**POOL BOILING OF ENHANCED HEAT TRANSFER
SURFACES IN REFRIGERANT-OIL MIXTURES AND
AQUEOUS CALCIUM SULFATE SOLUTIONS**

Topical Report

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August 1994

Work Performed Under Contract No. DE-FC07-88ID12772

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Sponsored by the Office of the Assistant Secretary
for Energy Efficiency and Renewable Energy
Office of Industrial Technologies
Washington, D.C.

Prepared by
Rensselaer Polytechnic Institute
Troy, New York

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ACKNOWLEDGEMENTS

This work was carried out for the U.S. Department of Energy under Grant No. DE-FC07-88ID12772. The project monitors were Mr. Gary Peterson of the DOE Idaho Operations Office and Dr. Manohar Sohal of EG&G Idaho. The enhanced surfaces were provided by Wolverine Tube Inc. with the assistance of Mr. Petur Thors and by Wieland-Werke AG with the assistance of Mr. Klaus Menze.

CONTENTS

	Page
ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iii
LIST OF TABLES.....	vi
LIST OF FIGURES.....	vii
NOMENCLATURE.....	x
 1. INTRODUCTION AND HISTORICAL REVIEW.....	 1
1.1 Background.....	1
1.2 Refrigerant—Oil Mixtures.....	7
1.3 Aqueous Solutions.....	14
 2. POOL BOILING IN REFRIGERANT—OIL MIXTURES.....	 38
2.1 Apparatus.....	38
2.1.1 Test Sections.....	38
2.1.2 Instrumentation.....	40
2.1.3 Equipment.....	41
2.2 Experimental Procedure.....	41
2.3 Data Reduction.....	45
2.4 Observations and Results.....	47
2.5 Discussion.....	62
 3. POOL BOILING IN AQUEOUS CALCIUM SULFATE SOLUTIONS....	 64
3.1 Apparatus.....	64
3.1.1 Test Sections.....	64
3.1.2 Instrumentation.....	65
3.1.3 Equipment.....	66
3.2 Experimental Procedure.....	67
3.3 Data Reduction.....	68
3.4 Observations and Results.....	70
3.5 Discussion.....	82
 4. CONCLUSIONS.....	 88
 5. LITERATURE CITED.....	 90

	Page
6. APPENDIX 1: TABULATION OF EXPERIMENTAL DATA.....	94
7. APPENDIX 2: SPREADSHEET FOR DATA REDUCTION.....	134
8. APPENDIX 3: THERMOPHYSICAL PROPERTIES.....	137
9. APPENDIX 4: PRECISION ANALYSIS.....	138
10. APPENDIX 5: PREPARATION OF SATURATED CALCIUM SULFATE SOLUTION.....	146
11. APPENDIX 6: TITRATION.....	147
12. APPENDIX 7: PHOTOGRAPHY.....	149

LIST OF TABLES

	Page
Table 1.1 Enhancement Ratios at a Heat Flux of 30 kW/m^2 [14, 16, 17].....	12
Table 2.1 Ratio of Observed Boiling Coefficients at a Heat Flux of 30 kW/m^2	54
Table 2.2 Observed Enhancement Ratios at a Heat Flux of 30 kW/m^2	57
Table 6.1 Reduced Experimental Data.....	94

LIST OF FIGURES

	Page
Figure 1.1 Transient Nature of Fouling.....	6
Figure 1.2 Mechanism of Scale Formation [22].....	18
Figure 1.3 Schematic of Precipitation Fouling [24].....	23
Figure 1.4 Scale Accumulation Rate [21].....	26
Figure 1.5 Fouling Curve [21].....	28
Figure 1.6 Fouling of High Flux Surface in Sea Water [3].....	33
Figure 1.7 Pool Boiling and Falling Film Evaporation Performances of High Flux Surface [26].....	35
Figure 1.8 Fouling Curve of High Flux Surface [26].....	36
Figure 2.1 Schematic of Test Section (Dimensions in inches) [37].....	39
Figure 2.2 Schematic of Mounting Arrangement.....	42
Figure 2.3 Pool Boiling Apparatus [37].....	43
Figure 2.4 Pool Boiling Curves of Plain Smooth Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil.....	48
Figure 2.5 Pool Boiling Curves of High Flux Large Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil.....	49
Figure 2.6 Pool Boiling Curves of High Flux Small Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil.....	50
Figure 2.7 Pool Boiling Curves of Turbo-B Very Open Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil...51	51
Figure 2.8 Pool Boiling Curves of Turbo-B Very Closed Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil...52	52
Figure 2.9 Pool Boiling Curves of High Flux Large Tube in Pure R113 Before (A) and After (C) Mixture Tests.....	58
Figure 2.10 Pool Boiling Curves of High Flux Small Tube in Pure R113 Before (A) and After (B) Mixture Tests.....	59
Figure 2.11 Pool Boiling Curves of Turbo-B Very Open Tube in Pure R113 Before (A) and After (B) Mixture Tests.....	60

	Page
Figure 2.12 Pool Boiling Curves of Turbo-B Very Closed Tube in Pure R113 Before (A) and After (B) Mixture Tests.....	61
Figure 3.1 Pool Boiling Curves of All Tubes in Distilled Water.....	71
Figure 3.2 Precipitation Fouling Curves of a Plain Smooth Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes.....	72
Figure 3.3 Precipitation Fouling Curves of a High Flux Large Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes.....	73
Figure 3.4 Precipitation Fouling Curves of a High Flux Small Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes.....	74
Figure 3.5 Precipitation Fouling Curves of a Turbo-B Very Open Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes.....	75
Figure 3.6 Precipitation Fouling Curves of a Turbo-B Very Closed Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes.....	76
Figure 3.7 Observed Effects of Fouling for All Tubes at Two Heat Fluxes (10 kW/m^2 and $75\text{--}80 \text{ kW/m}^2$).....	80
Figure 3.8 Photograph of Plain Smooth Tube in Aqueous Calcium Sulfate Solution, $Q'' = 51 \text{ kW/m}^2$, time = 2 min.....	81
Figure 3.9 Photograph of Plain Smooth Tube in Aqueous Calcium Sulfate Solution, $Q'' = 51 \text{ kW/m}^2$, time = 30 min.....	81
Figure 3.10 Photograph of Turbo-B Very Closed Tube in Aqueous Calcium Sulfate Solution, $Q'' = 10 \text{ kW/m}^2$, time = 3 hrs.....	81a
Figure 3.11 Photograph of Plain Smooth Tube After Run, $Q'' = 51 \text{ kW/m}^2$, Run Time = 6.7 hrs., Front View.....	81a
Figure 3.12 Photograph of Plain Smooth Tube After Run, $Q'' = 51 \text{ kW/m}^2$, Run Time = 6.7 hrs., Back View.....	83

	Page
Figure 3.13 Photograph of Plain Smooth Tube After Run, $Q'' = 10$ kW/m ² , Run Time = 24 hrs., Front View.....	83
Figure 3.14 Photograph of Plain Smooth Tube After Run, $Q'' = 10$ kW/m ² , Run Time = 24 hrs., Back View.....	84
Figure 3.15 Photograph of Plain Smooth Tube After Run, $Q'' = 10$ kW/m ² , Run Time = 24 hrs., Bottom View.....	84
Figure 7.1 Sample Spreadsheet.....	135

NOMENCLATURE

A:	heat transfer area [m^2]
a:	constant in Equations (1.3.5a and 1.3.5b)
b:	slope of solubility curve [$\text{kg}/(\text{m}^3 \cdot ^\circ\text{C})$]
C_1 :	integration constant, Equation (1.3.34)
C_b :	solubility at bulk temperature [kg/m^3]
C_s :	solubility at interface temperature [kg/m^3]
C_r :	concentration of material subject to crystallization [kg/m^3]
C_w :	concentration at the wall [kg/m^3]
D:	mass diffusivity [m^2/s]
d:	diameter of test section [m]
d_h :	duct hydraulic diameter [m]
e_r :	systematic error in radial position of thermocouple bead [m]
f:	Moody friction factor [dimensionless]
ΔH :	change in liquid level [m]
h:	heat transfer coefficient [$\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$]
h_c :	heat transfer coefficient for clean surface [$\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$]
I:	current [A]
I_{heater} :	current through the heater [A]
K:	coefficient of mass transfer defined by Equation (1.3.2)
K_1 :	constant defined by Equation (1.3.24)
K_3 :	constant in Equation (1.3.3)
K_r :	constant defined in Equation (1.3.20)
k:	thermal conductivity [$\text{W}/(\text{m} \cdot ^\circ\text{C})$]
k_f :	average thermal conductivity of fouling deposit [$\text{W}/(\text{m} \cdot ^\circ\text{C})$]

L:	length of test section [m]
l:	length [m]
M:	moles [dimensionless]
m, n:	constants in Equation (1.3.1)
m_{CaSO_4} :	mass of calcium sulfate (kg)
m_f :	mass of the deposit per unit area [kg/m^2]
$\dot{m}_f$:	net rate of accumulation of fouling deposit [$\text{kg}/(\text{m}^2 \cdot \text{s})$]
$\dot{m}_g$:	rate of deposit growth [$\text{kg}/(\text{m}^2 \cdot \text{s})$]
$\dot{m}_r$:	rate of deposit removal [$\text{kg}/(\text{m}^2 \cdot \text{s})$]
N:	mass flux [$\text{kg}/(\text{m}^2 \cdot \text{s})$]
P:	power [W]
p:	pressure [Pa]
P_{oil} :	mass percent oil [dimensionless]
Q'' :	heat flux [W/m^2]
q:	heat transfer rate [W]
R:	tube radius [m]
r:	radial position of thermocouples [m]
R_c :	convective thermal resistance [$(\text{m}^2 \cdot ^\circ\text{C})/\text{W}$]
R_f :	fouling thermal resistance [$(\text{m}^2 \cdot ^\circ\text{C})/\text{W}$]
R_{shunt} :	electrical resistance of shunt [Ω]
R_{total} :	total thermal resistance [$(\text{m}^2 \cdot ^\circ\text{C})/\text{W}$]
S:	solubility of scaling substance [kg/m^3]
T:	temperature [$^\circ\text{C}$]
T_b :	temperature of bulk fluid [$^\circ\text{C}$]
$T_{b,\text{avg}}$:	average bulk fluid temperature [$^\circ\text{C}$]

