimated with the analysis of Buchberg et al. (*15*), which was derived for a plate insulated on one side and for uniform and constant thermal and electrical properties. The general solution for this case is quite lengthy, but it may be shown that at values of the parameter $\omega b^2/\alpha > 1$ the asymptotic solution for a Biot modulus of zero is applicable to finite Biot moduli up to at least 1.0. For the asymptotic case, which applies to the present situation, the solution may be expressed as

$$a_o = \frac{\phi}{h\,[1 + (2\,\omega\,\tau)^2]^{1/2}} \tag{3}$$

which gives a 120 cycles/sec. fluctuation of the inside tube wall temperature at the ϕ_c of ±1.1°F. for the test sections used. This fluctuation represents the maximum for any part of the tube wall and is too small to affect any of the conclusions.

In a somewhat similar study recently reported, Costello and Frea (*16*) made an approximate determination of the average thermal resistance of the surface coating which formed on their tubes heated in tap water. Such a determination was not made during this program, but it is believed that with the exception of tube No. 2 the coating formed was quite thin. As indicated earlier there was almost no change in the surface microroughness during a test series. The values of wall superheat (Δt_{sat}) which are reported consequently refer to the outside heater wall rather than to the coating surface. It may be noted that if the deposit was unoxidized electrodeposited copper, as suspected, the change in Δt_{sat} for a film thickness of 1 mil and a heat flux of 4×10^5 B.t.u./hr. sq.ft. would be only 0.17°F. In any event the results from the clean heaters, especially tube No. 3, are the significant ones with regard to the assessment of inherent uncertainty.

The inside wall temperature t_{wi} was taken as the arithmetic average of the readings of the twelve thermocouples inside the tube, though any one reading would have sufficed almost as well, since there was very little difference between the calibrated outputs of these thermocouples at incipient burnout (the difference was typically <1°F.). The temporal response of the individual thermocouples naturally varied however during the burnout transient depending on their relative distances from the burnout site. Since nucleate boiling was also taking place on the unreduced wall portion of the test section when the critical flux was attained on the reduced wall portion, the temperature of the higher flux zone was only a few degrees higher than that of the rest of the tube. The calculated axial heat conduction from both ends of the reduced zone amounted to only ~0.01% of the heat generation rate at $\phi_o = 4 \times 10^5$ B.t.u./hr. sq.ft.

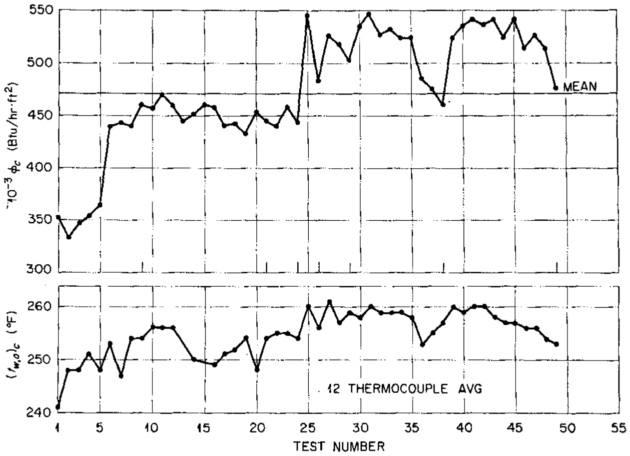


Fig. 4. Critical heat fluxes and outside wall temperatures for tube No. 1.

Regarding the effect of the transient approach to burnout on the critical flux, it may be noted that the ramp increases used were very slow in relation to test section and bubble time constants. Bernath (*17*) has pointed out that all transient investigations of water boiling in atmospheric pools have indicated that transient boiling processes, including burnout phenomena, are indistinguishable from the steady state for periods in excess of ~15 msec. for low thermal capacity test sections (for example ribbons), and that the critical period would be expected to be even shorter for more massive heaters. Bernath further proposes that periods in excess of ten mean lifetimes of surface bubbles are long enough to permit steady state phenomena to become established at the heated surface. On either basis the ramped approaches to ϕ_c used in this study (see Figure 2) were very slow and gave steady state results. At the highest power rise rate used (3.5% of ϕ_c/sec.), the *e* folding time at incipient burnout was ~47 sec. For tube No. 3 the power rise rates were all <1% of ϕ_c/sec., that is, <4,000 B.t.u./hr. sq.ft./sec. The only alternative method of attaining the critical heat flux is to use small step increments of ϕ, in which case burnout more often than not occurs during the rapid power application transient. For these reasons it is believed that the slow increases of heat flux by which the ϕ_c was attained had no effect on the measured values of ϕ_c.

