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**Low Temperature Boiling Enhancement
for the
SLOWPOKE Decay Heat Rejection System**

by

Morgan J. Brown, B.Sc.(Eng.)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Engineering
Department of Mechanical and Aeronautical Engineering
Carleton University
Ottawa, Ontario

July 24 1989

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Abstract

A heat pipe decay heat rejection system (DHRS) has been proposed for use in the low temperature SLOWPOKE 10MWth central heating reactor. A half-scale model of the DHRS evaporator was designed and built by the National Research Council of Canada Low Temperature Laboratory in Ottawa for an experimental program implemented by the author. The heat transfer performance of a plain stainless steel surface, and of the same surface with a teflon-coated wire covering 15% of the surface, was tested at low heat fluxes and subatmospheric pressures. The teflon wrapped surface has an improved heat transfer capability and system stability due to the non-wetting property of teflon and the improved nucleation provided by the wire-wrap geometry. Tests with a plain stainless steel instrumented test section designed by the author and built in the Carleton University workshops confirmed the use of Nusselt's film condensation equation and Rohsenow's pool boiling equation in modelling the heatpipe system. Using a simplified model of the evaporator, it is predicted that the teflon wire-wrapped surface would improve the heat transfer capability of the SLOWPOKE DHRS by 11 to 19 percent.

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Nomenclature

A	Area (m^2)
A_b	Boiling heat transfer area (m^2)
A_c	Condensing heat transfer area (m^2)
$c_{p,f}$	Specific heat of liquid water ($J/kg^\circ C$)
$C_{b,f}$	Rohsenow boiling surface-fluid coefficient
C_1	Coefficient containing fluid properties for the Nusselt condensation equation
C_2 & C_3	Parameter groups in the Rohsenow boiling equation
C_4	Lumped parameter group in rearrangement of Rohsenow boiling equation for best-fit equations
d	Diameter (m)
f	Flow friction factor
G	Mass flux ($kg/(m^2 s)$)
g	Gravitational acceleration (m/s^2)
Gr	Grashof number
h	Convective heat transfer coefficient ($W/m^2^\circ C$)
h_{boil}	Boiling heat transfer coefficient ($W/m^2^\circ C$)
h_{fg}	Heat of vapourization (J/kg)
h_m	Mean condensing heat transfer coefficient ($W/m^2^\circ C$)
H_{loss}	Loss coefficient from heatpipe2 ($W/^\circ C$)
Heatpipe1	The heatsource
Heatpipe2	The heatsink
K_{loss}	Power loss coefficient ($W/^\circ C$)
k_f	Thermal conductivity of liquid water ($W/m^\circ C$)
k_{ss}	Thermal conductivity of stainless steel ($W/m^\circ C$)
L	Heated length of heatpipe1 (m)
n	Exponent in best-fit equation version of Rohsenow boiling equation

m	Exponent in vertical plate free convection equation
m, n	Exponents for wall superheat/nucleation sites equation
N	Number of data points
N	Number of nucleation sites
Nu	Nusselt number based on either length (l) or diameter (d)
P_l	Liquid pressure (Pa)
P_g	Vapour pressure (Pa)
Pr	Prandtl number
P_{Gaussian}	Probability of a normal Gaussian distribution
P_{wr}	Input power to heatpipe1 (W)
q	Total heat transferred (W)
q_{ab}	Boiling heat flux (W/m ²)
q_{ac}	Condensing heat flux (W/m ²)
r^*	Spherical vapour nucleus radius (m)
Re	Reynolds number
R^2	Closeness of fit
R_i	Radius of the inside of heatpipe1 (m)
R_o	Radius of the outside of heatpipe1 (m)
T_g	Vapour temperature (°C)
T_{in}	Condenser inlet temperature (°C)
T_{out}	Condenser outlet temperature (°C)
T_{sat}	Saturation temperature (°C)
T_w	Wall temperature (°C)
T_{w1}	Inner wall temperature (condensing side) (°C)
T_{w2}	Outer wall temperature (boiling side) (°C)
T_1	Two-phase fluid temperature in heatpipe2 (°C)

T_2	Vapour temperature in heatpipe1 ($^{\circ}\text{C}$)
T_3	Ambient air temperature ($^{\circ}\text{C}$)
T_4	Vapour temperature in heatpipe2 ($^{\circ}\text{C}$)
T_5	Outer wall (of heatpipe1) temperature 12" from the bottom of the test section ($^{\circ}\text{C}$)
T_6	As above but 42" from the bottom, and 180° around the outside of heatpipe1 from T_5 ($^{\circ}\text{C}$)
$\Delta T_{\text{bo}-4}$	Boiling temperature difference ($^{\circ}\text{C}$)
ΔT_{1-4}	Temperature difference between the two-phase and vapour ($^{\circ}\text{C}$)
ΔT_{2-3}	Power loss temperature difference ($^{\circ}\text{C}$)
ΔT_{2-w1}	Condensation temperature difference between T_2 and the inner wall ($^{\circ}\text{C}$)
ΔT_{4-3}	Heatpipe2 heat loss temperature difference ($^{\circ}\text{C}$)
T_{rate}	Vapour temperature change rate ($^{\circ}\text{C}/\text{min}$)
ΔT_{5-4}	Temperature difference between wall thermocouple T_5 and the vapour ($^{\circ}\text{C}$)
ΔT_{6-4}	Temperature difference between wall thermocouple T_6 and the vapour ($^{\circ}\text{C}$)
β	Volume coefficient of expansion ($^{\circ}\text{C}^{-1}$)
ϵ_{AB}	Boiling area error (m^2)
ϵ_{C1}	C_1 error
$\epsilon_{C2} \text{ \& } \epsilon_{C3}$	C_2 and C_3 errors
ϵ_{Csf}	Rohsenow pool boiling surface-fluid coefficient error
ϵ_{loss}	Power loss coefficient error ($\text{W}/^{\circ}\text{C}$)
ϵ_P	Heatpipe1 power error (W)
ϵ_{qAB}	Boiling heat flux error (W/m^2)
ϵ_T	Temperature reading error ($^{\circ}\text{C}$)
$\epsilon_{\text{wo}-4}$	Boiling temperature difference error ($^{\circ}\text{C}$)
ϵ_{wo}	Outer wall temperature error ($^{\circ}\text{C}$)

ϵ_{2-w1}	Condensation temperature difference error ($^{\circ}\text{C}$)
μ_r	Water dynamic viscosity (kg/m-s)
ρ_r	Water liquid density (kg/m^3)
ρ_g	Water vapour density (kg/m^3)
σ_r	Water surface tension (N/m)
σ_T	Standard deviation of a temperature reading ($^{\circ}\text{C}$)

Note on Units: All of the calculations are done using S.I. units, but references to levels and dimensions are often in inches due to the original model design using imperial measurements. Hopefully this will not be too confusing.

Chapter One: Introduction

The SLOWPOKE ENERGY SYSTEM (SES) is a 10 MWth nuclear reactor designed to be an inherently safe and economical means of providing low grade heat for a central heating system. Operating at atmospheric pressure in a large steel-lined concrete pool (figure 1i), the bulk pool temperature, normally 63 to 65°C, will remain under a given set point (75° to 85°C), and the primary heat removal is via heat exchangers at the top of the chimney surrounding the core. Natural convection is the only means of circulation, and any power rise will increase the coolant flowrate through the core. Should boiling occur in the core, the negative void and temperature coefficients will limit the power; excess heat will be removed by the heat exchangers and by conduction through the pool walls. The pool lid will be sealed during normal operations to keep any gaseous radionuclides or activated products from entering the reactor building, which is not designed to act as a pressurized containment. Should the heat exchangers be shut down, for maintenance or due to a loss of power for the heat exchanger pumps, a backup heat rejection system may be necessary to remove the decay heat and prevent the pool from boiling. It is this Decay Heat Rejection System (DHRS) that is the topic of study for this thesis.

1.1 DHRS Configuration

The SES has simple and reliable shutdown systems, but the radioactive decay heat, nominally a maximum of 1% of the reactor thermal output (100 kW in this case), still requires rejection should the power plant "go black", i.e. lose all external power sources. As mentioned, the pool walls would conduct a considerable portion of the heat to the ground, and condensation on the underside of the pool lid will assist in heat rejection, but a further heat sink may be necessary to maintain the pool below the saturation point. A gas-charged heat pipe using water as the working fluid, with an annular evaporator in the SES pool and the external condenser cooled by naturally convecting air, is the present option for the DHRS. Being charged with gas (likely to be air) at sub-atmospheric pressure, the interface between the gas and the water vapour prevents the heat pipe from operating until the saturation temperature, and hence the saturation pressure, rises due to an increase in the SES pool temperature (figure 1ii). When the pool temperature, and thus that of the immersed evaporator, passes the operational set point, the gas-vapour interface is forced into the condenser, and heat begins to be rejected to the outside environment. The intention is that the DHRS should be fully operational when the SES pool reaches 95°C, and is able to prevent any further increase in the pool temperature.

By optimizing the DHRS design, one can reduce the system cost, and the number of units required for a given heat removal. An annular evaporator was proposed {1} in order to increase the convective heat transfer surface area over a plain cylinder design. Also, the inner surface might experience thermosyphon driven forced convection, thus further increasing the heat transfer, as opposed to the outer surface which would operate with natural convection.

1.2 DHRS Operation

When the DHRS operates, the temperature difference between the pool and the evaporator causes a natural convection loop, and pool water circulates down around the outside of the evaporator and down through the inner tube. The heat conducted through the evaporator walls, is used to boil the working fluid (water), and the steam travels to the condenser. Prior to the DHRS "turning on", the vapour/air interface blocks steam access to the condenser, preventing any heat removal from the pool and thus there is no heat flux into the evaporator. Therefore the initial evaporator saturation temperature when the DHRS "switches on" is the same as for the SES pool.

At a pool temperature of 95°C, the DHRS is designed to remove 10 kW of heat {2}; there obviously must then be a temperature difference between the pool and the evaporator liquid. The evaporator liquid must be superheated to

evaporate, and so at full heat rejection the saturation temperature of the DHRS must be lower than 95°C (the maximum allowable pool temperature) and above the SES pool set point (75°C to 85°C depending upon the final operational specifications).

The DHRS saturation temperature must be as high as needed to provide a sufficient saturation pressure to force the gas out of the condenser section. Thus it is imperative that the heat rejection system have the best possible heat transfer capability to go from zero to full capacity over a 10° to 20°C increase (dependent upon the SES pool temperature set point) in the pool temperature.

For the DHRS operating conditions (low heat flux), it can be shown that the convection heat transfer coefficient external to the evaporator is in a similar range to the boiling heat transfer coefficient internal to the evaporator. Enhancing the boiling heat transfer coefficient by modifying the surface will improve the heat rejection capacity of the DHRS. With the evaporator saturation temperature raised closer to the pool temperature by boiling enhancement, the evaporator vapour pressure will increase more for a given pool temperature increase and thus force more gas out of the condenser than for an unenhanced surface. This in turn increases the condenser capacity and thus the DHRS heat-rejection capability.

Since it is desirable to begin rejecting heat as soon as possible after the SES pool temperature passes the set point, the improved Decay Heat Rejection System capacity will provide better margins with respect to preventing the pool from boiling.

1.3 DHRS Boiling Enhancement

In order to enhance boiling (to lower the wall superheat) it is desirable to have a surface with many suitable nucleation sites; these sites are provided by small gas - or vapour - trapping cavities on the surface and/or by local low-wettability areas. Low wettability increases the surface/liquid contact angle and thereby reduces the ability of the liquid to flood the nucleation site. {3}

Since the DHRS is intended for a nuclear reactor, a copper evaporator was precluded from use {4}; any corrosion products would circulate throughout the pool and become activated in the core, increasing the occupational radiation dosage during operation, overhaul or refuelling. Thus a 304 stainless steel surface exposed to the pool was selected. As to the boiling surface itself (on the inside of the evaporator) it is best to have a stable, non-corrosive material; it is essential that the DHRS should remain

operable for many years unattended, and this implies a non-aging surface.

There have been many methods used to improve the boiling characteristics of surfaces, including spray welding {5} and plasma deposition {6}, layers of loose 200 μ m steel spheres laid on a heated surface {7}, machined grooves {8}, teflon fabrics {9} and sleeves {10}, wire meshes {9}, and sleeves with re-entrant holes {10}. Non-wetting teflon was first used by Young and Hummel {11} by spraying small spots onto a clean, smooth 304 stainless steel surface, and also by filling pits in another 304 plate. Their results demonstrated a much lower wall superheat than for either the smooth or pitted steel surfaces operating at the same heat flux. However, except for the work by Larkin {10}, much of the work has involved flat plates or horizontal tubes, as common in fire-tube boilers or heat exchangers. And again, largely except for Larkin's work, the emphasis has been (quite naturally) on high heat fluxes and temperatures. Porous surfaces give good boiling enhancement except that they suffer from high initial superheats {12}, undesirable in the DHRS application where it is essential to initiate boiling at low superheats.

In the present work, two surfaces were intended for study: as-manufactured steel, and the same surface partially wrapped with a teflon coated wire. This latter surface

enhancement was very easy to apply, and was the only simple means of maintaining a good contact between the teflon and the steel. At the steel/teflon junction non-wetted nucleation sites were formed in addition to those in the steel surface.

There was in fact one other surface used in the present work, created after a second, thicker-walled, tube was fitted with two thermocouples in slots at the surface. This instrumented test section was used to provide measured surface temperatures, in order to confirm (or disprove) the system analysis. Sandpaper was applied to the tube to remove excess solder, and the entire surface was so treated in order to maintain some semblance of uniformity. This "scratched" surface also proved to enhance boiling.

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Journal of Heat Transfer, Volume 104, p279-285 (1982)

FIGURE 111. DECAY HEAT REMOVAL SYSTEM OPERATION

Chapter Two: Experimental Setup and Procedure

The experimental apparatus was designed by Dr. B. Larkin of the National Research Council of Canada to model the inner wall of the DHRS evaporator annulus, at half linear scale, although the annular gap was approximately 80% full size. The test rig (figure 2i) consisted of two heat pipes, the inner one (heatpipe1) driving the outer (heatpipe2), and thus the common wall modelled the inner annulus wall of the DHRS evaporator. The annulus consisted of a one inch (0.0254m) outside diameter stainless steel tube within one of three inches (0.0762m) outside diameter. The heated common wall was a total of 47.6 inches (1.210m) long, and the overall height of the test rig was 96 inches (2.438m). Distilled water boiled by an electric element in the bottom of heatpipe1 condensed on the inside of the common wall, providing a virtually constant input temperature. The heat of condensation was conducted through the wall to heatpipe2, where it was used to evaporate the water. Water vapour from this latter process condensed at the top of the outermost wall of heatpipe2 in a water jacket condenser. The temperatures of the driving vapour in heatpipe1 (T_2), the two-phase mixture (T_1) and the vapour (T_4) in heatpipe2, and the ambient air (T_3) were measured and recorded, as was the power input to heatpipe1. Two temperatures of the common wall (T_5 and T_6) were also measured in the instrumented test section.

2.1 Heat Transfer Models:

The heatflux and wall superheat were determined for all cases as averages for the entire common wall; thermocouples T_3 and T_4 gave local wall temperatures that verified the method of solving the average superheat, but were not used to produce the overall results.

The heat transfer models, described in detail in chapter 3, began with the Rohsenow-modified Nusselt film condensation equation. Knowing the vapour temperature (T_2) and the net heat transferred - having accounted for heat losses in the heating element chamber - the average condensing heat transfer coefficient (h_m) on the inside of the common wall was determined, and hence the average inner wall temperature (T_{w1}). Using the one dimensional radial conduction equation and T_{w1} , the average outer wall temperature (T_{w0}) was solved. Since the vapour temperature (T_4) in heatpipe2 had been measured, the wall superheat was merely the difference between T_{w0} and T_4 (ΔT_{w0-4}).

Next, Rohsenow's pool boiling equation was solved for the surface-fluid coefficient C_{sf} , and it is this term that is used for comparing the various surfaces used in the author's work; although strictly for use in comparing various combinations of working fluid and surface, C_{sf} was also convenient for comparing the effect of the fluid level on the heat transfer performance in heatpipe2.

Chapter Four: Results

The plotted results are found in Appendix A, with the complete set of data in Appendix B; any data points marked with a "#" are considered unreliable due to rapidly changing temperatures, or to a lack of aspiration, and such points are not considered in this analysis, with one exception for the two-phase plots (DATA8 and DATA9).

4.1 Temperature Readings

Typical temperature readings for the constant heat flux and increasing/decreasing heat flux tests are shown in figures 4i and 4ii respectively. Both illustrate the instrumented test section at power levels in the order of 1100W, and a nominal fluid level of 48 inches. The plotted temperatures and standard deviations are of the five thermocouples located within the test rig (T_1 :two-phase, T_2 :heatpipe1 vapour, T_4 :heatpipe2 vapour, T_5 :lower wall, and T_6 :upper wall); T_3 measured the ambient temperature of about 20°C, and is thus well off-scale. It should be noted that the temperature points and standard deviations represent 25 samples each, spread out over the preceding minute.

Figure 4ii is a "snapshot" of 20 minutes of a 200 minute long test, showing three power level changes. For each power change, the condenser flow had to be adjusted, and thus the increasing/decreasing tests were a little less

2.3 Test Rig Calibration

A complete description of the test apparatus is found in Appendix C, although figure 21 illustrates most features. Aside from the test rig itself, there was a saturated core transformer and a Variac to provide the power, an adjustable head tank and valve to control the condenser flow rate, a computer and data acquisition system, six thermocouples and one wattmeter.

The thermocouples were calibrated with a steam source and an ice bath, as described in Appendix D, and the analog wattmeter was compared with a digital readout version. The heat loss coefficient K_{loss} , where

$$\text{Heat lost} = K_{loss} (T_2 - T_3) \quad [2.1]$$

was determined (Appendix D) to find the loss that occurred in the heater element chamber - heat that did not cross the test surface.

During 31 of the constant heat flux tests, the coolant flowrate and the influx and efflux temperatures to the condenser were measured, and the resultant heat removal was solved:

$$\text{Condenser Heat} = \text{mass-flow-rate} * c_p (T_{out} - T_{in}) \quad [2.2]$$

Since the input power and the lost heat (equation [2.1]) were known, a heat balance was solved and thus the adiabaticity of heatpipe2 was determined.

One final test described in Appendix D was that comparing the measured saturation temperature and the saturation pressure. The latter was measured with a mercury manometer, and the results (pD21) show that indeed the vapour thermocouple (T_4) read correctly.

2.4 Test Procedure

The tests were organized in the following manner: three surfaces/ three fluid levels in heatpipe2/ four constant power levels (plus increasing then decreasing power)/ (usually) five saturation temperatures (Table 2-I, parts i & ii). The surface wrapped with the teflon coated wire is known as the "teflon-15%" surface due to the wire covering a nominal 15% of the steel tube.

Table 2-I
Test Surface/Fluid Level/Power/Temperature Combinations

i) Plain Surface:

\Power Temp \ (W) T _a (°C)\	500	700	900	1100	Increasing then Decreasing
50	48 in.	48 in.	48 in.	48 in.	-----
60	40 in.	40 in.	40 in.	40 in.	-----
	44 in.	44 in.	44 in.	44 in.	-----
	48 in.	48 in.	48 in.	48 in.	-----
70	48 in.	48 in.	48 in.	48 in.	-----
75	-----	-----	-----	-----	40 inch
	-----	-----	-----	-----	44 inch
	-----	-----	-----	48 in.	48 inch
80	40 in.	40 in.	40 in.	40 in.	-----
	44 in.	44 in.	44 in.	44 in.	-----
	48 in.	48 in.	48 in.	48 in.	-----
85	-----	-----	-----	-----	48 inch
90	48 in.	48 in.	48 in.	48 in.	-----
100	40 in.	40 in.	40 in.	40 in.	-----
	44 in.	44 in.	44 in.	44 in.	-----
	48 in.	48 in.	48 in.	48 in.	-----

Table 2-I
Test Surface/Fluid Level/Power/Temperature Combinations

i1) Teflon-15% or Instrumented Surface:

\Power Temp \ {W} T _a {°C}\	500	700	900	1100	Increasing then Decreasing
60	40 in.	40 in.	40 in.	40 in.	-----
	44 in.	44 in.	44 in.	44 in.	-----
	48 in.	48 in.	48 in.	48 in.	-----
75	-----	-----	-----	-----	40 inch
	-----	-----	-----	-----	44 inch
	-----	-----	-----	-----	48 inch
80	40 in.	40 in.	40 in.	40 in.	-----
	44 in.	44 in.	44 in.	44 in.	-----
	48 in.	48 in.	48 in.	48 in.	-----
85	-----	-----	-----	-----	40 inch
	-----	-----	-----	-----	44 inch
	-----	-----	-----	-----	48 inch
100	40 in.	40 in.	40 in.	40 in.	-----
	44 in.	44 in.	44 in.	44 in.	-----
	48 in.	48 in.	48 in.	48 in.	-----

The surfaces of the tubes were cleaned and assembled, and the heat pipes filled with distilled water to the correct level, as described in Appendix C (pC9). The remaining valves and coolant lines were attached, and the air in the heat pipes was purged with an aspirator.

This latter process proved most important, as any air in the heat pipes caused the air/vapour interfaces to block the condensing vapour flows, and if the interface was below

thermocouples T_2 or T_4 , which read the vapour temperatures in heatpipe1 and heatpipe2 respectively, the vapour temperatures would be erroneously low.

When purging the system of air, the pipe stems extending from the top of the heat pipes became hot due to vapour condensation. A drop in temperature in the extension tube, as one moved one's hand upwards, showed the vapour/air interface location.

As described in Appendix C, the constant heat flux tests were started when the system temperature T_4 reached the desired saturation point (or close thereto) at a given power. The temperature was controlled by the coolant flowrate through the condenser jacket. This control method was difficult due to a time lag of at least two minutes. In most cases the saturation temperature was reached without much overshoot, but occasionally the initial temperature was too high and had to be lowered. During the test, the various temperatures were monitored to establish if the system was indeed stable; occasional trimming of the condenser flow was necessary, or the test was sometimes restarted.

The power was maintained constant and the temperature was altered monotonically upwards to the next test temperature during a set of tests; at the end of one set the power was

cut off and temperature allowed to drop 10°C below the new saturation point before the new power level was set.

The increasing/decreasing heat flux tests were similar to the constant heat flux tests except that the temperature was maintained approximately constant, while the power was changed (upwards to the maximum power, then downwards to the starting point) in a step-wise fashion with sufficient time at each power level for the system to stabilize. These tests were to test for hysteresis effects in the performance of the heat transfer surface.

FIGURE 2i
SYSTEM SETUP
 (Instrumented Section)

- Saturated Steam
 - Two-Phase Water
 - Insulation

Chapter Three: Theory

As briefly described in chapter 2, the analysis of the DHRS evaporator model was based upon average values of the heat flux, and the two vapour temperatures T_2 and T_4 . The local wall temperatures T_3 and T_4 were useful for confirming the calculated average wall temperature, and for determining the qualitative heat transfer behaviour of the evaporator, but were not used in the overall analysis. An illustration of the appropriate equations modelling the overall behaviour of the test rig is found in figure 3i, with the temperature locations.

3.1 Inner Wall Temperature

The first task was to calculate the average inner wall temperature T_{w1} . Knowing the driving vapour temperature T_2 and the net heat transferred to heatpipe2, the Rohsenow-modified Nusselt film condensation equation for a constant wall temperature (1) was invoked to provide an average condensing-side heat transfer coefficient:

$$h_m = 0.943 \left[\frac{k_f^3 g \rho_f (\rho_f - \rho_g) (h_{fg} + 0.68 c_{pf} (T_g - T_{w1}))}{\mu_f (T_g - T_w) L} \right]^{1/4} \quad [3.1]$$

Since only the average heat flux and the vapor temperature were known, the following substitutions and rearrangments were made:

$$q_{AB} = h_m (T_g - T_{w1}) R_1/R_o \quad [3.2]$$

Substitute equation [3.1] for h_m and thus:

$$q_{AB}^4 C_1 = h_{fg} (T_g - T_{w1})^3 + 0.68 c_p (T_g - T_{w1})^4 \quad [3.3]$$

where

$$C_1 = \left[\frac{R_o/R_1}{.943 \left[\frac{k_f^3 g p_f (p_f - p_g)}{\mu_f L} \right]^{1/4}} \right]^4 \quad [3.4]$$

and q_{AB} is the average heat flux based on the boiling surface area. R_o/R_1 is required to account for the different wall surface areas for the condensation and boiling heat fluxes. By using the rearranged condensation equation, and ignoring the second term:

$$0.68 c_p (T_g - T_{w1})^4$$

an initial guess of the condensing temperature difference was calculated. Successive iterations with an updated wall temperature (thus altering the film temperature) rapidly converged to provide the average wall temperature beneath the condensate film.

3.2 Outer Wall Temperature

Knowing the total heat transferred and the average inner wall temperature T_{wi} , and invoking the one dimensional radial conduction equation (2):

$$q = \frac{2\pi k_{ss} L (T_{wi} - T_{wo})}{\ln (R_o/R_i)} \quad [3.5]$$

the outside wall temperature T_{wo} was obtained; k_{ss} is the thermal conductivity of the stainless steel inner tube.

3.3 Boiling Surface Wall Superheat

The outside wall temperature T_{wo} (the innerwall of heatpipe2) was used to calculate the wall superheat for the boiling surface (ΔT_{wo-f}). Since the average boiling heat flux and wall superheat were known, the Rohsenow pool boiling (3) equation was solved for C_{sf} , the surface/fluid coefficient:

$$\frac{C_p (T_{wo} - T_{sat})}{h_{fg}} = C_{sf} \left[\frac{(q/A)}{\mu_f h_{fg}} \left[\frac{\sigma_f}{g (\rho_f - \rho_g)} \right]^{1/2} \right]^{1/3} Pr^{1.0} \quad [3.6]$$

C_{sf} proved to be the most effective way of comparing various surfaces and nominal fluid levels for, as the results show, it proved quite constant for a given surface/fluid level combination over the heat flux and temperature ranges studied. It must be stressed that Rohsenow intended C_{sf} as

a constant only for different surface and fluid combinations, and not for the geometry of the surface.

3.4 Fluid Level Effect

During the tests the water level rose in heatpipe2, due to a lower liquid density at elevated temperatures and to the two-phase effect. As previously mentioned, the levels were used to test the sensitivity of the boiling surface performance, as measured by C_{eff} , to the quantity of fluid present. As the fluid level rose higher it wetted more of the heated surface; if the evaporator was completely filled prior to heating up, the topmost fluid became excess to that required to wet all of the heated surface during a test. The excess fluid added an additional pressure head to the fluid that wetted the heated surface, forcing the local saturation pressures higher than if the fluid level was only enough to wet all the heated surface, and thus the average wall superheat was greater. If the level was too low, not all of the heated surface was wetted and the heat was transferred through a smaller area, subsequently increasing the local wall superheats.

3.5 Boiling Enhancement

Figure 3ii shows an axial cross section of the heat transfer surface, with the teflon covered wire sliced on the same plane. An idealized boiling nucleation site is shown, although in reality it would not be a regular shape, nor

would there be uniformity in size amongst the sites, unless the surface had been especially prepared.

The nucleation site, which holds a small amount of vapour or gas necessary to initiate boiling, will only work if there is sufficient local wall superheat for the vapour pressure to overcome the external liquid pressure and the surface tension of the forming bubble (4):

$$P_g - P_l = \frac{2\sigma}{r^*} \quad [3.7]$$

r^* is the radius of a spherical vapour nucleus. Thus for a larger nucleus, a lower pressure difference and hence lower wall superheat is necessary to initiate boiling. The local liquid temperature must also be superheated to overcome the bubble surface tension forces, in order to allow the bubble to grow, or at least to prevent its collapse.

If a nucleation site is adjacent to some non-wetting material, this material will allow a larger nucleation site because the liquid cannot penetrate, or flood, the site to the same degree as for a wettable site. Therefore the contact point between the teflon covered wire and the steel surface, as illustrated in figure 3ii, will be a larger nucleation site than if the wire was a wettable material. A nucleation site in the steel wall that is very close to the teflon/ steel contact point may also exhibit better boiling characteristics.

The geometry of wrapping a wire around the test surface provides more nucleation sites, regardless of whether or not the wire is non-wetting. In fact, the sites will all be of approximately the same size, provided that the wire is wrapped with some degree of uniformity regarding the contact pressure; a sloppily applied wire may not contact the surface, and thus provide no boiling enhancement. Also, the wire will increase the depth of the local boundary layer, allowing the local liquid temperature to rise and thus assist the bubble growth in the early stages.

The above factors contribute to enhancing the boiling process, even though the original surface has less surface area in contact with the working liquid because a teflon covered wire acts as an insulator. If the entire surface was wrapped in teflon coated wire, the few nucleation sites would work well, but the net heat transfer would be quite low. The wire was wrapped to cover a nominal (i.e. the shadow of the wire on the steel tube) 15% of the tube area.

3.6 Overall Performance

A rearrangement of Rohsenow's pool boiling equation [3.6] shows that the heat flux is proportional to the cube of the wall superheat for a given surface and fluid combination, thus giving a straight line on a log-log graph (fig. 3111). With an increased saturation temperature or an improved

surface, this curve is offset to lower wall superheats for the same heat flux.

At low heat fluxes, natural convection will dominate the heat transfer, with heat flux approximately proportional to the wall superheat. With an increase in heat flux, boiling will begin at the onset of nucleate boiling point. However, if the nucleation sites are flooded, a greater wall superheat may be required to initiate boiling, but then the vapour will trigger other sites, and the wall superheat will decrease for the same heat flux. Upon decreasing the heat flux, boiling will continue to a lower heat flux than that required for the onset of boiling, and a hysteresis loop will be formed (fig 3iv).

The geometry of the test rig was considerably different to that of most conventional pool boiling experiments; the surface was vertical and had an immersion depth from zero to 1.2 metres. The heat transfer is divided into three sections: a boiling-dominated region at the top, a transition region of developing boiling, and a convective region at the bottom.

As the heat flux increases, the boiling-dominated region extends to a greater depth, and eventually the entire surface is dominated by boiling, at some higher heat flux.

The heat flux during boiling is not truly dependent solely upon the wall superheat, but also upon the number of nucleation sites available, such that {5}:

$$q/A \approx (N/A)^n (\Delta T)^m \quad [3.8]$$

where N/A is the density of nucleation sites and ΔT the wall superheat. Thus if the number of activated sites increased considerably for a given increase in the heat flux, the wall superheat would not be required to increase as much to balance the equation. Thus on a log-log graph of heat flux versus wall superheat, an s-shaped curve rather than straight line may be obtained as seen in figure 3v. Some curves for tests performed with controllable heat flux apparatus, as in this case, have even exhibited a marked decrease in wall superheat with a heat flux increase {6}.

Thus in the present work, as the heat flux increases and the boiling dominated region extends to a greater depth, more nucleation sites will be activated, and the boiling curve may exhibit non-linear behaviour. However, with the uniformity of the teflon-15% surface, the s-curve behaviour may be less prevalent, especially if the majority of the surface is in the boiling dominated region at a lower heat flux (due to the boiling enhancement properties) than for the unenhanced surface.

The final model of the heat transfer behaviour of the DHRS evaporator model is illustrated in figure 3vi. The heat flux for the Nusselt film condensation equation [3.1] is illustrated on the right side, with the highest heat flux at the point where condensation begins. On the left side are plotted the wall and the two-phase fluid temperatures. Above the heat transfer region, the temperatures coincide, since it is in the vapour region, and the system is adiabatic (no heat transfer through the wall). As the two-phase region is entered, the local saturation temperature rises due to the static head increasing with immersion depth. In order to sustain boiling, the wall temperature must rise to maintain the local wall superheat necessary for nucleation. If the local superheat is a constant in the boiling dominated region, then the wall and two-phase temperatures will be parallel for any change in immersion depth.

In the developing boiling region, convective heat transfer begins to have an effect, and thus the local saturation temperature loses its domination on the wall temperature. As the heat transfer decreases further with greater depth, convection dominates, and the fluid temperature begins to fall, since a warmer (and less dense) liquid will rise. In the boiling region, the bubble flow dominates the fluid flow, regardless of the liquid density differences.

3.7 Computer Model

In order to take advantage of the overall test results, a simple computer model of the full-size DHRS evaporator was developed (its algorithm and listing are in Appendix E) as a means of predicting the overall heat transfer behaviour. It was assumed that the Rohsenow surface-fluid coefficient C_{sf} was equally applicable to all of the vertical evaporator surfaces, and that the evaporator was a straight annulus over its entire length (figure 3vii).

The computer model is based upon thermosyphon driven forced convective heat transfer through the centre of the evaporator, and vertical plane wall natural convection on the outside. One-dimensional radial conduction occurs only through the walls (end effects are ignored) and Rohsenow's pool boiling equation with the experimental C_{sf} values is employed for both walls. Refer to figure 3vii.

At the upper opening of the inner tube, water enters at the SES pool temperature. As heat is transferred to the evaporator, the water cools and thus becomes more dense; the difference in densities outside and inside the evaporator annulus drives the flow downwards, and the velocity is governed by a balance between the buoyant and wall shear stress forces. The annulus bulk temperature is the mean between the inlet (or SES pool) and outlet temperatures, and is used to determine the water density and viscosity in the

annulus. The inlet and outlet temperatures are the only interactive inputs to the program - the C_{ev} , evaporator length, diameters and other parameters are constants easily altered before compiling the program.

The model for flow in the inner tube balances the density pressure difference with turbulent wall shear stress:

$$f = \frac{P_{out} - P_{in}}{4(L/d) (\rho V^2 / 2)} \quad [3.9] \quad \{7\}$$

and the turbulent flow friction factor is:

$$f = \frac{0.046}{Re_d^{0.2}} \quad [3.10] \quad \{8\}$$

The pressure drop due to the difference in densities is:

$$P_{out} - P_{in} = (\rho - \rho_w) g L \quad [3.11]$$

where ρ is the local water density (at the annulus bulk temperature), and ρ_w is the SES pool water density. L is the length of the evaporator, d the diameter of the inner tube, and V the mean water velocity. Substituting [3.11] into [3.9] and equating with [3.10] gives:

$$\frac{0.046}{Re_d^{0.2}} = \frac{(\rho - \rho_w) g L}{4(L/d) (\rho V^2 / 2)} \quad [3.12]$$

Rearranging with $G = \rho V$:

$$G^{1.2} = \frac{(\rho - \rho_w) \rho g d^{1.2}}{\mu^{0.2} \cdot 2 \times 0.046} \quad [3.13]$$

This equation can be solved for G , knowing only the inlet and outlet temperatures of the evaporator inner tube, as entered in the program.

The heat transferred to the evaporator from the water flowing through the inner tube is the mass flow rate multiplied by the specific heat and the difference between the inlet and outlet temperatures:

$$q = G \pi \frac{d^2}{4} c_{pT} (T_{in} - T_{out}) \quad [3.14]$$

Using Nusselt's equation for the average heat transfer coefficient in developing turbulent flow in the entrance region (9):

$$Nu_d = 0.036 Re_d^{0.8} Pr^{0.333} (d/L)^{0.055} \quad [3.15]$$

the average heat transfer coefficient h is calculated. This equation is for $10 < L/d < 400$, and since $L/d = 32$ for the evaporator inner tube, it is suitable for this case.

Applying h and using the heat transferred, q , and the inner tube wall area, the average inner wall temperature is determined:

$$T_{wi} = T - \frac{q/A}{h} \quad [3.16]$$

where T is the annulus bulk temperature.

Employing the one-dimensional radial conduction equation [3.5] and Rohsenow's pool boiling equation [3.6], the evaporator vapour temperature was calculated.

For the outer wall, an initial temperature was assumed, and using the natural convection equation (10):

$$Nu_1 = 0.13 (Gr_1 Pr_1)^{0.333} \quad [3.17]$$

and subsequently the conduction [3.5] and boiling [3.6] equations, an evaporator vapour temperature was found. A second outer wall guess was made, and the resulting vapour temperature was linearly interpolated with the previous value and with the vapour temperature from the inner tube, providing a new outer wall temperature. This process was iterated until the vapour temperatures from both the inner and outer wall calculations were equal, and the total heat transfer calculated.

It was assumed that the inner evaporator tube is in the turbulent flow, forced convection heat transfer region; this model is valid except for very early on in the DHRS operation, when the heat transfer and liquid flows are negligible. According to the graph by Metais and Eckert, showing the regions of forced, mixed and free convective flow for a vertical tube (11), the evaporator model begins with mixed convection, but very soon moves to forced convection, and is always well into the turbulent flow region.

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FIGURE 3i Heat Transfer Models

FIGURE 3ii Boiling Nucleation

FIGURE 3iii BOILING HEAT FLUX vs TEMPERATURE DIFFERENCE

FIGURE 3iv CONVECTION - BOILING TRANSITION

FIGURE 3v BOILING HEAT FLUX S-CURVE BEHAVIOUR

FIGURE 3vi HEAT FLOW PATHS

- Steam
- Condensate or 1-Phase
- /// Insulation

$$(A) \quad G^{1.8} = \frac{(p - p_w) p g d^{1.2}}{\mu^{0.2} 2 \times 0.046}$$

$$(B) \quad Nu_d = 0.036 Re_d^{0.8} Pr^{0.333} (d/L)^{0.555}$$

$$(C) \quad Nu_L = 0.13 (Gr Pr)^{0.333}$$

$$(D) \quad \text{Radial Conduction Equation}$$

$$(E) \quad \text{Rohsenow Pool Boiling Equation}$$

FIGURE 3vii: Computer Model Heat and Flow Equations

Chapter Four: Results

The plotted results are found in Appendix A, with the complete set of data in Appendix B; any data points marked with a "#" are considered unreliable due to rapidly changing temperatures, or to a lack of aspiration, and such points are not considered in this analysis, with one exception for the two-phase plots (DATA8 and DATA9).

4.1 Temperature Readings

Typical temperature readings for the constant heat flux and increasing/decreasing heat flux tests are shown in figures 4i and 4ii respectively. Both illustrate the instrumented test section at power levels in the order of 1100W, and a nominal fluid level of 48 inches. The plotted temperatures and standard deviations are of the five thermocouples located within the test rig (T_1 :two-phase, T_2 :heatpipe1 vapour, T_4 :heatpipe2 vapour, T_5 :lower wall, and T_6 :upper wall); T_3 measured the ambient temperature of about 20°C, and is thus well off-scale. It should be noted that the temperature points and standard deviations represent 25 samples each, spread out over the preceding minute.

