Boiling Heat Transfer Phenomena
During Rapid Decompression

by

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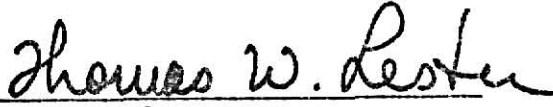B.S. National Tsing Hua University, 1972

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TABLE OF CONTENTS

I

NOMENCLATURE

A_L	Area of liquid column
A_T	Total area of heat transfer surface
A_v	Area of vapor column
c	Wave velocity
CHF	Critical heat flux
C_p	Heat capacity at constant pressure
D_{jet}	Diameter of vapor jet flow
f	Frequency of bubble release from heater surface
g	Gravitational acceleration
g_o	Universal gravitation constant
$\bar{h}_i$	Convection heat transfer coefficient
h_L	Enthalpy per unit mass of saturated liquid
h_v	Enthalpy per unit mass of saturated vapor
h_{Lv}	$h_v - h_L$ or the latent heat of liquid
I	Electric current through heater element
k_u	Kutateladze empirical constant
k	Thermal conductivity
M	Molecular weight
N	Number of active nucleation sites on bubbling surface
P_L	Liquid pressure
P_r	Prandtl number
$\dot{Q}$	Heat generation rate per unit volume
$(Q/A)_b$	Heat flux from boiling
$(Q/A)_{CHF}$	Critical heat flux
$(Q/A)_{CHF,k}$	Critical heat flux after Kutateladze
$(Q/A)_{cond}$	Heat flux from conduction

$(Q/A)_{nc}$	Heat flux from natural convection
$(Q/A)_{op}$	Operating heat flux
$(Q/A)_{Total}$	Total heat flux
R	Universal gas constant
R_b	Bubble departure radius
R_o	Electrical resistance of heating wire at 0°C
R_s	Resistance of precisive shunt resistor
R_{sys}	Resistance of heater element and connections
R_{th}	Theoretical resistance of the test wire
R_w	Resistance of the test wire
r	Radius of active site on heating surface
r_b	Bubble radius
r_s	The radius for which N would be one per unit area of heating surface
T_L	Liquid temperature
T_s	Saturation temperature
T_v	Vapor temperature
T_w	Heater element temperature
V_L	Liquid Velocity
V_{ME}	Average volume of microlayer evaporated
V_P	Voltage of the battery
V_v	Vapor velocity
V_w	Voltage across heater element and connections
$V_{pressure}$	Transient voltage signal from the pressure transducer
α	Thermal diffusivity
β	Three phase contact angle in Table 1.
δ	Bubble thermal boundary layer thickness

ε	Accommodation coefficient, dimensionless
η	Wave amplitude
λ	Wave length
ν	Viscosity
ρ_L	Liquid density
ρ_v	Vapor density
σ	Surface tension between liquid and its vapor

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

New developments in engineering applications often require that heat be transferred under not only steady-state, but also transient conditions. For example, during the operation of light water nuclear reactors, heat generated in the fuel rods is increased exponentially as the reactor is started up or is required to change power levels within a short time. If the period is significantly shorter than that at which the coolant can transfer all the heat generated in the fuel rods, the fuel rod cladding may be exposed, for short periods, to nucleate or to film boiling and rapid temperature fluctuations. Rapid decompressions are potentially more serious. If a reactor primary coolant pipe ruptures, the high pressure inside the reactor vessel will be released to the atmosphere in seconds. The coolant becomes superheated rapidly which in turn induces flashing throughout the reactor core and alters the local heat transfer mechanisms. An accurate knowledge of the boiling behavior during pressure transients of varying periods is, therefore, necessary for the designer to estimate the worst possible heat transfer during normal operation or abnormal occurrences.

Boiling heat transfer has been studied comprehensively for several decades. The majority of previous analyses and experiments have been concerned with steady-state, pool boiling. Most conventional applications of boiling processes involve steady-state phenomena, in which the liquids are at a certain pressure and only slow, incremental changes in heat flux are encountered. As a result of this extensive research, there are numerous equations, either experimentally or theoretically derived, available for the prediction of steady-state nucleate boiling heat fluxes and critical heat fluxes under various thermodynamic conditions and with different solid/liquid combinations.

Boiling heat transfer during both power and pressure transients has been studied more recently. Most effort has been devoted to power transients because of their more frequent occurrence in light water reactors. Empirical correlations have been developed which predict the transition from nucleate to film boiling as a function of transient power period, initial heat flux, and thermodynamic conditions. Pressure transients, on the other hand, have been studied only recently because of the increasing concern about the Loss of Coolant Accident (LOCA). However, no systematic study has been performed.

Power transient studies to date have reported that if the transient time constant is longer than about 100 milliseconds, the peak heat flux during the transient can be predicted adequately by steady-state conditions. If, however, the time constant is shorter than 20 milliseconds, the heat flux during the transient may reach a higher value than that predicted by steady-state correlations before the boiling transits from nucleate to film boiling. It has been observed that even under a step increase in power, nucleate boiling always precedes the transition to film boiling. Pressure transients have been much less thoroughly studied. Investigations in rod bundles have been performed more to provide design information rather than fundamental knowledge. In view of the few studies of relatively slow pressure transients, it has been suggested that the critical heat flux can be predicted with no significant errors by steady-state correlations. But the results of recent and more basic research into the heat flux and transient bubble growth indicate that the heat transfer mechanisms may be quite different. Because of the paucity of data on this topic, no solid conclusions have been made about the actual effects of pressure transients on boiling heat transfer.

Accordingly, as a first step in a comprehensive research program the effect of very rapid pressure transients on boiling heat transfer has been studied. The effects of two parameters, temperature of bulk liquid and initial heat flux level, on the temporal variation of heat flux and wire temperature are investigated during the depressurization of water from 760 to 420 torr in approximately 10 milliseconds. The review of pertinent literature, design of experiments, and experimental results are discussed in turn in the following sections.

II. LITERATURE REVIEW

In this section, steady-state boiling will be discussed briefly and applicable Critical Heat Flux correlations will be reviewed. Subsequently, critical heat flux during power transients and decompressions will be covered.

A. <u>The Mechanism and Current Theories of Steady-State Pool Boiling</u>

Steady-state boiling heat transfer studies have shown conclusively that different levels of wall superheat, the wall temperature excess above the saturation temperature, result in very different heat transfer phenomena, which are fundamental to the understanding of the boiling mechanism. The existence of several regimes of boiling was first clearly discussed by Nukiyama (41) in 1934 and followed by many papers. A typical steady-state boiling curve is shown in Fig. 1. The entire curve is generally divided into four regions: free convection, nucleate boiling, transition, and stable film boiling regions followed by film boiling with radiation augmentation. Nucleate boiling is characterized by the formation, growth, and detachment of vapor bubbles in the liquid near the heater surface. It results in a sharp increase in heat flux, but only a moderate increase in surface temperature. At low values of wall superheat, bubbles are far apart and are nearly independent of one another. As the superheat increases, more nucleation sites appear and bubbles form more rapidly. At high superheats, no discrete bubbles can be seen as they interfere with one another and unite to form bigger vapor patches. As point B is approached, a further increase in wall superheat will cause the heat flux to decrease since all heat must be transferred through a vapor layer. This is called transition boiling.
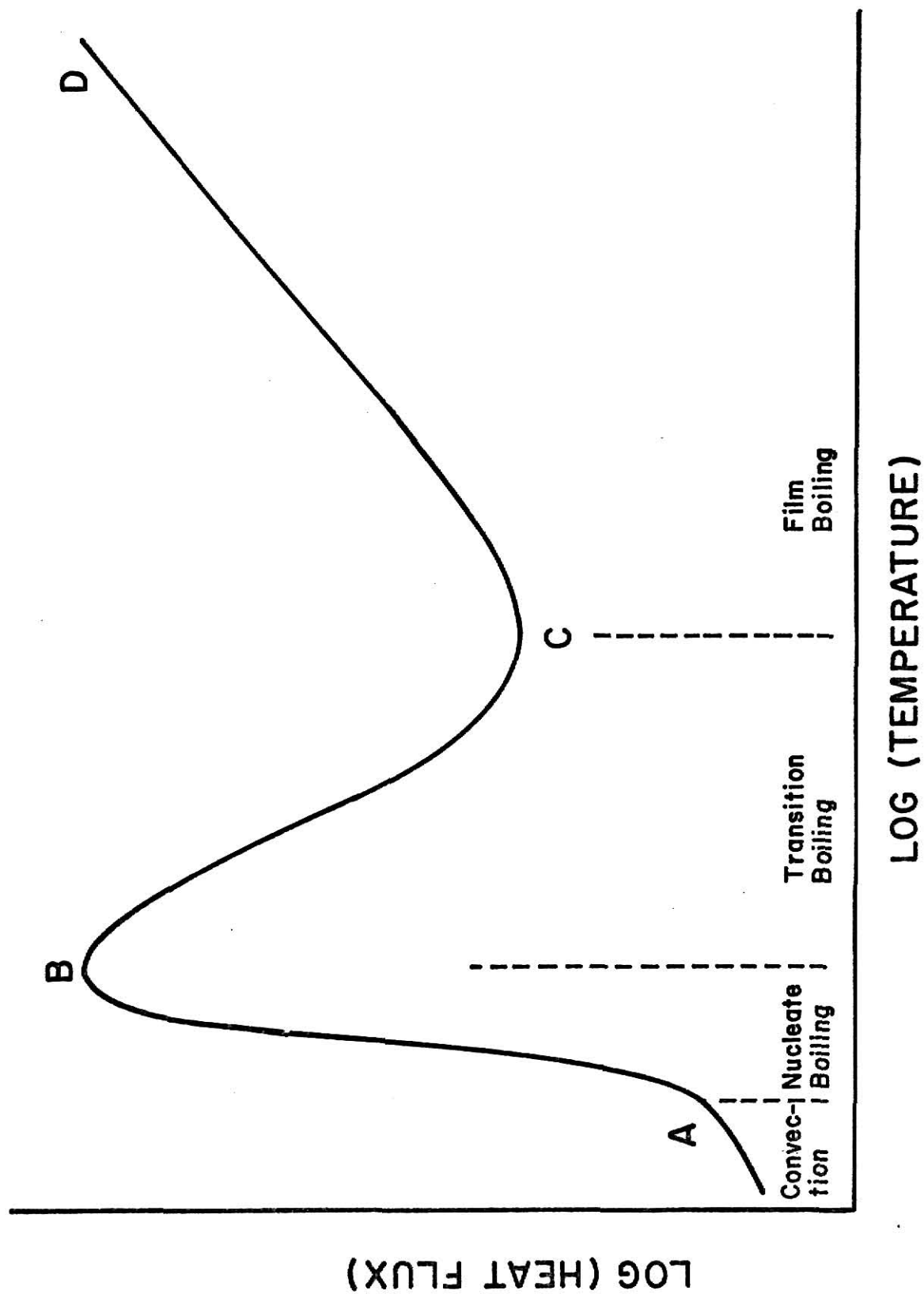
Fig. 1. A Typical Pool Boiling Curve.

Heat transfer during this region is unstable. Part of the surface is covered by vapor film, the rest is still undergoing stable nucleate boiling until the superheat is increased high enough to cause the coalesced bubbles to form a layer of vapor film covering the entire surface. This is called film boiling. The critical point B is known widely as DNB - depature from nucleate boiling, or the burnout point. Hereafter, this point will be referred to as the boiling transition and the heat flux at this point as the CHF - critical heat flux - as used most commonly in recent literature.

There are several plausible physical explanations for the high rate of heat transfer in nucleate boiling. Earlier researchers tended to focus on the agitation induced by the bubble formations on the heater surface. For example, Rohsenow and Clark (45) proposed that the bubbles behave as agitation agents which increase the heat transfer. This proposal has been studied by Robinson and Katz (43), by Grose et al. (19), and by Mixon et al. (38). These experiments showed that the bubble agitation does increase the heat transfer, but the heat fluxes in these studies were in the lower range of nucleate boiling. Other mechanisms which are not substantially different from the above include that of the "bubble action," whereby the bubbles are assumed to push the superheated liquid layer away from the heater surface (17), and the mechanisms which explain the high heat flux by the increased turbulence imparted to the boundary layer by the growing bubbles (21, 25).

More recently, latent heat transport mechanisms have been put forth by several investigators. Moore and Mesler (39), in a pioneering experiment, provided new data explaining the mechanism by which latent heat is transported away from the heated surface. A fast response thermocouple

was used during the nucleate boiling of water. Surface temperature drops of 11 °C to 16.7 °C within 2 milliseconds were observed indicating a rapid extraction of heat during a very short time. The authors suggested that there is a thin liquid layer underneath the growing bubbles and that the evaporation of this layer into the bubbles brings the surface temperature down during bubble growth. Further studies of this model have shown that it is insufficient to explain the very high heat flux (54). Most recently, Kirby and Westwater (32) and Katto and Yokoya (31) experimentally found that a thin liquid film exists beneath irregular vapor masses with the principal heat transfer mechanism at high heat flux being the evaporation from this liquid film. It appears that these different conceptual models reflect different stages of the boiling mechanism; consequently, no overall analytical solution or empirical correlation is available to accurately predict the CHF.

In a recent review of current nucleate boiling theory, Labuntsov (34) pointed out that future analyses should concentrate on the features and structure of a very thin, liquid-rich film directly on the heater surface which sustains the principal temperature drop. The existence of such a film over the entire range of nucleate boiling has been confirmed by probing local voids with micro thermocouples (7,26). Therefore, the bubble agitation model appears to be more satisfactory for lower heat fluxes in nucleate boiling, while the latent heat transfer model is more applicable at high heat fluxes. None of the models previously mentioned explains the results of the latter experiments. Hence present nucleate boiling models will have to be modified or a new model developed in order to describe the entire nucleate boiling regime adequately.

B. <u>Steady-State Pool Boiling Critical Heat Flux (CHF)</u>

Tong (52) and Balzhiser (4) have given comprehensive reviews of pool boiling heat transfer. They concluded that although the problem has been approached from many different points of view, no overall analytical solution has been obtained, and the design equations for CHF predictions are strictly empirical. For instance, Gambill (18) has noted that approximately fifty equations have been developed for predicting CHF in pool and flow boiling situations. Only those generalized CHF correlations that apply to saturated pool boiling will be discussed here.

In boiling, bubbles appear to form repeatedly at nucleation sites (cavities) on the heating surface, thus forming a "column" of bubbles. As the surface heat flux increases, visual observations indicate that the number of active nucleation sites per unit area increases (44). In addition, observations suggest that, as the heat flux increases to just below the critical value, the successive bubbles coming from a nucleation site converge into each other to form an undulating column of vapor. Rohsenow and Griffith (46) formulated a semi-empirical relation for the critical heat flux by combining observations from experiments in organic liquid and water with the conceptual model noted above. Their relation,

$$(Q/A)_{CHF} = 143 \; \rho_v h_{Lv} \; g^{1/4} \; (\frac{\rho_L - \rho_v}{\rho_v})^{0.6} \qquad (2.1)$$

was derived by tacitly assuming that the heater surface is covered by vapor bubbles at CHF.

Addoms (2) proposed a dimensionless correlation:

$$(Q/A)_{CHF} = 2.5 \ \lambda \rho_v (g\alpha)^{1/3} \ (\frac{\rho_L - \rho_v}{\rho_v})^{0.5} \tag{2.2}$$

which also agrees well with data from experiments in water and organic fluids.

Other researchers have developed semi-empirical correlations using a more universal approach. For instance, Zuber (55,56), basing his arguments on wave motion, postulated that the boiling crisis is due to a combination of Taylor's and Helmholtz's instabilities which deal with the instability of a plane interface and the relative velocity of the liquid and its vapor respectively. The resulting equation is:

$$(Q/A)_{CHF} = 0.18 \ \rho_v h_{Lv} \ [\frac{gg_o(\rho_L - \rho_v)}{\rho_v^2}]^{1/4} \ [\frac{\rho_L}{\rho_L + \rho_v}]^{1/2} \ . \tag{2.3}$$

Here the constant, 0.18, was determined empirically from the data shown in Fig. 2.

Kutateladze (33), Chang and Snyder (12), and Cobb and Park (14), have also developed equations which are nearly the same as those of Zuber and Addoms. Their equations, Berenson's modification of Zuber's analysis, in addition to some other pertinent correlations are listed in Table 1.

The examination of the above correlations does not make the effects of different parameters on the critical heat flux entirely obvious. However, from a thermodynamic point of view, it is apparent that the system pressure will be a dominant factor since it determines the latent heat of vaporization, the saturated vapor density and affects the surface tension. In fact, its effect has been well documented by many authors (13,15,18,24). Yet the CHF is far more complicated than this.
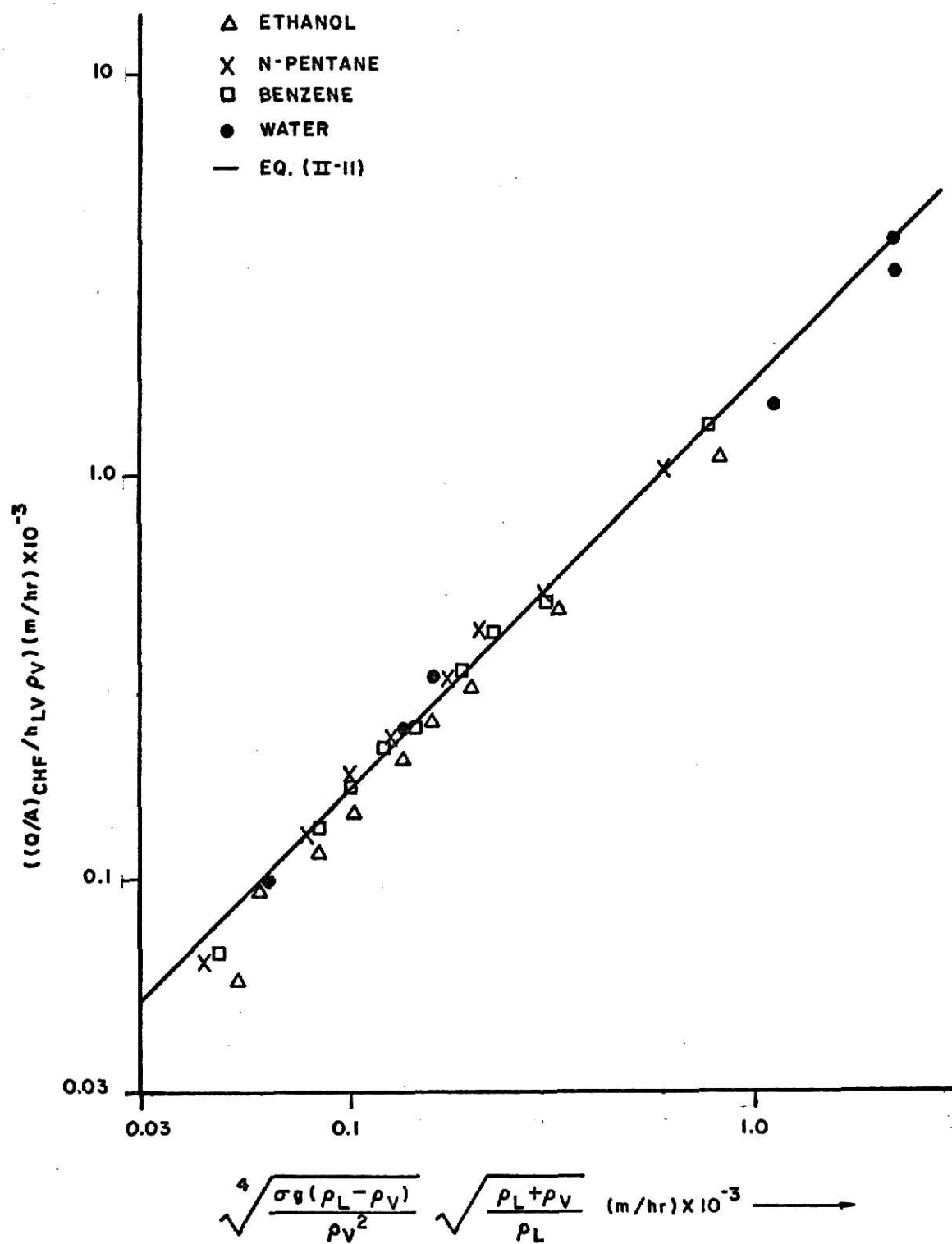
Fig. 2. Correlation of Critical Heat Flux in Pool Boiling.
[After Zuber (56)].