$T_{i,r}$:	temperature of thermocouple bead [$^{\circ}\text{C}$]
T_s :	temperature at deposit-fluid interface [$^{\circ}\text{C}$]
T_{sat} :	saturation temperature [$^{\circ}\text{C}$]
T_w :	outer wall temperature [$^{\circ}\text{C}$]
$T_{w,\text{avg}}$:	average outer wall temperature [$^{\circ}\text{C}$]
ΔT :	temperature difference [$^{\circ}\text{C}$]
ΔT_o :	clean temperature difference [$^{\circ}\text{C}$]
ΔT_s :	superheat [$^{\circ}\text{C}$]
U :	overall heat transfer coefficient [$\text{W}/(\text{m}^2 \cdot ^{\circ}\text{C})$]
U_o :	overall clean heat transfer coefficient [$\text{W}/(\text{m}^2 \cdot ^{\circ}\text{C})$]
u_m :	mean velocity [m/s]
V :	voltage [V]
V_{heater} :	voltage drop across heater [V]
V_{oil} :	volume of oil [ℓ]
V_{R113} :	volume of R113 [ℓ]
V_{shunt} :	voltage drop across shunt [V]
W :	mass of fouling deposit ($= m_f \cdot A$) [kg]
w :	width [m]
x :	average thickness of fouling deposit [m]
z :	distance from the deposit-liquid interface to completely mixed bulk solution [m]
$\bar{z}$:	width of hypothetical crystallization zone [m]
ρ :	density [kg/m^3]
ρ_f :	average bulk density of fouling deposit [kg/m^3]

ρ_{oil} : density of 3GS oil [kg/m^3]
 ρ_{R113} : density of R113 [kg/m^3]
 θ : time [s]
 ω : precision

PART 1

INTRODUCTION AND HISTORICAL REVIEW

1.1 Background

The recent development of compact heat exchangers relies heavily on the use of enhanced heat transfer surfaces, resulting in significant reductions in the size, weight, energy requirements, and cost of heat transfer equipment. In particular, a number of enhanced nucleate boiling heat transfer surfaces have been commercially available since the 1970's. The applications of these surfaces include heat recovery, refrigeration, petrochemical processing, air separation, gas liquefaction, electronic cooling, and ocean thermal energy conversion (OTEC) equipment.

Externally enhanced boiling tube surfaces may be divided into two groups [1]:

1. Porous Coatings, such as the Universal Oil Products (UOP) High Flux (formerly Linde Division, Union Carbide), Wolverine Korotex II, and the Copper Sprayed Boiling Surfaces (CSBS).
2. Integral Machined Surfaces, such as the Wolverine Turbo-B, Hitachi Thermoexcel-E and -HE, Wieland-Werke Gewa-T, Furukawa Metals ECR40, and tubes by the Trane Corporation.

Yilmaz and Westwater [1], along with Cunningham et al. [2], provide detailed descriptions of the various surfaces. In nucleate boiling, the enhanced surface augments the heat transfer by decreasing the wall superheat necessary for nucleation as compared to a plain, smooth surface.

This effect is attributed to its re-entrant cavity surface structure [3,4].

The porous surface structure consists of a matrix of metallic particles which are bonded to the outer tube surface. Examination of metallographic sections suggests that this matrix has numerous interconnected cavities, providing sites for vapor trapping and bubble generation [3]. A similar examination of the machined surface structure shows re-entrant cavities interconnected by tunnels below the outer surface. It is speculated that vapor entering these cavities prevents liquid flooding while a liquid film resides in the corners of the cavities [4]. The manufacturers claim that their respective surfaces may be adjusted to produce the optimum surface structure for a specific application by accounting for the thermophysical properties of the working fluid such as surface tension, viscosity, and thermal conductivity.

The thermal performance of a boiling heat transfer surface is often determined empirically by means of a pool boiling experiment. Pool boiling has been defined as vaporization of a liquid under the following conditions [5]:

1. the height of the liquid above the boiling surface is large compared to the maximum bubble diameter
2. an externally imposed velocity on the fluid is small enough to have negligible effects on the heat transfer
3. a force field, typically gravity, is present which causes the bubbles to travel away from the boiling surface.

Two fundamental quantities are measured, the heat flux from the boiling surface to the fluid and the temperature difference between the boiling

surface and the fluid (referred to as the wall superheat). A plot of heat flux on the ordinate and wall superheat (or some other characteristic temperature difference) on the abscissa is called a boiling curve.

A substantial body of work is available on the pool boiling of plain and enhanced surfaces in pure liquids. This is reviewed by Yilmaz and Wetswater [1]. Pool boiling in liquid mixtures has received much less attention [14]. In particular, the effect on heat transfer of oil and refrigerant mixtures, such as encountered in refrigeration and air conditioning systems, is not well understood. The present study is concerned with evaluating the pool boiling performance of externally enhanced single tubes in refrigerant-lubricating oil mixtures.

The fouling of externally enhanced tubes in pool boiling is also investigated. The increased resistance to both heat transfer and fluid flow due to the presence of deposits on the heat transfer surface is referred to as fouling. Fouling has the effect of reducing the efficiency of heat transfer equipment and can also result in the mechanical failure of a heat transfer surface where a locally hot region has developed. As a result, the designer of heat transfer equipment needs reliable information on fouling in order to meet the specified operating requirements. The most popular source of information on fouling is provided by the Tubular Exchanger Manufacturers Association (TEMA). The data, however, contain numerous deficiencies, such as: information for only a limited range of heat exchanger configurations and no consideration of the transient nature of the fouling process. Consequently, a much more systematic approach to the problem of fouling must be sought. [6]

Epstein [7] has recognized the following categories of fouling:

1. Precipitation fouling: the precipitation of dissolved matter on the heat transfer surface
2. Particulate fouling: the deposition of matter suspended in the fluid on the surface
3. Chemical reaction fouling: the formation of deposits produced by chemical reactions not involving the heat transfer surface
4. Corrosion fouling: the formation of deposits produced by a corrosion reaction involving the surface
5. Biological fouling: the adherence of organisms to the heat transfer surface
6. Freezing fouling: the solidification of a liquid onto a heat transfer surface.

Combinations of these categories can also exist on a surface. The effect of fouling is to increase the total thermal resistance by a quantity referred to as the fouling thermal resistance¹, R_f . As a result,

$$R_{\text{total}} = R_c + R_f \quad (1.1.1)$$

where R_c is the convective thermal resistance. The heat flux Q'' is given by

¹The widely used terminology fouling factor is better restricted to the case where, for design purposes, the fouling thermal resistance is assumed constant. Presumably this represents some maximum permissible or expected value of the time varying fouling thermal resistance.

$$Q'' = \frac{T_s - T_b}{R_{\text{total}}} \quad (1.1.2)$$

By virtue of (1.1.2), the heat flux is decreased by the presence of fouling. Hydrodynamically, fouling can increase the amount of friction a fluid encounters at the heat transfer surface. Also, for duct flow, fouling may cause a reduction of the flow area. The effect of fouling in both instances is to increase the pressure gradient since

$$\frac{dp}{dx} = \frac{f}{d_h} \cdot \left(\frac{1}{2} \rho u_m^2 \right) \quad (1.1.3)$$

Observations of the transient nature of fouling indicate that the fouling thermal resistance R_f varies with time in three general ways as shown in Figure 1.1. Curves 1, 2, and 3 represent respectively what are commonly called linear, falling rate, and asymptotic fouling while curve 4 shows a more practical form of the asymptotic case. Often there exists an initial induction time when no fouling is observed. [6]

Kern and Seaton [8, 9] first advanced the notion that fouling was the result of two competing processes, the formation and removal of a deposit. The basis for this model is that asymptotic fouling can easily be explained as the condition where the growth of the deposit is exactly balanced by its removal. Mathematically this model is

$$\dot{m}_f = \dot{m}_g - \dot{m}_r \quad (1.1.4)$$

Figure 1.1 Transient Nature of Fouling

Once $\dot{m}_g$ and $\dot{m}_r$ are determined, equation (1.1.4) can be integrated to obtain an expression for m_f , the mass of the deposit per unit area.

Then R_f is calculated by

$$R_f = \frac{m_f}{\rho_f k_f} \quad (1.1.5)$$

assuming ρ_f and k_f are invariant. Numerous empirical models for fouling have been advanced but the results fail to reveal the basic physics of the problem. As a result, this information cannot be generalized with confidence so the designer of heat transfer equipment must again rely on empirical data. This work hopes to provide such information.

1.2 Refrigerant–Oil Mixtures

Refrigeration systems with oil-lubricated compressors typically contain a mixture of oil and refrigerant as the working fluid. Although the concentration of oil is generally less than 10% by mass, the presence of oil alters the thermodynamic and transport properties of the refrigerant. For example, the vapor pressure of the refrigerant decreases while the viscosity and surface tension increases when oil is mixed with the refrigerant [10]. As a result, the heat transfer performance of components of the system (such as the condensers and evaporators) may be adversely affected.

Two opposing effects on the heat transfer coefficient have been observed in refrigerant–oil mixtures [5, 11]. First, as the refrigerant evaporates at the boiling surface, it is speculated that an oil-rich layer develops near the surface. Since the liquid–vapor surface tension and

surface adhesive tension are greater in this oil-rich layer, more energy is required for the formation and growth of bubbles [11]. Also, increased liquid viscosity reduces turbulence, decreasing liquid flow to the surface resulting in a lower heat transfer coefficient [5]. A second effect sometimes observed is the enhancement of the heat transfer coefficient at small oil concentrations. This effect is attributed to foaming which results in more vigorous refrigerant motion around the tube, augmenting the heat transfer [11]. Chaddock [12] presents a detailed discussion on the performance of evaporators with refrigerant-oil mixtures.

Of particular concern is the performance of externally enhanced heat transfer surfaces in refrigerant-oil mixtures. One could anticipate significantly larger concentrations of oil in the plentiful re-entrant cavities of an enhanced surface than in the bulk fluid. As a result, the effect of oil on an enhanced surface may be more pronounced than on a smooth surface.

Gottzmann et al. [3] presented data on the effect of compressor oil on the boiling performance of the High Flux surface in propylene. They reported about a 3% addition to the overall heat transfer resistance at a concentration of 4% oil by volume. They claimed that upon removal of the oil, the clean values were restored.

