

/INITIATION OF SUBCOOLED POOL BOILING
DURING PRESSURE TRANSIENTS/

by

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1. INTRODUCTION

Vapor bubble nucleation and growth phenomena have attracted the attention of researchers for many years. Nearly all of the attention has been placed on saturated nucleate boiling and the transition to film boiling. Studies of boiling under transient conditions have been devoted primarily to investigations of the transition to film boiling. The nature of boiling phenomena preceding the transition has received little attention. However, these phenomena are important aspects of the broader problem of understanding the sequence of events leading to boiling crises in high-pressure heat exchangers such as nuclear power reactors.

Transient initiation of boiling has been described by steady-state nucleation models, which use the size of active nucleation sites to determine superheats necessary for bubble nucleation from these sites. The required superheats for a simple transient situation can be achieved by an increase in the heater surface temperature or by a decrease in the fluid saturation temperature by means of a reduction in the fluid pressure.

Surface characteristics are important in the description of the sizes of cavities available as nucleation sites. The pressure and temperature conditions experienced prior to the initiation of boiling were also postulated to be of major importance by Fabric (1), since potential sites could be flooded by pre-pressurization. Studies performed to examine transient boiling caused by decompression (2-5) have employed conditions such that bulk liquid flashing occurs by the end of the decompression. Consequently, the behavior when boiling

initiation conditions are not met for the predicted cavity sizes and the reactivation of flooded surface cavities has not been thoroughly investigated.

In this work, the transition from convection to boiling during pressure transients was investigated for a horizontal, cylindrical platinum heating element submersed in a fluid. Maximum overpressures were applied to the system before subjecting the heating element to constant power delivery, maintained during transients by a custom made power supply driven by 12 volt wet cells. Separate runs were necessary to measure the system pressure as a function of time and the element temperature as a function of time. The element temperature was determined using resistance thermometry. The data were recorded using a digital oscilloscope, stored on a floppy disk, then transferred to a computer for analysis. The time at which the first bubble was seen or heard was recorded as the measured boiling initiation time. Initiation times were also estimated based on the point where the analyzed heater temperature began to decrease. Although these two methods did not always produce equivalent time values, ranges for true boiling initiation times were determined from these measurements.

Pressure transients displayed exponential reduction behavior over most of the pressure decrease, and they were reproducible in that region. Boiling initiation times provided conditions which tended to support the cavity deactivation by pre-pressurization hypothesis of Fabric, although the effects of initial pressures were not as pronounced as expected by the model. Boiling was observed even in cases where none was predicted, but subsequent nucleation site reactivation and recovery of the heater temperature to steady-state was impeded by increases in maximum pressure applied.

2. REVIEW OF PREVIOUS WORK

2.1 Convection Heat Transfer

In a system composed of a body immersed in a fluid, convection heat transfer will occur if the body and the bulk fluid temperature are at different temperatures. Quantifying the heat transfer analytically is not a simple matter because of the dependence not only on numerous fluid properties, but also on flow conditions and surface geometry.

Boundary-layer theory has been used to derive numerical solutions for horizontal cylinders. These solutions have been shown to be quite accurate for moderate Rayleigh numbers characterizing cases where the wake is confined to a small region at the rear of the cylinder. Churchill and Chu (6) examined a wide range of data on steady-state convective heat transfer from horizontal cylinders. They recommended the following correlation as being applicable to both constant cylinder surface temperature and constant heat flux for all Rayleigh and Prandtl numbers:

$$\text{Nu}^{\frac{1}{2}} = 0.60 + 0.387 f(\text{Pr})\text{Ra}^{1/6} \quad (2.1)$$

where the Rayleigh and Nusselt numbers are based on cylinder diameter, and

$$f(\text{Pr}) = [1 + (0.559/\text{Pr})^{9/16}]^{-8/27}. \quad (2.2)$$

Morgan (7) also carried out a thorough analysis of published experimental data on steady-state convection from horizontal cylinders, and recommended the following correlation as being applicable for gases and liquids (except liquid metals):

$$\text{Nu} = B \text{Ra}^m \quad (2.3)$$

where values of B and m are given in the following table:

Ra	B	m
$10^{-10} - 10^{-2}$	0.675	0.058
$10^{-2} - 10^{+2}$	1.02	0.148
$10^2 - 10^4$	0.850	0.188
$10^4 - 10^7$	0.480	0.250
$10^7 - 10^{12}$	0.125	0.333

Fujii, et al. (8) reported that for convection from horizontal cylinders, the following correlation shows good agreement with both calculated and measured heat transfer rates:

$$2/\text{Nu} = \ln [1 + 4.918g(\text{Pr})\text{Ra}^{-n}], \quad (2.4)$$

where

$$g(\text{Pr}) = [1 + (0.492/\text{Pr})^{9/16}]^{-4/9} \quad (2.5)$$

and

$$n = 0.25 + 1.0/(10 + 5\text{Ra}^{0.175}), \quad (2.6)$$

Table 2.1 shows a comparison of these three correlations for the Rayleigh number range of interest in this work.

2.2 Boiling Initiation

2.2.1 Steady-State Boiling Initiation

Many theoretical analyses and interpretations of experimental data on boiling initiation have been based on concepts introduced by Griffith and Wallis (9) and embellished by Hsu (10), Bergles and Rohsenow (11),

Table 2.1. Comparison of predictions of Churchill-Chu, Fujii, and Morgan correlations for natural convection heat transfer from a 0.25 mm diametric cylinder. Ambient conditions: $T = 20^{\circ}\text{C}$. Fluid properties are evaluated at the mean temperature between T_w and T_a .

$T_w - T_a$ ($^{\circ}\text{C}$)	Heat Flux (kW/m^2)		
	Churchill-Chu	Morgan	Fujii, et al.
10	26.2	29.4	31.1
20	60.3	68.0	72.5
30	100	113	121
40	145	163	176
50	195	218	237
60	249	278	304
70	308	341	376
80	371	409	453
90	438	483	535
100	509	564	622

Han and Griffith (12), Madejski (13), and Cole and co-workers (14, 15, 16). In its simplest form, the concept may be described as follows.

Consider present within a fluid a heating element within the surface of which is an active boiling initiation site with a circular aperture of radius r_c (Fig. 2.1). As the temperature of the heating element is increased beyond the saturation temperature of the fluid, a vapor bubble emerges from the aperture. The surface of the bubble is spherical shaped due to the effect of surface tension. The minimum radius of curvature of the bubble is r_c , the radius of the aperture. At this minimum radius, surface forces are maximum, and the excess of the vapor pressure within the bubble over the static fluid pressure must be maximum.

If the fluid surrounding the bubble is at temperature T_w , the excess pressure is given by

$$p_v(T_w) - p_v(T_s) = 2\sigma(T_w)/r_c, \quad (2.7)$$

in which T_s is the saturation temperature of the fluid at system pressure $p = p_v(T_s)$, $p_v(T_w)$ is the vapor pressure of the fluid at temperature T_w , and σ is the fluid-vapor surface tension evaluated at temperature T_w . The excess temperature of the fluid at the fluid-vapor interface of the bubble can be related to the excess pressure in the bubble through use of the Clausius-Clapeyron relation. Application of this relation leads to the approximation that

$$T_w = f_1(r_c) \cong T_s + \frac{2\sigma T_s}{\lambda \rho_v r_c}, \quad (2.8)$$

where ρ_v is the vapor phase density, assumed to be much less than that of the liquid phase, and λ is the latent heat of vaporization. This is the

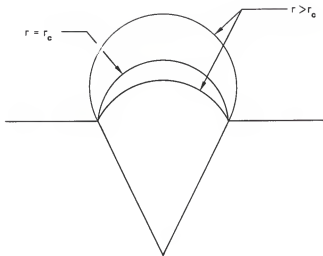


FIG. 2.1. Illustration of bubble growth from an active nucleation site.

threshold temperature which must be exceeded for the bubble to grow beyond radius r_c .

Now suppose that the fluid surrounding the heating element has a temperature distribution $T(r) = f_2(r)$, a function of distance r from the surface. Let T_w and T_a represent the surface temperature and the ambient temperature respectively. If q is the heat flux from the surface to the fluid, then approximately

$$f_2'(r) = dT/dr = -q/k, \quad (2.9)$$

and

$$f_2(r) = T(r) = T_w - qr/k, \quad (2.10)$$

where k is the thermal conductivity of the fluid.

Griffith and Wallis argued that for a bubble to grow in size beyond the radius r_c , the surface temperature of the heating element must exceed the threshold temperature, i.e., that $f_2(0) = f_1(r_c)$. Hsu contended that for the bubble to grow, it is necessary that the fluid temperature, not at the heating-element surface or base of the bubble, but at the cap of the bubble, exceed the threshold, i.e., that $f_2(r_c) = f_1(r_c)$. Han and Griffith argued that neither the temperature at the bubble base nor that at the bubble cap controlled the bubble growth. Rather, it was reasoned, the average liquid temperature surrounding the bubble was the controlling factor. This led to the criterion $f_2(ar_c) = f_1(r_c)$, where it was argued that $a = 3/2$. Sakurai and Shiotzu (17) accommodated in their arguments an empirical relationship between the cavity radius and the bubble radius at boiling inception, namely that the bubble radius is br_c . Allowing for this empiricism, the boiling initiation criterion may be stated as $f_2(ar_c) = f_1(br_c)$, or

$$T_w - T_s = \frac{qar_c}{k} + \frac{2\sigma T_s}{\lambda \rho_v br_c} \quad (2.11)$$

For the Griffith and Wallis approach, $a = 0$ and $b = 1$. For that of Hsu, $a = 1.6$ and $b = 1.25$. For that of Han and Griffith, $a = 1.5$ and $b = 1$. Sakurai and Shiotsu recommended that $a = 1.8$ and $b = 1.67$.

Suppose now that there are present on the heating element surface nucleation sites of a wide variety of radii. Cole (18), following the prescription of Bergles and Rohsenow (11), showed that, as the heat flux or surface temperature is increased, the first nucleation site to become active, i.e., from which the first bubble will emerge, is that one for which $r_c = r_*$ determined by $f'_2(ar_*) = f'_1(br_*)$. From Eqs. (2.8) and (2.9),

$$r_* = (2k\sigma T_s / \rho_v \lambda b^2 q)^{1/2} \quad (2.12)$$

Substitution of this value into Eq. (2.11) leads to the following expression for the minimum surface superheat required for boiling from a surface with a full size range of nucleation sites:

$$(T_w - T_s)_{\min} = (8\sigma T_s q / k \lambda \rho_v)^{1/2} \quad (2.13)$$

Bergles and Rohsenow offered the following correlation of computed values for water over the pressure range 15 to 2000 psia:

$$q = 1.55 \times 10^4 p^{1.156} [1.8(T_w - T_s)]^{2.047/p^{0.0234}} \quad (2.14)$$

where q is measured W/m^2 , T is K, and p is MPa. If, on the other hand, the largest nucleation site present has $r_c = r_m < r_*$, then the minimum surface superheat required for boiling initiation is the greater value

$$(T_w - T_s)_{\min} = \frac{qar_m}{k} + \frac{2\sigma T_s}{\lambda \rho_v br_m} \quad (2.15)$$

Selected values of minimum boiling superheat for H_2O are given in Table 2.2. For each saturation temperature, the last four values of r_m listed are the r_* values for the heat fluxes listed. Thus, superheats above and to the left of the horizontal lines are for the cases $r_m < r_*$.

One may ask how the superheat at boiling inception is affected by the subcooling of the ambient liquid. Suppose that a full range of initiation sites is available, so that the boiling superheat is governed by Eq. (2.13). Suppose that natural convection is the heat transfer mechanism, so that

$$q = C(T_w - T_s)^n \quad (2.16)$$

where $n \sim 1.2$. By equating the heat fluxes in Eqs. (2.13) and (2.16), and noting that $T_w - T_a = T_w - T_s + \Delta T_{\text{sub}}$, one can show that $(T_w - T_s)_{\min}$ is given by solution of the equation

$$(T_w - T_s)_{\min} = C' [(T_w - T_s)_{\min} + \Delta T_{\text{sub}}]^{n/2} \quad (2.17)$$

where $C' = (8\sigma T_s C / k \lambda \rho_v)^{1/2}$. Evaluation of $(T_w - T_s)_{\min}$ is illustrated in Fig. 2.2 where it may be seen that, as ΔT_{sub} increases, so also does the minimum boiling superheat. For example, for water at $T_s = 100^\circ\text{C}$, an increase in ΔT_{sub} from 10 to 30°C causes an increase of about 5°C in the minimum boiling superheat.

Madejski (13) developed a model for boiling initiation which allows for a non-spherical bubble shape and avoids specification of the distance from the heating surface at which the superheat criterion must be applied. As corrected by Schmidt and Cole (14), the result of the

Table 2.2. Minimum boiling superheat as a function of maximum cavity radius.

T_s ($^{\circ}\text{C}$)	r_m (μm)	q (MW/m^2)	Minimum Boiling Superheat (K) for $a=b=1$			
			0.1	0.2	0.5	1.0
100	1		32.9	33.1	33.5	34.3
	2		16.7	17.0	17.9	19.3
	4.73		7.6	8.3	10.4	13.8
	6.69		5.9	6.9	9.8	13.8
	10.6		4.7	6.2	9.8	13.8
	15.0		4.4	6.2	9.8	13.8
150	0.5		15.4	15.5	15.7	16.1
	1		7.8	8.0	8.4	9.1
	2.31		3.7	4.0	5.0	6.6
	3.26		2.8	3.3	4.7	6.6
	5.16		2.2	3.0	4.7	6.6
	7.30		2.1	3.0	4.7	6.6
195	0.5		5.1	5.2	5.4	5.8
	1		2.7	2.8	3.3	4.0
	1.31		2.1	2.3	2.9	3.9
	1.86		1.6	1.9	2.7	3.9
	2.93		1.3	1.7	2.7	3.9
	4.15		1.2	1.7	2.7	3.9

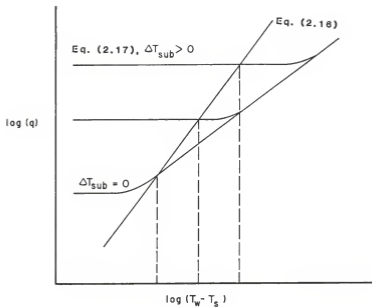


FIG. 2.2. Determination of boiling initiation superheat requirements based on Eqs. (2.13) and (2.16).

analysis is expressed as the ratio of the minimum surface superheat in a variable temperature situation to that required if the liquid were uniformly superheated, namely

$$\frac{(T_w - T_s)_{\min}}{(T_w - T_s)_{\infty}} = \text{fctn}[r_m k(T_w - T_a)/q]. \quad (2.18)$$

The function increases monotonically with its argument, reaching a value of about 4.5 at an argument of 3. The utility of the Madejski approach is limited by the availability of data for boiling initiation temperatures in uniformly superheated liquids.

2.2.2 Transient Boiling Initiation

Most of the work performed concerning transient boiling phenomena has focused on constant pressure systems subjected to transient heating. Few are of interest here because pressure effects generally were not considered. Those studies that used pressure as a parameter (e.g., references 19, 20, and 21) reported that the superheat required for boiling initiation decreased with increasing pressure. However, these studies examined boiling at various constant system pressures and did not test the effects of applying a temporary overpressure before an experimental run.

Fabic (1) thoroughly examined the consequences of the pressure-temperature history of a heating element on boiling initiation. He argued that the maximum radius of an active (unflooded) initiation site at the time of a test is governed by the maximum value of the ratio $(p - p_v)/\sigma$ experienced prior to the test. Here p is the system pressure and p_v the fluid vapor pressure. Call this maximum ratio $(p_o - p_{vo})/\sigma_o$. The maximum cavity radius is

$$r_c^+ = 2\sigma \frac{\cos(\pi - \theta_a)}{p_o - p_{vo}} \quad (2.19)$$

where θ_a ($>90^\circ$) is the contact angle between the cavity wall and the vapor-liquid interface within the cavity. The value of θ_a is taken as 108° for water at all temperatures and pressures. Values of the ratio and r_c^+ are given in Table 2.3 for water under various conditions.

Fabric noted that most test fluids at some time are at 20°C and atmospheric pressure. This leads to an upper bound of $r_c \equiv \hat{r}_c = 0.5 \mu\text{m}$, for radii of nucleation cavities. He argued that boiling initiation takes place with a contact angle θ_r between 0 and 66° , and at a surface temperature T_w which satisfies the equation

$$p_v(T_w) - p = 2\sigma \cos\theta_r / r_c^+, \quad r_c^+ \leq \hat{r}_c, \quad (2.20)$$

$$= 2\sigma \cos\theta_r / \hat{r}_c, \quad r_c^+ > \hat{r}_c, \quad (2.21)$$

where σ is evaluated at T_w . Upper and lower limits on T_w would depend on the choice of 0° or 66° for θ_r . If, in fact, the largest potential initiation site had a radius $r_m < r_c^+$, then that radius would apply.

One may inquire of the effect of boiling from the heating surface at test conditions for purposes of degassing the surface. Fabric argued that the process would "arm" previously inactive (flooded) sites with vapor and thus that the pressure and temperature under which the degassing took place would define r_c^+ .

One may also inquire of the effect of degassing at saturation conditions. Fabric is silent on this point. Presumably sites of all sizes would be activated and r_m would govern subsequent boiling initiation.

Table 2.3. Maximum active site radius as a function of temperature and pressure, computed using the Fabric Model [1].

Fluid Temp. (°C)	Pressure (MPa)	$(p-p_v)/\sigma$ (μm^{-1})	r_c^+ (μm)
20	0.101	1.35	0.46
	1.398	19.1	0.032
70	0.101	1.08	0.57
90	0.101	0.51	1.21
95	0.101	0.28	2.22
100	0.476	6.33	0.098
100	1.123	17.3	0.036
100	1.398	21.9	0.028
120	0.476	5.02	0.12
140	0.476	2.24	0.28
145	0.476	1.21	0.51
165	1.398	15.2	0.041
185	1.398	6.64	0.093
190	1.398	3.55	0.17

Winterton (2) also developed an expression for conditions at nucleation based on the pressure-temperature history of the heater,

$$p_v + p_g - p = \frac{1}{\gamma} \frac{\sigma}{\sigma_o} (p_o - p_{vo} - p_{go}) , \quad (2.22)$$

where p_g is the partial pressure of noncondensable gas, and γ is defined as

$$\gamma = \frac{\cos(\pi - \theta_a + \frac{\alpha}{2})}{\cos(\theta_r - \frac{\alpha}{2})} , \quad (2.23)$$

where α is the included apex angle of the cavity. It will be noted that Eq. (2.22) reduces to Eq. (2.20) for the case of a well degassed system and a cylindrical cavity ($\alpha = 0$). Winterton performed a number of experiments using vertical tubes to test theories of nucleation by surface cavities. He examined both transient heat flux - constant pressure and constant heat flux - transient pressure cases. Liquid pressures were in the range of approximately 0.01 to 0.1 MPa for both cases and true heat fluxes in the transient heat tests were 10 kW/m² maximum, resulting in a rate of rise in temperature of less than 1°C/s. For the transient heat case, he reported that the vapor pressure at nucleation increased with increasing overpressures, but that the effect was not as pronounced as indicated by the theory with γ set equal to unity. He reported that the order of magnitude of γ was 1, but his experiments indicated that the value was not constant. Instead, γ increased as the overpressure increased. The limitations of his experimental apparatus precluded making conclusions about the effect on the transient pressure case. However, for the conditions under which he was able to make both transient heat and transient pressure measurements,

he found no significant difference in the calculated cavity radius required for nucleation, thus confirming the equivalence of the two methods of nucleation. Gallagher and Winterton (4) performed a study which expanded on the power transient boiling work of Winterton. Again, a very low heat flux was used, and overpressures up to 0.7 MPa were applied before performing tests at 0.0122 MPa. They found that special preparation of the test section was necessary to produce consistent results. They reasoned that this preparation was associated with obtaining suitable and consistent values of contact angles within the surface cavities. Their results show a strong effect of pressure on deactivating cavities. They reported good agreement between their results and Eq. (2.22) using a constant value for γ of 5.4.

Faw and VanVleet (22), investigating boiling initiation from a horizontal wire in a subcooled pool of water, reported initiation conditions that were not consistent with any single size-distribution of nucleation sites. However, nearly all results were consistent with predictions made using Fabric's model. They also found that pre-pressurization well above saturation pressure led to greatly increased superheat requirements at boiling initiation consistent with the model. They noted that only the first test after pressurization was so affected; subsequent tests in the series had boiling initiation superheats approximately those expected in the absence of pre-pressurization. They postulated that the first test reactivated previously flooded sites.

Investigation of boiling phenomena during transient pressure conditions has been prompted by desire to determine the response of a high pressure, high temperature heat exchanger system (e.g., a nuclear

reactor) to a loss of pressure. Since the mechanical integrity of such a system can be breached by events resulting from inadequate heat transfer, most studies have examined the transition from nucleate to film boiling and critical heat fluxes (e.g., references 23, 24, and 25).

The initiation of boiling during decompression has received limited attention. Fabric argued that his pressure-temperature history modeling of boiling initiation would also apply to the pressure transient case. He noted that the nucleation event could occur due to a decrease in system pressure even if the surface temperature T_w did not change. In this case the system pressure p necessary for vapor nucleation could be predicted from Eqs. (2.20) and (2.21). Values of the boiling initiation pressure in water, based on the Fabric model, are given in Table 2.4 for water under various conditions.

It can be expected from Fabric's model that an increase in the initial overpressure applied to a system should cause an increase in the instantaneous surface superheat $[T_w - T_s(p)]$ necessary to initiate boiling. This increase would manifest itself by producing a measurable delay between the time boiling initiation is predicted by steady-state considerations and when it is actually observed. Hooper and Abdelmessih (26) observed just such an occurrence in a study of liquid flashing. However, Kenning and Thirunavukkarasu (27) found no indication of delay in bubble growth in their study of bubble nucleation characteristics of surfaces.

Weisman, et al. (3), in a study of boiling initiation using heated and unheated ribbons, found that measurable delays in boiling initiation could be encountered under appropriate conditions. They suggested that the results of Kenning and Thirunavukkarasu could be explained by the

Table 2.4. Boiling initiation system pressure values prescribed by the Fabric model (1) at $T_w = 100^\circ\text{C}$ and using $\theta_w = 66^\circ\text{a}$.
 $T_w = T_w^a$ until after initial pressure is applied.

P_i (MPa)	T_w ($^\circ\text{C}$)	P_b (MPa)
0.239	140	0.204
0.273		0.165
0.308		0.125
0.308	150	0.250
0.377		0.175
0.411		0.137
0.377	160	0.330
0.446		0.258
0.515		0.186
0.584		0.114
0.515	170	0.380
0.584		0.312
0.653		0.243
0.790		0.106
0.584	180	0.546
0.653		0.481
0.790		0.350
0.997		0.155

fact that the pressure was released very rapidly to well below saturation pressure, thus activating unflooded cavities and allowing bubble growth to begin almost immediately. In their own investigation, the authors also found that the superheat required to initiate boiling on an unheated ribbon increased with increasing rate of depressurization. This is consistent with results obtained in studies of the response of hot water to rapid depressurization (28)(29). Furthermore, Weisman et al. found that at low decompression rates the superheats required to initiate boiling showed no effects due to the pressure history, and instead approached steady-state values. These superheats, in the 3 - 4°C range, were substantially below those predicted for the pressure-time histories considered. The authors reasoned that small bubbles of noncondensable gas could remain at a cavity base after application of an overpressure. As pressure is reduced, vapor diffuses into the bubble, which then fills the cavity. Thus, an active cavity is present with a radius larger than the maximum unflooded radius predicted, and boiling is possible at a superheat below that predicted using the maximum unflooded radius. The authors speculated that the finite time to fill such a cavity could be the reason for the delay. Heated ribbons were used to verify that the first boiling in the system occurred on the ribbon. The authors noted that the superheats were higher than for the tests without heating, but they did not comment on how these superheats compared to predicted values.

Sakurai, et al. (5), examined transient boiling of a test heater caused by depressurization with near-exponential reduction periods ranging from 3 to 60 ms. The platinum wire test heater was initially in a nonboiling state in a pool of water, and the heat generation rate at

the heater was held constant throughout the experimental run. They used initial pressures of 0.59, 1.08, and 1.9 MPa with water temperatures of 353 and 373 K. Rapid decompression was achieved using a rupture disc device to vent the test section to atmosphere. The authors found that the heater surface temperature and true heat flux remained constant until boiling initiated. The incipient boiling point was assumed to have been reached at the time the heater temperature began to decrease. They argued that this gave the criterion for boiling initiation even if it may not have been the true incipient boiling point. They found that the pressure p_b , and the instantaneous surface superheat, ΔT_b , at the incipient boiling point depended upon the heat flux, even if the initial overpressure and the reduction period were the same. They noted that ΔT_b increased with decreasing p_b and was little dependent on the pressure reduction period, consistent with the incipient boiling model of Sakurai and Shiotsu [Eq. (2.11)].

2.3 Nucleate Boiling

A well-known correlation for fully-developed subcooled and saturated nucleate pool boiling is that of Rohsenow (30), which may be expressed in the form

$$q = C_1 (T_w - T_g)^3. \quad (2.24)$$

The factor C_1 is a function of pressure (fluid properties evaluated under saturation conditions) and fluid-surface combination, namely

$$C_1 = [(\rho_f \rho_v)g/\sigma]^{1/2} \mu \lambda Pr^{-3n} (c/\lambda C_2)^3, \quad (2.25)$$

where g is the acceleration of gravity, μ is the viscosity of the fluid, and c is the heat capacity of the fluid. The constant n and the value

of C_2 depend on the fluid-surface combination (18), and take the values 1.0 and 0.013 respectively for a platinum surface in water. Unless otherwise indicated, properties are those of the liquid phase. For example, for platinum-water at atmospheric pressure, $C_1 = 140 \text{ Wm}^{-2}\text{K}^{-3}$.

Stephan and Abdelsalam (31) carried out an exhaustive investigation of experimental data on pool boiling in various fluids and recommended the following correlation as being applicable to water

$$q = C_3 (T_w - T_s)^{3.06} \quad (2.26)$$

in which C_3 is a function of saturation temperature. Based on data in the paper, C_3 may be expressed empirically, in S.I. units, as

$$C_3 = 229 p^{0.649} \quad (2.27)$$

where p is in units of MPa for the range 0.1 to 20. As an example, for boiling at atmospheric pressure, $C_3 = 52 \text{ Wm}^{-2}\text{K}^{-3.06}$. Thus, for a given surface superheat, this correlation predicts a much lower heat flux than that predicted by the Rohsenow correlation.

3. THEORY

3.1 Determination of Largest Potentially Active Cavity

In the absence of free gas bubbles, nucleation sites for boiling initiation will be located at surface cavities which have vapor trapped in them. The rate of boiling heat transfer is governed by the spatial distribution and the size spectrum of nucleation sites. Heat flux and superheat required to initiate boiling generally depend on the size of the largest site. The largest potential nucleation site, i.e., a cavity, idealized by a conical shape, containing vapor, can be determined by considering the pressure-temperature history of the surface along with the fluid-surface wetting characteristics.

Consider an arbitrary surface cavity, idealized by a conical shape, containing vapor with a fluid of infinite extent covering the surface (Fig. 3.1). Assume a well degassed fluid so that the partial pressure of noncondensable gas is negligible compared to vapor pressure and fluid pressure. The system is initially at pressure p_{f1} and at temperature T_1 at which the vapor pressure is p_{v1} less than p_{f1} and the surface tension is σ_1 .

When a pressure $p_{f2} \gg p_{v1}$ is applied, the fluid will enter the mouth of the cavity. Mechanical equilibrium across the meniscus requires

$$p_{f2} - p_{v1} = \frac{2\sigma_1}{R_M}, \quad (3.1)$$

where R_M is the radius of curvature of the meniscus (see Fig. 3.1).

From a geometric consideration, the cavity radius r at the meniscus line of contact is given by

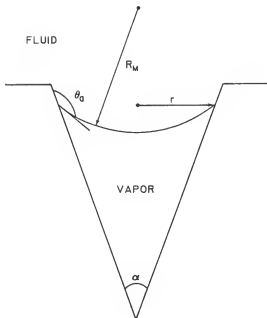


FIG. 3.1. Illustration of vapor entrapment at a potential nucleation site.

$$r = R_M \cos\left(\pi - \theta_a + \frac{\alpha}{2}\right),$$

or

$$r = \frac{2\sigma_1}{P_{f2} - P_{v1}} \cos\left(\pi - \theta_a + \frac{\alpha}{2}\right) \quad (3.2)$$

where θ_a is the advancing contact angle between the fluid and the cavity wall, and α is the included angle of the cavity apex. The minimum pressure necessary for the meniscus to enter a cavity with mouth radius r_c can also be obtained from Eq. (3.2). If this requirement is not met, then the contact angle is less than θ_a and the meniscus is at the mouth or the cavity is flooded.