TABLE 1-a. Equations for the Prediction of Nucleate Boiling Heat Flux

Equation	Theoretical Background	Validity	Author	Year
$(Q/A)_{Total} = \left(\dfrac{C_{pL}(T_w-T_s)}{h_{Lv}Pr^{1.7}}\right)^3 \left(\dfrac{\mu_L h_{Lv}}{C_{sg}^3}\right)\left[\dfrac{g_o\gamma}{g(\rho_L-\rho_g)}\right]^{-1/2}$	Dimensional Analysis	It predicts the shape of the nucleate boiling regime with good accuracy.	W.M. Rohsenow (44)	1952
$(Q/A)_{Total} = \dfrac{A_{nc}}{A_T}(Q/A)_{nc} + (Q/A)_b$ where $(Q/A)_b = C_1 \dfrac{C_2 C_3^{1/2} r_s^m}{\sqrt{\pi}\, 2^{m-1}}(k\rho C_p)_L^{1/2}\cdot \left(\dfrac{h_{Lv}\rho_v}{T_s\sigma}\right)^m \dfrac{\sigma g_o g(\rho_L-\rho_v)^{1/8}}{\rho_L^2}\cdot\left[\dfrac{\sigma g_o}{g(\rho_L-\rho_v)}\right]^{3/4}(Ja^*)^{15/8}\cdot(T_w-T_s)^{m+1}$	Assumes the main mechanism of heat transfer in nucleate boiling is transient heat conduction to, and subsequent replacement of, the superheated layer around boiling sites associated with bubble departure and considers effects of heat transfer surface characteristics.	For checking the equation, the required information about the boiling surface was found from q/A versus (T_w-T_s) data at one pressure and applied to all. The results are satisfactory.	Mikic and Rohsenow (37)	1969

TABLE 1-a. (Continued)

Equation	Theoretical Background	Validity	Author	Year
$c_1, c_2, c_3,$ and m are constants. $$Ja^* = \frac{\rho_L C_{pL} T_s}{\rho_v h_{Lv}}$$ $$(Q/A)_{nc} = 0.54 \, \rho_L C_{pL} \left[\frac{rg(T_w - T_s)^5 \alpha^3}{\sqrt{A_T} \cdot \alpha}\right]^{1/4}$$ for $10^5 < R_a < 2 \times 10^7$ $$(Q/A)_{nc} = 0.14 \, \rho_L C_{pL} \left[\frac{rg(T_w - T_s)^4 \alpha^2}{\nu}\right]^{1/2}$$ for $2 \times 10^5 < R_a < 3 \times 10^{10}$				
$(Q/A)_{Total} = 4.35 \times 10^8 \, (N/A_t) f \, \bar{V}_{ME}$ $+ 184 \, (T_w - T_L)^{4/3} \cdot$ $[1 - K\pi R_b^2 (N/A_T)]$ $+ 1543 \, k R_b^2 \sqrt{f} \cdot$ $(N/A_T) T_w - T_L)$	Incorporation of microlayer evaporation, natural convection, and nucleate boiling mechanisms	Microlayer evaporation heat transfer is the prominent feature of this model. More data needed to support this equation.	R. L. Judd (29)	1976

TABLE 1-b. Equations for the Prediction of Critical Heat Flux

Equation	Theoretical Background	Validity	Author	Year
$(Q/A)_{CHF} = K_u \rho_v^{1/2}[g\sigma(\rho_L-\rho_v)]^{1/4}$ $k_u:\ 0.14 \sim a/b$	Dimensional Analysis	Agrees well with large amount of data for water and organic liquids	Kutateladze (33)	1953
$(Q/A)_{CHF} = 2.5\,\rho_v(g\alpha)^{1/4}\left(\dfrac{\rho_L-\rho_v}{\rho_v}\right)^{1/2}$	Hydrodynamic Analysis	Agrees well with data of water and organic liquids	Addoms and improved by Ivey in 1961 (2)	1954
$(Q/A)_{CHF} = 0.18\,\rho_v^{1/2}\left[\dfrac{\sigma\,g(\rho_L-\rho_v)}{\rho_v^{2}}\right]^{1/4} \cdot$ $\left[\dfrac{\rho_L}{\rho_L+\rho_v}\right]^{1/2}$	Taylor and Helmholtz Instabilities	Agrees well with data of water and organic liquids.	Zuber (55,56)	1958
$(Q/A)_{CHF} = 0.145\,\rho_v^{1/2}\left[\dfrac{\rho_L+\rho_v}{\rho_L}\right]^{1/2} \cdot$ $[g\sigma(\rho_L-\rho_v)]^{1/4}$	2-Dimensional interfacial stability analysis	Agrees with Zuber's and Kutateladze's equations	Chang and Snyder (12)	1960

TABLE 1-b. (Continued)

Equation	Theoretical Background	Validity	Author	Year
$(Q/A)_{CHF} = 0.16\, \rho_v h_{Lv} \cdot (\frac{\rho_L + \rho_v}{\rho_L \rho_v})^{1/2} \cdot [g g_o \sigma(\rho_L - \rho_v)]^{1/4} / [1 + (\frac{\rho_v}{\rho_L})^{1/2} + (\frac{\rho_v}{\rho_L})^{2/3} + (\frac{\rho_v}{\rho_L})]$	A modification of Zuber's equation	Same as that of Zuber's but with more satisfactory theoretical consideration	Berenson [6]	1960
$(Q/A)_{CHF} = 143\, \rho_v h_{Lv} g^{1/4} (\frac{\rho_L - \rho_v}{\rho_v})^{0.6}$	Hydrodynamic Analysis	Good agreement with data of water and organic liquids	Rohsenow and Griffith [46]	1961
$(Q/A)_{CHF} = \dfrac{2570\, \rho_v}{[1 + (\frac{\rho_v}{\rho_L})^{1/2}]^2} (1 + 0.318 \frac{\rho_L}{\rho_v})^{1/2} [\dfrac{g g_o \sigma(\rho_L - \rho_v)}{\beta^2 \rho^2}]^{1/4}$	3-Dimensional analysis of a cylindrical vortex sheet	Limited because of the limited availability of data on the three phase contact angle for various combinations of fluids and solids	Adams [1]	1963

TABLE 1-b. (Continued)

Equation	Theoretical Background	Validity	Author	Year
$(Q/A)_{CHF} = 0.144\,\rho_v\left[\dfrac{\rho_L-\rho_v}{\rho_v}\right]\cdot\left[\dfrac{gg_o\sigma}{\rho_L}\right]^{1/4} Pr^{-0.245}$	A correction of Zuber's equation takes viscosity and conductivity of sodium into consideration	$0.003 \le Pr \le 11$	Noyes (40)	1963
$(Q/A)_{CHF} = 1.02\times10^6\,\dfrac{\rho_v k}{C_p\sigma}\cdot\left[\dfrac{\rho_L-\rho_v}{\rho_v}\right]^{0.65} Pr^{0.71}$	Dimensional Analysis	Agrees well with liquid metals, water, and organic liquids	Casell and Balzhiser (10)	1965
$(Q/A)_{CHF} = \dfrac{\pi}{24}\lambda\,\rho_v\left[\dfrac{\sigma g(\rho_L-\rho_v)}{g_o\rho_v^2}\right]^{1/4}\cdot\left(\dfrac{\rho_L}{\rho_L+\rho_v}\right)^{1/2}$ $+\displaystyle\int_{-\lambda/4}^{\lambda/4}\dfrac{(T_w-T_s)}{\cos\left(\frac{2\pi x}{\lambda}\right)}\,dx$ $\lambda = 2\pi\left[\dfrac{g_o\sigma}{g(\rho_L-\rho_v)}\right]^{1/2}$	Hydrodynamic Instability plus temperature profile model	Needs more supporting experiments	Balzhiser, et al. (4)	1971

16

TABLE 1-b. (Continued)

Equation	Theoretical Background	Validity	Author	Year
$(Q/A)_{CHF} = (Q/A)_{CHF,k} + 2(Q/A)_{cond}$ $= k_u h_{Lv}(\rho_v g)^{1/2}[\sigma(\rho_L-\rho_v)]^{1/4}$ $+ \dfrac{2(T_v-T_s)}{\dfrac{\delta}{k} + \dfrac{2\pi R T_v}{M}\left(\dfrac{T_s}{\varepsilon h_{Lv}^2 \rho_v}\right)}$	Kutateladze equation condensing heat flux within bubbles	Needs to be proven experimentally	Bankoff, et al. (5)	1974

Many other variables can influence the CHF experimentally and confuse data interpretation. For instance, Tong (53), commenting on the effects of wetting agents and surface conditions on the CHF in pool boiling, noted that the maximum heat flux is practically independent of surface material, cleanliness, and roughness. Berenson (6) found that a smooth surface has a higher superheat at boiling crisis than a rough surface, although both have approximately the same CHF. On the other hand, other investigators have obtained different results. Costello and Frea (53) found that deposits on stainless steel heater surfaces result in at least a 50% increase in the CHF. Ivey and Morris (53) stated that oxidized surfaces appear to yield a higher CHF than that associated with a clean metallic surface. Other parameters such as the diameter, the surface orientation geometry and system acceleration all have small effects on the CHF (53).

C. Boiling Heat Transfer in Transients

A clear interpretation of boiling behavior and CHF in both power and pressure transients remains elusive even though these phenomena have become of increasing importance. Because knowledge of the boiling behavior during power transients is required for nuclear reactor design and operation, basic studies of this phenomena are numerous while investigations of pressure transients have been more recent, relatively few, and unsystematic.

1. Boiling Heat Transfer in Power Transients

Transient thermal behavior originally became of interest because of the possible effects of a prompt supercritical period on fuel cladding integrity in nuclear reactors. Many studies have been performed on

this topic (27,28,30,48,49,51,52,53). Notable early work was performed by Rosenthal and Miller (47) and Johnson and Schrock (28), who studied exponential increases in power to simulate transient conditions in light water reactors. The experimental results have, in general, been consistent and are reviewed by Tong (52). Transient CHF increases as the power impulse time decreases. In fact, when the impulse time is larger than 200 milliseconds, the transient CHF does not deviate significantly from the steady-state CHF for similar subcooling. According to the results of Rosenthal and Miller (47), the power excursion effect on CHF decreases as the initial exponential period increases and gradually becomes insignificant at periods greater than 14 to 30 milliseconds. When time constants are extremely short the transient heat flux can surpass the steady-state value before the boiling transitions to film boiling. These effects are shown clearly by the data of Tachibana, et al. (50) in Fig. 3. These authors have speculated that the CHF during rapid power transients may increase because of a corresponding increase in the number of surface nucleation sites. This supposition agrees with the observation of Hall and Harrison (20) who observed that in extremely rapid exponential power impulses with periods as short as 0.7 milli-second, film boiling was invariably preceeded by a short burst of nucleate boiling. Furthermore, peak heat fluxes 5 to 10 times the steady-state CHF values under the same thermodynamic conditions were noted.

On the other hand, experiments of power transients with relatively long time constants have been conducted also. Fontana (16), for instance, studied transients with periods of up to 2 minutes, and Sakurai et al. (48) studied transients with periods up to 1 second. In both cases, the transient CHF was observed to be the same as the steady-state CHF for the same liquid temperature and pressure. Although Fontana found
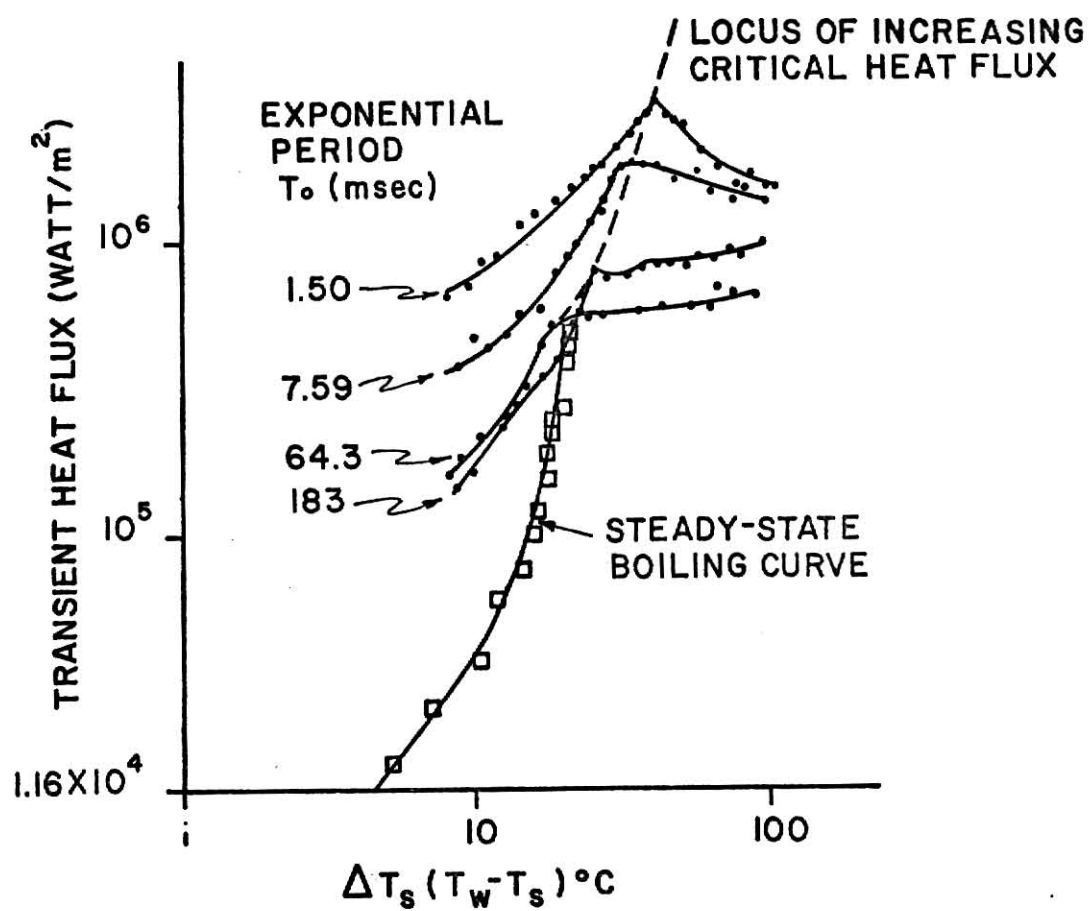
Fig. 3 Effect of Power Transient on CHF. [After Tachibana (50)].

this to be true only for periods greater than 10 seconds, Sakurai observed
that transient values of CHF corresponded with steady state levels for
periods down to 20 milliseconds. This agrees with earlier power transient
experiments conducted by Rosenthal and Miller (47).

It is well known that nucleation and subsequent bubble growth, which
are highly dependent on the thermodynamic conditions of the heater and
the liquid in the vicinity of the heater surface, directly influence
the heat flux. The effects of both power and pressure transients or the
CHF may be discussed on these bases. Equation (2.4), which is derived
from the surface tension of a spherical bubble and the Clausius - Clapeyron
equation, gives an estimation of the surface superheat required to
initiate nucleation,

$$T_v - T_s \simeq 2(\frac{R\,T_s^2\,\sigma}{h_{Lv}P_L r_b}) .$$

(2.4)

After nucleation and a few milliseconds after growth has begun, i.e.,
the later part of the bubble's life, according to Tong's analysis (53),
inertia of the surrounding liquid and the surface tension forces can
probably be neglected. The pressure can be considered uniform through-
out the bubble and liquid. At this stage, bubble growth is governed by
the rate at which heat can be supplied from the superheated liquid to
the bubble interface to facilitate the vapor formation associated with
growth.

If the liquid in the vicinity of the heating surface is very sub-
cooled initially, only a small amount of natural convection heat transfer
occurs. During a subsequent power transient, the heater surface tempera-
ture will surge because the heat input is rapidly increasing, but the
surrounding liquid, which remains cool, is not favorable to bubble growth.

However, the fluid temperature lags behind at a value below that necessary for incipient bubble growth. Nucleation may occur, however, on the heater surface due to rapid increase in surface temperature. Transition to film boiling results, as shown by the data of Rosenthal and Miller (49), Johnson and Schrock (28), in Fig. 4. The smaller the impulse power period, the more the temperature overshoot and the shorter the delay time.

If the heater is initially hot enough that the liquid layer surrounding it is close to the saturation temperature, the increasing power during the transient is more effectively transferred because of bubble nucleation and growth. In this case, the transient CHF is significantly different. The effect of the initial heat flux level on CHF is to lower the transient CHF considerably at low initial heat flux and to approach steady-state CHF at high initial heat flux (51).

2. Boiling Heat Transfer in Pressure Transients

The situation during a pressure transient is substantially more complex due to the changing thermodynamic conditions in the bulk fluid. As the pressure decay is initiated, the surface superheat increases due to the decrease of T_{sat}. The bulk coolant, instead of only the liquid layer in the vicinity of the heater, becomes warmer relative to the decreasing T_{sat}. The magnitude of the pressure decrease, of course, determines the corresponding decrease in T_{sat}. If the transient is sufficiently fast that it completes the depressurization before bubbles can detach from the heater surface, the heat transfer cannot increase until after the transient is completed. If the transient is slow, for example, 7.07×10^4 pascal/sec, there is ample time for many generations of bubbles to grow on the surface and equilibrium may be reached. Therefore the heat flux can follow the pressure change, and in this limiting case, the CHF can be predicted by steady-state correlations.
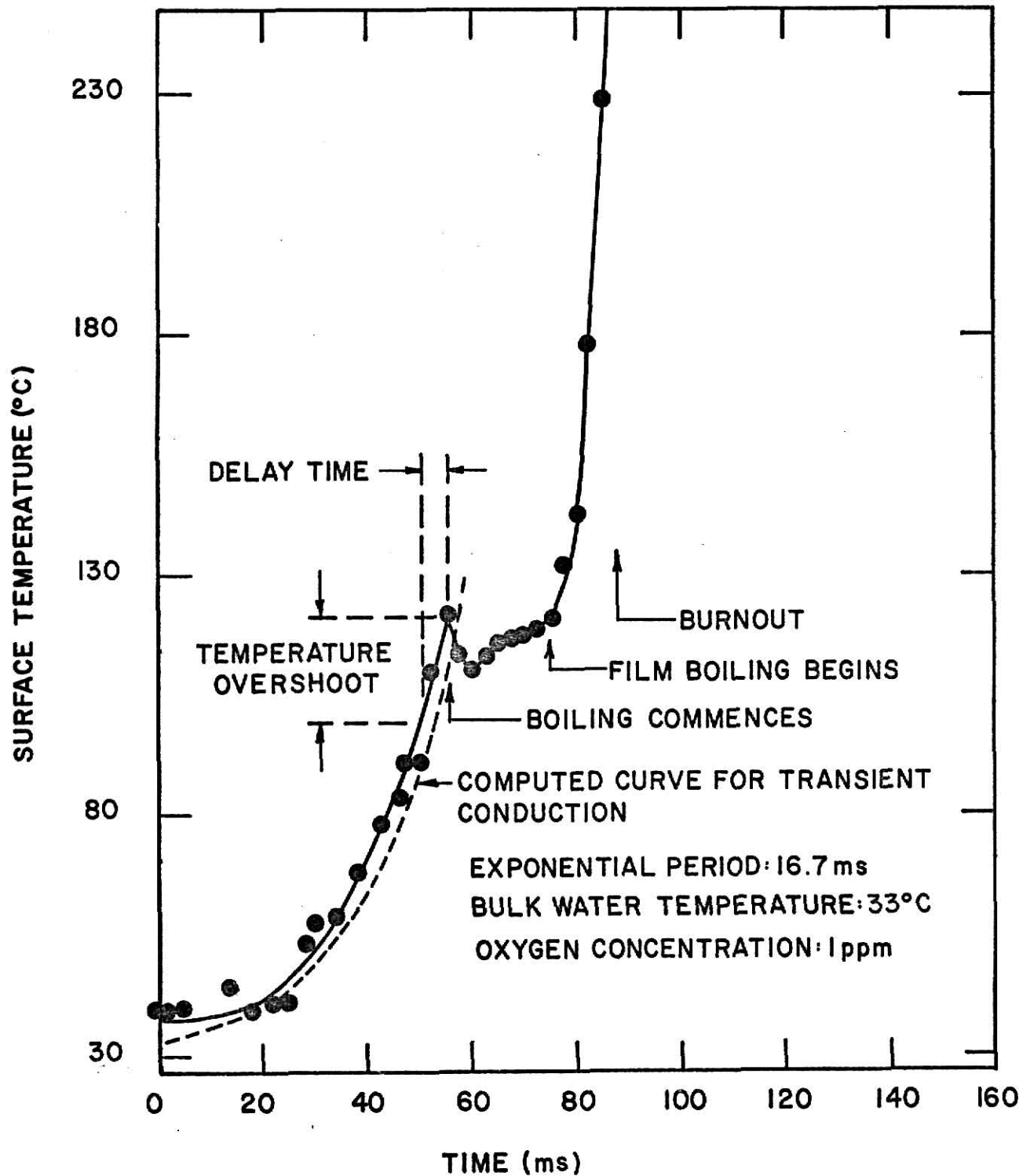
Fig. 4. Typical Temperature-Time Record for Platinum Ribbon in Sub-Cooled Water during Power Transient. [After Rosenthal and Miller (47)].

In practice, the pressure transient is more complicated because bulk flashing is often involved. The heater boundary will be disturbed by bubble agitation and heat transfer mechanisms observed in steady state circumstances may no longer apply shortly after the transient is triggered. No theoretical work has been done on this subject, and only a few experiments have been conducted toward increasing our understanding of this phenomena.

Howell and Bell (23) investigated the pressure transient effect in pool boiling experimentally. The pressurized saturated water was allowed to decay from moderate pressures to atmospheric via a quick-opening valve. Decompression was relatively slow. For example, it required 12 seconds to reach atmospheric pressure from 4.2×10^5 pascal. Because of this slow pressure transient, a link between steady-state and transient cases was attempted. A typical heater temperature behavior during transient boiling is shown in Fig. 5. The relation between transient events and the transient pressure is shown in Fig. 6. The ribbon temperature started to decrease once the decompression began and continued until point c, the inception of film boiling, was reached. The heater temperature then increased until the burnout point was detected. The magnitude of transient CHF appears higher than steady-state CHF by about 20 to 30 percent but independent of the decompression rate. During this experiment, only the initial heat flux was measured; hence, the magnitude of the fluctuation of the heater temperature and the resulting variation in heat flux were not indicated. The time from the start of decompression to the burnout point was discussed more fully. Thus, knowing the initial conditions and the decay rate, the time from point A to point B on Fig. 10b can be calculated. The period between point B until film boiling begins (from
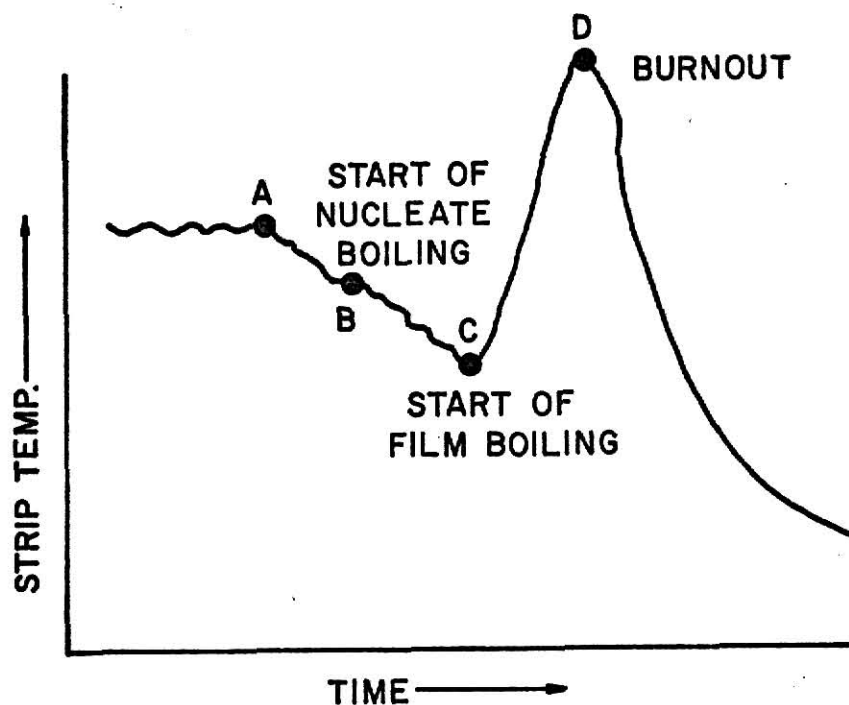
Fig. 5   Ribbon Temperature Behavior During Transient Boiling in
Decompression ($P_o \simeq 4$ atm).   [After Howell and Bell (23)].
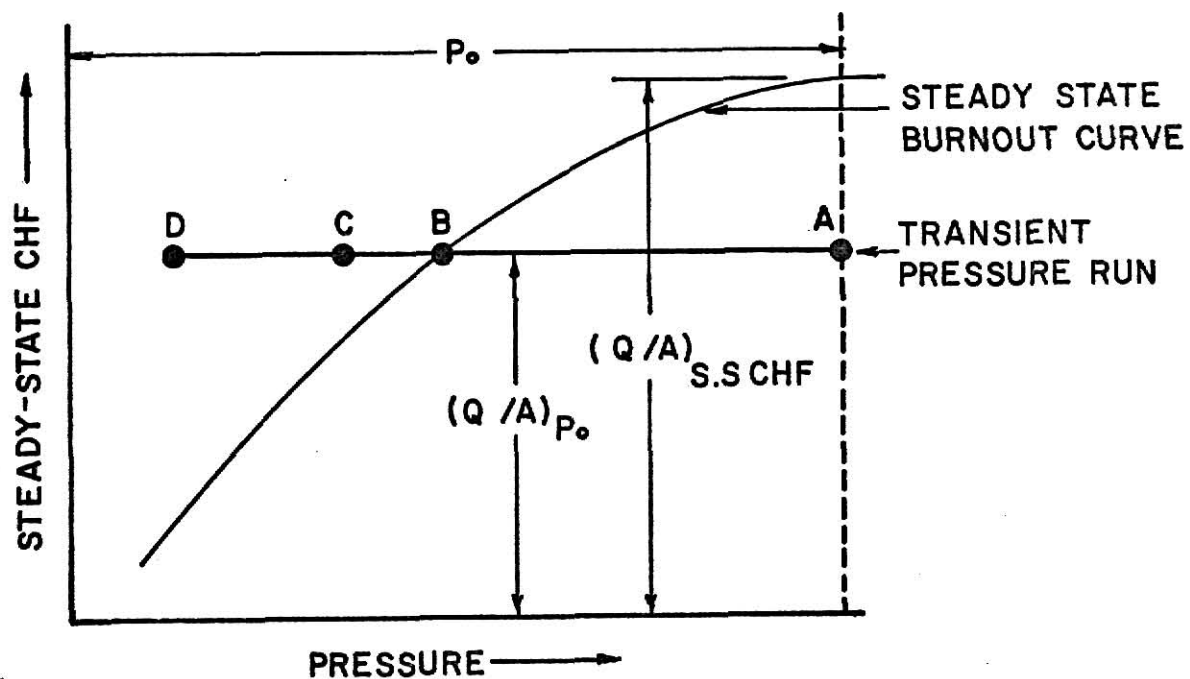
Fig. 6   Relation Between Transient Events and the Pressure.
[After Howell and Bell (23)].

point B to point C) is then found from a corrected experimental curve.
The final time segment, between the inception of film boiling and actual
burnout (point C to point D) can then be found analytically by assuming
complete insulation of the heating surface and calculating the time
required to reach the temperature of material failure. The time to
burnout was observed to increase with decreasing rate of pressure release.
Flashing, encountered in these experiments, was deemed responsible for
the delay of the boiling transition corresponding to the steady-state
prediction.