Sauer et al. [5] investigated the performance of low finned tubing in an R11/naphthene based oil mixture. Two oils at various concentrations were studied. They observed decreased heat transfer coefficients at higher oil concentrations and an increase in the saturation temperature at greater oil concentrations. The effect of oil, though, was no greater for the finned tube than for the plain tube. They concluded that an increase in oil in

R11 up to 3% by mass does not significantly affect the heat transfer coefficient and may increase it slightly. For oil concentrations greater than 5%, the heat transfer coefficient was significantly reduced.

Stephan and Mitrovic [13] studied boiling of R12/Shell Clavus G68 oil mixtures from Gewa-T tube bundles. They observed a decrease of at most 20% in the boiling heat transfer coefficient at a concentration of 6% oil by mass. At higher concentrations, substantial degradations in performance were observed.

Wanniarachchi et al. [14] made the following observations with a High Flux tube boiling in R114/oil mixtures. With pure R114, the High Flux tube resulted in an enhancement of the boiling heat transfer coefficient of about ten times that of a smooth tube. With up to 3% oil by mass, a 35% reduction in the heat transfer coefficient for the porous surface was observed at all heat fluxes. At concentrations of 6% and higher with heat fluxes greater than 30 kW/m^2 , the performance of the porous tube substantially decreased. Also, the effect of oil was observed to be more severe with the High Flux surface than with the smooth surface. The boiling heat transfer coefficient of the High Flux tube was still about seven times that of a smooth tube with up to 10% oil over the practical operating range of heat fluxes (10 kW/m^2 to 40 kW/m^2).

McManus et al. [15] evaluated both a spirally-roped High Flux tube and a Turbo-B tube in R114/oil mixtures. They found at a heat flux of 40 kW/m^2 with pure R114, the boiling coefficients of the High Flux and Turbo-B tubes were 14.6 and 6.4 times, respectively, those of a smooth tube. The factors (commonly called enhancement ratios) decreased to 7.0

and 4.9 respectively at 6% oil by mass. The rate of degradation with increasing oil concentration was seen to be less pronounced for the Turbo-B tube than for the High Flux tube.

Wanniarachchi et al. [16] observed the Gewa-T, Thermoexcel-E and -HE tubes in R114/York Oil C mixtures. Comparing their results with those obtained previously by Wanniarachchi et al. [14], they concluded that the Thermoexcel-E and -HE tubes performed better than the other tubes studied (High Flux, Gewa-T, and plain) for heat fluxes below 18 kW/m^2 . The High Flux tube showed the best performance at higher heat fluxes up to 6% oil by mass. At heat fluxes greater than 45 kW/m^2 with 6% or more oil, the Gewa-T tube gave the best performance.

Murphy [17] compared the Turbo-B surface to 26 fpi (1024 fpm) and 40 fpi (1575 fpm) finned tubes in R114/oil mixtures. He claimed the Turbo-B tube performed the best for both the pure and mixture situations up to 10% oil by mass. The boiling coefficient of the Turbo-B tube was also observed to be relatively insensitive to heat flux at various oil concentrations. Comparing his results with Wanniarachchi et al. [14], he noted that the Turbo-B tube provided about the same enhancement at a heat flux of 30 kW/m^2 as the High Flux tube. For lower heat fluxes, the Turbo-B tube performed better than the High Flux tube while the reverse was true at higher heat fluxes and oil concentrations less than or equal to 6%.

Grant et al. [18] examined the High Flux tube in R113/Shell Clavus 68 oil mixtures. They reported an enhancement ratio between two (at 80 kW/m^2) and three (at 10 kW/m^2) for pure R113. The High Flux tube

was more affected than the plain tube at low oil concentrations. The rate of degradation decreased with increasing oil concentrations (up to 10% by volume). A 40% reduction in the heat transfer coefficient was observed at 10% oil and a flux of 80 kW/m^2 . Also, the researchers could not restore the performance of the High Flux tube in pure R113 to the original values.

Marvillet [19] studied a copper finned tube (26 fpi) and an aluminum plasma sprayed tube in R12 and R22 mixtures with Mobil oil SHC 234 and 326. The R12/SHC 234 mixture is completely miscible while the R22/SHC 326 mixture is partially miscible. He concluded that in the R12/SHC 234 mixture at low heat fluxes (about 20 kW/m^2), the plasma sprayed tube out-performed the finned tube over the range of oil concentrations (0 to 16% by volume). At a high heat flux (40 kW/m^2), the plasma sprayed tube still offered better performance but for a smaller range of concentrations (0 to 4%). The original performance was not restored with the plasma sprayed tube in pure R22. This was not true for the case with the completely miscible mixture of R12/SHC 234.

To summarize the most complete set of data available, Table 1.1 lists values of the enhancement ratio at a heat flux of 30 kW/m^2 for various enhanced surfaces and oil concentrations reported in references 14, 16, and 17. The surfaces with the greatest enhancement for the pure refrigerant case generally suffer the largest degradation with the presence of oil.

Wanniarachchi et al. [16] sketch the probable mechanism present. As the mixture boils inside the re-entrant cavities, tunnels, or pores, the more volatile refrigerant evaporates, leaving behind the less volatile oil. Since a larger concentration of oil exists locally inside the cavities than in the bulk

Table 1.1 Enhancement Ratios in R114/Oil Mixtures
at a Heat Flux of 30 kW/m^2 [14, 16, 17]

Surface	Oil Concentration [⊕]		
	0%	3%	10%
UOP High Flux [14]	9.1	7.5	5.5
Hitachi Thermoexcel-E [16]	8.2	5.5	3.8
Hitachi Thermoexcel-HE [16]	6.8	5.5	3.8
Wolverine Turbo-B [17]	5.2	5.0	4.7
Wieland Gewa-T [16]	4.4	3.8	2.9
40 fpi [*] (1575 fpm) [17]	3.8	3.5	3.2
26 fpi [*] (1024 fpm) [17]	2.8	2.6	2.6

[⊕] only reference 16 specifies York Oil C; all other references do not specify oil used

^{*} fpi = fins per inch, fpm = fins per meter

mixture, oil then diffuses back to the bulk liquid. At a given bulk concentration and heat flux, steady-state conditions are reached when the flow of oil into the cavities is exactly balanced by the diffusion of oil to the bulk. An oil-enriched layer provides both a thermal and mass transfer resistance. As a result, the boiling performance is degraded.

The boiling heat transfer coefficient is also seen to decrease with increasing heat flux at a given oil concentration. At higher fluxes, the refrigerant evaporates at a greater rate, increasing the rate at which oil is left behind. Since the diffusion of oil back to the bulk must increase, the local oil concentration is necessarily higher.

The local oil concentration inside the cavities is also expected to increase as the cavity size decreases. A greater resistance to mass transfer exists in smaller passages. In addition, as the cavities become smaller, the effects of liquid convection within the pores are reduced. Thus, one would predict the High Flux tube to suffer the greatest degradation in performance. Table 1.1 supports this prediction.

The lack of complete understanding of the phenomenon of boiling heat transfer has prevented the development of generalized and reliable correlations. As a result, the designer of boiling heat transfer equipment must rely heavily on a broad base of empirical data. This study intends to evaluate the performance of various enhanced surfaces in single-tube pool boiling of R113/Suniso 3GS oil mixtures. The data presented is of limited design value. R12 and R22 are recognized to be the more widely used refrigerants while an entirely new class of refrigerants are about to replace the environmentally damaging chlorofluorocarbons. Also, conditions existing

in tube bundles may be dramatically different from those with a single tube. Yet the fundamental mechanisms present in pool boiling of a single tube may at least guide the designer of heat transfer equipment. This work intends to provide data which may help to reveal some of these mechanisms.

1.3 Fouling in Aqueous Solutions

Although the topic of scaling from salt solutions has received a good deal of attention since at least 1924, only a handful of articles deal with the effect of fouling on nucleate boiling heat transfer and still less investigate the effect on enhanced heat transfer surfaces. Partridge [20] presents a complete review of the knowledge on the formation and properties of boiler scale up to 1930 while Palen [21] gives a less detailed survey from 1924 to 1965. Freeborn and Lewis [22] extend Partridge's work to include a greater variety of salts. Reitzer [23] presents a mathematical model for precipitation fouling in boiling solutions. Palen and Westwater [24] discuss pool boiling with fouling on aluminum strips. Another article by Farrar and Marschall [25] deals primarily with reducing fouling by film boiling. Fouling with enhanced surfaces is discussed by Chyu [26] during his study of falling film evaporation while Gottzmann et al. [3] evaluate the performance of the High Flux surface.

Partridge [20] has identified the following as the most common constituents of boiler scales:

1. anhydrite (CaSO_4)
2. calcite (CaCO_3)
3. brucite ($\text{Mg}(\text{OH})_2$)

4. magnesium silicate

5. calcium silicate

In general, these substances are all characterized by having inverse solubility, that is their solubilities decrease with increasing temperature (a negatively-sloped solubility curve).

The mechanism involved in the formation of boiler scale has received a great deal of attention. In spite of this, our understanding of the problem is still insufficient. Knowledge of this mechanism is essential if fouling due to precipitation in boiling systems is to be reduced or accommodated to. If the parameters involved in this mass transfer process can be controlled, the rate of fouling may in turn be controlled.

It was generally believed that as steam was removed from a solution, the concentration of dissolved substances increased resulting in the supersaturation and precipitation of excess solute. These suspended particles were then thought to randomly attach themselves to the heating surfaces. Couste [27] disagreed, observing that scale grew most rapidly where the greatest heat was present. He deduced that calcium sulfate scale may form at these heating surfaces prior to the saturation of the bulk of the fluid. Hall [28] also concluded that hard adherent scales are the result of crystallization from the saturated water on the heating surface. In addition, he noted that inverse soluble salts resulted in adherent scale on a heating surface while normal soluble salts resulted in non-adherent crystals in the cooler regions of the solution.

Partridge [20] presented the following comprehensive theory of scale formation. For an inverse soluble salt, the film of water adjacent to the

heating surface tends to be supersaturated even when the bulk is merely saturated. This supersaturation is relieved by spontaneous crystallization possibly promoted by surface irregularities even in the absence of vaporization. When steam bubbles are present on the heating surface, though, the excess solute is deposited as crystals in the shape of rings at the surface-vapor-liquid triple interface. These existing crystals grow due to contact with the supersaturated liquid film at the heating surface. Further deposition of new crystals on top of the earlier deposit can also occur due to bubble evolution.

