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THERMAL BEHAVIOR IN THE TRANSITION REGION BETWEEN NUCLEATE AND FILM BOILING

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ABSTRACT

The prediction of post Critical Heat Flux (CHF) behavior is complicated by the highly nonlinear thermal behavior of boiling interfaces--ie by the nonlinear nature of the "boiling curve".

Nonlinearity in the boiling curve can and does cause thermal instability, resulting in temperature discontinuities. Thus the prediction of post CHF behavior requires the analysis of thermal stability. This in turn requires an accurate description of thermal behavior in transition boiling.

This article determines thermal behavior in transition boiling by analysis of literature data. It also describes design features which improve post CHF performance and are reported in the literature.

NOMENCLATURE

Symbols

P	pressure
q	heat flux
T	temperature of the boiling interface
ΔT	T minus saturation temperature

Subscripts

CHF	critical heat flux
DNB	departure from nucleate boiling
in	into
out	out of
tr	transition

INTRODUCTION

Nukiyama (1934) is widely considered the pioneer of the boiling curve--the first to demonstrate the highly nonlinear behavior of q(T), the function which relates heat flux (q) and temperature of the boiling interface (T).

Nukiyama's comprehensive experiment clearly demonstrated that q(T) for water exhibits a maximum, a minimum, and a negative slope region. The heat flux at the maximum is the Critical Heat Flux (CHF), the negative slope region is transition boiling, and the region beyond the minimum is film boiling.

Because q(T) is highly nonlinear, boiler operation in the region beyond CHF may result in thermal instability, causing large temperature discontinuities and pronounced hysteresis.

The prediction of discontinuous behavior in the post CHF region is accomplished by separately describing the behavior of heat flow into and out of the boiling interface. Heat flow behavior into the interface depends on boiler design, and is written $q_{in}(T)$. Heat flow behavior out of the interface is described by the boiling curve, and is written $q_{out}(T)$. Continuity requires that the two q's be equal.

Post CHF operation will result in temperature discontinuities and pronounced hysteresis unless Criterion (1) is satisfied throughout the operating envelope beyond CHF:

$$dq_{in}/dT < dq_{out}/dT \qquad (1)$$

Criterion (1) is the generic criterion for thermal stability. It was derived by Adiutori (1964), Stephan (1965), and Kovalev (1968).

This article determines $q_{out}(T)$ in transition boiling by analysis of literature data. In particular, it quantitatively determines dq_{out}/dT, the importance of which is established by Criterion (1). This article also describes design features which improve post CHF performance and are reported in the literature.

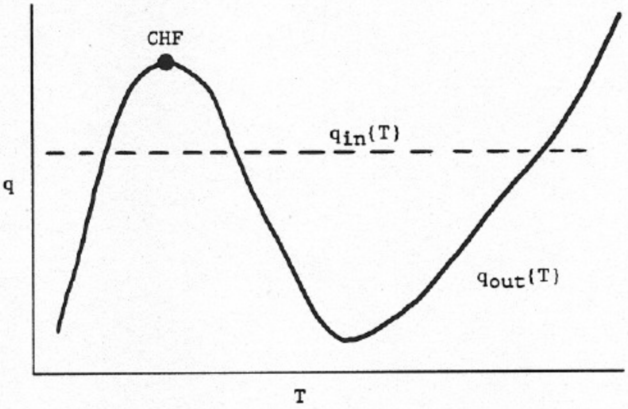
A SIMPLISTIC VIEW OF THERMAL STABILITY AND POST CHF BEHAVIOR

A simplistic view of thermal stability and post CHF behavior results from classifying boilers into two groups on the basis of the thermal parameter which is controlled:

- Controlled heat flux (such as a boiler plate heated directly by electricity.)
- Controlled temperature (such as a boiler plate heated by steam condensing on its backside.)

In this view, controlled heat flux boilers experience temperature discontinuities in the post CHF region, whereas controlled temperature boilers do not. This is illustrated by plotting $q_{in}(T)$ on a figure of the boiling curve, then inspecting the figure to determine the behavior which would result from monotonic changes in $q_{in}(T)$.

In controlled heat flux boilers, q_{in} is independent of T, and therefore $q_{in}(T)$ is a horizontal line as shown in Sketch 1.



Sketch 1 Graphical Analysis of Boiler Behavior

Inspection of Sketch (1) indicates that a temperature discontinuity would result if a horizontal $q_{in}(T)$ monotonically increased through CHF, and similarly if $q_{in}(T)$ monotonically decreased through the minimum.

In controlled temperature boilers, T is independent of q_{in}, and therefore $q_{in}(T)$ would be a vertical line in Sketch 1. Inspection of Sketch 1 indicates that no temperature discontinuity would result if a vertical $q_{in}(T)$ passed through CHF, or through the minimum.

THE RIGOROUS VIEW OF THERMAL STABILITY AND POST CHF BEHAVIOR

The difficulty with the above simplistic view is that $q_{in}(T)$ is seldom horizontal in "controlled heat flux" boilers, and is NEVER vertical in "controlled temperature" boilers.

In controlled heat flux boilers, there is generally interaction between heat input and interface temperature. For example, if the boiler plate were directly heated by electricity, q_{in} would be affected by changes in T unless the temperature coefficient of electrical resistivity (ϵ) were zero.

If the power supply were constant amperage and ϵ were positive, q_{in} would increase with T, dq/dT would be greater than zero, and the dashed line in Sketch 1 would exhibit positive slope. In this case, the temperature discontinuity would occur somewhat *before* CHF. (The boiler used by Nukiyama (1934) behaved in this way.)