Cermak, et al. (11) examined the effect of pressure blowdown on flow
CHF in rod bundles. It was observed that for pressures of 6.3×10^5 to
10.5×10^5 pascal and relatively short time constants of 1 second,
steady-state CHF agreed with the observed transient CHF values to about
5 percent.

Studies of fast pressure transients are very few. Aoki, et al. (3)
investigated the boiling and burnout phenomena during very fast pressure
transients of time periods of approximately 25 milliseconds from atmospheric
pressure down to at most 7.3×10^4 pascal or higher. Heater surface
temperature behaviors for different initial heat flux levels were studied.
According to their results, the initial heat flux level determines the
overall transient behavior, as shown in Fig. 7. The most interesting
findings are for type B behavior (see Fig. 7). Specifically, the investi-
gators noted a spike characteristic of heat fluxes slightly lower than the
steady-state CHF of the final equilibrium state, a secondary boiling
during which boiling transition occurred, (see Fig. 7), and an initial
temperature drop for all levels of heat flux. The third observation
was also reported by Howell and Bell, but the first two findings are
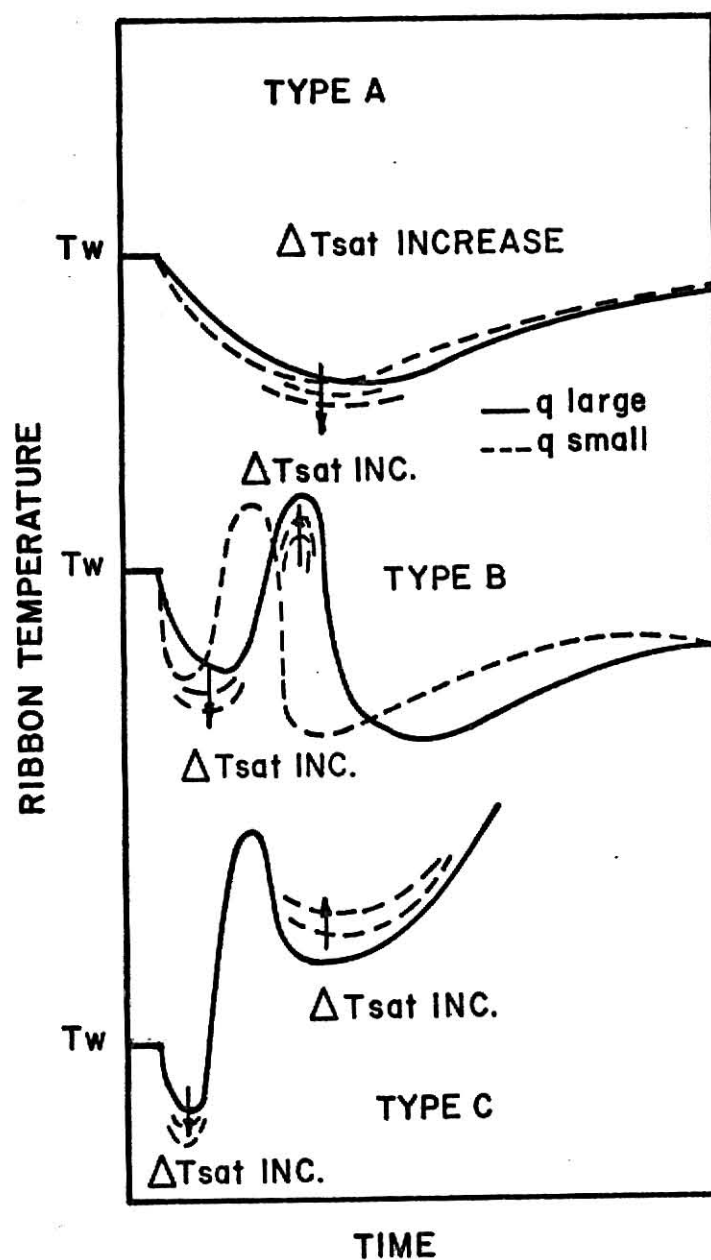
Fig. 7. Ribbon Temperature Behavior during Transient Boiling in Rapid Decompression from Atmospheric Pressure. [After Aoki, et al. (3)].

unique. By the use of high speed photography, Aoki, et al. were able to explain the bubble growth behavior in more depth than Howell and Bell. Thus, at medium heat flux level, the temperature falls during the initial sudden decompression but its drop ceases when the generated bubbles near the wall begin to coalesce. After the heater wall is covered with a large single coalesced bubble, the wall dries out and the temperature increases steeply. However, as the large bubble is removed from the surface by buoyancy, the temperature begins to drop and stable nucleate boiling insues.

When the initial heat flux was higher than the steady-state CHF, boiling transition and subsequent stable film boiling were observed. The transition, however, did not occur during the pressure drop but during the secondary boiling instead. By incorporating the thin liquid layer model for the bubble generation and detachment at high heat flux in nucleate boiling with their observations, the authors contend that boiling transition occurs when a second generation of bubbles is formed inside the thin liquid layer underlying the bubble layer from the primary boiling.

Summarizing previous decompression work, the following points should be noted. Howell and Bell tried to predict transient boiling transition on the basis of the initial conditions, i.e., operating heat flux, pressure decay rate, and range. And perhaps more importantly, they attempted to answer, if boiling transient occurs, at what stage in the decompression will it happen? Aoki, et al. (3), on the other hand, were interested in determining whether the boiling transition occurs during or after the pressure transient. The small time constant and comprehensive recording of heater temperatures accompanied by photo-graphic studies of bubble growth made their investigation more fundamental.

In steady-state boiling, the CHF is defined at the critical point as indicated in the beginning of this chapter. In power transients, the CHF is similarly defined as the point at which the heat flux decreases with further increase in heater temperature. Following the same line of thought and considering that the variation of the heat flux during the transient event is not controllable, perhaps the best definition of the CHF in pressure transients is that minimum initial heat flux which is sufficient to cause boiling transition during or shortly after the pressure transient event. Howell and Bell obtained some data for this purpose, but more data are necessary to establish a comprehensive relation. Aoki, et al. were unable to provide a comprehensive data set since the degree of superheat in their apparatus also affected the rate of decompression and the transient pressure behavior. Their observation of different temperature behaviors is of potential importance in the better understanding of pressure transient boiling phenomena.

The research reported herein is the initial stage in a comprehensive study of boiling transition under decompression. As an extension to the work described above, subcooled as well as saturated decompressions were studied to better elucidate the effect of flashing on the wire temperature behavior and boiling transition. In subsequent chapters, the experimental apparatus, technique, results, and conclusions are covered.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. Experimental Equipment

Because only low liquid temperatures (less than 100 °C) and low
pressures (less than atmospheric) were involved in this experiment,
pyrex glass and aluminum were used to construct the entire apparatus.
In order to produce very fast transients, a diaphragm bursting technique
was used instead of a quick opening valve. When burst by a spring-
loaded plunger, this method has yielded consistent results. A fast
response temperature sensor, in the form of a platinum wire, was used
for following the transient temperature history for a period of up to
500 milliseconds. The platinum wire was also used as the heater.
Details of the test assembly and the measuring circuit are described
in the following sections.

1. Test Assembly

A schematic diagram of the test assembly is shown in Fig. 8. The
test section was composed of an 800 ml Pyrex glass beaker that was fitted
with an aluminum flange. The reduced pressure, or blow-down tank, was
made of an eleven - liter glass vessel which has an aluminum flange and
valving to provide access to a vacuum pump. Aluminum pipe, 5.08 cm I.D.,
was used to connect the two sections through a diaphram section. Prior
to each transient run, an aluminum foil was clamped between the two
flanges of the diaphram section, and the pressure in the dump tank was
reduced to sub-atmospheric, in most experiments to 400 torr. An
aluminum tank was built originally to provide a constant temperature
environment for the test section during steady-state boiling experiments.
This was found to be unnecessary, and later experiments were performed

Fig. 8.   Schematic Diagram of the Experimental Apparatus.

ACCESS TO THE MANOMETER

ACCESS TO THE VACUUM PUMP

ALUMINUM PIPE

DIAPHRAGM SECTION

INSULATION

PRESSURE TRANSDUCER TO CHARGE AMPLIFiER

WATER LEVEL

GLASS BLOWDOWN TANK

ELECTRIC HOT PLATE

PLUNGER

COPPER ELECTRODE

MERCURY THERMOMETER

PLATINUM TEST WIRE
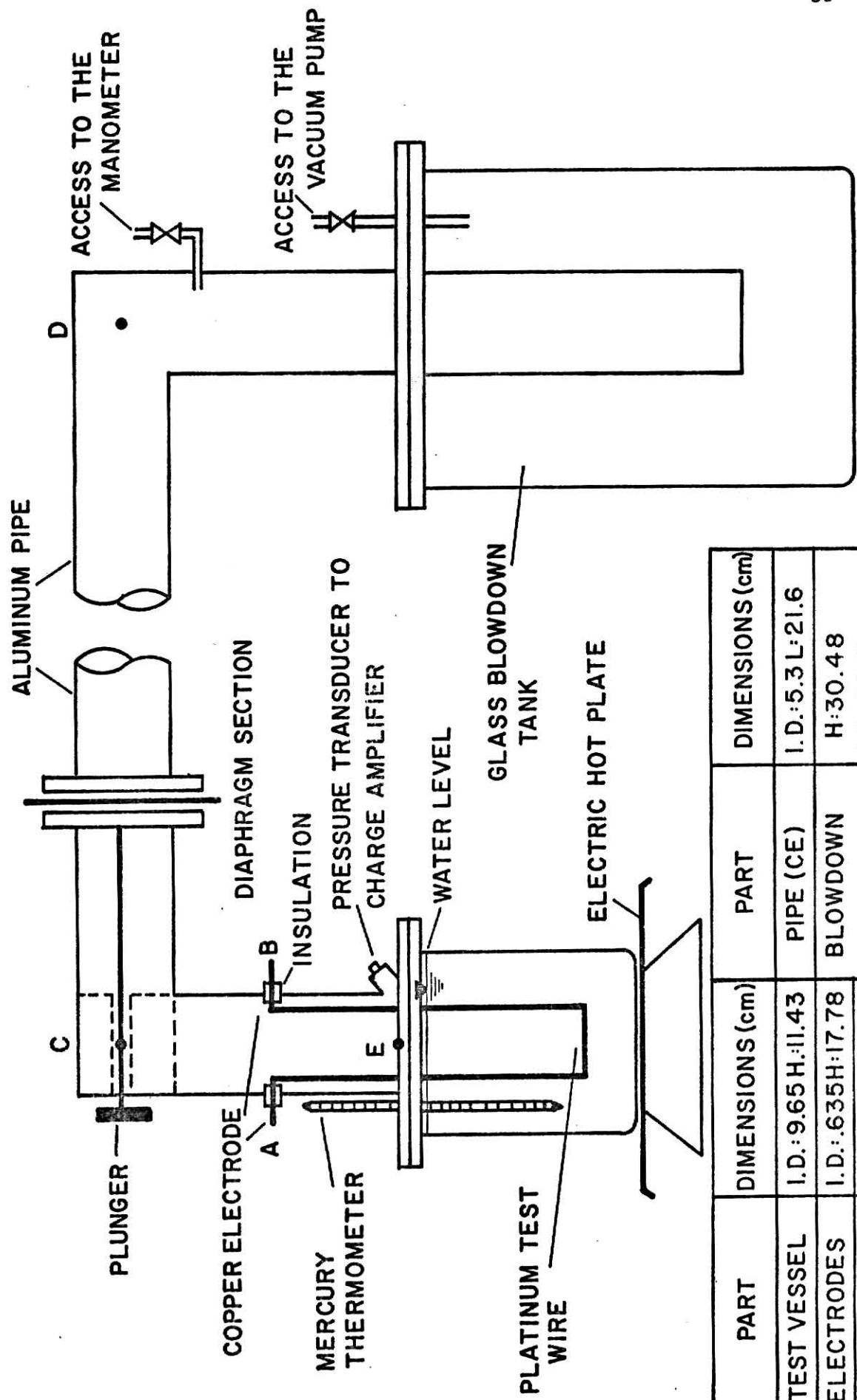
PART	DIMENSIONS (cm)	PART	DIMENSIONS (cm)
TEST VESSEL	I.D.:9.65 H:11.43	PIPE (CE)	I.D.:5.3 L:21.6
ELECTRODES	I.D.:.635 H:17.78	BLOWDOWN TANK	H:30.48 I.D.:20.3
PIPE (CD)	I.D.:5.3 L:55.3		

using a hot plate with a magnetic stirrer as the bath temperature control. Distilled and deionized water was used in the experimentation. No further filtration or purification was performed.

2. Electrical Circuit

The circuitry used in making steady-state and transient measurements is shown in Fig. 9. Resistors R_1, R_2, and R_3 are one 500 ohm and two-1 ohm high wattage resistors respectively for the control of current through the test wire. Resistor R_s is a 0.226 ohm precision shunt resistor. Current through the test wire is proportional to the voltage across R_s. Resistor R_w is the test wire resistance. The test specimen consisted of a 0.0127 cm-dia platinum wire approximately 2.0 cm in length. It was soldered on the ends of two copper electrodes and immersed in the water bath in the test vessel.

In steady-state measurements, as shown in 9a, the test wire was kept 8 cm below the water level to avoid surface effects as suggested by Aoki (3). The steady-state boiling curves for various pressures have been obtained by the use of a digital voltmeter to read wire voltage across A-B and current during operation up to the burnout point. Two 12-volt lead batteries provided stable wire current during each test run. Bulk water temperature was monitored by a mercury thermometer inserted inside the test vessel. Static pressure was read directly on a u-tube mercury manometer. Steady state resistances were measured by a Leeds and Northrup Type S bridge circuit.

For the transient experiments, a Tektronix type 551 dual-beam oscilloscope with a four-trace preamplifier was used to record the voltage variation across and the current through the test wire, in addition to the output signal from a Kistler type 603 piezoelectric
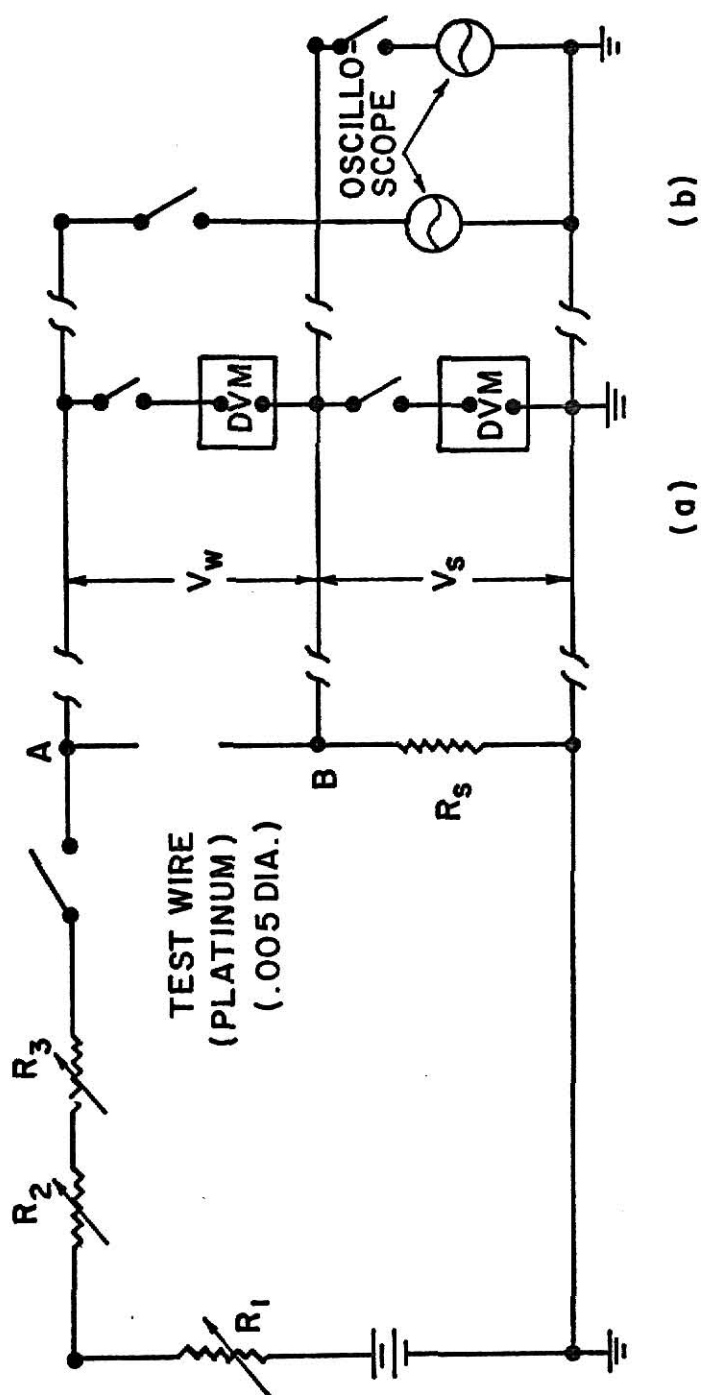
Fig. 9. Circuitry for Steady-State and Transient Measurements.

transducer with Kistler type 503 charge amplifier. The transient sweep

on the oscilloscope was recorded by a Polaroid scope camera.

B. Experimental Procedures

1. Steady-State Experiments

The following procedures were followed to produce steady-state

boiling curves at different pressures:

(1) The test vessel was cleaned and filled with deionized water which

   had been boiled for at least one hour. The test vessel was then

   placed in the constant temperature tank which had been previously

   brought up to the desired temperature. Later experiments were per-

   formed using a hot plate as the bath temperature control.

(2) The test wire was inspected by a 50X optical microscope and cleaned

   with benzene. The wire was heated in air with a two amp. current

   for twenty minutes after it was soldered to the ends of the electrodes.

   The length of the wire was measured to ± 0.05 cm.

(3) The electrical test assembly was inserted into the beaker. The

   system was closed and brought to the desired temperature at which

   time the resistance between points A and B on Fig. 8 was recorded.

   A vacuum pump was used to lower the pressure to the desired level.

(4) Power was applied to the test wire, and the wire voltage, V_w, the

   voltage across the precision resistor, V_s, and the voltage across

   the power supply, V_p, were recorded.

(5) The power level was raised incrementally in order that at least

   10 data points were taken prior to boiling transition.

(6) Information in the steady film boiling region was obtained by

   increasing the power until the wire burned out physically.

2. Transient Experiments

The following procedures were followed in recording the wire temperature behavior during and shortly after the pressure transient.

(1) The test assembly was prepared prior to each run in accordance with steps 1 and 2 from section 1 above.

(2) The test assembly was inserted into the test vessel and the whole system was brought to the desired temperature. The resistance between A and B in Fig. 8 was then recorded.

(3) The aluminum was inserted in the diaphram section and clamped. The pressure in the blow-down tank was reduced to 400 torr by the use of a mechanical vacuum pump.

(4) The DC power supply was turned on and the current through the test wire was brought up gradually to a pre-planned value by adjusting the variable resistors.

(5) The oscilloscope was DC balanced and proper sweep speed and sensitivity were selected.

(6) The triggering level on the oscilloscope was pre-set. The triggering level ajustment was the determing factor in the system sensitivity. The beginning of the transient was not recorded, since the scope was triggered by the pressure response. The voltage traces actually represent the transient behavior after several milliseconds into the transient.

(7) The voltage across the wire, V_w, the voltage across the precision resistor, V_s, and the voltage across the battery, V_p were recorded. Final adjustment of the system pressure was made.