For a normal soluble salt, the crystals may re-dissolve in the under-saturated liquid film at the heating surface. This effect, though, may be overwhelmed by the rate of deposition of new crystals due to bubble evolution. Partridge identified the slope of the solubility curve of the scaling substance and the heat transfer rate at the surface as the two primary factors in determining the rate of scale growth. He proposed an expression of the form

$$\frac{dW}{d\theta} = -K \left[\frac{dS}{dT} \right]^m \left[\frac{dq}{d\theta} \right]^n \quad (1.3.1)$$

where K , m , and n are empirical constants.

Freeborn and Lewis [22] extended Partridge's work. After observing a deposit from a normal solubility salt, they concluded that the deposit could not have been the result of precipitation but rather, of evaporation. Evaporation, though, could only occur into the steam bubble. The researchers proposed a static or dynamic mechanism at work. The static

mechanism involves steam being generated at the triple interface which forms a bubble. The deposit results from the evaporation producing the steam. In this case, the deposit is at most proportional to the volume of the bubble. The deposit grows as the result of successive bubbles.

The dynamic mechanism is illustrated by Figure 1.2. Water is continuously evaporated into the bubble. At the same time, water is continuously condensed at the outermost surface of the bubble where the bulk is cooler than the surface. The crystals are continuously deposited during the life of the bubble; the amount of deposit is independent of the volume of the bubble. The amount of the deposit depends on:

1. the amount of water evaporated at the triple interface
2. the amount of water evaporated at the vapor-liquid double interface
3. the solubility slope of the salt in the solution.

Evaporation into the bubbles occurs at the triple interface since the temperature of the general heating surface is greater than that of the liquid while the temperature of the surface under the bubble is greater than that of the general heating surface. The superheated steam in the bubble (caused by the surface under the bubble) comes in contact with the solution, causing further evaporation into the bubble at the liquid-vapor double interface resulting in precipitation on the surface of the bubble. In the absence of bubbles, precipitate results from the inverse solubility effect since the heating surface is hotter than the solution. With bubbles, this salt increases the amount of deposit at the triple and double interfaces while a normal soluble salt lessens this amount. Since the investigators

Figure 1.2 Mechanism of Scale Formation [22]

were unable to measure the amount of deposit produced by a single bubble, they could not conclude which mechanism, static or dynamic, was at work.

Banchero and Gordon [29] and Chandler [30] indicated that under sub-cooled boiling conditions with flow the initial deposition rate from saturated salt solutions depends strongly on the supersaturation at the heat transfer surface.

Reitzer [23] proposed the following mathematical model for precipitation fouling in boiling based on the rate equation

$$\frac{dW}{d\theta} = KA(C_b - C_w)^n \quad (1.3.2)$$

In highly agitated systems with slow crystal growth, n is equal to the order of the reaction. For diffusion-dominated quiescent systems, n is equal to unity. Solving for the effect of fouling as a function of time for a constant ΔT , he obtained an equation of the form

$$\frac{1}{U^2} - \frac{1}{U_o^2} = K_3 A (T_w - T_b) \theta \quad (1.3.3)$$

For the constant heat flux case, noting that $W = \rho x A$ for a deposit of thickness x , equation (1.3.2) becomes

$$\rho A \frac{dx}{d\theta} = KA(C_b - C_w)^n \quad (1.3.4)$$

Approximating the solubility as linear with temperature, one can write

$$C_b = a - bT_b \quad (1.3.5a)$$

$$C_w = a - bT_w \quad (1.3.5b)$$

For an inverse soluble salt, b is positive. Substituting (1.3.5a) and (1.3.5b) into (1.3.4):

$$\frac{dx}{d\theta} = \frac{Kb^n}{\rho} (T_w - T_b)^n \quad (1.3.6)$$

Defining an overall heat transfer coefficient U :

$$\frac{1}{U} = \frac{1}{U_o} + \frac{x}{k_f} \quad (1.3.7)$$

But,

$$Q'' = h(T_w - T_b) = U\Delta T \quad (1.3.8)$$

Equations (1.3.7) and (1.3.8) yield

$$T_w - T_b = \frac{k_f \Delta T}{h \left[\frac{k_f}{U_o} + x \right]} \quad (1.3.9)$$

Substituting (1.3.9) into (1.3.6)

$$\frac{dx}{d\theta} = \frac{Kb^n}{\rho} \left[\frac{k_f \Delta T}{h \left[\frac{k_f}{U_o} + x \right]} \right]^n \quad (1.3.10)$$

For constant flux

$$U_o \Delta T_o = U \Delta T \quad (1.3.11)$$

Equations (1.3.11) and (1.3.7) give

$$\begin{aligned} \Delta T &= U_o \Delta T_o \left[\frac{1}{U_o} + \frac{x}{k_f} \right] \\ &= U_o \Delta T_o \left[\frac{\frac{k_f}{U_o} + x}{k_f} \right] \end{aligned} \quad (1.3.12)$$

Substituting (1.3.12) into (1.3.10):

$$\frac{dx}{d\theta} = \frac{K}{\rho} \left[\frac{b U_o \Delta T_o}{h} \right]^n \quad (1.3.13)$$

Taking h to be constant, one can integrate (1.3.13) to obtain

$$x = \frac{K}{\rho} \left[\frac{b U_o \Delta T_o}{h} \right]^n \theta \quad (1.3.14)$$

Substituting (1.3.14) into (1.3.7)

$$\frac{1}{U} = \frac{1}{U_o} + \frac{K}{\rho k_f} \left[\frac{b}{h} \right]^n (U_o \Delta T_o)^n \theta \quad (1.3.15)$$

Since $Q'' = U\Delta T = U_o \Delta T_o$, Reitzer finds

$$\Delta T = \Delta T_o + \frac{K}{\rho k_f} \left[\frac{b}{h} \right]^n (Q'')^{n+1} \theta \quad (1.3.16)$$

Two important assumptions were made in this investigation: (1) there is no removal of the deposit and (2) h and U_o are assumed to be constant. The implication of (2) is that the deposit does not influence the boiling characteristics of the surface, a dubious assumption.

Palen and Westwater [24] conducted pool boiling experiments with strips of heated aluminum in a saturated calcium sulfate solution. They observed two distinct types of deposition. The first type occurred below the bubbles formed by intermittent nucleation sites. These deposits were circular (similar to Partridge's rings) and were the first type of deposit to be seen on the surface. The second type of deposit occurred on the regions of the surface where no boiling sites existed. The deposit was first visible as small specks. These specks grew while other small specks appeared at other locations. Eventually the specks merged until the surface was totally covered.

Palen and Westwater [24] presented the following analysis of a crystalline fouling system (Figure 1.3). Ions first diffuse through the solution to the crystallization zone adjacent to the surface, so Fick's first law applies:

Figure 1.3 Schematic of Precipitation Fouling [24]

$$N = D \frac{C_b - C_s}{z} \quad (1.3.17)$$

where a linear concentration gradient is assumed to exist through the liquid film.

$$N = \frac{(dW/d\theta)_{\text{surface}}}{A} \quad (1.3.18)$$

so that the rate of diffusion to the surface can be written as

$$\left. \frac{dW}{d\theta} \right]_{\text{diffusion}} = \frac{D}{z} A (C_b - C_s) \quad (1.3.19)$$

Formation of a solid molecule in the crystallization zone depends on the probability that two solute molecules, with the correct energy for combination, collide. Chemical kinetics govern this process:

$$\frac{dC_r}{d\theta} = -K_r (C_r)^2 \quad (1.3.20)$$

where C_r is the concentration of solute available for crystallization. This quantity is merely the supersaturation:

$$C_r = C_b - C_s \quad (1.3.21)$$

Introducing the dimensions of the crystallization zone, one may write

$$\frac{dC_r}{d\theta} = \frac{-d\left[\frac{W}{\bar{z}A}\right]}{d\theta} = \frac{-1}{\bar{z}A} \frac{dW}{d\theta} \quad (1.3.22)$$

so that (1.3.20) becomes:

$$\left. \frac{dW}{d\theta} \right]_{\text{crystallization}} = \bar{z}K_r A (C_b - C_s)^2 \quad (1.3.23)$$

Thus, equation (1.3.19) has the form of a diffusion-controlled process in the bulk region ($n=1$ in equation (1.3.2)) while equation (1.3.23) has the form of a second order process in the crystallization zone ($n=2$ in equation (1.3.2)).

To determine if the rate theory proposed by Reitzer is consistent with their data, Palen and Westwater manipulate equation (1.3.2). Their data (Figure 1.4) may be represented by an equation of the form

$$\frac{1}{A} \frac{dW}{d\theta} = K_1(Q'')^2 \quad (1.3.24)$$

Assuming the solubility of calcium sulfate can be approximated by a linear function of temperature in the range of interest, one can write:

$$C_b - C_s = b(T_s - T_b) \quad (1.3.25)$$

where b is the slope of the solubility curve. Also, note that

$$T_s - T_b = \frac{Q''}{h} \quad (1.3.26)$$

Figure 1.4 Scale Accumulation Rate [21]

so that equation (1.3.2) becomes

$$\frac{1}{A} \frac{dW}{d\theta} = \frac{K}{h^n} b^n (Q'')^n \quad (1.3.27)$$

If equation (1.3.24) is to be consistent with equation (1.3.27), one concludes

$$\frac{K}{h^2} b^2 = K_1 \quad (1.3.28)$$

Thus, Palen and Westwater predicted the rate of mass transfer to be proportional to the square of the concentration driving potential while the ratio of the mass transfer coefficient to the square of the heat transfer coefficient must be approximately constant. They found that the value of the constant for their system is

$$\frac{K}{h^2} = 4.6 \times 10^{-10} \frac{\text{hr} \cdot \text{ft}^8 \cdot ^\circ\text{F}^2}{\text{BTU}^2 \cdot \text{lb}}$$

K and h , the mass and heat transfer coefficients respectively, depend on the amount of turbulence. Although most analogies between heat and mass transfer have equal exponents on the two transport coefficients, the exponent $n=2$ in this case is a consequence of equation (1.3.2) which defines K .