The argument of the cosine must fall between 0 and $\frac{1}{2}\pi$ since r must exist for vapor to be trapped in the cavity. This provides a maximum value for the apex angle of the cavity,

$$\alpha_{\max} < 2\theta_a - \pi. \quad (3.3)$$

If α is greater than this value, the cavity will flood with fluid and become deactivated. It is also apparent from Eq. (3.3) that θ_a must be greater than $\frac{1}{2}\pi$ for vapor to be trapped in the cavity.

Equations (3.1), (3.2), and (3.3) describe the potential nucleation sites available for the pressure-temperature history of the system when P_{f2} equals $P_{f,\max}$. Cavities with mouth radii greater than or equal to the critical radius $r = r_c$ when $P_{f2} = P_{\max}$ and apex angles less than α_{\max} will have the meniscus located at the position inside the cavity where the local cavity radius is equal to r_c . Cavities with apex angles greater than α_{\max} will be flooded, while cavities with mouth radii less than r_c will not be affected.

The description of the meniscus behavior as conditions leading to nucleation are imposed depends on the manner in which these conditions arise. Boiling can be initiated by decreasing the fluid pressure, increasing the vapor pressure by heating, or a combination of these two actions.

3.2 Activation of a Nucleation Site

3.2.1 Decrease in Fluid Pressure

If the fluid pressure is released to a value p_f such that $p_{v1} \leq p_f \leq p_{f2}$, the radius of the meniscus will change to a new value given by

$$R_M = \frac{2\sigma_1}{p_f - p_{v1}} . \quad (3.4)$$

The radius of the meniscus line of contact remains constant at the value given by Eq. (3.2), and the contact angle θ must satisfy

$$r = \frac{2\sigma_1}{p_f - p_{v1}} \cos\left(\pi - \theta + \frac{\alpha}{2}\right) = r_c . \quad (3.5)$$

As p_f approaches p_{v1} , the contact angle θ must decrease so that r remains constant. However, as long as p_f is greater than p_{v1} , the meniscus will be concave on the fluid side.

When p_f becomes less than p_{v1} , the meniscus radius becomes negative by Eq. (3.4), i.e., the meniscus flips from concave to convex on the fluid side. From the force balance,

$$R_M = - \frac{2\sigma_1}{p_f - p_{v1}} . \quad (3.6)$$

With no boiling, r remains constant at the value determined by Eq.

(3.2). However, r can also be defined by

$$r = R_M \cos\left(\theta - \frac{\alpha}{2}\right)$$

$$= - \frac{2\sigma_1}{p_f - p_{v1}} \cos\left(\theta - \frac{\alpha}{2}\right) \quad (3.7)$$

Equation (3.7) shows that r will remain constant as θ decreases to the value of the receding contact angle θ_r . When θ equals θ_r the fluid will begin to recede over the previously wetted cavity wall and the meniscus line of contact will move towards the cavity mouth. This will occur when

$$p_{v1} - p_f' = \frac{2\sigma_1}{r_c} \cos\left(\theta_r - \frac{\alpha}{2}\right). \quad (3.8)$$

When the meniscus is at the cavity mouth, boiling inception will take place when the meniscus radius of curvature is at a minimum, i.e., at the cavity mouth radius, \hat{r}_c . This will occur at a pressure p_f'' such that

$$p_{v1} - p_f'' = \frac{2\sigma_1}{\hat{r}_c} \quad (3.9)$$

The application of these equations to a range of cavity sizes will be discussed later. However, it is apparent that $p_f'' < p_f'$ when $r_c = \hat{r}_c$.

3.2.2 Increase in Vapor Pressure

If a temperature $T_2 > T_1$ is applied at pressure p_f , where $p_{v1} \leq p_f \leq p_{f2}$, the surface tension and the vapor pressure will assume new values σ_2 and p_{v2} , respectively. If T_2 is less than the saturation

temperature at p_f the meniscus radius of curvature will change, but the line of contact will not, and the radius r at the line of contact will remain constant at the value given by Eq. (3.2). Here,

$$R_M = \frac{2\sigma_2}{p_f - p_{v2}}, \quad (3.10)$$

and

$$\begin{aligned} r &= R_M \cos(\pi - \theta + \frac{\alpha}{2}) \\ &= \frac{2\sigma_2}{p_f - p_{v2}} \cos(\pi - \theta + \frac{\alpha}{2}) = r_c. \end{aligned} \quad (3.11)$$

Again, the interface is stable with the meniscus concave on the fluid side for $(p_f - p_{v2}) > 0$.

When the applied temperature T_2 becomes greater than the saturation temperature at p_f , the meniscus radius of curvature becomes negative by Eq. (3.10) and the meniscus flips from concave to convex on the fluid side. The force balance in this case requires

$$R_M = - \frac{2\sigma_2}{p_f - p_{v2}}. \quad (3.12)$$

The radius of the meniscus line of contact is given by

$$\begin{aligned} r &= R_M \cos(\theta - \frac{\alpha}{2}) \\ &= - \frac{2\sigma_2}{p_f - p_{v2}} \cos(\theta - \frac{\alpha}{2}) = r_c. \end{aligned} \quad (3.13)$$

The meniscus radius of contact remains constant as θ decreases to the value of the receding contact angle θ_r . Movement of the meniscus line of contact towards the cavity mouth will commence when

$$p_{v2}^i - p_f = \frac{2\sigma^i}{r_c} \cos(\theta_r - \frac{\alpha}{2}) , \quad (3.14)$$

corresponding to a temperature T_2^i . Again, boiling will initiate when the meniscus radius of curvature reaches a minimum equal to the cavity mouth radius \hat{r}_c . This will occur at a temperature T_2^i such that

$$p_{v2}^i - p_f = \frac{2\sigma^i}{\hat{r}_c} . \quad (3.15)$$

Although σ decreases with increasing temperature, under usual conditions $p_{v2}^i > p_{v2}^j$ or $T_2^i > T_2^j$ when $r_c = \hat{r}_c$.

3.3 Cavity Geometry

Consider now a broad size range of active cavities present on the surface. The system has experienced conditions such that the meniscus radius of curvature is convex on the fluid side. If the meniscus line of contact is below the cavity mouth, an increase in $p_v - p_f$ can not be balanced in Eq. (3.8) or (3.14), and the line of contact will move towards the cavity mouth. First boiling will then occur from a cavity with mouth radius \tilde{r}_c such that

$$\tilde{r}_c = \hat{r}_c \sec(\theta_r - \frac{\alpha}{2}) , \quad (3.16)$$

since the threshold conditions for meniscus motion will also satisfy the requirement for nucleation from a cavity with mouth radius \tilde{r}_c .

The effect of the cavity apex angle in determining potential nucleation sites is revealed by Eq. (3.2), which shows that vapor can be trapped at lower liquid temperatures as α decreases. In other words, given two cavities with the same mouth radius, the cavity with the

smaller apex angle will boil first. Therefore, a cylindrical cavity ($\alpha = 0$) will be the largest potentially active nucleation site available, and the superheat required to achieve the receding contact angle θ_r will be less than for a conical cavity. The meniscus will rush out of the cylindrical cavity for an increase in $p_v - p_f$, and the relation of Eq. (3.9) or (3.15) must be satisfied to initiate boiling if the entrance angle to the cavity mouth is 90° . The superheat in this case may be higher than that required for a conical cavity with mouth radius \tilde{r}_c if α is sufficiently small. However, Fabic (1) argued that the cavity mouth would be rounded, and appropriate rounding at the entrance would allow boiling to initiate after the meniscus flip with no additional superheat. This special rounding would also apply to conical cavities, but the only effect would be to allow the superheat necessary for boiling inception in a cavity with mouth radius \hat{r}_c to approach the value for \tilde{r}_c . Since Fabic's argument provides the lower limit for boiling initiation, further discussion will consider cylindrical cavities where $r = r_c$ is the radius of the largest active cylindrical cavity according to Eq. (3.2).

3.4 Effect of Contact Angles

The contact angles used in this work are the same as those adopted by Fabic. He selected an advancing contact angle $\theta_a = 108^\circ$ for water on metal for all values of system pressures and temperatures. This value is based on reported findings that the largest contact angle water can make with a solid surface is $\theta_a = 105^\circ$ to 110° . His selection of the receding contact angle $\theta_r = 66^\circ$ was more arbitrary since it was a best fit value for his work. However, it also agreed with the observance of a 40° maximum difference between θ_a and θ_r .

Consider a horizontal surface immersed in well degassed water of infinite extent. The surface and the fluid are initially at uniform temperature T_1 when an initial pressure p_{f2} is applied. The surface is then heated to temperature $T_w = T_2$ such that no boiling occurs. Beginning at time $t = 0$, the system is subjected to a time-dependent decrease in the fluid pressure $p_f(t)$. No boiling will occur until p_f reaches the value necessary for boiling initiation.

The radius of the largest active cylindrical cavity is obtained from Eq. (3.2) for the conditions T_1 and p_{f2} ,

$$r_c = \frac{2\sigma_1}{p_{f2} - p_{v1}} \cos(\pi - \theta_a). \quad (3.17)$$

Since r_c remains constant until boiling is initiated, Eq. (3.13) also applies,

$$r_c = - \frac{2\sigma_2}{p_f - p_{v2}} \cos(\theta_r). \quad (3.18)$$

The fluid pressure necessary for boiling initiation, p_b , can be obtained by combining Eqs. (3.14) and (3.15),

$$p_b = p_{v2} - \frac{\sigma_2}{\sigma_1} \frac{\cos(\theta_r)}{\cos(\pi - \theta_a)} (p_{f2} - p_{v1}). \quad (3.19)$$

Figure 3.2 shows the effect of surface temperature on the incipient boiling pressure, where it is observed that increasing T_w causes p_b to increase. The figure also shows that for appropriate extreme conditions of initial pressure, no boiling is predicted.

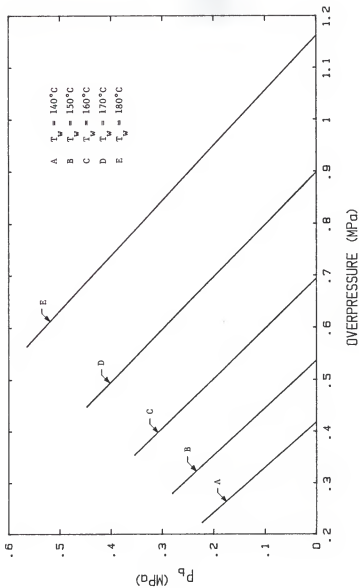


FIG. 3.2. Effect of surface temperature on incipient boiling pressure with $\theta_a = 108^\circ$ and $\theta_f = 66^\circ$. Overpressure is applied at ambient temperature $T_a = 100^\circ\text{C}$.

The influence of the advancing and receding contact angles on the boiling initiation pressure can be examined using Eq. (3.19). Increasing the ratio of the cosine terms, by decreasing θ_r or increasing θ_a , requires a lower value of p_b (and hence a higher superheat) to satisfy the condition for nucleation. Decreasing the ratio of the cosine terms has the opposite effect. The effect of selected changes in contact angles on the ratio of the cosine terms is shown in the following table, and the effect on p_b for a representative case is shown in Fig. 3.3. It is apparent that the value of p_b is very sensitive to small changes in the value of either contact angle.

θ_a	θ_r	$\frac{\cos(\theta_r)}{\cos(\pi - \theta_a)}$
108°	66°	1.316
110°	63.25°	1.316
106°	68.73°	1.316
106°	66°	1.476
108°	62.86°	1.476
108°	68.45°	1.189
110°	66°	1.189

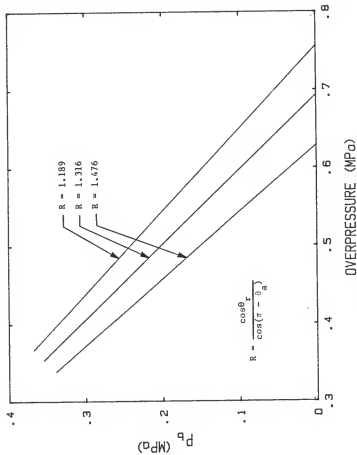


FIG. 3.3. Effect of selected changes in contact angle on incipient boiling pressure. Overpressure is applied at $T_a = 100^\circ\text{C}$ before the surface temperature is raised to $T_w = 160^\circ\text{C}$.

4. APPARATUS AND EXPERIMENTAL PROCEDURE

4.1 Pressure System

4.1.1 Pressure Vessel

The test vessel, shown in Fig. 4.1, is made of type 316 stainless steel. The vessel is 40.64 cm in length with an outer diameter of 12.065 cm and an inner diameter of 9.8425 cm. The end flanges are sealed with Ultek oxygen free hardened copper O-rings Model 2 68-4000, from Perkin-Elmer Corp. One end flange is penetrated by a 2 kW Firerod electrical heater, Model N6A22, from Watlow, Inc. This heater is used to maintain the ambient temperature of the test fluid. The other end flange is penetrated by the electrode assembly. A stainless steel-sheathed copper-constantan thermocouple from Watlow, Inc. penetrates the cylinder wall to provide constant monitoring of the bulk fluid temperature.

The two optical ports are essential to the observation of bubble growth behavior on the electrically heated test element. The design of the window housing is shown in Fig. 4.2. The windows are of T08 commercial grade clear fused quartz obtained from Amersil, Inc. The discs are 4.445 cm in diameter and 1.5 cm thick and, as estimated by Amersil, a pressure of 13.6 MPa may be used with an approximate safety factor of 3.5. The cushions and seals for the windows are fabricated of teflon.

4.1.2 Pressure Measurement System

A Kistler Quartz Miniature Pressure Transducer Model 603A penetrates the cylinder wall to provide the means to measure the pressure history during a transient. The point of penetration is between one of the optical ports and the end flange containing the electrode assembly, and

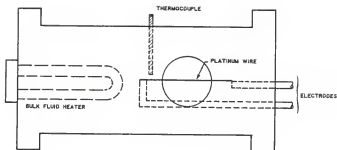


FIG. 4.1. Schematic diagram of the pressure vessel.

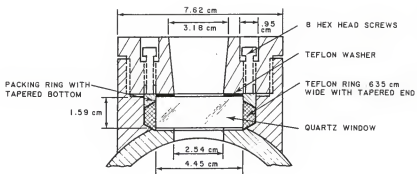


FIG. 4.2. Pressure vessel window housing.

on the horizontal plane through the test element. This location places the pressure transducer in closest proximity to the test element so that recorded information represents the actual pressure history of the test element during the experiment. Although the transducer will withstand sustained temperatures of up to 260°C without damage, its temperature must be limited to about 120°C to minimize drift and ensure good low frequency response. A water cooling adapter designed by Kistler provides this cooling capability, as well as being a most convenient means of attachment to the pressure vessel. Figure 4.3 shows details of the cylinder wall where the adaptor is mounted, and Fig. 4.4 shows the cooling adaptor design from Kistler. Since this design is for a physically larger transducer, an adaptor was designed to mount the Model 603A pressure transducer in the cooling jacket. The design of the second adaptor is shown in Fig. 4.5. Both adaptors were fabricated by machine shop personnel in the Department of Physics.

The quartz sensing element in the pressure transducer is oriented such that increasing applied pressure results in a negative-going charge signal that is inverted to a positive-going voltage signal by Kistler charge amplifiers. The Kistler Model 504E Dual Mode Amplifier is designed to develop the full capabilities of the quartz transducer while eliminating the attenuating effects of the cable and transducer capacitance.

Three factors must be considered when setting up the pressure measurement system for optimum performance: the system transfer function (i.e., volts output per measurand unit input), the correct time constant for the event, and the amplifier drift. All are directly affected by the settings on the dual mode amplifier.

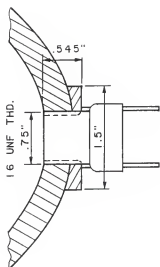


FIG. 4.3. Pressure transducer cooling adaptor mounting to the pressure vessel.

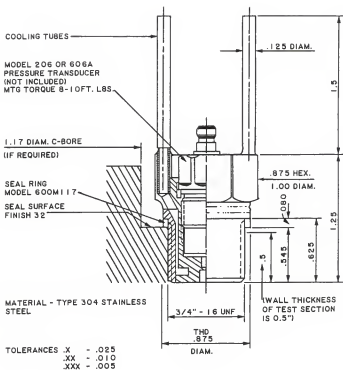


FIG. 4.4. Pressure transducer cooling adaptor, designed by Kistler.

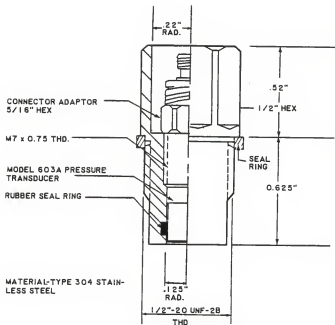


FIG. 4.5. Pressure transducer adaptor for mounting the Model 603A to the cooling adaptor.

The system transfer function is inversely proportional to the transducer sensitivity, which is set on the dual mode amplifier as a value between 1.00 and 11.00. Since the pressure transducer used in this study has a sensitivity less than 1.00 pC/psi, a range multiplier of 10 is automatically required in determining the transfer function. The transfer function is also dependent on the amplifier gain, which varies directly with the range switch position.

The time constant is selected according to the temporal behavior of the input signal. Since the depressurization rates used in this study were small, the long time constant setting was chosen to avoid signal decay before the end of the transient. Unfortunately, the improvement in low frequency response allowed by the long time constant setting is at the expense of amplifier drift as a function of time.

Amplifier drift is inversely proportional to the range setting. For the long time constant the drift is measured in millivolts per second. Thus the need to minimize drift must be balanced against the desire to establish a system transfer function that provides maximum deflection of the output signal for a given pressure change.

4.1.3 Pressurizer

The pressurization system, as shown in Fig. 4.6, consists of a bottle of commercial nitrogen, the pressurizer, Model 30A-10WS, from Greer Hydraulics, Inc. and the pressure vessel. Seamless stainless steel tubing (0.635 cm) with 0.635-cm taper-seal valves from High Pressure Equipment Company is used for gas delivery. The high pressure nitrogen enters one side of the pressurizer and inflates a neoprene rubber bag. This bag presses against the water in the other half of the pressurizer. Thus, pressure can be applied to the test fluid without having the

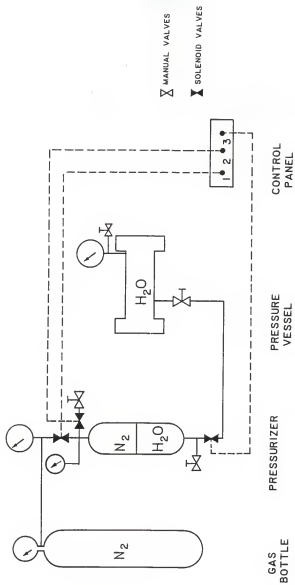


FIG. 4.6. Pressurization system.

pressurizing gas dissolve in the test fluid. The pressure vessel is also connected to the water side of the pressurizer using seamless stainless steel tubing. On the gas side, there are two Asco Red Hat solenoid valves, Model 8262A214 from Automatic Switch Co., one to control inflow of gas and another solenoid valve to control the flow of gas to the atmosphere. On the fluid side of the system, there is another solenoid valve. Once the system is pressurized, this valve can be closed so that the pressure in the pressure vessel remains constant while the pressure on the gas side of the bladder is raised or lowered. Then the valve can be opened causing an instantaneous compression or decompression. There are also two Model 63-5622 pressure gauges from Matheson Corp. and one Model 7108P-200 pressure gauge from Transcat associated with the system. One Matheson gauge is on the pressure vessel itself and the other is on the supply line of the nitrogen gas, while the Transcat gauge is on the gas side of the pressurizer.

4.2 Heating Element

The test element, shown in Fig. 4.7, consists of two brass rods each 0.6350 cm in diameter and a teflon block. The teflon block is used to prevent the rods from sagging. The vertical support assembly can be adjusted to provide for different lengths of platinum wire. The teflon seals at the penetration points of the electrodes served a double purpose of providing a water tight seal and also providing insulation between the electrodes and the pressure vessel.

The heating element is of pure platinum wire (SPPL-010 from Omega Engineering, Inc.) of diameter 2.50×10^{-4} m and is mounted horizontally. The maximum length of the heating element is 9.6 cm. The spring attachment provides tension across the wire. The platinum wire not only

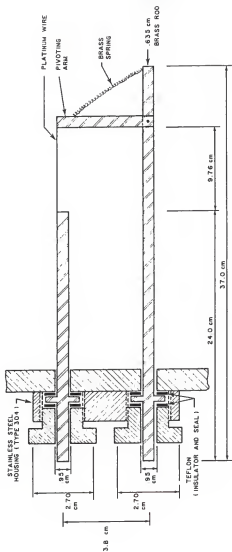


FIG. 4.7. Heating element construction.

acts as the test element but also as a temperature sensor. The resistance, $R(\theta)$, of pure platinum has a well characterized temperature dependence, (32)

$$R(\theta) = R_0 (1 + \alpha\theta + \beta\theta^2),$$

where

$$\alpha = 3.92 \times 10^{-3}$$

$$\beta = -5.5 \times 10^{-7}$$

θ = the temperature of the platinum wire in °C,

$R(\theta)$ = the resistance of the wire at temperature θ in ohms,

R_0 = the resistance of the platinum wire at 0°C.

Once the resistance is measured, the average temperature of the platinum wire can be calculated.

4.3 Electrical System

The electrical system consists of two twelve volt storage batteries, a control system, and a voltage bias system. The two storage batteries are wired in parallel and provide the dc current to the test element. The control system regulates current to the test element such that the power delivered remains constant with time. Figure 4.8 is a schematic diagram of the control system circuit. The voltage bias system is an EAI Analog Computer, Model TR-10. Simple linear summing circuits apply bucking voltages to the test voltages across the standard resistor and the test element so that only the variations in these voltages are recorded by the oscilloscope.

4.4 Data Measurement System

Data for the experimental runs are taken on a Nicolet Explorer III Digital Oscilloscope equipped with a floppy disc storage system and a

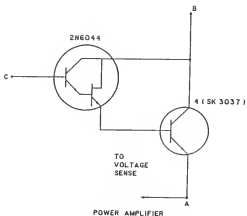
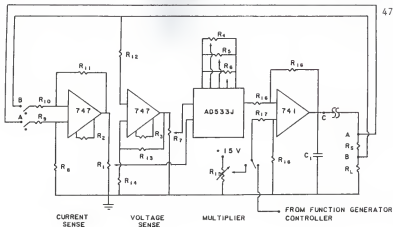


FIG. 4.8. Control system and power amplifier schematic diagrams.

RS-232C serial interface port for transmission of the stored data to other devices. The oscilloscope has two inputs, each with separate amplifying circuits. The oscilloscope is set in Cursor mode for triggering. In this mode the trigger source signal is continuously monitored until the triggering conditions are met or exceeded. At this instant the designated storage channel is assigned trigger time zero, and input signal regions both preceding and following the trigger time are stored for observstion. Thus, although the event time zero may not correspond to the trigger time zero, the entire transient can be captured by judicious choice of the storage channel for trigger time zero. Any difference between trigger and event time zero can be accounted for in analysis.

Three voltage signals are available during a transient: one relating to pressure vessel pressure, and two relating to test element temperature. Experimental runs to determine the pressure history during decompression are performed by recording the voltage signal from the pressure transducer amplifier, with the oscilloscope triggered by this signal. The unused input channel is turned off so that the total recording capacity of the oscilloscope is utilized for recording the single input voltage. This signal provides the information necessary for determining the pressure history of the test element during the transient. Experimental runs to determine the test element temperature history during decompression are performed by recording the variations in both the voltage across the test element and the voltage across a standard resistor, Model 79 21 from Ohmite, with the oscilloscope triggered by the latter signal. The two source signals are fed to the voltage bias system, where the voltages induced by the application of

power at initial conditions are cancelled by applying bucking voltages. The two recorded signals, together with their respective bucking voltages, provide the information necessary for determining the resistance of the test element and thus its temperature, as well as the power delivered to the test element. The computer code used in the analysis of temperature data is provided in Appendix A, and the computer code used in the analysis of pressure data is provided in Appendix B.

4.5 Test Element Installation

The test vessel is cleaned using acetone and then rinsed with the test fluid. The optical ports require special attention during cleaning to keep the windows clear of spots and also free from scratches.

The test element is soldered to the brass electrodes of the test section. The entire test section is then cleaned with acetone to remove excess flux or other contamination arising from the soldering process. The test section is then installed in the pressure vessel and the mounting bolts torqued to 80 to 110 Nm. A small voltage is applied across the test element in such a way that the wire glows cherry red. The air heating is done for approximately ten minutes. The heating of the wire tends to anneal the surface of the wire thus leading to consistent surface properties.

After the initial preparation of the test element, the test fluid is poured into the pressure vessel. The wire is then conditioned by applying a small voltage across it until boiling initiated. The wire is operated at this voltage for approximately ten minutes, then the voltage is increased slightly. This is repeated until the voltage across the wire reaches a maximum of 10 V. The purpose of this conditioning is to activate the cavities on the wire by driving out any trapped gas.

Each time a new test element is installed, the power supply must be calibrated. The following steps are used:

1. Set V_a and V_b equal to zero by grounding.
2. Adjust R_2 until the output of V_x is equal to zero.
3. Adjust R_3 until the output of V_y is equal to zero.
4. Adjust R_6 until the output of V_o is equal to zero.
5. Set V_a and V_b equal to each other and adjust R_4 so that the output of V_o is equal to zero.
6. Set V_b to zero (leaving V_a alone), then adjust R_5 so that the output of V_o is equal to zero.
7. Set V_a equal to zero and re-adjust R_6 so that the output of V_o is again equal to zero.
8. Set V_a equal to 8.245 V and V_b equal to 4.588 V.
9. Adjust R_1 until V_x is equal to 10.00 V.
10. Adjust R_7 until V_y is equal to 10.00 V.

4.6 Procedures

4.6.1 Preliminary Procedures

These steps are followed before each experimental session:

1. The test fluid is heated to boiling and boiled for one hour to remove dissolved gases.
2. A voltage is applied to the test element until vigorous boiling has commenced. The boiling from the element is continued for ten minutes.
3. The pressure vessel is refilled with de-gassed, near-boiling test fluid, and all valves to atmosphere are closed.
4. All associated electronic equipment is allowed to warm up for the hour required for de-gassing.

5. The oscilloscope Channel B trigger level is adjusted using a Wavetek Digital VCG Model 113.

4.6.2 Experimental Procedures

Since the oscilloscope has only two input channels for recording data, pressure data and temperature data must be recorded in separate experimental runs. However, most procedural steps are the same.

These steps are followed to set up each experimental run:

1. Vigorous boiling from the test element is achieved and continued for ten minutes at atmospheric pressure and the desired bulk fluid subcooling. This allows activation of the full size range of bubble nucleation sites.
2. The test element is allowed to cool to test fluid bulk temperature.
3. The system is slowly pressurized to the desired pressure while holding the bulk temperature constant. The system is maintained at this condition for ten minutes to allow it to stabilize.
4. Power is applied to the test element until the desired test element temperature is achieved.
5. The zero settings on the active input amplifiers of the oscilloscope are adjusted and the trigger time zero is checked. These settings are important for proper triggering of the oscilloscope and for use in the computer analysis of the run.
6. Voltage signals from the standard resistor and the test element are fed to the voltage bias system. Bucking voltages are applied such that the signals from the voltage bias system to

the oscilloscope are nominally zero. (This step is performed only if recording temperature data.)

If the boiling initiation time is not desired when performing a run to record pressure data, steps 1, 2, and 4 may be disregarded.

After the run has been set up, these steps are followed to continue the experiment:

7. Equipment settings are checked and recorded as necessary, and test fluid pressure and temperature are recorded. The gas supply solenoid valve is then closed.
8. The decompression is initiated and the oscilloscope is triggered by the appropriate input signal.
9. The recorded data are stored on floppy disc for later transmission to the computer.
10. Manually observed boiling initiation time is recorded (if measured).
11. Steps 1 through 10 are repeated until all data for this combination of test parameters are acquired.

The above steps are repeated for other test parameter combinations of interest.

5. RESULTS

5.1 Boiling Initiation

The initiation of boiling at a surface is governed by the size distribution of potential nucleation sites and the fluid temperature profile adjacent to the surface. The largest site will be the first to become active since it requires the least superheat for boiling. The mouth diameter of the largest potentially active site is estimated to be $0.35 \mu\text{m}$. This value was obtained from photo-micrographs of the surfaces of similar heating elements used in the concurrent study of pressure effects on boiling initiation during transient heating (22). As discussed in Chapter 3, the activation of a cavity occurs when the superheat has reached a prescribed magnitude at a distance from the surface comparable to the radius of the cavity mouth.