(8) The shutter control line of the scope camera was pressed. The plunger was released, breaking the diaphragm and then the shutter control was released.

(9) DC power supply was turned off and the access valve was opened.

(10) The Polaroid picture was developed.

IV. RESULTS AND DISCUSSION

A relatively straightforward but carefully controlled series of experiments have been performed. It was confirmed that the boiling mechanism is affected significantly during and shortly after fast transients. For instance, if flashing occurs in the bulk coolant, the mechanism of bubble formation and growth may be quite different than that expected when only local boiling around the wire is present. It is surprising, therefore, to observe that even when there was no bulk flashing, i.e., in the subcooled blowdown case, wire temperature behavior was similar to that in the presence of flashing. The understanding and the explanation of these boiling phenomena must be based in part, on a clear understanding of the steady state nucleate boiling mechanism, especially at high heat fluxes near the CHF. Unfortunately, as indicated in Chapter 2, this region is not yet understood fully. In this chapter, the results of both steady-state and transient boiling studies will be covered. Discussion is based on currently accepted boiling models, due to the lack of high speed photographic data in these first experiments.

A. Steady-State Experiments

In order to gain operating experience and to assure the consistency of the apparatus, steady-state boiling experiments were performed as a preliminary test. Data were collected under pressures from atmospheric to 200 torr in a nearly saturated pool of water to construct steady-state boiling curves. The circuitry used for steady-state measurements has been shown previously in Fig. 9a.

1. Interpretation of Steady-State Data

To calculate the temperature of the test wire from its resistance, the resistance-temperature relation of pure platinum wire was used:

$$R_W(T_W) = R_W(0°C)(1 + \alpha T_W + \beta T_W^2) , \qquad (4.1)$$

where

$\alpha = 3.95 \times 10^{-3} \text{ deg}^{-1} °K,$

$\beta = 5.85 \times 10^{-7} \text{ deg}^{-1} °K$ (Ref. 9),

T_W = the temperature of test wire in degress of Celsius,

$R_W(T_W)$ = the resistance of test wire at T_W in ohms.

$R_W(T_W)$ can be calculated from the experimentally obtained values of V_I and V_W was shown below. Due to the existence of a connection resistance and the small resistance of the copper electrodes, V_W must be corrected by an amount V_{stray}

where

$$V_{stray} = I R_{stray} , \qquad (4.2)$$

and

$$I = V_I/R_s . \qquad (4.3)$$

The stray resistance, R_{stray}, is assumed to be equal to the difference between the system resistance, R_{sys}, and the theoretical reistance, R_{th},

$$R_{stray} = R_{sys} - R_{th} , \qquad (4.4)$$

The resistance of the wire under operating conditions is then calculated as

$$R_W = V_W'/I = (V_W - V_{stray})/I . \qquad (4.5)$$

By solving Eq. IV.1, it is obtained:

$$T_w = \frac{-\alpha \pm \sqrt{\alpha^2 - 4\beta\gamma}}{2\beta} \, , \qquad (4.6)$$

where

$$\gamma = 1 - \frac{R_w(T_w)}{R_w(0°C)} \, . \qquad (4.7)$$

The operating heat flux $(Q/A)_{op}$, can be calculated by the formula

$$(Q/A)_{op} = IV'_w/A \, , \qquad (4.8)$$

where A is the surface area of the test wire.

The wire temperature was assumed uniform both axially and radially. The radial temperature distribution in a long cylindrical rod with internal heat generation is

$$\frac{T_w(r)}{T_{max}} = 1 - \frac{\dot{Q} \, r_o^2}{4kT_{max}} \, (\frac{r}{r_o})^2 \, . \qquad (4.9)$$

where r is the radial distance from the centerline.

Because r_o is only 0.0635 cm, and the thermal conductivity of platinum, k, is 0.722 (Watt/cm °K) at 27 °C or 0.775 (Watt/cm °K) at 927 °C, the right hand side of Eq. IV.9 is not far from unity, i.e., $T_w \simeq T_{max}$. Thus, the temperature distribution from the centerline to the surface is nearly uniform. However, neglecting any end effects may be an invalid assumption in the case of short wires, e.g. length of 1 cm or less. In this experiment, because the length of test wire is close to 2.5 cm and the temperature behavior of the entire wire was measured instead of the local temperature, the end effects were not considered. However, if the temperature distribution along the wire is known, the constant which relates the maximum temperature and the mean temperature of the wire can be calculated.

2. Discussion of Steady-State Results

The data were processed by a short computer program listed in Appendix A. All the results are presented in Appendix B. The boiling curve under atmospheric pressure was plotted along with Petersons' (42) and McAdom's (36) data and is shown in Fig. 10. Rohsenow's equation in Table I was also used and the calculated results are presented in the same figure for comparison.

The free convection region of the boiling curve in the present study deviated slightly from the previous results. This may indicate that an error was introduced because of uncertainty in wire length. For low heat fluxes, the heater temperature is very close to the bulk fluid temperature; therefore, the errors made in the measurement of the length and end effects, will be substantially more important than in the boiling region. One other factor that may have contributed to the uncertainty is the possible influence of augmented free convection on the heat transfer. Since the pool was held at constant temperature by a bottom hot plate, the resulting free convection may increase the heat transfer over that normally present from that induced only by the thermal boundary layer in the near-wire region.

The boiling mechanism becomes very unstable as the boiling transition is approached. Because the controlled variable in this experiment was the heat flux (as in most other studies except Peterson's (42)), it was impossible to precisely detect the critical point. As the point of transition was passed, the physical appearance of the wire changed noticeably. At one location, the wire began to grow red. This local behavior subsequently spread over the wire's entire surface except near
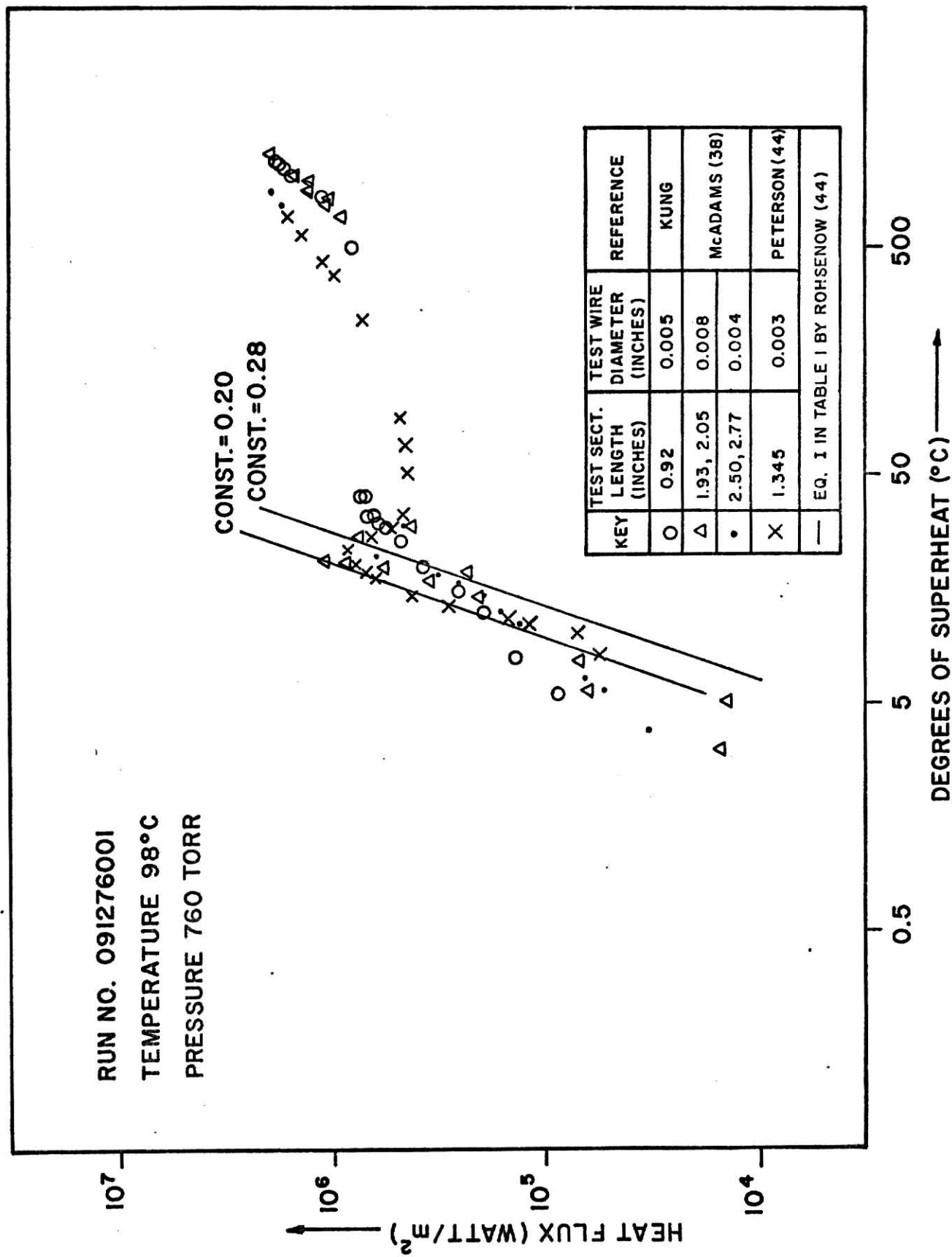
Fig. 10. Steady-State Boiling Curve at Atmospheric Pressure in a Saturated Pool of Water.

the ends where the surface temperature was lower. This phenomena corresponds to the case where the wire becomes engulfed in vapor and the boiling shifts to position D on the boiling curve (see Fig. 1), film boiling with radiation augmentation. The heat flux, as this transition was observed, was taken as the CHF. The results, shown in Fig. 11, are in good agreement with Aoki's data for a similar apparatus.

Frequently, the boiling transition was passed through without a clear indication of nucleate boiling. This behavior has been observed also by Aoki, et al. (3).

The steady-state experimentation described above gave confidence that the measurement system was reliable. Following this, transient data were gathered.

B. Boiling Heat Transfer During and Shortly after the Pressure Transient

1. The Interpretation of Transient Experimental Data

During decompression testing, the pressure decayed to 420 torr from atmospheric. If the water reached its saturation pressure during the run (as determined by the initial bulk fluid temperature), the final pressure was at most 30 torr higher than 420 torr. All the transient data were recorded by Polaroid pictures of oscilloscope traces. The test conditions examined during the experimentation are shown in Table 2. Four levels of heat fluxes were tested. At low heat flux, no bubbles appeared before or after the pressure transient. The ratio of the initial heat flux, $(Q/A)_{op}$, to the CHF corresponding to the final state, $(Q/A)_{CHF}$, was about .6. Medium heat flux level was when $(Q/A)_{op}/(Q/A)_{CHF}$ was about .8. High initial heat flux levels were close to the Q_{CHF}, and very high initial heat flux was higher than Q_{CHF}. For each level of heat flux, runs of different superheats and subcoolings were tested as recorded in Table 2.
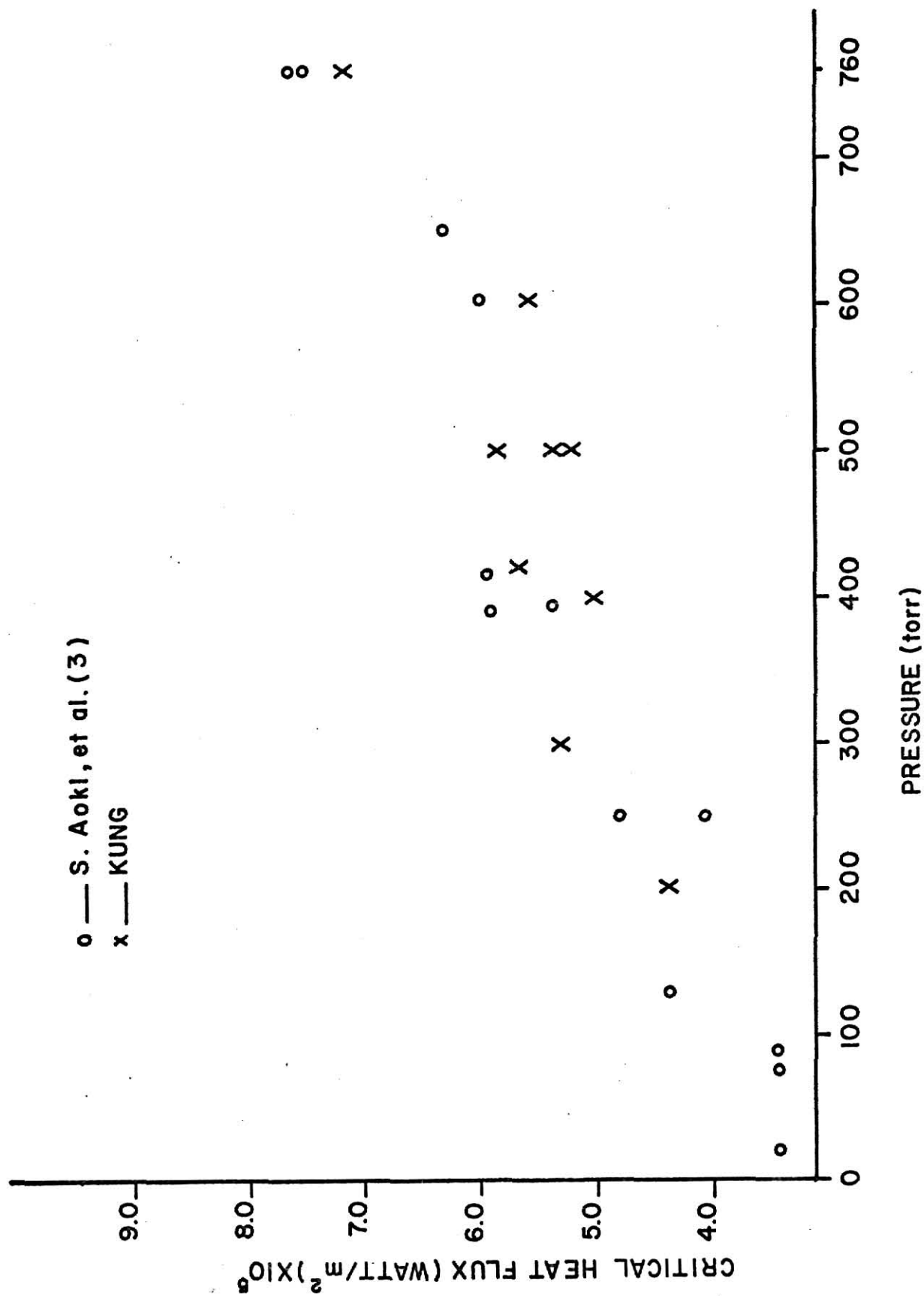
Fig. 11. Steady-State CHF at Sub-Atmospheric Pressures.

TABLE 2. Summary of the Test Conditions of the Transient Experiments

Initial Heat Flux Level $[(Q/A)_{op}/(Q/A)_{CHF}]$	Number of Runs	Initial Water Temp. T_L (°C)	Note
~0.5	10		Water became superheated after the transient was initiated. Degrees of superheat ranged from ~0 to 7°C. $[(Q/A)_{op}/(Q/A)_{CHF}]$ was approximately 0.5, 0.8, 1.0, and greater than 1.0. Corresponding levels are defined as low, medium, high, and very high heat fluxes respectively.
~0.8	7		
~1.0	21	≤ 84	
>1.0	12		
~0.5	7		Water remained subcooled after transient was initiated. Degrees of subcooling ranged from 1 to 34°C.
~0.8	5	< 84	
~1.0	8		
>1.0	9		

NOTE: $(Q/A)_{CHA}$ in saturated water under 420 torr is approximately 5.7×10^6 W/m^2 according to Figure 11.

It was assumed that the power supply provided a constant current source throughout the run; therefore, the voltage across the test wire, V_w, is proportional to the wire resistance, R_w,

$$V_w \simeq I R_w . \tag{4.10}$$

The time dependence of the current, I, introduces significant errors only at the end of the run, i.e. at the incidence of film boiling and later, and its neglect is therefore justified. From Eq. 4.10 it is apparent that

$$\Delta V_w \simeq I \, \Delta R_w \tag{4.11}$$

Differentiating Eq. IV.1, it is obtained,

$$\frac{\Delta R_w}{R_o} = \alpha \Delta T_w + 2\beta T_w \Delta T_w \simeq \alpha \Delta T_w \tag{4.12}$$

Therefore,

$$\Delta R \simeq k \, \Delta T_w \qquad \text{since } \alpha \gg \beta , \tag{4.13}$$

where

$$k = \alpha R_o = \alpha \, R_w(0 \, °C) . \tag{4.14}$$

Hence the voltage trace of the wire during the pressure transient gives a direct indication of the heater temperature variation. A typical oscilloscope trace is shown in Fig. 12. The top trace is the pressure transient behavior and indicates that the transient from 760 torr to 420 torr was complete within 10 milliseconds of initiation. The middle curve is the voltage across the test wire with respect to time. The lowest is the current trace which demonstrates that the current was constant during the time frame of interest. The small fluctuations are typical of medium and high heat flux levels because of nucleation and
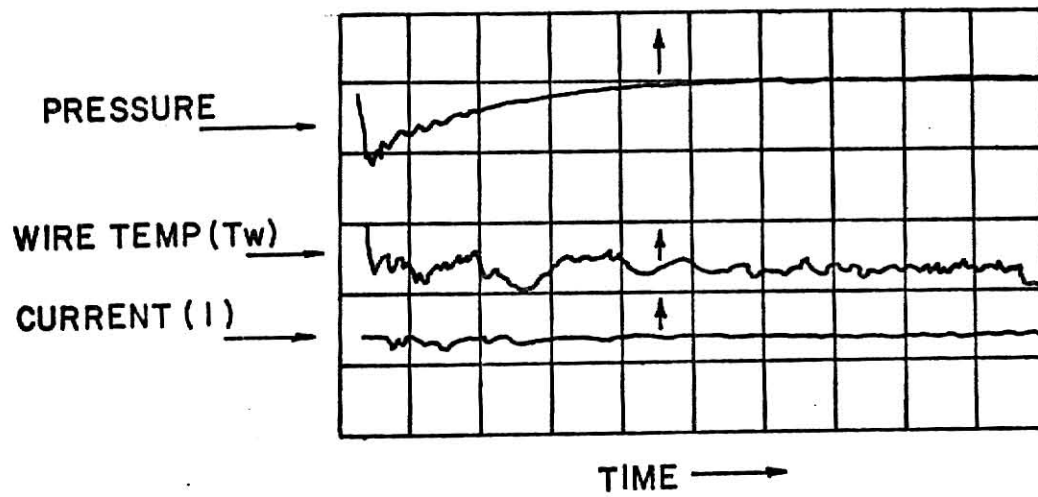
Fig. 12. Typical Pressure Transient Data.

Note: Arrows in the picture indicates positive increase
direction.

subsequent bubble detachments altering the surface temperature at high frequency (39). In superheated experiments, the response of the pressure transducer becomes unstable. The oscilloscope trace indicated that after the first dicompression, the pressure would decay further and went beyond the zero pressure level which is impossible. Hence, the pressure in superheated cases is assumed similar to that in subcooled cases. A summary of the experimental conditions and oscilloscope parameters for all the polaroid pictures cited here and after are listed in Table 3.

During the transient part of the experiment, 119 pictures were taken. The first 25 pictures were not useful for analysis because of the immature experimental technique. Out of the 94 following pictures, only 64 proved useful. Examples of these runs are shown and discussed in the following sections. Reduction of transient data is covered in Appendix C.

2. Discussion of the Results of Pressure Transient Experiments

i. Subcooled Case

When the bulk water remained subcooled during and after the pressure transient, no bulk flashing was induced. Typical results at different heat flux level are shown in Fig. 13, 14, and 15.

For low heat fluxes, no bubbles were generated on the heater surface before or after the transient. The heater temperature, T_w, was observed to drop almost 10 °C immediately after the transient. In this case, because natural convection was not affected significantly by the pressure, T_w always drifted back toward its original value at the end of the transient period.

TABLE 3. Summary of the Experimental Conditions and Oscilloscope Parameters for Fig. 12-20.

No. of Figure	$\left[\dfrac{(Q/A)_{op}}{(Q/A)_{CHF}}\right]$	T_L (± 0.2°C)	Sweep Speed (msec/Div.)	Voltage Sensitivity (Volts/Div.)			Observed Initial Voltage Drop of V_w (volts)	Estimated Initial Temp. Drop of T_w (°C)
				V_w	V_I	$V_{pressure}$		
12	~ 0.8	77	50	0.05 (DC)	0.05 (DC)	0.5 (AC)	0.035	7
13	~ 0.6	70	50	0.05 (DC)	0.02 (DC)	0.5 (DC)	0.03	8.5
14	~ 0.8	79	50	0.05 (DC)	0.05 (DC)	0.5 (AC)	0.04	8.2
15	~ 0.8	82	50	0.05 (DC)	0.05 (DC)	0.5 (AC)	0.058	10.13
16	~ 1.1	69	20	0.1 (DC)	0.05 (DC)	0.5 (DC)	0.060	11.9
17	~ 0.8	90	50	0.05 (DC)	0.05 (DC)	0.05 (DC)	0.065	15.7
18	~ 0.8	90	50	0.05 (DC)	0.05 (DC)	0.05 (AC)	0.064	12.9
19	~ 1.0	92	20	0.1 (DC)	0.05 (DC)	0.5 (AC)	0.03	6.5
20	~ 1.0	90	20	0.1 (DC)	0.05 (DC)	0.5 (DC)	0.05	11.8
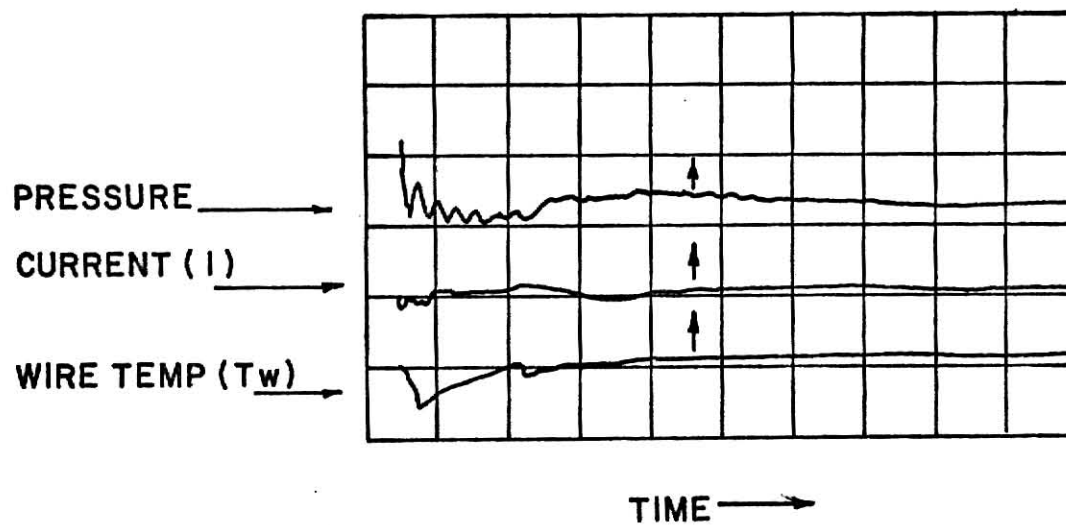
Figure 17.