The effect of fouling on pool boiling heat transfer with non-enhanced surfaces is discussed by Palen and Westwater [24]. Plotting the variation of wall superheat with time (Figure 1.5), they observed three distinct regions. They proposed the following. Region A is characterized by a very porous

Figure 1.5 Fouling Curve [21]

fouling deposit with a low thermal conductivity. As a result, the increase in the heating surface temperature is rapid. The deposit grows as vapor is forced from the imperfections in the surface into the new cavities in the fouling deposit. The decrease in the superheat in region B is due to the increase in the number of nucleation sites, increasing the heat transfer coefficient. Then the deposit thickness increases to the point where the temperature drop across the boiling film is negligible compared to that across the deposit. This is observed in region C; the superheat begins to increase linearly with time as the scale continues to deposit. The slope of the curve in region C is less than in region A since the deposit is more compacted after residing on the surface for a period of time. Many of the pores in the deposit are now active boiling sites and do not contain stagnant liquid as they did in region A. In no case did the deposit increase the overall heat transfer coefficient above that for a clean surface.

Palen and Westwater [24] have attempted to predict the effect of heat flux on the fouling rate. Note that

$$\frac{1}{A} \frac{dW}{d\theta} = \rho \frac{dx}{d\theta} \quad (1.3.29)$$

and $n = 2$, equation (1.3.3) can be re-written as

$$\frac{dx}{d\theta} = \frac{Kb^2}{\rho h^2} (Q'')^2 \quad (1.3.30)$$

Employing the Kern and Seaton model (Equation (1.1.4)), the net rate of accumulation of a deposit is the sum of a deposition rate (equation (1.3.23))

and a removal rate, which should depend on the type of surface and the fluid shearing stresses. In the investigation by Palen and Westwater, this removal rate was visually observed to be very low. As a result, the removal rate was assumed to be zero. With fouling present, the superheat is given by

$$\Delta T_s = \frac{Q''}{h} + Q'' \frac{x}{k_f} \quad (1.3.31)$$

Integration of equation (1.3.30) yields

$$x = (Q'')^2 \int \frac{Kb^2}{\rho h^2} d\theta \quad (1.3.32)$$

so that equation (1.3.31) becomes

$$\Delta T_s = \frac{Q''}{h} + \frac{(Q'')^3}{k_f} \int \frac{Kb^2}{\rho h^2} d\theta \quad (1.3.33)$$

The quantity $\frac{Kb^2}{h^2}$ was previously determined to be a constant K_1 (see equation 1.3.28). Assuming a constant average bulk density, (1.3.33) gives

$$\Delta T_s = \frac{Q''}{h} + K_1 \frac{1}{\rho k_f} (Q'')^3 \theta + C_1 \quad (1.3.34)$$

values of h , $1/(\rho k_f)$, and C_1 were determined empirically. An expression for the fouling thermal resistance R_f may be obtained via:

$$R_f = \frac{\Delta T_s}{Q''} - \frac{1}{h_c} \quad (1.3.35)$$

The clean coefficient of heat transfer h_c was determined from pool boiling curves with pure water.

The present work deals with enhanced cylindrical heat transfer surfaces. Specifically, the UOP High Flux surfaces and the Wolverine Turbo-B surfaces are investigated. The effect of fouling on these enhanced surfaces is a primary concern. Partridge [24] doubted that a specific surface could affect the mechanism of fouling, although the surface may influence how difficult it is to remove the scale. Partridge observed that calcium sulfate scales formed in a similar manner and in comparable quantities on surfaces of glass and highly polished metals as well as on a steel surface covered with a heavy layer of oxide.

Gottzmann et al. [3] reported that the High Flux surface is unaffected by light fouling (a condition not described by the authors) encountered in aqueous solutions. They attributed the resistance of these surfaces to fouling to the following features of the surface:

1. the high liquid recirculation rate through the porous matrix
2. the high capillarity of the porous matrix, resulting in
wetting of the surface, preventing local hot spots
or dryout
3. the high heat transfer coefficients, resulting in wall
temperatures close to the bulk liquid temperatures.

To substantiate the first claim, the investigators conducted a long term pool boiling test using concentrated sea water with a total of 8.71% (by mass)

of dissolved salts. The solubility limit for calcium sulfate is 9.74% (by mass). Figure 1.6 shows no degradation in the heat transfer performance. They concluded, on the basis of unspecified measurements, that no solids precipitated on the surface and determined that at least 9.4 pounds of liquid entered the porous matrix for every 1 pound of fluid vaporized.

Chyu [26] observed fouling of a UOP High Flux surface during his experiments with falling film evaporation. Microscopic examination showed that white crystals covered the internal surfaces of the pores. Chemical analysis yielded sodium zinc chloride trihydrate as the major soluble compound with lead chloride as the major insoluble compound along with lead chloride fluoride and quartz. Since the distilled water used in the tests contained silicon, chlorine, and lead, some other contaminant source must have been present. The sodium was believed to come from the 'Comet' used to clean the surface prior to the test. The zinc was traced to the soldering flux (used to locate the heater in the test section) which accidentally contacted the surface.

Chyu concluded that the scale originated from the contaminants remaining inside the porous matrix, such as the residual 'Comet' cleanser. These contaminants then reacted with the ions present in the water and with other contaminants on the surface. Crystallization occurred when the concentration of the scaling substance in the liquid film exceeded the saturation limit. Crystals then grew continuously from the nuclei. In testing a fouled tube, Chyu noticed that adding fresh distilled water dissolved some of the soluble portion of the scale prior to boiling while the insoluble portion remained on the surface. Since the nuclei were still

Figure 1.6 Fouling of High Flux Surface in Sea Water [3]

present, though, the soluble crystals began to grow in the high concentration, evaporating film. The insoluble crystals began to grow as well. The rate of crystal growth slowed as the ion concentration in the water decreased. The growth rate became steady as the ion concentration was maintained by adding fresh distilled water.

Chyu [26] noticed a substantial degradation in pool boiling performance of a High Flux surface. Figure 1.7 compares boiling curves of a High Flux surface when new to the same surface after about one and one-half years later under the fouling conditions discussed in the previous section. In a long term falling film evaporation test, Chyu observed how the superheat varied with time (Figure 1.8) at constant heat flux. At the start of the test, the data were close to that of the new surface. The superheat increased most rapidly in the first hour of the test and then slowed. Even after thirty-two hours, the increasing trend was still noticeable. Chyu concluded that although the porous surface may result in heat transfer performances many times better than a plain surface, the advantages must be weighed with respect to their vulnerability to fouling.

The conflicting reports of Gottzmann et al. and Chyu suggest a need to systematically approach the problem of fouling of enhanced heat transfer surfaces. Motivated by some of their objectives, it is proposed to adapt the experimental procedures of Palen and Westwater to the present work.

Thus, the goals of the present research are:

1. to determine how the heat transfer coefficient of a fouled surface in pool boiling compares to a clean surface
2. to determine the variation of the heat transfer coefficient

Figure 1.7 Pool Boiling and Falling Film Evaporation Performances of High Flux Surface [26]

Figure 1.8 Fouling Curve of High Flux Surface [26]

with time under fouling conditions

3. to determine the effect of heat flux on fouling
4. to compare the results obtained with the types of surface examined.

PART 2

POOL BOILING IN REFRIGERANT-OIL MIXTURES

2.1 Apparatus

2.1.1 Test Sections

All test sections were copper tubes with a heated length of 4 inches (101.6 mm), an outer diameter of 3/4 inch (19.05 mm), and an inner diameter of 1/4 inch (6.35 mm) (see Figure 2.1). The test sections had different outside structured surfaces. A total of five different test sections provided by Universal Oil Products Incorporated and Wolverine Tube Incorporated were examined. These test sections were given the following designations: Plain, Large (UOP High Flux R113 Large Pore), Small (UOP High Flux R113 Small Pore), Very Open (Wolverine Turbo-B Very Open), and Very Closed (Wolverine Turbo-B Very Closed).

The plain test section had a smooth surface polished with 600 grit paper. The High Flux surfaces consisted of a porous layer of copper particles with an approximate layer thickness of 0.015 inch (0.381 mm). The particle sizes differed for the Large and Small surfaces. For the Large surface, 20% of the particles pass through a 200 mesh (U.S. Standard Series) screen, another 40% pass through the 200 mesh screen but are retained by a 325 mesh screen, while the remaining 40% pass through the 325 mesh screen. All of the particles of the Small surface pass through the 325 mesh screen. [41] The Wolverine surfaces were manufactured by finning followed by successive cross-grooving and rolling operations. Cross-grooving and rolling deforms the tips of the fins, giving the general appearance of a grid of rectangular flattened blocks. The blocks of the Very Closed surface

Figure 2.1 Schematic of Test Section (Dimensions in inches) [37]

appeared to be more flattened than those of the Very Open surface.

2.1.2 Instrumentation

Power was supplied to the test section by means of a 1/4 " by 4" (6.35 mm x 101.6 mm) cartridge heater (Durex, 500W, 120VAC) and was adjusted with a variable AC transformer (Variac). A tolerance of 0.002" to 0.004" (0.0508 mm to 0.1016 mm) on the diameter of the heater allowed it to be press-fit into the test section. The power input to the heater was determined by measuring the voltage across the heater and the current from the voltage drop across a precision 0.01 Ω shunt in series with the heater. All voltage measurements were made with a digital multimeter (Keithly 177).

Temperatures were measured using copper-constantan thermocouples referenced to an electronic ice point. Four thermocouples were located inside the tube wall at 12/3/6/9 o'clock at the midpoint of the heated length as shown in Figure 2.1. Two additional thermocouples were located in the pool. One thermocouple was located approximately two inches (51 mm) under the test section while the remaining thermocouple was positioned approximately 1/8" (3.2 mm) above the surface of the test section in the vapor stream. The signals from the thermocouples were input to a multi-channel switch. The switch output was attached to the digital multimeter.

Glass thermometers provided the room temperature and the temperature of the outer bath.

2.1.3 Equipment

The apparatus consisted of two rectangular glass tanks, one placed inside the other (Figure 2.3). The inner tank (238 x 181 x 324 mm) contained the pool of R113 and the test section; the outer tank (308 x 308 x 305 mm) provided an insulating jacket of distilled water. An immersion heater was placed in the outer jacket and was kept at a constant temperature between 50°C and 60°C by means of a temperature controller. The bottom pool (R113) thermocouple was the controlling input.