Natural convection determines the temperature gradient in the fluid adjacent to the surface before decompression. After natural convection is fully established, the thermal boundary layer and the temperature profile do not change significantly until the fluid is agitated, either by boiling or by bulk fluid movement. The increase in superheat necessary to initiate boiling arises from the decrease in the bulk fluid saturation temperature associated with the decrease in system pressure.

The temperature of the test element should behave in a simple manner when a constant power is applied and natural convection from the surface to the fluid is fully established. The temperature would be constant before a pressure transient is initiated, and would remain so during the transient until the inception of boiling. At this point the test element temperature would begin to decrease. Thus, finding this

point of time in the temperature history and the pressure at this time from the pressure history of a test would establish the conditions for boiling inception.

In this study of boiling initiation during pressure transients, three voltage signals, one for pressure and two for temperature, were available for each test. However, the digital oscilloscope could only record two of these simultaneously. Since both temperature signals had to be recorded for quantitative results, the nature and reproducibility of the decompression event had to be investigated.

The system was prepared for experimental runs by bulk boiling of the water in the pressure vessel for one hour at atmospheric pressure, after which the fluid lost through evaporation was replaced with degassed water at near-boiling temperature. The pressure vessel vent to the atmosphere was closed after bulk boiling, and subsequent system venting to the atmosphere was accomplished by opening the gas side of the pressurizer to atmospheric pressure. This was followed by vigorous boiling from the platinum test element for ten minutes. Pressure and temperature runs were then conducted to examine the effect of the pressure-temperature history on boiling initiation.

5.2 Pressure Runs

The program used to analyze the pressure runs is provided in Appendix B. The choice of amplifier time constant and the effect of system temperature on the pressure signal is discussed in Appendix C. Representative results from the program are provided in Appendix D. All pressure runs are described in Table 5.1.

The reproducibility of the decompression was of primary importance. In all runs the ambient temperature was 100°C, and the decompression

Table 5.1. Results of measurements made to determine the behavior of the pressure transients.

Run	p_a (MPa)	Drift (V/s)	Transfer Function (MPa/V)
AP2-2	0.377	-0.005246	0.7942
AP2-6	0.377	-0.005246	0.8654
AP2-7	0.515	-0.0096	0.7798
AP2-8	0.515	-0.0096	0.7908
AP3-4	0.515	-0.0096	0.8131
AP3-5	0.446	-0.007801	0.7631
AP3-6	0.446	-0.007632	0.7705
AP4-2	0.446	-0.005812	0.7748
AP4-3	0.584	-0.006913	0.7631
AP4-7	0.584	-0.005800	0.7771
AP4-8	0.584	-0.005295	0.7690
AP7-5	0.377	-0.003981	0.9952
AP7-8	0.377	-0.003926	1.0297
AP8-6	0.377	-0.002703	0.8536
AP9-2	0.377	-0.004091	0.9432
AP9-8	0.377	-0.002093	0.8248

ended at atmospheric pressure. The pressure histories for decompressions from initial pressures of 0.377-0.584 MPa are illustrated in Figs. 5.1 - 5.4, where it is seen that the decompression event is reproducible over most of the initial pressure drop.

The results of runs AP2-7, AP2-8, and AP3-4 require special comment. For unknown reasons, analysis of the raw data indicated negligible drift and a pressure transducer sensitivity greater than the manufacturer's specification. Since this was not characteristic of previous experience, a drift value was arbitrarily specified to give a transfer function reasonable with expectations. However, results with this data should be viewed with caution.

The pressurizer tended to back-fill with water from the pressure vessel in the course of the repeated fluid temperature cyclings experienced. This process was slow enough that little effect on depressurization was observed until the pressurizer was almost completely full of water. When this occurred the decompression event became erratic and unreliable. When approximately two liters of water were removed from the pressurizer, allowing a larger gas volume for pressurization, the rate of decompression changed significantly (Fig. 5.5). However, the partial removal of water did not affect the reproducibility of subsequent pressure runs, as shown in Figs. 5.6 and 5.7.

The decompressions displayed near-exponential behaviors over the reproducible portions of the transients. Figures 5.8 and 5.9 illustrate this behavior for representative pressure runs, and Table 5.2 lists their approximate reduction periods. These periods were on the order of 4 s before the pressurizer was partially drained and on the order of 6.6 s afterward.

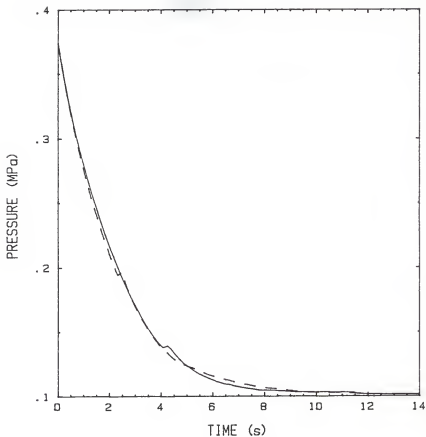


FIG. 5.1. Experimental pressure results for decompression from 0.377 to 0.101 MPa at $T_a = 100^\circ\text{C}$. The solid line represents results from run AP2-2. The dashed line represents results from run AP2-6.

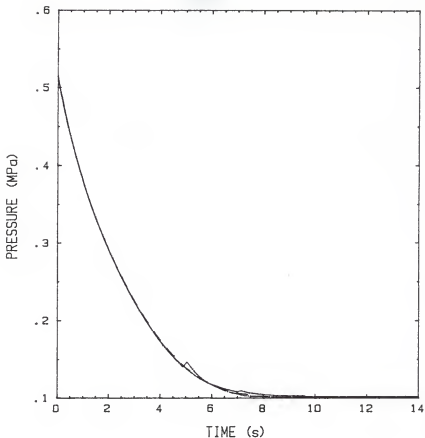


FIG. 5.2. Experimental pressure results for decompression from 0.515 to 0.101 MPa at $T_a = 100^\circ\text{C}$. The dashed line represents results from run AP2-7, the solid line represents results from run AP2-8, and the dot-dashed line represents results from run AP3-4.

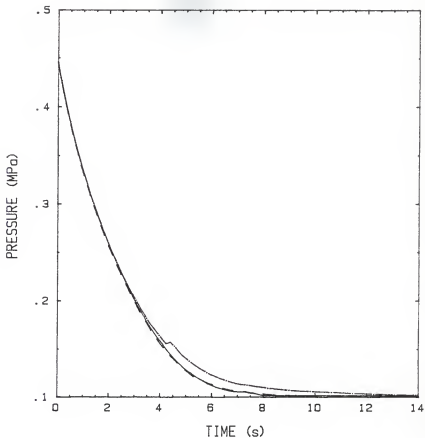


FIG. 5.3. Experimental pressure results for decompression from 0.446 to 0.101 MPa at $T_a = 100^\circ\text{C}$. The solid line represents results from run AP3-5, the dashed line represents results from run AP3-6, and the dot-dashed line represents results from run AP4-2.

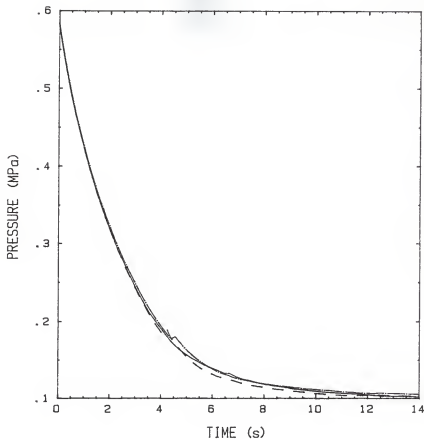


FIG. 5.4. Experimental pressure results for decompression from 0.584 to 0.101 MPa at $T_a = 100^\circ\text{C}$. The solid line represents results from run AP4-3, the dashed line represents results from run AP4-7, and the dot-dashed line represents results from run AP4-8.

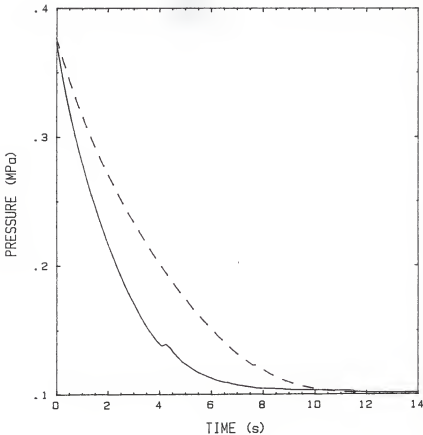


FIG. 5.5. Comparison of experimental pressure results for decompression from 0.377 to 0.101 MPa at $T_a = 100^\circ\text{C}$ before and after partial draining of the pressurizer. The solid line represents run AP2-2, performed before approximately 2 liters of water were removed from the pressurizer. The dashed line represents run AP8-8, performed after the quantity of water was removed.

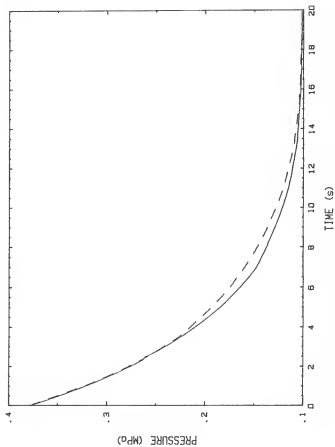


FIG. 5.6. Experimental pressure results for decompression from 0.377 to 0.101 MPa at $T_d = 100^\circ\text{C}$. The maximum system pressure was 0.377 MPa. The solid line represents results from run AP7-5. The dashed line represents results from run AP7-8.

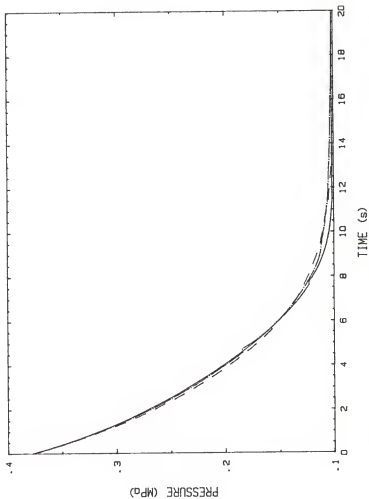


FIG. 5.7. Experimental pressure results for decompression from 0.377 to 0.101 MPa at $T_a = 100^\circ\text{C}$ after application of a maximum pressure greater than 0.377 MPa. The solid line represents results from run AP8-6, the dashed line represents results from run AP9-2, and the dot-dashed line represents results from run AP9-8.

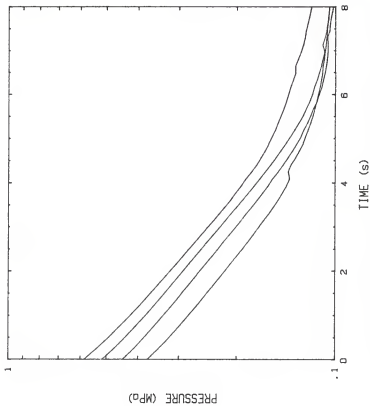


FIG. 5.8. Experimental pressure results for decompressions to 0.101 MPa at $T_a = 100^\circ\text{C}$. Initial pressures were 0.377 to 0.584 MPa. Results are from representative runs performed before removal of a quantity of water from the pressurizer.

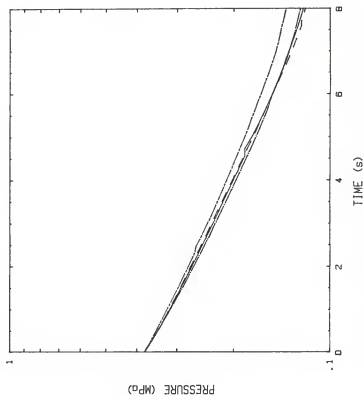


FIG. 5.9. Experimental pressure results for decompression from 0.377 to 0.101 MPa at $T = 100^{\circ}\text{C}$ after application of a maximum pressure $P_{a,\text{max}} = 0.377$ MPa. Results are from representative runs performed after removal of a quantity of water from the pressurizer.

Table 5.2. Approximate reduction periods for representative pressure runs.

Series	Run	t_1 (s)	t_2 (s)	$p(t_1)$ (MPa)	$p(t_2)$ (MPa)	τ (s)
1	AP2-2	0.56	3.60	0.3153	0.1496	4.078
2	AP2-8	0.56	3.60	0.4300	0.1921	3.773
3	AP3-5	0.56	3.60	0.3764	0.1733	3.920
4	AP4-3	0.56	3.60	0.4822	0.2089	3.634
5	AP7-5	0.56	5.52	0.3449	0.1736	7.225
6	AP8-6	0.48	10.08	0.3409	0.1612	6.622
7	AP9-2	0.56	5.52	0.3396	0.1587	6.519
8	AP9-8	0.56	5.52	0.3394	0.1615	6.680

5.3 Temperature Runs

The preparation of the system for a series of runs was described earlier. Additionally, each temperature run was preceded by vigorous boiling from the platinum test element for ten minutes at atmospheric pressure to ensure a consistent range of cavity sizes before pressurization.

In the series of tests presented, the system was pressurized to a maximum ambient pressure, $p_{a,max}$, while the bulk water temperature was held steady at 100°C. Power was then applied to the test element to elevate its temperature to 160°C. The decompression event was then initiated and a manual measurement of boiling initiation time t_b was obtained. The program used to analyze the temperature runs is provided in Appendix A. Representative results from the program are provided in Appendix E. All series are described in Table 5.3.

In series 1 the system was pressurized to a maximum pressure of 0.377 MPa. Figure 5.10 illustrates series 1, where it is observed that the temperature of the test element began to decrease almost immediately, while the measured boiling initiation time occurred after the temperature had dropped an appreciable amount.

In series 2 the system was pressurized to 0.515 MPa. The results of this series are shown in Fig. 5.11. The temperature of the test element remained constant for approximately two seconds, and the measured boiling times were close to the times at which the temperatures begin to decrease. Also apparent is the variability of the heater temperature recovery to a steady-state value.

Figures 5.12 and 5.13 illustrate series 3 and series 4, in which the system was pressurized to 0.446 and 0.584 MPa, respectively. Again, the heater temperature remained constant for a period of time after

Table 5.3. Experimental conditions for measurements to determine the effects of pressure-temperature history on boiling initiation. Initial conditions: wire temperature $T_w = 160^\circ\text{C}$, ambient temperature $T_a = 100^\circ\text{C}$.

Series	Run	Duration (s)	$p_{a,\max}$ (MPa)	$p_a(t=0)$ (MPa)	q (MW/m ²)
1	AP2-3	20	0.377	0.377	0.427
	AP2-4	20	0.377	0.377	0.430
	AP2-5	20	0.377	0.377	0.432
2	AP3-1	20	0.515	0.515	0.424
	AP3-2	20	0.515	0.515	0.424
	AP3-3	20	0.515	0.515	0.437
3	AP3-7	20	0.446	0.446	0.419
	AP3-8	20	0.446	0.446	0.419
	AP4-1	20	0.446	0.446	0.419
4	AP4-4	20	0.584	0.584	0.408
	AP4-5	20	0.584	0.584	0.416
	AP4-6	20	0.584	0.584	0.416
5	AP7-2	20	0.377	0.377	0.407
	AP7-3	20	0.377	0.377	0.419
	AP7-4	20	0.377	0.377	0.419
	AP7-6	20	0.377	0.377	0.419
	AP7-7	20	0.377	0.377	0.419
6	AP8-4	20	1.480	0.377	0.419
	AP8-5	20	>1.480	0.377	0.414
7	AP8-7	20	1.480	0.377	0.418
	AP8-8	100	1.480	0.377	0.424
8	AP9-4	200	0.791	0.377	0.418
	AP9-6	200	0.791	0.377	0.418

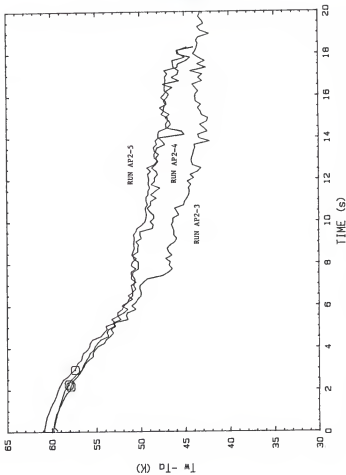


FIG. 5.10. Experimental temperature results for decompression from 0.377 to 0.101 MPa at $T_s = 100^\circ\text{C}$ and initial heater temperature $T_w = 160^\circ\text{C}$. The reduction period of the pressure transient was on the order of 4 s. The circles mark the measured boiling initiation times.

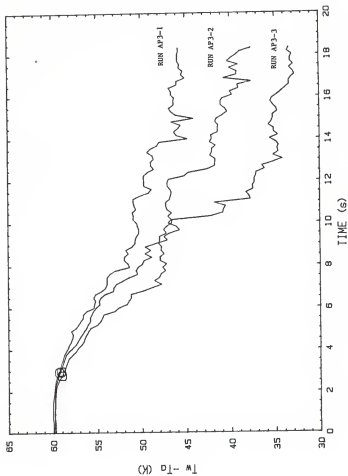


FIG. 5.11. Experimental temperature results for decompression from 0.515 to 0.101 MPa at $T_a = 100^\circ\text{C}$ and initial heater temperature $T_v = 160^\circ\text{C}$. The reduction period of the pressure transient was on the order of 4 s. The circles mark the measured boiling initiation times.

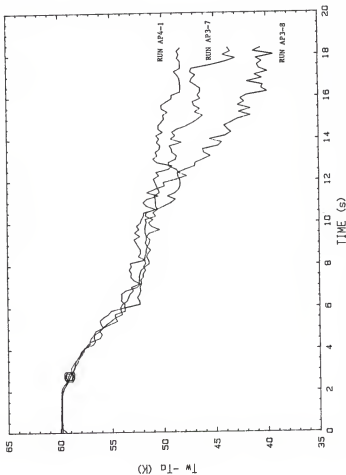


FIG. 5.12. Experimental temperature results for decompression from 0.446 to 0.101 MPa at $T_s = 100^\circ\text{C}$ and initial heater temperature $T_w = 160^\circ\text{C}$. The reduction period of the pressure transient was on the order of 4 s. The circles mark the measured boiling initiation times.

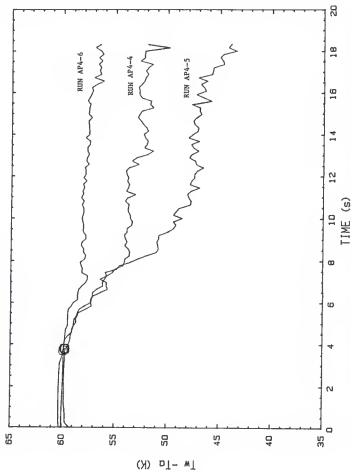


FIG. 5.13. Experimental temperature results for decompression from 0.584 to 0.101 MPa at $T_s = 100^\circ\text{C}$ and initial heater temperature $T_v = 160^\circ\text{C}$. The reduction period of the pressure transient was on the order of 4 s. The circles mark the measured boiling initiation times.

initiation of the pressure transient, and measured boiling times were close to the points where the temperatures began to decrease. Figure 5.13 also shows particularly well the variable nature of the heater temperature recovery after boiling had begun.

Series 5-8 were performed after removal of a quantity of water from the pressurizer. The rates of decompression in these runs were less than those for series 1-4 as discussed earlier. Additionally, the procedure was varied such that the system was subjected to a maximum pressure $p_{a,max}$, then slowly returned to a starting pressure $p_a(t=0)$, the pressure at the initiation of the pressure transient.

In series 5 the maximum pressure was 0.377 MPa. Measured boiling initiation times for all runs in this series except for run AP7-6 were well after the heater temperature had begun to decrease. As in series 1, the heater temperature began to decrease almost immediately after initiation of the pressure transient. Figure 5.14 illustrates this series.

In series 6 and series 7 the maximum pressure applied was 1.480 MPa. The exception was run AP8-5, which experienced an unknown maximum pressure greater than 1.480 MPa. In these runs the measured boiling time corresponds to the time of the first audible bubble collapse. Bubbles did not appear on the visible part of the test element until after the system had returned to atmospheric pressure. In series 6 (Fig. 5.15), the heater temperature began to decrease shortly after initiation of the pressure transient, but the decrease was very gradual until the end of the pressure transient. Heater temperature fluctuations indicative of substantial nucleate boiling then appeared, but the temperature decreased minimally compared to runs with less extreme overpressures.

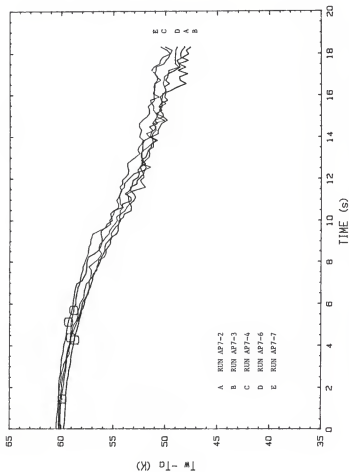


FIG. 5.14. Experimental temperature results for decompression from 0.377 to 0.101 MPa at $T_d = 100^\circ\text{C}$ and initial heater temperature $T_w = 160^\circ\text{C}$. The maximum pressure applied was 0.377 MPa and the pressure reduction period was on the order of 6.6 s. The circles mark the measured boiling initiation times.

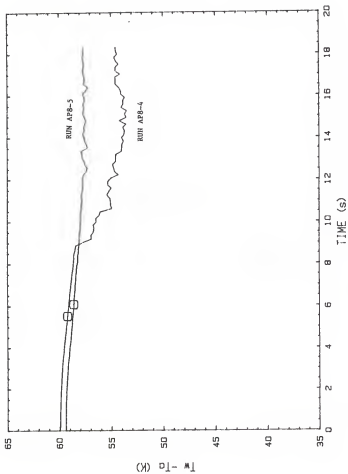


FIG. 5.15. Experimental temperature results for decompression from 0.377 to 0.101 MPa at $T_a = 100^\circ\text{C}$ and initial heater temperature $T_w = 160^\circ\text{C}$. The maximum pressure applied was 1.48 MPa and the pressure reduction period was on the order of 6.6 s. The circles mark the measured boiling initiation times.

This behavior was also observed in series 7, in which runs of 20 s and 100 s duration were performed. The temperature behavior during the first 20 s of the event is shown in Fig. 5.16(a). Even 100 s after the initiation of the pressure transient [Run AP8-8 and Fig. 5.16(b)] the heater temperature had only decreased about 7 K, as opposed to 10-12 K drops in 20 s seen in series 5, for example.

The long-term behavior of the heater temperature was of specific interest in series 8. The maximum pressure in this series was 0.791 MPa, and the duration of the runs was 200 s. Again, no bubbles were seen until after the system had returned to atmospheric pressure. Measured boiling initiation times were before substantial nucleate boiling was indicated by the temperature analysis. The minimal decrease in the heater temperature during the first 20 s of the event is illustrated in Fig. 5.17(a). After the initial drop, the temperature reached a plateau before experiencing a more sustained decrease. The heater temperature approached the steady-state boiling temperature at the same superficial heat flux by approximately 200 s. Series 8 and the corresponding steady-state boiling temperature traces are shown in Fig. 5.17(b).

If the point at which the heater temperature starts to decrease is taken as the incipient boiling point, conditions at boiling initiation can be determined from pressure and temperature values at this time. Normally, this estimated time should be equivalent to the measured boiling initiation time, with any difference accounted for by resolution of the data analysis, human error, and reaction time in operating the chronograph. However, a significant discrepancy could exist between these two times. If the resolution limit of the analyzed data is

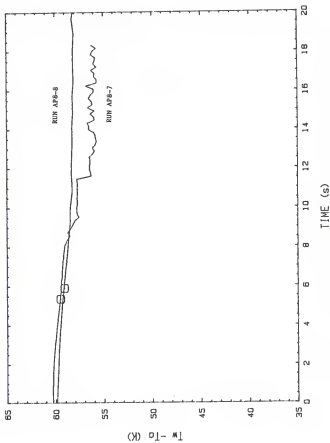


FIG. 5.16(a). Experimental temperature results showing the initial behavior of the heater temperature for $T_a = 100^\circ\text{C}$ and initial heater temperature $T_w = 160^\circ\text{C}$. The decompression was from 0.377 to 0.101 MPa after a maximum pressure of 1.48 MPa had been applied. The reduction period of the pressure transient was on the order of 6.6 s. The circles mark the measured boiling initiation times.

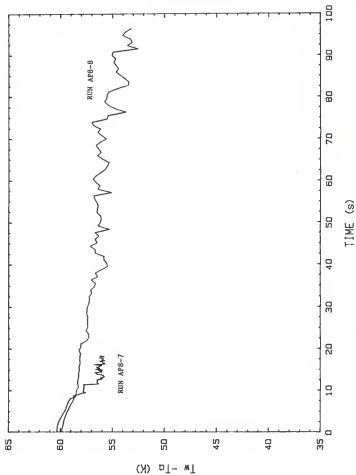


FIG. 5.16(b). Experimental temperature results showing the long-term behavior of the heater temperature for $T_a = 100^\circ\text{C}$ and initial heater temperature $T_v = 160^\circ\text{C}$. The decompression was from 0.377 to 0.101 MPa after a maximum pressure of 1.48 MPa had been applied. The reduction period of the pressure transient was on the order of 6.6 s.

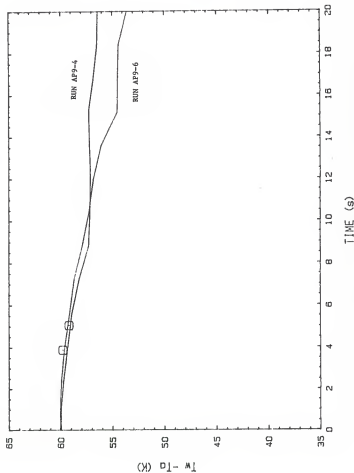


FIG. 5.17(a). Experimental temperature results showing the initial behavior of the heater temperature for $T_a = 100^\circ\text{C}$ and initial heater temperature $T_w = 160^\circ\text{C}$. The decompression was from 0.377 to 0.101 MPa after a maximum pressure of 0.791 MPa had been applied. The reduction period of the pressure transient was on the order of 6.6 s. The circles mark the measured boiling initiation times.

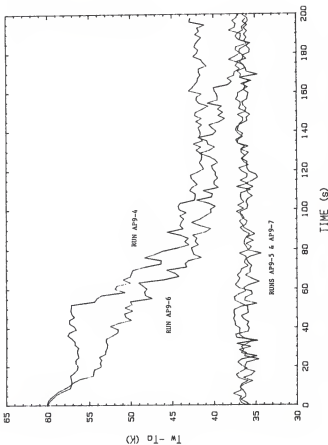


FIG. 5.17(b). Experimental temperature results showing the long-term recovery of the heater temperature to the steady-state nucleate boiling value at $T_c = 100^\circ\text{C}$. The decompression was from 0.377 to 0.101 MPa after a maximum pressure of 0.791 MPa had been applied. The initial heater temperature was $T_w = 160^\circ\text{C}$, and the reduction period of the pressure transient was on the order of 6.6 s. The superficial heat fluxes were the same for the transient and the steady-state runs. The time scale of the steady-state results as shown is multiplied by a factor of 10.

approached, the measured value should be selected as the true boiling initiation time. If boiling initiates on a part of the test element outside the visual range and the ambient noise level precludes audio detection, the measured time would be late and the estimated value should be selected as the true boiling initiation time. Additionally, although the partial pressure of noncondensable gas is assumed to be negligible, an isolated cavity could contain a bubble of noncondensable gas. Premature non-boiling bubble formation could occur at this site. The frequency of bubble formation would not display the periodicity of true nucleate boiling. Although conditions for boiling initiation would not have been achieved according to the criteria of this work, the chronograph would have been stopped at the appearance of the first bubble. Again, the estimated boiling initiation time should be selected. Following this prescription for determining true boiling initiation times, the measured and true boiling initiation times and conditions at boiling initiation are given in Table 5.4 for all series.

Table 5.4. Results of measurements made to determine the effects of pressure-temperature history on boiling initiation. In all cases, the heater is a platinum wire of 0.25 mm diameter and 9.6 cm length. Degassing was carried out at atmospheric pressure. True boiling initiation times are at the point the heater temperature began to show a substantial decrease. Initial conditions: Wire temperature $T_w = 160^\circ\text{C}$, ambient temperature $T_a = 100^\circ\text{C}$.