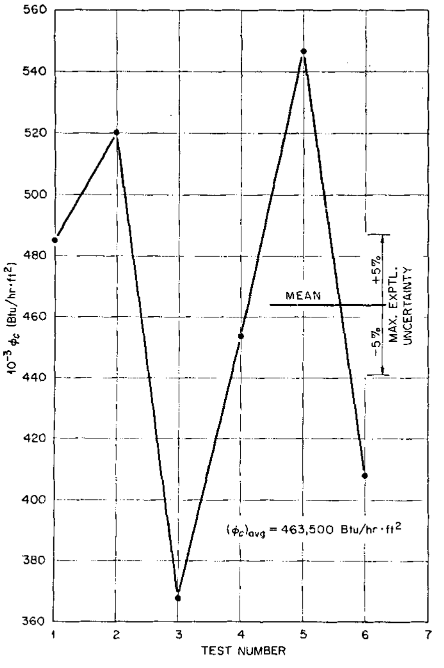


Fig. 3. Preliminary series of critical flux tests. (Tests concluded by physical burnout of test sections.)

RESULTS AND DISCUSSION

Critical Heat Fluxes

The critical fluxes determined during the preliminary test series when the burnout detector was being developed are plotted as Figure 3. The scatter about the mean value of ϕ_c obviously exceeds the maximum absolute experimental uncertainty.

Figures 4 through 8 show the critical heat fluxes and outside wall temperature at ϕ_c obtained with tubes 1, 2,

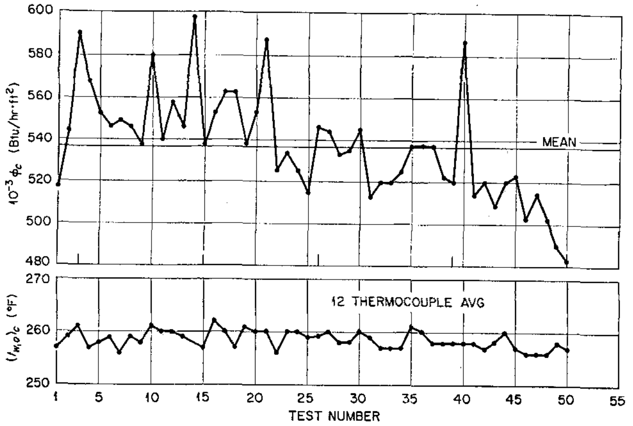


Fig. 5. Critical heat fluxes and outside wall temperatures for tube No. 2.

3, 4, and 4*a*, respectively. The marks on the upper abscissas of these illustrations indicate the last test conducted during a given day. It should be noted that tube 4*a* represents not a fifth test section but a brief continuation of testing with tube 4 after the outer surface was sanded. The data obtained with these test sections are summarized in Table 1.

The range of heat fluxes given in Table 1 corresponds to values of the coefficient '*K*' in the Kutateladze-Zuber equation for ϕ_c with saturated pool boiling (*18*) of 0.076 to 0.224. Previously available experimental saturated pool burnout data (*19, 20*) (~120 points for several fluids) give a maximum '*K*' range of 0.08 to 0.23.