Conversely, if the power supply were constant voltage and ϵ were positive, the dashed line in Fig. 1 would exhibit negative slope. In this case, the temperature discontinuity would not occur until somewhat *after* CHF. Moreover, if ϵ were sufficiently large that the slope of the dashed line were steeper than the steepest slope of the boiling curve beyond CHF, *NO* temperature discontinuity would result from post CHF operation. In spite of the fact that the boiler is a "controlled heat flux" boiler.

If the boiler plate were heated by steam condensing on its backside, $q_{in}(T)$ would be vertical only if the backside heat transfer coefficient and the plate thermal conductivity were infinite. Since they are always finite, $q_{in}(T)$ always exhibits finite, negative slope. And because the slope is finite, temperature discontinuities can and often do occur even in "controlled temperature" boilers.

In summary, there are two conflicting views of thermal stability and post CHF behavior:

- The simplistic view appraises thermal stability by supposing that the value of dq_{in}/dT is zero or infinite. Therefore the *sign* of dq_{out}/dT is necessary to appraise thermal stability, but the *value* of dq_{out}/dT is not.
- The rigorous view recognizes that dq_{in}/dT is seldom zero, and is never infinite. Therefore the value of dq_{out}/dT is as necessary as its sign.

THE POOL BOILING EXPERIMENT BY BERENSON (1960, 1962)

The main thrust of Berenson's (1960, 1962) experiment was the measurement of q(T) in the transition boiling region. Data were obtained in a vented pool boiler with a round, flat boiler plate which was the upper surface of a steam chamber. Steam condensed on the lower surface of the plate. The prime heat source was an electrical heater at the bottom of the steam chamber.

Data for 20 boiling curves are presented in the form q vs ΔT on log log graphs. In 17 of these curves, there is essentially no transition boiling data. These 17 curves were the bases for the conclusion that "transition boiling data lie along a straight line . . . on log log paper".

In 3 of the boiling curves, data were obtained throughout the transition region. The data from these 3 runs describe highly curved lines on log log paper. Since these 3 runs were a small fraction of the experiment, they were more or less disregarded.

Berenson's data for n-pentane boiling on copper has been replotted on linear coordinates in Figures 1 and 2. Notice in Figure 1 that:

- There is essentially *no data* in the transition region of Runs 2 and 17.
- The absence of the desired data indicates that it could not be obtained in spite of the fact that the boiler was a "controlled temperature" boiler.

In Figure 2, notice that:

- Run 7 contains data throughout the transition region, and the transition region data lie along a straight line on *LINEAR* paper.
- The slope of the line drawn through the transition region data from Run 7 is -3800 w/m^2C. In other words, $dq/d\Delta T$ throughout the transition region of Run 7 is -3800 w/m^2C.

The lack of the desired transition region data disproved the then current theory of thermal stability. In particular, the data disproved the widely accepted view stated by Rohsenow (1963):

With condensing vapor as the heat source on one side of a wall, any point on the entire (boiling) curve can be reached under stable conditions.

THE POOL BOILING EXPERIMENT BY HESSE (1973)

The pool boiling experiment by Hesse (1973) was performed after an understanding of thermal stability had been reached, and the boiler design accurately reflects the requirements of thermal stability.

In order to enhance the thermal stability of a boiler, the principal design requirement is that the left side of Criterion (1) approach negative infinity. This requires a large overall heat transfer coefficient from heat source to boiling interface.

Hesse's boiler design satisfies this requirement because the boiling interface is the outer surface of a *thin* wall tube, and the heat source is water pumped at *high* velocity through the tube.

Smooth tube data are reported in the form q vs ΔT on log log graphs. The data exhibit a high degree of curvature in the transition region.

Transition region data from Hesse (1973) is plotted on *linear* coordinates in Figures 3 to 5. Notice that the data points indicate q(ΔT) in the transition region is highly *LINEAR*. The slopes of the straight lines drawn through the data points are listed in Table 1, and are plotted in Figure 6.

ALTERING THE BOILING CURVE

If a design specification value of ΔT would normally result in post CHF operation, the designer should be aware that there are two alternatives:

- Design the equipment to operate in a satisfactory manner in the post CHF region.
- Avoid post CHF operation by incorporating a design feature which will increase ΔT at CHF to beyond the design value of ΔT.

The second alternative is often much simpler than the first, and therefore it is important that designers of boiling equipment be aware that designer controlled features greatly affect the boiling curve.

ALTERING THE BOILING CURVE--LYON ET AL (1955)

The experiment by Lyon et al (1955) investigated the effect of trace additives on the thermal behavior of liquid metal interfaces in pool boiling. The authors give the following description of their boiler:
The boiler tube is a 3/4 inch (O.D.) 16-gauge, type 316 stainless steel tube, 5 in. long. Chromel-alumel thermocouples were in the tube wall, which was heated internally by a 1/2 in. silicon carbide electric heating element. The boiler shell is constructed from 3.5 in. 304 stainless steel pipe.

The authors present their boiling curve data in the form q(ΔT) on log log paper. Figure 7 is a linear representation of lines faired through the data by the authors. Notice the following:

- The curve for pure mercury increases monotonically over the ΔT range tested--5 to 550 C. In other words, *NO MAXIMUM* was observed in q(*ΔT*). The authors state: *"The heat flux vs temperature difference curve for pure mercury . . . is smooth throughout the observed range of heat transfer, from simple convection to boiling at temperature differences above 1,000 F; no peak heat flux is apparent."*
- Trace additives greatly affect q(T).