Figure 4ii is a "snapshot" of 20 minutes of a 200 minute long test, showing three power level changes. For each power change, the condenser flow had to be adjusted, and thus the increasing/decreasing tests were a little less

stable with respect to T_s (the temperature that was held as constant as possible) than for the constant heat flux tests.

4.2 Heat Flux as a Function of Wall Superheat

The outcome of the averaged temperature and power data was used to determine the wall superheat (sections 3.1 to 3.3). The heat flux was then plotted as a function of the wall superheat, for both constant and increasing/decreasing heat flux tests - typical results are plotted in figures 4iii and 4iv. As discussed in section 3.6, higher saturation temperatures and improved surfaces reduce the wall superheat for a given heat flux (figure 4iii).

As illustrated in figures 4iii and 4iv, and A10 through A31, and by the best-fit analysis (pA8-A10), there is a strong tendency towards linearity on a log-log plot of heat flux versus the wall superheat, thus representing a power-law equation. The best-fitting exponents (Appendix A, tables A-I and A-II) lie in the range of 2 to 4, and 3 appears to be an average value (it is difficult to be more precise since there are many best-fit results of varying linearity and number of data points). Rohsenow's equation uses an exponent of 3 (Section 3.6).

Despite the strong trends towards a power-law function, there are some examples amongst the increasing/decreasing heat flux tests that require piece-wise curve fitting, as for figures A18 and A19. The latter may illustrate the boiling hysteresis (section 3.6).

Other figures show an "S" shape which again may be a transition between convection-dominated and boiling-dominated heat transfer, or may reflect more nucleation sites being activated for a small increase in heat flux. Figure 4iv, which is a combination of figures A18 and A24, compares the results for the plain and for the teflon-15% surfaces with the same nominal fluid level and saturation temperature; evidently the teflon wire-wrapped surface has much more linear results than the plain surface, and also provides much better heat transfer at low heat fluxes.

4.3 Two-Phase Temperature as a Function of Immersion Depth

Thermocouple T_1 was moved during some tests, providing data on the temperature of the two-phase fluid at various depths and about 1 cm from the heat transfer surface. Due to the better thermal conductivity of water as opposed to steam, T_1 measured primarily the single phase liquid temperature. The temperature difference between the two-phase and saturation temperatures is plotted as a function of the nominal immersion depth in figures A32 through A41; a generic

illustration is shown in figure 4v, and a typical result is figure 4viii. The nominal depth is the same as the collapsed depth - the distance the thermocouple would be beneath the surface at standard conditions with no void.

For each surface/fluid level/vapour temperature combination, a static head prediction line was plotted; this line was derived by using the nominal immersion depth and single-phase water density to determine the static head, which was added to the saturation pressure of vapour temperature T_1 (located above the two-phase fluid). The resulting local pressure was used to establish the local saturation temperature. The plotted points are the measured temperature differences at a particular immersion depth, and are parallel to the static head prediction (figures 4v and 4viii). At greater depths the temperature difference levels off, and some graphs show a decrease with further depth. Unfortunately, during the tests T_1 was not drawn out to the very bottom of heatpipe2, and depth measurements were made for only 37 tests.

Because the plotted points follow the static head prediction of saturation temperature, boiling dominates the heat transfer to the depth where the plotted points level off with increasing depth. At greater depths, the temperature difference decreases since convection dominates the heat transfer, and the hotter liquid rises to the top. For

higher heat fluxes, the plateau begins at greater depths, since boiling dominates over more of the surface. The difference between the plotted points and the predicted curve (figure 4v) is likely due to the requirement for a liquid superheat in order to make the vapour bubbles grow, or at least to prevent their collapse. And as is noticeable in figures A32 to A34, there is a rapid temperature rise indicating the vapour/two-phase interface. The discrepancy between the nominal depth of zero and the depth of the rapid temperature rise can be credited to the two-phase effect and the decreased liquid density at higher temperatures (as compared with standard conditions).

4.4 Wall Temperature Measurements

Figures 4ix (a reprint of A53) and A42 to A56 show the measured differences between the wall and vapour temperatures, for thermocouples T_5 and T_6 , as a function of heat flux. The most useful of these plots are those which illustrate points taken during increasing/decreasing heat flux tests (figures A43, 45, 48, 50, 53 and 56) where any aging effect would be minimal over the relatively short test period.

For the tests with a nominal level of 40 inches (figure 4vi, noting that the solid lines are for known temperatures, and dashed lines for postulated values), the topmost wall thermocouple T_6 is located above the initial liquid/vapour

interface. At zero heat flux the wall temperatures, driving vapour temperature T_2 , and vapour temperature T_4 should be equal (assuming that the whole test rig is adiabatic). As the power is increased, the differences between the wall and vapour temperatures increase, and since there is a low local heat flux at the level of T_4 (only vapour convection), this thermocouple reads a value close to the temperature of the condensing vapour T_2 , and thus ΔT_{4-4} rises rapidly with increasing power. At some power, the two-phase mixture rises high enough to wet the surface at T_4 and cause the local heat flux to increase rapidly; ΔT_{4-4} then drops accordingly as is quite evident in figure A43. With a further increase in heat flux, ΔT_{4-4} rises a little and then levels off; ΔT_{3-4} , however, continues to rise until it too levels off at a higher heat flux. From that point onwards, the difference between the wall temperatures is a constant, approximately equal to the difference in the two-phase temperatures corresponding to the wall thermocouple locations and same vapour temperature. The difference between T_3 and T_4 is larger for lower vapour temperatures, as is the difference between the two-phase temperatures measured at the same depths as T_3 and T_4 . This is due to larger difference between the local saturation temperatures for T_3 and T_4 at a lower vapour temperature.

For nominal levels of 44 and 48 inches (figures 4vii and 4ix), where T_{Δ} is covered by liquid to begin with, $\Delta T_{\Delta-4}$ rises to a plateau, since there is always good heat transfer at T_{Δ} . The temperature differences (ΔT_{w-4}) for both T_{Δ} and T_{Δ} are larger for higher nominal fluid levels; this is expected since an increased thermocouple immersion depth raises the corresponding local saturation pressure and temperature.

4.5 Rohsenow Surface-Fluid Coefficient

As expected, the Rohsenow pool boiling surface-fluid coefficient C_{Δ} (equation [3.6]) is a virtual constant for a given surface regardless of saturation temperature or heat flux. The results are tabulated in table 4-I and illustrated in figures A1 to A9 (p A11 to A19), with the bold line being the mean, and the dashed lines plus and minus one standard deviation. Results for the plain and teflon-15% surfaces at a fluid level of 48 inches are shown in figures 4x and 4x1.

It appears that at higher heat fluxes a spread in the C_{Δ} values occurs, with lower vapour temperatures giving higher values. However, the standard deviation on each graph is smaller than the average predicted error calculated in the error analysis (Appendix D and table 4-I) and thus any trends are not detectable.

Table 4-1
 C_{sf} Values for the 9 Surface/Fluid Level Combinations

Surface/Nominal Level	C_{sf}	$\sigma_{C_{sf}}$	$\sigma_{C_{sf}}(\%)$	$\epsilon_{C_{sf}}(\%)$	N
Plain 40 inches	0.0190	0.0011	5.8	16.0	32
Plain 44 inches	0.0200	0.0009	4.5	13.4	45
Plain 48 inches	0.0201	0.0020	10.0	13.3	94
Teflon-15% 40 inches	0.0157	0.0006	3.8	12.3	76
Teflon-15% 44 inches	0.0153	0.0008	5.2	12.3	73
Teflon-15% 48 inches	0.0169	0.0010	5.9	11.7	79
Instrumented 40 inches	0.0141	0.0014	9.9	16.9	60
Instrumented 44 inches	0.0153	0.0015	9.8	15.1	71
Instrumented 48 inches	0.0175	0.0021	12.0	14.1	94

The standard deviations and error analysis results are large in comparison to the differences between C_{sf} values for the same surface with different fluid levels; therefore the sensitivity of C_{sf} to the fluid level is not detectable with these results. The average C_{sf} values for the plain and teflon-15% surfaces are 0.0199 and 0.0160 respectively, showing that the teflon-15% surface requires only 80% of the wall superheat required by the plain surface. The instrumented section C_{sf} values must be treated with caution due to fluid contamination and surface aging problems, described in the next section, that arose during the testing of that surface.

4.6 Result Reliability

Early tests, namely some with the plain surface at a fluid level of 48 inches, were run while the test procedure was evolving. The purging of non-condensibles from the heat pipes was not initially done before each test; the only known examples of insufficient purging are seen in the results for DATA8 and DATA9, as compared with those of DATA37 and DATA38 respectively (Appendix B, p85), by which time regular aspiration was a required part of the test procedure.

The instrumented section had two thermocouples (T_3 and T_4) placed in slots in the heat transfer surface; the slots passed through the bottom flange (figure Cv1) which separated heatpipe2 from the external environment. The air leakage into heatpipe2 via the thermocouple slots was reduced virtually to zero by the application of solder and silicon sealant to the slots external to heatpipe2.

The instrumented section tests were run with considerably less reliability or repeatability than for either previous surface; the test rig proved more difficult to maintain at a steady state, especially with the increasing/decreasing heat flux tests, and the temperature standard deviations were larger than for the plain or instrumented sections. The result is that the average relative C_{eff} error is larger for

the instrumented surface than for either of the other surfaces, as shown in table 4-I.

The instrumented test surface had been thoroughly cleaned with toluene, as had the other surfaces, and Heatpipe2 was partially filled with water, operated briefly and then drained and refilled prior to the test set, in order to remove any remaining dirt. Upon final disassembly after the last test, the instrumented surface was found to be coated with a white film, and the solder had been partially transformed into a white crystalline substance. Both wall thermocouples had absorbed water into the thermocouple insulation (a hygroscopic material) through breaches in the sheathing - perhaps due to the assembly or sanding of the surface - and during the tests the water vaporized and the pressure split apart the sheathing; the thermocouples themselves worked well until the final test, when T_4 became intermittent.

It is believed that these problems, especially the presence of solder on the surface and dissolved in the water, contributed to the generally suspect results for the instrumented test section; certain additives like friction reducing agents (1) are known to enhance boiling, at least until they break down chemically.

The instrumented section results are useful in predicting the heat pipe behaviour in terms of the local wall superheat and the usefulness of the empirical models, but not as a reliable means of determining the C_{eff} value for the sanded surface. A comparison of the data in table 4-II indicates that the surface deteriorated or the working fluid became contaminated (increasing the C_{eff} in either case, thus raising the wall superheat for a given heat flux) over the course of the test program, a feature unnoticed with either the plain or teflon-15% surfaces.

Table 4-II

Surface Aging: Instrumented Section $T_4 = 80^\circ\text{C}$ Level = 48IN

DataSet	Date	$T_{\text{wall}} \{^\circ\text{C}\}$	Heat Flux $\{\text{W/m}^2\}$	C_{eff}
138	16Jan89	4.6 ± 0.7	4970 ± 46	0.0156 ± 0.0023
141	"	5.0 ± 0.7	6998 ± 47	0.0151 ± 0.0021
145	"	5.4 ± 0.6	9069 ± 47	0.0148 ± 0.0017
148	"	6.5 ± 0.9	11048 ± 47	0.0166 ± 0.0021
149	"	6.5 ± 0.8	10986 ± 47	0.0169 ± 0.0020
157	27Jan89	4.7 ± 0.8	4931 ± 46	0.0161 ± 0.0025
160	"	4.7 ± 0.8	6989 ± 46	0.0144 ± 0.0022
163	30Jan89	5.4 ± 0.9	9125 ± 46	0.0149 ± 0.0023
166	"	5.9 ± 0.7	11089 ± 47	0.0152 ± 0.0018
205	18Feb89	4.9 ± 0.8	4984 ± 47	0.0163 ± 0.0024
206	"	4.9 ± 0.7	4984 ± 47	0.0165 ± 0.0024
207	"	6.1 ± 0.8	6933 ± 48	0.0183 ± 0.0022
208	"	6.0 ± 0.7	6922 ± 48	0.0181 ± 0.0020
209	"	7.4 ± 0.8	8995 ± 49	0.0203 ± 0.0022
210	"	7.3 ± 0.7	8984 ± 49	0.0204 ± 0.0017
211	"	7.3 ± 0.7	11153 ± 50	0.0199 ± 0.0017
212	"	7.4 ± 0.7	11134 ± 50	0.0192 ± 0.0016

4.7. Error Analysis

An error analysis (Appendix D, pD1-D5) was done and the wall superheat, heatflux and C_{eff} errors are listed in the data records (Appendix B). Even at steady state boiling is a random process, contributing to the standard deviation on every temperature reading, and hence the calculated wall superheat, but the readings do appear to be normal in distribution (see Appendix D pD8).

For the constant heat flux data points, the average error is $\pm 0.94^{\circ}\text{C}$ with a standard deviation of 0.35; this amounts to a relative error of 9.5 to 27% for wall superheats ranging from 10 to 3°C . The increasing/ decreasing heat flux tests have an average error of 0.71°C with a standard deviation of 0.14°C , which is a relative error of 7 to 20% for wall superheats of 10 to 3°C . The difference in the sizes of the error and deviation between the test types is due to the fact that each constant heat flux point usually represents 500 temperature samples taken over 20 minutes, during which time the system temperature may have changed slightly. The increasing/decreasing heat flux data points represent in the order of 125 temperature samples over 5 minutes. The average relative error on C_{eff} is 13.7%.

4.8 Computer Model Results

The computed overall heat transfer rate (section 3.7) of the full-size DHRS evaporator is shown in figure 4xii and 4xiii for three experimental C_{eff} values - assuming that the surface improvements were applied to both vertical walls. For this model the SLOWPOKE pool temperature was increased such that the DHRS began to operate, but it was assumed that the evaporator steam temperature remained constant at the DHRS set point (75 or 85°C for figures 4xii and 4xiii respectively) regardless of the pool temperature. This assumption would be valid for a very large air reservoir (figure 1i) where only a small saturation pressure increase is necessary for full condenser operation. Naturally, for financial and safety reasons, this not true; nuclear reactors must be proven safe, reliable and forgiving in order to be licensed, and a large DHRS would be more susceptible to a debilitating air leak. But in the present evaporator approximation it is important only to show relative improvements, and the condenser performance is not modelled.

Another assumption is that the pool temperature is uniform, and does not have any temperature stratification.

The plotted results are with the evaporator vapour temperature held constant while the pool temperature was increased; the two interactive inputs to the program are the SES pool and inner annulus temperatures. Three examples of the inputs and results for a C_{se} value of 0.0169 are as follows, while maintaining an evaporator temperature of 75°C.

<u>Pool Temp</u>	<u>Outlet Temp</u>	<u>Evaporator Temp</u>	<u>Heat transferred</u>
78.35	78.15	74.99	740 W
78.95	78.70	75.01	1043 W
79.51	79.21	74.99	1381 W

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TEMPERATURE VS TIME

Constant Heat Flux Test, 1100W, Level-48IN, Instrumented Section DATA166
FIGURE 4i

TEMPERATURE VS TIME

Inc./Dec Heat Flux Test, 1120 to 881W, Level 48IN, Instrumented Section DATA201
FIGURE 4ii

CONSTANT HEAT FLUX TESTS

INCREASING/DECREASING HEAT FLUX TESTS

T4075C LEVEL-48IN DATA40-42 & DATA85-87
 Wall Superheat (°C)
 FIGURE 4iv

FIGURE 4v TWO PHASE TEMPERATURE vs DEPTH

FIGURE 4vi WALL TEMPERATURE 40 IN LEVEL

FIGURE 4vii WALL TEMPERATURE 44 and 48 IN LEVEL

Power Level

◇ 500W

□ 700W

× 900W

○ 1100W

PLAIN TUBE, 48IN LEVEL, T_{vapour}=70°C

FIGURE 4viii

FIGURE 4ix

Boiling Heat Flux (W/m²)
TEFLON - 15% LEVEL-48IN

FIGURE 4xi

Vapour Temp	
□	60°C
○	75°C
+	80°C
△	85°C
*	100°C

COMPUTER MODEL

HEAT TRANSFER CAPABILITY VS TEMPERATURE DIFFERENCE

Another effect of the various regions is that the C_{eff} value may decrease further with an increase in heat flux because more of the surface will be in the boiling region (better heat transfer). However, since the C_{eff} values are fairly constant for a given surface, it is likely that for the heat transfer range used in the present work, boiling dominated the majority of the surface.

5.3 Evaporator Performance Improvement

In the overall picture the C_{eff} value, and thus the wall superheat difference, is the lowest for the surface wrapped with teflon coated wire. This is due to the non-wetting properties of the teflon and to the geometry of wire wrapped about the heat transfer surface, increasing the number of nucleation sites.

Using a nominal water level of about 10% less than that required to completely cover the heated surface when the evaporator is not operating, may also have improved the heat transfer, but due to the experimental error this cannot be stated as fact. A lower fluid level reduces the static head and hence the local saturation pressure; as long as the entire heated surface is wetted during operation, the heat transfer would improve in comparison to an over- or under-filled evaporator.

Chapter Five: Conclusions and Recommendations

For the low saturation temperatures (less than 105°C) and low heat fluxes (under 12000 W/m²) used in testing the DHRS evaporator model, the Rohsenow pool boiling equation works very well for predicting the average wall superheat for a vertical wall.

5.1 Rohsenow Fluid/Surface Coefficient

The average $C_{s,f}$ values are listed in table 5-1 part A, along with other accepted values in part B (1).

Table 5-1
Rohsenow Pool Boiling Surface-Fluid Coefficient $C_{s,f}$

<u>Surface</u>	<u>$C_{s,f}$</u>
A: Vertical tube wall:	
1. Water on plain 304 stainless steel	0.0199
2. Water on Teflon-wrapped 304 stainless steel	0.0160
3. Water on sanded 304 stainless steel	0.0158
B: Flat plate or horizontal wire:	
4. Water on ground and polished stainless steel	0.0080
5. Water on Teflon pitted stainless steel	0.0058
6. Water on chemically etched stainless steel	0.0133
7. Water on mechanically polished stainless steel	0.0132
8. Rohsenow's recommended 'first guess' for any surface/fluid combination	0.013

The $C_{\bullet}$ values in section A of table 5-I are based on the overall wall superheat - the difference between the average (calculated) wall and the measured vapour temperatures. As seen in the two-phase temperature (section 4.3), and measured wall superheat (section 4.4) results, the local saturation and wall temperatures increase with immersion depth. Thus the local wall superheat (the difference between the local wall and local saturation temperatures) will be lower than the overall wall superheat. In turn the local $C_{\bullet}$ coefficients will be lower than the overall values shown in part A of table 5-I. This fact must be kept in mind when comparing the present results to $C_{\bullet}$ values from the literature for similar surface/fluid combinations as given in part B. Recognising this point, it can be seen that the present measured $C_{\bullet}$ values are similar to those in the literature; considering the sensitivity of boiling heat transfer to surface conditions, the results of the present work are generally quite reliable.

5.2 Heat Transfer Models

The instrumented test section results strongly support the method of calculating the average wall superheat; thus the models for determining the boiling heat transfer coefficient (Nusselt's film condensation, and one dimensional radial conduction), are suitable for this application. However, the instrumented test section $C_{\bullet}$ values are suspect, due to surface aging and fluid contamination.

The evaporator, as postulated in chapter 3, is divided into three heat transfer regions:

The topmost region is for fully developed boiling; the local wall superheat is virtually a constant, and remains that way regardless of the heatflux, until the entire surface has fully developed boiling.

Below the fully developed boiling domain is a region of developing boiling, where convective heat transfer has an effect.

In the deepest heat transfer region, natural convection (or perhaps forced convection driven by the boiling region above) dominates, with considerably lower heat flux than in the boiling regions.

The interaction between these regions is the likely cause of the non-linear (on a logarithmic scale) heatflux versus wall superheat behaviour especially evident with the plain surface. As the total heat flux increases, the boiling dominated region expands to greater depths. If, as in the case of the teflon-15% surface, the nucleation site density is uniform and the sites are large due to the non-wetting property of teflon, the non-linearity is much less pronounced because boiling occurs more uniformly and easily.

Another effect of the various regions is that the $C_{s,f}$ value may decrease further with an increase in heat flux because more of the surface will be in the boiling region (better heat transfer). However, since the $C_{s,f}$ values are fairly constant for a given surface, it is likely that for the heat transfer range used in the present work, boiling dominated the majority of the surface.

5.3 Evaporator Performance Improvement

In the overall picture the $C_{s,f}$ value, and thus the wall superheat difference, is the lowest for the surface wrapped with teflon coated wire. This is due to the non-wetting properties of the teflon and to the geometry of wire wrapped about the heat transfer surface, increasing the number of nucleation sites.

Using a nominal water level of about 10% less than that required to completely cover the heated surface when the evaporator is not operating, may also have improved the heat transfer, but due to the experimental error this cannot be stated as fact. A lower fluid level reduces the static head and hence the local saturation pressure; as long as the entire heated surface is wetted during operation, the heat transfer would improve in comparison to an over- or under-filled evaporator.

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number of data points for each equation is between 8 and 20, making the best-fit process much more credible than for the constant heat flux tests. Two plain wall section tests - DATA32-34 and DATA40-42 - were only piecewise linear, and were thus fitted with three curves each. The few points rejected in the data records (marked with a "#") were not used in this analysis. The best-fit equations are listed in Table A-II and are marked as to whether the heat flux was increasing (+) or decreasing (-). The value of the slope (m) is in the order of two to three.

It is important to note that although the Rohsenow boiling curve does appear to represent much of the test data, there is also strong evidence of mild non-linearity, especially for Figures A17 through A19. Although these particular tests were performed at an early stage, when the operating technique had not completely evolved, a subsequent analysis strongly indicated that the "S" shape of the curve was not a function of poor data. In fact, all of the increasing/decreasing heat flux tests illustrate this phenomena, with an inflection point in the order of 5000 W/m^2 . It should be noted that the error bands on the wall-vapour temperature difference, being at least $\pm 0.5 \text{ }^\circ\text{C}$, can easily account for this feature, but probably cannot completely explain it. It is likely that a combination of boiling and convection heat transfer, with the former dominating at higher heat fluxes, is responsible. Figures A19 and A26 may even be

3. Aging tests may prove the teflon unreliable, or at least establish an overhaul/renewal date. Teflon can age, especially if it is exposed to a gamma ray environment. The SLOWPOKE pool and the evaporator walls will shield the teflon, but it is imperative that there be further research into teflon reliability.
4. Further computer work would be useful, employing local C_{eff} values (constant in the fully developed boiling region) which can be applied with respect to the two-phase/depth relationship, and two-phase empirical models, in order to make a code able to determine the heat output for various evaporator configurations. Condenser operation envelopes could close the loop on the entire DHRS performance evaluation.

In conclusion, the test work provides a simple, empirically-based method of analysing pool boiling from long, vertical surfaces for relatively low heat fluxes - Rohsenow's boiling equation proved most satisfactory. As far as the SLOWPOKE Decay Heat Reaction System is concerned, simple boiling enhancement can have a worthwhile effect on the overall performance, making the reactor even safer.

1 Collier, J. G.

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Table 4.1 p127

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Appendix A

Results

General Notes on the Plotted Results	A1
Best-fit Equation Results	A8
Surface-Fluid Coefficient (C_{sf}).....	Figure A1
Constant Heat Flux Tests.....	Figure A10
Increasing/Decreasing Heat Flux Tests.....	Figure A16
Two-Phase Temperature vs Depth.....	Figure A32
Wall Temperature vs Heat Flux.....	Figure A42

General Notes on the Plotted Results

The first results are of the Rohsenow surface-fluid coefficient plotted against the boiling heat flux (figures A1 to A9), arranged with the 9 combinations of surface and nominal fluid level. It is evident that C_{sf} can be regarded as a constant, with a standard deviation less than 12% of the C_{sf} value in all fluid-surface combinations, the average being about 8%. The calculated error amounts to an average of 14% of the C_{sf} values, and since the plotted results are within these bands, the C_{sf} can be assumed constant. There may be some trends towards lower C_{sf} values with higher temperature as can be seen in figures A7 to A9 (especially with higher heat flux), but this may be merely data scatter. It should be noted that C_{sf} improves (decreases) as the surface is changed from plain to teflon-15% to instrumented.

The results of the constant heat flux tests (figures A10 to A15) are plotted for the three nominal fluid levels (40, 44 and 48 inches), and then the same results for three vapour temperatures (60, 80 and 100 °C). For each graph, all three surfaces and four power levels are illustrated. It should be noted that there are three general trends in the data:

- i) Higher vapour temperatures give lower boiling temperature differences for the same heat flux/level/surface combination.
- ii) The points for the same level/vapour temperature/surface combination are approximately linear on a log-log plot, indicating a power equation.

- iii) The boiling temperature difference for the same heat flux/vapour temperature/level combination decreases with the surfaces progressing from plain to teflon-15% to instrumented.

With respect to point ii) above, an attempt was made to apply the best-fit process to the constant heat flux tests; it must be stressed that only four data points were available for each surface/level/vapour temperature combination, and thus when the large (at least $\pm 0.5^\circ\text{C}$) temperature difference error is considered, one cannot apply any weight to the best-fit results, except that the Rohsenow pool boiling equation

$$\frac{C_{pf} \cdot \Delta T_{\text{bo}-s}}{h_{fg}} = C_{sf} \cdot \left[\frac{q_{AB}}{\mu_f \cdot h_{fg}} \cdot \left[\frac{\sigma_f}{g \cdot (p_f - p_g)} \right]^{1/2} \right]^{1/3} \cdot Pr$$

simplified as

$$q_{AB} = \Delta C_s (T_{\text{bo}-s})^m$$

seems to be a reasonable explanation of the heat transfer process. The value of m is expected to be 3.0, and the value R^2 represents the closeness (1.00 being a perfect fit) of the data to the best-fit equation. As seen in table A-1 the value of m is usually between 2 and 4.

The results for the increasing/decreasing heat flux tests (figures A16 to A31) are plotted with the appropriate best-fit power equations. Twelve of the sixteen increasing/decreasing heat flux tests show very good linearity, and the

number of data points for each equation is between 8 and 20, making the best-fit process much more credible than for the constant heat flux tests. Two plain wall section tests - DATA32-34 and DATA40-42 - were only piecewise linear, and were thus fitted with three curves each. The few points rejected in the data records (marked with a "#") were not used in this analysis. The best-fit equations are listed in Table A-II and are marked as to whether the heat flux was increasing (+) or decreasing (-). The value of the slope (m) is in the order of two to three.

It is important to note that although the Rohsenow boiling curve does appear to represent much of the test data, there is also strong evidence of mild non-linearity, especially for Figures A17 through A19. Although these particular tests were performed at an early stage, when the operating technique had not completely evolved, a subsequent analysis strongly indicated that the "S" shape of the curve was not a function of poor data. In fact, all of the increasing/decreasing heat flux tests illustrate this phenomena, with an inflection point in the order of 5000 W/m^2 . It should be noted that the error bands on the wall-vapour temperature difference, being at least $\pm 0.5 \text{ }^\circ\text{C}$, can easily account for this feature, but probably cannot completely explain it. It is likely that a combination of boiling and convection heat transfer, with the former dominating at higher heat fluxes, is responsible. Figures A19 and A26 may even be

illustrating a hysteresis loop, where convection rapidly gives way to boiling as the heat flux increases and activates more nucleation sites which remain active when the heat flux is decreased.

Another comment with respect to the increasing/decreasing heat flux tests is the very poor fit of some of the data to any curve, especially for Figure A19, equations 2 and 3. It is likely that the equation slope was much steeper, but the scatter did not permit better results, and hence the dreadful R^2 values.

Thermocouple T_1 was located in a copper tube 0.4 inches away from and parallel to the boiling surface, in the midst of the two-phase fluid of heatpipe2. During some tests temperature measurements of the two-phase fluid were made with T_1 at various depths. Although the thermocouple was unable to differentiate between the vapour and liquid phase temperatures, it measured an average two-phase temperature that is very close to the liquid temperature due to a low void at the low heat fluxes used. The results of the two-phase minus vapour temperature difference ($T_1 - T_4$) plotted against the nominal depth are seen in figures A32 to A41. The nominal depth is also known as the collapsed depth - the distance below the surface if all of the fluid was one phase at 20°C and one atmosphere pressure (the conditions for filling the heat pipe). The nominal depth can be

negative, representing the vapour region above the two-phase fluid. Only for the results with a nominal level of 40 inches was it possible to place T_1 above the two-phase/vapour interface when it was fully inserted in the copper tube, thus giving a negative nominal depth. For these tests (figures A32 to A34), one can see the rise in T_1 as it is lowered past the interface. At depths more negative than the interface, $T_1 - T_4$ is almost zero, indicating that T_1 was reading virtually the vapour temperature, with some interference from (hotter) liquid splashing upwards. As should be expected, the rise in T_1 at the vapour/two-phase interface is more marked with a lower vapour temperature, due to a larger liquid superheat being required to maintain the necessary vapour - liquid pressure difference for bubble growth. This superheat is likely to be responsible for the difference between the plotted points and the static head $T_1 - T_4$ line.

On each of the two-phase plots a theoretical line is plotted, showing the saturation minus vapour temperature difference increasing with depth, due only to the static head. There are likely to be some acceleration effects which would alter the pressure, but these are evidently small for the low heat flux of these tests. Also of note are the plotted points levelling off at greater depths, with some points showing a decline as the depth increases further (figure A35 especially). It is postulated that boiling

dominates the heat transfer over the depth range where the points are parallel to the theoretical curves, then at lower depths convection begins to dominate, and the two-phase (now actually one-phase) temperature should decrease.

Unfortunately, at test time T_1 was not completely drawn out to the maximum depth of 1.2 metres (48 inches).

Of further interest is that for almost all of the plots, the depth of levelling off is greater for the higher power (the heat flux is approximately ten times the power) at the same vapour temperature since the boiling dominated region occurs at greater depths. A final note is that the 500W results at 80 and 90°C (figures A38 and A39) are significantly higher than the rest of the results because heatpipe2 required aspiration. However, all this did was to lower T_4 , thus increasing the two-phase minus vapour temperature difference, but maintaining the plot parallel to the theoretical line.

The last set of results are of the differences between the two measured wall temperatures (T_3 0.3 metres and T_4 1.07 metres from the bottom of heatpipe2) and the vapour temperature (T_4), plotted against the average heat flux. For figures A42 to A46, thermocouple T_4 is actually above the nominal level, and gives a reading corresponding to the local heat transfer process. At low overall heat fluxes, T_4 is likely to experience only convection from the vapour, and

combined with the higher vapour temperature T_2 of heatpipe1, $T_4 - T_4$ should read high; figures A43 and A45 illustrate this for a heat flux below about 5000 W/m². As the overall heat flux increases, the two-phase fluid level rises until it passes T_4 and the local heat transfer coefficient is increased (due to boiling and liquid convection now occurring there) with a subsequent lowering of T_4 because of the increased wall conduction.

With many of the graphs in this instrumented set, the temperature difference $T_5 - T_4$ rises to a peak and then levels off at a certain heat flux, and the temperature difference $T_4 - T_4$ remains a constant (figures A43, A45, A48, A50, A53 and A55 especially as these were increasing/decreasing heat flux tests). This is likely due the boiling dominated region moving to greater depths with increasing heat flux, but once fully developed boiling occurs at a given site, the local boiling heat flux does not increase, and thus the wall-vapour temperature difference remains constant. If the experiments were done with higher heat fluxes than 12,000 W/m² (limited by the heater capacity), the two wall minus vapour temperature differences would have risen again at some higher heat flux, once the entire heatpipe2 surface was in the fully developed boiling regime.

Table A-I
Constant Heat flux Tests - Bestfit Results

Surface	T4 °C	Fluid Level inches	C4	m	R ²	N
Plain	60	40	1.58	3.94	0.9880	4
Plain	80	40	147.0	2.11	0.9917	4
Plain	100	40	296.0	1.98	0.9999	4
Plain	60	44	101.0	2.03	0.9773	4
Plain	80	44	8.27	3.49	0.9290	4
Plain	100	44	7.18	3.90	0.9701	4
Plain	60	48	0.3058	4.62	0.9495	4
Plain	80	48	10.1	3.48	0.1082	4
Plain	100	48	3.4E-6	12.5	0.6289	4
Teflon-15%	60	40	127.0	2.15	0.9127	4
Teflon-15%	80	40	27.5	3.31	0.9675	4
Teflon-15%	100	40	46.8	3.57	0.9375	4
Teflon-15%	60	44	114.0	2.10	0.9911	4
Teflon-15%	80	44	28.1	3.37	0.9803	4
Teflon-15%	100	44	72.7	3.43	0.9468	4
Teflon-15%	60	48	51.8	2.36	0.9925	4
Teflon-15%	80	48	34.3	3.07	0.9900	4
Teflon-15%	100	48	7.02	4.78	0.9662	4
Instrumented	60	40	516.0	1.48	0.0324	4
Instrumented	80	40	391.0	1.82	0.7929	4
Instrumented	100	40	371.0	2.31	0.8771	4
Instrumented	60	44	49.4	2.55	0.7196	4
Instrumented	80	44	40.4	3.09	0.5522	4
Instrumented	100	44	16.1	4.87	0.4759	4
Instrumented	60	48	0.421	4.83	0.5887	4
Instrumented	80	48	70.3	2.86	0.8303	4
Instrumented	100	48	1.83	6.37	0.7759	4

Table A-II
Increasing/Decreasing Heat flux Tests: Best-fit Results

Surface	T4 °C	Fluid Level inches	C4	m	R ²	N
Plain +	85	48	98.4	2.07	0.9786	16
Plain +	85	48	942.0	1.24	0.0410	14
Plain -	85	48	7.25	3.81	0.1640	8
Plain +	75	48	2.4E-7	13.2	0.7891	8
Plain +	75	48	413.0	1.55	0.9564	8
Plain -	75	48	155.0	2.03	0.9087	9
Plain +	75	44	23.2	2.96	0.9720	20
Plain -	75	44	26.5	2.87	0.9317	13
Plain +	75	40	113.0	2.19	0.8323	11
Plain -	75	40	127.0	2.12	0.7840	9
Teflon-15% +	75	48	31.9	2.98	0.9890	17
Teflon-15% -	75	48	46.5	2.75	0.9949	16
Teflon-15% +	75	44	30.3	3.19	0.9810	17
Teflon-15% -	75	44	46.3	2.95	0.9910	13
Teflon-15% +	75	40	43.0	2.95	0.9781	17
Teflon-15% -	75	40	41.4	2.97	0.9916	16
Teflon-15% +	85	40	36.0	3.33	0.9710	17
Teflon-15% -	85	40	32.7	3.41	0.9914	14
Teflon-15% +	85	44	49.0	3.27	0.9922	16
Teflon-15% -	85	44	54.2	3.13	0.9909	15
Teflon-15% +	85	48	21.4	3.57	0.9853	17
Teflon-15% -	85	48	37.3	3.24	0.9942	16

Table A-II (continued)
Increasing/Decreasing Heat flux Tests: Best-fit Results

Surface	T4 °C	Fluid Level inches	C4	m	R ²	N
Instrumented+	75	40	9.25	4.31	0.5336	15
Instrumented-	75	40	0.380	6.43	0.8013	13
Instrumented+	85	40	462.0	1.80	0.9338	14
Instrumented-	85	40	218.0	2.23	0.8868	14
Instrumented+	75	44	22.8	3.42	0.8958	15
Instrumented-	75	44	83.4	2.66	0.9532	14
Instrumented+	85	44	368.0	1.82	0.9484	15
Instrumented-	85	44	321.0	1.90	0.9302	14
Instrumented+	75	48	28.4	2.92	0.9359	15
Instrumented-	75	48	92.8	2.32	0.9095	14
Instrumented+	85	48	182.0	2.11	0.9617	15
Instrumented-	85	48	179.0	2.10	0.9555	14

2

MicroD

Vapour Temp	
□	60°C
○	75°C
+	80°C
*	100°C

Boiling Heat Flux (W/m²)
PLAIN TUBE LEVEL-44IN
FIGURE A2

FIGURE A2

Vapour Temp	
□	60°C
○	75°C
+	80°C
△	85°C
*	100°C

Boiling Heat Flux (W/m²)
TEFLON TUBE LEVEL-40IN
FIGURE A4

Vapour Temp

□ 60°C
 ○ 75°C
 + 80°C
 △ 85°C
 * 100°C

FIGURE A6

Vapour Temp

□ 60°C
 ○ 75°C
 + 80°C
 △ 85°C
 * 100°C

FIGURE A7

FIGURE A8

CONVARIANT HEAT FLUX TESTS

Wall-Vapour Temperature Difference (°C)
 NOMINAL LEVEL-40IN
 FIGURE A10

CONSTANT HEAT FLUX TESTS

Wall-to-Vapour Temperature Difference ($^{\circ}C$)

NOMINAL LEVEL-44IN

FIGURE A11

The graph plots Heat Flux (W/m²) on the y-axis (1000 to 1500) against Wall-Vapour Temperature Difference (°C) on the x-axis (3 to 11). Data series include:

- Series 1 (Stars):** Points at approximately (3.5, 1100), (4, 1150), (4.5, 1180), (5, 1200), (5.5, 1220), (6, 1240), (6.5, 1260), (7, 1280), (7.5, 1300), (8, 1320), (8.5, 1340), (9, 1360), (9.5, 1380), (10, 1400), (10.5, 1420), (11, 1440).
- Series 2 (Triangles):** Points at approximately (3.5, 900), (4, 950), (4.5, 1000), (5, 1050), (5.5, 1100), (6, 1150), (6.5, 1200), (7, 1250), (7.5, 1300), (8, 1350), (8.5, 1400), (9, 1450), (9.5, 1500).
- Series 3 (Squares):** Points at approximately (3.5, 700), (4, 750), (4.5, 800), (5, 850), (5.5, 900), (6, 950), (6.5, 1000), (7, 1050), (7.5, 1100), (8, 1150), (8.5, 1200), (9, 1250), (9.5, 1300), (10, 1350), (10.5, 1400), (11, 1450).
- Series 4 (Crosses):** Points at approximately (3.5, 500), (4, 550), (4.5, 600), (5, 650), (5.5, 700), (6, 750), (6.5, 800), (7, 850), (7.5, 900), (8, 950), (8.5, 1000), (9, 1050), (9.5, 1100), (10, 1150), (10.5, 1200), (11, 1250).
- Series 5 (Asterisks):** Points at approximately (3.5, 300), (4, 350), (4.5, 400), (5, 450), (5.5, 500), (6, 550), (6.5, 600), (7, 650), (7.5, 700), (8, 750), (8.5, 800), (9, 850), (9.5, 900), (10, 950), (10.5, 1000), (11, 1050).