The large increase of ϕ_c with test number for tube 1 and the slow but significant decline for tube 2 were clearly related to changes in the surface characteristics of these test sections. With tube 1 small silvery areas began forming on the tube surface during the early tests. These areas then turned gray and progressively darkened. The density of spots was greatest in the reduced wall region of highest heat flux. The largest color changes were noted after tests 7 and 26, which produced large increases in ϕ_c and initiated, in each instance, a series of tests at a higher plateau (see Figure 4). With tube 2 the surface coating was fully formed during the first three tests by the application of high power rise rates, that is ~3.5% of ϕ_c/sec. immediately preceding the critical flux. As the test series continued, small brightly flecked spots appeared which gradually grew into large bright areas until the tests were concluded. The deposit appeared to flake off the tube, perhaps because of the thermal cycling. It may be noted that ϕ_c decreased sharply during the tests immediately following each of the five peaks of Figure 5.

A semiquantitative spectrographic analysis was made of the surface coating on tube 1, which revealed that the only element present beyond a trace was copper. It was accordingly concluded that copper was being deposited onto the test section, and it was at this point, following testing with tube 2, that thin A-nickel liner sheets were placed inside the copper electrodes. In this way the pool coolant was allowed to contact only elements with standard electrode potentials equal to or greater than that of nickel.

Though the data obtained with tubes 1 and 2 were of little value in determining the inherent uncertainty originally sought because of the confounding influence of surface variability, it is felt that the equally important dependence of ϕ_c on surface characteristics (other than roughness) is clearly demonstrated and that this nonhydrodynamic effect could be of importance in certain situations. A similar conclusion was recently reached by Costello and Frea (*16*), who pretreated semicylindrical test sections by boiling tap water before determining ϕ_c in distilled water. The mineral deposits formed on their tubes increased the critical flux by ~50%, just as the surface coating inadvertently formed on tubes 1 and 2 of this study consistently increased the critical flux. The contention of reference *16*, that surface coatings may increase the wettability, thus decreasing the bubble contact angle measured from the horizontal, seems reasonable. In this event the net vertical force holding a bubble on the surface is decreased, and the decrease in bubble and vapor column diameters at detachment is accompanied by an increase in the bubble population density.

Other investigators who have noted an influence of the nature of the heating surface on the critical heat flux include Ivey and Morris (*21*), who obtained larger values of ϕ_c for aluminum and oxidized surfaces; Grigull (*22*), who states that ϕ_c "is also a function of the wettability of the wall by a given liquid;" and Aladyev (*23*), who cites the work of Labuntsov (*24*) in contending that there is experimental evidence that ϕ_c "depends on the properties of the heating surface." Aging effects in determinations of ϕ_c have been reported and were cited in the introduction (*7, 8*). Though the critical flux phenomenon does appear to be influenced primarily by the liquid-vapor hydrodynamics, as described extensively in previous papers (*1, 2, 18, 19*), the results of this study and of the others cited clearly show that under certain conditions the influence of surface variables not ordinarily included in the hydrodynamic treatment can be significant.

Great care was taken in conducting the tests with tube 3, and its external appearance changed very little during the test series. The nickel liner placed inside the electrodes following tests with tube No. 2 successfully eliminated the copper deposition, and all power rise rates were <1% of ϕ_c/sec. (average = 0.76%/sec.). The conditions during the tests made with tube 3, which are plotted as Figure 6, were most nearly those originally desired, and it is felt that the inherent scatter is best assessed with these data only. For tube 3 the arithmetic mean ϕ_c was 456,700 B.t.u./hr. sq.ft., and the maximum deviation about this

TABLE 1. SUMMARY OF EXPERIMENTAL RESULTS

Tube No.	Number of tests	$10^{-6}\phi_c$, B.t.u./hr. sq. ft. Minimum	Average	Maximum	Average $(\Delta t_{sat})_c$, °F.
1	49	0.334	0.472	0.548	44.1
2	50	0.483	0.537	0.596	47.8
3	52	0.413	0.457	0.498	39.8
4	54	0.299	0.353	0.450	33.1
4*a*	23	0.201	0.280	0.369	35.8
Overall	228	0.201	0.435	0.596	40.5