Typical Sub-Cooled Data at Low Heat Flux.
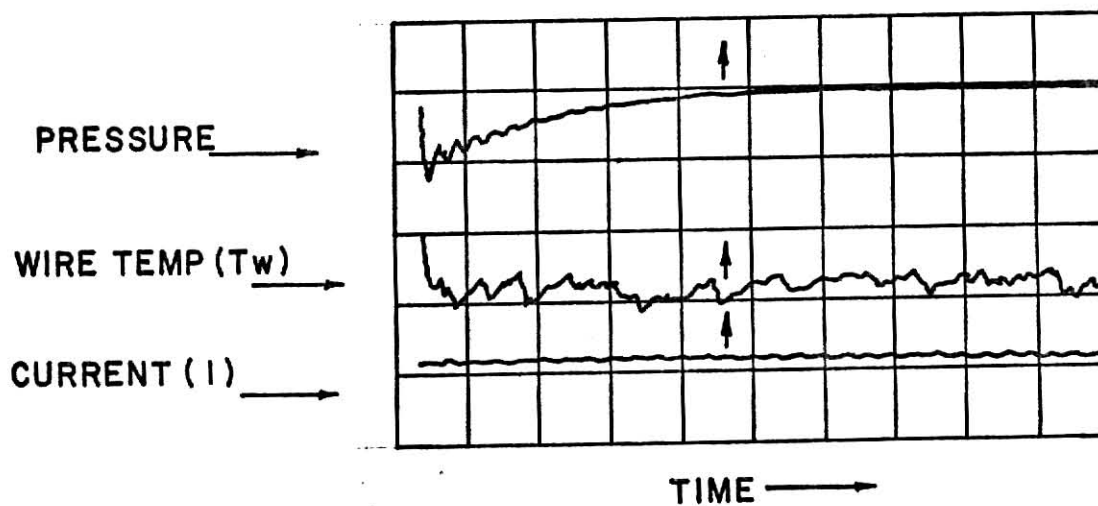
Figure 18.

Typical Sub-Cooled Data at Medium Heat Flux.

PRESSURE

WIRE TEMP (Tw)

CURRENT (I)

TIME ⟶

Fig. 15. Typical Sub-Cooled Data at Medium Heat Flux.

PRESSURE

WIRE TEMP (Tw)

CURRENT (I)

TIME ⟶
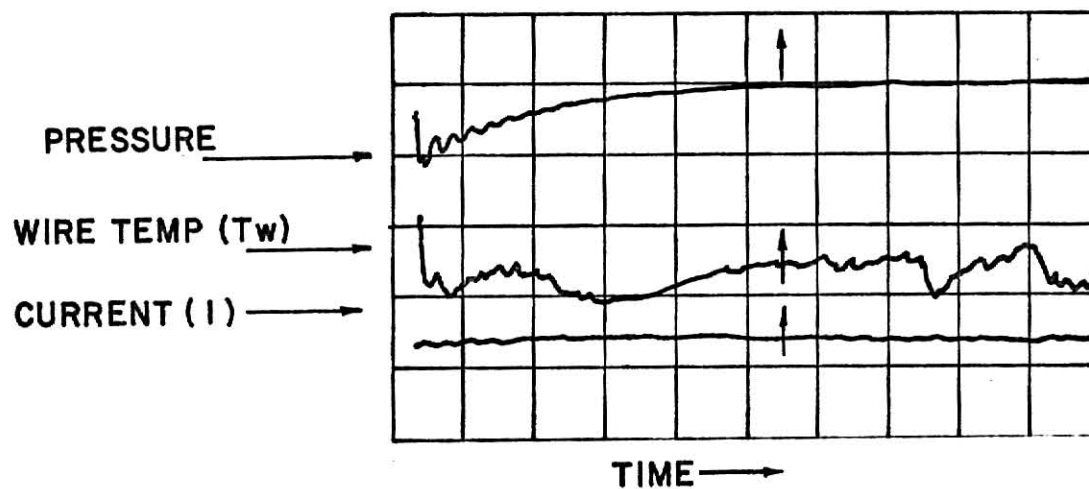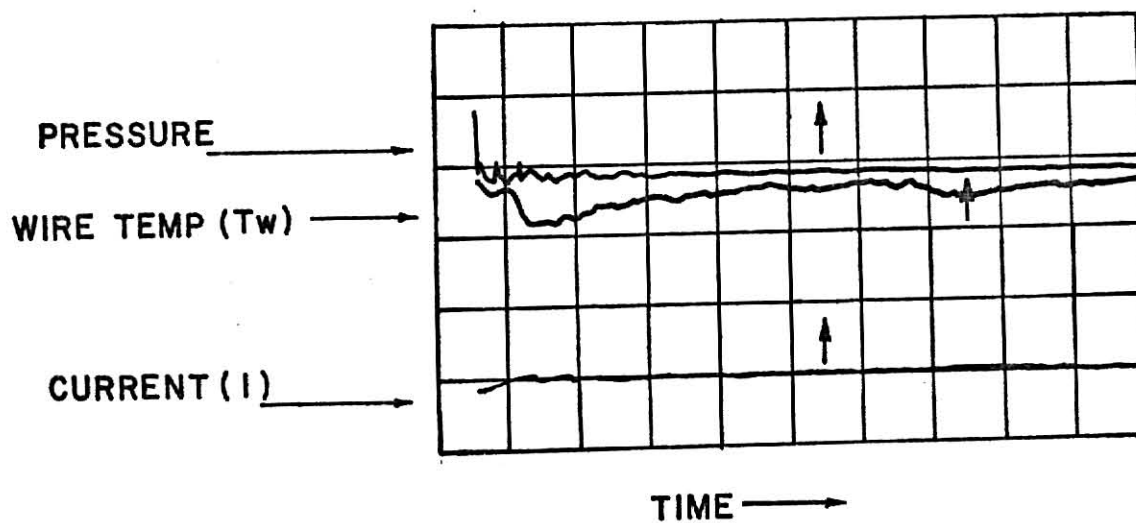
Fig. 16. Typical Sub-Cooled Data at High Heat Flux.

At medium levels of initial heat flux, nucleation was observed on the heater surface before the pressure transient. This bubble formation was enhanced by the reduced pressure during and after the decompression. Therefore, the heater temperature, which dropped initially during the decompression, remained at the reduced level due to the more vigorous nucleate boiling. The same result was obtained when another series of experiments with large initial subcoolings was conducted. In this case, a higher heat flux was applied. Consequently, even though the bulk fluid was well below the saturation temperature initially, nucleation on the wire was still present. T_w then stayed at the new reduced level of temperature after the transient. However, if the degree of initial subcooling was greatly increased, only natural convection contributed to the heat transfer. Therefore even if the applied heat flux was relatively high, T_w, in this case, drifted back to its original level. These results were shown in Fig. 15.

At high and very high heat flux levels, although T_w tended to drop initially as in the former cases, the boiling transited to film boiling and T_w increased due to reduced heat transfer. However, the delay from the start of the transient to the time of boiling transition was found to be very random. It ranged from 20 milliseconds to several hundred milliseconds. No boiling transition occurred during the decompression under any condition.

Two important results of subcooled depressurization deserve special emphasis. The first is the initial temperature drop under all conditions, even the most subcooled test in which no bubble mechanism existed during the entire event. This can be explained, perhaps, by turbulence in the surrounding liquid caused by the pressure wave. The rate of heat transfer

by convection between a solid boundary and a fluid is generally evaluated

by means of Newton's Law of Cooling:

$$q_{\text{surface to fluid}} = A\bar{h}_c (T_w - T_\infty) , \tag{4.15}$$

where

A = heat transfer surface

$\bar{h}_c$ = the convection coefficient,

T_∞ = the water temperature,

T_w = the temperature of test wire.

Once the pressure transient was initiated, the heat balance between the

heat generation, which follows Ohm's law as

$$q_{\text{generated}} = I^2 R_w(T_w) , \tag{4.16}$$

and the convection heat flux was disturbed. The convection coefficient

was increased because of the turbulence, and the wire temperature

started to drop. This forced convection heat flux continued to be

larger than the heat generation; therefore, the wire temperature con-

tinued to drop until thermal equilibrium was reestablished. In order

to evaluate the magnitude of the change in $\bar{h}_c$, the condition prior to the

pressure transient is referred to as 1, and 2 is the state of the

reestablished equilibrium. If the following equations are used:

$$I^2 R_w(T_1) = (T_1 - T_L)\bar{h}_{c1} A , \tag{4.17}$$

$$I^2 R_w(T_2) = (T_2 - T_L)\bar{h}_{c2} A , \tag{4.18}$$

or

$$\bar{h}_{c1} = \frac{I^2}{A} \frac{R_w(T_2)}{(T_1 - T_L)} , \tag{4.19}$$

$$\bar{h}_{c2} = \frac{I^2}{A} \frac{R_w(T_2)}{(T_2 - T_L)} , \qquad (4.20)$$

where current, I, is assumed constant, then from Eq. IV.1,

$$R_w(T_1) \simeq R_o(1 + \alpha T_1) , \qquad (4.21)$$

$$R_w(T_2) \simeq R_o(1 + \alpha T_2) . \qquad (4.22)$$

It may be easily found that the ratio of the heat transfer coefficients is:

$$\frac{\bar{h}_{c2}}{\bar{h}_{c_1}} = (\frac{1 + \alpha T_2}{1 + \alpha T_1})(\frac{T_1 - T_L}{T_2 - T_L}) . \qquad (4.23)$$

As an example, for run #64, T_1 was 170.5 °C, $T_2 - T_1 = -10$ °C, and $T_L = 82$ °C; therefore,

$$\frac{\bar{h}_{c2}}{\bar{h}_{c1}} = \frac{1 + 0.00395 \times 165}{1 + 0.00395 \times 175} \frac{88.5}{78.5} ,$$

$$= 1.10 .$$

The convection heat transfer caused by turbulence is estimated, in this case, to have been increased by 10%. Of course, further studies of the velocity field next to the wire are necessary to investigate this phenomena more completely. But, it can be seen that violent agitation by bubbles is not necessary to promote a heater surface temperature drops.

The second point of importance is the wire temperature behavior after the transient. It remained at a depressed level at high heat fluxes, but drifted back to its initial value at low heat fluxes. The explanation given in the first part of this section, which notes the presence of nucleate boiling for medium or high heat fluxes after the transient is applicable. But further study is needed because the heat transfer

immediately after the pressure transient is of special importance to the understanding of the effect of flashing, which will be discussed in the next section.

ii. Superheated Cases

Superheated blowdown is much more complex than the preceeding subcooled cases, since bulk flashing is generated which influences the wire heat transfer. In this series, water in the test vessel was slightly subcooled initially so that vapor bubbles were generated throughout the bulk volume once the decompression was initiated. Hence, the objective was to determine the direct effect of the pressure transient and the indirect effect of the flashing on the heat transfer and boiling transition.

When the initial heat flux was low, T_w dropped during the pressure transient and remained at the lower level. By increasing the heat flux, the effect of flashing could be seen by comparing the transient wall temperature behavior with the subcooled cases. Instead of aiding the heat transfer, the flashing actually caused the heat transfer from the wire to deteriorate which resulted in the temperature peaks shown in Fig. 17.

As the initial heat flux was increased, the results, shown in Fig. 18, became unpredictable, because during some runs nucleate boiling persisted during and after the transient while during others, the boiling transitioned to film boiling with radiation augmentation. The characteristic fluctuation observed by Aoki, et al. as shown in Fig. 7, however, was not duplicated in these runs.

High initial heat fluxes were also studied. In all cases, film boiling was evidenced by the rapid temperature rise, as shown in Fig. 19, 20.

PRESSURE ⟶

WIRE TEMP (Tw) ⟶
CURRENT (I) ⟶

TIME ⟶
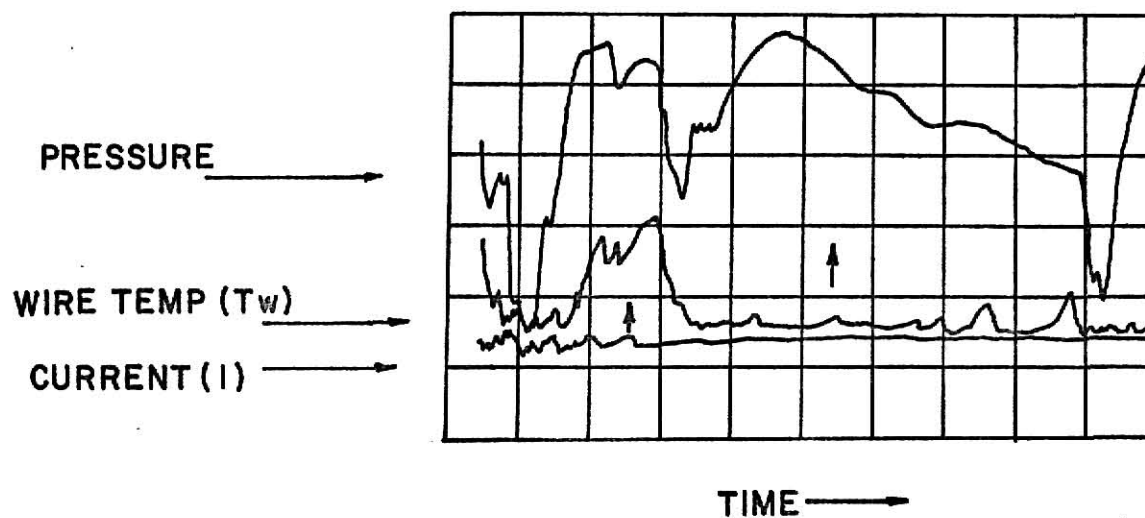
Fig. 17.   Typical Superheated Data at Low Heat Flux.

PRESSURE ⟶
CURRENT (I) ⟶

WIRE TEMP (Tw) ⟶

TIME ⟶
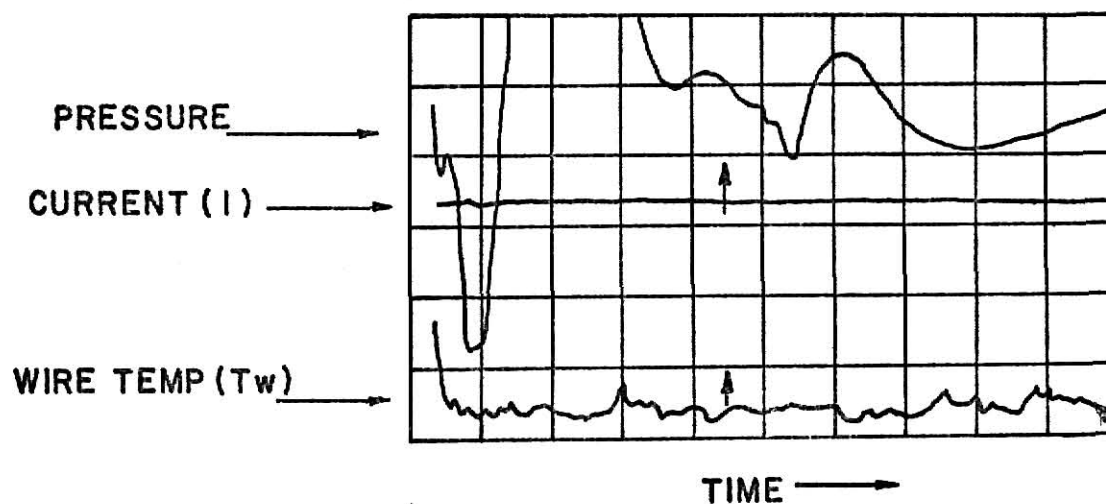
Fig. 18.   Typical Superheated Data at Medium Heat Flux.
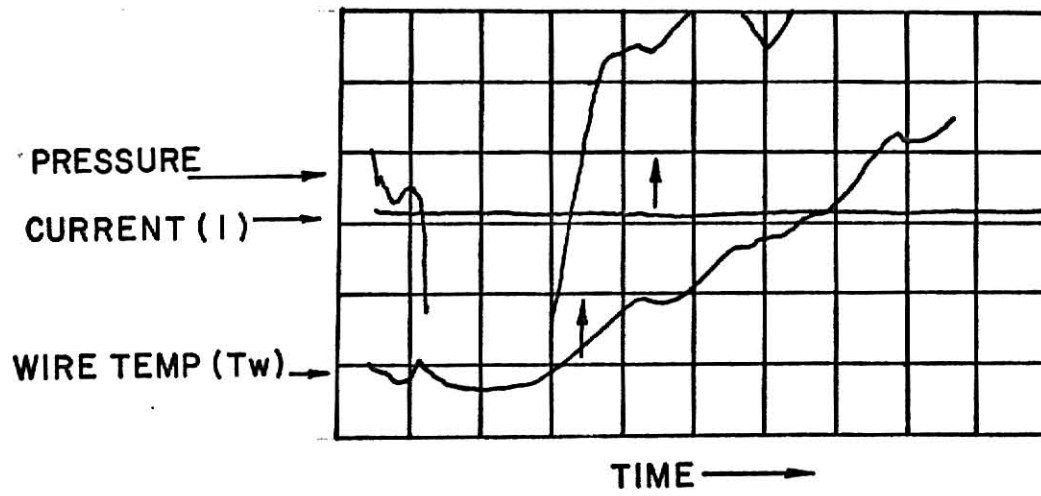
Fig. 19. Typical Superheated Data at High Heat Flux.
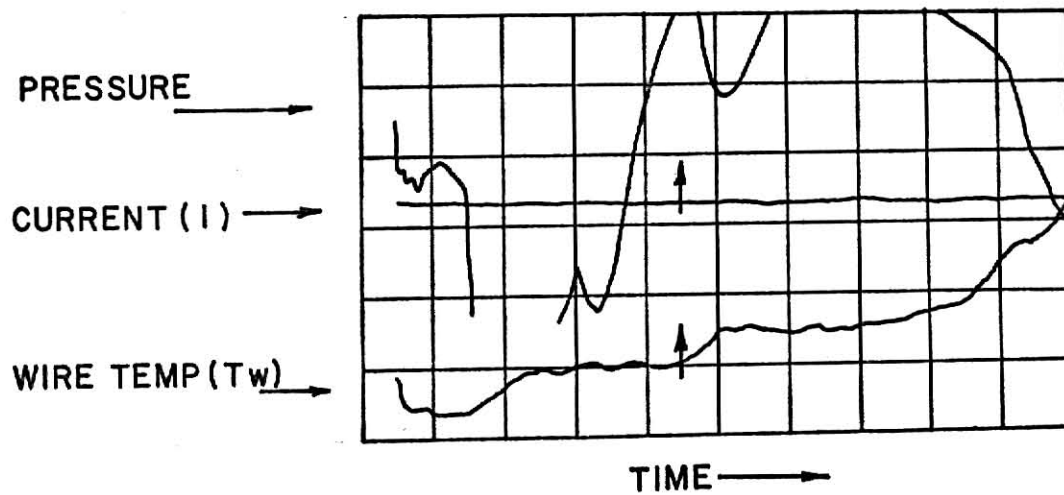
Fig. 20. Typical Superheated Data at High Heat Flux.

Figure 22.

In all the runs, T_w dropped during the decompression, and rose rapidly as film boiling began. The secondary boiling reported in Aoki's work (3) could not be clearly identified. However, there was a delay time to boiling transition under all conditions, a result that should be regarded as one of the most important findings of the present study.

It has been explained previously, see for instance Howell and Bell (23), that the drop in wire temperature during the decompression is due to the violent flashing accompanying the decompression. That this is not the case is shown clearly by comparing the present subcooled blowdown results. The wire temperature drop during the transient was observed to be remarkably insensitive to not only flashing, but also the bulk water temperature. No significant dependence on the bulk water temperature can be found. This is contrary to what Aoki, et al. had reported, wherein the drop of T_w increased with increasing superheat as shown in Fig. 7. These results were generated, however, from a limited amount of data from saturated decompression only. Hence it must be concluded that ΔT_w, the initial temperature drop, is a result of the pressure transient and not unique to flashing. Flashing, which only occurred in the super-heated experiments, probably did not become significant during the rapid pressure decay and, therefore, could have had little effect on ΔT_w. Hopper and Abdelmessih's investigation (22) supports this supposition. For decompression times of 5 milliseconds, they observed no bubble nucleation with less than 4 milliseconds delay beyond the termination of the decompression period. Moreover, it was found that several milli-seconds were required for bubbles to grow to a significant size.

iii. Conclusions of Transient Experiments

There are several interesting findings from this experiment, some
of which had not been reported before. Among these are:

(1) Boiling transition occurred after the completion of the pressure
transient. This observation, as shown in Fig. 19 and 20 was also
noted by Aoki, et al (3). But the "secondary boiling" postulated
by them to explain this phenomenon was not identified in the current
series of experiments. The time to the boiling transition after
transient initiation and the characteristic behavior of the heater
need to be studied further in order to make a definitive conclusion
about the importance of "secondary boiling" and the pressure transient
on transition.

(2) The heater temperature dropped immediately after the pressure
transient was initiated in both superheated and subcooled cases.
The temperature depression in the superheated case was expected, but
the temperature drop in subcooled transients has not been reported
before. Furthermore, the amount of drop in the subcooled case was
comparable to that in superheated depressurization. This, perhaps,
indicates the importance of the convection current induced by the
pressure wave propagation.

(3) The amount of the initial heater temperature drop was found to be
insensitive to the initial heat flux level and the surrounding coolant
temperature. This is different from what Aoki, et al (3) had observed
(see Fig. 7). However, the decompression rate in this experiment is
approximately twice as fast as that used in the previous work. Since
neither bubble nucleation in the bulk liquid nor that on the heating

surface is instantaneous, a critical decompression rate may exist which significantly alters the bubble growth history and, therefore, affects the heat transfer. This obviously places considerable importance on the study of bubble growth phenomena under pressure transients of varying time periods in future research.