T4	SURFACE
◇ 60C	Plain
□ 80C	Plain
X 100C	Plain
○ 60C	Teflon-15%
+ 80C	Teflon-15%
Δ 100C	Teflon-15%
⊗ 60C	Instrumented
* 80C	Instrumented
★ 100C	Instrumented

Wall-Vapour Temperature Difference (°C)
NOMINAL LEVEL-48IN
FIGURE A12

CONSTANT HEAT FLUX TESTS

Wall-Vapour Temperature Difference (°C)

VAPOUR TEMPERATURE T4=60C

FIGURE A13

CONSTANT HEAT FLUX TESTS

Level	SURFACE
40in	Plain
44in	Plain
48in	Plain
40in	Teflon-15%
44in	Teflon-15%
48in	Teflon-15%
40in	Instrumented
44in	Instrumented
48in	Instrumented

CONSTANT HEAT FLUX TESTS

Wall-Vapour Temperature Difference (°C)

VAPOUR TEMPERATURE T4=100C

FIGURE A15

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}C$)
T40/5C PLAIN TUBE LEVEL-40IN DATA61-63
FIGURE A16

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}C$)
T4075C PLAIN TUBE LEVEL-44IN DATA52-54
FIGURE A17

INCREASING/DECREASING HEAT FLUX TEST

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4085C PLAIN TUBE LEVEL-48IN DATA32-34

FIGURE A19

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4075C TEFLON-15% Level-40IN DATA118-120
FIGURE A20

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}C$)
T4085C TEFLON-15% LEVEL-40IN DATA121-123
FIGURE A21

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4075C TEFLON-15% LEVEL-44IN DATA103-105
FIGURE A22

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4085C TEFLON-15% LEVEL-44IN DATA124-126
FIGURE A23

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}C$)
 T4075C TEFLON-15% LEVEL-48IN DATA85-87

FIGURE A24

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}\text{C}$)
T4085C TEFLON-15% LEVEL-48IN DATA127-129
FIGURE A25

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4075C INSTRUMENTED LEVEL-40IN DATA193-194
FIGURE A26

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4085C INSTRUMENTED LEVEL-40IN DATA195-196
FIGURE A27

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}C$)
 T4@75C INSTRUMENTED LEVEL-44IN DATA197-198

FIGURE A28

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4085C INSTRUMENTED LEVEL-44IN DATA199-200
FIGURE A29

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference ($^{\circ}\text{C}$)
T4075C INSTRUMENTED LEVEL-48IN DATA201-202
FIGURE A30

INCREASING/DECREASING HEAT FLUX TEST

Wall-Vapour Temperature Difference (°C)
T4085C INSTRUMENTED LEVEL-48IN DATA203-204
FIGURE A31

PLAIN TUBE, 40IN LEVEL, $T_{\text{vapour}}=60^{\circ}\text{C}$
FIGURE A32

PLAIN TUBE, 40IN LEVEL, Tvapour=80°C

FIGURE A33

PLAIN TUBE, 40IN LEVEL, $T_{\text{vapour}}=100^{\circ}\text{C}$
FIGURE A34

PLAIN TUBE, 48IN LEVEL, $T_{\text{vapour}}=50^{\circ}\text{C}$
FIGURE A35

PLAIN TUBE, 48IN LEVEL, Tvapour=60°C

FIGURE A36

PLAIN TUBE, 48IN LEVEL, $T_{\text{vapour}}=70^{\circ}\text{C}$
FIGURE A37

PLAIN TUBE, 48IN LEVEL, $T_{\text{vapour}}=90^{\circ}\text{C}$
FIGURE A39

INSTRUMENTED TUBE, 48IN LEVEL, T_{vapour}=80°C
FIGURE A41

MEASURED WALL-VAPOUR TEMPERATURE VS HEAT FLUX

LEVEL 40IN, VAPOUR TEMPERATURE=60°C
FIGURE A42

MEASURED WALL-VAPOUR TEMPERATURE vs HEAT FLUX

LEVEL 40IN, VAPOUR TEMPERATURE=75°C
FIGURE A43

FIGURE A44

MEASURED WALL-VAPOUR TEMPERATURE VS HEAT FLUX

LEVEL 40IN, VAPOUR TEMPERATURE=85°C
FIGURE A45

FIGURE A46

LEVEL 44IN, VAPOUR TEMPERATURE=60°C
FIGURE A47

FIGURE A48

FIGURE A49

FIGURE A50

MEASURED WALL-VAPOUR TEMPERATURE vs HEAT FLUX

Average Heat Flux (W/m^2)
 LEVEL 44IN, VAPOUR TEMPERATURE=100°C
 FIGURE A51

LEVEL 48IN. VAPOUR TEMPERATURE=60°C
FIGURE A52

FIGURE A53

FIGURE A54

MEASURED WALL-VAPOUR TEMPERATURE vs HEAT FLUX

Average Heat Flux (W/m²)
LEVEL 48IN, VAPOUR TEMPERATURE=85°C
FIGURE A55

FIGURE A56

In the *Instrumented Section Record*, three different wall to vapour temperature differences are listed :

- i) ΔT_{w0-4} is the calculated value as in the other records;
- ii) ΔT_{2-4} is the difference between thermocouple T_2 in the wall of the boiling surface (12 inches from the bottom of the test section) and the vapour in the test section T_4 ;
- iii) ΔT_{4-4} is the difference between thermocouple T_4 (42 inches from the bottom of the test section) and T_4 .

The *Two-Phase Record* lists ΔT_{1-4} - the temperature difference between the two phase fluid and the vapour. This temperature difference is given as a function of the nominal fluid depth, also known as the collapsed depth, which is the distance of thermocouple T_1 below the surface of the fluid when the system is not in operation and at 20°C. Thus this nominal fluid depth is only a relative means of measuring the temperature of the two-phase fluid as the depth changes. Note that for the tests with the Level at 40 inches, some of the nominal fluid depths are listed as being negative; this indicates that the thermocouple was above the nominal surface level. As the thermocouple was lowered, the temperature difference ΔT_{1-4} rapidly rises from about 0.4°C to about 1.0°C, thus indicating the mean level of the two-phase/vapour interface.

Notes on the Test Record Summaries

Definitions:

A sample is a set of 4 or 6 thermocouple temperatures (depending on whether 4 or 6 thermocouples are used for that test) taken at one "moment" in time, and (usually) 25 samples are averaged into one reading, of which as many as possible are averaged into one data point listed in a summary table.

In the *Overall Test Record*, the *Increasing/Decreasing Heat Flux Test Record*, the *Instrumented Section Record*, and the *Two-Phase Record*, the temperature samples were read to two decimal places, but were manipulated, rounded, and averaged to only one decimal place. The T_4 rate is listed to three decimal places, but this is for comparison purposes only. There is only one sample of the power per reading, due to the relative stability of the power source.

Unless it was an increasing/decreasing heat flux test or is otherwise stated, a test consisted of 20 readings of 25 samples each, and the start of each reading was one minute apart. The samples were averaged into one reading, which was then manipulated to provide the calculated boiling temperature difference ΔT_{w_0-4} - in other words the temperature of the outside of the wall common to heat pipes 1 and 2, T_{w_0} , minus the vapour temperature, T_4 .

It should be noted that the ΔT_{w-o-4} listed in all of the tables is calculated from T_2 and T_4 - the vapour temperature in the source and test heat pipes respectively - and from the average heat flux based on the total heat transfer surface area. The listed data points are averages based on all of the samples in a given test; thus in the usual case T_4 and ΔT_{w-o-4} represent 500 samples taken over 20 minutes. The variations following the " $\pm$ " sign (for the heat flux, boiling temperature difference, and the Rohsenow boiling coefficient C_{boil}) are those based on the error analysis of appendix D.

The T_4 rate is the slope of the best-fit straight line (linear regression) passing through the T_4 readings, given as a measure of test stability. The boiling heat flux coefficient, h_{boil} , and the heat flux are both based on the total heat transfer area (0.965 m^2) available to the test fluid, whether liquid or vapour, regardless of the two phase fluid level; h_{boil} utilizes the calculated wall to vapour temperature difference ΔT_{w-o-4} . The level is the nominal depth of water at 20°C and atmospheric pressure.

The four constant heat flux data points marked with a "#" are tests which were deemed as highly unreliable (they occurred early in the test set, and were repeated later with much lower errors). In these cases the results were not used

in calculating an average C_{eff} value, nor were they plotted.

In the *Summary of Increasing/Decreasing Heat Flux Test Record*, the data points are the averages of several readings taken in succession at a particular power level. In later tests, due to practice and improvement in the experimental process, the power was kept constant for 7 to 8 minutes, and the latter 5 minutes were averaged before the power level was changed (if the system was moderately stable ie. the vapour temperature T_v remained steady). The data points listed in this summary are only those deemed to be the best possible average for the particular power level. However, in some earlier tests (DATA32-34, 40-42 and 61-63), the data points do not always represent such stability. As with the constant heat flux tests such poor data points are marked with a "#", representing a low confidence in that particular result, and thus omission from analysis. These excluded data points (13 out of a total of 494 data points in these tests) were deemed unreliable by the marked oscillations in temperature with time, where T_v readings were in the order of $\pm 1.5^\circ\text{C}$ from the previous and successive readings.

Most tests used 25 samples averaged into one reading; however, the following tests used fewer or more samples: DATA2 (5); DATA32 to DATA34 (30); DATA35,36,40-42 and 52-54 (40). DATA206, 208, 210 and 212 were tests of 100 readings of only one sample per reading.

In the *Instrumented Section Record*, three different wall to vapour temperature differences are listed :

- i) ΔT_{w0-4} is the calculated value as in the other records;
- ii) ΔT_{9-4} is the difference between thermocouple T_9 in the wall of the boiling surface (12 inches from the bottom of the test section) and the vapour in the test section T_4 ;
- iii) ΔT_{41-4} is the difference between thermocouple T_{41} (42 inches from the bottom of the test section) and T_4 .

The *Two-Phase Record* lists ΔT_{1-4} - the temperature difference between the two phase fluid and the vapour. This temperature difference is given as a function of the nominal fluid depth, also known as the collapsed depth, which is the distance of thermocouple T_1 below the surface of the fluid when the system is not in operation and at 20°C. Thus this nominal fluid depth is only a relative means of measuring the temperature of the two-phase fluid as the depth changes. Note that for the tests with the Level at 40 inches, some of the nominal fluid depths are listed as being negative; this indicates that the thermocouple was above the nominal surface level. As the thermocouple was lowered, the temperature difference ΔT_{1-4} rapidly rises from about 0.4°C to about 1.0°C, thus indicating the mean level of the two-phase/vapour interface.

Test Title	Record#	Overall Test Record		T4rate °C/min	Power W	hboil W/m²°C	heatflux W/m²	Csf
		Date	Two-4 °C	T4 °C				
Test#1 700W (Plain, Level-48IN)	DATA1#	26Sep88	9.3±1.6	58.9	-.061	697	760	7027±40 .0218±.0036
Test#2 700W T1#65C (Plain, Level-48IN)	DATA2	"	8.9±1.4	64.0	+.077	700	790	7038±41 .0224±.0033
Test#3 1100W T1#77C (Plain, Level-48IN)	DATA3	27Sep88	7.8±1.3	76.1	+.055	1098	1421	11111±46 .0194±.0030
Test#4 1100W T1#98C (Plain, Level-48IN)	DATA4#	"	7.4±2.5	94.8	-.007	1095	1497	11003±53 .0219±.0073
500W T2#60.0 (Plain, Level-48IN)	DATA5	03Oct88	9.1±1.0	50.8	+.011	496	549	4981±37 .0214±.0024
500W T2#70 (Plain, Level-48IN)	DATA6	"	8.1±0.9	61.0	+.017	500	614	4989±39 .0221±.0024
500W T2#80C (Plain, Level-48IN)	DATA7	"	7.0±1.3	72.3	-.001	498	705	4928±43 .0218±.0038
500W T2#89.5C (Plain, Level-48IN)	DATA8#	04Oct88	8.0±2.3	80.9	+.010	495	605	4855±46 .0276±.0077
500W T2#100C (Plain, Level-48IN)	DATA9#	"	7.9±1.9	91.4	+.028	498	616	4851±50 .0299±.0069
500W T2#110C (Plain, Level-48IN)	DATA10	"	5.4±1.4	103.6	+.011	497	895	4798±54 .0227±.0058
500W T2#60C (Plain, Level-48IN)	DATA11	"	10.6±1.1	48.1	+.016	497	471	4999±36 .0240±.0025
700W T2#60C (Plain, Level-48IN)	DATA12	06Oct88	10.9±1.3	47.7	-.007	695	644	7050±37 .0220±.0026
700W T2#70C (Plain, Level-48IN)	DATA13	"	8.9±1.0	60.2	-.002	696	789	7009±42 .0213±.0024
700W T2#80C (Plain, Level-48IN)	DATA14	"	7.9±1.3	70.7	-.058	697	885	6990±43 .0216±.0035
700W T2#90C (Plain, Level-48IN)	DATA15	07Oct88	6.4±1.1	81.8	-.003	691	1075	6889±46 .0198±.0033
700W T2#100C (Plain, Level-48IN)	DATA16	"	6.3±1.7	91.8	+.055	696	1091	6893±51 .0214±.0057
700W T2#110C (Plain, Level-48IN)	DATA17	"	5.6±1.3	103.9	-.001	695	1229	6835±55 .0210±.0047
700W T2#60C (Plain, Level-48IN, 10rdgs)	DATA18	"	10.4±1.3	48.5	+.055	696	676	7054±37 .0212±.0026
900W T2#60C T1-3IN increments (14 rdgs)	DATA19	13Oct88	11.4±1.1	50.2	-.044	889	793	9033±38 .0219±.0021
900W T4#50C (Plain, Level-48IN)	DATA20	"	11.2±1.1	50.5	-.019	901	815	9158±38 .0216±.0021
900W T4#60C (Plain, Level-48IN)	DATA21	"	9.4±1.0	60.4	-.011	894	958	9052±41 .0209±.0021
900W T4#70C (Plain, Level-48IN)	DATA22	17Oct88	7.8±0.9	70.7	+.007	895	1164	9029±44 .0195±.0021
900W T4#80C (Plain, Level-48IN)	DATA23	"	6.8±0.8	80.2	-.021	903	1343	9077±47 .0187±.0023
900W T4#90C (Plain, Level-48IN)	DATA24	"	5.7±1.0	90.5	+.001	897	1580	8976±51 .0174±.0029
900W T4#100C (Plain, Level-48IN)	DATA25	"	5.7±1.7	100.4	-.0001	895	1579	8923±54 .0190±.0054
1100W T4#50C (Plain, Level-48IN)	DATA26	18Oct88	11.7±1.1	51.6	+.015	1090	954	11113±39 .0214±.0019
1100W T4#60C (Plain, Level-48IN)	DATA27	"	9.5±1.0	61.1	+.025	1094	1170	11127±41 .0198±.0020
1100W T4#70C (Plain, Level-48IN)	DATA28	"	8.0±0.8	70.9	+.003	1102	1391	11166±45 .0188±.0019
1100W T4#80C (Plain, Level-48IN)	DATA29	"	6.9±0.8	79.7	+.004	1096	1609	11084±46 .0178±.0021
1100W T4#90C (Plain, Level-48IN)	DATA30	"	6.1±1.9	88.9	-.125	1098	1812	11070±50 .0173±.0050
1100W T4#100C (Plain, Level-48IN)	DATA31	"	5.6±1.5	100.8	-.025	1098	1965	11021±54 .0176±.0044
T4#85C Increasing heatflux (Plain, Level-48IN)	DATA32-34	20Oct88	Various results - see page B10					
Heatflux Increasing (cooling constant)	DATA35	25Oct88	Various results but no useful data					
Increasing/Decreasing Heatflux T4#75C	DATA36	27Oct88	Various results but heater failed					
500W T4#80C -2 (Plain, Level-48IN)	DATA37	31Oct88	6.8±1.0	79.8	+.020	500	725	4904±47 .0229±.0034
500W T4#90C -2 (Plain, Level-48IN)	DATA38	"	5.8±0.8	89.1	-.016	504	846	4908±50 .0215±.0029
1100W T4#95C -2 (Plain, Level-48IN)	DATA39	"	6.2±1.3	94.8	+.044	1096	1768	11012±53 .0186±.0038
Increasing/Decreasing Heatflux T4#75C	DATA40-42	31Oct88	Various results - see page B11					
500W T4#60C Level Lower-3IN (Plain)	DATA43	01Nov88	7.0±1.0	60.4	-.038	501	707	4982±41 .0190±.0025
500W T4#80C Level-44IN (Plain)	DATA44	"	6.4±0.8	80.8	+.007	496	756	4851±48 .0220±.0025
500W T4#100C Level-44IN (Plain)	DATA45	"	5.4±1.4	99.4	+.020	503	895	4851±55 .0220±.0054

Test Title	Record#	Date	Overall Test Record			Power W	hboil W/m ² °C	heatflux W/m ²	Csf
			Two-4 °C	T4 °C	T4rate °C/min				
700W T4060C Level-44IN (Plain)	DATA46	02Nov88	7.8±0.8	60.7	-.005	693	896	6968±41	.0189±.0018
700W T4080C Level-44IN (Plain)	DATA47	"	6.7±1.1	80.2	-.047	699	1035	6953±40	.0203±.0032
700W T40100C Level-44IN (Plain)	DATA48	"	5.7±1.8	99.9	+.029	699	1205	6878±55	.0200±.0063
900W T4060C Level-44IN (Plain)	DATA49	07Nov88	9.1±0.9	59.9	+.023	902	1004	9136±41	.0199±.0019
900W T4080C Level-44IN (Plain)	DATA50	"	7.3±1.0	80.2	-.017	901	1233	9051±47	.0204±.0025
900W T40100C Level-44IN (Plain)	DATA51	"	6.2±2.0	100.4	-.022	904	1451	9010±55	.0208±.0066
Increasing/Decreasing Hflux T4075C Level-44IN DATA52-54 08Nov88 Various results - see page B12									
1100W T4060C Level-44IN (Plain)	DATA55	10Nov88	10.3±1.1	60.8	+.003	1096	1080	11136±42	.0214±.0021
1100W T4080C Level-44IN (Plain)	DATA56	"	8.0±0.9	79.5	-.001	1096	1377	11068±48	.0207±.0023
1100W T40100C Level-44IN (Plain)	DATA57	"	6.6±1.7	101.0	+.046	1089	1644	10916±56	.0210±.0052
500W T4060C Level-40IN (Plain)	DATA58	19Nov88	7.7±2.4	60.4	+.061	580	650	4979±40	.0206±.0064
500W T4080C Level-40IN (Plain)	DATA59	"	5.2±1.5	80.0	-.026	497	940	4878±46	.0176±.0048
500W T40100C Level-40IN (Plain)	DATA60	"	4.1±1.2	100.6	+.030	501	1184	4844±54	.0168±.0048
Inc/Dec Htflx T4075C Level-40IN (Plain) DATA61-63 22Nov88 Various results - see page B13									
700W T4060C Level-40IN (Plain)	DATA64	25Nov88	8.5±2.5	60.0	+.027	696	828	7003±41	.0203±.0057
700W T4080C Level-40IN (Plain)	DATA65	"	6.3±0.7	79.8	-.005	702	1110	6992±47	.0189±.0021
700W T40100C Level-40IN (Plain)	DATA66	"	4.9±0.7	99.3	+.021	700	1396	6897±54	.0179±.0026
900W T4060C Level-40IN (Plain)	DATA67	28Nov88	9.1±1.6	58.9	+.005	897	998	9090±41	.0198±.0033
900W T4080C Level-40IN (Plain)	DATA68	"	7.1±1.1	79.9	-.002	896	1265	9004±47	.0197±.0029
900W T40100C Level-40IN (Plain)	DATA69	"	5.6±0.6	100.0	-.001	904	1606	9009±55	.0187±.0020
1100W T4060C Level-40IN (Plain)	DATA70	28Nov88	9.4±1.4	59.4	-.015	1099	1196	11182±41	.0190±.0028
1100W T4080C Level-40IN (Plain)	DATA71	"	7.6±1.0	79.3	+.001	1096	1459	11075±47	.0195±.0026
1100W T40100C Level-40IN (Plain)	DATA72	"	6.2±0.6	102.0	+.005	1095	1759	10977±56	.0198±.0020
500W Teflon-15% Level-48IN T4060C	DATA73	06Dec88	6.9±0.7	60.3	-.006	499	719	4969±40	.0186±.0017
500W Teflon-15% Level-48IN T4080C	DATA74	"	5.0±0.6	80.0	+.001	499	986	4893±47	.0168±.0019
500W Teflon-15% Level-48IN T40100C	DATA75	"	Data incorrect - needed aspiration - see DATA76						
500W Teflon-15% Level-48IN T40100C	DATA76	"	3.9±0.9	98.3	+.024	501	1229	4855±53	.0159±.0034
700W Teflon-15% Level-48IN T4060C	DATA77	07Dec88	8.0±0.7	59.6	+.004	697	872	7011±41	.0192±.0016
700W Teflon-15% Level-48IN T4080C	DATA78	"	5.7±0.7	80.1	+.025	701	1233	6977±48	.0171±.0021
700W Teflon-15% Level-48IN T40100C	DATA79	"	4.3±0.7	99.2	+.006	704	1617	6935±55	.0155±.0024
900W Teflon-15% Level-48IN T4060C	DATA80	08Dec88	Invalid due to T3 being in the wrong location						
900W Teflon-15% Level-48IN T4060C	DATA81	"	9.1±0.7	59.0	-.011	901	997	9122±41	.0198±.0015
900W Teflon-15% Level-48IN T4080C	DATA82	"	6.2±0.6	80.5	-.002	896	1455	8994±48	.0172±.0017
900W Teflon-15% Level-48IN T40100C	DATA83	"	4.5±1.0	100.0	+.047	908	2024	9046±55	.0149±.0033
900W Teflon-15% Level-48IN T40100C	DATA84	"	4.5±0.9	99.9	+.000	905	1990	9017±55	.0151±.0027

Inc/Dec Htflx Teflon-15% Level-48IN T4075C DATA85-87 09Dec88 Various results - see page B14

Test Title	Record#	Overall Test Record		T4rate °C/min	Power W	hboil W/m²°C	heatflux W/m²	Csf
		Date	Two-4 °C	T4 °C				
1100W Teflon-15% Level-40IN T4Q60C	DATA88	14Dec88	9.6±0.8	59.8	+0.06	1094	1157	11128±41 .0197±.0016
1100W Teflon-15% Level-40IN T4Q80C	DATA89	"	6.5±0.7	79.5	+0.08	1105	1729	11172±47 .0166±.0017
1100W Teflon-15% Level-40IN T4Q100C	DATA90	"	4.6±0.8	100.0	+0.06	1103	2397	11076±54 .0144±.0024
500W Teflon-15% Level-44IN T4Q60C	DATA91	15Dec88	6.1±0.7	60.5	+0.01	502	822	5012±39 .0164±.0019
500W Teflon-15% Level-44IN T4Q80C	DATA92	"	4.7±0.6	79.6	+0.02	499	1042	4907±45 .0159±.0018
500W Teflon-15% Level-44IN T4Q100C	DATA93	"	3.5±0.5	100.2	+0.08	508	1414	4919±53 .0142±.0021
700W Teflon-15% Level-44IN T4Q60C	DATA94	19Dec88	7.1±0.7	60.1	-0.04	703	994	7088±40 .0170±.0016
700W Teflon-15% Level-44IN T4Q80C	DATA95	"	5.1±0.6	80.3	+0.07	706	1378	7044±46 .0154±.0018
700W Teflon-15% Level-44IN T4Q100C	DATA96	"	3.7±0.6	100.1	+0.13	705	1861	6961±53 .0136±.0021
900W Teflon-15% Level-44IN T4Q60C	DATA97	19Dec88	7.9±0.8	60.2	+0.021	905	1158	9180±40 .0174±.0017
900W Teflon-15% Level-44IN T4Q80C	DATA98	"	5.5±0.7	80.2	+0.020	903	1643	9086±46 .0153±.0019
900W Teflon-15% Level-44IN T4Q100C	DATA99	"	4.0±0.5	100.1	+0.06	903	2258	9010±53 .0133±.0017
1100W Teflon-15% Level-44IN T4Q60C	DATA100	19Dec88	9.0±0.9	60.0	-0.12	1102	1249	11216±40 .0184±.0018
1100W Teflon-15% Level-44IN T4Q80C	DATA101	"	6.0±0.6	79.7	+0.02	1105	1863	11178±46 .0154±.0016
1100W Teflon-15% Level-44IN T4Q100C	DATA102	"	4.4±0.5	99.5	+0.04	1103	2524	11082±54 .0136±.0015
Inc/Dec Hflx Teflon-15% Level-44IN T4Q75C DATA103-105 20Dec88 Various results - see page B15								
500W Teflon-15% Level-40IN T4Q60C	DATA106	21Dec88	5.8±0.7	60.3	+0.07	499	863	4986±39 .0156±.0019
500W Teflon-15% Level-40IN T4Q80C	DATA107	"	4.8±0.6	80.1	+0.08	501	1036	4930±45 .0161±.0021
500W Teflon-15% Level-40IN T4Q100C	DATA108	"	3.7±0.6	99.9	+0.12	502	1311	4863±53 .0151±.0024
700W Teflon-15% Level-40IN T4Q60C	DATA109	21Dec88	6.3±0.8	60.3	+0.11	708	1142	7147±39 .0150±.0018
700W Teflon-15% Level-40IN T4Q80C	DATA110	"	5.3±0.6	80.5	+0.07	704	1333	7025±46 .0160±.0018
700W Teflon-15% Level-40IN T4Q100C	DATA111	"	4.0±0.6	99.8	+0.12	703	1731	6941±53 .0145±.0022
900W Teflon-15% Level-40IN T4Q60C	DATA112	22Dec88	7.0±0.8	60.3	+0.04	902	1314	9157±39 .0153±.0016
900W Teflon-15% Level-40IN T4Q80C	DATA113	23Dec88	5.9±0.7	79.2	+0.02	898	1531	9032±46 .0162±.0019
900W Teflon-15% Level-40IN T4Q100C	DATA114	"	4.5±0.6	99.9	-0.08	905	2028	9025±54 .0148±.0019
1100W Teflon-15% Level-40IN T4Q60C	DATA115	23Dec88	8.3±0.9	60.2	+0.02	1097	1351	11160±41 .0170±.0019
1100W Teflon-15% Level-40IN T4Q80C	DATA116	"	6.0±0.6	80.2	+0.05	1098	1859	11099±47 .0155±.0016
1100W Teflon-15% Level-40IN T4Q100C	DATA117	"	4.5±0.7	99.7	-0.18	1098	2445	11027±54 .0140±.0020

Inc/Dec Hflx Teflon-15% Level-40IN T4Q75C DATA118-120 30Dec88 Various results - see page B16

Inc/Dec Hflx Teflon-15% Level-40IN T4Q85C DATA121-123 " Various results - see page B17

Inc/Dec Hflx Teflon-15% Level-44IN T4Q85C DATA124-126 01Jan89 Various results - see page B18

Inc/Dec Hflx Teflon-15% Level-40IN T4Q85C DATA127-129 02Jan89 Various results - see page B19

Test Title	Record#	Overall Test Record				Power W	hboil W/m ² °C	heatflux W/m ²	Csf
		Date	Two-4 °C	T4 °C	T4rate °C/min				
500W Instrumented Level-48IN T4Q57C	DATA130	11Jan89	7.5±1.0	56.6	-.019	495	657	4942±39	.0193±.0025
500W Instrumented Level-48IN T4Q60C	DATA131	12Jan89	6.9±1.1	59.5	+.011	497	713	4955±40	.0185±.0028
500W Instrumented Level-48IN T4Q80C	DATA132	"	4.4±0.8	80.4	+.004	500	1129	4911±46	.0148±.0025
500W Instrumented Level-48IN T4Q60C	DATA133	13Jan89	7.6±0.9	59.8	+.014	503	657	5019±40	.0204±.0023
500W Instrumented Level-48IN T4Q80C	DATA134	"	4.4±0.6	81.0	-.009	497	1110	4882±46	.0151±.0021
500W Instrumented Level-48IN T4Q100C	DATA135	"	5.3±0.8	101.3	-.004	499	909	4817±54	.0220±.0030
500W Instrumented Level-48IN T4Q100C	DATA136	13Jan89	5.9±0.6	100.7	-.018	499	811	4816±54	.0245±.0026
500W Instrumented Level-48IN T4Q60C	DATA137	16Jan89	7.6±1.2	60.0	+.006	497	651	4952±40	.0204±.0032
500W Instrumented Level-48IN T4Q80C	DATA138	"	4.6±0.7	80.9	+.002	506	1085	4970±46	.0156±.0023
500W Instrumented Level-48IN T4Q100C	DATA139	"	3.4±0.8	100.9	-.026	502	1435	4853±54	.0140±.0032
700W Instrumented Level-48IN T4Q60C	DATA140	16Jan89	7.1±1.1	60.5	+.005	703	996	7084±40	.0171±.0025
700W Instrumented Level-48IN T4Q80C	DATA141	"	5.0±0.7	80.8	-.006	702	1411	6998±47	.0151±.0021
700W Instrumented Level-48IN T4Q100C	DATA142	"	4.0±1.3	100.3	-.009	698	1708	6882±54	.0147±.0047
700W Instrumented Level-48IN T4Q100C	DATA143	"	5.8±0.8	100.0	-.028	697	1176	6865±55	.0213±.0030
900W Instrumented Level-48IN T4Q60C	DATA144	16Jan89	7.5±1.0	60.8	-.014	904	1221	9160±41	.0166±.0021
900W Instrumented Level-48IN T4Q80C	DATA145	"	5.4±0.6	79.6	+.006	902	1692	9069±47	.0148±.0017
900W Instrumented Level-48IN T4Q100C	DATA146	"	3.5±0.8	99.5	+.006	902	2534	8995±54	.0118±.0027
1100W Instrumented Level-48IN T4Q60C	DATA147	17Jan89	7.9±0.9	60.8	-.009	1098	1410	11170±41	.0164±.0018
1100W Instrumented Level-48IN T4Q80C	DATA148	"	6.5±0.9	79.1	-.029	1093	1710	11048±47	.0166±.0021
1100W Instrumented Level-48IN T4Q80C	DATA149	"	6.5±0.8	79.2	+.028	1087	1677	10986±47	.0169±.0020
1100W Instrumented Level-48IN T4Q100C	DATA150	"	4.1±0.6	99.4	+.006	1108	2741	11129±54	.0126±.0018
Inc/Dec Hflx Instrumented Level-48IN T4Q75C DATA151-152 17Jan89 Various but system failed - unreliable data									
500W Instrumented Level-48IN T4Q60C	DATA153	18Jan89	8.1±1.4	59.4	+.011	505	619	5034±40	.0216±.0037
Inc/Dec Hflx Instrumented Level-48IN T4Q75C DATA154-155 19Jan89 Various results but unreliable data									
500W Instrumented Level-48IN T4Q60C	DATA156	27Jan89	7.4±1.5	59.8	+.011	501	678	4993±40	.0197±.0038
500W Instrumented Level-48IN T4Q80C	DATA157	"	4.7±0.8	80.1	-.002	502	1038	4931±46	.0161±.0025
500W Instrumented Level-48IN T4Q100C	DATA158	"	3.5±0.7	100.0	-.002	499	1372	4817±54	.0144±.0029
700W Instrumented Level-48IN T4Q60C	DATA159	"	7.4±1.2	59.9	+.033	702	952	7070±40	.0177±.0027
700W Instrumented Level-48IN T4Q80C	DATA160	"	4.7±0.8	80.4	-.011	701	1471	6989±46	.0144±.0022
700W Instrumented Level-48IN T4Q100C	DATA161	"	3.6±0.7	100.0	+.022	700	1939	6903±54	.0130±.0026
900W Instrumented Level-48IN T4Q60C	DATA162	27Jan89	7.5±1.1	60.3	+.022	902	1223	9136±41	.0165±.0024
900W Instrumented Level-48IN T4Q80C	DATA163	30Jan89	5.4±0.9	79.2	+.007	907	1674	9125±46	.0149±.0023
900W Instrumented Level-48IN T4Q100C	DATA164	"	3.9±0.6	99.5	+.005	900	2325	8974±54	.0128±.0020
1100W Instrumented Level-48IN T4Q60C	DATA165	30Jan89	8.3±0.9	60.0	+.003	1104	1350	11231±41	.0171±.0017
1100W Instrumented Level-48IN T4Q80C	DATA166	"	5.9±0.7	79.6	+.018	1097	1886	11089±47	.0152±.0018
1100W Instrumented Level-48IN T4Q100C	DATA167	"	3.8±0.7	99.6	+.022	1097	2938	11017±54	.0117±.0022

Notes: * These terms were taken with thermocouple adjustments that were the most accurate to the true temperatures, but all other temperatures listed were recorded with the original thermocouple adjustments.

Test Title	Record#	Overall Test Record			Power W	hboil W/m ² °C	heatflux W/m ²	Csf
		Date	Two-4 °C	T4 °C				
500W Instrumented Level-44IN T4060C	DATA168	30Jan89	6.3±1.1	60.2	+0.021	499	790	4980±39 .0169±.0029
500W Instrumented Level-44IN T4080C	DATA169	"	4.9±0.8	80.0	-0.005	506	1022	4976±46 .0164±.0026
500W Instrumented Level-44IN T40100C	DATA170	"	3.3±0.6	99.7	-0.001	505	1477	4889±53 .0135±.0023
700W Instrumented Level-44IN T4060C	DATA171	30Jan89	7.1±1.0	60.3	+0.005	706	1007	7111±41 .0169±.0023
700W Instrumented Level-44IN T4080C	DATA172	"	5.5±0.8	79.9	-0.007	705	1266	7025±47 .0167±.0025
700W Instrumented Level-44IN T40100C	DATA173	"	3.7±0.9	99.2	+0.010	706	1891	6960±54 .0133±.0031
900W Instrumented Level-44IN T4060C	DATA174	31Jan89	8.3±0.9	60.3	+0.016	901	1099	9119±42 .0183±.0020
900W Instrumented Level-44IN T4060C	DATA175	"	8.5±1.0	60.0	-0.025	899	1073	9098±42 .0186±.0020
900W Instrumented Level-44IN T4080C	DATA176	"	6.8±0.8	79.8	+0.009	897	1504	9007±48 .0166±.0021
900W Instrumented Level-44IN T40100C	DATA177	"	3.6±0.6	99.3	+0.0003	906	2463	9022±56 .0121±.0018
1100W Instrumented Level-44IN T4060C	DATA178	31Jan89	7.6±0.8	59.4	-0.010	1102	1467	11207±41 .0156±.0017
1100W Instrumented Level-44IN T4080C	DATA179	"	5.5±0.6	79.9	+0.001	1101	2018	11119±48 .0142±.0015
1100W Instrumented Level-44IN T40100C	DATA180	"	3.6±0.6	99.9	+0.002	1099	3063	11025±55 .0112±.0018
500W Instrumented Level-40IN T4060C	DATA181	01Feb89	6.4±1.0	60.1	+0.021	500	774	4984±40 .0173±.0026
500W Instrumented Level-40IN T4080C	DATA182	"	4.0±1.0	80.1	-0.025	500	1240	4911±46 .0134±.0032
500W Instrumented Level-40IN T40100C	DATA183	"	3.2±1.0	100.2	+0.046	502	1520	4849±54 .0142±.0024
700W Instrumented Level-40IN T4060C	DATA184	01Feb89	5.9±1.0	60.4	+0.035	703	1200	7079±41 .0142±.0024
700W Instrumented Level-40IN T4080C	DATA185	"	5.3±0.7	80.5	-0.004	703	1329	7002±47 .0160±.0022
700W Instrumented Level-40IN T40100C	DATA186	"	3.5±0.6	99.3	+0.012	702	1994	6920±54 .0125±.0022
900W Instrumented Level-40IN T4060C	DATA187	01Feb89	6.2±1.1	60.3	+0.044	902	1483	9136±41 .0136±.0023
900W Instrumented Level-40IN T4080C	DATA188	"	5.9±0.8	79.4	+0.011	900	1519	9039±48 .0164±.0021
900W Instrumented Level-40IN T40100C	DATA189	"	3.7±0.7	99.7	+0.006	899	2440	8956±55 .0122±.0023
1100W Instrumented Level-40IN T4060C	DATA190	01Feb89	6.5±1.2	60.5	+0.056	1108	1731	11268±41 .0134±.0024
1100W Instrumented Level-40IN T4080C	DATA191	"	5.6±0.7	79.1	-0.005	1106	1999	11175±48 .0143±.0017
1100W Instrumented Level-40IN T40100C	DATA192	"	4.5±0.6	99.7	+0.011	1105	2457	11083±56 .0140±.0018
Inc/Dec Hfx Instrumented Level-40IN T4075C	DATA193-194	16Feb89	Various results - see page B20					
Inc/Dec Hfx Instrumented Level-40IN T4085C	DATA195-196	"	Various results - see page B21					
Inc/Dec Hfx Instrumented Level-44IN T4075C	DATA197-198	17Feb89	Various results - see page B22					
Inc/Dec Hfx Instrumented Level-44IN T4085C	DATA199-200	"	Various results - see page B23					
Inc/Dec Hfx Instrumented Level-48IN T4075C	DATA201-202	18Feb89	Various results - see page B24					
Inc/Dec Hfx Instrumented Level-48IN T4085C	DATA203-204	"	Various results - see page B25					
The following occurred on 18Feb89:								
500W Instrumented Level-48IN T4080C	DATA205		4.9±0.8	79.4	+0.004	508	1026	4984±47 .0163±.0024
500W Instrumented Level-48IN T4080C (100smpl)	DATA206		4.9±0.7	79.3	+0.002	508	1009	4984±47 .0165±.0024
700W Instrumented Level-48IN T4080C	DATA207		6.1±0.8	79.8	+0.011	697	1142	6933±48 .0183±.0022
700W Instrumented Level-48IN T4080C (100smpl)	DATA208		6.0±0.7	79.7	-0.0003	696	1150	6922±48 .0181±.0020
900W Instrumented Level-48IN T4080C	DATA209		7.4±0.8	79.8	+0.023	897	1224	8995±49 .0203±.0022
900W Instrumented Level-48IN T4080C (100smpl)	DATA210		7.3±0.7	80.1	+0.002	896	1224	8984±49 .0204±.0017
1100W Instrumented Level-48IN T4080C	DATA211		7.3±0.7	80.9	+0.004	1106	1534	11153±50 .0189±.0017
1100W Instrumented Level-48IN T4080C(100smpl)	DATA212		7.4±0.7	80.8	-0.001	1104	1513	11134±50 .0192±.0016