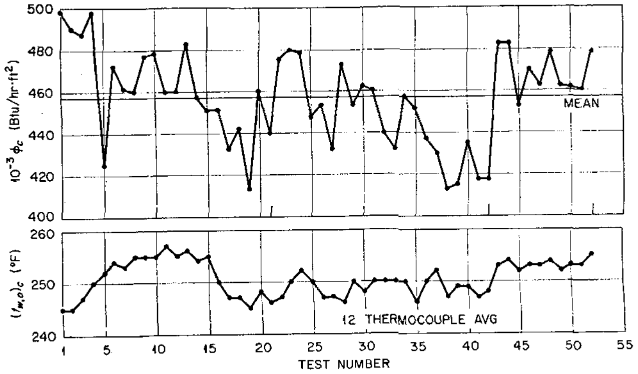


Fig. 6. Critical heat fluxes and outside wall temperatures for tube No. 3.

TABLE 2. ESTIMATES OF VARIABILITY*

Tube number	1	2	3	4
Standard deviations of Y_{ij}, B.t.u./hr. sq. ft.				
Point estimate	15,390	19,900	14,840	25,990
Lower confidence limit	12,610	16,470	12,330	21,680
Upper confidence limit	19,740	25,120	18,620	32,450
Standard deviations, % of mean				
Point estimate	3.26	3.70	3.25	7.37
Lower confidence limit	2.67	3.07	2.70	6.15
Upper confidence limit	4.18	4.68	4.08	9.20
Degrees of freedom	39	44	46	48
Arithmetic mean ϕ_c, B.t.u./hr. sq. ft.	472,242	537,196	456,698	352,602
Slope of regression line, B.t.u./hr. sq. ft.	−3,536.9	−1,942.4	−2,764.1	−5,902
Standard error of slope, B.t.u./hr. sq. ft.	844.7	850.6	678.7	1,125

* Day-to-day variability was eliminated by using a separate regression line for each day's tests. All the data were used except tests 25 and 26 for tube 1 (only two tests were made that day). The lower and upper confidence limits are the limits within which the standard deviation may be said to lie with 95% confidence. The regression line slopes are weighed averages obtained from the slopes of the regression lines for each day.

mean was +9.0 and −9.6%. The average deviations about the mean were +3.3 and −4.7%. Since the maximum scatter measured is approximately triple the maximum relative experimental uncertainty, it is concluded that the critical flux phenomenon is indeed characterized by an intrinsic randomness, whereby values of ϕ_c fluctuate about the most probable value. The experimental fluctuation approximates that predicted by the hydrodynamic instability theory of Zuber (*18*).

In terms of the standard deviations the conclusion regarding intrinsic randomness is equally convincing. The data were subjected (*30*) to a linear regression analysis with the model

$$Y_{ij} = \alpha_i + \beta X_{ij} + \epsilon_i \qquad (4)$$

in which Y_{ij} represents the jth observation of ϕ_c for the ith day, α_i is the intercept of the regression line for the ith day, X_{ij} is the jth test number on the ith day, and ϵ_{ij} is a random error. The results are summarized in Table 2. If the maximum relative experimental uncertainty is taken as equivalent to ±3 standard deviations when one considers tube No. 3 only, probability tables show that there is <1/2% chance that the maximum relative experimental uncertainty and the standard deviations given in Table 2 are the same. It is in other words extremely probable on the basis of these data that the burnout phenomenon is characterized by an inherent scatter band.

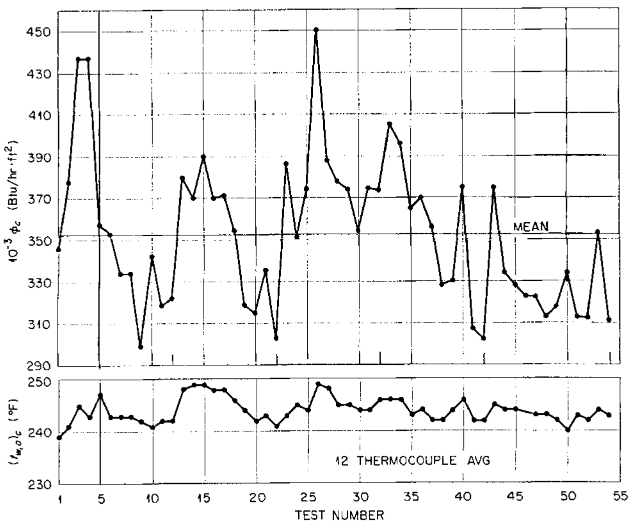


Fig. 7. Critical heat fluxes and outside wall temperatures for tube No. 4.