ALTERING THE BOILING CURVE--DUNSKUS AND WESTWATER (1961)

Dunskus and Westwater (1961) investigated the effect of trace amounts of additives on the pool boiling curve for isopropanol. They describe their apparatus as follows:
The liquids were boiled at atmospheric pressure outside a horizontal, steam heated copper tube, 1/4 in. O.D. . . The heating tube had a 10.5 in. length located inside an 11 in. by 9 in. by 4 in. experimental boiler made of 1/4 in. stainless steel plate.

Dunskus and Westwater present their boiling curve data in the form q(ΔT) on linear graphs. The data points in Figures 8 and 9 were obtained from their graphs. (The lines differ somewhat from those drawn by Dunskus and Westwater.) Notice that:

- In the transition region, q(ΔT) is quite linear.
- In the transition region, the slope for pure isopropanol is -5550 w/m^{2}C; with a trace of CO-210, the slope is -7250 w/m^{2}C; with a trace of CO-880, the slope is -3200 w/m^{2}C
- The addition of a trace additive to the boiling liquid greatly increased the values of q and ΔT at the maximum in q(ΔT).

The authors state: *". . . trace additives of the right kind and in the right amount can prevent or severely retard the onset of film boiling."*

ALTERING THE BOILING CURVE--EXTALE AND RIDDINGTON (1961) PATENT

The patent by Extale and Riddington (1961) describes how to avoid transition and film boiling by altering the boiling curve to obtain a greatly increased nucleate boiling region. The patent deals with the prevention of "spitting" in domestic steam irons. ("Spitting" is the carryover of liquid water droplets in steam.) The authors state:
The soleplate (of steam irons) is usually made of a metal such as aluminum. If the water is dropped onto a bare aluminum surface, there is a tendency for at least some of the water to collect in globules bouncing about on the hot surface in a well-known manner.

Such globules are frequently entrained (and) ejected as water onto the surface being ironed. This, of course, is undesirable for most satisfactory and effective steam ironing. In order to reduce the amount of such "spitting" it has been the practice to coat the surface of the boiler in some manner. Irons (coated with gypsum do not begin to spit until the surface temperature exceeds) about 400 degrees F.

In summary, coating prevents "spitting" at boiler surface temperatures to 400 F. The lack of spitting indicates that nucleate boiling occurs at ΔT's to 200 F, and that ΔT at CHF is 200 F. (The expected value of ΔT at CHF is approximately 50 F. For example, Afgan et al (1985) report 54 F.)

Extale and Riddington describe their new and improved coating method:

. . . we provide a coating material which does not allow "spitting" even at temperatures above 500 degrees F. Moreover, it is possible to apply this new coating uniformly and easily by spraying it . . . We have found that a very satisfactory composition for the purpose is a silica sol sold under the trade name "Ludox".

In other words, by simply spraying "Ludox" in water onto the boiling surface, the ΔT at CHF is increased to 300 F from an uncoated value of approximately 50 F!

It would of course be possible to design a steam iron to operate beyond CHF without "spitting"--perhaps by incorporating a moisture separator between the boiler and the steam ports. The point is that it is oftentimes much simpler to avoid post CHF operation by altering the boiling curve rather than designing the equipment to operate beyond CHF.

ALTERING THE BOILING CURVE--GAERTNER (1965)

Gaertner (1965) alters the boiling curve for water by applying a coating which *eliminates* the nucleate and transition regions. He states:

Double-distilled water was boiled at atmospheric pressure on two surfaces. One surface was coated with a thin film of polytetrafluoroethylene and the other surface was coated with a thin film of silicone *grease. . . . . It was found that after bubbles formed at nucleation sites they did not rise into the bulk liquid, but rather grew and spread on the surface, coalesced with their neighbors, and soon generated a continuous blanket of vapor over the entire surface. Heat transfer by nucleate boiling was impossible. Film boiling began at a heat flux of about 5400 Btu/hr ft^2, essentially the point of incipient nucleation and only one percent of the burnout heat flux noted in this paper.*

ALTERING THE BOILING CURVE--AFGAN ET AL (1985)

The experiment by Afgan et al (1985) resembles the patent application of Extale and Riddington (1961) in that both deal with the effect on the boiling curve of applying a porous coating to a metal surface. Afgan et al state:

"Boiling heat transfer on a porous surface was investigated in large volumes of distilled water, Freon-113 and ethyl alcohol at atmospheric pressures and with the natural convection taking place. A horizontal tube with the porous layer was heated by electric current flowing through the tube. . .

The sintered metal particle porous layer studied is a capillary- porous structure. Dendrite shaped and spherical 63-100 μm particles were sintered. Test samples Nos. 1-5 were Cr-Ni stainless steel on Cr-Ni whereas sample No. 6 was a Cr-Ni stainless steel6t6be with a titanium porous layer."

Afgan et al (1985) present their boiling curve data in the form q(ΔT) on log log graphs. Fig. 10 herein is a linear coordinates version of Fig. 3 by Afgan et al. In Fig. 10, notice that:

- For water boiling on an uncoated specimen, nucleate boiling ceases at 30 C. The maximum heat flux is $1x10^6$ W/m^2.
- For water boiling on coated "Sample 2", nucleate boiling extends to 150 C, and the maximum heat flux becomes $3.2x10^6$ W/m^2.
- For water boiling on coated "Sample 3", nucleate boiling extends to 450 C, and the maximum heat flux becomes $3.1x10^6$ w/m^2.
- For water boiling on coated "Sample 6", nucleate boiling extends to 150 C, and the maximum heat flux becomes $0.6x10^6$ w/m^2.