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m ² °C	heatflux W/m ²	Csf
T4@85C Increasing heatflux	32-1;2 {2}	3.4±0.5	84.9	147	367	1242±47	.0188±.0027
	32-4;5 {3}	3.5±0.6	84.9	158	384	1356±47	.0193±.0030
Plain tube, level 48IN	32-8;11 {4}	3.7±0.5	84.8	168	395	1450±47	.019±.0028
	32-14;17 {4}	3.9±0.6	84.7	184	415	1627±47	.0200±.0028
DATA32 to DATA34 20 Oct 1988	32-20;23 {4}	4.1±0.6	85.0	203	441	1822±47	.0204±.0031
	32-26;29 {4}	4.4±0.6	84.8	222	459	2019±47	.0210±.0026
	32-33;35 {3}	4.5±0.6	85.0	244	496	2245±47	.0209±.0028
	32-39;43 {5}	4.9±0.7	85.1	276	522	2575±47	.0217±.0029
	32-47;51 {5}	5.3±0.6	84.6	294	526	2763±47	.0225±.0026
	32-55;58 {4}	5.6±0.6	85.1	329	563	3130±47	.0230±.0026
	32-65;68 {4}	5.1±1.0	84.2	364	690	3493±47	.0200±.0036
	32-73;76 {4}	5.7±0.8	83.8	397	666	3831±47	.0219±.0030
	32-81;83 {3}	5.8±0.9	85.5	431	726	4176±48	.0217±.0031
	32-84;86 {3}	4.4±0.6	86.5	431	960	4176±48	.0166±.0022
	32-90;92 {3}	5.7±1.0	85.3	474	812	4622±48	.0207±.0035
	32-97;33-1{5}	6.4±1.1	84.6	514	788	5037±48	.0225±.0038
	33-5;8 {4}	6.8±0.7	84.8	532	766	5219±48	.0237±.0023
	33-13;17 {5}	7.0±0.7	85.3	563	792	5538±48	.0240±.0023
	33-21;25 {5}	7.3±0.8	85.3	593	802	5842±49	.0245±.0025
	33-31;34 {4}	6.3±1.1	85.7	625	983	6176±49	.0209±.0037
	33-37;40 {4}	6.3±1.0	85.6	657	1040	6508±49	.0204±.0033
	33-45;47 {3}	6.1±0.9	85.2	690	1127	6850±49	.0194±.0029
	33-51;54 {4}	6.4±1.0	85.0	726	1134	7225±49	.0200±.0031
	33-59;62 {4}	6.1±0.9	85.7	762	1243	7595±49	.0190±.0028
	33-67;70 {4}	6.5±1.1	85.4	798	1225	7966±49	.0198±.0033
	33-73;76 {4}	6.4±0.9	85.6	845	1323	8453±49	.0191±.0025
	33-80;83 {4}	6.0±0.8	85.5	876	1473	8781±48	.0176±.0022
	33-86;90 {5}	6.3±0.8	85.3	918	1474	9214±49	.0181±.0022
	33-93;97 {5}	6.3±0.8	85.5	958	1540	9626±49	.0179±.0021
	34-1;4 {4}	6.4±0.7	85.4	1000	1582	10059±49	.0179±.0020
	34-7;11 {5}	6.5±0.9	85.2	1039	1623	10468±49	.0179±.0024
	34-14;17 {4}	6.2±0.7	85.6	1090	1765	10998±49	.0171±.0019
	34-20;23 {4}	6.0±0.6	85.7	1128	1889	11391±49	.0164±.0016
	34-26;30 {5}	6.5±0.7	85.8	1179	1833	11917±49	.0174±.0018
	34-33;37 {5}	6.7±0.8	85.6	1219	1854	12332±49	.0176±.0020
	34-41;45 {5}	6.6±0.7	84.9	1136	1733	11475±48	.0178±.0019
	34-49;53 {5}	6.5±0.8	85.4	1049	1624	10573±49	.0181±.0021
	34-56;60 {5}	6.2±0.9	84.9	957	1560	9623±48	.0176±.0026
	34-66;71 {6}	6.0±0.7	83.3	831	1383	8326±47	.0177±.0019
	34-76;80 {5}	6.1±0.9	84.0	766	1252	7651±48	.0186±.0026
	34-86;88 {3}	6.3±0.9	84.4	685	1083	6809±48	.0200±.0028
	34-91;94 {4}	6.2±0.9	85.0	595	945	5875±48	.0209±.0029
	34-97;100 {4}	6.3±0.6	85.3	498	775	4869±48	.0225±.0020

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²°C	heatflux W/m²	Csf
Increasing/Decreasing Heatflux T4@75C	40-6;8 {3}	5.6±0.7	74.5	127	190	1066±44	.0297±.0037
	40-21;31 {11}	4.3±0.7	76.9	144	290	1236±45	.0221±.0035
Plain Tube, Level-48IN	40-42;47 {6}	5.1±0.8	75.0	173	305	1547±44	.0239±.0038
DATA40 to DATA42 Oct 31 1989	40-51;60 {10}	5.6±0.8	74.1	211	347	1937±44	.0242±.0032
	40-63;66 {4}	5.7±0.7	74.3	248	406	2318±44	.0233±.0026
	40-71;78 {8}	5.8±0.8	74.6	290	472	2757±44	.0226±.0029
	40-81;86 {6}	5.9±0.8	74.8	337	549	3238±44	.0217±.0029
	40-90;100 {11}	6.0±0.9	74.4	378	614	3663±45	.0210±.0030
	41-3;6 {4}	5.9±0.8	75.1	438	722	4288±44	.0200±.0027
	41-9;14 {6}	5.9±0.9	75.3	488	818	4800±45	.0191±.0029
	41-17;20 {4}	6.0±0.7	75.0	556	917	5504±45	.0186±.0022
	41-23;28 {6}	6.0±0.7	75.1	607	1007	6030±45	.0180±.0021
	41-31;35 {5}	6.0±0.7	75.3	668	1109	6664±45	.0175±.0020
	41-38;40 {3}	6.3±0.7	75.2	742	1176	7433±45	.0178±.0020
	41-43;46 {4}	6.6±0.7	75.4	806	1223	8093±45	.0181±.0019
	41-50;55 {6}	7.2±0.7	75.5	887	1248	8925±46	.0190±.0018
	41-58;60 {3}	7.6±0.6	75.3	965	1279	9730±46	.0196±.0015
	41-63;67 {5}	8.1±0.7	75.5	1055	1314	10658±46	.0203±.0016
	41-70;76 {7}	8.8±0.8	75.7	1135	1312	11489±46	.0214±.0018
	41-81;87 {7}	8.4±0.7	75.2	1054	1267	10652±46	.0210±.0018
	41-92;100 {9}	7.8±0.7	74.4	975	1255	9837±46	.0199±.0018
	42-8;13 {6}	7.3±0.9	75.1	891	1234	8970±45	.0192±.0023
	42-17;21 {5}	6.8±0.7	75.1	807	1188	8105±45	.0186±.0019
	42-24;27 {4}	6.4±0.7	75.0	738	1149	7390±45	.0181±.0020
	42-30;33 {4}	6.3±0.7	74.9	668	1063	6664±45	.0182±.0020
	42-36;38 {3}	6.0±0.7	75.0	607	999	6033±45	.0181±.0021
	42-41;43 {3}	5.9±0.7	74.8	546	909	5401±45	.0185±.0021
	42-46;50 {5}	5.9±0.8	75.0	488	815	4800±45	.0191±.0026

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m ² °C	heatflux W/m ²	Csf
Increasing/Decreasing Hflux Level-44IM T4@75C Plain Tube, DATA52 to DATA54, 8 Nov 1988	52-10;17 {8}	3.4±0.6	76.4	120	296	995±44	.0186±.0035
	52-24;29 {6}	3.8±0.6	75.6	145	333	1255±44	.0191±.0031
	52-33;40 {8}	4.1±0.7	74.9	171	371	1526±44	.0194±.0034
	52-44;49 {6}	4.9±0.7	74.4	208	392	1907±44	.0213±.0028
	52-53;61 {9}	5.0±0.7	75.1	242	454	2256±44	.0207±.0029
	52-64;66 {3}	5.2±0.5	75.3	285	515	2699±45	.0206±.0019
	52-73;79 {7}	5.5±0.8	75.5	337	591	3236±45	.0203±.0029
	52-82;87 {6}	5.7±0.8	75.3	384	650	3722±45	.0203±.0027
	52-91;100 {10}	5.9±0.7	75.8	437	725	4269±45	.0200±.0024
	53-5;11 {7}	6.1±0.8	75.7	493	800	4849±45	.0197±.0026
	53-14;18 {5}	6.0±0.8	75.6	543	887	5367±45	.0190±.0024
	53-21;26 {6}	6.3±0.8	75.8	609	960	6050±45	.0191±.0025
	53-29;33 {5}	6.4±0.8	76.0	671	1044	6690±45	.0188±.0022
	53-36;40 {5}	6.6±0.8	75.7	738	1127	7384±45	.0186±.0021
	53-43;47 {5}	6.9±0.8	76.1	818	1183	8209±46	.0191±.0020
	53-51;56 {6}	7.4±1.0	75.5	890	1210	8956±46	.0196±.0017
	53-61;66 {6}	7.8±0.8	75.5	970	1254	9782±46	.0201±.0020
	53-70;79 {10}	8.2±0.9	76.2	1047	1293	10575±46	.0207±.0021
	53-82;85 {4}	8.3±0.8	76.4	1127	1379	11402±47	.0204±.0020
	53-88;92 {5}	8.5±0.9	76.5	1195	1419	12104±47	.0207±.0020
	53-95;100 {6}	8.3±0.9	76.0	1129	1368	11424±47	.0205±.0022
	54-12;18 {7}	8.3±0.9	75.5	1049	1274	10598±46	.0209±.0021
	54-26;31 {6}	8.1±0.9	74.5	960	1203	9682±46	.0206±.0021
	54-35;40 {6}	7.6±0.8	74.4	887	1167	8929±45	.0201±.0020
	54-43;48 {6}	7.2±0.7	74.5	803	1119	8061±45	.0195±.0019
	54-51;55 {5}	6.8±0.8	74.6	739	1093	7398±45	.0189±.0021
	54-58;62 {5}	6.5±0.8	74.5	667	1024	6656±45	.0188±.0022
	54-65;68 {4}	6.4±0.8	74.7	605	944	6014±45	.0191±.0024
	54-71;75 {5}	6.1±0.8	74.4	544	880	5383±45	.0190±.0024
	54-78;80 {3}	6.1±0.9	74.5	488	786	4804±44	.0197±.0026
	54-85;88 {4}	6.0±0.8	74.0	433	708	4237±44	.0200±.0025
	54-91;94 {4}	5.9±0.9	74.6	383	632	3716±44	.0206±.0024
	54-97;100 {4}	5.6±0.6	75.1	331	568	3177±44	.0208±.0021

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²°C	heatflux W/m²	Csf
Inc/Dec Htflx T4@75C Level-40IN	61-4;7 {4}	6.3±0.6	75.3	144	195	1227±45	.0321±.0030
	61-22;23 {2}	5.4±1.3	75.5	174	288	1543±45	.0254±.0058
Plain tube, DATA61 to DATA63	61-33,35,37,41{4}	7.2±0.9	72.7	209	266	1909±45	.0308±.0037
22 Nov 1989	61-46;50 {5}	7.2±1.5	73.3	245	316	2279±45	.0293±.0058
Note: The datapoints for DATA61	61-57;59 {3}	7.5±1.2	74.3	287	359	2708±46	.0293±.0046
are especially poor, & must	61-67,69,71,73,75{5}	8.5±1.1	75.2	336	377	3208±46	.0316±.0039
be treated with scepticism.	61-78,82,86 {3}	8.1±1.0	75.9	383	454	3694±46	.0290±.0035
	61-96;100 {5}	5.9±1.7	75.8	433	712	4210±46	.0202±.0056
	62-5;9 {5}	6.1±1.5	73.5	490	795	4819±45	.0193±.0045
	62-14;20 {7}	5.6±1.1	74.1	540	945	5337±45	.0175±.0031
	62-26;31 {6}	5.6±1.2	75.4	606	1070	6015±45	.0170±.0035
	62-36;43 {8}	6.2±0.8	76.0	671	1085	6683±46	.0181±.0022
	62-46;52 {7}	6.6±0.7	75.8	743	1129	7428±46	.0186±.0019
	62-58;66 {9}	7.0±1.1	75.9	815	1172	8171±46	.0191±.0028
	62-70;76 {7}	7.1±0.9	76.5	879	1244	8831±47	.0191±.0022
	62-80;87 {8}	7.5±1.1	76.1	964	1302	9711±47	.0194±.0028
	62-91;97 {7}	7.9±1.0	76.1	1041	1330	10507±47	.0200±.0025
	63-4;10 {7}	8.3±0.9	76.0	1119	1358	11314±47	.0205±.0021
	63-13;16 {4}	7.8±0.9	75.9	1040	1358	10498±47	.0196±.0021
	63-19;24 {6}	7.7±0.9	74.9	963	1255	9705±46	.0198±.0021
	63-27;29 {3}	7.6±0.7	74.9	886	1166	8908±46	.0202±.0019
	63-32;35 {4}	7.1±0.7	74.5	812	1142	8144±46	.0194±.0018
	63-38;41 {4}	6.4±0.8	75.2	745	1157	7451±46	.0181±.0021
	63-44;46 {3}	5.9±0.9	75.2	668	1122	6656±46	.0173±.0025
	63-49;51 {3}	6.1±1.0	74.4	613	1005	6089±45	.0180±.0029
	63-54;58 {5}	6.2±1.0	73.8	537	861	5305±45	.0191±.0030
	63-61;63 {3}	6.1±1.1	74.8	483	784	4743±45	.0196±.0033

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m ² °C	heatflux W/m ²	Csf
Inc/Dec Htflx Teflon-15% Level-40IN T4@75C DATA85 to DATA87, 9 Dec 1988	85-1;5 {5}	4.0±0.6	75.1	209	483	1919±44	.0174±.0025
	85-9;18 {10}	4.2±0.6	75.2	244	545	2279±44	.0173±.0025
	85-23;31 {9}	4.6±0.6	75.3	290	605	2752±45	.0178±.0023
	85-34;42 {9}	4.7±0.6	75.3	338	687	3250±44	.0175±.0022
	85-45;53 {9}	5.0±0.6	75.3	382	745	3704±45	.0176±.0021
	85-57;62 {6}	5.2±0.6	75.3	433	805	4228±45	.0178±.0019
	85-65;74 {10}	5.3±0.6	75.7	487	898	4788±45	.0174±.0020
	85-80;84 {5}	5.6±0.6	75.2	542	959	5359±45	.0175±.0018
	85-87;94 {8}	5.7±0.6	75.3	601	1040	5967±45	.0174±.0018
	85-97;86-2 {6}	5.9±0.5	75.5	663	1121	6605±46	.0173±.0015
	86-9;17 {9}	6.1±0.7	74.9	736	1211	7366±45	.0171±.0018
	86-20;28 {9}	6.3±0.7	75.5	811	1294	8138±46	.0172±.0018
	86-31;36 {6}	6.4±0.6	75.3	882	1391	8872±46	.0169±.0017
	86-39;48 {10}	6.7±0.6	75.4	958	1435	9657±46	.0174±.0016
	86-51;58 {8}	7.1±0.6	75.5	1043	1486	10538±46	.0178±.0015
	86-61;67 {7}	7.4±0.6	75.8	1121	1541	11342±46	.0181±.0015
	86-70;76 {7}	7.6±0.7	75.2	1181	1574	11963±47	.0183±.0017
	86-79;83 {5}	7.4±0.7	75.3	1114	1529	11270±46	.0181±.0016
	86-86;89 {4}	7.1±0.6	75.2	1035	1462	10453±46	.0180±.0016
	86-92;97 {6}	6.9±0.7	75.1	956	1401	9640±46	.0177±.0016
	86-100;87-6 {7}	6.6±0.7	74.9	876	1331	8810±46	.0175±.0017
	87-9;14 {6}	6.5±0.7	74.8	810	1247	8128±46	.0177±.0017
	87-21;27 {7}	6.3±0.6	75.8	738	1179	7381±46	.0177±.0018
	87-31;36 {6}	6.1±0.6	75.3	671	1102	6689±45	.0177±.0018
	87-39;42 {4}	5.9±0.5	75.2	596	1000	5911±45	.0179±.0015
	87-45;48 {4}	5.6±0.6	75.1	541	947	5343±45	.0176±.0017
	87-51;55 {5}	5.4±0.6	75.1	484	874	4755±45	.0177±.0018
	87-58;61 {4}	5.2±0.6	75.1	427	803	4166±45	.0176±.0019
	87-64;67 {4}	5.0±0.6	75.1	379	735	3670±45	.0177±.0020
	87-70;73 {4}	4.8±0.6	75.1	334	673	3204±45	.0176±.0020
	87-76;79 {4}	4.4±0.6	75.4	290	632	2749±45	.0170±.0022
	87-85;88 {4}	4.0±0.7	75.9	243	566	2263±45	.0168±.0027
	87-91;100 {10}	3.8±0.6	76.0	207	501	1892±44	.0168±.0026

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²°C	heatflux W/m²	Csf
Inc/Dec Wflx Teflon-15% Level-44IN	103-1;5 {5}	7.7±0.6	75.1	206	517	1899±43	.0162±.0024
T4075C	103-9;12 {4}	4.0±0.6	75.3	251	591	2363±43	.0164±.0022
DATA103 to DATA105, 20 Dec 1989	103-15;104-1 {7}	4.2±0.5	75.4	289	663	2756±43	.0162±.0021
	104-4;8 {5}	4.3±0.6	75.3	334	747	3220±43	.0160±.0020
	104-11;15 {5}	4.5±0.6	75.3	377	819	3659±44	.0159±.0019
	104-18;21 {4}	4.7±0.6	75.2	425	887	4160±44	.0160±.0019
	104-24;28 {5}	4.8±0.6	75.3	481	987	4738±44	.0157±.0018
	104-31;35 {5}	5.1±0.6	75.2	538	1055	5329±44	.0158±.0018
	104-38;46 {9}	5.1±0.7	74.9	601	1166	5981±44	.0154±.0021
	104-49;55 {7}	5.4±0.6	75.1	666	1244	6653±44	.0156±.0017
	104-58;62 {5}	5.3±0.6	75.2	735	1383	7370±44	.0150±.0017
	104-65;69 {5}	5.6±0.6	75.0	811	1449	8156±44	.0153±.0015
	104-72;76 {5}	5.8±0.6	75.1	887	1542	8941±44	.0153±.0016
	104-79;84 {6}	6.0±0.7	75.1	960	1605	9694±45	.0155±.0017
	104-87;91 {5}	6.3±0.6	75.4	1033	1661	10446±45	.0158±.0015
	104-94;105-1 {8}	6.6±0.6	75.4	1119	1711	11341±45	.0163±.0015
	105-4;8 {5}	6.8±0.6	75.4	1175	1750	11917±45	.0164±.0014
	105-11;14 {4}	6.6±0.6	75.6	1133	1737	11481±45	.0162±.0015
	105-17;23 {7}	6.3±0.7	75.2	1036	1674	10479±45	.0157±.0016
	105-26;30 {5}	6.1±0.6	75.0	959	1593	9684±45	.0156±.0016
	105-33;37 {5}	5.8±0.7	74.8	881	1523	8881±44	.0154±.0017
	105-40;44 {5}	5.7±0.6	74.9	811	1429	8158±44	.0155±.0016
	105-47;51 {5}	5.5±0.6	74.4	733	1329	7351±44	.0155±.0017
	105-54;58 {5}	5.5±0.8	74.8	654	1196	6531±44	.0160±.0022
	105-61;66 {6}	5.3±0.6	75.3	614	1160	6114±44	.0158±.0017
	105-69;72 {4}	5.0±0.6	75.2	535	1055	5298±44	.0158±.0017
	105-75;78 {4}	4.8±0.6	75.1	478	975	4708±44	.0157±.0018
	105-81;84 {4}	4.6±0.6	74.9	422	889	4133±43	.0158±.0019
	105-87;92 {6}	4.4±0.5	74.9	375	823	3647±43	.0157±.0017
	105-95;100 {6}	4.2±0.6	75.0	331	758	3190±43	.0156±.0020

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²°C	heatflux W/m²	Csf
Inc/Dec Htflx Teflon-15% Level-40IN T4@75C DATA118 to DATA120, 30 Dec 1988	118-1;6 (6)	3.7±0.7	75.1	205	506	1879±44	.0164±.0028
	118-9;13 (5)	4.0±0.6	75.1	255	596	2397±44	.0164±.0024
	118-16;20 (5)	4.1±0.7	75.3	292	674	2777±44	.0161±.0025
	118-23;28 (6)	4.2±0.8	75.3	337	772	3242±44	.0155±.0030
	118-31;36 (6)	4.5±0.7	74.8	382	831	3711±44	.0157±.0024
	118-39;43 (5)	4.7±0.6	74.8	432	894	4228±44	.0159±.0019
	118-46;50 (5)	5.1±0.6	75.2	490	954	4825±44	.0164±.0018
	118-53;57 (5)	5.2±0.6	75.3	541	1035	5352±45	.0162±.0019
	118-60;64 (5)	5.3±0.6	75.3	598	1130	5944±44	.0159±.0017
	118-67;71 (5)	5.4±0.7	75.3	671	1238	6697±45	.0157±.0020
	118-74;78 (5)	5.6±0.6	75.3	741	1335	7421±45	.0156±.0018
	118-81;85 (5)	5.8±0.6	75.3	811	1412	8145±45	.0158±.0016
	118-88;92 (5)	5.8±0.7	75.5	885	1523	8911±45	.0155±.0019
	118-95;99 (5)	6.0±0.7	75.3	957	1601	9657±45	.0155±.0017
	119-2;6 (5)	6.4±0.6	75.7	1035	1637	10461±45	.0161±.0016
	119-9;13 (5)	6.8±0.6	75.2	1110	1653	11237±46	.0167±.0015
	119-16;20 (5)	7.1±0.7	75.4	1177	1685	11931±46	.0171±.0016
	119-23;27 (5)	6.8±0.7	75.1	1111	1647	11249±45	.0167±.0015
	119-30;34 (5)	6.6±0.6	74.9	1044	1587	10556±45	.0166±.0015
	119-37;41 (5)	6.2±0.7	74.7	958	1565	9669±45	.0158±.0017
	119-44;48 (5)	6.1±0.7	74.6	877	1457	8830±45	.0160±.0018
	119-51;55 (5)	5.8±0.7	74.8	807	1388	8108±45	.0159±.0019
	119-58;62 (5)	5.7±0.6	75.0	732	1281	7329±45	.0161±.0017
	119-65;69 (5)	5.4±0.7	75.2	673	1244	6720±45	.0157±.0020
	119-72;76 (5)	5.2±0.8	75.3	600	1141	5966±44	.0158±.0022
	119-79;83 (5)	5.2±0.7	75.1	543	1042	5375±44	.0161±.0020
	119-86;90 (5)	5.0±0.6	75.2	486	946	4785±44	.0164±.0019
	119-93;97 (5)	4.8±0.5	75.1	427	870	4176±44	.0163±.0017
	119-100;120-4 (5)	4.6±0.6	75.2	384	820	3732±44	.0160±.0019
	120-7;11 (5)	4.4±0.5	75.2	339	743	3263±44	.0162±.0018
	120-14;18 (5)	4.2±0.6	75.0	288	657	2738±44	.0163±.0023
	120-21;25 (5)	3.9±0.6	74.9	249	598	2337±44	.0160±.0024
	120-28;32 (5)	3.6±0.6	75.0	207	525	1903±43	.0160±.0024

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²·°C	heatflux W/m²	Csf
Inc/Dec Htflx Teflon-15% Level-40IM T4085C DATA121 to DATA123, Dec 30 1989	121-1;5 {5}	3.1±0.6	85.1	212	612	1915±47	.0152±.0029
	121-8;12 {5}	3.4±0.6	85.1	250	671	2307±47	.0157±.0027
	121-15;19 {5}	3.7±0.5	84.8	288	726	2702±47	.0161±.0022
	121-22;26 {5}	4.0±0.6	84.7	332	789	3157±47	.0164±.0023
	121-29;33 {5}	4.2±0.5	84.8	385	884	3703±46	.0163±.0018
	121-36;40 {5}	4.3±0.6	84.9	428	974	4149±47	.0160±.0020
	121-43;47 {5}	4.4±0.6	84.8	484	1075	4729±47	.0158±.0022
	121-50;54 {5}	4.6±0.6	84.9	543	1163	5338±48	.0159±.0020
	121-57;61 {5}	4.7±0.6	85.2	603	1259	5957±48	.0158±.0018
	121-64;68 {5}	4.8±0.6	85.0	674	1386	6694±48	.0155±.0019
	121-71;75 {5}	5.0±0.6	85.1	740	1470	7377±48	.0156±.0017
	121-78;82 {5}	5.1±0.7	85.1	808	1594	8080±48	.0153±.0020
	121-85;89 {5}	5.2±0.6	85.0	884	1721	8865±48	.0151±.0017
	121-92;96 {5}	5.2±0.6	85.0	961	1851	9664±48	.0149±.0017
	121-99;122-3 {5}	5.4±0.6	85.3	1045	1969	10532±48	.0149±.0016
	122-6;10 {5}	5.5±0.6	85.4	1130	2060	11410±49	.0150±.0016
	122-13;17 {5}	5.5±0.6	85.4	1172	2150	11844±49	.0147±.0014
	122-20;24 {5}	5.5±0.6	85.1	1116	2052	11267±49	.0149±.0015
	122-27;31 {5}	5.3±0.6	85.1	1041	1965	10492±48	.0148±.0017
	122-34;38 {5}	5.3±0.5	84.8	960	1835	9654±48	.0150±.0015
	122-41;45 {5}	5.1±0.6	84.8	881	1719	8837±48	.0150±.0016
	122-48;52 {5}	5.1±0.6	84.9	809	1596	8092±48	.0153±.0016
	122-55;59 {5}	4.9±0.6	84.6	735	1480	7328±48	.0154±.0017
	122-62;66 {5}	4.8±0.6	84.7	660	1371	6551±48	.0154±.0018
	122-69;73 {5}	4.7±0.6	84.9	512	1302	6054±48	.0154±.0019
	122-76;80 {5}	4.5±0.6	84.9	540	1188	5310±47	.0155±.0021
	122-83;87 {5}	4.3±0.6	84.9	424	1095	4731±47	.0155±.0020
	122-90;94 {5}	4.2±0.6	84.6	435	1011	4224±47	.0156±.0020
	122-97;123-1 {5}	4.0±0.5	84.8	385	920	3706±47	.0157±.0021
	123-4;8 {5}	3.8±0.5	84.7	333	836	3170±47	.0156±.0020
	123-11;15 {5}	3.6±0.5	85.0	289	750	2715±47	.0157±.0021

Increasing/Decreasing Heatflux Test Record

Test	Data Points	T _{wo-4} °C	T ₄ °C	Power W	h _{boil} W/m ² ·°C	heatflux W/m ²	Csf
Inc/Dec Htflx Teflon-15% Level-44IN T4005C DATA124 to DATA126, Jan 1 1989	124-1;5 {5}	3.3±0.5	85.1	250	729	2391±47	.0140±.0023
	124-8;11 {4}	3.4±0.5	85.1	289	799	2710±47	.0147±.0019
	124-14;18 {5}	3.6±0.5	85.2	334	880	3176±47	.0149±.0021
	124-24;29 {6}	3.7±0.6	85.0	379	981	3641±47	.0146±.0021
	124-32;36 {5}	3.9±0.6	84.9	426	1058	4128±47	.0147±.0020
	124-39;43 {5}	4.1±0.5	84.7	487	1158	4760±48	.0147±.0017
	124-46;50 {5}	4.3±0.6	84.8	544	1250	5349±48	.0148±.0019
	124-53;57 {5}	4.4±0.5	85.0	603	1351	5959±48	.0147±.0017
	124-60;125-4 {5}	4.5±0.6	85.1	663	1452	6577±48	.0147±.0019
	125-7;11 {5}	4.5±0.8	85.1	729	1600	7262±48	.0142±.0023
	125-14;18 {5}	4.7±0.7	85.2	803	1712	8028±48	.0142±.0019
	125-21;25 {5}	4.8±0.5	85.4	880	1831	8824±48	.0142±.0016
	125-28;32 {5}	5.0±0.5	85.2	951	1900	9559±48	.0144±.0014
	125-35;39 {5}	5.1±0.6	85.6	1028	2022	10354±49	.0143±.0015
	125-42;46 {5}	5.3±0.7	85.3	1120	2125	11305±49	.0144±.0019
	125-49;53 {5}	5.5±1.0	85.0	1174	2157	11866±49	.0146±.0025
	125-56;60 {5}	5.5±0.5	85.3	1134	2086	11452±49	.0148±.0014
	126-3;7 {5}	5.3±0.6	85.0	1031	1949	10386±49	.0148±.0016
	126-10;14 {5}	5.1±0.8	84.8	958	1870	9632±48	.0146±.0022
	126-17;21 {5}	5.1±0.5	84.6	883	1754	8857±48	.0147±.0014
	126-24;28 {5}	4.9±0.6	84.6	811	1656	8112±48	.0147±.0017
	126-31;35 {5}	4.8±0.6	84.6	738	1533	7358±48	.0149±.0016
	126-38;42 {5}	4.7±0.6	84.6	666	1410	6611±48	.0151±.0018
	126-45;49 {5}	4.5±0.6	84.7	603	1316	5960±48	.0151±.0018
	126-52;56 {5}	4.4±0.6	84.6	534	1201	5247±48	.0151±.0019
	126-59;63 {5}	4.2±0.8	84.5	480	1122	4688±47	.0151±.0026
	126-66;70 {5}	4.1±0.6	84.5	436	1043	4233±47	.0151±.0022
	126-73;77 {5}	3.9±0.6	84.5	375	926	3602±47	.0153±.0024
	126-80;84 {5}	3.7±0.6	84.5	334	871	3180±47	.0149±.0022
	126-87;91 {5}	3.4±0.7	84.5	285	774	2672±47	.0149±.0030
	126-94;100 {7}	3.2±0.7	84.3	241	682	2218±47	.0149±.0032

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²°C	heatflux W/m²	Csf
Inc/Dec Htflx Teflon-15% Level-48IN T4@85C DATA127 to DATA129, Jan 2 1989	127-1;5 {5}	3.4±0.7	84.7	208	551	1872±47	.0166±.0032
	127-8;12 {5}	3.7±0.5	84.8	250	619	2302±48	.0170±.0022
	127-15;19 {5}	3.8±0.5	84.8	283	698	2647±47	.0165±.0019
	127-22;26 {5}	4.1±0.6	84.8	340	790	3237±48	.0167±.0023
	127-29;33 {5}	4.3±0.5	84.7	378	840	3629±48	.0170±.0018
	127-36;40 {5}	4.5±0.6	84.5	428	921	4143±48	.0169±.0021
	127-43;47 {5}	4.7±0.5	84.5	486	1012	4747±48	.0168±.0019
	127-50;54 {5}	4.8±0.6	84.9	543	1114	5337±48	.0166±.0019
	127-57;61 {5}	4.9±0.6	85.0	611	1232	6036±48	.0163±.0020
	127-64;68 {5}	5.0±0.6	84.9	671	1332	6658±48	.0161±.0018
	127-71;75 {5}	5.0±0.6	85.0	729	1441	7261±48	.0158±.0017
	127-78;82 {5}	5.2±0.7	85.1	810	1548	8097±48	.0158±.0019
	127-85;89 {5}	5.3±0.6	85.3	879	1662	8808±49	.0156±.0017
	127-92;96 {5}	5.5±0.6	85.3	959	1762	9638±49	.0156±.0016
	127-99;128-3 {5}	5.5±0.6	85.4	1043	1911	10509±49	.0153±.0016
	128-6;10 {5}	5.8±0.6	85.3	1133	1989	11439±49	.0155±.0016
	128-13;17 {5}	5.9±0.7	85.3	1174	2007	11863±49	.0158±.0017
	128-20;24 {5}	5.7±0.6	85.3	1108	1965	11181±49	.0155±.0016
	128-27;31 {5}	5.6±0.6	85.2	1031	1838	10387±49	.0157±.0015
	128-34;38 {5}	5.5±0.6	85.1	958	1748	9630±49	.0157±.0017
	128-41;45 {5}	5.4±0.5	85.1	871	1610	8728±49	.0160±.0015
	128-48;52 {5}	5.3±0.6	85.1	809	1535	8090±48	.0159±.0018
	128-55;59 {5}	5.1±0.6	85.0	736	1430	7335±48	.0160±.0017
	128-62;66 {5}	5.0±0.6	85.0	666	1319	6609±48	.0162±.0019
	128-69;73 {5}	4.8±0.6	85.0	602	1231	5947±48	.0162±.0019
	128-76;80 {5}	4.7±0.6	84.7	533	1117	5238±47	.0163±.0021
	128-83;87 {5}	4.5±0.5	84.6	484	1042	4729±47	.0163±.0019
	128-90;94 {5}	4.4±0.7	84.8	436	970	4229±48	.0163±.0023
	128-97;129-1 {5}	4.1±0.6	84.8	376	872	3609±48	.0162±.0021
	129-4;8 {5}	3.9±0.6	85.2	338	821	3218±47	.0161±.0022
	129-11;15 {5}	3.8±0.5	84.8	288	714	2700±47	.0164±.0020
	129-18;22 {5}	3.5±0.5	84.9	243	640	2234±47	.0161±.0023
	129-25;29 {5}	3.3±0.5	85.0	207	571	1863±47	.0160±.0025

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m ² °C	heatflux W/m ²	Csf
Inc/Dec Hfx Instrumented Level-40IN T4@75C DATA193 to DATA194, Feb 16 1989	193-1;5 {5}	4.5±0.7	74.8	264	546	2477±45	.0103±.0027
	193-8;12 {5}	4.2±0.8	75.6	310	702	2950±45	.0161±.0031
	193-16;20 {5}	4.2±1.0	74.7	354	814	3410±45	.0151±.0034
	193-23;27 {5}	4.2±0.9	74.8	401	923	3896±45	.0146±.0028
	193-30;34 {5}	4.1±0.9	74.7	449	1079	4393±45	.0135±.0027
	193-37;41 {5}	4.1±0.9	74.8	510	1232	5025±45	.0130±.0027
	193-44;48 {5}	4.2±0.9	75.1	559	1316	5528±46	.0130±.0026
	193-51;55 {5}	4.1±0.8	75.7	627	1501	6230±46	.0124±.0022
	193-58;62 {5}	4.3±0.8	75.3	690	1597	6883±46	.0124±.0022
	193-65;69 {5}	4.6±0.7	75.2	755	1635	7554±46	.0129±.0019
	193-72;76 {5}	4.7±0.7	75.3	818	1757	8204±47	.0127±.0018
	193-79;83 {5}	4.9±0.7	75.4	906	1875	9114±47	.0128±.0018
	193-86;90 {5}	5.0±0.7	75.3	979	1963	9872±46	.0129±.0018
	193-93;97 {5}	5.1±0.7	75.1	1063	2090	10742±46	.0128±.0017
	193-100;194-4 {5}	5.0±0.6	75.6	1128	2301	11414±46	.0121±.0014
	194-7;11 {5}	5.0±0.6	75.5	1047	2118	10569±48	.0125±.0016
	194-14;18 {5}	4.9±0.7	75.1	966	1980	9741±46	.0126±.0017
	194-21;25 {5}	4.8±0.7	75.1	895	1892	9007±46	.0125±.0017
	194-28;32 {5}	4.7±0.7	75.1	823	1769	8262±46	.0126±.0019
	194-35;39 {5}	4.5±0.7	74.9	754	1685	7550±45	.0125±.0019
	194-42;46 {5}	4.5±0.8	75.0	688	1529	6867±45	.0129±.0023
	194-49;53 {5}	4.4±0.8	74.8	625	1403	6217±45	.0132±.0022
	194-56;60 {5}	4.3±0.8	74.9	566	1319	5607±45	.0131±.0023
	194-63;67 {5}	4.3±0.8	74.8	507	1159	4996±45	.0138±.0024
	194-70;74 {5}	4.3±0.9	75.1	452	1034	4426±45	.0142±.0027
	194-77;81 {5}	4.3±0.9	74.7	402	901	3910±45	.0150±.0030
	194-84;88 {5}	4.2±0.9	75.0	354	803	3413±45	.0154±.0033
	194-94;100 {7}	4.3±1.0	74.2	303	668	2887±44	.0164±.0036

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²°C	heatflux W/m²	Csf
Inc/Dec Nix Instrumented Level-40IM T4005C DATA195 to DATA196, Feb 16 1989	195-3;6 {4}	3.2±0.7	84.5	313	925	2951±48	.0134±.0030
	195-9;13 {5}	3.3±0.8	84.9	354	1019	3372±48	.0133±.0031
	195-16;20 {5}	3.3±0.7	85.0	402	1169	3868±49	.0127±.0026
	195-23;27 {5}	3.2±0.7	84.8	451	1347	4377±49	.0120±.0026
	195-30;34 {5}	3.5±0.6	85.3	507	1403	4954±49	.0126±.0020
	195-37;41 {5}	3.7±0.7	85.2	563	1483	5532±49	.0128±.0023
	195-44;48 {5}	4.0±0.7	85.0	628	1539	6202±50	.0133±.0023
	195-51;55 {5}	4.5±0.7	85.2	685	1526	6791±50	.0143±.0020
	195-61;64 {4}	4.9±0.7	85.8	757	1543	7528±50	.0152±.0022
	195-67;71 {5}	5.2±0.7	85.1	827	1590	8254±50	.0156±.0019
	195-74;78 {5}	5.3±0.9	85.4	899	1694	8997±51	.0155±.0025
	195-81;85 {5}	5.5±0.7	84.9	972	1761	9755±51	.0157±.0019
	195-88;92 {5}	5.7±0.7	85.2	1060	1874	10663±51	.0157±.0019
	195-95;99 {5}	5.8±0.7	85.1	1123	1951	11315±51	.0157±.0019
	196-2;6 {5}	5.8±0.7	84.8	1058	1848	10643±51	.0159±.0018
	196-9;13 {5}	5.5±0.7	84.8	972	1761	9754±51	.0157±.0018
	196-16;20 {5}	5.4±0.7	84.5	889	1657	8897±50	.0156±.0019
	196-23;27 {5}	5.2±0.8	84.6	825	1584	8236±50	.0155±.0022
	196-30;34 {5}	5.0±0.8	85.2	752	1490	7479±50	.0156±.0023
	196-37;41 {5}	4.7±0.7	85.2	684	1442	6777±50	.0151±.0022
	196-44;48 {5}	4.1±0.7	84.9	622	1487	6140±49	.0136±.0023
	196-51;55 {5}	4.0±0.8	85.3	571	1396	5612±49	.0137±.0026
	196-58;62 {5}	3.8±0.8	85.3	507	1320	4951±49	.0134±.0026
	196-65;69 {5}	3.5±0.7	85.0	452	1235	4384±49	.0131±.0026
	196-72;76 {5}	3.5±0.8	84.4	402	1105	3869±48	.0134±.0030
	196-79;83 {5}	3.6±0.8	85.0	351	938	3338±49	.0144±.0031
	196-86;90 {5}	3.4±0.8	85.2	304	827	2852±49	.0147±.0034
	196-95;100 {6}	3.5±0.9	85.3	266	710	2458±49	.0155±.0037