Series	Run	Measured t_b (s)	P_b (MPa)	$T_b - T_a$ (K)	True t_b (s)	P_b (MPa)	$T_b - T_a$ (K)	$T_b - T_a$ (K)
1	AP2-3	2.17	0.208	57.9	0.08 ^a	0.365	59.4	19.1
	AP2-4	2.95	0.173	57.4	0.08	0.365	60.8	20.5
	AP2-5	2.26	0.204	58.1	0.08	0.365	59.8	19.5
2	AP3-1	2.93	0.228	59.3	34.9	0.279	59.8	28.7
	AP3-2	2.98	0.225	59.1	35.1	0.279	59.7	28.6
	AP3-3	2.78	0.238	59.0	33.2	0.279	59.6	28.6
3	AP3-7	2.67	0.218	59.1	1.84	0.269	59.8	30.0
	AP3-8	2.75	0.214	59.0	36.6	0.269	59.8	30.0
	AP4-1	2.74	0.215	59.2	36.7	0.259	59.9	31.3
	AP4-4	3.78	0.201	59.8	39.4	0.194	59.8	40.5
4	AP4-5	3.76	0.202	59.7	39.1	0.202	59.7	39.1
	AP4-6	3.69	0.205	59.9	38.9	0.236	60.2	34.6
	AP7-2	4.28	0.202	58.7	38.2	0.299	59.5	26.1
5	AP7-3	5.14	0.181	59.3	42.2	0.299	60.2	26.8
	AP7-4	4.39	0.199	59.1	39.0	0.299	60.0	26.6
	AP7-6	1.46	0.299	59.9	26.5	0.299	59.9	26.5
	AP7-7	5.7	0.170	58.8	43.6	0.299	60.2	26.8
	AP8-4	5.22	0.161	59.2	45.7	0.110	58.4	56.1
6	AP8-5	6.08	0.149	58.6	47.4	0.101	57.7	57.7
	AP8-7	5.35	0.162	59.5	45.8	0.123	59.0	53.6
7	AP8-8	5.90	0.152	59.1	47.4	0.120	58.6	53.8
	AP9-4	5.05	0.174	59.2	43.3	0.131	58.2	50.8
8	AP9-6	3.88	0.203	59.8	39.1	0.131	58.7	51.3

^aListed times are first times for which temperature data were calculated. The estimated time range is 0.08 to 0.40 s.

^bListed times are from the measured time of Run AP7-6. The estimated time range is 1.0 to 2.5 s.

6. DISCUSSION OF RESULTS

6.1 Pressure Measurement

After the initiation of decompression the pressure vessel experienced a near-exponential reduction in pressure. Pressure transients were generally reproducible to times well beyond measured boiling initiation times. The spikes that occasionally appeared in the measurements are believed to be due to spurious electronic noise. The pressure measurement system sensitivity was less than expected due to installation constraints (see Appendix C). However, the system performed consistently except in the decompressions from 0.515 MPa (series 2). The reasons for the unusual behavior in those runs are unknown; therefore the results of series 2 are not considered in the following discussion.

6.2 Estimation of Boiling Initiation Times

Consider a heater experiencing a constant power application. In the case where heat transfer from the heater to a surrounding fluid is by natural convection, the inception of nucleate boiling will enhance the heat transfer and cause the heater surface temperature to decrease. Estimated boiling initiation times were obtained by determining the times at which the test heater temperature began to show a substantial decrease. These times provided an independent means of confirming measured boiling initiation times. The accuracy of the estimated times was dependent on the techniques used to obtain and analyze the raw voltage data. Since the variations in the voltages were expected to be small compared to the initial applied voltages, the measurement system was set up to measure only the variations. The analysis of the data required averaging the data over several points to minimize masking of

changes in true voltage by electrical noise. However, the data reduction resulted in coarse time steps and thus crude estimations of the time at which the heater temperature began to decrease. Although the two methods of determining boiling initiation times should have produced the same values, this was observed only in series 3 and series 4, where the inception of boiling was accompanied by a marked change in heater temperature. In these two series, the true boiling initiation times were the measured times adjusted according to the temperature histories. These adjustments were reasonable considering reaction times and human error. In the other series, however, experimental runs generally lacked a sharp change in heater temperature at boiling initiation, and the combination of test conditions helped to produce major differences in estimated and measured times. In series 1 the temperature began to decrease almost immediately, so true boiling initiation times were the first times for which temperature data were calculated. In series 5-8 poor data resolution combined with relatively slow pressure transients required specification of a range of boiling initiation times. Table 6.1 summarizes the conditions at boiling initiation for the series considered.

6.3 Effects of Pressure-Temperature History on Boiling Initiation

Runs in each series had been preceded by vigorous boiling from the test element for 10 minutes at atmospheric pressure and bulk fluid temperature $T_a = 100^\circ\text{C}$. The pressure was raised to the maximum value for each run before power was applied to the test heater to elevate its temperature.

In series 1, 3, and 4 the decompression began at the maximum pressure, and reduction periods were on the order of 4 s. The boiling

Table 6.1 Summary of results of measurements made to determine the effects of pressure-temperature history on boiling initiation. In all cases, the heater is a platinum wire of 0.25 mm diameter and 9.6 cm length. Degassing was carried out at atmospheric pressure. Initial conditions: $T_w = 160^\circ\text{C}$, $T_a = 100^\circ\text{C}$.

Series	$p_{a,\max}$ (MPa)	$p_a(t=0)$ (MPa)	t_b (s)	p_b (MPa)	$T_b - T_s$ (K)
1	0.377	0.377	0.08 - 0.40	0.365 - 0.330	19.7 - 23.2
3	0.446	0.446	1.84 - 2.00	0.269 - 0.259	30.2 - 31.4
4	0.584	0.584	3.12 - 3.92	0.236 - 0.194	34.4 - 40.7
5	0.377	0.377	1.0 - 2.5	0.321 - 0.260	24.1 - 31.3
6	1.48	0.377	8.88 - 12.24	0.110 - 0.101	57.7 - 60.0
7	1.48	0.377	7.6 - 9.2	0.127 - 0.114	53.6 - 56.7
8	0.791	0.377	6.4 - 8.0	0.144 - 0.121	49.9 - 55.0

initiation times increased with increasing initial pressure, and no overlapping of times was observed for the different series. Increasing initial pressure also resulted in decreasing boiling initiation pressures and increasing superheats at boiling inception.

In series 1, Fabric's hypothesis gives the largest available nucleation sites radii of $r_c = 0.132 \mu\text{m}$. This would lead to a boiling initiation pressure of 0.330 MPa and a boiling initiation superheat of 23.2 K. In series 3, $r_c = 0.106 \mu\text{m}$, leading to a boiling initiation pressure of 0.258 MPa and a boiling initiation superheat of 31.5 K. Both of these series are in excellent agreement with the Fabric model if the estimated boiling inception times are used. However, the model predicts a boiling initiation pressure of 0.114 MPa for the cavity size $r_c = 0.075 \mu\text{m}$ of series 4. This pressure is substantially below that observed in this series.

In series 5-8 the pressure transient was initiated from 0.377 MPa after the initial maximum pressure was applied. Reduction periods were on the order of 6.6 s. Boiling initiation times increased with increasing initial pressure, but the range of times tended to overlap for maximum pressures of 0.791 and 1.48 MPa.

Series 5 repeated the conditions of series 1 at a slower decompression rate. Although superheats were higher and pressures were lower at the inception of boiling in series 5, the results also support Fabric's model. Series 6-8 experienced such extremes in pressure that Fabric's model predicted no boiling for the given heater temperature. The model predicted a maximum cavity radius of $0.026 \mu\text{m}$ for series 6 and series 7, which would require a heater temperature of 192.3°C to initiate boiling. Series 8 would require a heater temperature of

169.7°C to initiate boiling from a predicted maximum cavity radius of 0.053 μm . However, the heater temperature history indicated that boiling began near the end of decompression, and after an additional period of time sites were seen to commence nucleating on the visible part of the test element.

6.4 Approach to Steady-State Boiling

Even though Fabric's model greatly underpredicted boiling initiation pressures (and overpredicted boiling initiation superheats) in series 4 and series 6-8, the pressure-temperature history did affect the reactivation of nucleation sites as the runs progressed.

The models used to predict boiling conditions based on cavity size can also explain the behavior of the heater temperature as steady-state nucleate boiling is approached. Consider Eq. (2.7),

$$p_v(T_w) - p_v(T_g) = 2\sigma(T_w)/r_c. \quad (2.7)$$

Although surface tension decreases with increasing temperature, vapor pressure is more sensitive to temperature variations and hence dominates the temperature dependence of Eq. (2.7). It is apparent that test element temperature results would be very sensitive to whether or not one or two cavities activate consistently in separate runs.

Since T_w remains constant until the inception of boiling, superheat increases with decreasing pressure until conditions for boiling are achieved. Once boiling begins, the heater cools, with the amount of cooling determined by the size and density of active sites. During the pressure transient, the cooling tends to offset the decrease in $p_v(T_g)$, thus restricting the activation of other nucleation sites.

After the decompression ends, a larger site rendered inactive by the pressure-temperature history experienced prior to the pressure transient could be activated in two ways. Vapor microbubbles created in the collapse of macroscopic bubbles in subcooled liquid could migrate from an adjacent active site and seed the cavity (33-36). If the cavity has vapor trapped at its base, activation could be accomplished either by vapor migration or by achievement of a sufficiently large local superheat to overcome the effects of pre-pressurization. Once the barrier to nucleation were breached, the cavity would remain active.

The temperature of the platinum wire test element was calculated using its resistance at 0°C (see Section 4.2). Based on measurements of the resistance at 100°C, the wire resistance at 0°C was $R_0 = 0.1961 \pm 0.0021$. This led to an uncertainty of ± 2.9 K in the value of the calculated wire temperature T_w . This was a systematic error that adds to the uncertainty in boiling initiation conditions beyond that reported in Table 6.1.

The system pressure during the decompression was calculated using the recorded value of the pressure at the initiation of the event. The error in this measurement, including the $\pm 0.25\%$ accuracy of the pressure gauge, was estimated to be ± 3.4 kPa. In addition, the pressure transducer had a linearity of $\pm 1.0\%$ (based on the manufacturer's performance data), and the dual mode amplifier had a range accuracy of $\pm 1\%$. The combination of these sources of error led to an uncertainty in the pressure measurement of approximately $\pm 8-9$ kPa, dependent upon the magnitude of the pressure drop recorded. This error also adds to the uncertainty in boiling conditions beyond that reported in Table 6.1.

6.5 Conclusions

Although this study did not allow a quantitative comparison of results to prediction based on Fabric's theory, the results did show a clear effect of the pressure-temperature history on the initiation of boiling during pressure transients. Increasing the initial pressure tended to delay the inception of boiling, showing that lower pressures and higher superheats were necessary to initiate boiling. Since smaller cavities require greater superheat to nucleate, this is consistent with predictions that the size of the largest potential nucleation site becomes progressively smaller as greater overpressures are applied. That boiling occurred in cases where none was predicted indicates that a simple time-independent theory using constant contact angles is inadequate.

7. SUGGESTIONS FOR FURTHER STUDY

A more comprehensive study of the pressure and temperature effects on boiling initiation during pressure transients needs to be performed, with a wide range of conditions and different heater geometries. Certain changes are recommended to improve the validity and efficiency of such a study.

The test heater power supply should be upgraded with additional deep-cycle storage batteries. This would improve stability and allow application of greater power levels. More stable power supplies to provide biasing voltages are also necessary to enhance the resolution of the small voltage variations associated with this study.

An electro-acoustical device should be used in an independent method for detecting the onset of nucleate boiling. The visual technique employed in this study was hampered by a limited field of vision and reaction times. Visual detection also becomes increasingly unreliable as pressure reduction periods decrease.

A much more sensitive pressure transducer should be installed. This would greatly improve the response of the pressure measurement system and minimize amplifier drift problems.

A four-channel recording digital oscilloscope and a captive computer system are also recommended. With a four-channel oscilloscope, all pertinent data for each experimental run could be recorded, and the reproducibility of the pressure transient would not be a major concern. A captive computer system would greatly improve the efficiency of the study, allowing each test to be analyzed during preparation for a subsequent experiment. Additionally, near immediate feedback of the effects of changes in test conditions would be available.

Finally, a study of decompression with heater temperature held constant needs to be performed, as well as an investigation of the effect of temperature on advancing and receding contact angles. These two subjects need to be addressed in order to develop a general model for boiling behavior during transient condition.

8. REFERENCES

1. Fabric, S., "Vapor nucleation on surfaces subjected to transient heating," Ph.D. Dissertation, Nuclear Engineering Department, University of California, Berkeley, 1964.
2. Winterton, R. H. S., "Nucleation of boiling and cavitation," J. Phys. D: Appl Phys., 10, 2041-2056 (1977).
3. Weisman, J., G. Bussell, and T. Hsieh, "The initiation of boiling during pressure transients," J. Heat Transfer, Nov. 1974, pp. 535-555.
4. Gallagher, J. P. and R. H. S. Winterton, "Effect of pressure on boiling nucleation," J. Phys. D: Appl. Phys., 16 L57-L61 (1983).
5. Sakurai, A., M. Shiotsu, and K. Hata, "Transient boiling caused by rapid depressurization from initial nonboiling state," 2d Multi-Phase Flow and Heat Transfer Symposium-Workshop, Miami Beach, Florida, 16-18 April 1979.
6. Churchill, S. W. and H. H. Chu, "Correlating equations for laminar and turbulent free convection from a horizontal cylinder," Int. J. Heat Mass Transfer, 18, 1049-1053 (1975).
7. Morgan, Vincent T., "The overall convective heat transfer from smooth circular cylinders," in Advances in Heat Transfer, Vol. 11, T. F. Irvine, Jr., & J. P. Hartnett (eds.), Academic Press, New York, 1975.
8. Fujii, T., M. Fujii, and T. Honda, "Theoretical and experimental studies of the free convection around a long horizontal thin wire in air," Heat Transfer 1982, Vol II, Seventh International Heat Transfer Conference, Munich, 1982, Paper NC32, pp. 311-316.
9. Griffith, Peter, and John D. Wallis, "The role of surface conditions in nucleate boiling," Chemical Engineering Progress Symposium Series, vol. 55, No. 30, 49-63 (1960).
10. Hsu, Y. Y., "On the size range of active nucleation cavities on a heating surface," J. Heat Trans., 84, 207-216 (1962).
11. Bergles, A. E., and W. M. Rohsenow, "The determination of forced-convection surface boiling heat transfer," J. Heat Transfer, 86, 365-372 (1964).
12. Han, C-Y, and Peter Griffith, "The mechanism of heat transfer in nucleate pool boiling - Part I, bubble initiation, growth, and departure," Int. J. Heat Mass Transfer, 8, 887-904 (1965).
13. Madejski, J., "Activation of nucleation cavities on a heating surface with temperature gradient in a superheated liquid," Int. J. Heat Mass Transfer, 9, 295-300 (1966).

14. Schmidt, R. J., and R. Cole, "Comments on activation of nucleation cavities on a heating surface with temperature gradient in a superheated liquid," *Int. J. Heat Mass Transfer*, 13, 443-445 (1970).
15. Schultz, R. R., S. Kasturirangan, and R. Cole, "Experimental studies of incipient vapor nucleation," *Can. J. Chem. Eng.*, 53, 408-413 (1975).
16. Schultz, R. R., and Robert Cole, "Initial bubble growth in slightly subcooled transient boiling," *AIChE Symposium Series, Heat Transfer - Orlando 1980*, vol. 76, Paper 199, pp. 310-317.
17. Sakurai, A, and M. Shiotsu, "Transient pool boiling heat transfer. Part 1: Incipient boiling superheat," *J. Heat Transfer*, 99, 547-553 (1977).
18. Cole, Robert, "Nucleate boiling heat transfer, a general survey," in *Boiling Phenomena*, Vol I, S. van Stralen and R. Cole (eds.), Hemisphere, New York, 1979, pp. 155-193.
19. Tolubinskiy, V. I., A. M. Kichigin, and S. G. Povsten, "Generalized equation for critical heat fluxes in free-convection boiling of liquids," *Heat Transfer - Soviet Research*, 8, No. 3, 23-31 (1976).
20. Tolubinski, V. I., Y. N. Ostrovskiy, and V. Y. Pisarev, "Transient heat transfer with phase transitions," *Heat Transfer - Soviet Research*, 11, No. 1, 18-23 (1979).
21. Johnson, H. A., "Transient boiling heat transfer to water," *Int. J. Heat Mass Trans.*, 14, 67-82 (1971).
22. Faw, R. E. and R. J. VanVleet, "Initiation of subcooled pool boiling during pressure and power transients," Report 161, Kansas Engineering Experiment Station, Manhattan, Kansas, 1984.
23. Howell, John R. and Kenneth J. Bell, "An experimental investigation of the effect of pressure transients on pool boiling burnout," *Heat Transfer - Houston, Chem. Eng. Progr., Symp. Ser.*, 59, 88-95.
24. Aoki, S., A. Inoue, and Y. Kozawa, "Transient boiling crisis during rapid depressurization," *Proc. 5th International Heat Transfer Conference, 1974*, Paper B6.3.
25. Kung, S., "Boiling heat transfer and bubble growth dynamics during rapid decompression," Ph.D. Dissertation, Nuclear Engineering Department, Kansas State University, Manhattan, Kansas, 1980.
26. Hooper, F. C. and A. H. Abdelmessih, "The flashing of liquids at higher superheats," *Heat Transfer 1966, Proc. 3rd Int. Heat Transfer Conf., Chicago, 1966*, Vol. 4, pp. 44-50.

27. Kenning, D. B. R. and K. Thirunavukkarasu, "Bubble nucleation following a sudden pressure reduction in water," Heat Transfer 1970, Proc. 4th Int. Heat Transfer Conf., Paris-Versailles, 1970, Vol. V, Paper B2.9.
28. Lienhard, J. H., Md. Alamgir, and M. Trela, "Early response of hot water to sudden release from high pressure," J. Heat Transfer, Trans. ASME, 100, 473-479 (1978).
29. Alamgir, Md., C. Y. Kan, and J. H. Lienhard, "An experimental study of the rapid depressurization of hot water," J. Heat Transfer 102, 433-438 (1980).
30. Rohsenow, W. M., "A method of correlating heat-transfer data for surface boiling," ASME Trans., 74, 969-976 (1952).
31. Stephan, K., and M. Abdelsalam, "Heat-transfer correlations for natural convection boiling," Int. J. Heat Mass Transfer, 23, 73-87 (1980).
32. Vines, R. F., The platinum metals and their alloys, International Nickel Co., New York, 1941.
33. Mesler, Russel, "Bubble nucleation," in Encyclopedia of Fluid Mechanics, N. P. Chermisinoff (ed.), Gulf Publishing (in press).
34. Mesler, Russell and Gregory Mallen, "Nucleate boiling in thin films," AIChE Journal, 23, 954-957 (1977).
35. Bergman, Theodore, and Russell Mesler, "Bubble nucleation studies, Part I: Formation of bubble nuclei in superheated water by bursting bubbles," AIChE Journal, 27, 851-853 (1981).
36. Carroll, Kenneth, and Russell Mesler, "Splashing liquid drops form vortex rings and not jets at low Froude numbers," J. Appl. Phys., 52(1), 507 (1981).

APPENDIX A

Program BOLL: Temperature Data Analysis

This program was written in Hewlett-Packard BASIC, Version 2.0, and run on the HP 9816 microcomputer. The program was originally written for analysis of power transient data from a concurrent study (22), and this capability is retained in the current version. In fact, the program parameters default to the power transient values, and changes in these values arising from choosing the pressure transient option are contained in the voltage input data set.

The voltage data for an experimental run are measured by a Nicolet Explorer III digital oscilloscope. The voltage input is converted to a corresponding channel number and stored. The channel number is obtained by dividing the sampled voltage by the conversion factor

$$V_{\text{norm}} = \{\text{Voltage Range}\}/2000 \quad \text{Volts/channel.}$$

There are 4096 voltage channels (-2048 to +2047), which allows a full scale voltage interval greater than -VR to +VR, where VR is the oscilloscope voltage range setting. There are also 4096 memory addresses available. Channel numbers are stored sequentially at a time interval determined by the Time Per Point switch. If both input channels A and B are active, the signals are stored in the sequence ABABAB, and the time interval defines the time between each sampling of the pair AB. Thus, the channel number defines the voltage and the memory address defines the time at which the voltage was sampled.

Voltage data is originally input to the program from the oscilloscope. The data is also saved on a disk for reference. The information required from each run depends on the case considered, i.e.,

transient power or transient pressure. The former is always performed in Normal Trigger mode on the oscilloscope, so the first datum is at time zero, while the latter is always performed in the Cursor Trigger mode. In this configuration the first datum time and the event initiation time must be recorded, as well as certain equipment settings. These values are stored as the first nine points in the data file when it is saved on the disk.

The program separates the raw voltage data into the two input signals, converts the data to true voltages, and then averages the data. The voltage is found from the expression

$$V = (\text{Channel number}) \frac{V_{\text{norm}}}{\text{Amp}} - V_{cz} + V_o,$$

where Amp is the signal amplification, V_{cz} is the zero input voltage level for the oscilloscope, and V_o is the biasing voltage. The biasing voltage is subtracted from the signal before it is amplified and sent to the oscilloscope to permit greater precision in the measurement of the small voltage changes associated with this case. The voltages are smoothed over n points, and the averaged voltage is assigned the averaged time value. Smoothing intervals are exclusive, i.e., no datum is used more than once in the averaging process.

Program output is available in an ASCII file for hardcopy printout or in binary data files for plotting the results.


```

1  '##### 801L #####
2  '##
3  '## PROGRAM CONVERTS VOLTAGE DATA MEASURED ACROSS A PLATINUM WIRE
4  '## AND A STANDAPO RESISTOR TO A TEMPERATURE HISTORY OF THE WIRE.
5  '## VOLTAGE DATA IS ORIGINALLY INPUT FROM THE NICOLET DIGITAL
6  '## OSCILLOSCOPE, BUT THESE DATA ARE ALSO STORED ON A DISC FOR
7  '## FUTURE REFERENCE. FROM THE TEMPERATURE DATA THE WIRE
8  '## SUPERHEAT, THE SUPERFICIAL HEAT FLUX AND THE MODIFIED
9  '## MUSSELT NUMBER HISTORIES ARE DETERMINED.
10 '##
11 '## PROGRAM WILL ANALYZE FOR TWO CASES: a) POWER TRANSIENTS AT
12 '## CONSTANT PRESSURE, and b) PRESSURE TRANSIENTS AT CONSTANT
13 '## POWER. THE DISTINCTION IS: a) NORMAL TRIGGER OF D-SCOPE,
14 '## and b) CURSOR TRIGGER OF D-SCOPE.
15 '##
16 '##
17 '## R.VANVLEET                                JSU NOV 1983
18 '##
19 '## revised for Case b and improved efficiency by
20 '##
21 '## G.SCHMIDT                                KSU SEP 1984
22 '##
23 '## update: "quack & dirty" plot (G.SCHMIDT)   KSU JAN 1985
24 '#####
25 '
110 OPTION BASE I
120 COM /Array/ Raw(4096),A(512),B(512),E(512),Z(512,4)
130 COM /Const/ Alph,Beta,Qbeg,Icnd
140 COM /Datum/ D1,Len,Ra,Rs,Ta,Tau,T0,Va0,Vb0,Vcz1,Vcz2,Vnorm,P$[35]
150 COM /Stat/ Amp,Mode,Nav,Nblock,Sigma
160 DIM Title$(80)
170 '
180 PRINT CHR$(12)
190 INPUT "RESET GRAPHICS (Y/N) ?";Reset$
200 INPUT "WHAT IS THE RUN NUMBER, e.g., RUN ?";Title$
210 Title$="RUN NUMBER "+Title$
220 PRINT Title$
230 '
240 ' MAIN PROGRAM
250 '
260 CALL Param
270 CALL Inpt(N$)
280 Tscale=Tau*(2000)
290 IF Reset$="Y" THEN CALL Graf set(Tscale)
300 PRINT Title$," ", " ", "SOURCE DATA FILE: ";N$
310 PRINT
320 PRINT "AVERAGING DATA - - -> ";Nav$; " POINT AVERAGING"
330 CALL Avg
340 PRINT "CALCULATING INITIAL WIRE RESISTANCE"
350 CALL Resis
360 PRINT "CALCULATING PROPERTIES"
370 CALL Prop$
380 CALL Outp(N$,Title$)
390 END
400 '
410 '
420 '
430 SUB Param
440 COM /Const/ Alph,Beta,Qbeg,Icnd
450 COM /Datum/ D1,Len,Ra,Rs,Ta,Tau,T0,Va0,Vb0,Vcz1,Vcz2,Vnorm,P$
460 COM /Stat/ Amp,Mode,Nav,Nblock,Sigma
470 '
480 ' DATA FOR THE WIRE, THE FLUID, AND THE SETTINGS ON THE SCOPE
490 ' DEFAULT FOR CONSTANT PRESSURE RUNS
500 '
510 Res=.2394+.00203 ' STANDARD RESISTANCE
520 D1=2.3E-4 ' WIRE DIAMETER
530 Len=.6E-2 ' WIRE LENGTH
540 '
550 Alph=.00292
560 Beta=-5.5E-7
570 Icnd=.6740 ' MEAN VALUE 70 TO 200 C IS .674 (WATER COND)
580 '

```

```

590 Vnorm=,002      ! 4V RANGE ON D-SCOPE
600 Vcz1=-4.       ! ZERO INPUT VOLTAGE LEVEL
610 Vcz2=4.
620 Va0=0.        ! BUCKING VOLTAGE
630 Vb0=0.
640 !
650 Qbeg=0.
660 Mode=1
670 Amp=1.
680 Nav=16
690 SUBEND
700 !
710 !
720 !
730 SUB Inpt(N#)
740 OPTION BASE 1
750 COM /Array/ Raw(4096),A(512),B(512),E(512),Z(512),4
760 COM /Const/ Alph,Beta,Qbeg,Icnd
770 COM /Outm/ St,Len,Ra,Rs,Ta,Tau,T0,Va0,Vb0,Vcz1,Vcz2,Vnorm,P#
780 COM /Stat/ Amp,Mode,Nav,NbLock,Signa
790 DIM Raw$(4096)(5)
800 !
810 INPUT "DATA SOURCE - - SCOPE = 1, BOAT FILE = 2",Tt
820 IF Tt=1 THEN
830 PRINT
840 PRINT "TRIGGER MODE - - NORMAL = 1, CURSOR = 2"
850 INPUT "(NORMAL if constant pressure run) ",Mode
860 END IF
870 CALL Reader(Tt,N#,Raw$(#))
880 IF Raw$(1)="CURSR" THEN Mode=2
890 IF Mode(>2) THEN Raw(1)=VAL(Raw$(1))
900 FOR I=2 TO 4096
910 Raw(I)=VAL(Raw$(I))
920 NEXT I
930 IF Mode=1 THEN 1040
940 Vnorm=Raw(2)
950 Ch0=Raw(3)
960 Tau=Raw(4)
970 Vcz1=Raw(5)/1000
980 Vcz2=Raw(6)/1000
990 Amp=Raw(7)
1000 Va0=Raw(8)
1010 Vb0=-Raw(9)
1020 Reserv=16
1030 P#=""
1040 BEEP 2197.26,,3
1050 INPUT "ENTER AMBIENT TEMPERATURE (C)",Ta
1060 INPUT "ENTER INITIAL WIRE TEMPERATURE (C)",T0
1070 IF Mode=2 THEN GOTO 1110
1080 INPUT "ENTER AMBIENT PRESSURE, e.g. 101.4,475.8,1397.8 (kPa)",P#
1090 INPUT "ENTER INITIAL HEAT FLUX ON THE WIRE (W/m^2)",Qbeg
1100 INPUT "ENTER SAMPLING TIME INCREMENT, E.G. IE-2 FOR 20 SEC RUN",Tau
1110 INPUT "ENTER [4,8,16] POINT RUNNING AVERAGE (DEFAULT = 16)",Nav
1120 IF Mode=1 THEN 1250
1130 INPUT "ENTER MAXIMUM PRESSURE",Pmax
1140 INPUT "ENTER STARTING PRESSURE FOR DECOMPRESSION",Pstart
1150 INPUT "UNITS ON VALUES JUST ENTERED - - K = kPa, P = psig",Unit#
1160 IF Unit#="K" THEN 1210
1170 Conv=(Pmax/14.696)+1#101.325
1180 Pmax=ROUND(Conv,5)
1190 Conv=(Pstart/14.696)+1#101.325
1200 Pstart=ROUND(Conv,5)
1210 IF Pstart<Pmax THEN P#="Max "VAL$(Pmax)&" "
1220 P#="Decompress from "VAL$(Pstart)
1230 Neg=INT((Ch0-1-Reserv)/Nav/2) ! ALLOWS CALCULATIONS FOR TIME<0
1240 Raw(10)=Ch0-Nav#Neg42 ! START CHANNEL
1250 Nch=(4096-(Raw(10)-1))/2
1260 NbLock=INT(Nch/Nav)
1270 PRINT CHR$(12)
1280 PRINT Raw$(1),Raw(2),Raw(3),Raw(4),Raw(5),Raw(6),Raw(7),Raw(8)
1290 PRINT
1300 SUBEND