In summary, Afgan et al (1985) demonstrate that the boiling curve can be greatly altered by coating a metal surface, and that the alteration increases the nucleate boiling region by as much as a factor of 15 in ΔT, and a factor of 3 in heat flux.

ALTERING THE BOILING CURVE--FUKUSAKO ET AL (1986)

Fukusako et al (1986) altered the boiling curve by placing a layer of beads on the boiling surface. The authors describe their experiment as follows:

The apparatus consists of an inner Pyrex tube 60 mm in diameter and 450 mm in height . . . filled with a liquid-saturated porous bed. (It was filled) with testing liquid and a constant liquid level was held above the heating surface. To prevent fluidization of the porous bed, a screen plate (26 mesh) on the bed was pressed downward with a mechanical screwjack.

In the nucleate boiling region, the heat fluxes for the porous bed at a prescribed ΔT increase in comparison with those for pool boiling without a porous bed. It is also observed in the figures that for the comparatively large bead diameters (4 to 16.3 mm, there is a well defined maximum in q(ΔT). The figures also) show that for small bead diameters (1.0, 1.1, and 2.0 mm) the heat flux increases continuously and monotonically from nucleate boiling to film boiling without going through a peak heat flux.

THE PIONEERING FLOW BOILING EXPERIMENT BY ELLION (1954)

Ellion (1954) was the first to build an electrically heated, forced convection boiler which could operate stably in much of the transition region. For several years, his was the only literature data on transition region flow boiling. Ellion's work has been largely overlooked, as evidenced by the following by Stephan and Hoffmann (1977):

Contrary to the large number of test results for the range of nucleate flow boiling in tubes, there exist . . . no data concerning heat transfer in the transition region of forced convection (boiling).

Ellion describes the rationale behind his innovative design:

The difficulty with conventional equipment which uses electrical heating is that a small increase in power above (CHF) causes the wall temperature to rise above the melting point. If the heat transfer could be made a monotonically increasing function of the wall temperature, stable operation would be obtained at any heat flux that requires a surface temperature below the melting point of the wall.

Ellion obtained a monotonically increasing heat flux with a double tube heat exchanger in which the boiling surface was the outer surface of the inner tube. The inner tube was electrically heated, and non-boiling fluid from a separate system flowed at high velocity through the inner tube. Ellion states:

Because of its function, (the inner tube fluid) is denoted as the stabilizing fluid. The fluid under study flows through the annulus formed by the tube and outer jacket. The electrical power supplied to the tube is dissipated outward to the test fluid and inward to the stabilizing fluid. By controlling the pressure of the stabilizing fluid, it is possible to study (transition) and (film) boiling regions for the test fluid over a wide range of variables.

It was thus possible with the use of this apparatus to study the three boiling regions in detail up to the melting point or yield point of the metal wall without danger of tube failure.

Figures 11 and 12 present Ellion's data on linear coordinates. Notice that, in 3 of the 4 runs, q(ΔT) is essentially linear in the transition boiling region. The values of dq/dΔT in the transition region are listed in Table 2.

THE FLOW BOILING EXPERIMENT BY MCDONOUGH ET AL (1961)

McDonough et al (1961) reported the first flow boiling, transition region experiment with water at pressures of practical importance in nuclear reactor engineering. The authors state:

"The (transition region) correlation should be of considerable value to the designer since no idea as to the magnitude of (transition region heat) flux has been available. No comparative heat transfer data are available in the (transition region)."

The boiler in the experiment by McDonough et al was a double tube, counterflow heat exchanger in which the boiling fluid flowed upward inside the inner tube. The authors state:

"A study to determine the surface (heat) flux in the (transition boiling) region of water at 800, 1200, and 2000 psia was made in a .25 in. O.D. vertical Inconel-X tube, 0.152 in. I.D. x 12.5 in. long. The water parameters were: mass flow rates approximately 0.2 to 1.5 x 10^6 lb/hrft^2 at inlet

enthalpies of about 200 to approximately 670 Btu/lb. NaK, a liquid metal, was used as the heating medium."

Equations (4) to (6) are correlations obtained for transition region flow boiling at 800, 1200, and 2000 psia. They reportedly apply at surface temperatures to approximately 1050 F, and agree with the data within 35%. (The units in the equations are Btu, lb, F, hr, ft except for P which is psia.)

$$q_{tr,800} = q_{max} - 1500(T_{tr} - T_{DNB}) \qquad (4)$$

$$q_{tr,1200} = q_{max} - 1180(T_{tr} - T_{DNB}) \qquad (5)$$

$$q_{tr,2000} = q_{max} - 985\ (T_{tr} - T_{DNB}) \qquad (6)$$

The authors note that Eq. 7 summarizes Eqs 4 to 6:

$$q_{tr} = q_{max} -730\ e^{576/P}(T_{tr} - T_{DNB}) \qquad (7)$$

Note the following in Equations (4) to (6) and (7):

- At pressures in the range 800 to 2000 psia, $q(\Delta T)$ is *linear* in the transition region.
- Equations (4) to (6) indicate that, at 800, 1200, and 2000 psia, the values of $dq/d\Delta T$ in the transition region are -1500, -1180, and -985 $B/hrft^2F$ (-8500, -6700, and -5600 w/m^2C).
- Differentiation of Equation (7) indicates that, in the range 800 to 2000 psia, the value of $dq/d\Delta T$ in the transition region is given by Eq. (8):

$$dq/d\Delta T_{tr} = -730\ e^{576/P} \qquad (8)$$

In summary, the results by McDonough et al (1961) quantitatively describe the thermal behavior of water in transition region flow boiling over a wide range of practical importance.