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m ² °C	heatflux W/m ²	Csf
Inc/Dec Hfx Instrumented Level-44IN T4@75C DATA197 to DATA198, Feb 17 1989	197-1;5 {5}	4.1±1.0	75.0	268	608	2512±46	.0166±.0037
	197-8;12 {5}	4.5±1.0	75.1	307	641	2897±51	.0173±.0036
	197-15;19 {5}	4.5±0.8	75.0	354	747	3392±47	.0165±.0026
	197-22;26 {5}	4.6±0.8	74.8	395	829	3820±46	.0161±.0026
	197-29;33 {5}	4.5±0.8	75.5	455	993	4439±47	.0149±.0027
	197-36;40 {5}	4.5±0.7	75.7	508	1121	4987±47	.0144±.0021
	197-43;47 {5}	4.7±0.8	75.3	565	1184	5578±47	.0146±.0023
	197-50;54 {5}	4.9±0.7	75.4	624	1250	6188±47	.0148±.0019
	197-57;61 {5}	5.3±0.7	75.5	686	1281	6826±47	.0155±.0020
	197-64;68 {5}	5.6±0.7	75.4	750	1329	7489±47	.0157±.0020
	197-71;75 {5}	5.9±0.7	75.5	829	1407	8304±48	.0160±.0019
	197-78;82 {5}	5.9±0.7	75.3	892	1526	8958±47	.0155±.0019
	197-85;89 {5}	5.8±0.6	75.6	976	1685	9825±48	.0158±.0015
	197-92;96 {5}	5.9±0.6	75.8	1068	1833	10777±48	.0147±.0015
	197-99;198-3 {5}	6.1±0.6	75.5	1130	1878	11418±48	.0149±.0014
	198-6;10 {5}	5.9±0.6	75.5	1060	1803	10695±48	.0148±.0015
	198-13;16 {4}	5.9±0.6	75.5	976	1677	9826±48	.0151±.0016
	198-20;24 {5}	6.1±0.7	75.4	901	1481	9050±48	.0161±.0017
	198-27;31 {5}	5.9±1.1	75.0	820	1390	8215±47	.0160±.0029
	198-34;38 {5}	5.5±0.8	74.6	750	1353	7494±47	.0154±.0021
	198-41;45 {5}	5.2±0.9	74.6	684	1313	6812±47	.0149±.0024
	198-48;52 {5}	5.0±0.8	74.6	622	1237	6174±46	.0148±.0022
	198-55;59 {5}	4.8±0.9	74.7	563	1171	5564±46	.0146±.0027
	198-62;66 {5}	4.5±0.9	74.5	505	1094	4966±46	.0145±.0028
	198-69;73 {5}	4.3±0.8	75.3	453	1039	4427±46	.0142±.0025
	198-76;80 {5}	4.1±0.8	75.3	404	949	3920±46	.0144±.0026
	198-83;87 {5}	4.0±0.8	75.3	351	844	3374±45	.0146±.0029
	198-90;94 {5}	3.9±0.8	75.2	311	759	2959±45	.0149±.0030
	198-97;100 {4}	3.9±0.8	74.9	268	646	2518±45	.0156±.0033

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²·°C	heatflux W/m²	Csf
Inc/Dec Hfx Instrumented Level-44IN T4085C DATA199 to DATA200, Feb 17 1989	199-1;5 {5}	3.1±0.7	85.2	269	808	2490±49	.0138±.0030
	199-8;12 {5}	3.2±0.8	85.0	306	904	2874±48	.0135±.0033
	199-15;19 {5}	3.2±0.6	85.3	357	1050	3401±49	.0131±.0025
	199-22;26 {5}	3.5±0.7	84.8	403	1108	3878±49	.0134±.0026
	199-29;33 {5}	3.8±0.6	84.5	453	1157	4395±49	.0140±.0022
	199-36;40 {5}	4.0±0.6	85.0	505	1245	4929±49	.0141±.0021
	199-43;47 {5}	4.4±0.7	84.7	562	1246	5518±49	.0151±.0022
	199-50;54 {5}	5.0±0.8	84.5	618	1224	6096±50	.0164±.0024
	199-57;61 {5}	5.4±0.7	85.1	694	1265	6880±50	.0174±.0020
	199-64;68 {5}	5.5±0.6	85.2	756	1375	7522±50	.0169±.0019
	199-71;75 {5}	5.6±0.6	85.4	826	1462	8244±50	.0170±.0018
	199-78;82 {5}	5.8±0.6	85.5	900	1567	9008±51	.0168±.0018
	199-85;89 {5}	6.0±0.7	85.6	976	1634	9790±51	.0171±.0018
	199-92;96 {5}	6.1±0.6	85.5	1057	1745	10626±52	.0169±.0017
	199-99;200-3 {5}	6.3±0.7	85.4	1120	1805	11279±51	.0170±.0018
	200-6;10 {5}	6.1±0.8	85.6	1059	1740	10648±51	.0170±.0023
	200-13;16 {4}	6.0±0.7	85.5	983	1644	9864±51	.0170±.0020
	200-20;24 {5}	5.8±1.1	84.7	888	1524	8886±50	.0170±.0030
	200-27;31 {5}	5.7±0.7	84.6	826	1449	8245±50	.0170±.0019
	200-34;38 {5}	5.5±0.9	84.8	757	1374	7532±50	.0169±.0027
	200-41;45 {5}	5.1±0.7	85.1	683	1337	6766±50	.0162±.0023
	200-48;52 {5}	4.7±0.7	84.9	620	1312	6116±50	.0154±.0023
	200-55;59 {5}	4.3±0.8	84.6	562	1280	5518±49	.0147±.0028
	200-62;66 {5}	4.0±0.6	84.3	500	1226	4879±49	.0141±.0021
	200-69;73 {5}	3.8±0.6	84.5	452	1150	4381±49	.0140±.0021
	200-76;80 {5}	3.6±0.6	84.9	403	1076	3874±49	.0139±.0022
	200-83;87 {5}	3.4±0.6	84.9	350	987	3326±49	.0136±.0022
	200-90;94 {5}	3.2±0.6	84.8	300	878	2810±49	.0137±.0025
	200-97;100 {5}	3.1±0.8	85.1	264	789	2436±49	.0139±.0034

Increasing/Decreasing Heatflux Test Record

Test	Data Points	T _{wo-4} °C	T ₄ °C	Power W	h _{boil} W/m ² °C	heatflux W/m ²	Csf
Inc/Dec Hfx Instrumented Level-401W T4075C DATA201 to DATA202, Feb 18 1989	201-1;5 (5)	4.8±0.9	74.9	267	525	2503±45	.0192±.0034
	201-8;12 (5)	5.0±0.7	75.1	306	581	2904±46	.0191±.0027
	201-15;19 (5)	5.3±0.7	75.1	349	638	3349±46	.0192±.0025
	201-22;26 (5)	5.4±0.6	75.3	403	724	3907±46	.0188±.0021
	201-29;33 (5)	5.4±0.7	75.3	452	811	4414±46	.0182±.0024
	201-36;40 (5)	5.7±0.8	74.9	504	876	4952±46	.0181±.0024
	201-43;47 (5)	5.9±0.8	74.9	559	934	5520±46	.0183±.0022
	201-50;54 (5)	6.3±0.7	75.1	624	984	6192±46	.0187±.0021
	201-57;61 (5)	6.6±0.8	75.1	692	1040	6897±46	.0191±.0022
	201-64;68 (5)	6.9±0.8	75.4	747	1076	7466±46	.0195±.0021
	201-71;75 (5)	7.4±0.8	75.4	831	1131	8334±47	.0200±.0020
	201-78;82 (5)	7.5±0.8	75.5	907	1211	9118±47	.0199±.0021
	201-85;89 (5)	7.7±0.7	76.1	980	1279	9871±47	.0199±.0018
	201-92;96 (5)	7.4±1.0	75.8	1055	1443	10650±47	.0185±.0023
	201-99;202-3 (5)	7.0±0.6	75.4	1119	1623	11314±47	.0171±.0015
	202-6;10 (5)	7.0±0.7	75.5	1056	1521	10663±47	.0175±.0016
	202-13;17 (5)	7.7±0.7	75.1	968	1262	9752±47	.0198±.0018
	202-20;23 (4)	7.6±0.8	74.6	883	1166	8876±46	.0200±.0020
	202-26;30 (5)	7.3±0.7	74.7	815	1124	8173±46	.0197±.0019
	202-33;37 (5)	6.8±0.7	74.7	754	1101	7544±46	.0190±.0020
	202-40;44 (5)	6.2±0.8	74.9	693	1108	6914±46	.0179±.0022
	202-47;51 (5)	5.7±0.8	74.8	620	1073	6158±46	.0171±.0024
	202-54;58 (5)	5.5±0.9	74.6	562	1017	5564±45	.0168±.0026
	202-61;65 (5)	5.3±0.9	74.8	506	941	4986±45	.0169±.0028
	202-68;72 (5)	5.1±0.9	75.0	453	868	4438±45	.0170±.0028
	202-75;79 (5)	4.9±0.8	74.8	394	777	3830±44	.0171±.0027
	202-82;86 (5)	4.8±0.8	74.5	352	712	3395±44	.0173±.0029
	202-89;93 (5)	4.7±0.9	74.5	307	625	2932±44	.0178±.0035
	202-96;100 (5)	4.6±1.0	74.9	269	547	2537±44	.0185±.0039

Increasing/Decreasing Heatflux Test Record

Test	Data Points	Two-4 °C	T4 °C	Power W	hboil W/m²·°C	heatflux W/m²	Csf
Inc/Dec Hfx Instrumented Level-40IW T4005C DATA203 to DATA204, Feb 18 1989	203-1;5 {5}	3.6±0.8	85.7	268	681	2486±48	.0164±.0033
	203-8;12 {5}	3.7±0.8	85.4	314	803	2962±48	.0156±.0032
	203-15;19 {5}	3.9±0.7	85.6	351	853	3344±48	.0159±.0027
	203-22;26 {5}	4.2±0.9	84.9	403	934	3884±48	.0160±.0033
	203-29;33 {5}	4.4±0.7	84.9	454	993	4411±48	.0164±.0025
	203-36;40 {5}	4.7±0.7	85.3	507	1061	4957±48	.0166±.0024
	203-43;47 {5}	5.2±0.7	85.2	563	1058	5535±49	.0179±.0023
	203-50;54 {5}	5.8±0.8	85.1	620	1063	6122±49	.0191±.0024
	203-57;61 {5}	6.1±0.7	85.1	692	1128	6867±49	.0194±.0020
	203-64;68 {5}	5.9±0.8	85.0	747	1260	7435±49	.0183±.0023
	203-71;75 {5}	6.1±0.7	85.1	824	1340	8229±50	.0185±.0020
	203-78;82 {5}	6.4±0.7	84.8	901	1416	9025±50	.0186±.0020
	203-85;89 {5}	6.4±0.7	85.3	965	1520	9685±50	.0182±.0020
	203-92;96 {5}	6.5±0.7	85.3	1057	1629	10636±50	.0181±.0018
	203-99;204-3 {5}	6.7±0.8	85.3	1119	1693	11276±51	.0181±.0021
	204-6;10 {5}	6.5±0.8	85.6	1058	1633	10645±51	.0181±.0021
	204-13;17 {5}	6.5±0.8	85.2	977	1511	9808±50	.0184±.0021
	204-20;24 {5}	6.4±0.8	85.2	899	1408	9000±50	.0187±.0021
	204-27;31 {5}	6.3±0.8	84.8	818	1290	8165±50	.0190±.0024
	204-34;38 {5}	6.4±1.0	85.0	750	1175	7459±50	.0197±.0031
	204-41;45 {5}	6.0±0.8	85.1	687	1137	6809±50	.0192±.0024
	204-48;52 {5}	5.5±1.2	85.1	623	1116	6149±50	.0182±.0038
	204-55;59 {5}	4.9±0.6	85.6	564	1123	5538±49	.0169±.0022
	204-62;66 {5}	4.6±0.8	85.6	508	1071	4960±49	.0165±.0028
	204-69;73 {5}	4.4±0.7	85.1	453	1001	4394±49	.0162±.0024
	204-76;80 {5}	4.2±0.7	85.1	396	908	3806±49	.0162±.0026
	204-83;87 {5}	4.0±0.7	85.1	348	830	3310±48	.0162±.0026
	204-90;94 {5}	3.8±0.7	85.1	302	747	2833±48	.0162±.0028
	204-97;100 {4}	3.7±0.7	85.3	266	671	2462±48	.0165±.0028

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	T ₂₀ -4 °C	T ₅ -4 °C	T ₆ -4 °C	
500W Instrumented Level-48IN T4057C	DATA130	7.5	8.9	6.7	4942
500W Instrumented Level-48IN T4060C	DATA131	6.9	8.1	5.8	4955
500W Instrumented Level-48IN T4080C	DATA132	4.4	5.5	3.5	4911*
500W Instrumented Level-48IN T4060C	DATA133	7.6	8.7	6.3	5019
500W Instrumented Level-48IN T4080C	DATA134	4.4	5.3	3.4	4882
500W Instrumented Level-48IN T40100C	DATA135	5.3	3.9	2.5	4817
500W Instrumented Level-48IN T40100C	DATA136	5.9	4.1	2.8	4816
500W Instrumented Level-48IN T4060C	DATA137	7.6	8.6	6.7	4952
500W Instrumented Level-48IN T4080C	DATA138	4.6	5.6	3.9	4970
500W Instrumented Level-48IN T40100C	DATA139	3.4	4.2	2.8	4853
700W Instrumented Level-48IN T4060C	DATA140	7.1	8.8	6.5	7084
700W Instrumented Level-48IN T4080C	DATA141	5.0	6.5	4.2	6598
700W Instrumented Level-48IN T40100C	DATA142	4.0	4.5	2.9	6882
700W Instrumented Level-48IN T40100C	DATA143	5.8	4.5	2.9	6865
900W Instrumented Level-48IN T4060C	DATA144	7.5	9.7	6.8	9160
900W Instrumented Level-48IN T4080C	DATA145	5.4	7.5	4.5	9069
900W Instrumented Level-48IN T40100C	DATA146	3.5	4.7	3.1	8995
1100W Instrumented Level-48IN T4060C	DATA147	7.9	10.7	6.8	11170
1100W Instrumented Level-48IN T4080C	DATA148	6.5	7.7	3.8	11047
1100W Instrumented Level-48IN T4080C	DATA149	6.5	7.9	3.3	10986
1100W Instrumented Level-48IN T40100C	DATA150	4.1	5.1	3.0	11129
Inc/Dec Hflx Instrumented Level-48IN T4075C	DATA151-152 Various but system failed				unreliable data
500W Instrumented Level-48IN T4060C	DATA153	8.1	9.1	5.8	5034
Inc/Dec Hflx Instrumented Level-48IN T4075C	DATA154-155 Various results but unreliable data				
500W Instrumented Level-48IN T4060C	DATA156	7.4	8.3	6.7	4993
500W Instrumented Level-48IN T4080C	DATA157	4.7	5.7	3.9	4931
500W Instrumented Level-48IN T40100C	DATA158	3.5	4.4	2.7	4817
700W Instrumented Level-48IN T4060C	DATA159	7.4	9.2	6.2	7070
700W Instrumented Level-48IN T4080C	DATA160	4.7	6.3	4.1	6989
700W Instrumented Level-48IN T40100C	DATA161	3.6	4.8	2.8	6903
900W Instrumented Level-48IN T4060C	DATA162	7.5	9.7	6.6	9136
900W Instrumented Level-48IN T4080C	DATA163	5.4	7.4	4.6	9125
900W Instrumented Level-48IN T40100C	DATA164	3.9	5.2	2.6	8974
1100W Instrumented Level-48IN T4060C	DATA165	8.3	10.7	6.2	11231
1100W Instrumented Level-48IN T4080C	DATA166	5.9	8.3	4.1	11089
1100W Instrumented Level-48IN T40100C	DATA167	3.8	5.4	2.9	11017

Note: * these terms were taken with thermocouple adjustments that were the most accurate to the true temperatures, but all other temperatures listed were recorded with the original adjustments.

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	T6-4 °C	T5-4 °C	T6-4 °C	
500W Instrumented Level-44IN T4060C	DATA168	6.3	7.4	5.6	4980
500W Instrumented Level-44IN T4080C	DATA169	1.9	5.8	3.5	4976
500W Instrumented Level-44IN T40100C	DATA170	3.3	4.3	2.4	4889
700W Instrumented Level-44IN T4060C	DATA171	7.1	8.6	5.1	7111
700W Instrumented Level-44IN T4080C	DATA172	5.5	7.7	2.9	7025
700W Instrumented Level-44IN T40100C	DATA173	3.7	5.1	2.6	6960
900W Instrumented Level-44IN T4060C	DATA174	8.3	10.7	4.5	9119
900W Instrumented Level-44IN T4080C	DATA175	8.5	10.5	4.7	9098
900W Instrumented Level-44IN T4080C	DATA176	6.0	7.3	2.6	9007
900W Instrumented Level-44IN T40100C	DATA177	3.6	4.5	1.4	9022
1100W Instrumented Level-44IN T4060C	DATA178	7.6	10.6	5.3	11207
1100W Instrumented Level-44IN T4080C	DATA179	5.5	8.1	3.7	11119
1100W Instrumented Level-44IN T40100C	DATA180	3.6	4.8	2.7	11025
500W Instrumented Level-40IN T4060C	DATA181	6.4	7.4	1.1	4984
500W Instrumented Level-40IN T4080C	DATA182	4.0	4.9	1.5	4911
500W Instrumented Level-40IN T40100C	DATA183	3.2	3.7	1.3	4849
700W Instrumented Level-40IN T4060C	DATA184	5.9	7.6	2.2	7079
700W Instrumented Level-40IN T4080C	DATA185	5.3	6.9	1.8	7002
700W Instrumented Level-40IN T40100C	DATA186	3.5	4.0	1.7	6920
900W Instrumented Level-40IN T4060C	DATA187	6.2	8.5	2.6	9136
900W Instrumented Level-40IN T4080C	DATA188	5.9	7.9	2.4	9039
900W Instrumented Level-40IN T40100C	DATA189	3.7	4.3	2.0	8956
1100W Instrumented Level-40IN T4060C	DATA190	6.5	9.4	3.5	11268
1100W Instrumented Level-40IN T4080C	DATA191	5.6	8.1	2.9	11175
1100W Instrumented Level-40IN T40100C	DATA192	4.5	5.1	2.2	11083
Inc/Dec Hfx Instrumented Level-40IN T4075C	DATA193-194 Various results - see page B28				
Inc/Dec Hfx Instrumented Level-40IN T4085C	DATA195-196 Various results - see page B29				
Inc/Dec Hfx Instrumented Level-44IN T4075C	DATA197-198 Various results - see page B30				
Inc/Dec Hfx Instrumented Level-44IN T4085C	DATA199-200 Various results - see page B31				
Inc/Dec Hfx Instrumented Level-48IN T4075C	DATA201-202 Various results - see page B32				
Inc/Dec Hfx Instrumented Level-48IN T4085C	DATA203-204 Various results - see page B33				

The following occurred on 18Feb89:

500W Instrumented Level-48IN T4080C	DATA205	4.9	6.0	3.9	4984
500W Instrumented Level-48IN T4080C(100smpl)	DATA206	4.9	6.1	4.0	4984
700W Instrumented Level-48IN T4080C	DATA207	6.1	7.4	4.2	6933
700W Instrumented Level-48IN T4080C(100smpl)	DATA208	6.0	7.3	4.1	6922
900W Instrumented Level-48IN T4080C	DATA209	7.4	9.1	4.1	8995
900W Instrumented Level-48IN T4080C(100smpl)	DATA210	7.3	9.1	4.0	8984
1100W Instrumented Level-48IN T4080C	DATA211	7.3	7.8	3.9	11153
1100W Instrumented Level-48IN T4080(100smpl)	DATA212	7.4	8.3	3.9	11134

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	Two-4 °C	T5-4 °C	T6-4 °C	
Inc/Dec Hfx Instrumented Level-40IN T4@75C	193-1:5 {5}	4.5	4.9	4.1	2477
	193-8;12 {5}	4.2	4.7	3.5	2950
DATA193 to DATA194, Feb 16 1989	193-17;20 {4}	4.2	4.9	2.8	3410
	193-23;27 {5}	4.2	4.9	2.8	3896
	193-30;34 {5}	4.1	5.0	2.4	4393
	193-37;41 {5}	4.1	5.1	1.3	5025
	193-44;48 {5}	4.2	5.4	1.5	5528
	193-51;55 {5}	4.1	5.5	1.5	6230
	193-58;62 {5}	4.3	5.8	1.7	6883
	193-65;69 {5}	4.6	6.3	2.0	7554
	193-72;76 {5}	4.7	6.5	2.1	8204
	193-79;83 {5}	4.9	7.0	2.3	9114
	193-86;90 {5}	5.0	7.4	2.4	9872
	193-93;97 {5}	5.1	7.6	2.6	10742
	193-100;194-4 {5}	5.0	7.0	2.7	11414
	194-7;11 {5}	5.0	7.3	2.6	10569
	194-14;18 {5}	4.9	7.1	2.5	9741
	194-21;25 {5}	4.8	6.8	2.3	9007
	194-28;32 {5}	4.7	6.5	2.1	8262
	194-35;39 {5}	4.5	6.2	1.9	7550
	194-42;46 {5}	4.5	5.9	1.7	6867
	194-49;53 {5}	4.4	5.8	1.7	6217
	194-56;60 {5}	4.3	5.5	1.2	5607
	194-63;67 {5}	4.3	5.3	1.4	4996
	194-70;74 {5}	4.3	5.1	2.1	4426
	194-77;81 {5}	4.3	5.1	2.6	3910
	194-84;88 {5}	4.2	4.9	2.7	3413
	194-94;100 {7}	4.3	4.8	3.5	2887

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	T ₂ -4 °C	T ₅ -4 °C	T ₆ -4 °C	
Inc/Dec Hfx Instrumented Level-401N T4085C	195-3;6 {4}	3.2	3.7	1.2	2951
	195-9;13 {5}	3.3	3.9	1.6	3372
DATA195 to DATA196, Feb 16 1989	195-16;20 {5}	3.3	4.0	1.3	3868
	195-23;27 {5}	3.2	4.1	1.3	4377
	195-30;34 {5}	3.5	4.5	1.7	4954
	195-37;41 {5}	3.7	4.5	1.8	5532
	195-44;48 {5}	4.0	4.9	1.8	6202
	195-51;55 {5}	4.5	5.3	1.9	6791
	195-61;64 {4}	4.9	5.7	2.0	7528
	195-67;71 {5}	5.2	5.9	1.9	8254
	195-74;78 {5}	5.3	5.8	1.9	8997
	195-81;85 {5}	5.5	6.2	2.0	9755
	195-88;92 {5}	5.7	6.1	2.1	10663
	195-95;99 {5}	5.8	6.1	2.2	11315
	196-2;6 {5}	5.8	6.3	2.1	10643
	196-9;13 {5}	5.5	6.2	1.9	9754
	196-16;20 {5}	5.4	6.2	1.9	8897
	196-23;27 {5}	5.2	6.2	2.1	8236
	196-30;34 {5}	5.0	6.2	1.9	7479
	196-37;41 {5}	4.7	5.9	2.0	6777
	196-44;48 {5}	4.1	5.2	1.7	6140
	196-51;55 {5}	4.0	4.9	1.7	5612
	196-58;62 {5}	3.8	4.8	1.5	4951
	196-65;69 {5}	3.5	4.4	1.2	4384
	196-72;76 {5}	3.5	4.3	1.3	3869
	196-79;83 {5}	3.5	4.2	1.6	3338
	196-86;90 {5}	3.4	4.0	2.0	2852
	196-95;100 {6}	3.5	3.9	2.8	2458

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	Two-4 °C	T5-4 °C	T6-4 °C	
Inc/Dec Mix Instrumented Level-44IW T4@75C	197-1;5 {5}	4.1	4.6	3.6	2512
	197-8;12 {5}	4.5	5.0	3.8	2897
DATA197 to DATA198, Feb 17 1989	197-15;19 {5}	4.5	5.2	3.5	3392
	197-22;26 {5}	4.6	5.4	3.6	3820
	197-29;23 {5}	4.5	5.3	3.4	4439
	197-36;40 {5}	4.5	4.5	3.3	4987
	197-43;47 {5}	4.7	6.0	3.4	5578
	197-50;54 {5}	4.9	6.2	3.4	6188
	197-57;61 {5}	5.3	6.5	3.5	6826
	197-64;68 {5}	5.6	7.0	3.7	7489
	197-71;75 {5}	5.9	7.3	3.8	8304
	197-78;82 {5}	5.9	7.5	3.9	8958
	197-85;89 {5}	5.8	7.7	3.6	9825
	197-92;96 {5}	5.9	8.4	3.7	10777
	197-99;198-3 {5}	6.1	8.5	3.7	11418
	198-6;10 {5}	5.9	8.3	3.7	10695
	198-13;16 {4}	5.9	7.8	3.8	9826
	198-20;24 {5}	6.1	7.8	3.6	9050
	198-27;31 {5}	5.9	7.4	3.7	8215
	198-34;38 {5}	5.5	6.9	3.7	7494
	198-41;45 {5}	5.2	6.5	3.7	6812
	198-48;52 {5}	5.0	6.3	3.7	6174
	198-55;59 {5}	4.8	5.9	3.7	5564
	198-62;66 {5}	4.5	5.7	3.4	4966
	198-69;73 {5}	4.3	5.2	3.6	4427
	198-76;80 {5}	4.1	5.0	3.5	3920
	198-83;87 {5}	4.0	4.7	3.6	3374
	198-90;94 {5}	3.9	4.4	3.6	2959
	198-97;100 {4}	3.9	4.4	3.8	2518

Test Title	Instrumented Section Record				heatflux W/m²
	Record#	Two-4 °C	T5-4 °C	T6-4 °C	
Inc/Dec Wfx Instrumented Level-44IN T4885C	199-1;5 {5}	3.1	3.5	2.9	2490
	199-8;12 {5}	3.2	3.8	3.1	2874
DATA199 to DATA200, Feb 17 1989	199-15;19 {5}	3.2	4.0	2.7	3401
	199-22;26 {5}	3.5	4.3	2.8	3878
	199-29;33 {5}	3.8	4.7	3.0	4395
	199-36;40 {5}	4.0	4.8	3.0	4929
	199-43;47 {5}	4.4	5.3	2.9	5518
	199-50;54 {5}	5.0	6.1	3.0	6096
	199-57;61 {5}	5.4	6.6	2.6	6880
	199-64;68 {5}	5.5	6.3	2.4	7522
	199-71;75 {5}	5.6	6.7	2.4	8244
	199-78;82 {5}	5.8	6.5	2.5	9008
	199-85;89 {5}	6.0	6.5	2.5	9790
	199-92;96 {5}	6.1	6.4	2.5	10626
	199-99;200-3 {5}	6.3	6.6	2.7	11279
	200-6;10 {5}	6.1	6.5	2.6	10648
	200-13;16 {4}	6.0	6.4	2.6	9964
	200-20;24 {5}	5.8	6.4	2.7	8886
	200-27;31 {5}	5.7	6.6	3.0	8245
	200-34;38 {5}	5.5	6.6	3.3	7532
	200-41;45 {5}	5.1	6.2	3.1	6766
	200-48;52 {5}	4.7	5.8	3.0	6116
	200-55;59 {5}	4.3	5.4	3.0	5518
	200-62;66 {5}	4.0	5.1	3.0	4879
	200-69;73 {5}	3.8	4.8	3.1	4381
	200-76;80 {5}	3.6	4.4	2.9	3874
	200-83;87 {5}	3.4	4.2	2.9	3326
	200-90;94 {5}	3.2	3.8	2.9	2810
	200-97;100 {5}	3.1	3.7	3.1	2436

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	T20-4 °C	T5-4 °C	T6-4 °C	
Inc/Dec Hfx Instrumented Level-48IN T4075C	201-1;5 {5}	4.8	5.2	4.3	2503
	201-8;12 {5}	5.0	5.5	4.7	2904
DATA201 to DATA202, Feb 18 1989	201-15;19 {5}	5.3	5.9	4.3	3349
	201-22;26 {5}	5.4	6.1	4.2	3907
	201-29;33 {5}	5.4	6.3	4.2	4414
	201-36;40 {5}	5.7	6.7	4.3	4952
	201-43;47 {5}	5.9	7.0	4.5	5520
	201-50;54 {5}	6.3	7.3	4.4	6192
	201-57;61 {5}	6.6	7.8	4.6	6897
	201-64;68 {5}	6.9	8.2	4.6	7466
	201-71;75 {5}	7.4	8.8	4.6	8334
	201-78;82 {5}	7.5	9.1	4.7	9118
	201-85;89 {5}	7.7	9.5	4.5	9871
	201-92;96 {5}	7.4	9.4	4.6	10650
	201-99;202-3 {5}	7.0	9.6	4.6	11314
	202-6;10 {5}	7.0	9.2	4.5	10663
	202-13;17 {5}	7.7	9.5	4.7	9752
	202-20;23 {5}	7.6	9.3	4.8	8876
	202-26;30 {5}	7.3	8.7	4.5	8173
	202-33;37 {5}	6.8	9.1	4.6	7544
	202-40;44 {5}	6.2	7.5	4.5	6914
	202-47;51 {5}	5.7	6.8	4.4	6158
	202-54;58 {5}	5.5	6.6	4.4	5564
	202-61;65 {5}	5.3	6.4	4.4	4986
	202-68;72 {5}	5.1	6.0	4.4	4438
	202-75;79 {5}	4.9	5.7	4.3	3830
	202-82;86 {5}	4.8	5.5	4.2	3395
	202-89;93 {5}	4.7	5.3	4.3	2932
	202-96;100 {5}	4.6	5.1	4.5	2537

Test Title	Instrumented Section Record				heatflux W/m ²
	Record#	T _{vo} -4 °C	T ₅ -4 °C	T ₆ -4 °C	
Inc/Dec Hfx Instrumented Level-401M T4005C	203-1;5 {5}	3.6	4.1	3.5	2486
	203-8;12 {5}	3.7	4.3	3.3	2962
DATA203 to DATA204, Feb 18 1989	203-15;19 {5}	3.9	4.7	3.4	3344
	203-22;26 {5}	4.2	5.0	3.5	3884
	203-29;33 {5}	4.4	5.4	3.5	4411
	203-36;40 {5}	4.7	5.5	3.6	4957
	203-43;47 {5}	5.2	6.2	3.7	5535
	203-50;54 {5}	5.8	6.9	3.6	6122
	203-57;61 {5}	6.1	7.6	3.2	6867
	203-64;68 {5}	5.9	6.8	3.1	7435
	203-71;75 {5}	6.1	7.2	3.2	8229
	203-78;82 {5}	6.4	7.3	3.3	9025
	203-85;89 {5}	6.4	7.1	3.2	9685
	203-92;96 {5}	6.5	7.1	3.2	10636
	203-99;204-3 {5}	6.7	7.2	3.4	11276
	204-6;10 {5}	6.5	7.1	3.2	10645
	204-13;17 {5}	6.5	7.2	3.2	9808
	204-20;24 {5}	6.4	7.2	3.4	9000
	204-27;31 {5}	6.3	7.3	3.6	8165
	204-34;38 {5}	6.4	7.6	3.9	7459
	204-41;45 {5}	6.0	7.3	3.9	6809
	204-48;52 {5}	5.5	6.6	4.0	6149
	204-55;59 {5}	4.9	5.9	3.7	5538
	204-62;66 {5}	4.6	5.7	3.6	4960
	204-69;73 {5}	4.4	5.3	3.6	4394
	204-69;73 {5}	4.2	5.1	3.5	3806
	204-83;87 {5}	4.0	4.7	3.4	3310
	204-90;94 {5}	3.8	4.4	3.3	2833
	204-97;100 {4}	3.7	4.2	3.2	2462

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
500W T1@31W increments out {T2@70}	0.095	1.7	61.7
	0.170	2.5	61.5
Plain Tube, Level-481W	0.250	3.2	61.8
Taken after DATA6, 03Oct88	0.325	4.0	61.5
T4avg = 61.8°C, T4rate = +.007°C/min	0.400	5.1	62.0
Power = 500W, Heatflux = 4991W/m², Samplesize = 25	0.475	4.6	62.0
Two-4 = 8.1°C (For DATA6)	0.550	5.3	61.8
	0.630	5.6	61.9
	0.705	5.9	61.9
	0.780	5.8	62.2
	0.855	6.3	61.9
	0.935	6.1	62.1
	1.010	6.1	62.0
	0.095	1.6	61.8
500W T2@80C 31W increment	0.095	1.5	72.9
	0.170	1.8	73.4
Plain Tube, Level-481W	0.250	2.5	73.4
Taken after DATA7, 03Oct88	0.325	2.4	73.8
T4avg = 73.4°C, T4rate = +.043°C/min	0.400	3.4	73.3
Power = 498W, Heatflux = 4931W/m², Samplesize = 25	0.475	4.0	72.7
Two-4 = 7.0°C (For DATA7)	0.550	4.8	73.2
	0.630	4.8	73.3
	0.705	4.7	73.7
	0.780	5.5	73.0
	0.855	4.7	74.0
	0.935	4.8	73.9
	1.010	5.3	73.3
	0.095	1.6	73.6
500W T2@89.5C 31W increments	0.095	3.9	79.5
	0.170	1.6	83.1
Plain Tube, Level-481W	0.250	3.6	81.7
Taken after DATA8, 04Oct88	0.325	5.2	81.1
T4avg = 80.8°C, T4rate = -.051°C/min	0.400	5.7	80.0
Power = 496W, Heatflux = 4863W/m², Samplesize = 25	0.475	6.6	79.5
Two-4 = 8.0°C (For DATA8)	0.550	4.1	82.4
	0.630	6.4	80.4
	0.705	6.9	80.1
	0.780	7.3	79.8
	0.855	4.7	82.4
	0.935	5.0	82.2
	1.010	7.2	79.8
	0.095	4.3	79.6

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
500W T2@100C T1-31W increments	0.095	4.1	90.8
	0.170	3.4	91.7
Plain Tube, Level-481W	0.250	3.3	92.2
Taken after DATA9, 04Oct88	0.325	3.9	92.1
T4avg = 91.5°C, T4rate = + 0.3°C/min	0.400	5.7	90.7
Power = 499W, Heatflux = 4849W/m², Samplesize = 25	0.475	5.6	91.1
Two-4 = 7.9°C (For DATA9)	0.550	6.2	90.9
	0.630	6.0	91.4
	0.705	6.2	91.2
	0.780	5.8	91.8
	0.855	6.7	91.3
	0.935	5.0	93.0
	1.010	6.7	91.2
	0.095	3.6	92.2
500W T2@110C T1-31W increments	0.095	1.8	104.3
	0.170	1.8	104.9
Plain Tube, Level-481W	0.250	2.0	104.7
Taken after DATA 10, 04Oct88	0.325	3.4	103.2
T4avg = 104.0°C, T4rate = -0.038°C/min	0.400	2.2	104.3
Power = 497W, Heatflux = 4860W/m², Samplesize = 25	0.475	2.8	103.7
Two-4 = 5.4°C (For DATA10)	0.550	3.4	103.2
	0.630	3.8	103.1
	0.705	3.0	104.0
	0.780	3.6	103.8
	0.855	3.5	104.3
	0.935	3.5	104.4
	1.010	3.6	104.2
	0.095	2.7	103.3
700W T2@60C T1-31W increments	0.095	2.2	48.2
	0.170	2.7	48.1
Plain Tube, Level-481W	0.250	3.1	48.6
Taken after DATA12, 06Oct88	0.325	4.4	49.2
T4avg = 48.0°C, T4rate = -0.044°C/min	0.400	5.8	47.7
Power = 696W, Heatflux = 7065W/m², Samplesize = 25	0.475	6.8	47.7
Two-4 = 10.9°C (For DATA12)	0.550	8.1	47.3
	0.630	6.7	48.5
	0.705	7.1	48.4
	0.780	8.4	47.7
	0.855	9.6	47.0
	0.935	8.8	48.0
	1.010	8.6	48.1
	0.095	2.0	47.8

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
700W T2@70C T1-3IN increments	0.095	1.8	59.7
	0.170	2.2	60.2
Plain Tube, Level-48IN	0.250	2.6	60.1
Taken after DATA13, 06Oct88	0.325	3.4	60.0
T4avg = 60.1°C, T4rate = +.018°C/min	0.400	4.0	60.3
Power = 697W, Heatflux = 7031W/m², Samplesize = 25	0.475	5.2	60.0
Two-4 = 8.9°C (For DATA13)	0.550	5.9	59.9
	0.630	6.4	59.9
	0.705	6.3	60.5
	0.780	6.6	60.2
	0.855	6.8	60.2
	0.935	6.7	60.4
	1.010	7.3	59.9
	0.095	1.7	60.1
700W T2@80C T1-3IN increments	0.095	1.5	71.3
	0.170	2.0	71.6
Plain Tube, Level-48IN	0.250	2.6	71.5
Taken after DATA14, 06Oct88	0.325	2.7	71.5
T4avg = 71.6°C, T4rate = +.029°C/min	0.400	3.4	71.6
Power = 696W, Heatflux = 6983W/m², Samplesize = 25	0.475	4.0	71.6
Two-4 = 7.9°C (For DATA14)	0.550	4.5	71.5
	0.630	5.0	71.4
	0.705	4.7	71.8
	0.780	5.6	71.6
	0.855	5.3	71.9
	0.935	5.6	71.4
	1.010	5.4	71.8
	0.095	1.5	71.5
700W T2@90C T1-3IN increments	0.095	1.5	81.5
	0.170	1.9	81.9
Plain Tube, Level-48IN	0.250	2.6	81.4
Taken after DATA15, 07Oct88	0.325	2.7	81.9
T4avg = 82.0°C, T4rate = +.064°C/min	0.400	3.1	81.8
Power = 693W, Heatflux = 6908W/m², Samplesize = 25	0.475	3.0	82.2
Two-4 = 6.4°C (For DATA15)	0.550	3.9	81.9
	0.630	4.4	81.6
	0.705	4.1	82.0
	0.780	4.5	82.2
	0.855	5.1	81.9
	0.935	4.7	82.3
	1.010	4.7	82.3
	0.095	1.3	82.3