A 1/4" (6.35 mm) thick Lexan lid was placed on the top of the inner tank. A strip of closed-cell sponge rubber placed under the lid sealed the tank. Several holes were drilled in the lid to allow access to the pool for instrumentation.

The test section was mounted on a Lexan plate (as shown in Figure 2.2) which was attached to the lid. A Buna-N cap sealed one end of the test section while a protection tube carried the heater and thermocouple wires to the lid of the inner tank. A copper coil condenser was located beneath the lid while an open Graham condenser was placed in the lid to provide atmospheric pressure in the vapor space above the pool. Tap water was the cooling fluid.

2.2 Experimental Procedure

Pool boiling experiments were conducted in the following manner:

1. Turn on tap water to the condensers (approximately 0.1 ℓ /min.).
2. Heat the pool to the saturation temperature (vapor is observed to condense inside the Graham condenser

Figure 2.2 Schematic of Mounting Arrangement

Test Section Mounted on Support in Tank

1. Protection tube for power and thermocouple leads
2. Elbow
3. Connector
4. Thermocouples recording fluid temperature
5. Thermocouples recording test section temperature
6. End seal
7. Cartridge heater
8. Test section
9. O-ring seal
10. O-ring seal
11. Test section support
12. Thermocouple leads
13. Power leads

Figure 2.2 Schematic of Mounting Arrangement (continued)

Figure 2.3 Pool Boiling Apparatus [37]

at this temperature) via the temperature-controlled outer jacket.

3. Adjust the tap water flow rate so that a small amount of vapor condenses inside the Graham condenser.
4. De-gas the pool and test section by applying a heat flux of at least $3 \times 10^4 \text{ W/m}^2$ to the test section for about one hour.
5. Switch off the power to the test section.
6. Seal all openings to the pool and allow the test section to cool to the pool temperature.
7. Measure and record the atmospheric pressure, the height of the liquid above the tube centerline, the room temperature, and the temperature of the outer jacket.
8. Measure and record the thermocouple voltages upon stabilizing.
9. Apply power to the test section with the Variac.
10. Measure and record the heater and shunt voltages.
11. Repeat steps 7-9, increasing the voltage in about 10 volt increments to the maximum desired heat flux (typically $5.8 \times 10^4 \text{ W/m}^2$).
12. Repeat steps 7-9, decreasing the voltage in about 20 volt decrements to zero power.
13. Repeat step 6.

Steps 1-6 took approximately three hours while steps 7-12 required another

two hours. After each mixture run, the surface was soaked in de-natured alcohol for at least 48 hours to clean it (see Section 2.4).

2.3 Data Reduction

All raw data was entered into a spreadsheet (see Appendix 2) and reduced. Power supplied is determined by:

$$P = I_{\text{heater}} V_{\text{heater}} \quad (2.1)$$

V_{heater} is measured directly. The current is obtained by:

$$I_{\text{heater}} = V_{\text{shunt}} / R_{\text{shunt}} \quad (2.2)$$

where $R_{\text{shunt}} = 0.01 \Omega$. Thus, the power is given by:

$$P = \frac{V_{\text{shunt}}}{0.01 \Omega} V_{\text{heater}} \quad (2.3)$$

Finally, the heat flux to the test section is calculated:

$$Q'' = P / A \quad (2.4)$$

where A is the surface area of the test section. For a $3/4'' \times 4''$ (19.05 mm x 101.6 mm) tube, A is given by:

$$A = \pi dL = \pi(3/4'')(4'')(0.0254^2 \text{ m}^2/1^2 \text{ in.}^2) \quad (2.5)$$

or

$$A = 0.00608 \text{ m}^2$$

The heat flux is then:

$$Q'' = P / (0.00608 \text{ m}^2) \quad (2.6)$$

Conversion of thermocouple voltages to temperatures was accomplished with the National Bureau of Standards curvefit for type-T thermocouples (see Appendix 2). The temperature of the bulk pool was obtained from the thermocouple located approximately 1/8" above the test section. An average bulk temperature for the entire run was calculated by averaging the bulk temperatures for each data point. A typical run contained twenty data points so

$$T_{b,avg} = \frac{\sum_{j=1}^{20} T_{b,j}}{20} \quad (2.7)$$

The average temperature of the outer tube surface was determined from the four thermocouples located inside the tube wall, accounting for one-dimensional conduction through the wall, i.e.

$$T_{w,avg} = \frac{\sum_{i=1}^4 T_{w,i}}{4} \quad (2.8)$$

where

$$T_{w,i} = T_{i,r} - \frac{Q'' R}{k} \ln \left[\frac{R}{r} \right] \quad (2.9)$$

The temperature difference between the surface and the bulk is then

$$\Delta T = T_{w,avg} - T_{b,avg} \quad (2.10)$$

The enhancement ratio (E.R.) is computed by

$$E.R. = \frac{\Delta T_{plain}}{\Delta T_{enhanced}} \quad (2.11)$$

at a given heat flux and oil concentration. The ratio of boiling coefficients is found from

$$\frac{h_{with\ oil}}{h_{without\ oil}} = \frac{\Delta T_{without\ oil}}{\Delta T_{with\ oil}} \quad (2.12)$$

again at a given heat flux and oil concentration.

2.4 Observations and Results

Figures 2.4 to 2.8 present pool boiling curves for the five surfaces examined at four mass concentrations of 3GS (155 SSU) oil. It is important to note that the temperature difference is referenced to an average over time of the measured bulk temperature (from the thermocouple located 1/8 " above the test section) and not on a saturation temperature predicted from the pressure at the axis of the test section. The primary motivation for choosing this *in situ* temperature was the lack of any data on the saturation temperature of refrigerant-oil mixtures in general or for R113 at various mass concentrations of 3GS oil in particular. The pure

Figure 2.4 Pool Boiling Curves of Plain Smooth Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil

Figure 2.5 Pool Boiling Curves of High Flux Large Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil

Figure 2.6 Pool Boiling Curves of High Flux Small Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil

Figure 2.7 Pool Boiling Curves of Turbo-B Very Open Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil

Figure 2.8 Pool Boiling Curves of Turbo-B Very Closed Tube in R113 at 0%, 1%, 5%, and 10% Mass Concentrations of 3GS Oil

R113 data were also based on a measured bulk temperature to be consistent. It was observed that the measured bulk temperature increased with increasing oil concentration. For example, an average bulk temperature of 47.6°C was observed in the pure R113 runs compared to 49.4°C in the 10% oil runs (see Appendix 1).

The effect of oil concentration on a particular surface may be observed by comparing the various pool boiling curves of that surface (Figures 2.4 to 2.8). Table 2.1 also shows the effect of oil at a heat flux of 30 kW/m² by presenting the ratio

$$\frac{\Delta T_{\text{without oil}}}{\Delta T_{\text{with oil}}}$$

for a given surface at various oil concentrations. This quantity may also be interpreted as the ratio of boiling coefficients

$$\frac{h_{\text{with oil}}}{h_{\text{without oil}}}$$

The boiling curves for the plain tube (Fig. 2.4) show a general decrease in heat transfer performance with increasing oil concentration, particularly at heat fluxes above 20 kW/m². At the highest heat flux the degradation is seen to be quite dramatic at 10% oil, considering the logarithmic nature of the plot. Table 2.1 supports this observation at a lower heat flux of 30 kW/m². While no statistically significant change in the ratio of boiling coefficients is observed between 1% and 5% oil, there is

Table 2.1 Ratio of Observed Boiling Coefficients
at a Heat Flux of 30 kW/m²

Oil Concentration [Ⓢ]	Surface				
	Turbo-B ¹ Very Open	High Flux ² Small	Turbo-B Very Closed	Plain	High Flux Large
1%	1.0	0.9	0.8	0.7	0.6
5%	0.7	0.7	0.6	0.6	0.5
10%	0.6	0.4	0.4	0.3	0.4

[Ⓢ]Suniso 3GS (155 SSU) Oil

¹Wolverine Tube Incorporated.

²Universal Oil Products Incorporated (formerly Linde Division, Union Carbide Corporation).

a significant decrease in the ratio between 0% and 1% oil as well as between 5% and 10% oil.

The High Flux Large surface (Fig. 2.5) experienced a degradation with the addition of oil (compared to the pure R113 curve) at all heat fluxes. No significant difference in performance was observed between the 1% and 5% oil runs while a degradation was observed between 5% and 10% oil for fluxes above about 30 kW/m^2 . At 30 kW/m^2 , Table 2.1 shows a significant change in the ratio of boiling coefficients between the pure R113 run and the runs with oil although no significant difference was observed between the various concentrations of oil.

The effect of 1% oil on the High Flux Small tube (Fig. 2.6) was seen to be significant at only the highest heat flux while a reduction in performance between 0% and 5% oil was seen at fluxes above about 30 kW/m^2 . The effect of 10% oil was observed at fluxes above about 6 kW/m^2 with a dramatic degradation at the highest flux. Table 2.1 also shows a change in the ratio of boiling coefficients at 30 kW/m^2 between 0% and 5% oil as well as between 5% and 10% oil.

No significant effect was observed between 0% and 1% oil with the Turbo-B Very Open tube (Fig. 2.7) at all fluxes. A degradation was noted with the addition of 5% or 10% oil at all fluxes. Table 2.1 supports these observations at a heat flux of 30 kW/m^2 , also suggesting no significant effect between 5% and 10% oil.

The Turbo-B Very Closed tube (Fig. 2.8) was affected by the presence of 5% or 10% oil at fluxes above about 2 kW/m^2 with no effect with 1% oil. Table 2.1 confirms this at a flux of 30 kW/m^2 , and suggests

no change in the ratio of boiling coefficients between the 1% and 5% oil cases or the 5% and 10% oil runs.

To compare the performance of various surfaces at a given oil concentration and heat flux, it is convenient to introduce the enhancement ratio

$$\frac{\Delta T_{\text{plain}}}{\Delta T_{\text{enhanced}}}$$

Table 2.2 presents enhancement ratios for a flux of 30 kW/m². In pure R113, the Small surface performed better than the Turbo-B surfaces. At 1% and 5% oil, the Small surface provided a lower boiling coefficient than both the Large and Very Closed surfaces. With 10% oil, the Small and Very Open surfaces out-performed the Very Closed surface. Some researchers [14, 16, 17] have observed a decrease in the enhancement ratio with increasing oil concentration. No general trend with oil concentration was observed in this study.