```

```

1310
1320
1330
1340 SUB Reader (Tit,Name$,Raw$(#))
1350 OPTION BASE 1
1360 COM /Stat/ Aep,Mode,Nav,Nblock,Sigma
1370
1380 PRINT
1390 PRINT "PLEASE INSERT DATA DISC INTO DISC DRIVE 0"
1400 INPUT "PLEASE ENTER A UNIQUE NAME FOR THE BOAT FILE.",Name$
1410 DISP "WORKING, PLEASE WAIT."
1420 MASS STORAGE IS "HPB2901,700,0"
1430 IF Tit=2 THEN I&50
1440
1450 ASSIGN #Scope TO ?
1460 CONTROL 9,3;9600
1470 ASSIGN #Scope:FORMAT ON
1480 CONTROL 9,5;3
1490 CONTROL 9,4;2
1500 OUTPUT #Scope:CHR$(1);
1510 OUTPUT #Scope:CHR$(49);CHR$(48);CHR$(48);CHR$(49);CHR$(48);CHR$(48);
1520 OUTPUT #Scope:CHR$(79);CHR$(52);CHR$(48);CHR$(57);CHR$(54)
1530 OUTPUT #Scope:CHR$(2);
1540 ENTER #Scope USING "SA,I,1";Raw$(#)
1550 CONTROL 9,5;0
1560 ASSIGN #Scope TO #
1570 IF Mode=2 THEN CALL Scope_set(Raw$(#))
1580 DISP "WORKING, PLEASE WAIT."
1590 CREATE BOAT Name$,40%,5
1600 ASSIGN #Path TO Name$
1610 OUTPUT #Path USING "SA";Raw$(#)
1620 ASSIGN #Path TO #
1630 SUBEXIT
1640
1650 ASSIGN #Path TO Name$
1660 ENTER #Path USING "SA";Raw$(#)
1670 ASSIGN #Path TO #
1680 SUBEND
1690
1700
1710
1720 SUB Scope_set(Raw$(#))
1730 OPTION BASE 1
1740 REEP I&27.60,.3
1750 INPUT "ENTER TIME FOR FIRST DATA POINT (sec)",Ch10
1760 INPUT "ENTER TIME OF EVENT INITIATION (sec)",Event0
1770 INPUT "ENTER TIME INCREMENT, e.g. 1E-2 FOR A 20 s RUN ",Tau
1780 INPUT "ENTER VOLTAGE RANGE (V)",Range
1790 INPUT "ENTER DC LEVEL ZERO FOR CHANNEL A (V)",Oca
1800 INPUT "ENTER DC LEVEL ZERO FOR CHANNEL B (V)",Ocb
1810 INPUT "ENTER BUCKING VOLTAGE FOR CHANNEL A (V)",Va0
1820 INPUT "ENTER BUCKING VOLTAGE FOR CHANNEL B (V)",Vb0
1830 INPUT "ENTER SIGNAL AMPLIFICATION OF ANALOG COMPUTER",Aep
1840
1850 Raw$(1)="CURSR"
1860 Raw$(2)=VAL$(Range/2000)      ! Vnorm
1870 Ch0=(ABS(Ch10)-ABS(Event0))/2/Tau+1
1880 Raw$(3)=VAL$(Ch0)
1890 Raw$(4)=VAL$(Tau)
1900 Raw$(5)=VAL$(Oca/1000)      ! Vcz1
1910 Raw$(6)=VAL$(Ocb/1000)      ! Vcz2
1920 Raw$(7)=VAL$(Aep)
1930 Raw$(8)=VAL$(Va0)
1940 Raw$(9)=VAL$(ABS(Vb0))
1950 SUBEND
1960
1970
1980

```

```

1990 SUB Avg
2098 OPTION BASE 1
2010 COM /Array/ Raw(4096),A(512),B(512),E(512),I(512),4)
2020 COM /Datum/ B1,Len,Ra,Rs,Ta,Tau,T0,Va0,Vb0,Vcz1,Vcz2,Vncra,P8
2030 COM /Stat/ Aep,Mode,Nav,Mblock,Sigma
2040 !
2050 ! THIS SUBROUTINE SEPARATES THE DATA FOR THE STANDARD RESISTOR
2060 ! PLUS THE WIRE (A(I)) AND THE WIRE (B(I)) AND CALCULATES
2070 ! THEIR RUNNING AVERAGES
2080 !
2090 IF Mode=2 THEN Cstart=Raw(10)-1
2100 Jstart=Cstart+1
2110 FOR I=1 TO Nblock
2120 Sumx=0
2130 Sumy=0
2140 Jend=Jstart+2*Nav-1
2150 FOR J=Jstart TO Jend-1 STEP 2
2160 Sumx=Sumx+Raw(J)+Vncra/Aep ! CONVERT TO TRUE VOLTAGE
2170 Sumy=Sumy+Raw(J)+1+Vncra/Aep ! AND AVERAGE
2180 NEXT J
2190 A(I)=(Sumx/Nav-Vcz1/Aep+Va0 ! SUBTRACT ZERO LEVEL AND
2200 B(I)=(Sumy/Nav-Vcz2/Aep+Vb0 ! ADD BUCKING VOLTAGES
2210 Jstart=Jend+1
2220 NEXT I
2230 SUBEND
2240 !
2250 !
2260 !
2270 SUB Resis
2280 OPTION BASE 1
2290 COM /Array/ Raw(4096),A(512),B(512),E(512),I(512),4)
2300 COM /Datum/ O1,Len,Ra,Rs,Ta,Tau,T0,Va0,Vb0,Vcz1,Vcz2,Vncra,P8
2310 COM /Stat/ Aep,Mode,Nav,Mblock,Sigma
2320 !
2330 ! THIS SUBROUTINE CALCULATES THE INITIAL RESISTANCE OF THE WIRE
2340 !
2350 IF Mode>2 THEN GOTO 2380
2360 Ra=-Vb0/Va0*Rs-.00277 ! FOR INITIAL FLUX ON WIRE
2370 SUBEIT
2380 !
2390 Sumx=0 ! NO INITIAL FLUX, USE LEAST SQUARES FIT
2400 Sumz=0
2410 Sumy=0
2420 Sumy2=0
2430 Sumxy=0
2440 Iz=10
2450 FOR I=3 TO 12
2460 J1=(I-.5)*Nav ! TIME
2470 R=(B(I)*Rs/A(I)-.00277
2480 T1ae=J1*.125 ! EMPIRICAL ADJUSTMENT FOR BETTER FIT
2490 Sumx=Sumx+T1ae
2500 Sumz2=Sumz2+T1ae^2
2510 Sumy=Sumy+R
2520 Sumy2=Sumy2+R^2
2530 Sumxy=Sumxy+T1ae*R
2540 NEXT I
2550 Beta1=(Sumxy-(Sumx*Sumy)/Iz)/(Sumz2-(Sumx^2)/Iz)
2560 Beta0=(Sumy/Iz)-Beta1*(Sumx/Iz)
2570 S=(Sumz2-(Sumy^2)/Iz)
2580 T=(Sumz2-(Sumx^2)/Iz)
2590 U=1./(Iz-.2)
2600 V=Beta1^2
2610 W=U*(S-V*Iz) ! VARIANCE ABOUT REGRESSION
2620 Sigma=SQR(W*Sumz2/Iz/T) ! EST OF STD DEV OF INTERCEPT
2630 Ra=Beta0
2640 !
2650 BEEP 2197,26,.3
2660 PRINT " ",Ra=";Ra;" AT ";T0;" C"
2670 New=Ra
2680 INPUT "Enter new value for RA or accept default",New
2690 IF New=Ra THEN 2720
2700 PRINT "### NEW VALUE ###",Ra=";New;" AT ";T0;" C"
2710 Ra=New
2720 SUBEND

```

```

2730      |
2740      |
2750      |
2760      | SUB Props
2770      | OPTION BASE 1
2780      | COM /Array/ Raw(4096),A(512),B(512),E(512),Z(512,4)
2790      | COM /Const/ Alph,Beta,Bbeg,Xcnd
2800      | COM /Datum/ O1,Len,Ra,Rs,Ta,Tau,To,Vo0,Vb0,Vcz1,Vcz2,Vnorm,P#
2810      | COM /Stat/ Aep,Mode,Nav,Mblock,Sigma
2820      |
2830      |
2840      | THIS SUBROUTINE CALCULATES THE PROPERTIES OF THE WIRE:
2850      |
2860      | Z(1,1) = TIME
2870      | Z(2,2) = SUPERFICIAL HEAT FLUX
2880      | Z(3,3) = THETA ( T(wire) - T(ambient) )
2890      | Z(1,4) = MODIFIED NUSSLETT NUMBER
2900      |
2910      | Const=Ra/(1.+Alph#T0+Beta#T0^2) ! R(wire) AT T=0 C
2920      | IF Mode=1 THEN 2990
2930      | Neg=INT((Raw(3)-Raw(10))/Nav/2)
2940      | PRINT * *, "WIRE PROPERTY : ",R(wire) [ AT T=0 C ] = *,Const
2950      | New=Const
2960      | INPUT "Enter new value for R(wire) or accept default",New
2970      | IF New=Const THEN 2990
2980      | PRINT "### NEW VALUE ###",R(wire) [ AT T=0 C ] = *,New
2990      | Const=New
3000      | Bb=Alph/Beta
3010      | Ba=-.5#Bb
3020      | Bz=Bb^2
3030      | FOR I=1 TO Mblock
3040      | Z(1,1)=Tau#Nav#(1-Neg-.5)
3050      | Z(1,2)=A(1)#A(1)#(1-B(1)/A(1)-.00277/Rs)/(Rs#.1415#B(1)#Len)#Bbeg
3060      | R=(1-B(1))/Rs/A(1)-.00277
3070      | F=Bz+(4./Beta)#R/Const-1.)
3080      | Z(1,3)=Ba-.5#Bb#F-Ta
3090      | Z(1,4)=Z(1,2)#O1/(Xcnd#Z(1,3))
3100      |
3110      | Er1=(Vnorm^2)/(A(1)^2)
3120      | Er2=(Vnorm^2)/(B(1)^2)
3130      | Er3=(Sigma^2)/(Ra^2)
3140      | E(1)=(Er1+Er2+Er3)/((1-(Ra/R))^2)
3150      | NEXT I
3160      |
3170      | SUBEND
3180      |
3190      |
3200      | SUB Outp(W#,Title#)
3210      | OPTION BASE 1
3220      | COM /Array/ Raw(4096),A(512),B(512),E(512),Z(512,4)
3230      | COM /Datum/ O1,Len,Ra,Rs,Ta,Tau,To,Vo0,Vb0,Vcz1,Vcz2,Vnorm,P#
3240      | COM /Stat/ Aep,Mode,Nav,Mblock,Sigma
3250      | DIM Str$(16),He1$(80),He2$(80),He3$(80),Inb$(7),Pre$(18),R1$(80)
3260      | DIM Str$(80),S1$(80),T1$(80),W1$(80),N2$(80),Out$(3)$(80),Z1$(110)
3270      |
3280      | Mq=INT(Mblock/47) ! INFORMATION ABOUT FILE SIZE
3290      | N#Mblock-Mq#47
3300      | IF N#42 THEN Mblock=Mblock-(N#42)
3310      | IF N#0 THEN Mq=Mq-1
3320      | Mq=Mq+1
3330      | Size=15#Mq
3340      | ALLOCATE G(Mblock,2) ! "QUICK & DIRTY" PLOT
3350      | Abs=3
3360      | Ord=2 ! - HEAT FLUX v THETA if PRESSURE = const
3370      | IF Mode=2 THEN Ord=3 ! - THETA v TIME if HEAT FLUX = const
3380      | FOR I=1 TO Mblock
3390      | G(I,1)=Z(1,Abs)
3400      | G(I,2)=Z(1,Ord)
3410      | NEXT I
3420      |
3430      | BEEP 1&27.60,,J
3440      | PRINT CHR$(12)
3450      | CALL Scr Plot(B1#)
3460      | DEALLOCATE G(1)

```

```

3470
3480 INPUT "Do you wish to have a HARD COPY of the numbers ? ( Y/N ).",Ans#
3490 IF Ans#(1)"Y" THEN 4060
3500 PRINT Title$, " ", " ", "SOURCE DATA FILE: ";Ns#
3510 PRINT
3520 PRINT "#### PLEASE INSERT A DISC INTO DISC DRIVE 1"
3530 PRINT
3540 PRINT "AN ASCII FILE WILL BE CREATED ON THE DISC. THIS FILE CAN THEN"
3550 PRINT "BE TRANSFERED TO THE MAIN COMPUTER FOR PRINT OUT."
3560 INPUT "PLEASE ENTER A UNIQUE NAME FOR THE ASCII FILE.",Ans#
3570 Pres="
3580 Add$="
3590 Inb$="
3600 St$="
3610 He1$="
3620 He2$="
3630 He3$="
3640 Ra$=VAL$(Ra)
3650 Ra$=Ra$(1,7)
3660 P1$=Add$+"PRESSURE = " & P1$ & " lPa"
3670 R1$=Add$+"INITIAL RESIS. = " & R1$ & " OHMS AT " & VAL$(T0) & " C"
3680 Sig$=VAL$(Sigma)
3690 Sig$=Sig$(1,7)
3700 S1$=Add$+"SIGMA = " & S1$ & "
3710 T1$=Add$+"AMBIENT TEMP. = " & VAL$(Ta) & " C"
3720 W1$=Add$+"WIRE LENGTH = " & VAL$(Len1) & " M"
3730 M2$=Add$+"WIRE DIAMETER = " & VAL$(D1) & " M"
3740 Npg=1
3750 Lin=1
3760 MASS STORAGE IS ":HP82901,700,1"
3770 CREATE ASCII As$,Size
3780 ASSIGN #Path TO As#
3790 OUTPUT #Path;Add$+Title$,Inb$,W1$,M2$
3800 OUTPUT #Path;T1$,P1$,R1$
3810 OUTPUT #Path;S1$,Inb$,St$,Inb$,He1$
3820 OUTPUT #Path;He2$,Inb$,St$,Inb$
3830 FOR I=1 TO Nblock STEP 3
3840 CALL Dec(1,2$(I))
3850 Out$(1)=Pres$(1) & Inb$(2) & Inb$(3) & Inb$(4)
3860 IF I<=Nblock THEN CALL Dec(1+1,2$(I))
3870 Out$(2)=Pres$(1) & Inb$(2) & Inb$(3) & Inb$(4)
3880 IF I+2<=Nblock THEN CALL Dec(1+2,2$(I))
3890 Out$(3)=Pres$(1) & Inb$(2) & Inb$(3) & Inb$(4)
3900 IF I+1>Nblock THEN Out$(2)=Add$
3910 IF I+2>Nblock THEN Out$(3)=Add$
3920 OUTPUT #Path;Out$(1),Out$(2),Out$(3)
3930 Lin=Lin+1
3940 IF Npg=1 AND Lin=15 THEN GOTO 3960
3950 IF Lin=17 THEN
3960 OUTPUT #Path;Inb$,Inb$,Inb$,Inb$,Inb$,Inb$,Inb$,Inb$
3970 T1$=Add$+Title$&He3$&VAL$(Npg+1)
3980 OUTPUT #Path;T1$,Inb$,St$,Inb$
3990 OUTPUT #Path;He1$,He2$,Inb$,St$,Inb$,Inb$
4000 Lin=1
4010 Npg=Npg+1
4020 END IF
4030 NEXT I
4040 MASS STORAGE IS ":HP82901,700,0"
4050 BEEP 1302.08,.3
4060
4070 INPUT "Do you wish to have a PLOT of the numbers (Y/N) ?",Ans#
4080 IF Ans#(1)"Y" THEN 4610
4090 PRINT CHR$(12)
4100 PRINT Title$, " ", " ", "SOURCE DATA FILE: ";Ns#
4110 PRINT
4120 PRINT "#### PLEASE INSERT A DISC INTO DISC DRIVE 1"
4130 PRINT
4140 PRINT "BLOT FILES WILL BE CREATED ON THE DISC. THESE FILES CAN THEN"
4150 PRINT "BE PLOTTED USING THE GENERAL PLOTTING PROGRAM"
4160 PRINT

```

```

4170 PRINT "THE TYPE OF PLOTS POSSIBLE ARE:"
4180 PRINT
4190 PRINT "      1 = MUSSELT NUMBER vs TIME"
4200 PRINT "      2 = HEAT FLUX vs THETA"
4210 PRINT "      3 = BOTH PLOTS 1 AND 2 (plot 1 recorded first)"
4220 PRINT "      4 = HEAT FLUX vs TIME"
4230 PRINT "      5 = THETA vs TIME"
4240 PRINT "      6 = BOTH PLOTS 4 AND 5 (plot 4 recorded first)"
4250 INPUT "CHOOSE THE TYPE OF PLOT YOU WISH.",Qq
4260 IF Mode=1 THEN CALL Man1
4270 Format$="N1,000,0"
4280 ALLOCATE G(Nb1ock,2)
4290 MASS STORAGE IS " :HPB2901,700,1"
4300 IF Qq=1 OR Qq=3 THEN 4340
4310 IF Qq=2 THEN 4370
4320 IF Qq=4 OR Qq=6 THEN 4400
4330 IF Qq=5 THEN 4430
4340 Abs=1
4350 Ord=4
4360 GOTO 4460
4370 Abs=3
4380 Ord=2
4390 GOTO 4460
4400 Abs=1
4410 Ord=2
4420 GOTO 4460
4430 Abs=1
4440 Ord=3
4450
4460 INPUT "PLEASE ENTER A UNIQUE NAME FOR THE BOAT FILE.",Bd$
4470 FOR Q=1 TO Nb1ock
4480 G(Q,1)=I(Q,Abs)
4490 G(Q,2)=Z(Q,Ord)
4500 NEXT Q
4510 CREATE BOAT Bd$, (2*Nb1ock),9
4520 ASSIGN PPath TO Bd$
4530 OUTPUT PPath USING Format$:G(Q)
4540 ASSIGN PPath TO #
4550 PRINT
4560 PRINT "BOAT files: " :Bd$,Nb1ock;" points", "Data format: N1.000E"
4570 IF Qq=3 THEN 4370
4580 IF Qq=6 THEN 4430
4590 DEALLOCATE G(Q)
4600 MASS STORAGE IS " :HPB2901,700,0"
4610 BEEP 3126,94,.1
4620 PRINT "      END"
4630 SUBEND
4640
4650
4660
4670 SUB Dec(I,Z$(I))
4680 OPTION BASE 1
4690 COM /Array/ Raw(4096),A(512),B(512),E(512),Z(512,4)
4700
4710 THIS SUBROUTINE ENSURES THAT ALL VALUES HAVE THE
4720 CORRECT FIELD LENGTH FOR OUTPUT
4730
4740 Long=5
4750 Dec4="0"
4760 Per="."
4770 FOR J=1 TO 4
4780 Z=Z(I,J)
4790 IF Z<0 THEN I:=$VAL$(ROUND(FNRound(Z,3),5))
4800 IF Z<0 THEN 4880
4810 Z:=$VAL$(ROUND(Z,5))
4820 IF Z<1 THEN 4930
4830 GOTO 4980
4840 Z(I,J)=Z:Z
4850 Long=6
4860 NEXT J
4870 GOTO 5970

```

```

4890      FDR ZZ<0
4895      IF LEN(Zz$)>Long THEN Zz$=Zz$(1,Long)
4900      IF LEN(Zz$)<Long THEN Zz$=Zz$Dec$
4910      IF LEN(Zz$)<<Long THEN 4900
4920      GOTO 4840
4970      FOR 0<ZZ<1
4940      IF LEN(Zz$)>Long THEN Zz$=Zz$(1,Long-1)
4950      IF LEN(Zz$)<Long THEN Zz$=Dec$Zz$
4960      IF LEN(Zz$)<<Long THEN 5040
4970      GOTO 4840
4980      FOR ZZ>1
4990      P$="N"
5000      FOR F=LEN(Zz$) TO 1 STEP -1
5010      IF Zz$(F,F)=". " THEN P$="Y"
5020      NEXT F
5030      IF P$="N" AND LEN(Zz$)<Long THEN Zz$=Zz$Per$
5040      IF Zz$(1,E+5 AND LEN(Zz$)<Long THEN Zz$=Zz$Dec$
5050      IF Zz$(1,E+5 AND LEN(Zz$)<<Long THEN 5040
5060      GOTO 4840
5070      SUBEND
5080
5090
5100
5110      DEF FNRound(Z,Np)
5120      Nu=INT(Z*10^Np+.5)
5130      Nu=Nu/10^Np
5140      RETURN Nu
5150      FNEND
5160
5170
5180
5190      SUB Main
5200      OPTION BASE 1
5210      CON /Array/ Raw(4096),A(512),B(512),E(512),Z(512,4)
5220      CON /Stat/ Amp,Node,Nav,Nblock,Sigma
5230
5240      THIS SUBROUTINE EVALUATES THE ERROR TERM CALCULATED
5250      IN SUBROUTINE PROPS IN ORDER TO ELIMINATE THOSE FIRST
5260      VALUES THAT HAVE ST DR NDRE ERRDR
5270
5280      Nt=0
5290      FOR I=1 TO Nblock
5300      Nt=1
5310      IF (E(I)<.05 AND Z(I,3)>0.) THEN GOTO 5330
5320      NEXT I
5330      Nblock=Nblock-Nt
5340      IF Nblock=0 THEN GOTO 5410
5350      FOR J=1 TO Nblock
5360      Z(J,1)=Z(J+Nt,1)
5370      Z(J,2)=Z(J+Nt,2)
5380      Z(J,3)=Z(J+Nt,3)
5390      Z(J,4)=Z(J+Nt,4)
5400      NEXT J
5410      SUBEND
5420
5430
5440
5450      SUB Graf set(Tscale)
5460      CON /Stat/ Amp,Node,Nav,Nblock,Sigma
5470
5480      READ Y$,Y$,X1,X2,Y1,Y2
5490      IF Node=2 THEN READ Y$,Y$,X1,X2,Y1,Y2
5500      IF Node=2 THEN X2=Tscale
5510      GINIT
5520      GRAPHICS OFF
5530      VIEWPORT 0,130,15,100
5540      PEN 1
5550      LDIR P1/2
5560      LTRB 6
5570      NDVE 0,57
5580      LABEL Y$

```



```

5590 LDIR 0
5600 LORG 4
5610 MOVE 65,15
5620 LABEL X4
5630 CSIZE 3.7,.5
5640 MOVE 15,15
5650 LABEL X1
5660 MOVE 127,15
5670 LABEL X2
5680 LORG 2
5690 MOVE 0,20
5700 LABEL Y1
5710 MOVE 0,98
5720 LABEL Y2
5730 IF Mode=2 THEN 5700
5740 X1=LGT(X1)
5750 X2=LGT(X2)
5760 Y1=LGT(Y1)
5770 Y2=LGT(Y2)
5780 VIEWPORT 15,120,20,100
5790 WINDOW X1,X2,Y1,Y2
5800 FRAME
5810 IF Mode=1 THEN 5840
5820 MOVE 0,Y1
5830 DRAW 0,Y2
5840 !
5850 DATA "THETA","NEAT FLUX",10,100,IE4,IE6
5860 DATA "TINE"," THETA",-2,20,30,70
5870 SUBEND
5880 !
5890 !
5900 !
5910 SUB Scr plot (G(I))
5920 OPTION BASE 1
5930 COM /Stat/ Ang,Mode,Nav,Nblock,Sigma
5940 Er$="N"
5950 Istart=1
5960 IF Mode=2 THEN 6020
5970 FOR I=1 TO Nblock
5980 IF G(I,1)<0 OR G(I,2)<0 THEN Istart=I+1
5990 IF Istart=I+1 THEN 6020
6000 G(I,1)=LGT(G(I,1))
6010 G(I,2)=LGT(G(I,2))
6020 NEXT I
6030 LINE TYPE 1
6040 PEN 1
6050 ALPHA OFF
6060 GRAPHICS ON
6070 MOVE G(Istart,1),G(Istart,2)
6080 FOR I=Istart TO Nblock
6090 DRAW G(I,1),G(I,2)
6100 NEXT I
6110 MOVE 0,0
6120 IF Er$="Y" THEN 6190
6130 IF Mode=1 THEN OISP * *** LOG-LOG SCALING ***
6140 WAIT 5
6150 INPUT " ERASE THIS PLOT (Y/N) ? ",Er$
6160 IF Er$(1)="Y" THEN 6190
6170 PEN -1
6180 GOTO 6070
6190 GRAPHICS OFF
6200 ALPHA ON
6210 SUBEND

```

APPENDIX B

Program PRESSURE: Pressure Data Analysis

This program was written in Hewlett-Packard BASIC, Version 2.0, and run on the HP 9816 microcomputer. Experimental parameters are included in the voltage input data set, similar to the pressure transient option of program BOIL. Manipulation of data provided by the digital oscilloscope is as described in Appendix A; however, since the entire capacity of the oscilloscope is used to record the pressure signal, separation of data by input channel is not necessary. The program structure is identical to that of BOIL, and the output is arranged such that instantaneous pressures are reported at the same experimental times as the output from BOIL.

```

1  '##### PRESSURE #####
2  '##
3  '## PROGRAM CONVERTS VOLTAGE DATA MEASURED FROM A PRESSURE
4  '## TRANSDUCER (VIA A CHARGE AMPLIFIER) TO A PRESSURE HISTORY
5  '## OF THE PRESSURE VESSEL. VOLTAGE DATA IS ORIGINALLY INPUT
6  '## FROM THE NICOLET DIGITAL OSCILLOSCOPE, BUT THESE DATA ARE
7  '## ALSO STORED ON A DISC FOR FUTURE REFERENCE.
8  '## --NOTE-- D-SCOPE IS CURSOR TRIGGERED.
9  '##
10 '##
11 '## O.SCHNIOT KSU SEP 1984
12 '##
13 '## update: "quick & dirty" plot (O.SCHNIOT) KSU JAN 1985
14 '#####
15
110 OPTION BASE 1
120 DIM /Stat/ Ch0,Drift,Nav,Nblock,Pperv,Ta,Tau,Vnorm
130 DIM /Array/ A(1025),Raw(4096)
140 DIM Title$(80)
150
160 PRINT CHR$(12)
170 INPUT "RESET GRAPHICS (Y/N) ? ",Reset$
180 INPUT "WHAT IS THE RUN NUMBER ? ",Title$
190 Title$="RUN NUMBER " & Title$
200 PRINT Title$
210
220
230
240
250 Tscale=Tau/4000
260 IF Reset$="Y" THEN CALL Graf_set(Raw(6),Tscale)
270 PRINT Title$," ", " ", "SOURCE DATA FILE: ";N$
280 PRINT
290 PRINT "AVERAGING DATA - - -> ";Nav$; " POINT AVERAGING"
300 CALL Avg
310 PRINT "CALCULATING AMP DRIFT"
320 CALL Amp_drift
330 PRINT "CALCULATING PRESSURE HISTORY"
340 CALL Pressure
350 CALL Outp(N$,Title$)
360 INPUT "RECALCULATE WITH SAME SOURCE DATA (Y/N) ? ",Ans$
370 IF Ans$="Y" THEN 400
380 PRINT CHR$(12)
390 GOTO 270
400 END
410
420
430
440 SUB Inpt(N$)
450 OPTION BASE 1
460 DIM /Stat/ Ch0,Drift,Nav,Nblock,Pperv,Ta,Tau,Vnorm
470 DIM /Array/ A(1025),Raw(4096)
480 DIM Raw$(4096)(5)
490
500 INPUT "DATA SOURCE - - - SCOPE = 1, BDAT FILE = 2",Tt
510 CALL Reader(Tt,N$,Raw$(1))
520 FOR I=2 TO 4096
530 Raw(I)=VAL(Raw$(I))
540 NEXT I
550 Vnorm=Raw(2)
560 Ch0=Raw(3)
570 Tau=Raw(4)
580 Ta=Raw(5)
590 BEEP 2197.26,.3
600 Nav=B
610 INPUT "ENTER (4,0,16) POINT RUNNING AVERAGE (DEFAULT=8) ",Nav
620 Nch=4096-Ch0-Nav/2
630 Nblock=INT(Nch/Nav)
640 PRINT CHR$(12)
650 PRINT Raw$(1),Raw(2),Raw(3),Raw(4),Raw(5),Raw(6),Raw(7)
660 PRINT
670 SUBEND
680
690
700