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
700W T2@100C T1-3IN increments	0.095	2.7	91.1
	0.170	1.9	92.4
Plain Tube, Level-48IN	0.250	3.2	91.1
Taken after DATA16, 07Oct88	0.325	3.8	90.9
T4avg = 91.7°C, T4rate = +.092°C/min	0.400	4.5	90.6
Power = 696W, Heatflux = 6890W/m², Samplesize = 25	0.475	3.5	91.9
Two-4 = 6.3°C (For DATA16)	0.550	3.4	92.3
	0.630	3.6	92.1
	0.705	4.3	91.8
	0.780	4.0	92.5
	0.855	5.2	91.3
	0.935	5.1	91.9
	1.010	4.6	92.3
	0.095	1.7	92.4
700W T2@110C T1-3IN increments	0.095	1.2	105.1
	0.170	1.7	105.0
Plain Tube, Level-48IN	0.250	2.5	104.4
Taken after DATA17, 07Oct88	0.325	1.8	105.2
T4avg = 104.7°C, T4rate = -.036°C/min	0.400	2.4	104.7
Power = 695W, Heatflux = 6836W/m², Samplesize = 25	0.475	2.4	105.0
Two-4 = 5.6°C (For DATA17)	0.550	3.0	104.5
	0.630	3.2	104.4
	0.705	3.3	104.6
	0.780	3.2	104.8
	0.855	4.6	103.8
	0.935	4.7	103.8
	1.010	3.4	105.1
	0.095	1.3	105.2

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
900W T2@60C T1-31M increments	0.095	1.8	50.4
	0.170	2.3	50.3
Plain Tube Level-481M	0.250	3.0	50.7
DATA19, 13Oct88	0.325	3.7	51.9
T4avg = 50.2°C, T4rate = -.044°C/min	0.400	6.2	49.9
Power = 889W, Heatflux = 9033W/m², Samplesize = 25	0.475	6.5	50.1
Two-4 = 11.4°C	0.550	6.9	50.1
	0.630	8.4	49.8
	0.705	8.1	50.3
	0.780	8.7	50.3
	0.855	9.2	50.2
	0.935	9.5	50.0
	1.010	9.7	50.2
	0.095	2.1	49.7
900W T4@61C T1-31M increments	0.095	1.7	61.4
	0.170	2.1	61.2
Plain Tube Level-481M	0.250	2.7	61.2
Taken before DATA21, 13Oct88	0.325	3.2	61.2
T4avg = 61.0°C, T4rate = -.036°C/min	0.400	4.7	60.9
Power = 895W, Heatflux = 9056W/m², Samplesize = 25	0.475	5.8	61.1
Two-4 = 9.5°C (For DATA21)	0.550	7.1	61.0
	0.630	6.1	61.0
	0.705	6.6	61.0
	0.780	7.3	60.9
	0.855	7.5	60.8
	0.935	7.7	60.7
	1.010	7.7	60.9
	0.095	1.7	61.0
900W T4@61C T1-31M increments	0.095	1.7	60.8
	0.170	2.2	60.9
Plain Tube, Level-481M	0.250	3.7	61.0
Taken before DATA21, 13Oct88	0.325	3.5	60.3
T4avg = 60.5°C, T4rate = -.019°C/min	0.400	4.1	60.6
Power = 894W, Heatflux = 9050W/m², Samplesize = 100	0.475	4.8	60.7
Two-4 = 9.5°C (For DATA21)	0.550	6.2	60.3
	0.630	6.3	60.8
	0.705	6.9	60.4
	0.780	7.3	60.3
	0.855	7.7	60.3
	0.935	8.0	60.2
	1.010	7.7	60.4
	1.085	8.0	60.0

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
900W T4@70C T1-3IN increments	0.095	1.6	70.5
	0.170	2.0	70.6
Plain Tube Level-48IN	0.250	2.3	71.0
Taken before DATA22, 17Oct88	0.325	2.9	70.7
T4avg = 70.5°C, T4rate = -.016°C/min	0.400	3.2	70.6
Power = 897W, Heatflux = 9243W/m², Samplesize = 50	0.475	3.5	70.7
Two-4 = 7.8°C (For DATA22)	0.550	4.4	70.5
	0.630	5.1	70.4
	0.705	5.7	70.2
	0.780	5.8	70.4
	0.855	5.8	70.7
	0.935	6.1	70.6
	1.010	6.4	70.2
	1.085	6.3	70.4
900W T4@80C T1-3IN increments	0.095	1.4	80.4
	0.170	1.6	80.5
Plain Tube Level-48IN	0.250	1.9	80.7
Taken before DATA23, 17Oct88	0.325	2.3	80.5
T4avg = 80.4°C, T4rate = -.015°C/min	0.400	2.9	80.1
Power = 904W, Heatflux = 9082W/m², Samplesize = 50	0.475	3.0	80.5
Two-4 = 6.8°C (For DATA23)	0.550	3.9	80.2
	0.630	3.4	80.7
	0.705	5.1	80.0
	0.780	5.2	80.1
	0.855	5.4	80.3
	0.935	5.2	80.4
	1.010	5.2	80.3
	1.085	5.2	80.2
900W T4@90C 3IN increment	0.095	1.3	90.7
	0.170	1.5	90.7
Plain Tube Level-48IN	0.250	1.7	90.9
Taken before DATA24, 17Oct88	0.325	1.9	90.8
T4avg = 90.6°C, T4rate = -.016°C/min	0.400	2.2	90.8
Power = 898W, Heatflux = 8979W/m², Samplesize = 50	0.475	2.4	90.7
Two-4 = 5.7°C (For DATA24)	0.550	2.7	90.7
	0.630	2.9	90.8
	0.705	4.2	90.0
	0.780	4.3	90.5
	0.855	4.0	90.6
	0.935	4.2	90.6
	1.010	4.4	90.6
	1.085	4.3	90.5

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
900W T4@100C T1-3IN increments	0.095	1.1	101.9
	0.170	2.5	100.7
Plain Tube Level-48IN	0.250	1.6	101.8
Taken before DATA25, 17Oct88	0.325	3.3	100.2
T4avg = 100.5°C, T4rate = -.051°C/min	0.400	4.2	99.4
Power = 896W, Heatflux = 8926W/m², Samplesize = 50	0.475	4.1	99.7
Two-4 = 5.7°C (For DATA25)	0.550	2.7	101.1
	0.630	2.7	101.3
	0.705	4.4	99.7
	0.780	5.6	99.0
	0.855	4.6	100.2
	0.935	3.8	101.1
	1.010	4.4	100.6
	1.085	4.8	100.1
1100W T4@51C T1-3IN increment	0.095	2.0	51.4
	0.170	1.6	51.1
Plain Tube Level-48IN	0.250	2.8	51.0
Taken before DATA26, 18Oct88	0.325	3.8	50.7
T4avg = 51.0°C, T4rate = -.013°C/min	0.400	4.7	51.1
Power = 1094W, Heatflux = 11170W/m², Samplesize = 50	0.475	6.7	50.6
Two-4 = 11.7°C (For DATA24)	0.550	6.9	51.1
	0.630	6.7	51.5
	0.705	7.9	51.2
	0.780	9.0	50.9
	0.855	9.8	50.4
	0.935	9.9	50.7
	1.010	9.7	50.8
	1.085	9.1	51.3
1100W T4@60C T1-3IN increments	0.095	1.6	59.2
	0.170	2.0	59.2
Plain Tube Level-48IN	0.250	2.5	58.9
Taken before DATA27, 18Oct88	0.325	3.0	58.6
T4avg = 58.7°C, T4rate = -.065°C/min	0.400	4.6	58.0
Power = 1095W, Heatflux = 11156W/m², Samplesize = 50	0.475	4.6	58.8
Two-4 = 9.5°C (For DATA27)	0.550	6.4	59.2
	0.630	5.4	59.1
	0.705	7.4	59.3
	0.780	7.8	58.3
	0.855	8.0	58.4
	0.935	8.4	58.6
	1.010	7.8	59.0
	1.085	7.8	59.0

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MicroD

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
1100W T4@70C T1-3IN increments	0.095	1.5	70.0
	0.170	1.9	70.1
Plain Tube Level-48IN	0.250	2.2	69.8
Taken before DATA28, 18Oct88	0.325	2.6	69.9
T4avg = 70.1°C, T4rate = +.031°C/min	0.400	3.2	69.8
Power = 1102W, Heatflux = 11175W/m², Samplesize = 50	0.475	3.7	69.8
Two-4 = 8.0°C (For DATA28)	0.550	3.8	70.3
	0.630	4.0	70.5
	0.705	5.5	70.0
	0.780	5.4	70.1
	0.855	5.9	70.3
	0.935	6.3	70.3
	1.010	6.2	70.4
	1.085	5.9	70.5
1100W T4@80C T1-3IN increments	0.095	1.2	79.8
	0.170	1.6	79.8
Plain Tube Level-48IN	0.250	1.8	80.0
Taken before DATA29, 18Oct88	0.325	2.2	79.7
T4avg = 79.8°C, T4rate = +.0004°C/min	0.400	2.4	79.6
Power = 1097W, Heatflux = 11090W/m², Samplesize = 50	0.475	2.7	79.5
Two-4 = 6.9°C (For DATA29)	0.550	3.1	79.8
	0.630	3.9	79.6
	0.705	4.5	79.7
	0.780	4.5	79.8
	0.855	4.8	79.9
	0.935	5.1	79.7
	1.010	5.2	79.8
	1.085	5.1	79.9
1100W T4@90C T1-3IN increments	0.095	1.1	89.3
	0.170	1.3	89.6
Plain Tube Level-48IN	0.250	1.6	89.6
Taken before DATA30, 18Oct88	0.325	1.9	89.5
T4avg = 89.8°C, T4rate = +.045°C/min	0.400	2.0	89.5
Power = 1099W, Heatflux = 11077W/m², Samplesize = 50	0.475	2.3	89.4
Two-4 = 6.1°C (For DATA30)	0.550	2.5	90.0
	0.630	3.5	89.8
	0.705	3.8	90.0
	0.780	4.1	90.0
	0.855	4.0	90.2
	0.935	4.5	90.1
	1.010	4.3	90.3
	1.085	4.4	90.2

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
1100W T4@100C T1-3IN increments	0.095	1.3	100.2
	0.170	2.2	99.8
Plain Tube Level-40IN	0.250	1.8	100.5
Taken before DATA31, 18Oct88	0.325	2.7	90.9
T4avg = 100.4°C, T4rate = +.033°C/min	0.400	2.8	100.0
Power = 1097W, Heatflux = 11010W/m², Samplesize = 50	0.475	2.5	100.7
Two-4 = 5.6°C (For DATA31)	0.550	3.4	100.1
	0.630	2.7	100.9
	0.705	3.8	100.2
	0.780	3.9	100.7
	0.855	3.8	101.0
	0.935	4.7	100.4
	1.010	4.9	100.1
	1.085	4.1	100.9
500W T4@60C Level-40IN	-0.108	0.2	60.5
	-0.108	0.3	60.7
Plain Tube	-0.108	0.3	60.4
DATA58, 19Nov88	-0.032	0.4	59.7
T4avg = 60.4°C, T4rate = +.061°C/min	-0.032	0.5	59.2
Power = 500W, Heatflux = 4979W/m², Samplesize = 25	0.044	3.3	59.2
Two-4 = 7.7°C	0.121	2.7	60.3
	0.121	3.2	60.0
	0.044	3.6	59.5
	0.019	3.6	59.5
	0.019	2.6	60.6
	-0.006	2.0	61.2
	-0.006	2.3	61.0
	-0.006	3.1	60.6
	-0.032	0.5	61.4
	-0.032	0.4	60.6
	-0.019	0.8	61.1
	-0.019	0.8	60.6
	-0.013	1.5	61.9
	-0.013	2.7	60.0

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
500W T4@60C Level-40IN	-0.013	2.1	61.3
	-0.013	1.8	61.6
Plain Tube	-0.019	1.0	61.1
Taken after DATA58, 19Nov88	-0.019	1.0	60.8
T4avg = 60.9°C, T4rate = -.032°C/min	-0.006	2.4	61.0
Power = 500W, Heatflux = 4979W/m², Samplesize = 25	-0.006	1.8	61.7
Two-4 = 7.7°C (For DATA58)	-0.006	2.1	60.9
	0.019	3.1	59.9
	0.019	2.2	61.3
	0.044	2.7	60.9
	0.044	2.9	60.6
	0.121	2.7	60.4
	0.121	3.3	60.1
	0.197	2.6	61.1
	0.197	3.2	60.7
	0.273	3.9	60.6
	0.349	4.2	60.7
	0.502	4.9	60.9
	0.654	5.6	60.4
	0.806	5.1	61.1
500W T4@80C Level-40IN	-0.108	0.4	80.6
	-0.108	0.4	80.6
Plain Tube	-0.032	0.7	80.8
DATA59, 19Oct88	-0.032	0.7	80.0
T4avg = 80.0°C, T4rate = -.026°C/min	-0.006	1.8	80.4
Power = 497W, Heatflux = 4878W/m², Samplesize = 25	-0.006	1.9	79.9
Two-4 = 5.2°C	0.019	2.1	79.5
	0.019	2.0	79.9
	0.044	1.9	79.9
	0.044	1.7	80.1
	0.121	1.9	80.6
	0.197	2.2	80.0
	0.273	2.6	80.0
	0.349	2.7	79.8
	0.502	4.1	79.2
	0.654	3.5	80.0
	0.806	3.7	80.1
	-0.019	1.5	79.8
	-0.025	1.3	80.2
	-0.032	0.8	80.2

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
500W T4@100C Level-40IN	-0.108	0.4	99.9
	-0.038	1.2	99.8
Plain Tube	-0.038	1.1	100.3
DATA60, 19Nov88	-0.044	0.7	100.5
T4avg = 100.6°C, T4rate = +.030°C/min	-0.044	0.7	100.5
Power = 501W, Heatflux = 4844W/m², Samplesize = 25	-0.051	0.6	100.6
Two-4 = 4.1°C	-0.051	0.6	100.7
	-0.032	1.2	100.6
	-0.032	1.3	100.6
	-0.025	1.3	100.8
	-0.025	1.3	100.8
	-0.019	1.3	101.0
	-0.019	1.2	100.6
	-0.013	1.2	100.6
	-0.006	1.2	100.8
	+0.006	1.0	101.1
	0.019	1.1	100.8
	0.044	1.2	100.6
	0.121	1.3	100.6
	0.349	1.8	100.4
	0.502	2.5	100.3
	0.654	2.7	100.4
	0.806	3.0	100.2
700W T4@60C Level-40IN	-0.038	0.5	60.5
	-0.038	0.5	60.3
Plain Tube	-0.035	0.5	59.3
DATA64, 25Nov88	-0.035	0.5	60.2
T4avg = 60.0°C, T4rate = +.027°C/min	-0.032	0.5	58.8
Power = 696W, Heatflux = 7003W/m², Samplesize = 25	-0.032	0.4	59.2
Two-4 = 0.5°C	-0.029	0.6	60.0
	-0.029	0.5	60.2
	-0.025	0.5	59.4
	-0.025	0.7	60.8
	-0.022	0.7	60.5
	-0.022	0.7	60.9
	-0.019	0.9	59.9
	-0.019	1.1	58.3
	-0.016	1.4	60.1
	-0.016	1.2	60.5
	-0.013	1.8	59.5
	-0.013	2.5	59.7
	-0.108	0.3	61.2
	-0.108	0.4	60.8

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
700W T4@8°C Level-40IN	-0.108	0.4	80.0
	-0.108	0.4	80.0
Plain Tube	-0.044	0.7	79.8
DATA65, 25Nov88	-0.044	0.7	79.8
T4avg = 79.8°C, T4rate = -.005°C/min	-0.051	0.6	79.8
Power = 702W, Heatflux = 6992W/m², Samplesize = 25	-0.051	0.6	79.9
Two-4 = 6.3°C	-0.051	0.6	79.8
	-0.051	0.6	79.9
	-0.051	0.6	79.6
	-0.038	0.8	79.7
	-0.038	0.8	79.7
	-0.032	0.9	79.7
	-0.032	0.9	79.8
	-0.025	1.0	79.7
	-0.025	1.0	79.9
	-0.019	1.1	79.8
	-0.019	1.1	79.8
	-0.006	1.1	79.8
	-0.006	1.1	79.7
	-0.070	0.1	80.0
700W T4@10°C Level-40IN	-0.108	0.5	99.4
	-0.083	0.5	99.3
Plain Tube	-0.070	0.6	99.2
DATA66, 25Nov88	-0.057	0.8	99.1
T4avg = 99.3°C, T4rate = +.021°C/min	-0.057	0.8	99.1
Power = 700W, Heatflux = 6897W/m², Samplesize = 25	-0.044	0.9	99.1
Two-4 = 4.9°C	-0.032	1.0	99.1
	-0.032	1.0	99.1
	-0.019	1.0	99.0
	-0.006	1.0	99.1
	+0.006	1.0	99.1
	0.019	1.0	99.2
	0.019	1.0	99.2
	0.044	1.0	99.2
	0.095	1.2	99.3
	0.197	1.5	99.3
	0.273	1.7	99.5
	0.349	1.8	99.6
	0.502	1.9	99.7
	0.654	2.9	99.6

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
900W T4@100C Level-40IN	-0.108	0.6	100.0
	-0.076	0.8	100.0
Plain Tube	-0.070	0.8	100.0
DATA69, 28Nov88	-0.083	0.7	100.0
T4avg = 100.0°C, T4rate = -.001°C/min	-0.063	0.9	100.1
Power = 904W, Heatflux = 9009W/m², Samplesize = 25	-0.057	1.0	99.9
Two-4 = 5.6°C	-0.051	1.0	100.0
	-0.044	1.0	100.0
	-0.038	1.0	100.0
	-0.032	1.0	100.0
	-0.019	1.0	100.0
	-0.006	1.0	100.0
	+0.044	1.2	99.9
	0.121	1.3	100.0
	0.197	1.5	100.1
	0.273	1.8	100.0
	0.349	2.0	100.0
	0.502	2.4	100.0
	0.654	3.2	99.9
	0.806	3.5	100.0
1100W T4@60C Level-40IN	-0.108	0.4	59.0
	-0.083	0.4	59.5
Plain Tube	-0.076	0.4	59.6
DATA70, 28Nov88	-0.070	0.4	59.5
T4avg = 59.4°C, T4rate = -.015°C/min	-0.063	0.4	59.5
Power = 1099W, Heatflux = 11182W/m², Samplesize = 25	0.057	0.6	58.9
Two-4 = 9.4°C	-0.051	0.5	59.7
	-0.044	0.6	59.6
	-0.038	0.7	59.4
	-0.032	0.7	59.3
	-0.019	0.9	59.6
	-0.006	1.1	59.6
	+0.044	1.4	59.5
	0.121	1.7	59.7
	0.197	2.6	59.1
	0.273	3.0	59.3
	0.349	3.6	59.3
	0.502	5.5	58.8
	0.654	6.8	58.8
	0.806	7.0	59.4

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
1100W T4@80C Level-40IN	-0.108	0.4	79.1
	-0.083	0.5	79.2
Plain Tube	-0.070	0.5	79.2
DATA71, 28Nov88	-0.057	0.6	79.2
T4avg = 79.4°C, T4rate = +.001°C/min	-0.051	0.7	79.2
Power = 1096W, Heatflux = 11075W/m², Samplesize = 25-0.044	-0.044	0.7	79.5
Two-4 = 7.6°C	-0.038	0.8	79.5
	-0.032	0.9	79.6
	-0.025	1.0	79.6
	-0.019	1.0	79.6
	-0.006	1.1	79.5
	+0.019	1.1	79.6
	0.044	1.3	79.5
	0.121	1.6	79.5
	0.197	1.9	79.2
	0.273	2.1	79.2
	0.349	2.6	79.0
	0.502	3.9	79.0
	0.654	4.6	79.1
	0.806	4.9	79.7
1100W T4@100C Level-40IN	-0.108	0.5	102.1
	-0.083	0.7	102.0
Plain Tube	-0.070	0.7	102.1
DATA72, 28Nov88	-0.057	0.8	102.0
T4avg = 102.0°C, T4rate = +.005°C/min	-0.051	0.8	102.0
Power = 1095W, Heatflux = 10977W/m², Samplesize = 25-0.044	-0.044	0.9	101.9
Two-4 = 6.2°C	-0.038	0.9	102.0
	-0.032	0.9	102.0
	-0.025	0.9	102.0
	-0.019	0.8	102.0
	-0.006	0.9	102.0
	+0.019	0.8	102.1
	0.044	0.9	102.0
	0.121	1.2	102.0
	0.197	1.2	102.1
	0.273	1.6	102.0
	0.349	1.7	102.1
	0.502	2.3	102.0
	0.654	2.8	102.1
	0.806	3.3	102.2

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1- °C	T4 °C
500W Instrumented Level-48IN T4@80C	0.095	1.1	79.4
	0.121	1.1	79.4
DATA205, 18Feb89	0.146	1.1	79.4
T4avg = 79.4°C, T4rate = +.004°C/min	0.172	1.3	79.4
Power = 508W, Heatflux = 4984W/m², Samplesize = 25	0.197	1.3	79.4
Two-4 = 4.9°C	0.222	1.3	79.3
	0.248	1.4	79.3
	0.273	1.6	79.3
	0.299	1.6	79.3
	0.325	1.3	79.3
	0.350	1.7	79.4
	0.400	1.9	79.4
	0.476	2.2	79.5
	0.553	2.5	79.4
	0.629	2.8	79.4
	0.705	3.0	79.4
	0.781	3.1	79.5
	0.857	3.4	79.5
	0.934	3.6	79.4
	1.010	3.4	79.4
700W Instrumented Level-48IN T4@80C	0.095	1.0	79.7
	0.121	1.1	79.7
DATA207, 18Feb89	0.146	1.2	79.6
T4avg = 79.8°C, T4rate = +.011°C/min	0.172	1.2	79.7
Power = 697W, Heatflux = 6933W/m², Samplesize = 25	0.197	1.4	79.7
Two-4 = 6.1°C	0.222	1.4	79.8
	0.248	1.4	79.8
	0.273	1.6	79.8
	0.299	1.8	79.8
	0.325	1.7	79.8
	0.350	1.9	79.9
	0.400	2.1	79.9
	0.476	2.3	79.9
	0.553	2.5	79.9
	0.629	2.9	79.9
	0.705	3.8	79.8
	0.781	4.1	79.9
	0.857	4.3	79.7

Two-Phase Record

Test Title and Details	Nominal Fluid Depth (metres)	T1-4 °C	T4 °C
900W Instrumented Level-48IN T4@80C	0.095	0.9	79.5
	0.121	1.0	79.4
DATA209, 18Feb89	0.146	1.0	79.5
T4avg = 79.8°C, T4rate = +.023°C/min	0.172	1.2	79.5
Power = 897W, Heatflux = 8995W/m², Samplesize = 25	0.197	1.3	79.7
Two-4 = 7.4°C	0.222	1.5	79.7
	0.248	1.6	79.8
	0.273	1.6	79.9
	0.299	1.7	79.9
	0.325	1.8	79.9
	0.350	1.9	80.0
	0.400	2.1	79.9
	0.451	2.3	79.8
	0.553	2.6	79.8
	0.629	3.1	79.8
	0.705	4.1	79.8
	0.781	4.3	79.9
	0.857	5.1	79.9
	0.934	5.2	79.9
	1.010	5.3	80.0
1100W Instrumented Level-48IN T4@80C	0.095	0.8	80.8
	0.121	1.1	80.7
DATA211, 18Feb89	0.146	1.1	80.8
T4avg = 80.9°C, T4rate = +.004°C/min	0.172	1.2	80.9
Power = 1106W, Heatflux = 11153W/m², Samplesize = 25	0.197	1.3	80.9
Two-4 = 7.3°C	0.222	1.3	81.0
	0.248	1.5	80.9
	0.273	1.5	80.9
	0.299	1.7	80.8
	0.325	1.8	80.8
	0.400	2.1	80.8
	0.476	2.3	80.9
	0.553	2.7	80.9
	0.629	2.8	80.9
	0.705	3.2	80.9
	0.781	3.3	80.9
	0.857	4.2	80.9
	0.934	4.4	80.9
	1.010	4.5	80.9

Appendix C

Experimental Setup and Procedure

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The Experimental Apparatus

A schematic illustration of the complete experimental system is found in figure Ci, with the accompanying photograph figure Cii.

The Test rig:

The heart of the experiment was the test rig itself, a scale drawing shown in figure Ciii. In order to imitate the evaporator annulus inner wall of the decay heat rejection system, the test rig consisted of a one inch diameter stainless steel tube inside a three inch diameter stainless steel tube; another 3 inch diameter section was attached at the base of the 1 inch pipe for the heating element chamber. In the full size model the 1 inch and 3 inch tubes are 3.5 and 6 inches respectively. The length of the experimental evaporator was 47.6 inches long, approximately half scale.

In order to provide heat to the annulus inner wall, done by down-flowing water driven by natural convection in the full size version, the experimental setup utilized a commercial 120VAC 1000W hot water heater (figure Civ) to boil water, the vapour then condensing on the inside of the annulus. A 1500W element was used briefly, but an insufficient water level in the heating element chamber led to its early demise.

It was intended that the entire test rig should be built of 304 stainless steel, but for certain parts this proved impossible; the stainless steel sheathed thermocouples were fed into 0.075 inch outside diameter copper tubes which provided the pressure barrier. The junctions between the copper tubes and the stainless steel flange or the end cap were silver soldered. All of the permanent joints between stainless steel parts were welded in place. The seals between the top end cap and the bottom flange plate on the 3 inch outer pipe were 1.25 and 3.5 inside diameter o-rings. The groove for the 3.5 inch o-ring is best seen in the photograph of the bottom flange, figure Cvi. One other non-steel intrusion into the apparatus was the solder "backfill" in the instrumented section, but more on this later.

The plain walled and teflon-15% test sections used the same 1 inch o.d. pipe, with a wall thickness of one-sixteenth of an inch. The roughness of the outside of this pipe (i.e. the boiling surface) was in the order of an arithmetic average from the mean of $R_a = 17\mu\text{in}$ taken at 7 locations. The teflon-15% section, illustrated in figure Cv, involved winding a 0.040 inch outside diameter teflon coated copper wire 72 turns upwards (47.6 inches from the bottom flange) with a constant pitch, then the same number of turns and rotational direction back down. The "shadow" of this helix covered 15% of the heated surface. The return winding, plus the addition of stainless steel wire loops every 6 inches,

held the teflon firmly in place, and maintained a good contact with the steel surface. After the completion of the teflon section tests, and disassembly, the teflon was still firmly in place.

The instrumented test section proved the most difficult for assembly, and equally trying for test purposes. In order to place thermocouples T_a and T_b at the wall surface (measuring T_{wo}), two 0.032 inch channels were cut in the axial direction of the 1 inch tube 180° from each other (fig Ciii). These slots passed through the pressure barrier at the bottom flange plates for a further 6 inches. The thermocouples were laid in the slots, the flange plate slid over top, and the entire test rig was assembled in order to fix the position of the flange. Two tack welds were made, away from the thermocouples, and the rig disassembled. The welds were then completed to within about an eighth of an inch of the thermocouples, in order to avoid burning through the thermocouple sheathing. An acid flux was applied to the milled slots and embedded thermocouples, both of which had been cleaned before assembly, and solder was applied to fill the remaining gaps between the flange and the tube (fig Cvi). The thermocouples were acid fluxed and covered with solder, with some excess coverage. This excess was scraped off, and then sanded - the solder covered potential nucleation sites.

Because it was desirable to have a reasonably uniform surface, it was decided (perhaps rashly in retrospect) to sand the entire heating surface circumferentially with 100 grit emery cloth. This gave the surface an arithmetic roughness of $R_a = 31 \mu\text{in}$ from 11 locations. The final surface is illustrated in figure Cvii, noting that the solder didn't really cover the thermocouple, but rather gave an improved heat conduction with the sides (and perhaps inside) of the slot. As with the plain and teflon sections, the surface was cleaned with toluene before assembly with the (also cleaned) 3 inch pipe. The instrumented section proved leaky during the initial tests, and it wasn't until it had been disassembled twice, resoldered and thoroughly caulked with silicone sealant on the outside that the leaks were stopped. Air had been seeping between the thermocouples and the bottom of the slots, as solder had failed to be drawn in sufficiently by capillary action.

The other points of note with the test rig are seen in figure Ci. At the top of the heated section, on the inside of the 1 inch pipe, a stainless steel plug provides the pressure barrier between heatpipe and the environment. The stainless steel tube with the valve at the top provides a means of purging heatpipe of air; the flaired out section just below the valve enables the operator to detect the location of the vapour/air interface (merely by touching it to feel where the temperature changes rapidly). By having

larger volume section, any leakage would take considerably longer to fill the pipe leading to heatpipe1. A similar tube comes out of heatpipe2 to remove any air. The other pipes entering either heat pipe are thermocouple tubes for T_1 , T_2 and T_4 .

On the outside, at the top of heatpipe2, is the condensor of 4 inches o.d.: a volume of about 0.5 litres with an inlet at the bottom and an outlet at the top diametrically opposed.

Power and Control System:

A 240Vac source was used to drive the saturated core transformer. The latter was used to attempt to stabilize the input voltage, which fluctuated due to compressors, fans and other heavy current devices in the National Research Council facility. A 120Vac tapping into the transformer was made, with a Variac variable transformer placed on one line. This had a capability of control from 0 to 130Vac, thus giving the ability to overpower the heater by 20%. As the variac, and perhaps the saturated core transformer, heated up with time, a slight downward drift in voltage, and thus power, was detected, in some cases requiring adjustment to the variac. Another cause of this drift could have been the heater itself, with resistance proportional to temperature.

Next on line was a wattmeter, intended for 1000 to 10000 W with a linear output of 0.5 to 5.0 Vdc. As more completely described in Appendix D (Wattmeter Output pg.D13), this device worked effectively in the lower range. Following the wattmeter was a temperature controlled switch, with a thermocouple attached to the outside of the heating element chamber. It was set such that should this temperature reach the order of 110°C, the switch would be thrown, only to turn on again after dropping below about 90°C. This switch was necessary to avoid undue heating of the rig, which was not intended as a pressure vessel. If the test rig was left on at low power overnight, in order to save time the next day, this switch was turned down to perhaps 80°C.

Aside from the power control to control the heat flux, the condensor flow was used to control the system temperature. A variable height head tank was fed from the mains, with an overflow to maintain the head. The final adjustment was a quarter inch valve on the line entering the condensor. With the head tank fully raised and the valve fully open, a flow of about 3 litres per minute could be maintained, more than enough for the tests. In fact, flows in the order of 0.2 to 0.7 litres per minute proved normal, depending on temperature and power. This flow control system proved somewhat awkward to use, especially during the increasing/decreasing heat flux tests, due to time lags in the order of a couple of minutes before the condensor reached steady

state. In some of the early tests, the valve was situated on the efflux line; combined with a siphon effect to the drain lowering the pressure, boiling oscillation in the condensor occurred when T_4 was moderately high, causing further control problems.

Data Acquisition:

Controlled by a Hewlett-Packard 9826 computer, the data acquisition was done via a Hewlett-Packard 9421A 30 channel unit, reading up to six K-type (chromel/alumel) miniature thermocouples, and the wattmeter. The unit supplied a reference temperature for each thermocouple, which was then converted to a voltage, added to the thermocouple voltage, and then multiplied by the thermocouple constants for K-type thermocouples, supplied by the HP9241A operating manual (see lines 1310-1330 on pg. E7). The data rate was controlled to provide 3 significant digits (line 1280, pE7), thus giving good accuracy and speed. Even so, 25 samples of 6 thermocouples, plus one wattmeter reading, took in the order of 50 seconds, and thus the reading starts for all of the tests were set at one minute apart.

The thermocouples T_3 and T_4 were 0.040 inch diameter stainless steel sheathed K-type with miniature plugs. Thermocouples T_1 , T_2 , T_5 and T_6 were 0.032 inch diameter of the same type. The thermocouple calibration is detailed in

appendix D page D6. Thermocouple T_4 failed intermittently right near the end of the tests (DATA212), and upon disassembly of the test rig, the stainless steel sheaths on both T_3 and T_4 were split open over considerable lengths. It is presumed that water somehow leaked beneath the sheathing, perhaps due to scratches from the surface sanding, and was absorbed into the hygroscopic insulating material. Upon rapidly heating the test rig, the moisture could not be expelled quickly enough, and the sheathing ruptured. Despite this evident problem, the results of the wall-buried thermocouples were very consistent, and supported the analytical results well - the only noticeable problem being the occasional wrong reading in the last test.

Experimental Technique

The standard techniques for testing the given power/level/surface/temperature combinations evolved and improved through the plain wall tests, and early mistakes, especially with respect to insufficient purging of the air from the top of the heat pipes, certainly contributed to the errors in the results. The calibration tests for the thermocouples, loss coefficient and wattmeter, and the pressure/temperature and adiabaticity tests are all found in appendix D.

As mentioned previously, the surfaces of heatpipe2 were cleaned with toluene, and after assembly, both heat pipes were filled with distilled water to the appropriate levels. Later test programs involved heating up the test rig and letting it boil the water for a while, and then dumping and refilling with fresh water. This latter technique was only used with the instrumented section, due to its repeated disassembly. However, with all the test surfaces, a slight film was evident after the completion of the tests, and the instrumented section was particularly dirty.

Heatpipe1 was filled with distilled water to a level calculated to be well above the heater element, although a mistake was made with the 1500W element. With heatpipe2, it was filled over the calculated limit, and a 0.075 inch o.d. copper tube, attached to an aspirator, was fed downwards into the water to a predetermined depth from the top of the

rig, and water was removed until the level reached the bottom of the aspirator tube. Naturally there was some error due to the bending of the copper tube, but it was maintained as straight as possible, and marks painted on the tube ensured equivalent depths for each test section.

Having filled, and adjusted the nominal water levels in the heat pipes, valves were attached to the ends of the pipes extending down to the heat pipes, and the valves then attached to an aspirator. The latter was a venturi arrangement in a water mains outlet, and proved capable of drawing about 27 inches of mercury, albeit at low flow rates.

The aspiration process worked best with the test rig at an elevated temperature - the vapour pressure was higher and thus the aspirator could draw a higher flow, and also the boiling process caused the dissolution of any air in the water. A heat pipe was considered aspirated when water vapour was drawn into the aspirator line - the temperature of the tubes extending from the heat pipes rose very noticeably. It was realized during the plain section tests that repeated aspirations were necessary, especially after air had been let into the system for such things as nominal level changes. Prior to a set of data readings, the tubes extending from the heat pipes were touched, and occasionally it was decided to aspirate further. Sometimes, when the

system was at steady state, a temperature reading would drop quickly over a few minutes, and it was due to the air/vapour interface dropping below that particular thermocouple (usually T_4).

Constant Heat Flux Tests:

It was standard that for the constant heat flux tests, after one test was completed, the temperature would be allowed to rise by reducing the condensor flow, but leaving the power constant. As the temperature approached the desired level, the coolant flow was increased incrementally, and eventually temperature overshoots became the exception. The system was then allowed to reach a steady state, and as can be seen in the results, T_4 often was close to, but not at, the desired level. These errors were deemed acceptable, rather than attempting to adjust the system to exactly the right temperature. As it was, changing the system to a steady state at a different temperature proved time consuming, although with practice the time between tests took as little as an hour. If a test at a higher power was next in the test series, the system was cooled at zero power to below the new test temperature, power was set at the new value, and the temperature allowed to rise to a steady state value. The actual tests usually took 20 minutes, with 20 readings of 25 samples each, and small coolant flow rate changes were often needed to maintain the temperature moderately

constant. As illustrated in the overall test record, the system temperature did change over the duration of the test, but usually under $\pm 0.040^{\circ}\text{C}/\text{minute}$ - later tests cut this rate in half. During a test a running record of temperature trends was kept, and sometimes this led to a test restart, especially if a temperature jump occurred.

The only other note to the constant heat flux tests is that sometimes T_1 was drawn out a certain amount before each reading began, often a multiple of three inches, in order to establish the two-phase temperature. These results are found in appendix B, in the Two-Phase Record.

Increasing/Decreasing Heat Flux Tests:

These tests were long (three to five hours) and proved much less controllable than those at constant heat flux. The aim was to increase the heat flux in a stepwise fashion while maintaining the system at a constant temperature. As with the constant heat flux tests, T_4 was used as an indicator of system steady state. The changes in heat flux were not uniform, but were 5 volt steps in the variac voltage. Due to power being proportional to V^2/R , the heat flux rose more rapidly at higher voltages, but this does not have a marked effect on the spacing of points on the graphs.

With a change in power, and thus heat flux, the condensor flow rate had to be changed immediately, and any misadjustment would be observed in a large temperature rate after about two minutes. This time lag, along with that of T_2 to T_4 (heatpipe1 to heatpipe2), proved frustrating at times, and very erratic results occurred with early tests, especially DATA61 to 63. The optimum test pattern, used for the teflon and instrumented increasing/decreasing heat flux tests, was to allow 7 minutes between each change in heat flux, and to use the latter 5 readings for analysis purposes. This system proved very workable, and the results seemed as reliable as tests with 10 to 15 minutes between heat flux changes.

FIGURE Ci
SYSTEM SETUP
 (Instrumented Section)

- Saturated Section
- ▨ Saturated Steam
- ⋈ Two-Phase Water
- ⋯ Insulation

Figure Cii
System Setup

On floor under bench:	Wattmeter
On bench (L to R):	Computer, Data acquisition unit, Variac, Temperature limit switch
Behind bench (unseen):	Saturated core transformer
Right side:	Test rig
Top right:	Adjustable head tank

Figure C1v
Heat Source

Heating element chamber and a 1000W immersion heater
Thermocouple T6 plug resting on the chamber.

Figure Cv
Teflon Wrapped Surface

The 0.040 inch o.d. teflon wrapped wire in a helix upwards, then back down, with 72 turns each way, held on by stainless steelwire every 8 inches. The teflon covered a nominal 15% of the surface. Note also the 0.075 inch copper tube for thermocouple T1.