(4) The flashing may inhibit rather than inhance the heat transfer. Temperature peaks, observed only in the superheated cases, may imply that the heater surface experienced partial vapor insulation for a short period of time. The large amount of vapor generated during the process of flashing provides favorable conditions for the formation of a temporary vapor film on the heating surface.

C. Suggestions for Future Research

Since part of the purpose of this study was to be a first step in a comprehensive program, suggestions for future apparatus and areas of future interest are:

(1) Since the input heat flux dominates the temporal behavior of the heater, as discussed in previous sections, a constant heat flux is desirable during and after the pressure transient. Therefore, a heating source isolated from the heat transfer surface is suggested.

(2) At high heat fluxes in the nucleate boiling region, high frequency detachments from heating surface cause rapid fluctuations in both local and overall surface temperatures. Efficient averaging methods need to be developed to obtain reliable temperature measurements.

(3) For rapid decompression work, the pressure history at the location of the heat transfer surface needs to be precisely recorded. A

pressure transducer for transient hydraulic pressure measurement mounted close to the heat transfer surface is recommended.

(4) The pressure range needs to be extended, and a variable decompression rate is required to determine the actual effect of pressure transients on boiling heat transfer and transition.

(5) Fast photography is recommended to investigate transient bubble growth. Such data, in turn, provides part of the information necessary for fundamental qualitative and quantitative analysis of the boiling process.

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ACKNOWLEDGEMENT

APPENDICES

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FORTRAN IV G LEVEL  21              MAIN           DATE = 77175        10/48/18        PAGE 0001

0001          REAL IS(100),LENTH
0002          DIMENSION XARRAY(100),YARRAY(100)
0003          DIMENSION VS(100),VW(100),RW(100),H1(100),H2(100),H3(100),T(100),
             1 DT(100)
0004          DIMENSION IBUF(20000),IXNAME(30),IYNAME(30)
0005          DIMENSION TITLE(10)
0006          DIMENSION TITL(10),TIT(10)
0007          DIMENSION NN(3)
       C
       C      THIS PROGRAM IS FOR PROCESSING STEADY-STATE DATA AND PLOTTING
       C      BOILING CURVE AT DIFFERENT PRESSURES
       C
       C      WHERE    LENTH:   LENGTH OF THE TEST WIRE
       C               TEMP:    WATER TEMPERATURE
       C               RSYS:    RESISTANCE OF THE TEST WIRE INCLUDING THE
       C                        ELECTRODES AND THE CONNECTIONS
       C               PRES:    SYSTEM PRESSURE
       C               VS:      VOLTAGE ACROSS THE SHUNT RESISTOR
       C               VW:      VOLTAGE ACROSS THE TEST WIRE
       C               DT:      WALL SUPERHEAT
       C               T:       CALCULATED WIRE TEMPERATURE
       C               AREA:    SURFACE AREA OF THE WIRE
       C               RTHEO:   THEORETICAL RESISTANCE OF THE TEST WIRE AT
       C                        OPERATING TEMPERATURE
       C
       C      SET UP PLOTTING PARAMETERS
       C
0008          YFIRS=10**3
0009          YCYPIN=4.C/6.0
0010          YLEN=6.0
0011          XFIRS=0.1
0012          XLCN=8.
0013          XCYPIN=5.0/8.0
0014          READ(5,600C)(IXNAME(I),I=1,7)
0015          READ(5,6000)(IYNAME(I),I=1,7)
0016          READ(5,7000)N
0017          DO 400 M=1,N
0018          READ(5,8000)(NN(I),I=1,3)
0019          READ(5,10000)(TITLE(I),I=1,5)
0020          READ(5,10C00)(TITL(I),I=1,5)
0021          READ(5,10000)(TIT(I),I=1,5)
0022          READ(5,1)FS,R20
0023        1 FORMAT(2F6.4)
0024          READ(5,2)LENTH,TEMP,RSYS,PRES,RTI20,M
0025        2 FORMAT(F5.3,F5.2,F5.4,F5.1,F8.6,I3)
       C
       C      READ INPUT CATA
       C
0026          READ(5,3)(VS(I),VW(I),I=1,M)
0027          WRITE(6,9000)NN
0028          WRITE(6,16000)TEMP
0029          WRITE(6,17000)PRES
0030          WRITE(6,18000)LENTH
0031          WRITE(6,19000)RSYS
0032          WRITE(6,15000)
0033          WRITE(6,14000)(I,VS(I),VW(I),I=1,M)
0034        3 FORMAT(12F6.4)
```

Appendix A (continued)

```
0C35          WRITE(6,20000)
0C36          WRITE(6,3000)
0C37          WRITE(6,4000)
0C38          XARRAY(M+1)=-1.0
0C39          XARRAY(M+2)=5.0/XLEN
0C40          YARRAY(M+1)=3.0
0C41          YARRAY(M+2)=4.0/YLEN
0C42          NUMY=28
0C43          NUMX=28

       C
       C                CALCULATION
       C
0C44          A=0.00392
0C45          B=-0.0000CC588
0C46          RTI=1+A*TEMP+B*TEMP**2.0
0C47          RTI=RTI/RTI20
0C48          RTHEC=LENTH*R20*RTI
0C49          SR=PSYS-RTHEC
0C50          AREA=LENTH*3.1416*.005*2.54*2.54
0C50          DO 100 I=1,M
0C51          IS(I)=VS(I)/RS
0C52          RW(I)=VW(I)/IS(I)-SR
0C53          HI(I)=RW(I)*IS(I)**2.0/AREA
0C54          H2(I)=HI(I)*3170.2
0C55          H3(I)=H2(I)*2.7126
0C56          T(I)=(-A+(A**2.0-4.0*B*(1.0-RTI*RTI20*RW(I)/RTHEO))**0.5)/(2.0*B)
0C57          CT(I)=(T(I)-TEMP)
0C58          WRITE(6,5000)I,IS(I),H2(I),H3(I),DT(I),RW(I),T(I)
0C59    100   CONTINUE
0C60          WRITE(6,11000)
0C61          DC 300 I=1,M
0C62          XARRAY(I)=ALOG10(DT(I))
0C63          YARRAY(I)=ALCG10(H2(I))
0C64    300   CONTINUE
0C66          IF(MM-1)10,10,20

       C
       C                PLCT
       C
0C67    10    CALL LIMITS(150.,11.0,25,6,-3)
0C68          CALL PLOTS(IBUF,20000)
0C69    20    CALL PLCT(0.,-11.,-3)
0C70          CALL PLOT(12.,1.5,-3)
0C71          CALL CLOGAX(0.,0.,XLEN,XCYPIN,0.,-1)
0C72          CALL SLCGAX(XFIRS,+1,-1,IXNAME,-NUMX)
0C73          CALL CLOGAX(0.,0.,YLEN,YCYPIN,90.,+1)
0C74          CALL SLCGAX(YFIRS,+3,+1,IYNAME,-NUMY)
0C75          CALL CLOGAX(0.,YLEN,XLEN,XCYPIN,0.,+1)
0C76          CALL DLOGAX(XLEN,0.,YLEN,YCYPIN,90.,-1)
0C77          CALL LINE(XARRAY,YARRAY,M,1,-1,1)
0C78          CALL SYMBCL(0.5,5.0,0.125,TITLE,0.0,20)
0C79          CALL SYMBCL(0.5,4.5,0.125,TIIL,0.0,20)
0C80          CALL SYMBCL(0.5,4.0,0.125,TIT,0.0,20)
0C81          GO TO 400
0C82    400   CONTINUE
0C83          CALL PLOT(XLEN+5.0,0.,999)
0C84    3000  FORMAT(//4X,'NO.',3X,'CLRRENT(A4P)',15X,'HEAT FLUX',16X,'WALL SU
             1PERHEAT(C)',3X,'RESISTANCE OF WIRE (OHM)',3X,'WIRE TEMP.(C)'//)
0C85    4000  FORMAT(32X,'BTU/FT**2HR',5X,'KCAL/M**2HR'//)
```

68

Appendix A (continued)

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FORTRAN IV G LEVEL  21                    MAIN                     DATE = 77175          10/48/18          PAGE 0003

0086      5000  FCRMAT(3X,I2,6X,E13.6,7X,E13.6,3X,E13.6,5X,E13.6,9X,E13.6,12X,E13
                1.6)
0087      6000  FCRMAT(7A4)
0088      7000  FCRMAT(I2)
0089      8000  FCRMAT(3I3)
0090      9000  FCRMAT(2X,'RUN NO.',2X,3I3/)
0091     10000  FCRMAT(5I4)
0092     11000  FCRMAT(1H1)
0093     12000  FCRMAT(F4.1)
0094     13000  FCRMAT(1X,6E13.6,1X,2I4)
0095     14000  FCRMAT(3X,I2,14X,F6.4,2CX,F6.4)
0096     15000  FCRMAT(1X,'CATA PCINT',2X,'V. ACRCSS SHUNT RESISTOR',2X,'V. ACROS
                1S TEST WIRE'/)
0097     16000  FCRMAT(/2X,'WATER TEMPERATURE =',2X,F4.1,'C'/)
0098     17000  FCRMAT(2X,'SYSTEM PRESSURE =',2X,F4.0,1X,'TCRR'/)
0099     18000  FCRMAT(2X,'TEST WIRE LENGTH =',2X,F5.3,1X,'INCH'/)
0100     19000  FCRMAT(2X,'SYSTEM RESISTANCE AT SYSTEM TEMPERATURE =',1X,F5.4,1X,
                1'OHM'/)
0101     20000  FCRMAT(///2X,'RESULTS OF CALCULATICN'/)
0102            STOP
0103            END
```

Appendix A (continued)

RUN NC. 101276 1

WATER TEMPERATURE = 83.0C

SYSTEM PRESSURE = 420. TCRR

TEST WIRE LENGTH = C.860 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2390 OHM

DATA FCINT V. ACROSS SHUNT RESISTCR   V. ACROSS TEST WIRE

1	0.0534	0.0583
2	0.1010	0.1111
3	0.2142	0.2357
4	0.4050	0.4520
5	0.6390	0.7280
6	0.8040	0.9350
7	0.5380	1.1010
8	0.9690	1.1650
9	0.5510	1.1930
10	0.5580	3.0600
11	0.8130	3.0900
12	1.0240	1.2470
13	0.7800	2.7800
14	0.7470	2.4100
15	0.8350	3.3400
16	0.8670	3.6000
17	0.8820	3.8000

RESULTS CF CALCULATICN

NO.	CURRENT(AMP)	HEAT FLUX BTL/FT**2HR	KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.236283E 00	C.472249E 03	0.128102E 04	0.119165E 02	0.232544E 00	0.949165E 02
2	0.449C03E 00	0.17C252E 04	0.461935E 04	0.147537E 02	0.234406E 00	0.979937E 02
3	0.547788E 00	0.766209E 04	0.207842E 05	0.149233E 02	0.234491E 00	0.979213E 02
4	0.179C04E 01	C.278055E 05	0.754252E 05	0.204016E 02	0.230033E 00	0.103402E 03
5	0.2E2743E 01	0.707452E 05	0.191903E 06	0.285356E 02	0.243784E 00	0.115536E 03
6	0.355752E 01	C.1144586E 06	0.310430E 06	0.368393E 02	0.248630E 00	0.119839E 03
7	0.415344E 01	C.157326E 06	0.426761E 06	0.406494E 02	0.251079E 00	0.123649E 03
8	0.423761E 01	0.172703E 06	0.467119E 06	0.506951E 02	0.257519E 00	0.133695E 03
9	0.434465E 01	C.180358E 06	0.492399E 06	0.512473E 02	0.257873E 00	0.134247E 03
10	0.441593E 01	0.481455E 06	0.130599E 07	0.795313E 03	0.678752E 00	0.878313E 03
11	0.359735F 01	0.376653E 06	0.107867E 07	0.116345E 04	0.844773E 00	0.124345E 04
12	0.455309E 01	C.195822E 06	0.531187E 06	0.543903E 02	0.259686E 00	0.137080E 03
13	0.345133E 01	0.342854E 06	0.930026E 06	0.103625E 04	0.791293E 00	0.111925E 04
14	0.330521E 01	C.284113E 06	0.770686E 06	0.870118E 03	0.714936E 00	0.953118E 03
15	0.369469E 01	0.441826E 06	0.119850E 07	0.127108E 04	0.889806E 00	0.135408E 04
16	0.383628E 01	0.494759E 06	0.134208E 07	0.135996E 04	0.924214E 00	0.144296E 04

Appendix A (continued)

RUN NC. 150776 4

WATER TEMPERATURE = 93.5C

SYSTEM PRESSURE = 600. TORR

TEST WIRE LENGTH = 0.760 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2190 OHM

DATA POINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0574	0.0581
2	0.0658	0.0668
3	0.0712	0.0722
4	0.0815	0.0828
5	0.0925	0.0939
6	0.1067	0.1064
7	0.1214	0.1235
8	0.1345	0.1368
9	0.1430	0.1465
10	0.1627	0.1660
11	0.1717	0.1754
12	0.1931	0.1977
13	0.2131	0.2185
14	0.2378	0.2448
15	0.2470	0.2545
16	0.2575	0.2656
17	0.2809	0.2904
18	0.3440	0.3581
19	0.2645	0.2811
20	0.3859	0.4055
21	0.4133	0.4360
22	0.4429	0.4659
23	0.4700	0.5000
24	0.4925	0.5258
25	0.5001	0.5360
26	0.5257	0.5660
27	0.5212	0.5567
28	0.5429	0.5800
29	0.5735	0.6147
30	0.5974	0.6350
31	0.6136	0.6510
32	0.6374	0.6790
33	0.6240	0.7070
34	0.6675	0.7350
35	0.7524	0.8060
36	0.7754	0.8300
37	0.7891	0.8460
38	0.8116	0.8730
39	0.9138	0.9790
40	0.9240	0.9910
41	0.9407	1.0080
42	0.9420	1.0090
43	0.9514	1.0150
44	0.9590	1.0290
45	0.9827	1.0520
46	0.7810	2.2600

Appendix A (continued)

47	0.7640	2.1600
48	0.7420	1.5800
49	0.7270	1.8600
50	0.7240	1.8000
51	0.6900	1.5000
52	0.6630	1.3400
53	0.5734	0.6153
54	0.8460	0.9230
55	0.8845	0.9690
56	0.9687	1.0580
57	0.8290	2.6000
58	0.8380	2.6700
59	0.8490	2.7800
60	0.8540	2.8600
61	0.8680	2.9600
62	0.8970	3.1900
63	0.9100	3.2900
64	0.9240	3.4000
65	0.9470	3.6100
66	0.9750	3.8300

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX BTU/FT**2HR	HEAT FLUX KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.253982E 00	0.569352E 03	0.154453E 04	0.170738E 02	0.214447E 00	0.110574E 03
2	0.291150E 00	0.750605E 03	0.203609E 04	0.182629E 02	0.215125E 00	0.111763E 03
3	0.315044E 00	0.877994E 03	0.238113E 04	0.178052E 02	0.214865E 00	0.113305E 03
4	0.363619E 00	0.115244E 04	0.312611E 04	0.185641E 02	0.215295E 00	0.112064E 03
5	0.409292E 00	0.148325E 04	0.402346E 04	0.182384E 02	0.215111E 00	0.111738E 03
6	0.472124E 00	0.197526E 04	0.535803E 04	0.185549E 02	0.215291E 00	0.112055E 03
7	0.537168E 00	0.256068E 04	0.694609E 04	0.190986E 02	0.215600E 00	0.112599E 03
8	0.555335E 00	0.314247E 04	0.852427E 04	0.190189E 02	0.215555E 00	0.112519E 03
9	0.636726E 00	0.360071E 04	0.976729E 04	0.194027E 02	0.215774E 00	0.112903E 03
10	0.719912E 00	0.461368E 04	0.125151E 05	0.202810E 02	0.216274E 00	0.113781E 03
11	0.754734E 00	0.514503E 04	0.139564E 05	0.207845E 02	0.216561E 00	0.114284E 03
12	0.854255E 00	0.652251E 04	0.176940E 05	0.216069E 02	0.217074E 00	0.115187E 03
13	0.542520E 00	0.755663E 04	0.215832E 05	0.229913E 02	0.217417E 00	0.115791E 03
14	0.105721E 01	0.595018E 04	0.269409E 05	0.239172E 02	0.218343E 00	0.117417E 03
15	0.109292E 01	0.107453E 05	0.291477E 05	0.242884E 02	0.218553E 00	0.117888E 03
16	0.113538E 01	0.116915E 05	0.317143E 05	0.247203E 02	0.218800E 00	0.118221E 03
17	0.124292E 01	0.139469E 05	0.378323E 05	0.256619E 02	0.219334E 00	0.119162E 03
18	0.152212E 01	0.210711E 05	0.571574E 05	0.285114E 02	0.220954E 00	0.120011E 03
19	0.161283E 01	0.237675E 05	0.644717E 05	0.303270E 02	0.221983E 00	0.123827E 03
20	0.170708E 01	0.267760E 05	0.726326E 05	0.325238E 02	0.223231E 00	0.126024E 03
21	0.182875E 01	0.308494E 05	0.836822E 05	0.340651E 02	0.224103E 00	0.127565E 03
22	0.159973E 01	0.356341E 05	0.966611E 05	0.363815E 02	0.225417E 00	0.129882E 03
23	0.207965E 01	0.402527E 05	0.109190E 06	0.376156E 02	0.226116E 00	0.131116E 03
24	0.217920E 01	0.443661E 05	0.120348E 06	0.391270E 02	0.226971E 00	0.132627E 03
25	0.221283E 01	0.459360E 05	0.124606E 06	0.407931E 02	0.227914E 00	0.134293E 03
26	0.232611E 01	0.510045E 05	0.138355E 06	0.427420E 02	0.229016E 00	0.136242E 03
27	0.235044E 01	0.515722E 05	0.139845E 06	0.388156E 02	0.226794E 00	0.132316E 03

Appendix A (continued)

Row	C1	C2	C3	C4	C5	C6
28	0.2429221E 01	0.5354999E 05	0.1463456E 06	0.3941696E 02	0.2271356E 00	0.1329176E 03
29	0.2537761E 01	0.6641286E 05	0.1638766E 06	0.4081446E 02	0.2279266E 00	0.1343146E 03
30	0.2643365E 01	0.6497456E 05	0.1762506E 06	0.3726146E 02	0.2255156E 00	0.1307616E 03
31	0.2715C46E 01	0.6840986E 05	0.1855686E 06	0.3646716E 02	0.2254666E 00	0.1299676E 03
32	0.2820356E 01	0.7413896E 05	0.2011096E 06	0.3818976E 02	0.2264406E 00	0.1316906E 03
33	0.2761046E 01	0.7585876E 05	0.2057746E 06	0.6535216E 02	0.2417516E 00	0.1588526E 03
34	0.3042046E 01	0.8658C86E 05	0.2348596E 06	0.3471906E 02	0.2273056E 00	0.1332196E 03
35	0.3292926E 01	0.1039216E 06	0.2818956E 06	0.4057656E 02	0.2277906E 00	0.1340766E 03
36	0.3435976E 01	0.1102816E 06	0.2991436E 06	0.4024736E 02	0.2276046E 00	0.1337476E 03
37	0.3491596E 01	0.1214447E 06	0.3103336E 06	0.4092146E 02	0.2279876E 00	0.1344216E 03
38	0.3591156E 01	0.1153C64E 06	0.3294366E 06	0.4233956E 02	0.2287886E 00	0.1358406E 03
39	0.4043366E 01	0.1569266E 06	0.4158536E 06	0.4061926E 02	0.2278166E 00	0.1341196E 03
40	0.4038506E 01	0.1624946E 06	0.4256776E 06	0.4108296E 02	0.2230786E 00	0.1345836E 03
41	0.4102396E 01	0.1661306E 06	0.4407806E 06	0.4069546E 02	0.2278596E 00	0.1341956E 03
42	0.4159146E 01	0.1691206E 06	0.4418176E 06	0.4053076E 02	0.2277656E 00	0.1340316E 03
43	0.4209736E 01	0.1771146E 06	0.4506456E 06	0.4050026E 02	0.2277486E 00	0.1340006E 03
44	0.4243356E 01	0.3144336E 06	0.4587556E 06	0.4127516E 02	0.2281876E 00	0.1347756E 03
45	0.4348236E 01	0.2939246E 06	0.4805306E 06	0.4028986E 02	0.2276286E 00	0.1337906E 03
46	0.3456756E 01	0.2612226E 06	0.8529306E 06	0.8783896E 03	0.6396726E 00	0.9718896E 03
47	0.3340536E 01	0.2401826E 06	0.7970276E 06	0.8426656E 03	0.6246436E 00	0.9361656E 03
48	0.3288196E 01	0.1830126E 06	0.7086026E 06	0.7544586E 03	0.5887636E 00	0.8529586E 03
49	0.3216916E 01	0.1567376E 06	0.6515196E 06	0.7034046E 03	0.5639026E 00	0.7969046E 03
50	0.3203546E 01	0.6046566E 05	0.6274366E 06	0.6672546E 03	0.5475696E 00	0.7607456E 03
51	0.3C53106E 01	0.1335636E 06	0.4964396E 06	0.5165116E 03	0.4769556E 00	0.6100116E 03
52	0.2653636E 01	0.1754396E 06	0.4251656E 06	0.4457176E 03	0.4424636E 00	0.5392176E 03
53	0.2537776E 01	0.3846336E 06	0.1640196E 06	0.4130866E 02	0.2282056E 00	0.1348096E 03
54	0.3743366E 01	0.3954C66E 06	0.3633876E 06	0.4848726E 02	0.2322606E 00	0.1419876E 03
55	0.3913726E 01	0.4215496E 06	0.3980236E 06	0.4984436E 02	0.2333026E 00	0.1433446E 03
56	0.4286286E 01	0.4364276E 06	0.4769806E 06	0.4855586E 02	0.2325246E 00	0.1424566E 03
57	0.3668146E 01	0.4592496E 06	0.1043366E 07	0.1013566E 04	0.7045096E 00	0.1107066E 04
58	0.3707956E 01	0.5118686E 06	0.1083436E 07	0.1042366E 04	0.7257146E 00	0.1135866E 04
59	0.3756646E 01	0.5457236E 06	0.1143496E 07	0.1094336E 04	0.7425526E 00	0.1187836E 04
60	0.3778766E 01	0.5623276E 06	0.1183856E 07	0.1139186E 04	0.7563826E 00	0.1232686E 04
61	0.3940716E 01	0.6122946E 06	0.1245766E 07	0.1176756E 04	0.7894146E 00	0.1270256E 04
62	0.3569C3E 01	0.6651496E 06	0.1386496E 07	0.1269386E 04	0.8027676E 00	0.1362896E 04
63	0.4026056E 01		0.1453206E 07	0.1308086E 04	0.8172926E 00	0.1401586E 04
64	0.4088506E 01		0.1525376E 07	0.1351096E 04	0.8472196E 00	0.1444596E 04
65	0.4190276E 01		0.1660916E 07	0.1442916E 04	0.8734656E 00	0.1536416E 04
66	0.4314166E 01		0.1815136E 07	0.1527536E 04		0.1621036E 04