THE FLOW BOILING EXPERIMENT BY STEPHAN AND HOFFMANN (1977)

Stephan and Hoffmann (1977) performed a flow boiling experiment which included operation in the transition region. They state:

"The experiments were performed with refrigerant R114, flowing inside a horizontal tube at mass flow rates between 1200 and 4000 kg/m²s and pressures between 5 and 15 bar. The measurements reported here were done at low vapor qualities (less than 10%).

In all experiments the vapor content at the inlet of the test section was kept zero. . . . Boiling occurred inside the horizontal tube of 14 mm diameter of the test section. This tube was heated by the stabilizing liquid in an annular space outside of 3 mm width. . . As stabilizing liquid fully degassed water was chosen."

The authors present $q(\Delta T)$ graphs in which lines are drawn. The lines indicate that:

- The ratio of maximum to minimum heat flux is less than a factor of two. This is much smaller than the ratio in pool boiling.
- The minimum in $q(\Delta T)$ is quite broad. There is a wide region in which the value of $dq/d\Delta T$ is approximately zero.

With regard to the lines, the authors state: *In the region of transition boiling the heat flux over the difference between wall and saturation temperature approaches a horizontal curve.*

This result differs considerably from water results by Ellion (1954) and McDonough et al (1961).

THE FLOW BOILING EXPERIMENT BY RAGHEB ET AL (1981)

Ragheb et al (1981) investigated transition region boiling in flowing water. The test matrix included mass flow rates of 70 to 200 kg/m^2s, 0 to 30 C subcooling, interface ΔT's of a few degrees to 300 C, and a pressure "near atmospheric". The boiling interface was the inner surface of a 1.3 cm diameter tube, 5 to 15 cm long.

The results presented in Ragheb et al are reported in digital form in ANL reports. Figure 13 is based on the digital values reported in Cheng et al (1978) for a mass flow rate of 203 kg/m^2s. In Figure 13, notice that:

- In the transition region, the boiling curves are highly *linear*.
- In the transition region, the $dq/d\Delta T$ values are -31000, -44000, and -36000 w/m^2C at subcooling values of 0, 13.9, and 27.8 C.

CONCLUSIONS

- Thermal behavior in transition boiling is quite *linear*. This is true of both pool boiling and flow boiling.

- The value of $dq/d\Delta T$ in transition boiling strongly depends on the boiling fluid and the nature of the boiling surface. References cited here report values ranging from -4000 to -40000 w/m^2C.

- Table 1 lists values for pool boiling refrigerants at pressures of 0.5 to 20 kg/cm^2. Table 2 lists values for flow boiling water at 1 to 4 kg/cm^2. Equation (12) describes $dq/d\Delta T$ for the flow boiling of water at pressures of 55 to 140 kg/cm^2 (800 to 2000 psi).

- The pool boiling curve can be greatly altered by coating the boiler surface. Coatings can increase or decrease the nucleate boiling region, and can altogether eliminate the nucleate boiling region and the maximum in the boiling curve.

- Surface coatings can greatly improve the post CHF performance of pool boilers by increasing the nucleate boiling region so that CHF is outside the normal operating envelope, or by increasing the value of the right side of Criterion (1).

- Adding trace additives to a boiling liquid can greatly extend the nucleate boiling region.

- It is possible to design controlled heat flux and controlled temperature boilers to operate stably beyond CHF. However, it is oftentimes much simpler to alter the boiling curve so as to avoid post CHF operation.

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TABLE 1

TRANSITION REGION VALUES OF dq/dΔT BASED ON HESSE'S (1973) DATA REPLOTTED IN FIGURES 3 TO 5

Fluid	Pressure bars*	dq/dΔT w/m^2C
R114	3	-9100
	6**	-11900
	9**	-13400
	12	-15200
	15	-16300
	20	-16900
R113	0.5	-5300
	1.0	-6000
R12	7	-9600
	14	-17000

* One bar is 0.98692 atmospheres.
**For clarity, these data are not shown in Figure 3.

TABLE 2

TEST CONDITIONS IN ELLION (1954), AND TRANSITION REGION VALUES OF dq/dΔT BASED ON REPLOTTING ELLION'S DATA IN FIGURES 11 AND 12

Pressure, psia	Velocity, ft/sec	Subcooling, F	dq/dΔT, $B/hrft^2F$	dq/dΔT, $watts/m^2C$
16	1.1	50	-1300	-7400
16	5	50	-2370	-13400
16	1.1	100	nonlinear	nonlinear
60	1.1	60	-1850	-10500