Figure Cvi
Instrumented Test Section and Flange

The dark line on the surface of heatpipe1 is thermocouple T5 piercing the junction with the bottom flange. The junction is mainly welded, but the thermocouple is sealed in the slot with solder. The outer milled slot is for the 3.25 inch o-ring to seal with the outer pipe flange. Note the small hole in the inner slot for the 0.075 inch copper tube for thermocouple T1.

Figure Cvii
Instrumented Test Section Thermocouple

Thermocouple T6 in the wall slot, with
solder fill and excess removed.

Figure Cviii
Data Acquisition and Control Systems

Left to right: HP9826 computer and printer
HP9421A data acquisition unit
0-130 Vac Variac
Voltmeter
Temperature limit switch

Appendix D

Error Analysis

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Equation Error Analysis

Measured Quantities:

1. **Temperatures:** From the thermocouple calibration tests, it was established that the thermocouples have an instrument error of $\pm 0.20^\circ\text{C}$. Each temperature data point has a standard deviation based on the constituent samples (usually 500 per data point). The error analysis uses 1σ on the temperature readings. Thus the conservative error on each temperature datapoint is:

$$\epsilon_T = (\sigma_T + 0.20) \{^\circ\text{C}\}$$

2. **Power:** The input power to the heater element was read as a voltage from a 0 to 10,000 Watt power meter. In the lower power range, a linear correlation of:

$$\text{Pwr} = 2025 * \text{Volts} + 17$$

worked well for power above 100 Watts, but due to slight non-linearity in this region, the power error is:

$$\epsilon_P = 3 \text{ (W)}$$

3. **Boiling Area:** Due to the inexactitude of the actual boiling fluid level, and the fact that there is some convective heat transfer to the vapour above the 2ϕ fluid, it was decided to maintain the boiling area as a constant 0.0965 m^2 . Thus for the same test rig, one can directly compare data with the same heat fluxes for different nominal (1ϕ) fluid levels.

4. K_{loss} : This factor is used to determine how much power was lost to the environment without being used in the boiling process. K_{loss} was determined experimentally, and ranged from 0.34 to 0.38 W/°C, and was set at 0.4 for the tests. The error on K_{loss} was set as:

$$\epsilon_{K_{loss}} = 0.05 \text{ (W/°C)}$$

5. Boiling Heat flux: Using the known power, driving steam temperature (T_2), ambient temperature (T_3), and their associated errors:

$$q_{AB} = \frac{P_{wr} - K_{loss} (T_2 - T_3)}{A_B} \quad \text{(W/m}^2\text{)}$$

Using uncertainty analysis, with the associated partial derivatives of the heat flux equation:

$$\epsilon_{q_{AB}} = \left[\left[\frac{\epsilon_P}{A_B} \right]^2 + \left[\frac{2(T_2 - T_3) \epsilon_{K_{loss}}}{A_B} \right]^2 + \left[\frac{-K_{loss} (\epsilon_2 + \epsilon_3)}{A_B} \right]^2 \right]^{1/2}$$

6. Property Values: There is no relevant error introduced by using steam table approximation equations rather than the tables themselves. However, in some cases the error in temperature can cause property differences to have a significant effect.

7. **Condensation Heat flux Equation:** Using Rohsenow's modified condensation equation, arranged as follows:

$$C_1 q_{ab}^4 = h_{fg} T_{2-w1}^3 + .68 c_p T_{2-w1}^4$$

where

$$C_1 = \left[\frac{R_o/R_i}{.943 \left[\frac{p_f (p_f - p_g) g k_f^3}{\mu_f * L} \right]^{1/4}} \right]^4$$

From results for a conservative error in T_2

$$\epsilon_{C_1} = \text{Half the difference between } C_1 \text{ (@ } T_2 - \epsilon_2 \text{) + } C_1 \text{ (@ } T_2 + \epsilon_2 \text{)}$$

Applying uncertainty analysis on the condensation equation, noting that $(.68 c_p) / h_{fg} \equiv .001$ and thus $(.68 c_p T_{2-w1}^4)$ is ignored since T_{2-w1} is small :

$$\epsilon_{2-w1} = \left[\left[\frac{4 C_1 q_{ab}^3 \epsilon_{q/a}}{3 h_{fg} \Delta T_{2-w1}^2} \right]^2 + \left[\frac{q_{ab}^4 \epsilon_{C_1}}{3 h_{fg} \Delta T_{2-w1}^2} \right]^2 \right]^{1/2}$$

8. **Conduction Heat flux Equation:** Using the radial conduction equation for a thin-walled tube :

$$T_{wo} = T_2 - \Delta T_{2-w1} - \left[\frac{\text{Net Pwr} * \ln(R_o/R_i)}{2 \pi k_{ss} L} \right] \text{ (}^\circ\text{C)}$$

$$\epsilon_{wo} = \epsilon_2 + \epsilon_{2-w1} + \epsilon_p * \frac{\ln(R_o/R_i)}{2 \pi k_{ss} L} \text{ (}^\circ\text{C)}$$

9. **Total Error on Boiling Temperature Difference:** The total error on the boiling temperature difference is:

$$\epsilon_{wo-4} = \epsilon_4 + \epsilon_2 + \epsilon_{2-w1} + \epsilon_p * \frac{\ln(R_o/R_i)}{2 \pi k_{ss} L} \text{ (}^\circ\text{C)}$$

10. Rohsenow Pool Boiling Equation "Csf" Error: Using the equation :

$$\frac{C_{sf} \Delta T_{w0-4}}{h_{fg}} = C_{sf} \left[\frac{q_{AB}}{\mu_f h_{fg}} \left[\frac{\sigma_f}{g (\rho_f - \rho_g)} \right]^{1/2} \right]^{1/3} Pr^{1.0}$$

Rearranged : $C_{sf} = C_2 C_3^{.33} \Delta T_{w0-4} q_{AB}^{-.33}$

$$C_2 = \frac{k_f}{\mu_f h_{fg}} \quad C_3 = \frac{\mu_f h_{fg}}{\left[\frac{\sigma_f}{g (\rho_f - \rho_g)} \right]^{1/2}}$$

Based on a conservative temperature error of ϵ_2

ϵ_{C2} = Half the difference between $C_2(@T_2 + \epsilon_2)$ + $C_2(@T_2 - \epsilon_2)$

ϵ_{C3} = Half the difference between $C_3(@T_3 + \epsilon_3)$ + $C_3(@T_3 - \epsilon_3)$

Using uncertainty analysis:

$$\epsilon_{C_{sf}} = \left[\left[C_3^{.33} \Delta T_{w0-4} q_{AB}^{-.33} \epsilon_{C2} \right]^2 + \left[0.33 C_2 C_3^{-.67} \Delta T_{w0-4} q_{AB}^{-.33} \epsilon_{C3} \right]^2 + \left[C_2 C_3^{.33} q_{AB}^{-.33} \epsilon_{w0-4} \right]^2 + \left[-0.33 C_2 C_3^{.33} \Delta T_{w0-4} q_{AB}^{-1.33} \epsilon_{q_{AB}} \right]^2 \right]^{1/2}$$

11. **Bestfit Equations:** Based on the Rohsenow pool boiling equation, it should be noted that the points used in determining a given bestfitting line may not be precisely at the nominal conditions of the line. As an example, the bestfitting equation for the plain tube at 60°C and a nominal level of 40 inches has vapour temperatures (T_4) of 60.4, 60.0, 58.9, and 59.4 °C for the four different power levels.

Thermocouple Calibrations

For the initial tests and calibration of the loss coefficient K_{loss} , four thermocouples were wrapped together in insulation, left for 45 minutes to come to equilibrium, and the temperature was then read:

Thermocouple	Temperature
AA	25.4
O	25.4
C	25.2
F	25.1

For the K_{loss} calibration, no thermocouple adjustments were necessary due to the small effect such adjustments would have on the value of K_{loss} .

Utilizing a simple steam bath (figure Di), the thermocouples were calibrated at atmospheric boiling temperature, and also at the freezing point in an ice bath. The differences in readings were accounted for in the data acquisition program as follows:

T1 (Thermocouple O)	+ 0.30°C
T2 (Thermocouple AA)	+ 0.30°C
T3 (Thermocouple C)	+ 0.30°C
T4 (Thermocouple F)	+ 0.50°C
T5 (Thermocouple Q)	+ 0.69°C
T6 (Thermocouple P)	+ 0.82°C

A later calibration altered the adjustments slightly, but as the test series was already half done, these adjustments were not used. The only tests using the improved adjustments are DATA130 to DATA135, but these results are not used in the analysis. Note that the 0.20°C instrument error added to the temperature reading standard deviation (see Error Analysis) covers this calibration discrepancy.

Figure Di
Thermocouple Calibration

A steam bath with thermocouples in copper tubes joined together with a solder blob in the center. The apparatus is normally covered in insulation.

Temperature Data Scatter

Boiling, being a random process, causes deviations in the temperature readings even when the system is at 'steady state'. Six tests were performed in which individual temperatures were stored, plotted in histograms and then Chi-squared tests were performed to test the probability of Gaussian distribution. The results are as follows:

- 1a. 900W Plain Tube Level-48IN 100 samples
 $T_1 = 62.21^{\circ}\text{C}$, $\sigma_1 = 0.36^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.060$
 $T_2 = 72.12^{\circ}\text{C}$, $\sigma_2 = 0.20^{\circ}\text{C}$, $P_{\text{Gaussian}} \leq 0.005$
 $T_4 = 60.85^{\circ}\text{C}$, $\sigma_4 = 0.46^{\circ}\text{C}$, $P_{\text{Gaussian}} \leq 0.005$
- 2a. 900W Plain Tube Level-48IN 106 samples
 $T_1 = 69.29^{\circ}\text{C}$, $\sigma_1 = 0.32^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.070$
 $T_2 = 78.07^{\circ}\text{C}$, $\sigma_2 = 0.24^{\circ}\text{C}$, $P_{\text{Gaussian}} \leq 0.005$
 $T_4 = 67.98^{\circ}\text{C}$, $\sigma_4 = 0.40^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.0006$

The above two tests occurred as the temperature was rising over the test period, and thus this slanted the distribution. Assuming a constant temperature rise rate, and applying it to the data points in chronological order, the following results reflect a more promising distribution:

- 1b. 900W Plain Tube Level-48IN 100 samples
 $T_1 = 62.08^{\circ}\text{C}$, $\sigma_1 = 0.35^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.120$
 $T_2 = 71.99^{\circ}\text{C}$, $\sigma_2 = 0.20^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.860$
 $T_4 = 60.72^{\circ}\text{C}$, $\sigma_4 = 0.45^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.310$
- 2a. 900W Plain Tube Level-48IN 106 samples
 $T_1 = 69.13^{\circ}\text{C}$, $\sigma_1 = 0.29^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.198$
 $T_2 = 77.92^{\circ}\text{C}$, $\sigma_2 = 0.19^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.811$
 $T_4 = 67.82^{\circ}\text{C}$, $\sigma_4 = 0.38^{\circ}\text{C}$, $P_{\text{Gaussian}} = 0.070$

The results for the above two tests (and the enhanced versions) are plotted in figures Dii and Diii.

For the tests stored in DATA206, 208, 210 and 212, a similar analysis was performed for all six thermocouples, but due to the relative stability of the system, there was no need to adjust the data.

3. DATA206 500W Instrumented Level-48IN 100 samples

$T_1 = 80.36^\circ\text{C}$,	$\sigma_1 = 0.08^\circ\text{C}$,	$P_{\text{deviation}} < 0.005$
$T_2 = 85.81^\circ\text{C}$,	$\sigma_2 = 0.07^\circ\text{C}$,	$P_{\text{deviation}} \text{ unknown}$
$T_3 = 18.35^\circ\text{C}$,	$\sigma_3 = 0.18^\circ\text{C}$,	$P_{\text{deviation}} \geq 0.025$
$T_4 = 79.28^\circ\text{C}$,	$\sigma_4 = 0.26^\circ\text{C}$,	$P_{\text{deviation}} \leq 0.005$
$T_5 = 85.41^\circ\text{C}$,	$\sigma_5 = 0.13^\circ\text{C}$,	$P_{\text{deviation}} = 0.120$
$T_6 = 83.30^\circ\text{C}$,	$\sigma_6 = 0.46^\circ\text{C}$,	$P_{\text{deviation}} = 0.080$

See Figure Div

4. DATA208 700W Instrumented Level-48IN 100 samples

$T_1 = 80.66^\circ\text{C}$,	$\sigma_1 = 0.10^\circ\text{C}$,	$P_{\text{deviation}} = 0.015$
$T_2 = 88.02^\circ\text{C}$,	$\sigma_2 = 0.08^\circ\text{C}$,	$P_{\text{deviation}} = 0.400$
$T_3 = 17.99^\circ\text{C}$,	$\sigma_3 = 0.18^\circ\text{C}$,	$P_{\text{deviation}} = 0.050$
$T_4 = 79.71^\circ\text{C}$,	$\sigma_4 = 0.18^\circ\text{C}$,	$P_{\text{deviation}} = 0.600$
$T_5 = 87.03^\circ\text{C}$,	$\sigma_5 = 0.14^\circ\text{C}$,	$P_{\text{deviation}} = 0.700$
$T_6 = 83.87^\circ\text{C}$,	$\sigma_6 = 0.35^\circ\text{C}$,	$P_{\text{deviation}} \leq 0.005$

See Figure Dv

5. DATA210 900W Instrumented Level-48IN 100 samples

$T_1 = 80.98^\circ\text{C}$,	$\sigma_1 = 0.10^\circ\text{C}$,	$P_{\text{deviation}} = 0.150$
$T_2 = 90.47^\circ\text{C}$,	$\sigma_2 = 0.06^\circ\text{C}$,	$P_{\text{deviation}} < 0.005$
$T_3 = 17.76^\circ\text{C}$,	$\sigma_3 = 0.23^\circ\text{C}$,	$P_{\text{deviation}} < 0.005$
$T_4 = 80.07^\circ\text{C}$,	$\sigma_4 = 0.13^\circ\text{C}$,	$P_{\text{deviation}} = 0.250$
$T_5 = 88.35^\circ\text{C}$,	$\sigma_5 = 0.23^\circ\text{C}$,	$P_{\text{deviation}} = 0.100$
$T_6 = 84.15^\circ\text{C}$,	$\sigma_6 = 0.39^\circ\text{C}$,	$P_{\text{deviation}} = 0.250$

See Figure Dvi

6. DATA212 1100W Instrumented Level-48IN 100 samples

$T_1 = 81.67^\circ\text{C}$,	$\sigma_1 = 0.12^\circ\text{C}$,	$P_{\text{deviation}} = 0.020$
$T_2 = 92.04^\circ\text{C}$,	$\sigma_2 = 0.12^\circ\text{C}$,	$P_{\text{deviation}} = 0.480$
$T_3 = 17.80^\circ\text{C}$,	$\sigma_3 = 0.29^\circ\text{C}$,	$P_{\text{deviation}} = 0.030$
$T_4 = 80.79^\circ\text{C}$,	$\sigma_4 = 0.12^\circ\text{C}$,	$P_{\text{deviation}} = 0.050$
$T_5 = 89.04^\circ\text{C}$,	$\sigma_5 = 0.45^\circ\text{C}$,	$P_{\text{deviation}} = 0.300$
$T_6 = 84.67^\circ\text{C}$,	$\sigma_6 = 0.43^\circ\text{C}$,	$P_{\text{deviation}} = 0.350$

See Figure Dvii

Figure Dii TEMPERATURE DISTRIBUTION
900W Plain Tube Level-48IN T4060C

The above graphs are for the unadjusted data. However, due to the drift upwards of the mean temperature (0.35C over the test period) the graphs below compensate for this drift.

Figure Diii TEMPERATURE DISTRIBUTION
900W Plain Tube Level-48IN T4068C

The above graphs are for the unadjusted data. However, due to the drift upwards of the mean temperature (0.40C over the test period), the graphs below compensate for this drift.

Figure Dv TEMPERATURE DISTRIBUTION DATA206

500W Instrumented Level-48IN T4080C

Figure Dv TEMPERATURE DISTRIBUTION DATA206

700W Instrumented Level-48IN T4080C

Figure Dvi TEMPERATURE DISTRIBUTION DATA 210
900W Instrumented Level-48IN T400C

Figure Dvi TEMPERATURE DISTRIBUTION DATA 212
1100W Instrumented Level-48IN T400C

Wattmeter Output

The wattmeter was necessary to measure the AC power delivered to the 1000W heating element, the majority of which is then transferred to the test surface. The wattmeter transducer used for the tests was designed for use in the 1000 to 10000 watt range, with a linear DC voltage output of 0.5 to 5.0V over that range. Since the tests were performed at powers between 200 and 1150 watts, the transducer operated in the lower 10% of its range. Despite this, the transducer performed well in this range, with a linear response of:

$$Pwr = 2025V + 17$$

where V is the voltage output of the transducer. Of course at low power this equation breaks down, but this was irrelevant for the test program. In order to determine the power transducer equation, a second power meter with an LED output was placed in the power circuit in order to provide the power readings. In the case of the power loss coefficient (K_{loss}) analysis, this equation was not used due to the low level power required; instead the second power meter was used to provide an accurate power reading.

The wattmeter equation worked well for the tests, and an error of $\pm 3W$ covers any slight drift from the true power input.

Power Loss Coefficient Calibration

It was essential to know the heat loss from heatpipe1 directly to the atmosphere in order to more accurately know the heat flux at the test surface. The calibration of this heat loss coefficient was simple, albeit somewhat crude; a thermocouple (AA) was attached to the outer surface of the heating element chamber beneath the layer of insulation that normally encased the whole test rig. Due to the low power, and thus heat flux, through the walls of the chamber, T_{AA} was assumed to read the same temperature as the vapour within the heater chamber (T_2). Thermocouple C took its usual role, and gave the ambient temperature (T_3). Knowing the power, and the temperature difference $T_2 - T_3$, an assumption is made that the loss is in the form of convective heat loss:

$$P_{w_{loss}} = K_{loss} * T_2 - T_3$$

In order to prevent further heatloss up the rest of heatpipe1 and into the coolant in heatpipe2, air was admitted into heatpipe1 in order to maintain a gas-vapour interface at the top of the heater chamber. Water vapour is prevented from travelling past the interface and only a small amount of heat is conducted up the walls of heatpipe1 - the majority of the heat produced should be transferred through the walls of the heater chamber, the insulation and then to the atmosphere.

The difficult part of the heatloss calibration test was knowing the location of the interface; two thermocouples were attached to heatpipe1 near the flange junction with heatpipe2. Since the wall above the interface was cool in comparison with the wall below (water vapour condensing on the wall below the interface provided a high heat transfer, and there was only a limited amount of conduction and convection above the interface), when the two thermocouples - F above and D below - registered a large temperature difference, it was assumed that the interface lay between them. By cautious admission or evacuation of air to and from heatpipe1, the interface was adjusted to the correct position; and when it stayed virtually motionless, a reading of the K_{1000} value was made. This process, along with the fine adjustments of the input power, proved tedious while awaiting "steady state" - the results can only be considered reasonable approximations:

Power	T_{2-3}	K_{1000}
17.3	51.0	0.34
21.6	58.5	0.38
24.7	66.7	0.37

In order to be conservative, a K_{1000} value of 0.4 W/°C was used for the test series, with an error of $\pm 0.05^\circ\text{C}$. For further enlightenment on the calibration technique, refer to figures Dviii and Dix.

Figure Dviii
Heatloss Coefficient Calibration

Thermocouple C (marked T3) measures ambient temperature, while AA (T1) measures the wall temperature beneath the insulation. T2 and T4 measure the location of the air/vapour interface in heatpipe1.

Figure Dix
Kloss CALIBRATION SETUP

Test Rig Adiabaticity

The test rig was wrapped with a double layer of foil backed fiberglass insulation (a total thickness of about 1.5 inches) in order to reduce the effect of changing ambient conditions (the bay where the experiments were conducted was subject to temperature drops of 8°C and considerable drafts at times), and to more closely imitate the full scale backup decay heat rejection system. The primary cooling of heatpipe2 occurred in the condensor at the top of the test rig, and the condensate ran down its outer wall. Insulating the outer wall reduced the heatloss by conduction through the two-phase fluid, and thus the majority of the heat was used in vapourizing the water. In the full scale backup decay heat rejection system, the evaporator section is entirely immersed in the SLOWPOKE pool, and all of the heat input is used for vapourization, with heat rejection only in the condensor section. Thus it was appropriate for the test rig to dispose of the heat only in its condensor.

Tests of the adiabaticity of the wall were relatively simple; knowing the heat input, and the losses to the atmosphere in the heater section (K_{loss}), the net heat input was disposed of via the condensor and through the outer wall of heatpipe2. The coolant flow rate with its input and output temperatures was measured, and using the specific heat of water (4200 J/kg°C) the total heat rejection to the condensor was calculated. The difference between this and the net heat input provided a measure of the adiabaticity of the outer walls of heatpipe2. It should be noted that the coolant flow rates were low, especially when the heat flux was low and the vapour temperature was high. This introduced considerable error in this analysis, and also caused control problems for the test rig - low flow rates proved difficult to adjust in small steps. This was a third reason for insulating the rig; with the condensor providing the majority of the cooling a larger and more controllable coolant flow was required. Based on the difference between the vapour temperature (T_4) in heatpipe2 and the ambient temperature T_3 , H_{loss} is the overall heat loss coefficient.

Adiabaticity Test Results:

Test set	Wall losses W	ΔT_{4-3} °C	H_{loss} W/°C
DATA1	48.8	36.5	1.3
DATA3	-27.3!	54.3	-.-
DATA5	34.7	27.9	1.2
DATA6	80.8	37.2	2.2
DATA7	45.7	48.2	0.9
DATA8	100.4	57.2	1.8
DATA9	74.6	65.9	1.1
DATA12	79.9	24.3	3.3
DATA13	-118.1!	38.8	-.-
DATA15	106.2	57.9	1.8
DATA16	99.8	69.3	1.4
DATA17	279.6	81.6	3.4
DATA22	95.8	49.7	1.9
DATA23	94.6	59.2	1.6
DATA24	107.5	69.7	1.5
DATA26	70.3	29.8	2.4
DATA27	24.8	38.6	0.6
DATA28	134.3	50.9	2.6
DATA29	113.9	56.8	2.0
DATA30	146.2	66.0	2.2
DATA44	131.0	42.6	3.1
DATA50	104.8	59.9	1.8
-----	43.0	45.7	0.9
-----	50.0	48.2	1.0
-----	49.3	47.2	1.0
DATA77	57.0	41.8	1.4
DATA78	94.1	62.3	1.5
DATA79	128.3	81.4	1.6
DATA84	132.6	80.7	1.6
-----	72.0	75.6	1.0
-----	67.7	37.0	1.8

The average H_{loss} is 1.7 W/°C. For a worse case with a total power of 500W, $T_4 = 100^\circ\text{C}$, $T_3 = 20^\circ\text{C}$ and $T_2 = 110^\circ\text{C}$, the net heat input is 464W. Using H_{loss} , the loss through the outer walls of heatpipe2 is 29% of the net heat input. For a best case with power = 1100W, $T_4 = 60^\circ\text{C}$, $T_3 = 20^\circ\text{C}$ and $T_2 = 70^\circ\text{C}$, the heat input is 1050W. The heat loss through the outer walls is 6.5% of the net heat input. H_{loss} is a conservative value due to an uninsulated condensor, but evidently heatpipe2 is reasonably well insulated.

Saturation Pressure-Temperature Relationship

It was deemed necessary to show that the thermocouple measuring the vapour temperature T_4 was indeed providing the saturated steam temperature for heatpipe2. A mercury-filled manometer was attached to a three way connector attached to the top of heatpipe2. One passage from the connector led to an aspirator, and at the beginning of a test a valve was opened in order to remove air from heatpipe2. When the short steel pipe stem from heatpipe2 became hot, the water vapour in that heat pipe was evidently condensing there, and thus all of the air had been evacuated. Only then was T_4 truly registering the steam temperature; the connection to the manometer was now reading the saturation pressure.

The results for the tests are as follows:

<u>T_4</u> °C	<u>Pressure</u> kPa	<u>Saturation Temperature</u> °C
93.8	81.0	94.0
80.8	50.4	81.5
71.2	34.4	72.3

When the errors in the manometer (± 0.2 inches Hg or 0.7 kPa) are considered, along with the 0.2°C thermocouple error and the fluctuations in steam temperature normally seen during a test, it is evident that T_4 provides a very good measurement of the true steam saturation temperature. Only if air managed to leak into heatpipe2 would T_4 give an incorrect saturation temperature, and as mentioned above, the tests were only done after the aspirator was engaged, and the pipe stem had become hot.

Steam Table Best Fit Curves

The following equations were used in the PASCAL computer program BOILDATA, UNIT SteamTbl. They are merely best-fit curves developed for the temperature range of 40 to 120°C, using data from Steam and Air Tables in SI Units.

Thermal Conductivity:

$$k_r = 0.4670013 \quad T^{0.08187892} \quad \{W/m^\circ C\}$$

Dynamic Viscosity:

$$\mu_r = \frac{1}{110 + 34.20351 \quad T} \quad \{kg/m-s\}$$

Surface Tension:

$$\sigma_r = 7.708394 \times 10^{-2} - 1.827858 \times 10^{-4} \quad T \quad \{N/m\}$$

Specific Heat:

$$c_{p,r} = 4143.714 + 0.7321429 \quad T \quad \{W/m^\circ C\}$$

Liquid Density:

$$\rho_r = 1009.8685 - 0.0028308 \quad (T + 41.79)^{1.9797107} \quad \{kg/m^3\}$$

Vapour Density:

$$\rho_g = 7.9639 \times 10^{-7} \quad T^{2.9341} \quad \{kg/m^3\}$$

Heat of Vapourization:

$$h_{r,g} = 3.250 \times 10^6 - 3.47345 \times 10^{-3} \quad (T + 957)^{2.796377} \quad \{J/kg\}$$

Appendix E

Computer Programs and Algorithms

Computer Program Description.....	E1
THERMO1 Algorithm.....	E2
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Math UNIT Listing.....	E28
SteamTbl Listing.....	E31

Computer Program Description

THERM01, written in HP-BASIC for the HP 9826 computer, controlled the Hewlett Packard 3421A data acquisition unit, read data, converted the input voltages to temperature and power readings, and stored these readings on floppy disks.

DATA CRUNCH, the second HP computer program, manipulated the readings stored by THERM01 into the boiling temperature difference ΔT_{boil} , and printed this out along with the temperatures, power, heat flux and standard deviations.

Boiling_Data and Boiling_Data_Inc/DecHeatflux were basically the same program, one for constant heat flux, the other for increasing/decreasing heat flux tests. Written in Turbo Pascal 4.0 for the IBM PC, these programs were similar to DATA CRUNCH except that they reprocessed the raw temperature data points, with the associated standard deviations and power levels. These programs used improved steam table approximations, and produced the error bands developed in Appendix D, along with the Rohsenow surface coefficient C_{sf} .

DECAYHRS was developed to model the heat output of the entire full scale evaporator. The inputs are the temperatures of the pool and of the inner annulus output; the inner vapour temperature and total theoretical heat transfer are calculated from natural convection and pool boiling equations.

THERMO1 Algorithm and Listing

- A) 10 - 110: Initialize the array variables, and read the time and date.
- B) 120 - 210: Read reference temperature and thermocouple coefficients (for the conversion of voltages to temperatures), and set constants.
- C) 220 - 330: The main program, where line 270 invokes a SPIN statement to hold the program in a loop until a subroutine is called.
- D) 340 - 1000: Subroutine **Takedata**
- i) 350 - 430: Initialize printing to screen, set a hot key to break subroutine. Input title, number of readings (<100), samplesize, time between readings, and whether or not the output is to be printed.
 - ii) 440 - 550: Send reminder notice to screen of thermocouple location. Set printer as output (rather than screen) if requested. Set D\$ and T\$ to store time and date of the beginning of the test.

iii) 560 - 910: Loop until the last reading is taken.

1) 570: Set reference time to the present

2) 580 - 630: Write time, date & reading number to the screen or printer (as previously set).

3) 640 - 670: Input reference temperatures for each thermocouple.

4) 680: Call Subroutine **Temperature**

5) 690 - 740: Thermocouple temperature adjustments

6) 750 - 820: Read power meter voltage, convert it to a power, then to a heat flux.

7) 830 - 860: Output temperatures and their standard deviations.

8) 870 - 900: Delay loop (if needed) between readings, printer page feed (if needed).

iv) 920 - 970: Write to screen reading set finished.

E) 1010 - 1170: Subroutine **Datastor**

i) 1020 - 1080: List disk catalogue, prompt as to whether it is the correct disk.

ii) 1090 - 1140: Input filename, set storage path, output data to file, close file.

F) 1180 - 1470: Temperature subroutine

- i) 1190: Set a break key
- ii) 1210 - 1250: Initialize temperature summing variables to 0 .
- iii) 1260 - 1380: Loop from 1 to samplesize
 - 1) 1270 - 1280: Display samplenum on screen, set output speed & precision.
 - 2) 1290 - 1360: Loop from 1 to number of thermocouples, enter voltage for each thermocouple, convert it to a temperature and store it in the appropriate temperature sum.
- iv) 1390 - 1440: Loop from 1 to number of thermocouples, produce average temperature and the standard deviation for each reading.

G) 1500 - 1510: DATA statements for the thermocouple and reference temperature coefficients.

H) 1520: END statement


```

10 PRINT "K-TYPE THERMOCOUPLE PROGRAM"
20 PRINT "H-P 9826 VERSION WITH 3421A DATA ACQUISITION"
30 DIM R(0:2), P(0:9), Temp(6,100), Sgmex(6,100), Htf1x(100), Wattmtr(100), Rf(6), Sumt(6), Sumt2(6)
40 DIM Title$(50)
50 REAL S, Samplesize
60 INTEGER N1
70 PRINTER IS 1
80 INPUT "Enter DATE eg: 2 AUG 1988", D$
90 INPUT "Enter TIME eg: 19:32:17", T$
100 SET TIMEDATE DATE(D$)
110 SET TIME TIME(T$)
120          ' READ COEFFICIENTS
130 P(0) = -8.2E-7
140 R(1) = 3.964E-5
150 P(2) = 1.6E-8
160 FOR H = 0 TO 9
170     READ P(H)
180 NEXT H
190 Losscoef = .4 ' W/degC FOR TEMP2-TEMP3
200 Boilarea = .0965 ' BOILING SURFACE AREA IN m^2
210 Nather = 6 ' 6 THERMOCOUPLES ARE READ
220 ON KEY 0 LABEL "TAKEDATA" GOSUB Takedata
230 ON KEY 1 LABEL "DATASTOP" GOSUB Datastop
240 ON KEY 2 LABEL "STOP" GOTO 300
250          '
260          '
270 Spin: GOTO Spin
280          '
290          '
300 PRINT "Program stopped"
310 STOP
320          '
330          '
340 Takedata: ' OBTAINS DATA SET FROM 3421A
350 PRINTER IS 1
360 ON KEY 3 LABEL "BREAK2", 2 GOTO 970
370 INPUT "Enter TITLE of test", Title$
380 INPUT "Enter NUMBER OF READINGS (1-100)", N1
390 IF N1 < 100 OR N1 > 1 THEN 380
400 INPUT "Enter samplesize", Samplesize
410 IF Samplesize < 2 THEN Samplesize = 2
420 INPUT "Enter TIME between readings (sec)", Dtime
430 INPUT "Hardcopy (Y or N)", R$
440 PRINT "T'couple # Location"
450 PRINT "*****"
460 PRINT " 1 2-phase in heatpipe #2"
470 PRINT " 2 Vapour in heatpipe #1"
480 PRINT " 3 Ambient"
490 PRINT " 4 Vapour in heatpipe #2"
500 PRINT " 5 Inner surface heatpipe #2"

```

```

510 PRINT " 6 Inner surface heatpipe #2"
520 IF Q$ = "Y" THEN PRINTER IS 801
530 D$ = DATE$(TIMEDATE)
540 T$ = TIME$(TIMEDATE)
550 !
560 FOR J = 1 TO N1 ' N1 Total readings
570 Rftime = TIMEDATE
580 IF (J-1) MOD 10 <> 0 OR Q$ = "N" THEN 630
590 PRINT Title$
600 PRINT "Temperature (T1,T2,T3,T4) in Celsius, Power in Watts, Heatflux in W/m^2"
610 PRINT "Samplesize;"samples per reading."
620 PRINT "*****"
630 PRINT DATE$(TIMEDATE);" ";TIME$(TIMEDATE);" Reading#;J;
640 FOR I = 1 TO Nather
650 OUTPUT 715;"REF";I+2
660 ENTER 715;Rf(I)
670 NEXT I
680 GOSUB Temperature
690 Temp(1,J) = Temp(1,J) + .3 'Adjustments to the thermocouples
700 Temp(2,J) = Temp(2,J) + .3 'from tests done at 100degC
710 Temp(3,J) = Temp(3,J) + .3
720 Temp(4,J) = Temp(4,J) + .3
730 Temp(5,J) = Temp(5,J) + .69
740 Temp(6,J) = Temp(6,J) + .82
750 OUTPUT 715;"DCV9"
760 ENTER 715;Wattvolt
770 Wattmtr(J) = DROUND(2025 + Wattvolt + 17, 4)
780 IF Wattmtr(J) < 17 THEN Wattmtr(J) = 0
790 Htflx(J) = DROUND(Wattmtr(J) - Losscoef * (Temp(2,J) - Temp(3,J))) / Boilarea, 4)
800 IF Wattmtr(J) < 10 THEN Htflx(J) = 0
810 PRINT " Power=";Wattmtr(J);" Heatflux=";Htflx(J)
820 IF Htflx(J) < 0 THEN Htflx(J) = 0
830 PRINT "T1=";Temp(1,J);"S1=";Sgma(1,J);" T2=";Temp(2,J);"S2=";Sgma(2,J)
840 PRINT "T3=";Temp(3,J);"S3=";Sgma(3,J);" T4=";Temp(4,J);"S4=";Sgma(4,J)
850 PRINT "T5=";Temp(5,J);"S5=";Sgma(5,J);" T6=";Temp(6,J);"S6=";Sgma(6,J)
860 PRINT "-----"
870 IF J = N1 THEN 910
880 IF TIMEDATE - Rftime = Ditime THEN 900
890 GOTO 880
900 IF J MOD 14 = 0 AND Q$ = "Y" THEN PRINT USING "e"
910 NEXT J
920 !
930 DISP " "
940 PRINTER IS 1
950 PRINT "READING SET OVER"
960 GOTO 980
970 DISP "SECOND BREAK"
980 RETURN 'Takedata
990 !
1000 !

```

```

1010  Daststor:      ! STORES DATA IN A FILE
1020    CAT
1030  INPUT "Correct disk (Y or N)?",R$
1040    IF R$ = "Y" THEN 1090
1050  PRINT "Change disk, ENTER 'Y' when ready"
1060  INPUT P$
1070    IF P$ = "Y" THEN 1020
1080  GOTO 1050
1090  INPUT "ENTER FILE NAME FOR DATA",Stor$
1100  CREATE BDAT Stor$,51
1110  ASSIGN @Path1 TO Stor$;FORMAT ON
1120  OUTPUT @Path1;D$,T$,Nather,N1,Dltime,Samplesize,Temp(*),Htflx(*),Wattmtr(*),Sgma(*),Title$
1130  ASSIGN @Path1 TO *
1140  PRINT "Data stored in";Stor$
1150  RETURN          ' Daststor
1160      '
1170      '
1180  Temperature:   'CONVERTS EMF TO TEMPERATURE
1190  ON KEY 3 LABEL "BREAK1",5 GOTO 1460
1200      '
1210  FOR I = 1 TO Nather
1220    Sumt(I) = 0
1230    Sumt2(I) = 0
1240  NEXT I
1250      '
1260  FOR k = 1 TO Samplesize
1270    DISP "Sample #";K;"of";Samplesize
1280    OUTPUT 715;"TOLSO-B;FIZONST3"
1290    FOR I = 1 TO Nather
1300      ENTER 715;V
1310      V = R(0) + Rf(I) * (R(1) + Rf(I)*R(2)) + V
1320      T=V * (P(5) + V * (P(5) + V * (P(7) + V * (P(8) + V * P(9))))))
1330      T = P(0) + V * (P(1) + V * (P(2) + V * (P(3) + V * (P(4) + T))))
1340      Sumt(I) = Sumt(I) + T
1350      Sumt2(I) = Sumt2(I) + T^2
1360    NEXT I
1370  NEXT K
1380      '
1390  FOR I=1 TO Nather
1400    S = (Samplesize * Sumt2(I) - Sumt(I)^2) / (Samplesize * (Samplesize - 1))
1410    IF S <= 0 THEN S = 0
1420    Sgma(I,J) = DROUND(SQR(S),1)
1430    Temp(I,J) = DROUND(Sumt(I)/Samplesize,4)
1440  NEXT I
1450  GOTO 1470
1460  PRINT "FIRST BREAK"
1470  RETURN          'Temperature
1480      '
1490      '
1500  DATA -5.1E-2, 2.48503E4, -3.826E2E5, 9.9661057E7, -1.0820624E10, 6.0392855E11, -1.9109E13
1510  DATA 3.4782347E14, -3.3991028E15, 1.3828514E16
1520  END

```

Boiling Data Algorithm and Listing

- A) PROGRAM Initialization: USES Math UNIT to provide exponentiation (Powers FUNCTION), and SteamTbl UNIT to provide saturated steam properties; these UNITS are listed at the end of this appendix. Variable and constant declaration.
- B) PROCEDURE LineOfChars: Prints a line of characters (character & number specified in PROCEDURE call).
- C) PROCEDURE Directory: Performs DOS directory command depending upon input mask from FUNCTION GetFileName.
- D) FUNCTION GetFileName: Prompts user for filename, and adds the extension ".dat". If user types in a DOS-style mask (like Data??? or simply a <RETURN>), the mask is sent to FUNCTION Directory.
- E) PROCEDURE LastData: Reads the entire specified file, and writes to screen the last data set placed in that file.

F) PROCEDURE FileOpen: Calls FUNCTION GetFileName, attempts to open specified file. If file exists, the PROCEDURE LastData is called, and new data later input to the program will be appended to file. If file is non-existent, a new file will be opened; if there is some file writing error, the user is informed. Before leaving FileOpen, the user is prompted as to whether the file now opened is correct.

G) FUNCTION TrueS: Returns the true standard deviation for the temperatures in a data point; the main PROGRAM receives the standard deviations for the several data readings which make up the data point.