Appendix A (continued)

RUN NO. 270776 5

WATER TEMPERATURE = 86.5C

SYSTEM PRESSURE = 500. TORR

TEST WIRE LENGTH = 0.800 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2450 OHM

DATA POINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0484	0.0550
2	0.0556	0.0632
3	0.0625	0.0770
4	0.0926	0.1053
5	0.0990	0.1128
6	0.1198	0.1367
7	0.1282	0.1582
8	0.1558	0.1782
9	0.1733	0.1903
10	0.1831	0.2058
11	0.2054	0.2360
12	0.2225	0.2560
13	0.2498	0.2880
14	0.2712	0.3140
15	0.2956	0.3435
16	0.3265	0.3804
17	0.3981	0.4570
18	0.4145	0.4670
19	0.4443	0.5210
20	0.4788	0.5650
21	0.5210	0.6100
22	0.5683	0.6654
23	0.5986	0.7025
24	0.6345	0.7450
25	0.6817	0.8005
26	0.6954	0.8220
27	0.7172	0.8410
28	0.7450	0.8750
29	0.7519	0.8850
30	0.7250	0.9100
31	0.7541	0.9370
32	0.8091	0.9570
33	0.8214	0.5715
34	3.8457	1.0030
35	0.8682	1.0310
36	0.8860	1.0540
37	0.9085	1.0810
38	0.9271	1.1050
39	0.9491	1.1330
40	0.9668	1.1570
41	0.7150	2.0000
42	0.6810	1.7800
43	0.7650	2.4800
44	0.7450	2.2800
45	0.7290	2.1600
46	0.7140	2.0600

Appendix A (continued)

47	0.7040	1.5500
48	0.6710	1.7500
49	0.6570	1.6300
50	0.7750	2.5000
51	0.7670	2.6500
52	0.8040	2.7800
53	0.8080	2.8300
54	0.8170	2.5900
55	0.9290	2.9800
56	0.8470	3.1500
57	0.8650	3.2800
58	0.8750	3.3400
59	0.8800	3.4300
60	0.8530	3.5700
61	0.9070	3.6800
62	0.9190	3.7200
63	0.9280	3.7800
64	0.9370	3.6500
65	0.9480	3.9500
66	0.9570	4.0700

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX BTU/FT**2HR	KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.214159E 00	0.402201E 03	0.109101E 04	0.196263E 02	0.224265E 00	0.108126E 03
2	0.246019E 00	0.530940E 03	0.144023E 04	0.197455E 02	0.224338E 00	0.108249E 03
3	0.276546E 00	0.669349E 03	0.181569E 04	0.189451E 02	0.223821E 00	0.107385E 03
4	0.437355E 00	0.147339E 04	0.399672E 04	0.192217E 02	0.224442E 00	0.104422E 03
5	0.433053E 00	0.168790E 04	0.457840E 04	0.207673E 02	0.224449E 00	0.109267E 03
6	0.530288E 00	0.247583E 04	0.671593E 04	0.213975E 02	0.225328E 00	0.109898E 03
7	0.611504E 00	0.330681E 04	0.897005E 04	0.227113E 02	0.226153E 00	0.111271E 03
8	0.643816E 00	0.419873E 04	0.113895E 05	0.224149E 02	0.225939E 00	0.119915E 03
9	0.766814E 00	0.516746E 04	0.140786E 05	0.225993E 02	0.226049E 00	0.111099E 03
10	0.910177E 00	0.581097E 04	0.157628E 05	0.231893E 02	0.226402E 00	0.111689E 03
11	0.609853E 00	0.623566E 04	0.164987E 05	0.243782E 02	0.227115E 00	0.112878E 03
12	0.984511E 00	0.842149E 04	0.233066E 05	0.244739E 02	0.227473E 00	0.113474E 03
13	0.110531E 01	0.108924E 05	0.295468E 05	0.256642E 02	0.228007E 00	0.114364E 03
14	0.120000E 01	0.129009E 05	0.349950E 05	0.277119E 02	0.229113E 00	0.116212E 03
15	0.130766E 01	0.153907E 05	0.417487E 05	0.293068E 02	0.230068E 00	0.117807E 03
16	0.144469E 01	0.188326E 05	0.510853E 05	0.304565E 02	0.230755E 00	0.118957E 03
17	0.171726E 01	0.269335E 05	0.730598E 05	0.351616E 02	0.233568E 00	0.123662E 03
18	0.183407E 01	0.306444E 05	0.831261E 05	0.341697E 02	0.232976E 00	0.122670E 03
19	0.196563E 01	0.351313E 05	0.952972E 05	0.333093E 02	0.232461E 00	0.121809E 03
20	0.211855E 01	0.410926E 05	0.114468E 06	0.361074E 02	0.234134E 00	0.124607E 03
21	0.230531E 01	0.482230E 05	0.130810E 06	0.326260E 02	0.232053E 00	0.121126E 03
22	0.251681E 01	0.574219E 05	0.155763E 06	0.324493E 02	0.231828E 00	0.120749E 03
23	0.264867E 01	0.638281E 05	0.173140E 06	0.336645E 02	0.232674E 00	0.122164E 03
24	0.280752E 01	0.717541E 05	0.194640E 06	0.338848E 02	0.232805E 00	0.122385E 03
25	0.301637E 01	0.828361E 05	0.224701E 06	0.339278E 02	0.232831E 00	0.122428E 03
26	0.304695E 01	0.872800E 05	0.236756E 06	0.343166E 02	0.233063E 00	0.122817E 03
27	0.317345E 01	0.915410E 05	0.248314E 06	0.333031E 02	0.232458E 00	0.121803E 03

Appendix A (continued)

#						
28	0.122514E 03	0.232883E 00	0.340135E 02	0.264428E 06	0.989558E 05	0.329646E 01
29	0.123469E 03	0.233452E 00	0.349688E 02	0.274292E 06	0.101044E 06	0.332699E 01
30	0.153171E 03	0.251115E 00	0.646708E 02	0.274111E 06	0.101051E 06	0.320795E 01
31	0.124577E 03	0.234116E 00	0.360767E 02	0.306593E 06	0.113024E 06	0.351372E 01
32	0.125654E 03	0.234758E 00	0.371538E 02	0.319155E 06	0.117657E 06	0.353009E 01
33	0.125632E 03	0.234745E 00	0.371322E 02	0.328914E 06	0.121254E 06	0.363451E 01
34	0.126869E 03	0.235482E 00	0.363678E 02	0.349758E 06	0.126939E 06	0.374204E 01
35	0.127440E 03	0.235824E 00	0.389398E 02	0.361535E 06	0.136088E 06	0.384159E 01
36	0.128237E 03	0.236300E 00	0.397376E 02	0.385219E 06	0.142011E 06	0.392035E 01
37	0.128335E 03	0.236358E 00	0.398355E 02	0.405132E 06	0.149352E 06	0.401091E 01
38	0.129096E 03	0.236813E 00	0.405963E 02	0.427704E 06	0.158330E 06	0.410221E 01
39	0.129809E 03	0.237237E 00	0.413083E 02	0.437955E 06	0.163605E 06	0.419956E 01
40	0.130092E 03	0.237908E 00	0.424324E 02	0.461806E 06	0.170245E 06	0.427733E 01
41	0.809716E 03	0.599614E 00	0.721216E 03	0.636593E 06	0.234680E 06	0.316372E 01
42	0.722965E 03	0.558166E 00	0.634465E 03	0.537569E 06	0.196175E 06	0.301327E 01
43	0.103358E 04	0.703100E 00	0.545079E 03	0.850864E 06	0.213671E 06	0.338496E 01
44	0.939703E 03	0.659097E 00	0.851203E 03	0.759695E 06	0.280062E 06	0.326646E 01
45	0.890775E 03	0.637076E 00	0.802275E 03	0.703111E 06	0.255202E 06	0.322555E 01
46	0.852395E 03	0.614491E 00	0.763895E 03	0.655856E 06	0.241782E 06	0.315922E 01
47	0.796607E 03	0.593441E 00	0.708107E 03	0.610301E 06	0.225172E 06	0.311504E 01
48	0.720290E 03	0.556865E 00	0.631790E 03	0.520682E 06	0.191949E 06	0.295903E 01
49	0.661893E 03	0.528146E 03	0.573393E 03	0.473436E 06	0.174532E 06	0.280708E 01
50	0.102513E 04	0.696479E 00	0.536355E 03	0.868737E 06	0.320263E 06	0.342020E 01
51	0.110076E 04	0.728437E 00	0.101226E 04	0.936956E 06	0.345409E 06	0.348230E 01
52	0.115054E 04	0.749889E 00	0.106204E 04	0.100533E 07	0.376614E 06	0.355752E 01
53	0.117558E 04	0.759006E 00	0.108708E 04	0.102907E 07	0.376367E 06	0.367522E 01
54	0.126597E 04	0.794545E 00	0.117747E 04	0.110139E 07	0.406027E 06	0.361504E 01
55	0.122811E 04	0.779847E 00	0.113961E 04	0.113009E 07	0.410309E 06	0.365314E 01
56	0.130108E 04	0.807942E 00	0.121258E 04	0.120372E 07	0.443750E 06	0.374779E 01
57	0.134511E 04	0.824417E 00	0.125661E 04	0.129102E 07	0.472494E 06	0.382743E 01
58	0.136058E 04	0.830120E 00	0.127208E 04	0.131988E 07	0.436575E 06	0.387169E 01
59	0.141083E 04	0.848333E 00	0.132233E 04	0.136430E 07	0.502943E 06	0.389381E 01
60	0.147508E 04	0.870940E 00	0.138658E 04	0.142234E 07	0.531720E 06	0.395133E 01
61	0.151442E 04	0.864403E 00	0.142592E 04	0.151092E 07	0.557002E 06	0.401327E 01
62	0.151106E 04	0.883263E 00	0.142580E 04	0.154580E 07	0.565859E 06	0.406195E 01
63	0.152510E 04	0.880006E 00	0.143660E 04	0.158814E 07	0.585469E 06	0.410620E 01
64	0.154915E 04	0.896048E 00	0.146065E 04	0.163376E 07	0.602285E 06	0.414602E 01
65	0.158894E 04	0.909113E 00	0.150044E 04	0.169673E 07	0.625448E 06	0.419469E 01
66	0.165001E 04	0.928596E 00	0.156151E 04	0.176615E 07	0.651091E 06	0.423451E 01

Appendix A (continued)

RUN NO. 27C776 6

WATER TEMPERATURE = 88.5C

SYSTEM PRESSURE = 5CC. TORR

TEST WIRE LENGTH = 0.800 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2210 OHM

DATA PCINT	V. ACROSS SHUNT RESISTOR	V. ACRCSS TEST WIRE
1	0.0735	0.C754
2	0.CE83	0.C9C6
3	0.1103	C.1340
4	0.1237	0.1293
5	0.1438	0.1481
6	0.1585	0.1637
7	0.1925	0.1990
8	0.2204	0.2282
9	0.2681	0.2764
10	0.3C40	0.3280
11	0.3634	C.3825
12	0.4746	0.5116
13	0.5179	0.5634
14	0.6254	0.6680
15	0.6587	0.7498
16	0.7565	C.8130
17	0.7781	0.8360
18	0.8C82	0.8690
19	0.8235	0.887C
20	0.8325	0.8960
21	0.8487	C.9160
22	0.8769	0.9360
23	0.8942	0.9650
24	0.9294	1.C120
25	0.5829	1.C58C
26	1.C197	1.0960
27	0.8130	2.575C
28	0.6975	1.7300
29	0.6800	1.5600
30	0.67CC	1.457C
31	0.6610	1.3800
32	0.6578	1.3600
33	0.6998	0.7800
34	0.7565	0.8890

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX		WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
		BTL/FT**2HR	KCAL/M**2HR			

Appendix A (continued)

0.106499E 03	0.223289E 00	0.179989E 02	0.250507E 04	0.523443E 03	0.325221E 00
0.106573E 03	0.223333E 00	0.180727E 02	0.361620E 04	0.133311E 04	0.390708E 00
0.178428E 03	0.266007E 00	0.599276E 02	0.672079E 04	0.247762E 04	0.480535E 00
0.113815E 03	0.227678E 00	0.253146E 02	0.723457E 04	0.266717E 04	0.547345E 00
0.139025E 03	0.224204E 00	0.195249E 02	0.962806E 04	0.354939E 04	0.635263E 00
0.109120E 03	0.224861E 00	0.206198E 02	0.117314E 05	0.632478E 04	0.701327E 00
0.109480E 03	0.225077E 00	0.205796E 02	0.173209E 05	0.651770E 04	0.651770E 00
0.113091E 03	0.225444E 00	0.215913E 02	0.227426E 05	0.638407E 04	0.575221E 00
0.112639E 03	0.226972E 00	0.243386E 02	0.338300E 05	0.124899E 05	0.118628E 01
0.121242E 03	0.232122E 00	0.327425E 02	0.457293E 05	0.168581E 05	0.136283E 01
0.117604E 03	0.229947E 00	0.291043E 02	0.630630E 05	0.234242E 05	0.160796E 01
0.126168E 03	0.235065E 00	0.376675E 02	0.109957E 06	0.405355E 05	0.210000E 01
0.129918E 03	0.237302E 00	0.414182E 02	0.132181E 06	0.487286E 05	0.229159E 01
0.124443E 03	0.232841E 00	0.339430E 02	0.189126E 06	0.657213E 05	0.309159E 01
0.124341E 03	0.239975E 00	0.358411E 02	0.237207E 06	0.874465E 05	0.334735E 01
0.124929E 03	0.234325E 00	0.364285E 02	0.278493E 06	0.102666E 06	0.344292E 01
0.124825E 03	0.234263E 00	0.363246E 02	0.295454E 06	0.108584E 06	0.357611E 01
0.124665E 03	0.234168E 00	0.361654E 02	0.317640E 06	0.117100E 06	0.364391E 01
0.122171E 03	0.234873E 00	0.373464E 02	0.330779E 06	0.121942E 06	0.368363E 01
0.126629E 03	0.235340E 00	0.370314E 02	0.337777E 06	0.124522E 06	0.375531E 01
0.125531E 03	0.235368E 00	0.381754E 02	0.352073E 06	0.129792E 06	0.388009E 01
0.126752E 03	0.232678E 00	0.336706E 02	0.371563E 06	0.136677E 06	0.395664E 01
0.125580E 03	0.235340E 00	0.381294E 02	0.390789E 06	0.144064E 06	0.415221E 01
0.125381E 03	0.234714E 00	0.382518E 02	0.430510E 06	0.156767E 06	0.434912E 01
0.105035E 04	0.234595E 00	0.370803E 02	0.470907E 06	0.174600E 06	0.450752E 01
0.710285E 03	0.707252E 00	0.368813E 02	0.505579E 06	0.186382E 06	0.359735E 01
0.625477E 03	0.551991E 00	0.561850E 03	0.970807E 06	0.357388E 06	0.305029E 01
0.572417E 03	0.509917E 00	0.621785E 03	0.557696E 06	0.205595E 06	0.308085E 01
0.534467E 03	0.482912E 00	0.536677E 03	0.489660E 06	0.180513E 06	0.256460E 01
0.525696E 03	0.463277E 00	0.489917E 02	0.450189E 06	0.165562E 06	0.292478E 01
0.140072E 03	0.458701E 00	0.459967E 02	0.420359E 06	0.154565E 06	0.251062E 01
0.139061E 03	0.243347E 00	0.515723E 02	0.412187E 06	0.151953E 06	0.309646E 01
	0.242746E 00	0.505611E 02	0.247486E 06	0.912358E 05	0.353761E 01
			0.322230E 06	0.118750E 06	

Appendix A (continued)

RUN NO. 310776 7

WATER TEMPERATURE = 88.5C

SYSTEM PRESSURE = 500. TORR

TEST WIRE LENGTH = 0.720 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2120 OHM

DATA POINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0745	0.0730
2	0.1048	0.1030
3	0.1631	0.1639
4	0.1589	0.1970
5	0.2370	0.2354
6	0.2940	0.2940
7	0.3637	0.3681
8	0.4370	0.4446
9	0.4780	0.4654
10	0.5693	0.5805
11	0.6926	0.7073
12	0.7478	0.7645
13	0.8135	0.8315
14	0.8941	0.9135
15	0.9325	0.9631
16	0.5610	0.9900
17	0.8270	2.5340
18	0.7575	2.0440
19	0.7000	1.6540
20	0.6560	1.3500

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX BTU/FT**2HR	KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.329646E 00	0.947336E 03	0.256974E 04	0.174295E 02	0.200651E 00	0.105929E 03
2	0.463717E 03	0.188087E 04	0.510205E 04	0.186667E 02	0.201320E 00	0.107167E 03
3	0.7216631E C0	0.457444E 04	0.124086E 05	0.202076E 02	0.202153E 00	0.108708E 03
4	0.683389E 00	0.683292E 04	0.185350E 05	0.218556E 02	0.203043E 00	0.110356E 03
5	0.104867E 01	0.973163E 04	0.263990E 05	0.230295E 02	0.203676E 00	0.111529E 03
6	0.133088E 01	0.150878E 05	0.409270E 05	0.258581E 02	0.205202E 00	0.114358E 03
7	0.160929E 01	0.239773E 05	0.634674E 05	0.309317E 02	0.207936E 00	0.119432E 03
8	0.193363E 01	0.339729E 05	0.921549E 05	0.315561E 02	0.209132E 00	0.121656E 03
9	0.211504E 01	0.405629E 05	0.110031E 06	0.323534E 02	0.208700E 00	0.120853E 03
10	0.251903E 01	0.577942E 05	0.156786E 06	0.341145E 02	0.209648E 00	0.122614E 03
11	0.206460E 01	0.656858E 05	0.234422E 06	0.347667E 02	0.209998E 00	0.123267E 03
12	0.330985E 01	0.100012E 06	0.271293E 06	0.352321E 02	0.210249E 00	0.123732E 03
13	0.360000E 01	0.118345E 06	0.321022E 06	0.350912E 02	0.210174E 00	0.123591E 03

Appendix A (continued)

14	0.123466E 03	0.210105E 00	0.349656E 02	0.387564E 06	0.142876E 06	0.395619E 01
15	0.128140E 03	0.212618E 00	0.396399E 02	0.426611E 06	0.157270E 06	0.412611E 01
16	0.127030E 03	0.212022E 00	0.385300E 02	0.451816E 06	0.166562E 06	0.425221E 01
17	0.114421E 04	0.671685E 00	0.105571E 04	0.106301E 07	0.390775E 06	0.365929E 01
18	0.929354E 03	0.589029E 00	0.840854E 03	0.779855E 06	0.287508E 06	0.335177E 01
19	0.747916E 03	0.513207E 00	0.659416E 03	0.580261E 06	0.213913E 06	0.309735E 01
20	0.593409E 03	0.444293E 00	0.504909E 03	0.441176E 06	0.162639E 06	0.292065E 01

Appendix A (continued)

RUN NC. 1C676 8

WATER TEMPERATURE = 82.7C

SYSTEM PRESSURE = 400. TCRR

TEST WIRE LENGTH = 0.800 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2030 OHM

DATA PCINT   V. ACROSS SHUNT RESISTOR   V. ACROSS TEST WIRE

DATA PCINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0675	0.0632
2	0.0522	0.0870
3	0.1225	0.1149
4	0.1783	0.1676
5	0.2323	0.2195
6	0.2681	0.2845
7	0.3924	0.3756
8	0.4484	0.4375
9	0.5703	0.5672
10	0.6170	0.6140
11	0.7070	0.7000
12	0.8110	0.8130
13	0.8780	0.8930
14	0.9170	0.9290
15	0.9270	0.9360
16	0.9480	0.9500
17	0.8330	2.5910
18	0.7603	2.0700
19	0.6770	1.5250

RESULTS CF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX BTL/FT**2HR	HEAT FLUX KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.298673E 00	0.758832E 03	0.205941E 04	0.142481E 02	0.217544E 00	0.964481E 02
2	0.412399E 00	0.144243E 04	0.391274E 04	0.131893E 02	0.216906E 00	0.958893E 02
3	0.542035E 00	0.250557E 04	0.679119E 04	0.148715E 02	0.217919E 00	0.975715E 02
4	0.767611E 00	0.530582E 04	0.143926E 05	0.162289E 02	0.218736E 00	0.989289E C2
5	0.102655E 01	0.905574E 04	0.245646E 05	0.179373E 02	0.219764E 00	0.100637E 03
6	0.131903E 01	0.150780E 05	0.409006E 05	0.210404E 02	0.221630E 00	0.103740E 03
7	0.173629E 01	0.264727E 05	0.718368E 05	0.259303E 02	0.224568E 00	0.108631E 03
8	0.193407E 01	0.346569E 05	0.945529E 05	0.290629E 02	0.226447E 00	0.111763E 03
9	0.253455E 01	0.574471E 05	0.155831E 06	0.361829E 02	0.230712E 00	0.118883E 03
10	0.273009E 01	0.672764E 05	0.182499E 06	0.364007E 02	0.230842E 00	0.119101E 03
11	0.312832E 01	0.879016F 05	0.238442E 06	0.349644E 02	0.229703E 00	0.117196E 03
12	0.359850E 01	0.117072E 06	0.317569E 06	0.391705E 02	0.232498E 00	0.121870E 03
13	0.368496E 01	0.139164E 06	0.377456E 06	0.447030S 02	0.235802E 00	0.127403E 03
14	0.405752E 01	0.151220E 06	0.410200E 06	0.431892E 02	0.234858E 00	0.125889E 03

Appendix A (continued)

15	0.410177E 01	0.154034E 06	0.417833E 06	0.419104E 02	0.234135E 00	0.124610E 03
16	0.419469E 01	0.159910E 06	0.433773E 06	0.360356E 02	0.232417E 00	0.121736E 03
17	0.368584E 01	0.376589E 06	0.102153E 07	0.571533E 03	0.708901E 00	0.105423E 04
18	0.336283E 01	0.274824E 06	0.745483E 06	0.774035E 03	0.621493E 00	0.856736E 03
19	0.299557E 01	0.180716E 06	0.490213E 06	0.552930E 03	0.515025E 00	0.635630E 03