Table 2.1 shows that the Large surface is the one most affected by the presence of 1% and 5% oil (compared to pure R113). The addition of 10% oil is seen to affect the plain tube more than the other four surfaces. The Very Open surface was least affected by oil at all concentrations.

Figures 2.9 to 2.12 present data for the four enhanced surfaces in pure R113 before and after the oil mixture runs. Between each run, every surface was soaked in de-natured alcohol for at least 48 hours to clean the surface. The Small surface showed a decrease in the boiling coefficient at only the highest heat flux examined in the post-oil experiment. All other

Table 2.2 Observed Enhancement Ratios at a Heat Flux of 30 kW/m²

Surface	Oil Concentration [⊕]			
	0%	1%	5%	10%
High Flux ¹ Small	7	8	7	8
High Flux Large	5	4	4	6
Turbo-B ² Very Open	4	6	5	8
Turbo-B Very Closed	3	4	4	4

[⊕]Suniso 3GS (155 SSU) Oil

¹Universal Oil Products Incorporated (formerly Linde Division, Union Carbide Corporation).

²Wolverine Tube Incorporated.

Figure 2.9 Pool Boiling Curves of High Flux Large Tube in Pure R113 Before (A) and After (C) Mixture Tests

Figure 2.10 Pool Boiling Curves of High Flux Small Tube in Pure R113 Before (A) and After (B) Mixture Tests

Figure 2.11 Pool Boiling Curves of Turbo-B Very Open Tube in Pure R113 Before (A) and After (B) Mixture Tests

Figure 2.12 Pool Boiling Curves of Turbo-B Very Closed Tube in Pure R113 Before (A) and After (B) Mixture Tests

surfaces were observed to experience no significant change in performance.

The presence of oil in the R113 resulted in a syrup-like consistency increasing with increasing oil concentration. The pool also became cloudy. Foam was observed at the top of the pool when boiling with oil. More foam existed at higher concentrations. An oily residue was observed on the plain tube following experiments in R113/oil mixtures. No noticeable difference was observed in the time it took to achieve steady-state conditions between the pure refrigerant experiments and the mixture experiments. In both cases, the wall temperature became steady within five minutes of adjusting the power.

2.5 Discussion

The observed decrease in heat transfer performance with increasing oil concentration is speculated to be the result of an oil-rich layer adjacent to the tube surface. This layer develops as the refrigerant (the more volatile component) evaporates at the boiling surface, leaving behind the less volatile oil. The liquid-vapor surface tension and the surface adhesive tension associated with the oil-rich layer are significantly higher than those of the pure refrigerant [10]. As a result, more energy is needed for the evolution of bubbles. Also, since the oil/refrigerant mixture has a greater liquid viscosity than the pure refrigerant [10], the turbulent motion in the pool is reduced, lessening the flow of liquid to the boiling surface. Both effects increase as the oil concentration increases. The result is a decrease in the boiling heat transfer coefficient.

No surface examined in this study was found to be especially immune or more vulnerable to the phenomenon than another surface. In general,

of the surfaces experience only a slight decrease in performance when 1% oil is present while all the surfaces suffer a substantial degradation at 10% oil (see Table 2.1).

To compare the results obtained in Table 2.2 with those in Table 1.1, it is important to note that the specific surface structures of the High Flux and Turbo-B surfaces examined in references 14 and 17 are not known. Thus it is not likely that the surfaces examined in this study have the same structure as those in Table 1.1. In the pure refrigerant tests, all observed enhancement ratios were between 30% and 82% lower than those reported in Table 1.1. At 10% oil, the observed enhancement ratios for the High Flux Large and Turbo-B Very Closed surfaces were about the same (less than 20% difference) as those reported in references 14 and 17. Both values of the enhancement ratio for the High Flux Small and Turbo-B Very Open surfaces were between 30% and 40% larger than those obtained by Wanniarachchi [14] and Murphy [17]. Table 1.1 shows a monotonic decrease in the enhancement ratio with increasing oil concentration for all surfaces. No general trend in the enhancement ratio was observed in this study.

The fact that the original performance of all the enhanced tubes was practically restored when soaked in de-natured alcohol and re-tested in pure R113 suggests that the miscible mixture of R113 and 3GS oil does not lead to an irreversible degradation of the heat transfer surface. Other miscible mixtures such as R12 and Mobil oil SHC 234 have yielded similar results. [19].

PART 3

POOL BOILING IN AN AQUEOUS CALCIUM SULFATE SOLUTION

3.1 Apparatus

3.1.1 Test Sections

All test sections were copper tubes with a heated length of 4 inches (101.6 mm), an outer diameter of 3/4 inch (19.05 mm), and an inner diameter of 1/4 inch (6.35 mm) (see Figure 2.1). The test sections had different outside structured surfaces. A total of five different test sections provided by Universal Oil Products Incorporated and Wolverine Tube Incorporated were examined. These test sections were given the following designations: Plain, Large (UOP High Flux R113 Large Pore), Small (UOP High Flux R113 Small Pore), Very Open (Wolverine Turbo-B Very Open), Very Closed (Wolverine Turbo-B Very Closed).

The plain test section had a smooth surface polished with 600 grit paper. The High Flux surfaces consisted of a porous layer of copper particles with an approximate layer thickness of 0.015 inch (0.381 mm). The particle sizes differed for the Large and Small surfaces. For the Large surface, 20% of the particles pass through a 200 mesh (U.S. Standard Series) screen, another 40% pass through the 200 mesh screen but are retained by a 325 mesh screen, while the remaining 40% pass through the 325 mesh screen. All of the particles of the Small surface pass through the 325 mesh screen. [41]. The Wolverine surfaces were manufactured by finning followed by successive cross-grooving and rolling operations. Cross-grooving and rolling deforms the tips of the fins, giving the general appearance of a grid of rectangular flattened blocks. The blocks of the

Very Closed surface appear to be more flattened than those of the Very Open surface.

3.1.2 Instrumentation

Power was supplied to the test section by means of a 1/4 " by 4" (6.35 mm x 101.6 mm) cartridge heater (Durex, 500W, 120VAC) and was adjusted with a variable AC transformer (Variac). A tolerance of 0.002" to 0.004" (0.0508 mm to 0.1016 mm) on the diameter of the heater allowed it to be press-fit into the test section. The power input to the heater was determined by measuring the voltage across the heater and the current from the voltage drop across a precision 0.01 Ω shunt in series with the heater. All voltage measurements were made with a digital multimeter (Keithly 177).

Temperatures were measured using copper-constantan thermocouples referenced to an electronic ice point. Four thermocouples were located inside the tube wall at 12/3/6/9 o'clock at the midpoint of the heated length as shown in Figure 2.1. Two additional thermocouples were located in the pool. One thermocouple was located approximately two inches (51 mm) under the test section while the remaining thermocouple was positioned approximately 1/8" (3.2 mm) above the surface of the test section in the vapor stream. The signals from the thermocouples were input to a multi-channel switch. The switch output was attached to the digital multimeter.

A mercury barometer was used to measure the atmospheric pressure while glass thermometers provided the room temperature and the temperature of the outer bath. A pH electrode was placed about 1/4"

(6.35 mm) above the test section and was connected to a pH metering pump. A conductivity probe was input to a conductivity module attached to a millivolt meter to measure the ionic characteristics of the pool.

3.1.3. Equipment

The apparatus consisted of two rectangular glass tanks, one placed inside the other (Figure 2.3). The inner tank (238 x 181 x 324 mm) contained the pool of saturated aqueous calcium sulfate solution and the test section; the outer tank (308 x 308 x 305 mm) provided an insulating jacket of ethylene glycol. An immersion heater was placed in the outer jacket and was kept at constant temperature between 120°C and 140°C by means of a temperature controller. The bottom pool (CaSO_4) thermocouple was the controlling input. Glass wool and beaded styrofoam insulated the walls of the outer tank. Openings in the insulation were made for visual and photographic observations (see Appendix 7).

A 1/4" (6.35 mm) thick Lexan lid was placed on the top of the inner tank. A strip of closed-cell sponge rubber placed under the lid sealed the tank. Several holes were drilled in the lid to allow access to the pool for instrumentation.

The test section was mounted on a Lexan plate (as shown in Figure 2.2) which was attached to the lid. A Buna-N cap sealed one end of the test section while a protection tube carried the heater and thermocouple wires to the lid of the inner tank. A copper coil condenser was located beneath the lid while an open Graham condenser was placed in the lid to provide atmospheric pressure in the vapor space above the pool. Tap water was the cooling fluid. A pH metering pump maintained the pH of the

aqueous solution by adding fresh solution to the pool when the pH of the pool deviated from its initial value or when the liquid level became low.

3.2 Experimental Procedure

Pool boiling experiments were conducted in the following manner:

1. Turn on tap water to the condensers (approximately 0.1 $\ell/\text{min.}$).
2. Heat the pool to the saturation temperature (as predicted from the pressure at the tube axis, see Appendix 2) via the temperature-controlled outer jacket.
3. Adjust the tap water flow rate so that a small amount of vapor condenses inside the Graham condenser.
4. De-gas the pool and test section for about one hour by boiling from immersed cartridge heaters in the pool. Remove the heaters at the end of the period.
5. Seal all openings to the pool.
6. Measure and record the atmospheric pressure, the height of the liquid above the tube centerline, the room temperature, and the temperature of the outer jacket.
7. Measure and record the thermocouple voltages at fixed intervals (see Appendix 1).
8. Apply power to the test section with the Variac.
9. Measure and record the heater and shunt voltages at fixed intervals (see Appendix 1).

10. Steps 6 and 8 continued until a general trend is evident typically between 15 and 24 hours.

Steps 1-6 took about six hours. The pH and electrical conductivity were monitored at the beginning and end of the run. Although an automatic pump for supplying fresh solution under the control of the pH electrode was available, the pump was activated manually since additions were made only occasionally when the pH deviated from its initial value or when the liquid level became low.