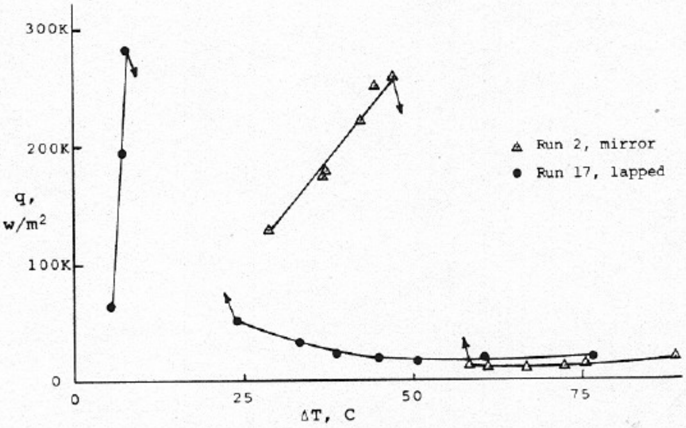

FIGURE 1 BERENSON (1962) DATA REPLOTTED ON LINEAR COORDINATES. *NOTICE LACK OF DATA IN TRANSITION REGION.* CURVES DESCRIBE EFFECT OF SURFACE FINISH ON THERMAL BEHAVIOR OF N-PENTANE BOILING ON COPPER AT ONE ATMOSPHERE

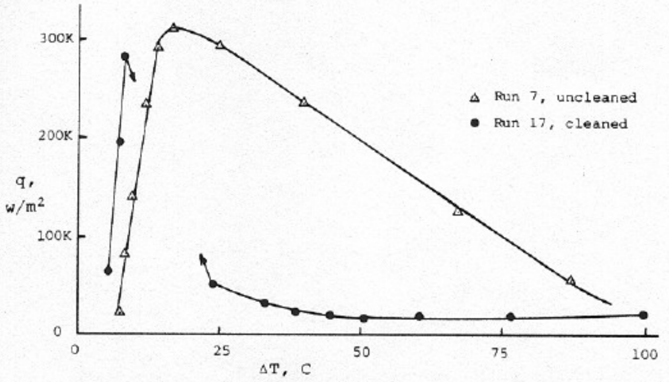

FIGURE 2 BERENSON (1962) DATA REPLOTTED ON LINEAR COORDINATES. *NOTICE PRESENCE OF DATA IN TRANSITION REGION OF RUN 7. ALSO NOTICE LINEARITY OF DATA IN TRANSITION REGION.* CURVES DESCRIBE EFFECT OF SURFACE CLEANLINESS ON THERMAL BEHAVIOR OF N-PENTANE BOILING ON COPPER AT ONE ATMOSPHERE

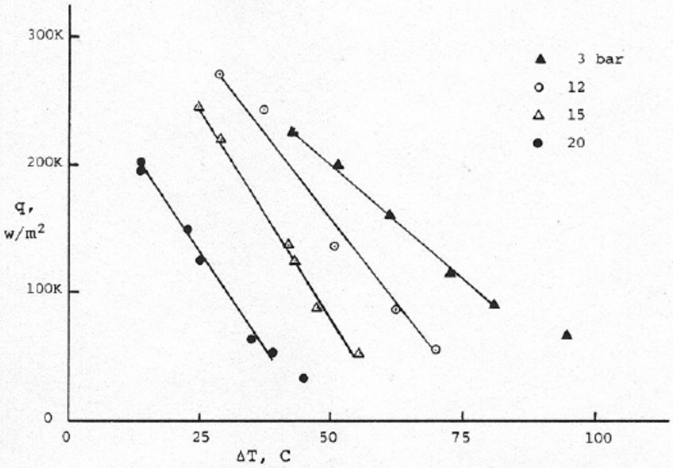

FIGURE 3 TRANSITION REGION DATA FOR R114 BOILING ON NICKEL--HESSE (1973) DATA REPLOTTED ON LINEAR COORDINATES. *NOTICE THE PRONOUNCED LINEARITY IN THE DATA.*