Appendix A (continued)

RUN NO. 1C876 9

WATER TEMPERATURE = 76.0C

SYSTEM PRESSURE = 300. TORR

TEST WIRE LENGTH = 0.780 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2020 OHM

DATA POINT   V. ACROSS SHUNT RESISTOR   V. ACROSS TEST WIRE

DATA POINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0766	0.0720
2	0.1239	0.1167
3	0.1998	0.1894
4	0.2562	0.2436
5	0.3438	0.3326
6	0.4125	0.4027
7	0.5100	0.5063
8	0.6030	0.6067
9	0.6574	0.6929
10	0.7790	0.7830
11	0.8350	0.8410
12	0.8950	0.9053
13	0.9180	0.9150
14	0.9300	0.9320
15	0.9500	0.9440
16	0.9830	0.9780
17	0.8490	3.0300
18	0.7210	1.5800
19	0.6580	1.5790
20	0.8250	2.7870
21	0.8750	3.1420
22	0.8990	3.2730

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX		WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
		BTU/FT**2HR	KCAL/M**2HR			
1	0.339938E 00	0.568399E 03	0.262688E 04	0.176871E 02	0.210189E 00	0.936871E 02
2	0.547788E 00	0.253687E 04	0.688151E 04	0.187251E 02	0.210799E 00	0.947251E 02
3	0.884071E 00	0.664519E 04	0.180257E 05	0.207630E 02	0.211997E 00	0.967630E 02
4	0.113363E 01	0.109598E 05	0.297295E 05	0.218709E 02	0.212646E 00	0.978709E 02
5	0.152124E 01	0.200841E 05	0.544801E 05	0.282670E 02	0.216398E 00	0.104267E 03
6	0.182522E 01	0.291750E 05	0.791509E 05	0.316712E 02	0.218391E 00	0.107671E 03
7	0.225664E 01	0.453646E 05	0.123056E 06	0.380481E 02	0.221121E 00	0.114048E 03
8	0.269227E 01	0.648055E 05	0.175802E 06	0.400277E 02	0.223277E 00	0.116028E 03
9	0.305584E 01	0.848976E 05	0.230293E 06	0.383581E 02	0.222302E 00	0.114358E 03
10	0.344650E 01	0.107115E 06	0.290722E 06	0.428431E 02	0.224921E 00	0.118843E 03
11	0.369469E 01	0.123351E 06	0.334711E 06	0.436400E 02	0.225384E 00	0.119640E 03

Appendix A (continued)

12	0.119441E 03	0.225269E 00	0.434408E 02	0.387787E 06	0.142958E 06	0.397788E 01
13	0.117276E 03	0.224007E 00	0.412742E 02	0.402086E 06	0.148229E 06	0.406155F 01
14	0.117687E 03	0.224247E 00	0.416872E 02	0.413108E 06	0.152292E 06	0.411504E 01
15	0.116448E 03	0.223523E 00	0.404480E 02	0.426676E 06	0.158400E 06	0.420354E 01
16	0.114886E 03	0.222611E 00	0.388861E 02	0.458170E 06	0.168904E 06	0.434956E 01
17	0.134657E 04	0.804333E 00	0.127057E 04	0.123488E 07	0.455238E 06	0.375664E 01
18	0.884575E 03	0.618398E 00	0.808575E 03	0.664719E 06	0.252421E 06	0.319327E 01
19	0.714282E 03	0.540092E 00	0.638282E 03	0.498072E 06	0.183614E 06	0.291150E 01
20	0.123042E 04	0.761229E 00	0.115442E 04	0.110356E 07	0.406828E 06	0.365044E 01
21	0.136038E 04	0.809294E 00	0.128438E 04	0.131976E 07	0.486531E 06	0.387163E 01
22	0.139211E 04	0.820561E 00	0.131611E 04	0.141255E 07	0.520736E 06	0.397788E 01

Appendix A (continued)

RUN NC. 30177 1

WATER TEMPERATURE = 63.0C

SYSTEM PRESSURE = 200. TORR

TEST WIRE LENGTH = 0.860 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2170 OHM

DATA PCINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0500	0.0500
2	0.0900	0.0860
3	0.1550	0.1550
4	0.2900	0.2940
5	0.3580	0.4080
6	0.6640	0.7100
7	0.7670	0.6600
8	0.8550	0.6600
9	0.8860	0.5350
10	0.8540	1.0000
11	0.7650	1.0030
12	0.7110	2.6000
13	0.7900	2.0100
14	0.8280	2.5800
15	0.8520	3.2700
		3.5800

RESULTS OF CALCULATION

NC.	CURRENT(AMP)	HEAT FLUX BTU/FT**2HR	KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.2212390E 03	0.393045E 03	0.106617E 04	0.137803E 02	0.2237590E 00	0.767803E 02
2	0.3605315E C0	0.116278E 04	0.315417E 04	0.137803E 02	0.2207590E 00	0.767803E 02
3	0.685841E 00	0.377716E 04	0.102459E 05	0.137803E 02	0.2207590E 00	0.767803E 02
4	0.128319E 01	0.134387E 05	0.363725E 05	0.185690E 02	0.223877E 00	0.815690E 02
5	0.176104E 01	0.255445E 05	0.692921E 05	0.225081E 02	0.225438E 00	0.855081E 02
6	0.253905E C1	0.742328E 05	0.201364E 06	0.378995E 02	0.236416E 00	0.100899E 03
7	0.339381E 01	0.103970E 06	0.282030E 06	0.561129E 02	0.248162E 00	0.119113E 03
8	0.378319E 01	0.125939E 06	0.341623E 06	0.463956E 02	0.241906E 00	0.109400E 03
9	0.392035E C1	0.139672E 06	0.378874E 06	0.587204E 02	0.249838E 00	0.121720E C3
10	0.395575E C1	0.141338E 06	0.383944E C6	0.563489E 02	0.248314E 00	0.119349E 03
11	0.338466E 01	0.317946E 06	0.862459E 06	0.992978E 02	0.762864E 00	0.105598E 04
12	0.314602E 01	0.228129E 06	0.618322E C6	0.725176E 03	0.633662E 00	0.788176E 03
13	0.349557E 01	0.376579E 06	0.102151E 07	0.118642E 04	0.847266E 00	0.124942E 04
14	0.363372E C1	0.433224E 06	0.117516E 07	0.128475E 04	0.887295E 00	0.134775E 04
15	0.376991E 01	0.488215E 06	0.132433E 07	0.143406E 04	0.944384E 00	0.149706E 04

Appendix A (continued)

RUN NO. 30177 2

WATER TEMPERATURE = 63.0C

SYSTEM PRESSURE = 200. TORR

TEST WIRE LENGTH = 0.860 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2170 OHM

DATA POINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.0450	0.0450
2	0.0870	0.0870
3	0.1550	0.1550
4	0.2740	0.2770
5	0.3920	0.4000
6	0.6700	0.7100
7	0.7680	0.8340
8	0.8530	0.9240
9	0.9450	1.0250
10	1.0150	1.1100

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX		WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
		BTU/FT**2HR	KCAL/M**2HR			
1	0.199115E 00	0.318366E 03	0.863600E 03	0.137803E 02	0.220759E 00	0.767803E 02
2	0.384956E 00	0.118598E 04	0.322955E 04	0.137803E 02	0.220759E 00	0.767803E 02
3	0.695841E 00	0.377716E 04	0.102459E 05	0.137803E 02	0.220759E 00	0.767803E 02
4	0.121239E 01	0.115355E 05	0.323765E 05	0.175744E 02	0.223234E 00	0.805794E 02
5	0.173451E 01	0.246635E 05	0.669021E 05	0.208660E 02	0.225372E 00	0.838660E 02
6	0.266460E 01	0.748886E 05	0.203143E 06	0.345561E 02	0.234252E 00	0.975561E 02
7	0.339823E 01	0.100889E 06	0.273672E 06	0.437266E 02	0.240181E 00	0.106727E 03
8	0.377434E 01	0.124141E 06	0.336744E 06	0.427788E 02	0.239571E 00	0.105779E 03

Appendix A (continued)

RUN NO. 270277 1

WATER TEMPERATURE = 99.0C

SYSTEM PRESSURE = 760. TORR

TEST WIRE LENGTH = 0.800 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2340 OHM

DATA PCINT	V. ACROSS SHUNT RESISTOR	V. ACRCSS TEST WIRE
1	0.0440	0.0470
2	0.0540	0.1010
3	0.1860	0.2000
4	0.2970	0.3200
5	0.3540	0.4270
6	0.4880	0.5340
7	0.5850	0.6400
8	0.6850	0.7600
9	0.7840	0.6660
10	0.8270	0.9250
11	0.9020	1.0080
12	0.9430	1.0610
13	0.9580	1.0900
14	0.8200	2.7000
15	0.8570	2.8800

RESULTS CF CALCULATICN

NO.	CURRENT(AMP)	HEAT FLUX BTL/FT**2HR	KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.194690E 00	0.335247E 03	0.909390E 03	0.123297E 02	0.226187E 00	0.111330E 03
2	0.415929E 00	0.153969E 04	0.417657E 04	0.146980E 02	0.227607E 00	0.113698E 03
3	0.823009E 00	0.603322E 04	0.163657E 05	0.150019E 02	0.227788E 00	0.114002E 03
4	0.131416E 01	0.154160E 05	0.418174E 05	0.158216E 02	0.228279E 00	0.114822E 03
5	0.174336E 01	0.272957E 05	0.740531E 05	0.182026E 02	0.229707E 00	0.117203E 03
6	0.215929E 01	0.423127E 05	0.114777E 06	0.221722E 02	0.232081E 00	0.121172E 03
7	0.258850E 01	0.607909E 05	0.164901E 06	0.220801E 02	0.232025E 00	0.121080E 03
8	0.303057E 01	0.846066E 05	0.229504E 06	0.275351E 02	0.235522E 00	0.126935E 03
9	0.346903E 01	0.110309E 06	0.299223E 06	0.260786E 02	0.234415E 00	0.125079E 03
10	0.365929E 01	0.124387E 06	0.337411E 06	0.213490E 02	0.237559E 00	0.130349E 03
11	0.399115E 01	0.147832E 06	0.401009E 06	0.207764E 02	0.237336E 00	0.129976E 03
12	0.417257E 01	0.162749E 06	0.441472E 06	0.338620E 02	0.239057E 00	0.132862E 03
13	0.423894E 01	0.169977E 06	0.461078E 06	0.386687E 02	0.241917E 00	0.137669E 03
14	0.362832E 01	0.375233E 06	0.101786E 07	0.100293E 04	0.728924E 00	0.101193E 04
15	0.379204E 01	0.418486E 06	0.113518E 07	0.104018E 04	0.744264E 00	0.113918E 04

Appendix A (continued)

RUN NO. 91276 1

WATER TEMPERATURE = 98.0C

SYSTEM PRESSURE = 760. TORR

TEST WIRE LENGTH = C.920 INCH

SYSTEM RESISTANCE AT SYSTEM TEMPERATURE = .2590 OHM

DATA POINT	V. ACROSS SHUNT RESISTOR	V. ACROSS TEST WIRE
1	0.3017	0.3466
2	0.3990	0.4640
3	0.4590	0.5840
4	0.5910	C.7000
5	0.6710	0.8010
6	0.8090	0.5770
7	0.9080	1.1130
8	0.5760	1.2080
9	1.0130	1.2570
10	1.0400	1.2990
11	1.0650	1.3350
12	1.075C	1.3660
13	1.0810	1.3750
14	1.1090	1.4100
15	0.9080	3.5000
16	0.8220	2.8000
17	0.8050	2.0800
18	0.9230	3.7100
19	0.9370	3.6400
20	0.9500	3.9800

RESULTS OF CALCULATION

NO.	CURRENT(AMP)	HEAT FLUX BTU/FT**2HR	KCAL/M**2HR	WALL SUPERHEAT(C)	RESISTANCE OF WIRE (OHM)	WIRE TEMP.(C)
1	0.133496E 01	0.152421E C5	0.413457E C5	0.513467E 00	0.251536E 00	0.989135E 02
2	0.176549E 01	0.269561E 05	0.732295E 05	0.551564E 01	0.254715E 00	0.103516E 03
3	0.220766E 01	0.425022E 05	0.115291E 06	0.794492E 01	0.256399E 00	0.105945E 03
4	0.261504E 01	0.603555E 05	0.163731E C6	0.125584E 02	0.255584E 00	0.110558E 03
5	0.296903E 01	0.784370E 05	0.212768E 06	0.156089E 02	0.261687E 00	0.113604E 03
6	0.357965E 01	0.115389E 06	0.313004E C6	0.201778E 02	0.264834E 00	0.118178E 03
7	0.401770E 01	0.147604E 06	0.400390E 06	0.261299E 02	0.268926E 00	0.124130E 03
8	0.431850E 01	0.172250E 06	0.467245E 06	0.300603E 02	0.271623E 00	0.128060E 03
9	0.448230E 01	0.186046E 06	0.504668E 06	0.311025E 02	0.272338E 00	0.129102E 03
10	0.460177E 01	0.197425E 06	0.535536E 06	0.337967E 02	0.274184E 00	0.131797E 03
11	0.473009E 01	0.206553E C6	0.565721E C6	0.337264E 02	0.274137E 00	0.131726E 03
12	0.475664E 01	0.214703E 06	0.582404E 06	0.409453E 02	0.279079E 00	0.138945E 03
13	0.478318E 01	0.217330E 06	0.585530E 06	0.413688E 02	0.279367E 00	0.139369E 03

Appendix A (continued)

0.139183E 03	0.279242E 00	0.411829E 02	0.620187E 06	0.226632E 06	0.460703E 01
0.115444E 04	0.863047E 00	0.105644E 04	0.123495E 07	0.473696E 06	0.421773E 01
0.947072E 03	0.761731E 00	0.846072E 03	0.929448E 06	0.342641E 06	0.363717E 01
0.607332E 04	0.575852E 00	0.529332E 03	0.673977E 06	0.744425E 06	0.354165E 01
0.123586E 04	0.900309E 00	0.113786E 04	0.138508E 07	0.510609E 06	0.464407E 01
0.127585E 04	0.918091E 00	0.117785E 04	0.145561E 07	0.536610E 06	0.414602E 01
0.132325E 04	0.938723E 00	0.122525E 04	0.152990E 07	0.562993E 06	0.427354E 01

14
15
16
17
18
19
20

Appendix A (continued)

RUN NO.   101276001

TEMPERATURE 83 C

PRESSURE 420 TORRS

DEGREES OF SUPER HEAT (C)

HEAT FLUX (BTU/HOUR FT**2)

Appendix A (continued)

RUN NO. 15077600<del></del>4

TEMPERATURE 93.5 C

PRESSURE 600 TORRS

Appendix A (continued)

RUN NO.   2707760005

TEMPERATURE 89.5

PRESSURE 500 TORRS

DEGREES OF SUPER HEAT (C)

HEAT FLUX (BTU/HOUR FT**2)

Appendix A (continued)

RUN NO. 270776006

TEMPERATURE 89.5

PRESSURE 500 TORRS

Appendix A (continued)

RUN NO. 3i0776007

TEMPERATURE 89.5 C

PRESSURE 500 TORRS

HEAT FLUX (BTU/HOUR FT**2)

DEGREES OF SUPER HEAT (C)

Appendix A (continued)

RUN NO.   010876008

TEMPERATURE 82.7 C

PRESSURE 400 TORRS

Appendix A (continued)

RUN NO.09 010875U009

TEMPERATURE 76.0 C

PRESSURE 300 TORRS

Appendix A (continued)

RUN NO. 030177001

TEMPERATURE 63 C

PRESSURE 200 TORRS

RUN NO.   030177002

TEMPERATURE 63 C

PRESSURE 200 TORRS

HEAT FLUX (BTU/HOUR FT**2)

DEGREES OF SUPER HEAT (C)

Appendix A (continued)

RUN NO. 270277001

TEMPERATURE 99 C

PRESSURE 760 TORRS

HEAT FLUX (BTU/HOUR FT**2)

DEGREES OF SUPER HEAT (C)

Appendix B Computer Program for Processing Transient Experimental Data and Results

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FORTRAN IV G LEVEL 21        MAIN        DATE = 77202        19/01/17        PAGE 0001

C       THIS PROGRAM IS FOR PROCESSING THE PRESSURE TRANSIENT DATA
C
C           WHERE   LENTH    THE LENGTH OF THE TEST WIRE
C                   TX       INITIAL WIRE TEMP.
C                   CT       TEMP. DROP CORRESPONDING TO DV
C                   DV       INITIAL WIRE VOLTAGE DROP
C                   TEMPA    TEMPERATURE OF WATER
C                   RTH      THEORETICAL RESISTANCE OF TEST WIRE AT
C                            OPERATING TEMPERATURE
C                   RSYS     WIRE RESISTANCE INCLUDING ELECTRODES AND
C                            CONNECTIONS
C                   VI       VOLTAGE ACROSS THE SHUNT RESISTOR
C                   VW       VOLTAGE ACROSS THE TEST WIRE
C
0001          INTEGER RUNO
0002          REAL IC,LENTH
0003          WRITE(6,6)
0004          WRITE(6,2)
0005          WRITE(6,3)
0006    100   READ(5,1,END=10)RUNO,TEMPA,LENTH,RSYS,VI,VW,CV
0007    1     FORMAT(I6,F3.1,F3.2,F4.3,F5.4,F5.4,F4.3)
0008          P20=1.07816
0009          A=0.00362
0010          B=-0.000000588
0011          RS=0.226
0012          IC=VI/RS
0013          RTH=0.19787*LENTH*(1.0+A*TEMPA+B*TEMPA**2)
0014          RSTRAY=RSYS-RTH
0015          VWP=VW-IC*RSTRAY
0016          RC=VWP/IC
0017          DT=DV/(A*(VW-VI*RSTRAY/RS))
0018          HFLUX1=3170.2*IC*VWP/(3.1416*0.005*LENTH*2.54**2)
0019          HFLX2=HFLUX1/0.3687
0020          TX=(RO*(1.0+A*TEMPA)/RTH-1.0)/A
0021          WRITE(6,4)RUNO,HFLUX2,HFLUX1,TEMPA,TX,DT
0022    2     FORMAT(//3X,'RUN NO.',13X,'INITIAL HEAT FLUX',10X,'WATER TEMP.',4
              1X,'INITIAL WIRE TEMP.',5X,'INITIAL WIRE TEMP. DROP'/)
0023    3     FORMAT(16X,'(KCAL/HR M**2)',4X,'(BTU/FT**2 HR)',6X,'(C)',15X,'(C)
              1',17X,'(C)'/)
0024    4     FORMAT(3X,I6,6X,E13.6,6X,E13.67X,F5.2,11X,F7.2,15X,F5.2/)
0025    6     FORMAT(1H1)
0026          GO TO 100
0027    10    CONTINUE
0028          STOP
0029          END
```

Appendix B (continued)

RUN NO.	INITIAL HEAT FLUX (KCAL/HR M**2)	(BTU/FT**2 HR)	WATER TEMP. (C)	INITIAL WIRE TEMP. (C)	INITIAL WIRE TEMP. DROP (C)
63	0.2890017E 06	0.1045561E 05	70.00	141.40	7.94
83	0.2955455E 06	0.1104444E 06	84.00	150.20	13.68
89	0.2938425E 06	0.1083340E 06	79.00	148.24	12.55
60	0.2919785E 06	0.1076155E 06	74.00	145.42	8.42
93	0.2990017E 06	0.1065418E 06	70.00	141.40	8.51
64	0.2937665E 06	0.1070218E 06	69.50	143.10	14.12
69	0.3943465E 06	0.1453955E 06	75.00	169.59	19.23
61	0.3939812E 06	0.1451098E 06	77.00	165.07	7.09
62	0.3916845E 06	0.1444738E 06	79.00	166.01	8.16
64	0.3949755E 06	0.1456278E 06	82.00	173.46	10.10
78	0.5534735E 06	0.2040655E 06	79.00	167.18	10.16
79	0.5512785E 06	0.2032565E 06	74.50	172.13	12.14
80	0.5654765E 06	0.2079655E 06	69.00	173.17	11.93
81	0.5259825E 06	0.1939305E 06	50.00	150.37	8.50
55	0.2342665E 06	0.9000505E 05	88.00	81.27	12.52
54	0.2430775E 06	0.8962255E 05	85.00	78.70	15.95
53	0.2458905E 06	0.9065555E 05	84.00	81.63	1.94
56	0.2467845E 06	0.9098915E 05	90.00	82.99	13.80
65	0.3915475E 06	0.1443635E 06	84.00	166.82	18.34
65	0.3963265E 06	0.1461265E 06	86.00	172.02	16.51
67	0.3701235E 06	0.1364685E 06	88.70	143.85	16.17
67	0.3666435E 06	0.1463305E 06	90.00	171.46	12.34
69	0.3567835E 06	0.1506805E 06	66.00	184.30	9.78
66	0.3802575E 06	0.1431655E 06	83.50	161.34	16.48
67	0.3345435E 06	0.1417815E 06	90.00	157.45	15.67
92	0.5501795E 06	0.2065385E 06	83.50	172.42	24.09
83	0.5664555E 06	0.2014795E 06	86.00	162.01	9.83

Appendix B (continued)

85	0.541851E 06	0.199780E 06	50.00	158.61	13.49
87	0.543234E 06	0.200290E 06	88.00	159.61	1.86
100	0.547489E 06	0.201859E 06	91.00	158.63	6.86
101	0.507729E 06	0.187203E 06	85.00	141.04	7.54
102	0.527588E 06	0.194669E 06	92.00	151.29	6.52
103	0.495047E 06	0.182524E 06	90.00	128.93	11.82
105	0.550930E 06	0.203150E 06	89.00	168.04	2.19

BOILING HEAT TRANSFER PHENOMENA
DURING RAPID DECOMPRESSION

by

Shin-Ping Kung

B.S., National Tsing Hua University, 1972

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirement for the degree

MASTER OF SCIENCE

Department of Nuclear Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1977

ABSTRACT

Results of an experimental study of the temporal behavior of the
transient behavior of local boiling under rapid decompression are
presented. Specifically, the heat transfer from a thin wire heating
element to water during and shortly after the decompression is discussed.
The fast pressure transient is observed to cause an initial heater
temperature drop and delay the boiling transition in both totally
subcooled depressurization and depressurization with flashing. Flashing,
which has been considered responsible for the enhanced heat transfer
during and after a pressure transient, is found to be of questionable
importance in this experiment, since at this rapid decompression rate,
flashing does not become significant until the decompression is complete.