Tests were conducted in a similar fashion with tube 4, but as shown by Figure 7 the results were considerably more erratic. Dark spots formed on the middle of the tube during the first tests and later at the left and right ends. After fifty-four tests were made with tube 4, it was sanded with 400- and then 600-grit paper and washed with acetone. A short series of twenty-three tests was conducted to determine the influence of the sanding on ϕ_c, and the results are shown in Figure 8. Prior to test 20 it was observed that sudden power application at $\phi \approx 10^5$ B.t.u./hr. sq.ft. resulted in very uniform nucleation in the high-flux portion of the tube. Following test 20 however a dark spot made its appearance, and when the power was applied in the same way, bubbles began nucleating first on the unchanged surface and an instant later on the dark spot.

The last three tests of the 4*a* series (21 to 23) were conducted differently than any of the earlier runs. Prior to

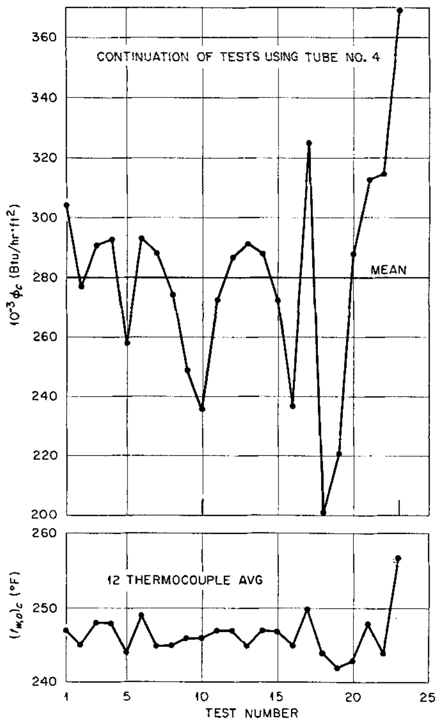


Fig. 8. Critical heat fluxes and outside wall temperatures for tube No. 4a.

tests 21 and 22 an advance adjustment was made to the saturable reactor so that the voltage suddenly impressed across the test section when the power was applied would exceed the burnout voltage of test 20 by ~20%. In each case the burnout detector tripped the circuit breaker, and the subsequent burnout tests made with slow power application gave critical fluxes appreciably greater than those attained in tests 18 through 20. Before test 23 a much more severe heat treatment of the same type was given the tube. The power was adjusted first to give an instantaneous ϕ at power application approximately double the ϕ_c of test 20. The tube wall temperatures rose to ~700°F. before this transient terminated, but there was no change in the appearance of the tube. The power was then adjusted so that the initially imposed flux was approximately triple the ϕ_c of test 20. During this transient the tube glowed red for ~3 sec. over the entire reduced wall section, following which the previously dark spot was a copper color and the rest of the tube a straw shade. The ϕ_c subsequently determined (test 23) was ~18% larger than those obtained in tests 21 and 22. It is also apparent that the sanding of the surface reduced the entire level of critical fluxes determined in test series 4*a*.

The frequency distribution of all the measured critical fluxes is shown as Figure 9. Though peaks exist on either side of $\phi_c = 0.5 \times 10^6$, the spectrum is surprisingly broad. The threefold range in ϕ_c of 0.201×10^6 to 0.596×10^6 B.t.u./hr. sq. ft. compares favorably with the overall range obtained from twenty-two literature references of 0.200×10^6 to 0.651×10^6 B.t.u./hr. sq. ft. A representative selection of the data in the literature is given in Figure 10(*b*) of reference 25. It may be noted that for tube No. 3 alone 46% of the critical heat fluxes fell within the narrow range of 450,000 to 475,000 B.t.u./hr. sq. ft. (which range corresponds closely with the maximum relative experimental uncertainty of ± 3%).