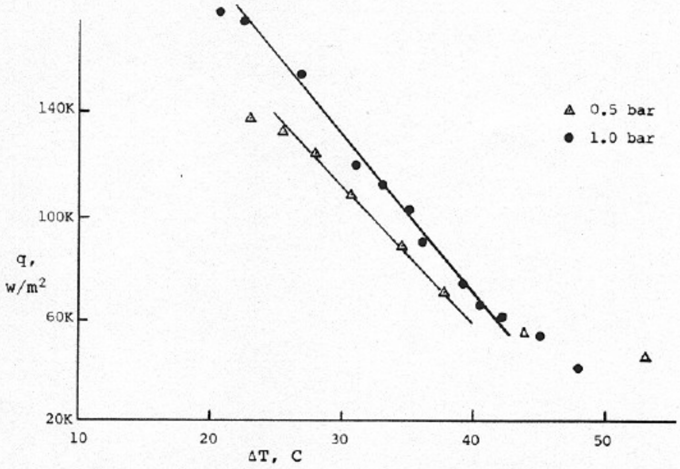

FIGURE 4 TRANSITION REGION DATA FOR R113 BOILING ON NICKEL--HESSE (1973) DATA REPLOTTED ON LINEAR COORDINATES

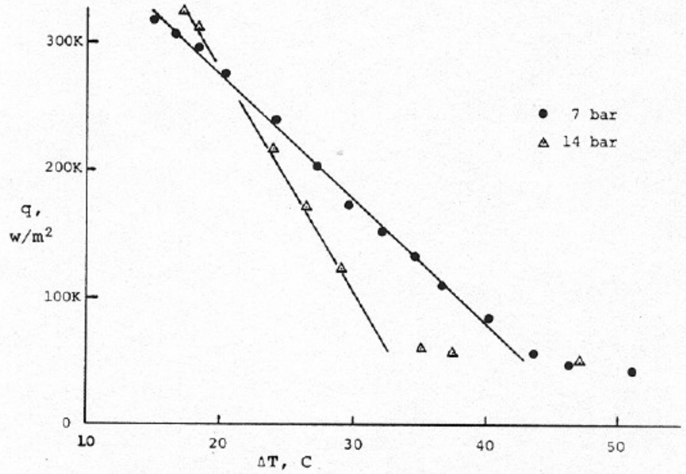

FIGURE 5 TRANSITION REGION DATA FOR R12 BOILING ON NICKEL--HESSE (1973) DATA REPLOTTED ON LINEAR COORDINATES

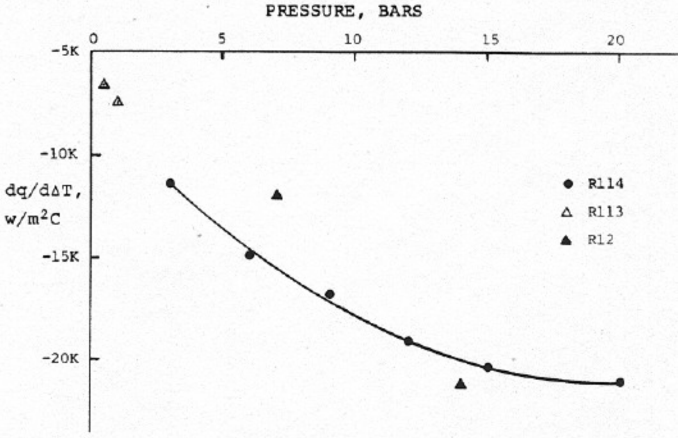

FIGURE 6 EFFECT OF PRESSURE ON dq/dΔT IN THE TRANSITION REGION--FROM TABLE 1 RESULTS BASED ON DATA BY HESSE (1973)

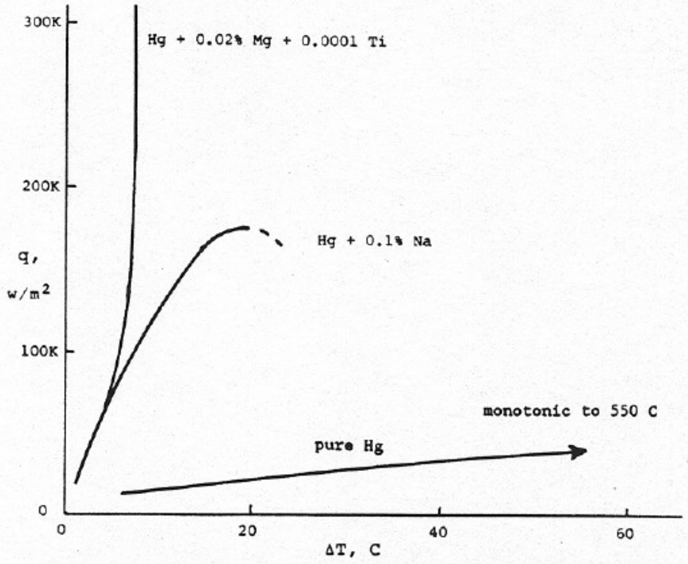

FIGURE 7 DATA BY LYON ET AL (1955) REPLOTTED ON LINEAR COORDINATES. CURVES DESCRIBE EFFECT OF TRACE ADDITIVES ON BOILING CURVES. *NOTICE THAT THERE IS NO MAXIMUM IN THE CURVE FOR PURE MERCURY*

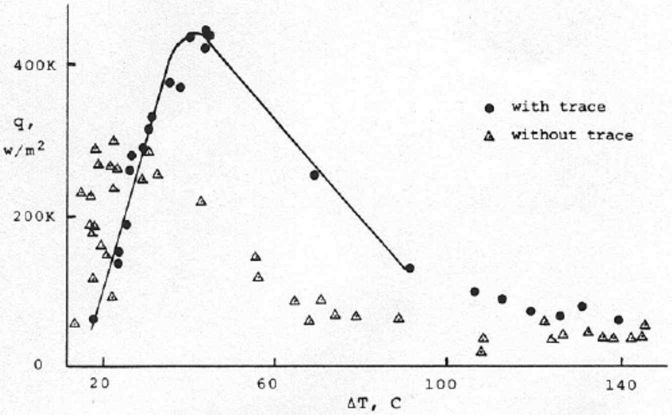

FIGURE 8 DATA BY DUNSKUS AND WESTWATER (1961). CURVES SHOW EFFECT OF A TRACE AMOUNT OF IGEPAL CO-210 ON THE BOILING CURVE FOR ISOPROPANOL

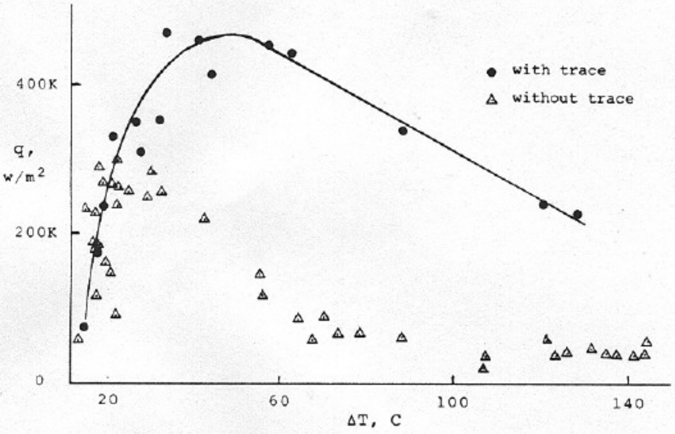

FIGURE 9 DATA BY DUNSKUS AND WESTWATER (1961). CURVES SHOW EFFECT OF A TRACE AMOUNT OF IGEPAL CO-880 ON THE BOILING CURVE FOR ISOPROPANOL