```

```

710 SUB Reader (Tit,Name$,Raw$(#))
720 OPTION BASE 1
730 PRINT
740 PRINT "PLEASE INSERT DATA DISC INTO DISC DRIVE 0"
750 INPUT "PLEASE ENTER A UNIQUE NAME FOR THE BOAT FILE.",Name$
760 DISP "WORKING, PLEASE WAIT."
770 MASS STORAGE IS ":HPB2901,700,0"
780 IF Tit=2 THEN 1000
790
800 ASSIGN #Scope TO 9
810 CONTROL 9,3;9600
820 ASSIGN #Scope;FORMAT ON
830 CONTROL 9,5;3
840 CONTROL 9,4;2
850 OUTPUT #Scope;CHR$(1);
860 OUTPUT #Scope;CHR$(69);CHR$(148);CHR$(68);CHR$(49);CHR$(68);CHR$(148);
870 OUTPUT #Scope;CHR$(79);CHR$(52);CHR$(48);CHR$(57);CHR$(54)
880 OUTPUT #Scope;CHR$(2);
890 ENTER #Scope USING "SA,I,X";Raw$(#)
900 CONTROL 9,5;0
910 ASSIGN #Scope TO #
920 CALL Scope set (Raw$(#))
930 DISP "WORKING, PLEASE WAIT."
940 CREATE BOAT Name$,4096,5
950 ASSIGN #Path TO Name$
960 OUTPUT #Path USING "SA";Raw$(#)
970 ASSIGN #Path TO #
980 SUBEXIT
990
1000 ASSIGN #Path TO Name$
1010 ENTER #Path USING "SA";Raw$(#)
1020 ASSIGN #Path TO #
1030 SUBEND
1040
1050
1060
1070 SUB Scope set (Raw$(#))
1080 OPTION BASE 1
1090 BEEP 1627.69,,3
1100 INPUT "ENTER TIME FOR FIRST DATA POINT (sec)",Ch1to
1110 INPUT "ENTER TIME OF EVENT INITIATION (sec)",Event0
1120 INPUT "ENTER TIME INCREMENT, e.g. SE-3 FOR 20 SEC RUN",Tau
1130 INPUT "ENTER VOLTAGE RANGE (V)",Range
1140 INPUT "ENTER INITIAL PRESSURE (psig)",Po
1150 INPUT "ENTER FINAL PRESSURE (psig)",Pf
1160 INPUT "ENTER AMBIENT TEMPERATURE (C)",Ta
1170
1180 Raw$(1)="PRESS" ! For error if read by "BOIL"
1190 Raw$(2)=VAL$(Range/2000) ! Vnorm
1200 Raw$(3)=VAL$(ABS(Ch1to)-ABS(Event0))/Tau) ! Ch0
1210 Raw$(4)=VAL$(Tau)
1220 Raw$(5)=VAL$(Ta)
1230 Raw$(6)=VAL$(Po)
1240 Raw$(7)=VAL$(Pf)
1250 SUBEND
1260
1270
1280
1290 SUB Avg
1300 OPTION BASE 1
1310 DIM /Stat/ Ch0,Drift,Nav,Nblock,Pperv,Ta,Tau,Vnorm
1320 DIM /Array/ A(1025),Raw(4096)
1330
1340 ! THIS SUBROUTINE CALCULATES THE RUNNING AVERAGES OF THE DATA
1350
1360 Adj=INT(Nav/2)-1
1370 Jstart=Ch0-Adj
1380 FOR I=1 TO Nblock
1390 Sum=0
1400 Jend=Jstart+Nav-1
1410 FOR J=Jstart TO Jend ! CONVERT TO TRUE VOLTAGE
1420 Sum=Sum+Raw(J)*Vnorm ! AND AVERAGE
1430 NEXT J
1440 A(I)=(Sum/Nav)
1450 Jstart=Jend+1
1460 NEXT I
1470 SUBEND

```

```

1480 1
1490 1
1500 1
1510 SUB Amp drift
1520 OPTION BASE 1
1530 COM /Stat/ Ch0,Drift,Nav,Nblock,Pperv,Ta,Tau,Vnorm
1540 COM /Array/ A(1025),Raw(4096)
1550 1
1560 1 THIS SUBROUTINE CALCULATES THE DRIFT IN THE CHARGE AMP SIGNAL
1570 1 IT IS ASSUMED THAT DEPRESSURIZATION IS COMPLETE BY THE TIME
1580 1 OF INTEREST FOR THIS CALCULATION
1590 1
1600 Sumx=0
1610 Sumx2=0
1620 Sumy=0
1630 Sumxy=0
1640 Zz=14
1650 FOR I=(Nblock-15) TO (Nblock-2)
1660 I=Tau*Nav*(I-1) ! TIME
1670 Sumx=Sumx+I
1680 Sumx2=Sumx2+I^2
1690 Sumy=Sumy+A(I)
1700 Sumxy=Sumxy+A(I)*I
1710 NEXT I
1720 Drift=ROUND((Sumxy-(Sumx*Sumy)/Zz)/(Sumx2-(Sumx^2)/Zz),6)
1730 SUBEND
1740 1
1750 1
1760 1
1770 SUB Pressure
1780 OPTION BASE 1
1790 COM /Stat/ Ch0,Drift,Nav,Nblock,Pperv,Ta,Tau,Vnorm
1800 COM /Array/ A(1025),Raw(4096)
1810 DIM Test(1025)
1820 1
1830 I=0
1840 Amin=100
1850 FOR I=1 TO Nblock ! ADJUST VOLTAGE FOR DRIFT
1860 Vdrift=Tau*Nav*(I-1)*Drift
1870 Test(I)=A(I)-Vdrift
1880 IF Test(I)>Amin THEN 1910
1890 Amin=Test(I)
1900 I=I+1
1910 NEXT I
1920 Pperv=ROUND((Raw(6)-Raw(7))/(A(1)-Amin),6) ! psi/volt
1930 1
1940 IF I=0 THEN BEEP 2197.26,.3
1950 PRINT " ",ORIFT = ";Drift;" Volts per second", " ",PSI/VOLT = ";Pperv
1960 New=Drift
1970 INPUT "Enter new value for ORIFT or accept default",New
1980 IF New=Drift THEN 2030
1990 Drift=New
2000 I=1
2010 DISP "RECALCULATING ---> PSI/VOLT"
2020 GOTO 1840
2030 FOR I=1 TO Nblock
2040 A(I)=Raw(6)-(Test(I)-Test(1))*Pperv ! CONVERT TO PRESSURE
2050 IF I<Amin THEN A(I)=A(Amin)
2060 NEXT I
2070 SUBEND
2080 1
2090 1
2100 1
2110 SUB Outp(%,Title%)
2120 OPTION BASE 1
2130 COM /Stat/ Ch0,Drift,Nav,Nblock,Pperv,Ta,Tau,Vnorm
2140 COM /Array/ A(1025),Raw(4096)
2150 DIM Add#(16),He1#(80),He2#(80),He3#(80),Inb#(5),St#(80)
2160 DIM T#(80),T2#(80),Out#(5)(80),Zs(4)(10)
2170 1
2180 Istart=16/Nav+1 ! FILE SIZE INFORMATION
2190 Step=(Istart-1)*42
2200 Size=INT(Nblock/Step+.5)
2210 ALLOCATE G(Size,2)
2220 G(1,1)=0
2230 G(1,2)=Raw(6)

```

```

2240 J=1
2250 FOR I=Istart TO Nblock STEP Step
2260   J=J+1
2270   IF J>Size THEN 2300
2280   G(I,1)=Tau*Navt(I-1)           ! TIME
2290   G(I,2)=A(I)                   ! PRESSURE
2300   NEXT I
2310
2320   PRINT
2330   PRINT " ", "*****"
2340   PRINT " ", "the **DUICK & DIRTY** screen plot will be"
2350   PRINT " ", "      PSIG v TIME regardless of output units choice"
2360   INPUT "ENTER PRESSURE UNITS FOR OUTPUT : K = kPa, P = psig",Units
2370   BEEP 1&27,60,,J
2380   PRINT CHR$(12)                 ! "DUICK & DIRTY" PLOT
2390   CALL Scr_plot(G(I),Size)       ! PSIG v TIME
2400
2410   IF Units="P" THEN 2470
2420   DISP "CONVERTING psig ----> kPa "
2430   Pperv=Pperv/14.696#101.325
2440   FOR I=1 TO Size                 ! CONVERT TO kPa (absolute)
2450     G(I,2)=(G(I,2)/14.696+1)#101.325
2460   NEXT I
2470   INPUT "Do you wish to have a HARD COPY of the numbers ? (Y/N)",Ans#
2480   IF Ans#="Y" THEN 2000
2490   PRINT Title$, " ", " ", "SOURCE DATA FILE: ",N#
2500   PRINT
2510   PRINT "#### PLEASE INSERT A DISC INTO DISC DRIVE I "
2520   PRINT
2530   PRINT "AN ASCII FILE WILL BE CREATED ON THE DISC. THIS FILE CAN THEN"
2540   PRINT "BE TRANSFERRED TO THE MAIN COMPUTER FOR PRINT OUT"
2550   INPUT "PLEASE ENTER A UNIQUE NAME FOR THE ASCII FILE ",As#
2560   Add#=" "
2570   Inb#=" "
2580   St#=" "
2590   He1#=" "
2600   He2#=" "
2610   He3#=" "
2620   T1#=Add#+"AMBIENT TEMP. = " & VAL$(Ta)*" C"
2630   T2#=Add#+"PSI PER VOLT = " & VAL$(OROUND(Pperv,6))
2640   IF Units="P" THEN 2670
2650   He2#=" " (s) (kPa) (s) (kPa)
2660   T2#=Add#+"kPa PER VOLT = " & VAL$(OROUND(Pperv,6))
2670   Istart=I
2680   Iend=45
2690   Npg=1
2700   MASS STORAGE IS ":HPB290I,700,1"
2710   CREATE ASCII As#,60
2720   ASSIGN #Path TO As#
2730   OUTPUT #Path;Add#Title$,Inb#,T1#,T2#,Inb#
2740   OUTPUT #Path;St#,Inb#,He1#,He2#
2750   OUTPUT #Path;Inb#,St#,Inb#
2760   FOR I=Istart TO Iend STEP 3
2770     CALL Dec(I,G(I),T#(I),Size)
2780     Out$(1)=Add#&T#(1)&Inb#&T#(2)&Add#&T#(3)&Inb#&T#(4)
2790     IF I<=Size THEN CALL Dec(I+1,G(I),T#(I),Size)
2800     Out$(2)=Add#&T#(1)&Inb#&T#(2)&Add#&T#(3)&Inb#&T#(4)
2810     IF I+2<=Size THEN CALL Dec(I+2,G(I),T#(I),Size)
2820     Out$(3)=Add#&T#(1)&Inb#&T#(2)&Add#&T#(3)&Inb#&T#(4)
2830     IF I+1>Size THEN Out$(2)=Add#
2840     IF I+2>Size THEN Out$(3)=Add#
2850     OUTPUT #Path;Out$(1),Out$(2),Out$(3)
2860   NEXT I
2870   IF Iend=Size THEN 2970
2880   OUTPUT #Path;Inb#,Inb#,Inb#,Inb#,Inb#,Inb#,Inb#,Inb#
2890   Npg=Npg+1
2900   T1#=Add#&T#Title#&He3#&VAL$(Npg)
2910   Istart=Iend+46
2920   Iend=Istart+44
2930   IF Iend>Size THEN Iend=Size
2940   OUTPUT #Path;T1#,Inb#,St#,Inb#,He1#
2950   OUTPUT #Path;He2#,Inb#,St#,Inb#,Inb#
2960   GOTO 2760
2970   ASSIGN #Path TO #
2980   MASS STORAGE IS ":HPB290I,700,0"
2990   BEEP 1302,08,,J

```

```

3000 INPUT "Do you wish to have a PLOT of the numbers ? (Y/N)",Ans$
3010 IF Ans$(1) THEN 3200
3020 PRINT CHR$(12)
3030 PRINT Title$, " ", " ", "SOURCE DATA FILE : ";Ns
3050 PRINT
3060 PRINT "#### PLEASE INSERT A DISC INTO DISC DRIVE 1"
3070 PRINT
3080 PRINT "A BOAT FILE WILL BE CREATED ON THE DISC. THIS FILE CAN THEM"
3090 PRINT "BE PLOTTED USING THE GENERAL PLOTTING PROGRAM"
3100 INPUT "PLEASE ENTER A UNIQUE NAME FOR THE BOAT FILE ",Bd$
3110 MASS STORAGE IS "HPB2901,700,1"
3120 CREATE BOAT Bd$, (24*Size),9
3130 ASSIGN #Path TO Bd$
3140 Format="MZ.000E,8"
3150 OUTPUT #Path USING Format;G(I)
3160 ASSIGN #Path TO #
3170 MASS STORAGE IS "HPB2901,700,0"
3180 PRINT
3190 PRINT "BOAT files ";Bd$,Size;" points", "Data format: MZ.000E"
3200 DEALLOCATE G(I)
3210 REEP 5126.94,.1
3220 PRINT " END"
3230 SUBEND
3240
3250
3260
3270 SUB Dec(I,Z(I),Z(I),Size)
3280 OPTION BASE 1
3290
3300 THIS SUBROUTINE ENSURES THAT ALL VALUES HAVE THE
3310 CORRECT FIELD LENGTH FOR OUTPUT
3320
3330 Ii=1
3340 A=0
3350 Dec$=""
3360 Per$=""
3370 Z$(1)=""
3380 Z$(4)=""
3390 Long=5
3400 FOR J=1 TO 2
3410 Zz=Z(Ii,J)
3420 IF Zz<0 THEN Zz$=VAL$(ROUND(FNROUND(Zz,3),5))
3430 IF Zz<0 THEN 3550
3440 Zz$=VAL$(ROUND(Zz,5))
3450 IF Zz<1.E-5 THEN Zz$=".0000000"
3460 IF Zz<1.0 THEN 3600
3470 BOTO 3650
3480 Z$(J+A)=Zz$
3490 Long=6
3500 NEXT J
3510 IF Ii<>1 OR I+45>Size THEN 3740
3520 A=2
3530 Ii=I+45
3540 GOTO 3390
3550 FOR ZZ<0
3560 IF LEN(Zz$)>Long THEN Zz$=Zz$[1,Long]
3570 IF LEN(Zz$)<Long THEN Zz$=Zz$&Dec$
3580 IF LEN(Zz$)<Long THEN 3570
3590 GOTO 3480
3600 FOR CZZ<1
3610 IF LEN(Zz$)>Long THEN Zz$=Zz$[1,Long-1]
3620 IF LEN(Zz$)<Long THEN Zz$=Dec$&Zz$
3630 IF LEN(Zz$)<Long THEN 3710
3640 GOTO 3480
3650 FOR ZZ>1
3660 P$=""
3670 FOR F=LEN(Zz$) TO 1 STEP -1
3680 IF Zz$(F,F)="" THEN P$=P$+" "
3690 NEXT F
3700 IF P$="" AND LEN(Zz$)<Long THEN Zz$=Zz$&P$
3710 IF Zz<1.E+5 AND LEN(Zz$)<Long THEN Zz$=Zz$&Dec$
3720 IF Zz<1.E+5 AND LEN(Zz$)<Long THEN 3710
3730 GOTO 3480
3740 SUBEND

```

```

3750  !
3760  !
3770  !
3780  DEF FNRound(L,Mp)
3790  Nu=INT(L/10*Mp+.5)          ! ROUNDING FOR Z<0
3800  Nu=Nu/10*Mp
3810  RETURN Nu
3820  FNREND
3830  !
3840  !
3850  !
3860  SUB Graf set(P2,Tscale)
3870  @IWIT
3880  GRAPHICS OFF
3890  VIEWPORT 0,130,15,100
3900  PEN 1
3910  LDIR P1/2
3920  LORG 6
3930  MOVE 0,57
3940  LABEL *PRESSURE (psig)*
3950  LDIR 0
3960  LORG 4
3970  MOVE 65,15
3980  LABEL *TIME (s)*
3990  CSIZE 3.7,.5
4000  MOVE 7,15
4010  LABEL *0*
4020  MOVE 128,15
4030  LABEL Tscale
4040  LORG 2
4050  MOVE 0,20
4060  LABEL *-5*
4070  MOVE 0,98
4080  LABEL P2
4090  VIEWPORT 7,130,20,100
4100  WINDOW 0,Tscale,-5,P2
4110  FRAME
4120  ATES 1,1,0,0,5,5,2
4130  SUBEND
4140  !
4150  !
4160  !
4170  SUB Scr plot(G(I),Numdata)
4180  OPTION BASE 1
4190  Er$="N"
4200  LINE TYPE 1
4210  PEN 1
4220  ALPHA OFF
4230  GRAPHICS ON
4240  MOVE G(I,1),G(I,2)
4250  FOR I=1 TO Numdata
4260  IF G(I,1)=0 AND I>1 THEN 4280
4270  DRAW G(I,1),G(I,2)
4280  NEXT I
4290  MOVE 0,0
4300  IF Er$="Y" THEN 4360
4310  MALT 5
4320  INPUT *      ERASE THIS PLOT (Y/N)?*,Er$
4330  IF Er$="Y" THEN 4360
4340  PEN -1
4350  GOTO 4240
4360  GRAPHICS OFF
4370  ALPHA ON
4380  SUBEND

```


APPENDIX C

System Performance

Control System Performance

The ability of the control system to provide a constant power delivery (superficial heat flux) to the test element is illustrated in Fig. C1. It will be noted that, in spite of the substantial change in wire temperature (and the rapidity at which this change is possible), with associated change in wire resistance, the control system provides constant power delivery.

Pressure Measurement System Performance

The ability of the pressure measurement system to yield an accurate pressure history of an experiment depends on proper setup for test conditions. Best accuracy requires flush mounting of the pressure transducer to the test section. However, this was not possible due to the necessity of providing cooling capability for the transducer with the cooling adaptor. The choice of the amplifier time constant also affects the accuracy, and a dramatic effect on the voltage signal measured for a given pressure drop. Use of the short and medium time constant settings resulted in signal decay during the pressure transient, while use of the log time constant introduced the complication of signal drift (Fig. C2).

The effect of temperature on the measure voltage signal is illustrated in Fig. C3. The figure compares measurements at an ambient temperature $T_a = 27^\circ\text{C}$ to measurements at $T_a = 100^\circ\text{C}$. For the long time constant setting, the drift is adversely affected by increasing temperature (no significant difference in behavior was found in the medium and short time constant cases). Additionally, as seen in Fig.

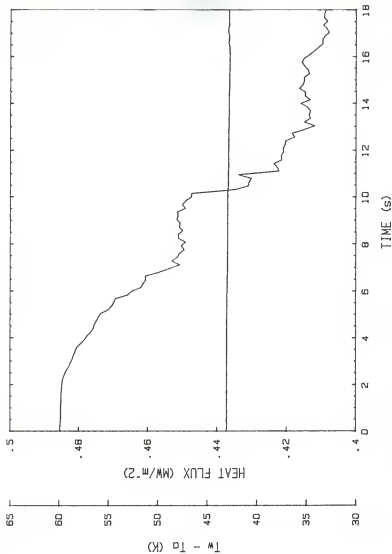


FIG. C1. Control system performance for a 20 s run. The straight line is the heat flux as a function of time. The curve is the test heater temperature as a function of time. Results are from run AP3-3, with ambient temperature $T_a = 100^\circ\text{C}$.

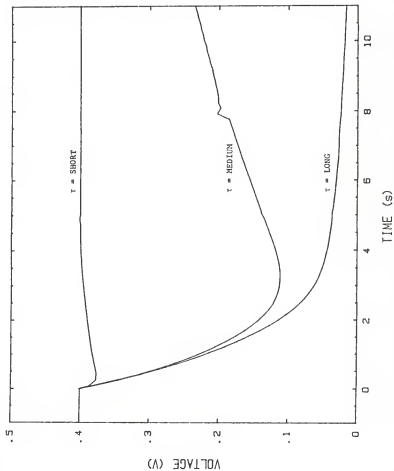


FIG. C2. Effect of pressure transducer amplifier time constant on the signal measured for a 0.377 to 0.101 MPa pressure drop at $T_a = 100^\circ\text{C}$.

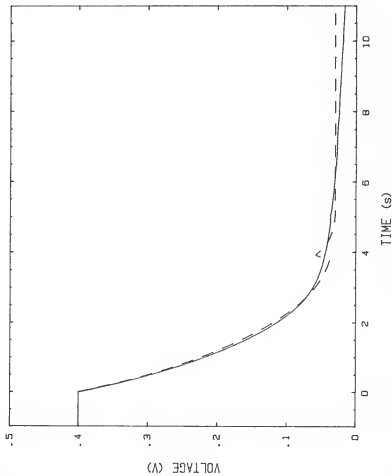


FIG. C3. Effect of ambient temperature on the signal measured for a 0.377 to 0.101 MPa pressure drop. The dashed line is the signal measured at $T_a = 27^\circ\text{C}$. The solid line is the signal measured at $T_a = 100^\circ\text{C}$.

C4, there was little consistency in the value of the drift beyond the individual run. Therefore, the analysis program determined the average drift for each run and corrected the data for this drift, then translated the data from voltage units to pressure units based on the observed pressure drop. Using the same data as Fig. C3, these two steps are illustrated in Figs. C5 and C6, comparing the results from a test with significant drift to the results from a test with zero drift. Figure C7 also illustrates the effect of ambient temperature on the pressure transient, comparing results for $T_a = 95^\circ\text{C}$ to results for $T_a = 100^\circ\text{C}$.

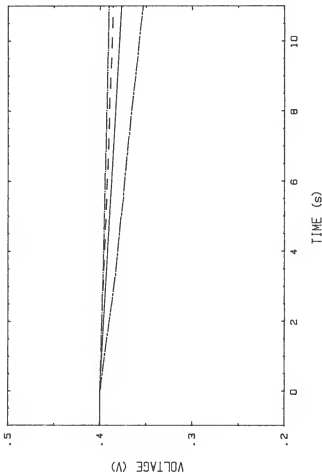


FIG. C4. Representative measurements of the pressure transducer amplifier drift at constant pressure and $T_a = 100^\circ\text{C}$. The solid line is the drift of the corresponding signal shown in Fig. C3, the short dash-long dash line is data from run AP1-6, the dashed line is data from run AP9-1, and the dot-dashed line is data from run AP10-1.

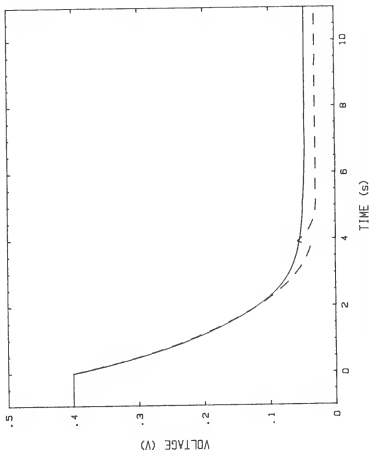


FIG. C5. Drift corrected signals for a 0.377 to 0.101 MPa pressure drop. The dashed line is the zero-drift signal measured at $T_a = 27^\circ\text{C}$. The solid line is the signal measured at $T_a = 100^\circ\text{C}$ corrected for drift by the prescription of data analysis program PRESSURE.

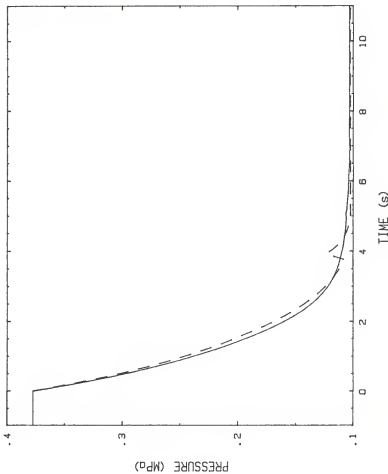


FIG. C6. Translation of data from units of voltage to units of pressure. The dashed line is the pressure history for $T_a = 27^\circ\text{C}$. The solid line is the drift-corrected pressure history for $T_a = 100^\circ\text{C}$.

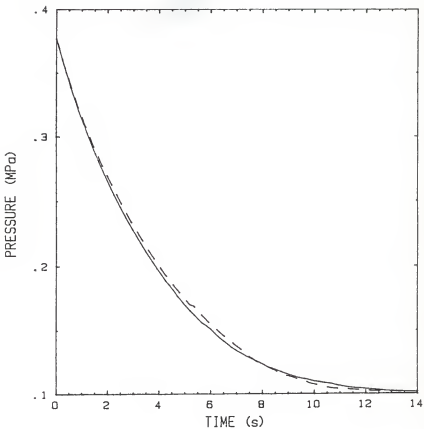


FIG. C7. Effect of ambient temperature on a 0.377 to 0.101 MPa pressure drop. The dashed line is the pressure history for $T_a = 95^\circ\text{C}$. The solid line is the pressure history for $T_a = 100^\circ\text{C}$.

APPENDIX D

Selected Listings of Experimental Pressure Data
Representative runs for series 1-8 (Table 5.2)

RUN NUMBER AP-2

AMBIENT TEMP. = 100 C
PPA PER VOLT = 194.197

TIME (S)	PRESSURE (KPA)	TIME (S)	PRESSURE (KPA)
0.000	373.67	7.120	106.73
0.000	366.71	7.200	107.73
0.240	366.37	7.440	105.31
0.480	379.09	7.680	105.98
0.720	315.32	7.920	104.63
0.960	331.50	8.160	104.45
1.200	258.92	8.400	104.52
1.440	277.10	8.640	104.41
1.680	255.77	8.880	104.33
1.920	245.09	9.120	104.00
2.160	235.15	9.360	103.71
2.400	216.77	9.600	103.27
2.640	205.72	9.840	103.34
2.880	192.76	10.080	103.15
3.120	185.30	10.320	103.30
3.360	172.37	10.560	103.13
3.600	165.32	10.800	102.81
3.840	150.03	11.040	103.20
4.080	134.64	11.280	102.92
4.320	149.61	11.520	103.13
4.560	145.18	11.760	103.14
4.800	141.06	12.000	103.07
5.040	137.03	12.240	102.92
5.280	130.35	12.480	101.83
5.520	125.27	12.720	101.83
5.760	120.73	12.960	101.50
6.000	125.38	13.200	101.33
6.240	123.19	13.440	101.33
6.480	120.90	13.680	101.33
6.720	118.64	13.920	101.33
6.960	116.79	14.160	101.33
7.200	115.29	14.400	101.33
7.440	112.67	14.640	101.33
7.680	111.27	14.880	101.33
7.920	111.28	15.120	101.33
8.160	110.35	15.360	101.33
8.400	109.37	15.600	101.33
8.640	109.13	15.840	101.33
8.880	108.03	16.080	101.33
9.120	107.46	16.320	101.33

RUN NUMBER AP-2-B

AMBIENT TEMP. = 100 C
PPA PER VOLT = 190.66

TIME (S)	PRESSURE (KPA)	TIME (S)	PRESSURE (KPA)
0.000	515.01	7.120	139.56
0.240	494.29	7.200	137.73
0.480	450.94	7.440	135.98
0.720	430.05	7.680	135.07
0.960	410.12	7.920	134.42
1.200	392.00	8.160	133.90
1.440	374.44	8.400	133.57
1.680	358.83	8.640	133.05
1.920	343.66	8.880	132.66
2.160	328.59	9.120	132.23
2.400	314.05	9.360	131.80
2.640	303.02	9.600	131.45
2.880	290.78	9.840	131.20
3.120	279.20	10.080	131.03
3.360	267.77	10.320	131.03
3.600	256.81	10.560	131.58
3.840	246.77	10.800	131.33
4.080	236.54	11.040	131.33
4.320	226.83	11.280	131.33
4.560	217.01	11.520	131.33
4.800	207.01	11.760	131.33
5.040	200.29	12.000	131.33
5.280	192.13	12.240	131.33
5.520	184.31	12.480	131.33
5.760	177.13	12.720	131.33
6.000	170.33	12.960	131.33
6.240	163.84	13.200	131.33
6.480	157.54	13.440	131.33
6.720	151.46	13.680	131.33
6.960	145.58	13.920	131.33
7.200	139.02	14.160	131.33
7.440	132.86	14.400	131.33
7.680	128.37	14.640	131.33
7.920	125.15	14.880	131.33
8.160	122.41	15.120	131.33
8.400	119.51	15.360	131.33
8.640	116.33	15.600	131.33
8.880	113.67	15.840	131.33
9.120	111.07	16.080	131.33
9.360	108.42	16.320	131.33
9.600	105.42	16.560	131.33
9.840	102.97	16.800	131.33

RUN NUMBER AP3-5

AMBIENT TEMP = 800 C
KPA PER VOLT = 103.102

TIME (S)	PRESSURE (KPA)	TIME (S)	PRESSURE (KPA)
0-000	446.96	7-120	105.29
0-060	434.73	7-240	126.94
0-120	422.50	7-360	105.18
0-180	393.38	7-440	103.06
0-240	376.79	7-520	101.93
0-300	360.36	7-720	101.93
0-360	344.89	8-040	101.33
0-420	330.60	8-240	101.33
1-000	316.78	8-400	101.33
1-360	303.62	8-560	101.33
1-520	292.15	8-720	101.33
1-960	280.22	8-800	101.33
2-040	269.68	9-040	101.33
2-140	248.28	9-160	101.33
2-320	238.17	9-520	101.33
2-480	228.75	9-600	101.33
2-640	220.24	9-840	101.33
2-800	211.36	10-000	101.33
2-960	202.76	10-16	101.33
3-120	194.80	10-32	101.33
3-240	187.24	10-48	101.33
3-440	180.20	10-64	101.33
3-600	173.32	10-80	101.33
3-760	166.85	10-96	101.33
3-920	160.86	11-12	101.33
4-080	155.82	11-28	101.33
4-240	149.63	11-44	101.33
4-400	144.46	11-60	101.33
4-560	139.50	11-76	101.33
4-720	134.13	11-92	101.33
4-880	129.23	12-08	101.33
5-040	124.53	12-24	101.33
5-200	124.65	12-40	101.33
5-360	121.39	12-56	101.33
5-520	118.74	12-72	131.33
5-680	116.54	12-88	131.33
5-840	113.74	13-04	101.33
6-000	111.96	13-20	101.33
6-160	110.03	13-36	101.33
6-320	107.77	13-52	101.33
6-480	107.57	13-68	131.33
6-640	106.59	13-84	131.33
6-800	105.89	14-00	131.33
6-960	105.41	14-16	131.33