H) PROCEDURE Condensing Coefficient: Returns the value of C_1 , which is derived from the Nusselt condensation equation :

$$C_1 q_{AB}^4 = h_{fg} \Delta T_{2-w1}^3 + .68 c_p \Delta T_{2-w1}^4$$

$$C_1 = \left[\frac{R_o/R_i}{.943 \left[\frac{p_r (p_r - p_a) g k_r^3}{\mu_r L} \right]^{1/4}} \right]^4$$

The R_o/R_i { $RoRi$ } value is necessary since the boiling heat flux is used in the condensation equation, rather than the condensing heat flux.

I) **PROCEDURE DataInput:** It prompts the user for test title, the number of readings, the number of samples per reading, the average power for the readings, the ratio R_0/R_1 , and the average ambient temperature and its standard deviation. This initial data input is written to screen, and asks the user if it is acceptable. The **sumT**, **sumTsqr**, and **sumSsqr** values (ΣT , ΣT^2 , Σs^2) are initialized to zero for both T2 and T4. DataInput then uses a loop from 1 to the number of readings (**m**) to read from the keyboard the **m** readings (T2, s2, T4, s4), with a small check loop to ensure proper data formatting. After the reading is entered, the appropriate **sumT**, **sumTsqr** and **sumSsqr** values are updated.

J) **PROCEDURE SaturatedProperties:** Returns the saturated steam properties from the **SteamTbl** UNIT for whatever temperature was in the PROCEDURE call (Note that the steam table equations were only fitted to work in the 40°C to 120°C range).

K) **PROCEDURE PrintData:** Prints out the entire contents of a file in compressed print mode.

L) Main PROGRAM: Clears screen, program title written to screen.

i) REPEAT loop UNTIL user is finished with the program.

1) Call PROCEDURE FileOpen, ask whether to store data in the now open file, to print the file, or to quit to either leave the program or to seek another file.

2) If data is to be stored, and the open file is valid, call PROCEDURE DataInput to read in the data readings for a given dataset. Using the sumT , sumTsqr and SumSsqr values, solve the average $T2$ and $T4$ values with their associated standard deviations, adding to the latter to give the errors $W2$ and $W4$, and also $W3$.

3) Solve the netPower into the test section, and the boiling heat flux qAB and the error $WqAB$. Call on PROCEDURE SaturatedProperties and PROCEDURE CondensingCoefficient for $T2-W2$, $T2$, and $T2+W2$, providing the respective condensing coefficients C_{minus} , $C1$ and C_{plus} .

4) Make first guesses for the condensing temperature difference $T2wi$; $T2wi1 = (qAB^4 * C1/hfg)^{.333}$

$$T2wi2 = 0.90 * T2wi1$$

the first guess being a close approximation of the simplified condensing equation in section H.

- 5) Use a REPEAT loop to solve the left (lhs) and right (rhs) sides of the equation from section H:

$$q_{\text{as}}^4 * C_1 = h_{\text{fg}} * T_{2-\text{wi}}^3 + .68 * c_p * T_{2-\text{wi}}^4$$

with the latest values of T2wi1 and T2wi2 and the corresponding C1 values, and the relevant property values updated at the latest film temperature.

The new value of T2wi2 is a linear interpolation of T2wi1, T2wi2, rhs1, rhs2 and lhs. When the old and new values of T2wi are very close to each other, the equation is considered solved and the loop exited.

- 6) The value of T2wi now solved, the error on the condensing coefficient is established, and with it the error W2wi. Using simple one radial conduction, the outer wall temperature Two and its error Wwo is established, and thus Two4 and its error Wwo4 can be deduced.

- 7) The Rohsenow boiling surface coefficient Csf is calculated, with the corresponding error band.

- 8) The averaged temperatures, heat flux, power, Csf, Two4, errors, sample size and number of readings, plus the title, is stored in the file, and the user is prompted as to whether or not to enter a new dataset.

- ii) If selected to print out a file, PROCEDURE PrintData is invoked, but only after asking the user if the file is correct.

M) PROGRAM END.


```
PROGRAM Boiling_Data; {Program receives temperature, power and other data from
                        the keyboard, manipulates it & then stores it in a file}
```

```
USES DOS, CRT, PRINTER,
```

```
    Math,
```

```
                                {Provides Powers FUNCTION}
```

```
    SteamTbl;
```

```
                                {Provides kf, muf, sigmaf, cpf, pf, pg, hfg}
```

```
{M 16384, 0, 0}
```

```
VAR
```

```
    dataFile: TEXT;
```

```
    dataFileName, title, auxTitle, dataSet, testDate: STRING;
```

```
    continueKey, dataRoute, RoRiKey: CHAR;
```

```
    openFile, newFile: BOOLEAN;
```

```
    power, netPower, RoP1, S2, S3, S4, sumT2, sumT4, sumT2sqr,
```

```
    sumT4sqr, sumS2sqr, sumS4sqr, W2, W3, W4, WqAB, W2wi, WC1, Wwo, Wwo4,
```

```
    Wc2, Wc3, Wcsf, qAB, C1, C2, C3, C1plus, C1minus, C2plus, C2minus,
```

```
    C3plus, C3minus, Csf, rhs1, rhs2, lhs, T2, T3, T4, T2wi, T2wi1, T2wi2,
```

```
    T2wiTemporary, Two, Two4: REAL;
```

```
    m,n,j, ioCode: INTEGER;
```

```
CONST
```

```
    wp = 3.0;
```

```
                                {Power error in Watts}
```

```
    Kloss = 0.4;
```

```
                                {Power loss coefficient (dependent upon T2-T3)}
```

```
    wKloss = 0.05;
```

```
                                {Error in power loss coefficient}
```

```
    condensingLength = 1.2065; {Length of the tube on which condensation occurs}
```

```
    g = 9.81;
```

```
                                {gravitational acceleration in m/s2}
```

```
    error1 = 0.001; {Error used in calculating condensation temperature drop}
```

```
    kss = 17.3;
```

```
                                {Stainless steel thermal conductivity in W/m-K}
```

```
    areaBoil = 0.0965; {Total heat transfer area in m2, regardless of level}
```

```
PROCEDURE LineOfChars (displayChar: CHAR; lineLength: BYTE);
```

```
VAR
```

```
    i: INTEGER;
```

```
BEGIN
```

```
    FOR i:= 1 to lineLength DO
```

```
        WRITE (displayChar);
```

```
    WRITELN
```

```
END;
```

```
                                {LineOfChars}
```

```
PROCEDURE Directory (mask:STRING);
```

```
BEGIN
```

```
    LineOfChars ('.', 75);
```

```
    EXEC('a:\COMMAND.COM', '/C DIR ' + mask + '/w');
```

```
    LineOfChars ('.', 75)
```

END; {Directory}

```
FUNCTION GetFileName: STRING;      {Elicits filename or DIR mask from keyboard}
```

VAR

```
goodName, dirRequest: BOOLEAN;
```

```
lnName:          STRING;
```

```
periodPos:      BYTE;
```

BEGIN

```
goodName := FALSE;
```

```
WHILE NOT goodName DO
```

BEGIN

WRITELN;

```
WRITE ('Account Name? ');
```

```
READLN (InName);
```

```
IF InName = '' THEN (If <RETURN> pressed, display *.DAT in directory)
    Directory('*.DAT')
```

```
Directory('*.*.DAT')
```

ELSE

BEGIN (Search for wildcard inputs in the input)

dirRequest :=

```
(POS('*', inName) <> 0) OR (POS('?', inName) <> 0);
```

```
IF dirRequest THEN
```

Directory (inName)

ELSE

```
goodName := TRUE;
```

```
periodPos := POS('.', inName);    {Eliminate any given extension}
```

```
IF periodPos <> 0 THEN
```

```
inName := COPY(inName, 1, periodPos - 1);
```

END

END;

```
GetFileName := inName + '.DAT' (Add .DAT as extension, & return filename)
```

```
END;      (GetFileName FUNCTION)
```

PROCEDURE LastData: (Writes to screen the last data set within a given file)

BEGIN

```
RESET (dataFile);
```

```
WHILE NOT EOF(dataFile) DO
```

BEGIN

```
READLINE (dataFile,title);
```

```
READLN (dataFile, m, n, power, T2, W2, T3, W3, T4, W4, Two4, Wwo4,
        qAB, wqAB, Csf, Wcsf);
```

END:

```
LineOfChars ('=',75);
```

```
WRITELN ('The most recent data input in file: ',dataFileName);
```

```

LineOfChars(' ',75);
WRITELN (title);
WRITELN (m,' readings at ',power:2,' Watts. ');
WRITE ('Ambient temperature = ',T3:1,' °C ');
WRITELN ('Driving vapour temp = ',T2:1,' °C');
WRITELN ('Saturation temp = ',T4:1,' °C');
WRITELN ('Heatflux = ',qAB:0,' ± ',wqAB:0,' W/m²');
WRITELN ('Boiling temperature difference= ',Two4:2,' ± ',Wwo4:2,' °C');
WRITELN ('Rohsenow boiling coefficient = ',Csf:5,' ± ',Wcsf:5);
LineOfChars (' ',75);

END;                                     {LastData PROCEDURE}

PROCEDURE FileOpen;                     {Requests a file, and opens it}

BEGIN
  REPEAT
    dataFileName := GetFileName; {Call GetFileName to elicit target file}
    ASSIGN (dataFile, dataFileName);
    openFile := TRUE;
    newFile := FALSE;
    { $I- }
    APPEND (dataFile); {First try to open the file in the APPEND mode}

    IF IORESULT <> 0 THEN
      BEGIN
        REWRITE (dataFile); {If file doesn't exist yet, open as new file}
        { $I+ }
        newFile := TRUE;
        IF IORESULT <> 0 THEN {If REWRITE gave err, filename unusable}
          BEGIN
            WRITELN;
            WRITELN (' *** Can't Open File ***');
            WRITELN;
            openFile := FALSE;
          END
        ELSE
          WRITELN(dataFileName, ' newly created.')

        END

      ELSE
        LastData;

        WRITE(' Correct File (y or n)? ');
        continueKey := READKEY;
        UNTIL continueKey = 'y'

    END;

  END;                                     {FileOpen}

```

```
FUNCTION TrueS (sumSSqr, sumTSqr, Tavg : REAL) : REAL;
```

```
  BEGIN    (Supplies true standard deviation from several standard deviations)
    TrueS := SQRT( ( (N-1)*sumSSqr + N*sumTSqr - M*N*SQR(Tavg) ) / (M*N-1) )
  END;
```

```
PROCEDURE CondensingCoefficient ;
```

```
  BEGIN
    C1 := Powers( RoR1 / (0.943 *
      Powers( pf*(pf-pg)*g*kf*kf*kf / (muf * condensingLength),0.25 ),4)
  END;
```

```
PROCEDURE DataInput;
```

```
  BEGIN
    REPEAT
      WRITELN;
      WRITELN ('Input test Title');          READLN (title);
      WRITE ('Input DATA set (ie : "20")');  READLN (dataSet);
      WRITE ('Input test date (ie : "07 Nov 88")'); READLN (testDate);
      title := title + ' ' + 'DATA' + dataSet + ' ' + testDate;
      WRITE ('Number of readings?');          READLN (m);
      WRITE ('Number of samples per reading?'); READLN (n);

      WRITELN ('Ro/Ri ratio - 8/7<a> or 4/3<b> ?');
      RoRiKey := READKEY;
      IF RoRiKey = 'b' THEN
        RoR1 := 1.3333
      ELSE
        RoR1 := 1.1429;

      WRITE ('Average Power?');              READLN (power);
      WRITE ('Avg ambient temp, std deviation?'); READLN (T3, S3);

      LineOfChars('-',75);
      WRITELN (title);
      WRITE('n, ' readings of ',n, ' samples/rdg. ');
      WRITELN ('Po/R1 = ',RoR1:5:4, ' The average power is ',power:5:0, ' Watts');
      WRITELN ('Ambient Temperature = ',T3:3:1, '°',S3:3:1, ' °C');
      LineOfChars('-',75);

      WRITELN;
      WRITELN ('Correct setup (y or n)?');
      continueKey := READKEY

    UNTIL continueKey = 'y';
```

```

sumT2 := 0;      sumT4 := 0;
sumT2sqr := 0;  sumT4sqr := 0;
sumS2sqr := 0;  sumS4sqr := 0;

FOR j := 1 to n DO
  BEGIN
    REPEAT
      WRITE ('Reading#',j),' :type T2, S2, T4 & S4: ');
      { $I- }
      READLN (T2, S2, T4, S4);
      { $I+ }
      ioCode := IORESULT;
      IF ioCode  $\neq$  0 THEN
        WRITELN (#7,'Bad data: PE-ENTER DATA');
      UNTIL ioCode = 0;

      sumT2 := sumT2 + T2;          sumT4 := sumT4 + T4;
      sumT2sqr := sumT2sqr + SQR(T2);  sumT4sqr := sumT4sqr + SQR(T4);
      sumS2sqr := sumS2sqr + SQR(S2);  sumS4sqr := sumS4sqr + SQR(S4);
    END
      (loop input of temperatures and standard deviations)

  END;
  (DataInput Procedure)

```

```
PROCEDURE SaturatedProperties (saturatedTemperature:PEAL);
```

```

BEGIN
  SpecificHeat (saturatedTemperature);      {cpf}
  HeatOfVapourization (saturatedTemperature); {hfg}
  VapourDensity (saturatedTemperature);      {pg}
  LiquidDensity(saturatedTemperature);      {pf}
  ThermalConductivity (saturatedTemperature); {kf}
  Viscosity (saturatedTemperature);          {muf}
  SurfaceTension (saturatedTemperature);    {sigmaf}
END;
  (SaturatedProperties)

```

```
PROCEDURE PrintData;
```

```

BEGIN
  WRITELN ('Enter title for this entire set of data');
  READLN (auxTitle);

  WRITE (Lst,#27#108#10);          {Set left margin}
  WRITE (Lst,#27#97#1,auxTitle,#27#97#0); {auxTitle centered}
  WRITE (Lst,#15);                 {Compressed print}
  WRITELN (Lst,#27#68#65#75#90#105#0); {Set tabs}

  WRITELN (Lst,'Test Title',#27#102#0#53,'Saturation Boiling ',
    ' Boiling Rohsenow');
  WRITELN (Lst,#27#102#0#63,'Temperature Heatflux',

```

```

      ' Temp Difference Coefficient');
WRITELN (Lst,#27#102#0#67,' °C      W/m²      °C      Csf');

RESET (dataFile);
WHILE NOT EOF(dataFile) DO
  BEGIN
    READLN (dataFile,title);
    READLN (dataFile, m, n, power, T2, W2, T3, W3, T4, W4, Two4, Wwo4,
      qAB, wqAB, Csf, Wcsf);
    WRITELN (Lst,title,#9, T4:5:1,#9, qAB:5:0,' ± ',wqAB:3:0,#9,
      Two4:4:1,' ± ',Wwo4:3:1,#9,Csf:5:4,' ± ',Wcsf:6:4);
  END;

  WRITELN (Lst,#18);           {Restore printer to normal print}
  WRITELN (Lst,#27#108#0)      {Restore normal margins}

END;                           {Printing PROCEDURE}

BEGIN                           {BoilData program}
  CLRSCR;
  WRITELN ('      BOILDATA PROGRAM');
  LineOfChars ('*',75);

  REPEAT
    FileOpen;

    REPEAT
      WRITELN (' <f>ile storage, or <p>rint data or <q>uit?');
      dataRoute := READKEY
    UNTIL (dataRoute = 'f') OR (dataRoute = 'p') OR (dataRoute = 'q');

    IF dataRoute = 'f' THEN
      BEGIN
        IF openFile THEN           {If it's a valid, open file}      BEGIN
          IF NOT newFile THEN
            APPEND(dataFile);

          REPEAT
            DataInput;           {Reads the input for a test}

            T2 := sumT2 / m;
            T4 := sumT4 / m;
            S2 := TrueS (sumS2sqr, sumT2sqr, T2);  W2 := 0.2 + S2;
            S3 := 0.2 + S3;
            S4 := TrueS (sumS4sqr, sumT4sqr, T4);  W4 := 0.2 + S4;

            {SOLVE THE HEATFLUX, IN W/m²}
            netPower := power - Kloss * (T2 - T3);
            qAB := netPower / areaBoil;
            WqAB := SQR( SQR( wp/areaBoil ) +
              SQR( (T2-T3)*wKloss / areaBoil ) +
              SQR( Kloss*(W2+W3) / areaBoil ) );

```

```

                                (SOLVE CONDENSING TEMPERATURE DIFFERENCE)
SaturatedProperties (T2 + W2);
CondensingCoefficient;
C1plus := C1;

SaturatedProperties (T2 - W2);
CondensingCoefficient;
C1minus := C1;

SaturatedProperties (T2);
CondensingCoefficient;

                                (FIRST GUESSES OF CONDENSING TEMP DIFFERENCE T2wi)
T2wi1 := Powers( Powers( qAB,4 ) * C1/hfg, 0.3333 );
T2wi2 := 0.90 * T2wi1;
rhs1 := (hfg + 0.68 * cpf * T2wi1) * Powers(T2wi1, 3);

REPEAT

    LiquidDensity(T2 - T2wi2 * 0.5);
    ThermalConductivity (T2 - T2wi2 * 0.5);
    Viscosity (T2 - 0.75 * T2wi2);
    CondensingCoefficient;

    lhs := Powers( qAB, 4 ) * C1;
    rhs2 := (hfg + 0.68 * cpf * T2wi2) * Powers(T2wi2, 3);
    T2wiTemporary := T2wi1 + (T2wi2-T2wi1)*(rhs1-lhs) / (rhs1-rhs2);
    T2wi1 := T2wi2;
    T2wi2 := T2wiTemporary;
    rhs1 := rhs2;

UNTIL ABS(T2wi2 - T2wi1) <= error1;

T2wi := T2wi2;
WC1 := ABS(C1plus-C1minus) / 2.0;
W2wi := SQRT( SQRT( 4*C1*Powers(qAB,3)*WqAB / (3*hfg*SQRT( T2wi ) ) )
              +SQRT( Powers(qAB,4) * WC1 / (3*hfg* SQRT( T2wi ) ) ) );

Two := T2 - T2wi - netPower*LN(RoR1) / (2*PI*kss*condensingLength);
Wwo := W2 + W2wi + Wp * LN(RoR1) / (2*PI*kss*condensingLength);
Two4 := Two - T4;
Wwo4 := W4 + Wwo;

                                (Rohsenow Pool Boiling Equation - solving Csf)
SaturatedProperties (T4);
C2 := kf / (muf * hfg);
C3 := (muf * hfg) / SQRT( sigmaf / (g * (pf-pg) ) );
Csf := C2 * Powers(C3, 0.333) * Two4 * Powers(qAB, -0.33);

SaturatedProperties (T4 + W4);
C2plus := kf / (muf * hfg);
C3plus := (muf * hfg) / SQRT( sigmaf / (g * (pf-pg) ) );

```


Decay Heat Rejection System Algorithm and Listing

A) PROGRAM Initialization: USES **Math** UNIT to provide exponentiation (**Powers** FUNCTION), and **SteamTbl** UNIT to provide saturated steam properties; these UNITS are listed at the end of this appendix. Variable and constant declaration.

B) PROCEDURE **TemperatureVapour6**: Receives outside wall temperature of outer 6 inch pipe (**T6wo**), solves film temperature (**T6film**), establishes steam table properties at **T6film**. Solves volume coefficient of expansion β (**BetaFilm6**) by best-fit curve to steam table data. Grashof number calculated, **C4** previously calculated as $g \times \text{Length}^3$. Length-based Nusselt number **Nu16** calculated from vertical plates free convection equation:

$$\text{Nu}_1 = \text{C5} * (\text{Gr} * \text{Pr})^m$$

C5 = 0.13 and $m = 0.3333$ for $\text{Gr} * \text{Pr} > 10^9$. Convective heat transfer coefficient **hconv6** and total heat **q6** to outer wall are solved. Inside wall temperature **Tw16** found from radial conduction, and average heat flux **q6BoilArea** solved. Steam properties @ **Tw16** (vapour temperature first guess), and Prandtl number are solved. **Tg6** calculated from Rohsenow pool boiling equation, using experimental **Csf** value (used for both walls of evaporator). REPEAT loop iterates **Tg6** to best value by solving boiling equation with properties established at latest value **Tg6**.

C) Main Program Part1: Solution to inner evaporator wall.

Establishes 3 inch inner pipe & wall areas, coefficients for pressure drop through inner annulus (C1) and for heat transfer equation (C2). Prompts user for and reads inner annulus outlet and pool temperatures. Solves properties at bulk temperature mass flux G3 from pressure balance:

$$G^{1.75} = \frac{(p - p_{\infty})}{\mu^{0.2}} \frac{p}{2} \frac{q}{\pi} \frac{d^{1.25}}{0.046}$$

where p is liquid density at bulk temperature, and p_{∞} @ pool temperature. Pressure balance based on assumption of constant pool temperature outside evaporator. d is inner annulus diameter. Reynolds number Re_3 found. Nusselt number Nu_3 based on diameter solved from Nusselt's entrance region turbulent flow equation:

$$Nu_d = 0.036 Re_d^{0.8} Pr^{0.333} (d/L)^{0.055}$$

Convective heat transfer coefficient (h_{conv3}), $massFlowRate3$, total heat (q_3) and inside wall temperature T_{wi3} solved. Outside wall temp (actually inside the evaporator) T_{wo3} solved by radial conduction. Solve vapour temperature T_{g3} iteratively as mentioned for T_{g6} in PROCEDURE VapourTemperature6. WRITE output to printer.

D) Main PROGRAM part 2: Solution to outer evaporator wall.

First guess of $T_{6wo2} = T_{3out}$ (Outlet temperature of the pool water flowing through inner annulus). Solves outer wall areas, boiling area, C_4 . Calls `TemperatureVapour6` with T_{6wo2} , gives T_{g62} as vapour temperature first guess. Second guess of T_{6wo1} as T_{6wo2} lowered by half the difference between T_{g3} and T_{g62} . Call `TemperatureVapour6` with T_{6wo1} , gives T_{g61} as vapour temperature second guess.

i) REPEAT loop: uses linear interpolation between T_{g3} and T_{g6} to provide new guess for outside wall temp T_{6wo} . Calls `TemperatureVapour6` to update T_{g6} , and repeats loop until $T_{g6} = T_{g3}$ (or close approximation).

WRITE output to printer such that for given pool and outlet temperature there is one vapour temperature and two sources of heat transfer (natural convection on outer wall and thermosyphoning giving forced convection in inner annulus)

```
PROGRAM Decay_Heat_Rejection_System;
```

```
USES PRINTER, CRT, Math, SteamTbl;
```

```
VAR
```

```
Tinf, T3out, T3bulk, T3wo, T3wi, Tg3, Ro3inf, C1, C2, Re3, Nud3, Pr3, hconv3,  
G3, massFlowRate3, q3, q3boilarea, RoRi3, Tg3i, InsidePipeWallArea3, BoilArea3, PipeArea3,
```

```
T6fil6, T6wo1, T6wo2, T6wo3, T6wi, Tg6, C4, Gr6, Nul6, Pr6, hconv6, Nufil6,  
BetaFil6, q6, q6boilarea, RoRi6, BoilArea6, OutsidePipeWallArea6,  
Tg6i, Tg62, Tg63 : REAL;
```

```
Newset : CHAR;
```

```
CONST
```

```
gravAccn = 9.81;  
length = 2.438;  
inner3Diameter = 0.0889;  
Outer3Diameter = 0.1016;  
Inner6diameter = 0.1397;  
Outer6diameter = 0.1524;  
kss = 17.3;  
C5 = 0.13;                               (Gr6 * Pr6 > 10^9)  
Tgerror = 0.01;  
Csf = 0.0169;                           (Teflon Tube, 48in level)  
Tg6error = 0.05;
```

```
PROCEDURE TemperatureVapour6 (T6wo:REAL);
```

```
BEGIN
```

```
  T6fil6 := (Tinf + T6wo) / 2.0;
```

```
  LiquidDensity (T6fil6);                               (Returns  $\rho_f$  @ T6fil6)  
  Viscosity (T6fil6);                                   (Returns  $\mu_f$  @ T6fil6)  
  ThermalConductivity (T6fil6);                       (Returns  $k_f$  @ T6fil6)  
  SpecificHeat (T6fil6);                               (Returns  $c_{pf}$  @ T6fil6)  
  Nufil6 :=  $\mu_f / \rho_f$ ;                                   (Kinematic Viscosity)  
  Pr6 :=  $c_{pf} * \mu_f / k_f$ ;                              (Prandtl Number)  
  BetaFil6 :=  $(133.19 + 6.48012 * T6fil6) / 1000000$ ;
```

```
  Gr6 :=  $C4 * BetaFil6 * (Tinf - T6wo) / \text{SQRT}(Nufil6)$ ;   (Grashof number)
```

```
  Nul6 :=  $C5 * \text{powers}(Gr6 * Pr6, 0.333333)$ ;   (length-based Nusselt number)
```

```
  hconv6 :=  $Nul6 * k_f / \text{length}$ ;
```

```
  q6 :=  $\text{OutsidePipeWallArea6} * hconv6 * (Tinf - T6wo)$ ;
```

```
  T6wi :=  $T6wo - q6 * \ln(RoRi6) / (2 * PI * kss * \text{Length})$ ;
```

```
  q6boilarea :=  $q6 / \text{BoilArea6}$ ;
```

```
  VapourDensity (T6wi);
```

```

LiquidDensity (T6wi);
SpecificHeat (T6wi);
HeatOfVapourization (T6wi);
ThermalConductivity (T6wi);
Viscosity (T6wi);
SurfaceTension (T6wi);

Pr6 := cpf * muf / kf;
Tg6 := T6wi - (hfg*Csf*Pr6 / cpf) * Powers(q6boilarea *
    SQR(sigmaf / (gravaccn * (pf-pg)) ) / (muf*hfg), 0.333);

REPEAT
    Tg61 := Tg6;

    SurfaceTension(Tg61);           {Returns sigmaf @ Tg61}
    LiquidDensity (Tg61);
    VapourDensity (Tg61);           {Returns pg @ Tg61}
    Viscosity (Tg61);               {Returns muf @ Tg61}
    HeatOfVapourization (Tg61);     {Returns hfg @ Tg61}
    SpecificHeat (Tg61);            {Returns cpf @ Tg61}
    ThermalConductivity (Tg61);

    Pr6 := cpf * muf / kf;
    Tg6 := T6wi - (hfg*Csf*Pr6 / cpf) * Powers(q6boilarea *
        SQR(sigmaf / (gravaccn * (pf-pg)) ) / (muf*hfg), 0.333);
UNTIL ABS(Tg61-Tg6) < Tgerror;
END;                                {PROCEDURE TemperatureVapour6}

BEGIN                                {Main program}
    RoRi3 := Outer3Diameter/Inner3Diameter;
    PipeArea3 := PI * SQR (Inner3Diameter) / 4.0;
    InsidePipeWallArea3 := PI * Inner3Diameter * Length;
    BoilArea3 := RoRi3 * InsidePipeWallArea3;
    C1 := 1.0 / ( 0.092 / (gravaccn * powers( inner3Diameter, 1.2 ) ) );
    C2 := 0.036 * powers( inner3Diameter/length,0.055);

    REPEAT
        REPEAT
            WRITELN ('*****');
            WRITELN ('Input outlet temp To, pool temp Tinf ie. 85 89');
            READLN (T3out, Tinf);
        UNTIL Tinf >= T3out;

        T3Bulk := (Tinf + T3out) / 2.0;

        LiquidDensity (Tinf);       {Returns pf @ Tinf}
        RoeInf := pf;
        LiquidDensity (T3bulk);     {Returns pf @ T3bulk}
        Viscosity (T3bulk);         {Returns muf @ T3bulk}
        ThermalConductivity (T3bulk); {Returns kf @ T3bulk}
        SpecificHeat (T3bulk);      {Returns cpf @ T3bulk}
        Pr3 := cpf * muf / kf;      {Prandtl Number}

```

```

G3 := powers( ( pf - RoInf ) * pf * C1 / powers(muf,0.2) , 0.55555);

Re3 := G3 * inner3Diameter / muf;

Nud3 := C2 * powers(Re3, 0.8) * Powers(Pr3, 0.333);

hconv3 := Nud3 * kf / inner3Diameter;

massFlowRate3 := G3 * pipeArea3;

q3 := cpf * massflowrate3 * (Tinf - T3out);

T3wi := T3bulk - q3/ (hconv3 * InsidePipeWallArea3);

T3wo := T3wi - q3 * ln(RoRi3) / (2 * PI * kss * Length);

q3boilarea := q3 / boilarea3;

VapourDensity (T3wo);           {First Guess of Tg3 is T3wo}
LiquidDensity (T3wo);
SpecificHeat (T3wo);
HeatOfVapourization (T3wo);
ThermalConductivity (T3wo);
Viscosity (T3wo);
SurfaceTension (T3wo);

Pr3 := cpf * muf / kf;
Tg3 := T3wo - (hfg*Csf*T3 / cpf) * Powers(q3boilarea *
    SQRT(sigmaf / (gravaccn * (pf-pg))) / (muf*hfg), 0.333);

REPEAT
    Tg31 := Tg3;

    SurfaceTension(Tg31);           {Returns sigmaf @ Tg31}
    LiquidDensity (Tg31);
    VapourDensity (Tg31);           {Returns pg @ Tg31}
    Viscosity (Tg31);               {Returns muf @ Tg31}
    HeatOfVapourization (Tg31);     {Returns hfg @ Tg31}
    SpecificHeat (Tg31);            {Returns cpf @ Tg31}
    ThermalConductivity (Tg31);

    Pr3 := cpf * muf / kf;
    Tg3 := T3wo - (hfg*Csf*Pr3 / cpf) * Powers(q3boilarea *
        SQRT(sigmaf / (gravaccn * (pf-pg))) / (muf*hfg), 0.333);
UNTIL ABS(Tg31-Tg3) < Tgerror;

WRITELN (1st,'*****');
WRITE (1st,'Rohsenow Csf = ',Csf:6:4,' Pool Temp = ',Tinf:6:2,'°C');
WRITELN (1st,' Outlet temp = ',T3out:6:2,'°C');
WRITELN (1st,'T3wi = ',T3wi:6:2,'°C   T3wo = ',T3wo:6:2,'°C');
WRITELN (1st,'hconv3 = ',hconv3:6:0,'W/m²°C   HeatTransferred3 = ',q3:6:1,' W ');
WRITELN (1st,'qAboil3 = ',q3boilarea:6:0,'W/m²   Tvapour = ',Tg3:6:2,'°C');
WRITELN (1st,'.....');

```

```

(OUTER WALL OF EVAPORATOR)
T6wo2 := T3out;                                ( T6wo initial Guess)
RoRi6 := Outer6Diameter/Inner6Diameter;
OutsidePipeWallArea6 := PI * Outer6Diameter * Length;
BoilArea6 := OutsidePipeWallArea6 / RoRi6;
C4 := gravaccn * length * length * length;

TemperatureVapour6 (T6wo2);
Tg62 := Tg6;

T6wo1 := T6wo2 - (Tg62 - Tg3)/2;                (T6wo second guess)
TemperatureVapour6 (T6wo1);
Tg61 := Tg6;

REPEAT
  T6wo3 := T6wo2;
  T6wo2 := T6wo1;
  Tg63 := Tg62;
  Tg62 := Tg61;

  T6wo1 := (Tg3-Tg62)/(Tg63 - Tg62) * (T6wo3-T6wo2) + T6wo2;
  {Gives new approximation of T6wo based on closeness of Tg6 to Tg3}

  TemperatureVapour6 (T6wo1);
  Tg61 := Tg6;
UNTIL ABS(Tg61-Tg62) < Tg6error;

WRITELN (1st,'T6wo = ',T6wo1:6:2,'°C   T6w1 = ',T6w1:6:2,'°C');
WRITELN (1st,'q6Boil = ',q6boilarea:6:0,' W/m²   hconv6 = ',hconv6:5:0,' W/m² °C ');
WRITELN (1st,'                               HeatTransferred6 = ',q6:6:1,'W');

WRITELN ('Another set (y or n)?');
Newset := READKEY;
UNTIL (Newset = 'n') or (Newset = 'N')
END.

```

INTERFACE

```

FUNCTION Arccos (x : REAL) : REAL; {gives angle in radians}
FUNCTION Arcsin (x : REAL) : REAL; {gives angle in radians}
FUNCTION Tan (angle: REAL) : REAL; {x is in radians}
FUNCTION Log (x, n : REAL) : REAL; {Log to base n of x}
FUNCTION Powers (x, n : REAL) : REAL; {x raised to the nth power}
FUNCTION DegToRad (deg : REAL) : REAL; {degrees converted to radians}
FUNCTION RadToDeg (rad : REAL) : REAL; {radians converted to degrees}
FUNCTION Sinh (x : REAL) : REAL;
FUNCTION Cosh (x : REAL) : REAL;
FUNCTION Tanh (x : REAL) : REAL;

```

IMPLEMENTATION

```

FUNCTION Arccos;
BEGIN
  IF x = 1.0 THEN
    Arccos := 0.0
  ELSE
    IF x = -1.0 THEN
      Arccos := PI
    ELSE
      Arccos := PI/2.0 - ARCTAN( x / (SQRT(1.0 - SQR( x ) ) ) )
    END; {Arccos}

```

```

FUNCTION Arcsin;
BEGIN
  IF x = 1.0 THEN
    Arcsin := PI / 2.0
  ELSE
    IF x = -1.0 THEN
      Arcsin := - PI / 2.0
    ELSE
      Arcsin := ARCTAN( x / (SQRT(1.0 - SQR( x ) ) ) )
    END;

```

```

FUNCTION Tan;
BEGIN
  IF COS(Angle) = 0.0 THEN
    TAN := 1.0E38
  ELSE
    TAN := SIN(ANGLE) / COS(ANGLE);
  END;

```



```

FUNCTION Log;
  BEGIN
    Log := LN(x) / LN(n)
  END;

```

```

FUNCTION Powers;

```

```

  VAR

```

```

    sign :REAL;

```

```

  BEGIN

```

```

    IF x = 0 THEN      (0^n = 0 in all cases)
      Powers := 0

```

```

    ELSE
      BEGIN

```

```

        IF x > 0 THEN (x^n for all n, with x positive & real)
          Powers := EXP( n * LN(x))

```

```

        ELSE

```

```

          IF FRAC(n) = 0 THEN {Positive or negative integer powers are allowed}

```

```

            BEGIN

```

```

              sign := 1.0;

```

```

              IF ODD(TRUNC(n)) THEN

```

```

                sign := -1.0;

```

```

                Powers := sign * EXP( n * LN( ABS(x) ) )

```

```

            END

```

```

          ELSE (Only positive or negative odd roots are allowed
              ie. -10^1.2 (fifth root) is allowed,
              but -10^1.5 (square root) is not allowed.)

```

```

            BEGIN

```

```

              IF FRAC(1.0/n) <= 0.101 THEN {Allows roots: .3333,.142857,etc to
                  approximate 3d, 7th, etc roots}

```

```

                BEGIN

```

```

                  sign := 0.0; (IF n not an odd root then returns 0.0)

```

```

                  IF ODD(TRUNC(1.0/n)) THEN

```

```

                    sign := -1.

```

```

                    Powers := sign * (EXP( n * LN( ABS(x) ) ) )

```

```

                END

```

```

            END

```

END
END; (Powers FUNCTION)

FUNCTION DegToRad;
BEGIN
 DegToRad := Deg/180 * PI
END;

FUNCTION RadToDeg;
BEGIN
 RadToDeg := Rad/PI * 180
END;

FUNCTION Sinh;
BEGIN
 Sinh := (EXP(x) - EXP(-x)) / 2.0
END;

FUNCTION Cosh;
BEGIN
 Cosh := (EXP(x) + EXP(-x)) / 2.0
END;

FUNCTION Tanh;
BEGIN
 Tanh := (EXP(2*x) - 1.0) / (EXP(2*x) + 1.0)
END;

END. (Math UNIT)

UNIT SteamTbl;

INTERFACE

```

PROCEDURE ThermalConductivity (tVapour:REAL);
PROCEDURE Viscosity           (tVapour:REAL);
PROCEDURE SurfaceTension      (tVapour:Real);
PROCEDURE SpecificHeat        (tVapour:REAL);
PROCEDURE LiquidDensity       (tVapour:REAL);
PROCEDURE VapourDensity        (tVapour:REAL);
PROCEDURE HeatOfVapourization (tVapour:REAL);

```

VAR

```

kf, muf, sigmaf, cpf, pf, pg, hfg: REAL;

```

IMPLEMENTATION

```

PROCEDURE ThermalConductivity; {kf in W/(mK)}

```

CONST

```

kf1 = 0.4670013;
kf2 = 0.08187892;

```

BEGIN

```

kf := kf1 * exp(kf2*ln(Tvapour));
END;

```

```

PROCEDURE Viscosity; {dynamic viscosity  $\mu_f$  in kg/(m-s)}

```

CONST

```

muf1 = 110;
muf2 = 34.20351;

```

BEGIN

```

muf := 1/(muf1 + muf2*Tvapour);
END;

```

```

PROCEDURE SurfaceTension; { $\sigma_f$  in N/m}

```

CONST

```

sigmaf1 = 7.708394E-2;
sigmaf2 = 1.827858E-4;

```

BEGIN

```

sigmaf := sigmaf1 - sigmaf2*Tvapour;
END;

```

```
PROCEDURE SpecificHeat; (cpf in W/(m°C))
```

```
CONST
```

```
  cpf1 = 4143.714;
```

```
  cpf2 = 0.7321429;
```

```
BEGIN
```

```
  Cpf := cpf1 + cpf2 * Tvapour;
```

```
END;
```

```
PROCEDURE LiquidDensity; (pf in kg/m^3)
```

```
CONST
```

```
  pf1 = 1009.8685;
```

```
  pf2 = 0.0028308;
```

```
  pf3 = 41.79;
```

```
  pf4 = 1.9797107;
```

```
BEGIN
```

```
  pf := pf1 - pf2 * exp(pf4 * ln(Tvapour + pf3));
```

```
END;
```

```
PROCEDURE VapourDensity; (pg in kg/m^3)
```

```
CONST
```

```
  pg1 = 7.9639E-7;
```

```
  pg2 = 2.9341;
```

```
BEGIN
```

```
  pg := pg1 * exp(pg2 * ln(Tvapour));
```

```
END;
```

```
PROCEDURE HeatOfVapourization; (hfg in J/kg)
```

```
CONST
```

```
  hfg1 = -3.47345E-6;
```

```
  hfg2 = 957;
```

```
  hfg3 = 2.796377;
```

```
  hfg4 = 3250;
```

```
BEGIN
```

```
  hfg := 1000 * (hfg1 * exp(hfg3 * ln(Tvapour + hfg2)) + hfg4);
```

```
END;
```

```
END.
```

END

21/09/90

FIN