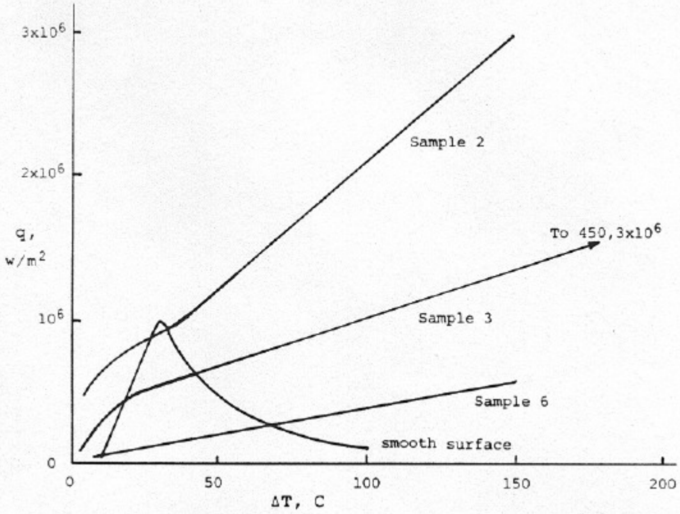

FIGURE 10 LINES BY AFGAN ET AL (1985) REPLOTTED ON LINEAR COORDINATES. LINES SHOW EFFECT OF VARIOUS COATINGS ON BOILING CURVES.

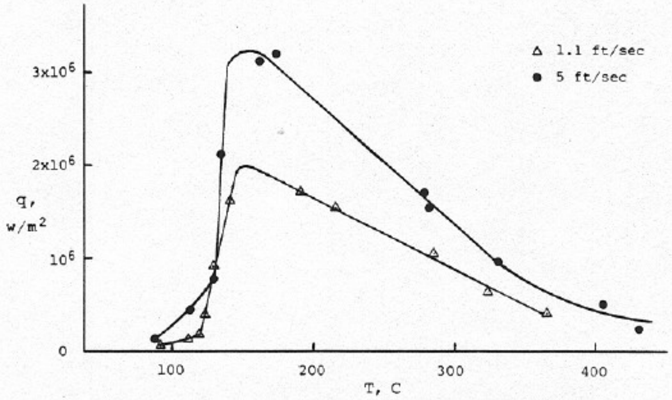

FIGURE 11 DATA BY ELLION (1954) REPLOTTED ON LINEAR COORDINATES. CURVES SHOW EFFECT OF VELOCITY ON BOILING CURVES FOR WATER.

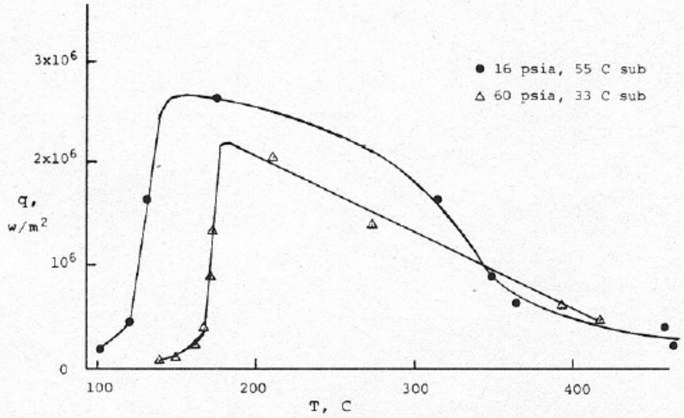

FIGURE 12 DATA BY ELLION (1954) REPLOTTED ON LINEAR COORDINATES. CURVES SHOW COMBINED EFFECT OF PRESSURE AND SUBCOOLING ON BOILING CURVES FOR WATER.

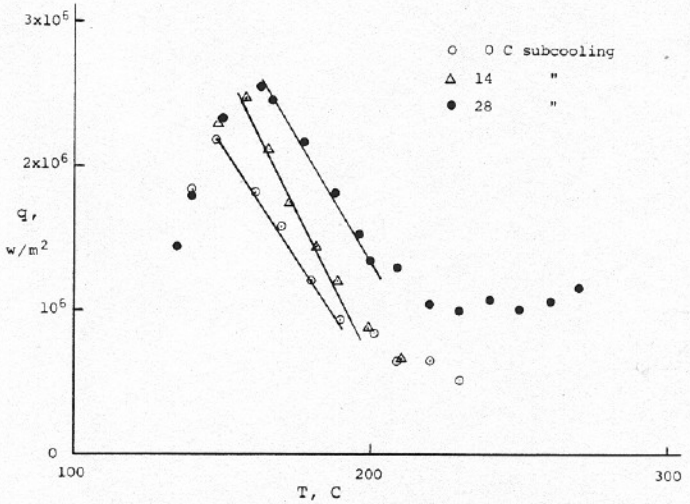

FIGURE 13 DATA BY RAGHEB ET AL (1981) PLOTTED ON LINEAR COORDINATES. CURVES SHOW EFFECT OF SUBCOOLING ON BOILING CURVES. *NOTICE THAT THE TRANSITION REGION IS HIGHLY LINEAR.*