RUN NUMBER 4PA-3

TIME (S)	PRESSURE (KPA)
14.32	101.80
14.40	101.68
14.64	101.81
14.80	101.89
14.96	101.75
15.12	101.67
15.28	101.94
15.44	101.70
15.60	101.66
15.76	101.65
15.92	101.65
16.08	101.49
16.24	101.52
16.40	101.60
16.56	101.78
16.72	101.48
16.88	101.70
17.04	101.64
17.20	101.57
17.36	101.57
17.52	101.64
17.68	101.53
17.84	101.47
18.00	101.51
18.16	101.73
18.32	101.52
18.48	101.33

RUN NUMBER 4PA-1

AMBIENT TEMP = 100 C
 #PA PER VCLT = 763.137

TIME (S)	PRESSURE (KPA)
0.050	583.96
0.070	587.73
0.240	556.48
3.463	509.27
0.500	482.22
0.720	459.60
3.650	417.40
1.200	397.43
1.350	310.12
1.680	344.04
1.840	348.04
2.000	333.00
2.160	319.63
2.320	292.32
2.480	288.52
2.640	284.52
2.800	277.37
2.960	266.72
3.120	256.35
3.280	226.75
3.440	217.58
3.600	208.55
3.760	231.86
3.920	177.26
4.080	166.66
4.240	189.45
4.400	173.94
4.560	169.64
4.720	163.76
4.880	159.04
5.040	155.91
5.200	152.12
5.360	149.34
5.520	143.45
5.680	143.45
5.840	141.00
6.000	134.89
6.160	136.92
6.320	134.52
6.480	132.21
6.640	132.53
6.800	129.00
6.960	127.45

TIME (S)	PRESSURE (KPA)
7.120	125.43
7.280	123.84
7.440	123.02
7.600	121.62
7.760	120.17
7.920	113.22
8.080	117.62
8.240	116.82
8.400	115.47
8.560	114.70
8.720	113.92
8.880	112.62
9.040	111.62
9.200	111.25
9.360	110.92
9.520	110.13
9.680	110.13
9.840	109.02
10.000	109.02
10.160	108.56
10.320	107.97
10.480	107.53
10.640	107.17
10.800	106.88
10.960	106.47
11.120	106.37
11.280	106.02
11.440	106.02
11.600	105.97
11.760	105.31
11.920	104.77
12.080	104.32
12.240	103.70
12.400	103.75
12.560	103.76
12.720	103.03
12.880	102.60
13.040	102.57
13.200	102.56
13.360	102.78
13.520	102.45
13.680	102.73
13.840	102.17
14.000	101.83
14.160	101.45

RUN NUMBER APT-5

RUN NUMBER APT-5

RUN NUMBER APT-5
 AMBIENT TEMP = 100 C
 KPA PER VOLT = 995.193

TIME PRESSURE
 (S) (KPA)

TIME PRESSURE
 (S) (KPA)

TIME PRESSURE
 (S) (KPA)

14.32 104.81
 14.45 104.55
 14.64 104.34
 14.80 104.10
 14.96 103.91
 15.12 103.70
 15.28 103.41
 15.44 102.92
 15.60 102.92
 15.76 102.73
 15.92 102.54
 16.08 102.53
 16.24 102.19
 16.40 102.18
 16.56 102.09
 16.72 101.95
 16.88 101.89
 17.04 101.79
 17.20 101.99
 17.36 101.97
 17.52 101.94
 17.68 101.77
 17.84 101.66
 18.00 101.77
 18.16 101.44
 18.32 101.32
 18.48 101.32
 18.64 101.32
 18.80 101.32
 18.96 101.32
 19.12 101.32
 19.28 101.32
 19.44 101.32
 19.60 101.32
 19.76 101.32

146.05
 144.14
 142.84
 139.58
 137.99
 136.61
 135.14
 133.83
 132.52
 130.84
 129.48
 128.09
 126.93
 125.99
 124.38
 123.13
 121.58
 119.90
 118.99
 117.84
 116.90
 115.13
 114.32
 113.89
 112.88
 112.20
 111.66
 111.28
 110.82
 110.52
 109.92
 109.83
 108.25
 107.69
 107.10
 106.65
 106.13
 105.82
 105.46
 105.24
 104.92

0.000 374.11
 0.160 373.45
 0.320 364.04
 0.480 364.92
 0.640 336.05
 0.800 327.38
 1.040 319.23
 1.200 311.31
 1.360 303.93
 1.520 296.40
 1.680 282.93
 1.840 275.72
 2.000 269.33
 2.160 263.15
 2.320 260.67
 2.480 253.04
 2.640 247.51
 2.800 241.68
 2.960 236.09
 3.120 235.96
 3.280 226.87
 3.440 216.26
 3.600 211.57
 3.760 207.55
 3.920 202.98
 4.080 198.99
 4.240 194.30
 4.400 187.08
 4.560 183.26
 4.720 179.89
 4.880 176.57
 5.040 173.60
 5.200 170.27
 5.360 167.08
 5.520 163.93
 5.680 161.28
 5.840 158.36
 6.000 152.78
 6.160 150.20
 6.320 147.75

RUN NUMBER APP-0

 AMBIENT TEMP = 100 C
 APA PER VOLT = 853.596

TIME (S)	PRESSURE (KPA)	TIME (S)	PRESSURE (KPA)
0-000	377-11	7-120	129-76
0-040	361-72	7-260	124-34
0-080	350-55	7-400	122-92
0-160	340-91	7-600	122-75
0-240	331-57	7-800	120-21
0-320	322-57	8-000	115-22
1-040	314-66	8-200	116-23
1-200	306-39	8-400	114-00
1-360	298-78	8-560	112-56
1-520	291-36	8-720	111-54
1-680	284-16	8-880	109-10
1-840	277-58	8-960	108-06
2-000	271-06	9-200	107-02
2-160	264-49	9-360	106-28
2-320	258-23	9-520	105-54
2-480	251-90	9-680	104-94
2-640	245-97	9-840	104-16
2-800	240-13	10-00	103-72
2-960	234-86	10-16	103-26
3-120	229-16	10-32	102-66
3-280	224-16	10-48	102-06
3-440	218-99	10-64	102-05
3-600	213-53	10-80	102-25
3-760	208-56	10-96	102-09
3-920	203-70	11-12	101-73
4-080	198-87	11-28	101-44
4-240	194-50	11-44	101-33
4-400	190-00	11-60	101-33
4-560	185-42	11-76	101-33
4-720	180-85	11-92	101-33
4-880	176-85	12-08	101-33
5-040	172-78	12-24	101-33
5-200	168-61	12-40	101-33
5-360	164-94	12-56	101-33
5-520	161-24	12-72	101-33
5-680	157-66	12-88	101-33
5-840	154-46	13-04	101-33
6-000	150-86	13-20	101-33
6-160	147-26	13-36	101-33
6-320	143-15	13-52	101-33
6-480	138-06	13-68	101-33
6-640	133-06	13-84	101-33
6-800	128-06	14-00	101-33
6-960	122-29	14-16	101-33

RUN NUMBER APP-2

 AMBIENT TEMP = 100 C
 APA PER VOLT = 963.158

TIME (S)	PRESSURE (KPA)	TIME (S)	PRESSURE (KPA)
0-000	377-11	7-120	132-60
0-040	361-72	7-260	128-78
0-080	350-08	7-400	127-40
0-160	339-59	7-600	125-85
0-240	329-83	7-820	124-35
0-320	320-31	8-080	122-70
1-040	311-80	8-240	120-86
1-200	302-90	8-400	120-02
1-360	294-77	8-560	119-70
1-520	287-31	8-720	118-11
1-680	279-31	8-880	116-17
1-840	272-40	9-040	115-04
2-000	265-36	9-200	114-03
2-160	258-66	9-360	112-88
2-320	252-09	9-520	112-06
2-480	245-94	9-680	111-64
2-640	239-91	9-840	110-79
2-800	233-97	10-00	109-92
2-960	228-22	10-16	109-56
3-120	222-88	10-32	109-18
3-280	217-88	10-48	108-84
3-440	212-70	10-64	108-01
3-600	207-70	10-80	107-04
3-760	202-94	10-96	106-39
3-920	198-25	11-12	105-80
4-080	193-80	11-28	105-15
4-240	189-16	11-44	104-75
4-400	185-44	11-60	104-42
4-560	181-72	11-76	104-26
4-720	177-89	11-92	104-06
4-880	172-89	12-08	103-57
5-040	169-05	12-24	103-33
5-200	165-44	12-40	103-06
5-360	162-15	12-56	102-66
5-520	158-71	12-72	102-33
5-680	155-67	12-88	102-08
5-840	153-39	13-04	102-11
6-000	150-99	13-20	101-31
6-160	148-64	13-36	101-58
6-320	146-44	13-52	101-68
6-480	141-87	13-68	101-62
6-640	139-38	13-84	101-33
6-800	136-62	14-00	101-33
6-960	134-53	14-16	101-33

RUN NUMBER AP9-B

TIME PRESSURE
(S) (KPA)

14.32	103.19
14.43	103.04
14.54	103.15
14.65	103.16
14.76	103.16
14.87	103.16
14.98	103.16
15.09	103.16
15.12	102.99
15.23	103.08
15.34	103.08
15.44	102.78
15.60	102.62
15.76	102.77
15.92	102.55
16.08	102.52
16.24	102.59
16.40	102.14
16.56	102.07
16.72	101.91
16.88	101.94
17.04	101.99
17.20	101.79
17.36	101.82
17.52	101.75
17.68	101.62
17.84	101.62
18.00	101.71
18.16	101.74
18.32	101.62
18.48	101.57
18.64	101.66
18.80	101.55
18.96	101.41
19.12	101.50
19.28	101.57
19.44	101.66

RUN NUMBER AP9-B

AMBIENT TEMP. = 100 C
 APA PER VOLT = 024.762

TIME PRESSURE
(S) (KPA)

0.000	377.11
0.200	377.11
0.400	377.11
0.600	377.11
0.800	377.11
1.000	377.11
1.200	377.11
1.400	377.11
1.600	377.11
1.800	377.11
2.000	377.11
2.200	377.11
2.400	377.11
2.600	377.11
2.800	377.11
3.000	377.11
3.200	377.11
3.400	377.11
3.600	377.11
3.800	377.11
4.000	377.11
4.200	377.11
4.400	377.11
4.600	377.11
4.800	377.11
5.000	377.11
5.200	377.11
5.400	377.11
5.600	377.11
5.800	377.11
6.000	377.11
6.200	377.11
6.400	377.11
6.600	377.11
6.800	377.11
7.000	377.11
7.200	377.11
7.400	377.11
7.600	377.11
7.800	377.11
8.000	377.11
8.200	377.11
8.400	377.11
8.600	377.11
8.800	377.11
9.000	377.11
9.200	377.11
9.400	377.11
9.600	377.11
9.800	377.11
10.000	377.11
10.200	377.11
10.400	377.11
10.600	377.11
10.800	377.11
11.000	377.11
11.200	377.11
11.400	377.11
11.600	377.11
11.800	377.11
12.000	377.11
12.200	377.11
12.400	377.11
12.600	377.11
12.800	377.11
13.000	377.11
13.200	377.11
13.400	377.11
13.600	377.11
13.800	377.11
14.000	377.11
14.200	377.11
14.400	377.11
14.600	377.11
14.800	377.11
15.000	377.11
15.200	377.11
15.400	377.11
15.600	377.11
15.800	377.11
16.000	377.11
16.200	377.11
16.400	377.11
16.600	377.11
16.800	377.11
17.000	377.11
17.200	377.11
17.400	377.11
17.600	377.11
17.800	377.11
18.000	377.11
18.200	377.11
18.400	377.11
18.600	377.11
18.800	377.11
19.000	377.11
19.200	377.11
19.400	377.11
19.600	377.11
19.800	377.11
20.000	377.11

TIME PRESSURE
(S) (KPA)

7.120	132.37
7.280	129.92
7.440	129.92
7.600	129.92
7.760	129.92
7.920	129.92
8.080	129.92
8.240	129.92
8.400	129.92
8.560	129.92
8.720	129.92
8.880	129.92
9.040	129.92
9.200	129.92
9.360	129.92
9.520	129.92
9.680	129.92
9.840	129.92
10.000	129.92
10.160	129.92
10.320	129.92
10.480	129.92
10.640	129.92
10.800	129.92
10.960	129.92
11.120	129.92
11.280	129.92
11.440	129.92
11.600	129.92
11.760	129.92
11.920	129.92
12.080	129.92
12.240	129.92
12.400	129.92
12.560	129.92
12.720	129.92
12.880	129.92
13.040	129.92
13.200	129.92
13.360	129.92
13.520	129.92
13.680	129.92
13.840	129.92
14.000	129.92
14.160	129.92

APPENDIX E

Selected Listings of Experimental Temperature Data

First run in each of series 1-8 (Table 5.3). THETA is the platinum heater temperature less the ambient temperature. The NUSSELT NUMBER is based on the superficial heat flux.

PAGE 2

RUN NUMBER AP2-3

WIRE LENGTH = .096 M
 WIRE DIAMETER = .00025 M
 AMBIENT TEMP. = 21.0 C
 PRESSURE = MAX 377.11, DECOMPRESS FROM 373.67 KPA
 INITIAL PRESS. = .316163 UNMS AT 100 C
 SIGMA = 0

RUN NUMBER AP2-3

TIME (S)	HEAT FLUX (W/CM ²)	THEA (C)	RUSSET NUMBER
0.080	426570	59.491	2.6662
0.240	426750	59.747	2.6500
0.400	426840	59.631	2.6542
0.560	426810	59.570	2.6576
0.720	426870	59.465	2.6625
0.880	426830	59.373	2.6685
1.040	426810	59.271	2.6719
1.200	426810	59.169	2.6782
1.360	426830	59.069	2.6852
1.520	426810	58.974	2.6930
1.680	426810	58.881	2.7018
1.840	426850	58.787	2.7149
2.000	426820	58.693	2.7339
2.160	426790	58.605	2.7356
2.320	426805	58.716	2.7429
2.480	426770	58.526	2.7517
2.640	426805	58.430	2.7739
2.800	426770	58.330	2.7982
2.960	426770	58.610	2.8085
3.120	426760	58.353	2.8085
3.280	426760	58.189	2.8172
3.440	426710	58.010	2.8354
3.600	426740	58.339	2.8603
3.760	426730	58.382	2.8580
3.920	426720	58.123	2.8711
4.080	426750	58.805	2.8906
4.240	426750	58.753	2.9152
4.400	426760	43.664	3.0583
4.560	426660	43.400	3.0634
4.720	426710	53.071	2.9823
4.880	426640	53.347	2.9659
5.040	426680	52.860	2.9852
5.200	426650	53.050	2.9878
5.360	426630	51.653	3.0755
5.520	426650	51.621	3.0657
5.680	426640	50.714	3.0784
5.840	426640	50.513	3.0846
6.000	426660	50.993	3.1031
6.160	426610	50.562	3.1308
6.320	426640	50.305	3.1458
6.480	426600	49.912	3.1690
6.640	426600	49.744	3.1681

RUN NUMBER AP2-3

TIME (S)	HEAT FLUX (W/CM ²)	THEA (C)	RUSSET NUMBER
6.800	426610	50.093	3.1589
6.960	426590	50.061	3.1607
7.120	426580	49.658	3.1864
7.280	426580	49.218	3.2147
7.440	426590	48.815	3.2388
7.600	426640	48.413	3.2618
7.760	426640	48.012	3.2818
7.920	426640	47.776	3.3018
8.080	426640	48.644	3.3913
8.240	426640	48.179	3.3529
8.400	426650	48.664	3.4094
8.560	426650	48.860	3.3756
8.720	426660	47.009	3.3650
8.880	426660	46.807	3.3881
9.040	426640	46.605	3.4112
9.200	426650	45.919	3.4447
9.360	426610	46.210	3.4231
9.520	426650	46.210	3.4231
9.680	426630	46.362	3.4117
9.840	426680	46.517	3.4207
10.000	426650	46.315	3.4153
10.160	426640	46.348	3.4127
10.320	426650	45.638	3.4625
10.480	426650	46.170	3.4271
10.640	426640	46.153	3.4271
10.800	426640	45.099	3.5075
10.960	426620	45.013	3.5139
11.120	426650	44.759	3.5341
11.280	426640	44.546	3.5509
11.440	426650	44.452	3.5584
11.600	426620	44.289	3.5476
11.760	426650	43.972	3.5713
11.920	426650	43.572	3.5862
12.080	426650	44.384	3.5635
12.240	426640	43.564	3.5635
12.400	426630	43.162	3.6038
12.560	426620	43.162	3.6645
12.720	426690	44.138	3.5842
12.880	426670	44.261	3.5739
13.040	426660	44.212	3.5778
13.200	426650	44.071	3.5892
13.360	426660	43.889	3.5960
13.520	426660	43.728	3.6038
13.680	426640	43.928	3.6009
13.840	426640	43.186	3.7495
14.000	426630	43.401	3.6445
14.160	426630	43.522	3.6343
14.320	426640	42.438	3.7272

RUN NUMBER AP2-3

PAGE 3

RUN NUMBER AP3-1

WIRE LENGTH = .006 M
 WIRE DIAMETER = .003 M
 AMBIENT TEMP = 100 C
 PRESSURE = DECOMPRESS FROM 515.01 KPA
 INITIAL RESIS. = -316156 OHMS AT 160 C
 SIGMA = C

TIME (S)	HEAT FLUX (W/CM ²)	THETA (C)	MUSSEL NUMBER	TIME (S)	HEAT FLUX (W/CM ²)	THETA (C)	MUSSEL NUMBER
14.48	428450	42.620	3.6940	-1.84	423510	59.983	2.6188
14.64	428450	43.294	3.6536	-1.68	423500	59.991	2.6185
14.80	428440	42.946	3.7239	-1.52	423510	59.977	2.6193
14.96	428450	42.706	3.7384	-1.36	423540	59.987	2.6189
15.12	428470	42.706	3.7384	-1.20	423530	59.989	2.6192
15.28	428430	43.215	3.6602	-1.04	423500	59.980	2.6191
15.44	428510	43.511	3.6399	-0.88	423510	59.982	2.6191
15.60	428470	43.139	3.6669	-0.72	423510	59.982	2.6189
15.76	428470	43.711	3.6156	-0.56	423530	59.966	2.6197
15.92	428500	43.816	3.6107	-0.40	423500	59.974	2.6194
16.08	428490	43.759	3.6150	-0.24	423540	59.965	2.6201
16.24	428490	43.466	3.6412	-0.08	423520	60.002	2.6182
16.40	428490	43.700	3.6126	0.08	423530	60.003	2.6182
16.56	428490	43.700	3.6126	0.24	423540	60.002	2.6187
16.72	428470	43.021	3.6717	0.40	423540	60.002	2.6187
16.88	428490	43.441	3.6416	0.56	423570	60.006	2.6183
17.04	428470	42.993	3.6819	0.72	423540	60.002	2.6182
17.20	428490	44.308	3.5763	0.88	423500	60.002	2.6201
17.36	428490	42.529	3.7193	1.04	423540	60.002	2.6182
17.52	428460	43.524	3.6348	1.20	423520	60.002	2.6181
17.68	428460	42.675	3.7055	1.36	423530	60.003	2.6182
17.84	428490	43.460	3.6445	1.52	423540	60.002	2.6187
18.00	428490	43.282	3.6782	1.68	423540	60.002	2.6187
18.16	428500	43.498	3.6382	1.84	423540	60.006	2.6183
18.32	428470	43.852	3.6376	2.00	423540	60.002	2.6182
18.48	428500	43.422	3.6408	2.16	423500	60.013	2.6182
18.64	428490	43.637	3.6257	2.32	423570	60.016	2.6178
18.80	428460	43.376	3.6488	2.48	423570	59.984	2.6182
18.96	428460	42.168	3.7512	2.64	423590	59.930	2.6217
19.12	428320	43.196	3.6625	2.80	423590	59.873	2.6242
19.28	428300	43.489	3.6376	2.96	423590	59.841	2.6256
19.44	428300	43.489	3.6376	3.12	423590	59.841	2.6256
19.60	428300	42.612	3.6959	3.28	423600	59.824	2.6252
19.76	428490	43.392	3.6486	3.44	423600	59.824	2.6252
19.92	428300	43.201	3.6619	3.60	423620	59.609	2.6374
20.08	428520	43.188	3.6699	3.76	423620	59.600	2.6384
20.24	428510	43.152	3.6681	3.92	423640	59.458	2.6426
				4.08	423640	59.273	2.6511
				4.24	423620	59.165	2.6558
				4.40	423630	59.062	2.6605
				4.56	423630	58.929	2.6663
				4.72	423630	58.797	2.6717
				4.88	423630	58.783	2.6724
				5.04	423630	58.503	2.6857
				5.20	423600	58.290	2.6960
				5.36	423600	58.117	2.7035
				5.52	423560	57.915	2.7127
				5.68	423560	57.776	2.7194
				5.84	423600	57.700	2.7230

RUN NUMBER AP 3-1

PAGE 2

RUN NUMBER AP 3-1

PAGE 3

TIME (S)	HEAT FLUX (W/CM ²)	THETA (C)	MUSSELT NUMBER	TIME (S)	HEAT FLUX (W/CM ²)	THETA (C)	MUSSELT NUMBER
4.880	42.3600	57.942	2.7117	12.56	42.3390	43.584	3.2324
5.040	42.3580	57.371	2.7366	12.72	42.3360	44.925	3.2098
5.200	42.3570	57.096	2.7517	12.88	42.3400	44.951	3.2081
5.360	42.3560	56.819	2.7624	13.04	42.3350	44.598	3.2312
5.520	42.3550	56.542	2.7730	13.20	42.3340	44.761	3.2203
5.680	42.3540	56.265	2.7837	13.36	42.3330	44.924	3.2079
5.840	42.3530	56.209	2.7900	13.52	42.3360	44.952	3.2079
6.000	42.3520	56.209	2.7960	13.68	42.3360	44.952	3.2079
6.160	42.3510	56.367	2.8374	13.84	42.3270	47.952	3.2761
6.320	42.3500	55.307	2.8405	14.00	42.3220	44.776	3.5059
6.480	42.3490	55.495	2.8354	14.16	42.3240	46.039	3.4099
6.640	42.3480	55.205	2.8454	14.32	42.3260	46.312	3.3899
6.800	42.3470	54.404	2.8630	14.48	42.3260	45.826	3.4259
6.960	42.3460	54.004	2.9065	14.64	42.3210	45.560	3.4471
7.120	42.3450	53.815	2.9124	14.80	42.3160	45.106	3.4592
7.280	42.3440	53.887	2.9124	14.96	42.3200	44.788	3.4592
7.440	42.3430	53.872	2.9136	15.12	42.3230	46.100	3.4033
7.600	42.3420	53.584	2.9314	15.28	42.3220	46.616	3.3675
7.760	42.3410	52.072	2.9652	15.44	42.3250	46.858	3.3504
7.920	42.3400	51.372	3.0587	15.60	42.3230	46.313	3.3899
8.080	42.3400	51.593	3.0466	15.76	42.3250	46.346	3.3872
8.240	42.3400	51.950	3.0237	15.92	42.3220	46.236	3.5952
8.400	42.3400	51.995	3.0237	16.08	42.3250	46.619	3.3676
8.560	42.3400	51.995	3.0303	16.24	42.3210	46.611	3.3676
8.720	42.3400	51.737	3.0303	16.40	42.3210	46.611	3.3676
8.880	42.3400	51.066	3.0799	16.56	42.3210	45.993	3.4140
9.040	42.3400	50.727	3.0993	16.72	42.3210	45.971	3.4147
9.200	42.3400	50.652	3.0993	16.88	42.3230	45.037	3.4814
9.360	42.3400	50.552	3.0993	17.04	42.3190	45.458	3.4531
9.520	42.3400	50.289	3.1233	17.20	42.3240	45.264	3.4681
9.680	42.3400	50.319	3.1214	17.36	42.3220	45.707	3.4544
9.840	42.3400	50.458	3.1126	17.52	42.3250	45.617	3.4413
10.000	42.3400	50.597	3.1052	17.68	42.3200	45.898	3.4211
10.16	42.3400	50.597	3.1052	17.84	42.3200	45.898	3.4211
10.32	42.3400	50.888	3.0824	18.00	42.3250	44.937	3.4259
10.48	42.3400	51.066	3.0769	18.16	42.3260	45.725	3.4313
10.64	42.3400	50.654	3.1016	18.32	42.3250	45.789	3.4285
10.80	42.3400	50.824	3.0904				
10.96	42.3400	50.935	3.0837				
11.12	42.3400	50.999	3.0820				
11.28	42.3400	50.277	3.1270				
11.44	42.3400	48.146	3.1944				
11.60	42.3400	48.146	3.1944				
11.76	42.3400	49.718	3.1480				
11.92	42.3400	49.717	3.1590				
12.08	42.3410	49.747	3.1570				
12.24	42.3390	48.724	3.1583				
12.40	42.3410	49.302	3.1855				

RUN NUMBER AP3-7

RUN NUMBER AP3-7

WIRE LENGTH = .006 M
 WIRE DIAMETER = .0005 M
 AMBIENT TEMP = 100 C
 PRESSURE = DECOMPRESS FROM 440.06 MPa
 INITIAL RESIS. = .316133 OHMS AT 159.9 C
 SIGMA = C

TIME (S)	HEAT FLUX (W/CM ²)	THETA (C)	MUSSETT NUMBER
-1.84	418620	59.8029	2.5953
-1.68	418610	59.827	2.5956
-1.52	418610	59.827	2.5954
-1.36	418620	59.817	2.5958
-1.20	418900	59.808	2.5960
-1.04	418600	59.8031	2.5964
-0.88	418600	59.799	2.5962
-0.72	418610	59.799	2.5962
-0.56	418620	59.792	2.5968
-0.40	418620	59.795	2.5968
-0.24	418900	59.795	2.5969
-0.08	418900	59.773	2.5975
0.08	418600	59.813	2.5959
0.24	418610	59.813	2.5959
0.40	418600	59.815	2.5958
0.56	418600	59.815	2.5959
0.72	418600	59.815	2.5959
0.88	418610	59.810	2.5963
1.04	418900	59.814	2.5958
1.20	418610	59.832	2.5951
1.36	418600	59.829	2.5951
1.52	418900	59.838	2.5947
1.68	418900	59.827	2.5957
1.84	418900	59.844	2.5943
2.00	418600	59.825	2.5983
2.16	418700	59.825	2.5983
2.32	418900	59.805	2.5983
2.48	418600	59.197	2.6227
2.64	418900	59.087	2.6275
2.80	418600	58.951	2.6336
2.96	418900	58.712	2.6444
3.12	418900	58.662	2.6474
3.28	418600	58.456	2.6558
3.44	418600	58.135	2.6656
3.60	418700	57.735	2.6656
3.76	418900	57.857	2.6833
3.92	418900	57.693	2.6910
4.08	418900	57.629	2.6938
4.24	418610	57.108	2.7143
4.40	418900	57.093	2.7191
4.56	418900	56.973	2.7248
4.72	418900	56.899	2.7376