Heat-Transfer Coefficients

Figure 10 is a plot of the critical heat fluxes vs. the corresponding wall superheats at ϕ_c. The average values of h_c for each test section are listed in the table on the figure. A frequency distribution plot of the individual heat transfer coefficients shows a sharp peaking, with 71% occurring between the limits 10,000 and 12,000 B.t.u./hr. sq.ft. °F. The overall data indicate proportional variations in ϕ_c and $(\Delta t_{sat})_c$, but it should be noted that the data tend to group according to tube number, as indicated by the lines bounding typical data groups in Figure 10.

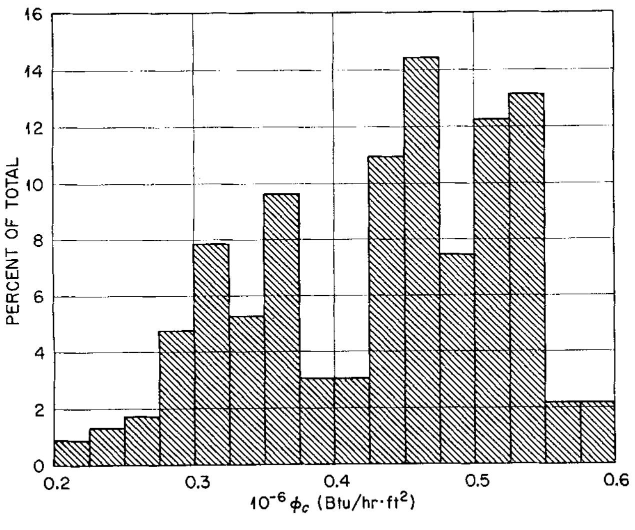


Fig. 9. Frequency distribution of critical heat fluxes for all tests.

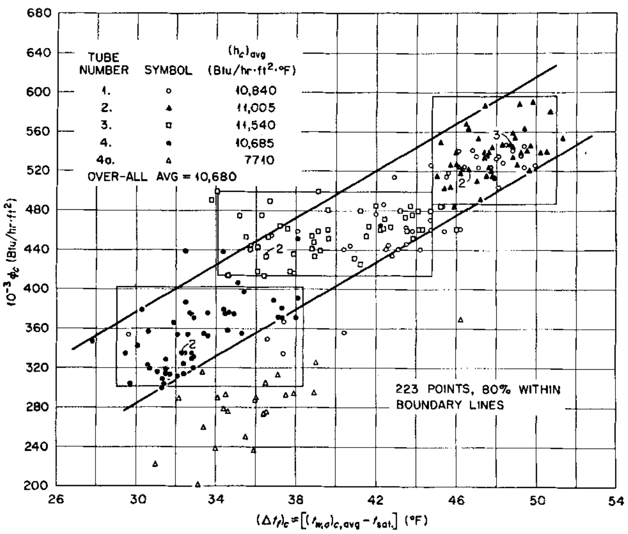


Fig. 10. Critical heat flux vs. critical wall superheat.

Power Rise Rates

The power rise rates were derived from the wattmeter traces. Of the total ~71% were between ½ and 1½% of ϕ_c/sec. Comparison of the average ϕ_c for those tests with power rise rates ≧1.0% and <1.0% of ϕ_c/sec. showed that the critical fluxes approached slowly averaged 13.6% higher than those attained more rapidly. Because of the sometimes obscuring effects of surface variability and the preceding discussion regarding the highly unlikely influence of the power rise rate however, this result is not considered as significant.

Critical Wall Superheats

That the critical wall superheat is quite dependent on the surface and material of the heater has been conclusively demonstrated by Stock (*26*), Berenson (*27*), and Bonilla (*28*), who cites a 49°F. difference in $(\Delta t_{sat})_c$ for water at 1 atm. abs. boiling on blackened P_t and P_b surfaces. Costello and Adams (*29*) have shown that measured superheats can vary considerably depending on how many burnouts at high heat fluxes the heater has endured. In Figure 4 of their paper (*29*) a critical superheat of only ~23°F. is given for a new carbon heater. In view of these observations it is not surprising that a considerable number of the critical wall superheats measured in this study are smaller than the 45° to 50°F. values often reported (see Figure 10). The proportional changes in Δt_c with ϕ_c however (which give rise to the approximate constancy in h_c) is different from the behavior noted in some other studies, wherein Δt_c varies considerably for different surfaces but ϕ_c remains approximately constant.

Effect of Liquid Level on ϕ_c

Four auxiliary tests were conducted with tube 3 in order to determine the variation of ϕ_c with liquid level when the liquid is even with or below the top surface of a horizontal tube. The tube was carefully levelled to within 1/6 deg. of the horizontal, and the pool was maintained at t_{sat} throughout the tests. A heat flux was preset and the water allowed to vaporize until the burnout detector interrupted the power at which time the liquid level was immediately measured. The results are shown in Figure 11, wherein the heat flux ϕ was computed with the total external surface area of the tube. The heat transferred at low liquid levels without transition is surprisingly high, and even when the liquid just wets the lower tube surface a flux of $\sim 10^5$ B.t.u./hr. sq.ft. can be transmitted without overheating. If the heat flux were computed on the basis of the wetted surface area only, it would obviously be

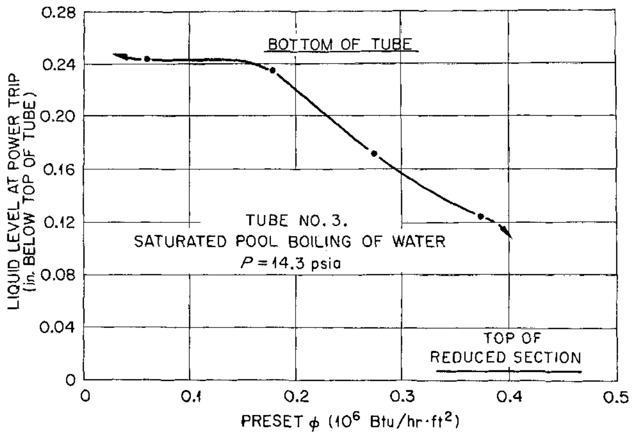


Fig. 11. Effect of liquid level on the critical heat flux for a horizontal tube.

larger, but application of such a local heat flux would require an estimate of the circumferential heat conduction in the tube wall.

GENERAL CONCLUSIONS

1. There is an inherent uncertainty or intrinsic randomness in the critical heat flux determined under saturated pool boiling conditions with minimum surface variability ($\sim\pm 9.3\%$) which approximates that predicted by the hydrodynamic instability theory ($\sim\pm 14\%$).
2. The nature and condition of the cooled surface can constitute an important influence on the critical heat flux.
3. Significant heat fluxes can be transferred in saturated nucleate pool boiling from horizontal tubes without overheating of the tube wall even at very low liquid levels.

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NOTATION

a_o = sinusoidal tube wall temperature amplitude
b = wall thickness
c = volumetric heat capacity of tube wall material
d = tube diameter
f = a.c. current frequency (cycles per unit time)
h = heat transfer coefficient
k = thermal conductivity of tube metal
L_h = overall heated length
L_v = length between voltage taps
r = tube radius
s = cooled surface area per unit length
t = temperature
Δt_f = film temperature drop, $(t_{w,o} - t_b)$
Δt_{sat} = wall superheat, $(t_{w,o} - t_{sat})$
Δt_w = temperature drop across tube wall, $(t_i - t_o)_w$
v = volume of tube wall per unit length

Greek Letters

α = thermal diffusivity of tube wall material
ϵ = surface asperity height
ρ_e = electrical resistivity of water
τ = thermal time constant of test section
ϕ = heat flux into coolant
ω = a.c. current frequency (radians per unit time)

Subscripts

ac = with ac heating
avg = average
b = bulk
c = critical
dc = with dc heating
i = inside
m = arithmetic mean
o = outside
sat = saturation
w = wall

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