TIME (S)	HEAT FLUX (W/CM ²)	THETA (C)	MUSSETT NUMBER
4.88	418480	56.536	2.7455
5.04	418480	55.382	2.7776
5.20	418900	55.207	2.8118
5.36	418450	54.458	2.8501
5.52	418460	54.841	2.8406
5.68	418430	53.975	2.8758
5.84	418420	54.110	2.8678
6.00	418420	54.139	2.8667
6.16	418420	53.886	2.9010
6.32	418410	53.886	2.9010
6.48	418410	53.352	2.9089
6.64	418370	53.214	2.9162
6.80	418370	52.894	2.9338
6.96	418380	53.094	2.9229
7.12	418380	52.309	2.9667
7.28	418380	52.295	2.9675
7.44	418350	52.321	2.9658
7.60	418350	52.415	2.9750
7.76	418350	52.415	2.9750
7.92	418320	51.736	2.9973
8.08	418320	51.736	2.9973
8.24	418300	51.408	3.0226
8.40	418340	51.408	3.0181
8.56	418320	51.454	3.0076
8.72	418320	51.198	3.0155
8.88	418320	51.593	3.0307
9.04	418310	51.593	3.0209
9.20	418320	51.323	3.0030
9.36	418320	51.273	3.0036
9.52	418350	51.200	3.0249
9.68	418350	51.200	3.0249
9.84	418300	50.326	3.0830
10.00	418300	51.108	3.0758
10.16	418360	51.192	3.0196
10.32	418310	50.981	3.0447
10.48	418350	51.680	3.0026
10.64	418330	51.613	3.0084
10.80	418310	50.744	3.0577
10.96	418250	51.899	3.0577
11.12	418360	51.899	2.9999
11.28	418360	51.532	3.0111
11.44	418330	50.635	3.0765
11.60	418330	51.537	3.0108
11.76	418340	50.756	3.0272
11.92	418300	49.825	3.1140
12.08	418340	49.825	3.1044
12.24	418340	49.825	3.1543
12.40	418340	49.825	3.1543
12.56	418310	48.446	3.2027

RUN NUMBER AP3-7

PAGE 3

RUN NUMBER AP4-4

WIRE LENGTH = .096 M
 WIRE DIAMETER = .00025 M
 AMBIENT TEMP = 100 C
 PRESSURE = DECCPRESS FROM 503.96 KPA
 INITIAL RESIS. = .316095 OHMS AT 159.9 C
 SIGMA = 0

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*****
TIME      HEAT FLUX      THETA      NUSSLET
(1)      (W/MM^2)      (C)      NUMBER
*****
12.36      418300      48.700      3.1859
12.72      418310      49.425      3.1393
13.08      418310      49.447      3.1379
13.46      418290      48.732      3.1838
13.82      418300      48.631      3.1906
14.18      418300      49.180      3.1873
14.54      418340      49.335      3.1451
14.90      418320      48.167      3.2211
15.26      418290      49.193      3.1542
15.62      418300      48.777      3.1805
15.98      418320      49.071      3.1620
16.34      418310      48.575      3.1942
16.70      418290      47.853      3.2559
17.06      418300      48.513      3.2010
17.42      418280      46.513      3.1646
17.78      418280      46.849      3.1117
18.14      418240      46.379      3.1450
18.50      418300      46.956      3.2043
18.86      418260      46.324      3.2591
19.22      418270      46.575      3.3489
19.58      418270      46.329      3.3311
19.94      418290      46.329      3.3466
20.30      418300      46.762      3.3510
20.66      418260      47.265      3.2820
21.02      418280      47.102      3.2939
21.38      418260      46.775      3.3169
21.74      418300      47.280      3.3159
22.10      418290      47.121      3.2926
22.46      418260      45.322      3.4232
22.82      418270      45.912      3.4329
23.18      418250      46.138      3.4128
23.54      418260      46.138      3.4128
23.90      418220      45.738      3.4738
24.26      418220      43.610      3.5738
24.62      418240      43.674      3.5521
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*****
TIME      HEAT FLUX      THETA      NUSSLET
(1)      (W/MM^2)      (C)      NUMBER
*****
-1.84      408170      60.049      2.5213
-1.52      408160      60.040      2.5207
-1.36      408200      60.065      2.5207
-1.20      408120      60.069      2.5201
-1.04      408170      60.055      2.5210
-.880      408170      60.067      2.5205
-.720      408160      60.057      2.5208
-.560      408140      60.037      2.5216
-.400      408140      60.030      2.5218
-.240      408150      60.047      2.5219
-.080      408150      60.043      2.5219
0.080      408140      60.045      2.5213
0.240      408170      60.033      2.5219
0.400      408150      60.021      2.5223
0.560      408150      60.009      2.5228
0.720      408130      60.021      2.5222
0.880      408140      59.998      2.5232
1.040      408150      59.994      2.5235
1.200      408170      59.978      2.5240
1.360      408120      59.971      2.5251
1.520      408120      59.950      2.5251
1.680      408120      59.927      2.5251
1.840      408130      59.927      2.5264
2.000      408160      59.926      2.5264
2.160      408160      59.911      2.5270
2.320      408150      59.907      2.5271
2.480      408000      59.895      2.5271
2.640      408150      59.878      2.5278
2.800      408150      59.868      2.5281
2.960      408170      59.868      2.5281
3.120      408180      59.876      2.5286
3.280      408120      59.863      2.5288
3.440      408180      59.852      2.5297
3.600      408150      59.801      2.5316
3.760      408170      59.801      2.5317
3.920      408120      59.799      2.5315
4.080      408140      59.759      2.5333
4.240      408150      59.650      2.5361
4.400      408110      59.550      2.5361
4.560      408130      59.080      2.5623
4.720      408130      59.001      2.5658
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TIME (S)	HEAT FLUX (W/MM)	THETA (C)	MUSSELY NUMBER	TIME (S)	HEAT FLUX (W/MM)	THETA (C)	MUSSELY NUMBER
4.300	408110	53.921	2.5691	12.56	408010	52.790	2.8608
5.040	408130	58.631	2.5798	12.72	408000	53.410	2.8335
5.700	408140	58.765	2.5771	12.88	407980	52.987	2.8500
5.360	408120	59.547	2.5856	13.04	407960	51.380	2.9453
5.200	408100	59.728	2.5905	13.20	407940	52.262	2.8968
5.840	408120	57.203	2.6408	13.36	407920	52.003	2.9099
6.000	408110	57.326	2.6406	13.52	407900	51.900	2.9158
6.160	408130	57.282	2.6428	13.68	407880	52.175	2.9005
6.320	408120	57.109	2.6507	13.84	407860	52.317	2.8925
6.480	408100	57.090	2.6514	14.00	407840	51.894	2.9160
6.800	408090	56.131	2.6967	14.16	407820	52.075	2.9051
6.960	408090	56.170	2.6943	14.32	407800	52.305	2.8790
7.120	408090	55.920	2.7153	14.48	407780	52.587	2.8536
7.280	408060	55.730	2.7158	14.64	407760	52.887	2.8615
7.440	408090	55.200	2.7422	14.80	407740	52.723	2.8703
7.600	408090	54.994	2.7524	14.96	407720	52.507	2.8822
7.760	408040	54.209	2.7920	15.12	407700	52.407	2.8942
7.920	408040	54.081	2.7986	15.28	407680	51.395	2.9442
8.080	408010	54.026	2.8012	15.44	407660	51.718	2.9255
8.240	408030	53.599	2.8237	15.60	407640	51.604	2.9324
8.400	408030	53.586	2.8244	15.76	407620	52.526	2.8810
8.560	408050	53.079	2.8169	15.92	408000	52.179	2.8894
8.720	408060	53.079	2.8169	16.08	407980	52.647	2.8536
8.880	408040	53.337	2.8113	16.24	407960	52.867	2.8610
9.040	408050	54.009	2.8024	16.40	408010	52.261	2.8953
9.200	408030	54.124	2.7963	16.56	407980	52.149	2.9018
9.360	408060	53.847	2.8111	16.72	407960	52.149	2.9018
9.520	408020	53.643	2.8109	16.88	407940	51.911	2.9151
9.680	408060	53.399	2.8341	17.04	408010	52.146	2.9022
9.840	408020	53.323	2.8360	17.20	407960	51.876	2.9170
10.000	408000	53.553	2.8257	17.36	407940	51.859	2.9406
10.160	408000	53.771	2.8274	17.52	407920	52.274	2.8974
10.320	408030	53.771	2.8274	17.68	407900	52.529	2.8974
10.480	407990	53.784	2.8137	17.84	407880	52.177	2.9002
10.640	408030	53.668	2.8201	18.00	407860	52.177	2.9002
10.800	408020	54.054	2.7995	18.16	407840	49.850	3.0154
10.960	408040	53.819	2.8122	18.32	407820	51.950	2.9129
11.120	408000	53.054	2.8525				
11.280	408000	53.952	2.8090				
11.440	408030	53.750	2.8193				
11.600	408020	53.805	2.8107				
11.760	408000	53.745	2.8196				
11.920	408000	53.924	2.8066				
12.080	407960	53.924	2.8066				
12.240	408030	54.001	2.8027				
12.400	408000	53.708	2.8177				

PAGE 2

RUN NUMBER: AP7-2

WIRE LENGTH = -0.96 M
 WIRE DIAMETER = .00025 M
 INITIAL TEMP = 300.0 C
 PRESSURE TEMP = DECOMPRESSION FROM 377.11 KPA
 INITIAL RESIS. = .316161 OHMS AT 100 C
 SIGMA = 0

RUN NUMBER: AP7-2

TIME (S) HEAT FLUX (W/MM²) THETA (C) RUSSELL NUMBER
 4.880 407200 58.413 2.5657
 5.040 407210 53.344 2.5932
 5.200 407200 54.187 2.5965
 5.360 407190 58.059 2.6010
 5.520 407180 58.041 2.6020
 5.680 407160 58.001 2.6101
 5.840 407190 57.864 2.6150
 6.000 407260 57.754 2.6171
 6.160 407170 57.709 2.6236
 6.320 407160 57.564 2.6276
 6.480 407140 57.860 2.6319
 6.640 407130 57.860 2.6408
 6.800 407110 57.185 2.6452
 6.960 407100 57.087 2.6522
 7.120 407120 56.981 2.6516
 7.280 407110 56.776 2.6587
 7.440 407110 56.667 2.6647
 7.600 407590 56.667 2.6738
 7.760 407090 56.319 2.6811
 7.920 407090 56.126 2.6904
 8.080 40700 56.126 2.6997
 8.240 40700 55.932 2.7060
 8.400 40700 55.800 2.7059
 8.560 407100 55.804 2.7098
 8.720 407110 55.724 2.7225
 8.880 407110 55.454 2.7304
 9.040 407090 55.100 2.7605
 9.200 40700 54.808 2.7676
 9.360 40700 54.519 2.7715
 9.520 40700 54.431 2.7726
 9.680 407110 54.462 2.7936
 9.840 40700 54.939 2.7993
 10.00 407080 54.050 2.8333
 10.16 407050 53.288 2.8347
 10.32 40760 53.265 2.8472
 10.48 407070 53.407 2.8557
 10.64 407060 52.844 2.8626
 10.80 407090 52.844 2.8668
 10.96 407090 51.378 2.8728
 11.12 407090 51.378 2.8795
 11.28 407090 51.367 2.8924
 11.44 407090 51.367 2.8951
 11.60 407100 51.706 2.8651
 11.76 407110 51.706 2.8825
 11.92 407120 51.387 2.8825
 12.08 407120 51.387 2.8884
 12.24 40760 51.387 2.8952
 12.40 407100 51.336 2.8952

TIME (S) HEAT FLUX (W/MM²) THETA (C) RUSSELL NUMBER
 -1.84 407260 59.625 2.5335
 -1.68 407270 59.630 2.5333
 -1.52 407260 59.627 2.5335
 -1.36 407250 59.642 2.5327
 -1.20 407270 59.632 2.5333
 -1.04 407290 59.636 2.5332
 -.880 407280 59.633 2.5331
 -.720 407280 59.634 2.5331
 -.560 407250 59.633 2.5331
 -.400 407280 59.630 2.5330
 -.240 407260 59.636 2.5330
 -.080 407250 59.659 2.5320
 0.080 407260 59.729 2.5291
 0.240 407270 59.651 2.5325
 0.400 407260 59.628 2.5334
 0.560 407260 59.607 2.5362
 0.720 407260 59.592 2.5350
 0.880 407260 59.587 2.5357
 1.040 407290 59.551 2.5357
 1.200 407280 59.544 2.5371
 1.360 407250 59.532 2.5374
 1.520 407270 59.515 2.5362
 1.680 407260 59.514 2.5382
 1.840 407270 59.489 2.5394
 2.000 407280 59.452 2.5410
 2.160 407260 59.428 2.5419
 2.320 407260 59.428 2.5419
 2.480 407260 59.312 2.5431
 2.640 407260 59.258 2.5492
 2.800 407290 59.239 2.5502
 2.960 407290 59.155 2.5518
 3.120 407270 59.309 2.5564
 3.280 407250 59.400 2.5584
 3.440 407270 59.403 2.5588
 3.600 407250 58.985 2.5609
 3.760 407250 58.985 2.5630
 3.920 407260 58.716 2.5655
 4.080 407220 58.765 2.5685
 4.240 407230 58.741 2.5712
 4.400 407210 58.689 2.5716
 4.560 407180 58.611 2.5760
 4.720 407210 58.492 2.5823

RUN NUMBER AP7-2

PAGE 3

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*****
TIME          HEAT FLUX      THETA      MUSSELT
(ES)          (W/M^2)         (C)      NUMBER
*****
12.56        407090          51.421    2.6005
12.72        407100          51.902    2.9094
12.88        407110          51.274    2.8848
13.04        407120          51.183    2.9103
13.20        407130          51.744    2.9183
13.36        407140          51.637    2.9238
13.52        407110          51.350    2.9407
13.68        407100          51.312    2.9428
13.84        407060          50.777    2.9736
14.00        407080          51.405    2.9773
14.16        407030          50.694    2.9782
14.32        407010          50.702    2.9780
14.48        407070          51.376    2.9891
14.64        407070          49.826    3.0201
14.80        407030          49.826    3.0073
14.96        407050          50.209    3.0073
15.12        407100          50.270    3.0038
15.28        407070          50.607    2.9836
15.44        407060          50.308    3.0012
15.60        407050          50.370    2.9975
15.76        407060          50.363    2.9980
15.92        407060          50.363    2.9980
16.08        407050          49.027    3.0027
16.24        407050          49.431    3.0544
16.40        407050          48.846    3.0509
16.56        407000          48.014    3.1442
16.72        407030          48.000    3.1064
16.88        407610          48.658    3.1026
17.04        406980          47.860    3.1541
17.20        407040          48.786    3.0547
17.36        407040          48.091    3.1814
17.52        407040          47.860    3.0547
17.68        407600          47.003    3.0580
17.84        407000          48.529    3.1108
18.00        407000          48.553    3.1095
18.16        407000          48.396    3.1155
18.32        407040          48.131    3.1269
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RUN NUMBER AP8-4

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WIRE LENGTH = 0.06 M
WIRE DIAMETER = 0.002 M
WIRE WEIGHT = 1.00 G
ARRIVAL TEMP = 100 C
PRESSURE = MAX 1430.3, DECOMPRESS FROM 377.13 KPA
INITIAL RESIS. = 316.205 OHMS AT 160 C
SIGMA = C

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*****
TIME          HEAT FLUX      THETA      MUSSELT
(ES)          (W/M^2)         (C)      NUMBER
*****
-1.84        419280          59.844    2.5887
-1.68        419300          59.848    2.5921
-1.52        419310          59.855    2.5884
-1.36        419310          59.864    2.5980
-1.20        419320          59.859    2.5984
-1.04        419290          59.866    2.5978
-0.88        419280          59.868    2.5978
-0.72        419280          59.840    2.5973
-0.56        419280          59.872    2.5975
-0.40        419240          59.888    2.5969
-0.24        419270          59.885    2.5965
-0.08        419230          60.093    2.5914
0.08        419250          59.732    2.5948
0.24        419260          59.895    2.5964
0.40        419280          59.900    2.5963
0.56        419280          59.899    2.5962
0.72        419280          59.894    2.5964
0.88        419280          59.894    2.5964
1.04        419260          59.879    2.5971
1.20        419250          59.877    2.5974
1.36        419260          59.859    2.5980
1.52        419280          59.859    2.5985
1.68        419290          59.841    2.5985
1.84        419280          59.828    2.5985
2.00        419280          59.820    2.5985
2.16        419300          59.810    2.6010
2.32        419300          59.773    2.6019
2.48        419290          59.761    2.6024
2.64        419250          59.730    2.6035
2.80        419280          59.719    2.6042
2.96        419270          59.694    2.6052
3.12        419280          59.676    2.6061
3.28        419280          59.696    2.6074
3.44        419280          59.687    2.6074
3.60        419280          59.587    2.6100
3.76        419270          59.545    2.6118
3.92        419280          59.530    2.6124
4.08        419280          59.491    2.6142
4.24        419260          59.459    2.6155
4.40        419250          59.419    2.6177
4.56        419260          59.385    2.6187
4.72        419270          59.350    2.6204
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RUN NUMBER APB-4

PAGE 2

RUN NUMBER APB-4

PAGE 3

TIME (S)	HEAT FLUX (W/CM ²)	THETA (CI)	MUSSELT NUMBER	TIME (S)	HEAT FLUX (W/CM ²)	THETA (CI)	MUSSELT NUMBER
4.800	419270	59.314	2.6219	12.56	419200	54.766	2.8392
5.040	419270	59.790	2.6270	12.72	419250	54.856	2.8348
5.280	419260	59.243	2.6250	12.88	419230	54.543	2.8510
5.520	419250	59.688	2.6258	13.04	419210	54.557	2.8501
5.760	419250	59.183	2.6258	13.20	419200	53.974	2.8801
6.000	419240	59.636	2.6312	13.36	419200	53.964	2.8814
6.240	419270	59.094	2.6317	13.52	419210	55.926	2.8835
6.480	419270	59.667	2.6329	13.68	419190	53.781	2.8911
6.720	419270	59.012	2.6353	14.00	419220	53.967	2.8813
6.960	419270	59.778	2.6389	14.16	419200	53.717	2.8945
7.200	419270	59.352	2.6380	14.32	419200	53.679	2.8967
7.440	419270	58.899	2.6405	14.48	419200	53.841	2.8979
7.680	419270	58.412	2.6412	14.64	419210	54.061	2.8956
7.920	419270	58.782	2.6432	14.80	419210	54.193	2.8693
8.160	419270	58.782	2.6432	14.96	419200	53.541	2.9040
8.400	419250	58.760	2.6465	15.12	419210	53.694	2.8959
8.640	419270	58.717	2.6486	15.28	419210	53.493	2.9068
8.880	419270	58.660	2.6512	15.44	419210	54.016	2.8787
9.120	419200	58.633	2.6525	15.60	419210	53.023	2.8690
9.360	419280	58.598	2.6540	15.76	419200	53.866	2.8866
9.600	419280	58.573	2.6550	15.92	419210	53.680	2.8967
9.840	419280	58.506	2.6596	16.08	419240	54.061	2.8756
10.080	419280	58.428	2.6638	16.24	419240	54.265	2.8657
10.320	419240	58.369	2.6641	16.40	419230	54.590	2.8485
10.560	419240	57.872	2.6693	16.56	419240	54.565	2.8499
10.800	419230	56.882	2.6737	16.72	419240	54.607	2.8477
11.040	419240	56.932	2.6712	16.88	419240	54.139	2.8723
11.280	419240	56.697	2.6747	17.04	419240	54.593	2.8484
11.520	419210	56.630	2.6789	17.20	419230	54.582	2.8489
11.760	419220	56.727	2.6742	17.36	419230	54.215	2.8852
12.000	419220	56.483	2.6795	17.52	419230	54.702	2.8424
12.240	419240	56.429	2.6705	17.68	419230	54.613	2.8578
12.480	419240	56.944	2.6747	17.84	419230	54.542	2.8509
12.720	419200	54.944	2.8299	18.00	419260	54.564	2.8501
12.960	419210	55.074	2.8234	18.16			
13.200	419210	55.063	2.8237				
13.440	419200	55.126	2.8206				
13.680	419230	55.397	2.8070				
13.920	419220	55.382	2.8137				
14.160	419220	55.334	2.8102				
14.400	419230	55.309	2.8115				
14.640	419210	55.029	2.8261				
14.880	419190	54.305	2.8632				
15.120	419210	54.674	2.8440				

PAGE 2

RUN NUMBER APB-7

WIRE LENGTH = .036 N
 WIRE AREA = .0001 N
 AMBIENT TEMP = 100 C
 PRESSURE TEMP = MAX 1480.3, DECOMPRESS FROM 377.11 KPA
 INITIAL RESIS. = .11108 OHMS AT 100 C
 SIGMA = 0

RUN NUMBER APB-7

TIME
 ISI

HEAT FLUX
 (M/CM²)

THETA
 (CI)

MUSSELT
 NUMBER

TIME ISI	HEAT FLUX (M/CM ²)	THETA (CI)	MUSSELT NUMBER
-1.84	417990	60.262	2.5728
-1.68	418000	60.261	2.5729
-1.52	418020	60.260	2.5727
-1.36	418020	60.266	2.5728
-1.20	418020	60.273	2.5725
-1.04	418000	60.272	2.5724
-0.88	418000	60.273	2.5725
-0.72	418030	60.273	2.5725
-0.56	418020	60.282	2.5721
-0.40	418000	60.291	2.5716
-0.24	418010	60.300	2.5713
-0.08	418010	60.295	2.5715
0.08	418020	60.306	2.5711
0.24	418000	60.319	2.5704
0.40	418020	60.327	2.5702
0.56	418000	60.304	2.5711
0.72	418000	60.304	2.5711
0.88	418020	60.287	2.5719
1.04	418010	60.273	2.5724
1.20	418010	60.283	2.5720
1.36	418000	60.258	2.5731
1.52	418020	60.253	2.5733
1.68	418030	60.245	2.5738
1.84	417990	60.219	2.5746
2.00	418000	60.195	2.5754
2.16	418010	60.181	2.5754
2.32	418010	60.161	2.5771
2.48	418030	60.139	2.5783
2.64	417990	60.111	2.5793
2.80	418040	60.085	2.5807
2.96	418030	60.061	2.5816
3.12	417990	60.027	2.5829
3.28	418000	59.975	2.5853
3.44	418030	59.923	2.5876
3.60	418000	59.872	2.5896
3.76	418030	59.877	2.5896
3.92	418030	59.851	2.5907
4.08	418030	59.812	2.5924
4.24	417990	59.759	2.5944
4.40	418000	59.746	2.5951
4.56	417990	59.704	2.5968
4.72	418010	59.661	2.5988

RUN NUMBER APB-7

TIME
 ISI

HEAT FLUX
 (M/CM²)

THETA
 (CI)

MUSSELT
 NUMBER

TIME ISI	HEAT FLUX (M/CM ²)	THETA (CI)	MUSSELT NUMBER
4.880	418020	59.616	2.6008
5.040	417980	59.586	2.6019
5.200	418010	59.532	2.6046
5.360	418010	59.490	2.6063
5.520	418010	59.455	2.6076
5.680	418010	59.408	2.6088
5.840	418010	59.416	2.6096
6.000	417990	59.399	2.6102
6.160	418000	59.381	2.6110
6.320	418000	59.372	2.6112
6.480	418010	59.372	2.6112
6.640	418000	59.396	2.6148
6.800	418020	59.396	2.6148
6.960	418010	59.283	2.6154
7.120	418030	59.238	2.6175
7.280	418000	59.232	2.6176
7.440	417990	59.164	2.6205
7.600	418010	59.104	2.6207
7.760	418000	59.104	2.6231
7.920	418020	59.065	2.6251
8.080	418000	59.068	2.6251
8.240	417510	58.984	2.6336
8.400	418010	58.716	2.6406
8.560	417970	58.496	2.6504
8.720	418000	58.777	2.6375
8.880	417980	58.509	2.6498
9.040	417640	58.273	2.6673
9.200	418000	58.128	2.6802
9.360	417640	57.947	2.6974
9.520	417600	57.725	2.7146
9.680	417600	57.507	2.7318
9.840	417640	57.408	2.7480
10.000	417950	57.408	2.7618
10.160	417970	57.696	2.6819
10.320	417990	57.739	2.6952
10.480	417640	57.780	2.6832
10.640	417640	57.702	2.6866
10.800	417970	57.738	2.6851
10.960	417970	57.738	2.6851
11.120	417990	57.732	2.6852
11.280	417990	57.756	2.6843
11.440	417980	57.803	2.6822
11.600	417960	56.293	2.7440
11.760	417640	56.378	2.7497
11.920	417930	56.489	2.7442
12.080	417050	56.471	2.7452
12.240	417660	56.425	2.7475
12.400	417640	56.420	2.7476

RUN NUMBER APS-3

PAGE 3

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*****
TIME           HEAT FLUX      THETA      NUSSLET
(°)           (W/CMH)      (C)        NUMBER
*****
12.56         417950         56.502     2.7437
12.72         417940         56.163     2.7602
12.88         417960         56.942     2.7712
13.04         417820         56.172     2.7996
13.20         417950         55.825     2.7754
13.36         417950         55.643     2.7742
13.52         417950         55.683     2.7742
13.68         417950         55.885     2.7741
13.84         417950         56.034     2.7667
14.00         417970         56.564     2.7609
14.16         417870         56.322     2.7428
14.32         417980         56.659     2.7343
14.48         413000         56.956     2.7708
14.64         417950         56.322     2.7672
14.80         417950         56.339     2.7715
14.96         417950         56.037     2.7379
15.12         417950         56.637     2.7379
15.28         417970         56.168     2.7602
15.44         417950         56.445     2.7562
15.60         417950         56.352     2.7413
15.76         417950         56.339     2.7517
15.92         417980         56.025     2.7673
16.08         417990         56.031     2.7671
16.24         417950         55.789     2.7503
16.40         417960         55.708     2.7428
16.56         417940         55.708     2.7428
16.72         417990         55.659     2.7659
16.88         417970         55.933     2.7718
17.04         417540         56.276     2.7546
17.20         417990         59.717     2.7827
17.36         417960         56.040     2.7664
17.52         417960         57.274     2.7740
17.68         417950         56.295     2.7760
17.84         417950         56.134     2.7814
18.00         417960         56.134     2.7797
18.16         417960         55.773     2.7797
18.32         417980         56.209     2.7592
*****

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RUN NUMBER AP9-4

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*****
WIRE LENGTH = .096 M
WIRE DIAMETER = .00025 M
AMBIENT TEMP. = 100 C
PRESSURE TEMP. = MAX 790.8, DECOMPRESS FROM 377.11 KPA
INITIAL RESIS. = .316198 OHMS AT 100 C
SIGMA = C
*****

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*****
TIME           HEAT FLUX      THETA      NUSSLET
(°)           (W/CMH)      (C)        NUMBER
*****
-2.40         417840         59.828     2.5908
-1.80         417940         59.979     2.5846
0.800         417980         59.092     2.5843
2.400         417950         59.718     2.5960
4.000         417930         59.306     2.6140
5.600         417540         59.707     2.6316
7.200         417830         58.215     2.6622
8.800         417860         57.288     2.7048
10.400        417950         57.113     2.7048
12.000        417770         57.160     2.7113
13.600        417870         57.210     2.7093
15.200        417900         57.283     2.7060
16.800        417930         56.007     2.7268
18.400        417930         56.439     2.7467
20.000        417510         56.361     2.7503
21.600        417940         56.621     2.7380
23.200        417520         56.657     2.7360
24.800        417510         56.268     2.7590
26.400        417510         56.268     2.7590
28.000        417500         56.474     2.7448
29.600        417900         56.273     2.7546
31.200        417930         56.229     2.7320
32.800        417770         56.740     2.7311
34.400        417720         57.090     2.7140
36.000        417750         57.593     2.6904
37.600        417690         57.398     2.6992
39.200        417690         56.590     2.7377
40.800        417690         57.584     2.7050
42.400        417640         57.584     2.6995
44.000        417190         57.416     2.6991
45.600        417830         56.805     2.7283
47.200        417870         57.123     2.7134
48.800        417900         57.239     2.7080
50.400        417900         57.138     2.7129
52.000        417910         57.137     2.7129
53.600        417840         56.314     2.8035
55.200        417840         57.693     2.8070
56.800        417850         57.499     2.8070
58.400        417800         50.055     3.0993
60.000        417850         51.876     2.9877
61.600        417870         51.634     3.0006
63.200        417860         50.037     3.0975
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INITIATION OF SUBCOOLED POOL BOILING
DURING PRESSURE TRANSIENTS

by

DONALD L. SCHMIDT

B.S., Kansas State University, 1983

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

An experimental investigation of boiling initiation during pressure transients has been made. A platinum wire heating element of dimensions 0.25 mm diameter and 9.6 cm length was immersed in distilled and degassed water. Maximum pressures from 0.377 to 1.48 MPa were applied with the water and test element temperatures at 100°C before heating the platinum wire to 160°C. The wire experienced constant superficial heat fluxes of approximately 0.42 MW/m^2 while the system was subjected to near-exponential decompressions to atmospheric pressure. Pressure reduction periods were approximately 4 and 6.6 s, and pressure transients were reproducible over most of the pressure drop. Boiling initiation times provided conditions for boiling initiation which depended on the pressure-temperature history of the test element and the surrounding fluid. These conditions tended to be overpredicted by a model accounting for the deactivating effect of pre-pressurization on potential nucleation sites. Reactivation of nucleation sites and recovery of the test element temperature to steady-state were seen to be strongly affected by increases in the maximum pressure applied.