3.3 Data Reduction

All raw data was entered into a spreadsheet (see Appendix 2) and reduced. Power supplied is determined by:

$$P = I_{\text{heater}} V_{\text{heater}} \quad (3.1)$$

V_{heater} is measured directly. The current is obtained by:

$$I_{\text{heater}} = V_{\text{shunt}} / R_{\text{shunt}} \quad (3.2)$$

where $R_{\text{shunt}} = 0.01 \, \Omega$. Thus, the power is given by:

$$P = \frac{V_{\text{shunt}}}{0.01 \, \Omega} V_{\text{heater}} \quad (3.3)$$

Finally, the heat flux to the test section is calculated:

$$Q'' = P / A \quad (3.4)$$

where A is the surface area of the test section. For a $3/4'' \times 4''$ (19.05 mm x 101.6 mm) tube, A is given by:

$$A = \pi dL = \pi(3/4'')(4'')(0.0254^2 \text{ m}^2/1^2 \text{ in.}^2) \quad (3.5)$$

or
$$A = 0.00608 \text{ m}^2$$

The heat flux is then:

$$Q'' = P / (0.00608 \text{ m}^2) \quad (3.6)$$

Conversion of thermocouple voltages to temperatures was accomplished with the National Bureau of Standards curvefit for type-T thermocouples (see Appendix 2). The saturation temperature of water was obtained via a curvefit of the ASME Steam Tables (see Appendix 2) using the pressure at the tube axis. The wall superheat is

$$T_{w,avg} - T_{sat} \quad (3.7)$$

The change in wall superheat due to fouling is taken to be the difference between the superheat at twenty hours in the fouling experiment and the clean value obtained in the pure water test at the same heat flux. The deposit is assumed to be only calcium sulfate anhydrite when calculating the mass of deposit on the surface. The details of the

calculation are given in Appendix 6.

3.4 Observations and Results

Figure 3.1 presents pool boiling curves in distilled water for the five surfaces examined. Figures 3.2 to 3.6 present fouling curves for the five surfaces at two heat fluxes in a saturated aqueous calcium sulfate solution. The temperature difference is referenced to a saturation temperature predicted from the pressure at the tube axis. This temperature was chosen when it was discovered that the pool boiling experiments in distilled water were conducted under slightly sub-cooled conditions. The average bulk temperature for these runs was 99.3°C while the average saturation temperature predicted from the pressure was 100.3°C (see Appendix 1). To be consistent, the fouling curves were also based on a saturation temperature predicted from the pressure. Thus, it was assumed that the saturation temperature of a saturated aqueous solution of calcium sulfate was equal to the saturation temperature of pure water at the same pressure. As will be seen below, this assumption is believed to result in difficulties in defining the superheat in certain instances.

The "clean" data points presented at time zero on Figures 3.2 to 3.6 are obtained by interpolation of the pool boiling curves presented in Figure 3.1. An experiment was also conducted with the plain tube in distilled water to determine the time it took to achieve steady state conditions after applying a fixed power to the cartridge heater. This time was found to be less than one minute. It was assumed the other surfaces performed similarly.

Figure 3.2 shows the fouling curves for the plain surface. At a heat

Figure 3.1 Pool Boiling Curves of All Tubes in Distilled Water

Figure 3.2 Precipitation Fouling Curves of a Plain Smooth Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes

Figure 3.3 Precipitation Fouling Curves of a High Flux Large Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes

Figure 3.4 Precipitation Fouling Curves of a High Flux Small Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes

Figure 3.5 Precipitation Fouling Curves of a Turbo-B Very Open Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes

Figure 3.6 Precipitation Fouling Curves of a Turbo-B Very Closed Tube in a Saturated Aqueous Solution of Calcium Sulfate at Two Heat Fluxes

flux of 10 kW/m^2 , the wall superheat was seen to increase 2.7°C from the clean value within the first hour of the run. No significant change in superheat was observed for the remaining twenty-four hours of the run. At a heat flux of 80 kW/m^2 , the superheat increased 5.0°C within the first hour. An additional 1.0°C increase in the superheat was observed after twenty hours.

Figure 3.3 depicts fouling data for the High Flux Large tube. No statistically significant change in superheat was observed at a heat flux of 10 kW/m^2 . The appearance of physically unreasonable values of the superheat for the fouled surface which are less than those for the clean surface are discussed below. At a heat flux of 80 kW/m^2 , a monotonic increase in superheat was observed from a clean value of 5.4°C to a value of 6.5°C at two hours. No significant change was observed for the rest of the run.

The High Flux Small tube (Fig. 3.4) shows no statistically significant change in wall superheat over the course of the fouling experiments at both heat fluxes. In this case the superheat values for the fouled surfaces at both heat fluxes were again less than the corresponding clean values (see below).

The Turbo-B Very Open tube (Fig. 3.5) at a heat flux of 10 kW/m^2 gave no significant change in the superheat, but it will be noted that negative values of superheat are presented. These are discussed below, as are the relative positions of the clean and fouled superheat values. At a heat flux of 79 kW/m^2 , a monotonic increase in superheat was observed from a clean value of 1.6°C to a value of 4.7°C at twenty hours. No maximum value of superheat was observed.

No change in wall superheat was observed with the Very Closed tube (Fig. 3.6) at a flux of 10 kW/m^2 . Again, negative values of superheat and fouled superheats which are less than the clean superheats are shown (see below). A monotonic increase in superheat was observed at a flux of 75 kW/m^2 from a clean value of 2.0°C to a value of 3.2°C within the first fifteen minutes of the run. No further change was observed during the remainder of the run.

The negative values of superheat (Figs. 3.5 and 3.6) are not believed to be a real effect and are a result of using an incorrect saturation temperature (namely the saturation temperature of pure water at the same pressure) to represent the unknown saturation temperature of the saturated aqueous calcium sulfate solution. If these negative values do not exceed the estimate of the greatest possible difference ($\pm 0.4^\circ\text{C}$, see Appendix 4) between the true saturation temperature and our estimated value, then the observed difference is a result of the assumption for the saturation temperature.

The negative changes in the wall superheat between a fouled and a clean surface (Figs. 3.3 to 3.7) are again not believed to be a real effect but rather a consequence of taking the difference of data points from two separate experiments, namely an experiment to determine the clean superheat (carried out in distilled water) and a fouling experiment (in a saturated calcium sulfate solution). Fine white crystals were observed to randomly deposit on the upper surface of all the test sections prior to the beginning of the experiment (during the de-gassing of the pool). Numerous crystals were present on the base of the tank and in the pool. These crystals were

mobilized by the strong convective currents in the pool caused by the heaters that de-gassed the pool and were probably the source of the pre-run deposit. In addition to this visual evidence of a deposit, chemical analysis (Fig. 3.7) also provided data to support the fact that material was present on all of the surfaces. As a result, it is physically impossible for a clean superheat value to exceed a fouled superheat value.

Figure 3.7 plots the amount of deposit on a surface at the two heat fluxes against the change in the wall superheat from the clean value (in the distilled water experiment) to a value at twenty hours (in the fouling experiment). Generally, a given surface experienced a greater change in the superheat and had a greater amount of deposit at the high heat flux than at the low flux. The plain surface suffered the greatest change in superheat (at a flux of 80 kW/m^2) but the Very Open surface had the largest weight of deposit (also at a flux of 80 kW/m^2). The High Flux surfaces had about the same amount of deposit at each flux, and had smaller amounts of deposit than the other surfaces.

Some visual observations were made during the course of the fouling experiments. Less turbulent motion was observed in the vicinity of the test section at the lower heat flux for all the surfaces. The plain surface had fewer nucleation sites than the enhanced surfaces at the lower flux. A white solid material was seen to grow on the plain surface at both fluxes (Figures 3.8 and 3.9). No material could be detected by visual observation on the enhanced surfaces while it was in the tank (Figure 3.10). Also, no removal of a deposit was ever observed on any surface during the course of any test.

Figure 3.7 Observed Effects of Fouling for All Tubes at Two Heat Fluxes (10 kW/m^2 and $75\text{--}80 \text{ kW/m}^2$)

Figure 3.8 Photograph of Plain Smooth Tube in Aqueous Calcium Sulfate Solution, $Q'' = 51 \text{ kW/m}^2$, time = 2 min.

Figure 3.9 Photograph of Plain Smooth Tube in Aqueous Calcium Sulfate Solution. $Q'' = 51 \text{ kW/m}^2$, time = 30 min.

Figure 3.10 Photograph of Turbo-B Very Closed Tube in Aqueous Calcium Sulfate Solution, $Q'' = 10 \text{ kW/m}^2$, time = 3 hrs.

Figure 3.11 Photograph of Plain Smooth Tube After Run. $Q'' = 51 \text{ kW/m}^2$, Run Time = 6.7 hrs.. Front View

Visual observations were also made after the surface had been removed from the pool at the conclusion of a run. The plain tube after the 10 kW/m^2 run showed a thin but strongly adherent white scale covering about half of the surface (Figures 3.13–3.15). A similar but slightly thicker scale covered a greater portion of the same tube after the 80 kW/m^2 run. White crystals could be seen inside the porous matrix of the High Flux tubes. These crystals were more noticeable on the upper portion of the tubes. The Turbo-B tubes had a light dusting of fine white powder on the surface which was again more pronounced on the top of the tubes.

3.5 Discussion

The observed increase in the wall superheat with time is attributed to the accumulation of a deposit of calcium sulfate (of unknown hydration) on the boiling surface. Although the thickness of this deposit may be small, it has a substantially lower thermal conductivity than the copper tube. As a result, the total thermal resistance increases since now

$$R_{\text{total}} = R_c + R_f$$

For the constant heat flux case, an increase in R_{total} causes an increase in the temperature difference $T_{w,\text{avg}} - T_{\text{sat}}$ since

$$Q'' = \frac{T_{w,\text{avg}} - T_{\text{sat}}}{R_{\text{total}}}$$

Figure 3.12 Photograph of Plain Smooth Tube After Run, $Q'' = 51$
 kW/m^2 , Run Time = 6.7 hrs., Back View

Figure 3.13 Photograph of Plain Smooth Tube After Run, $Q'' = 10$
 kW/m^2 , Run Time = 24 hrs., Front View

Figure 3.14 Photograph of Plain Smooth Tube After Run, $Q'' = 10$ kW/m^2 , Run Time = 24 hrs., Back View

Figure 3.15 Photograph of Plain Smooth Tube After Run, $Q'' = 10$ kW/m^2 , Run Time = 24 hrs., Bottom View

As discussed in Part 1, Kern and Seaton [8,9] model the net rate of accumulation of a deposit as the sum of a deposition rate and a removal rate. The deposition rate, according to Reitzer [23], is given by

$$\frac{dW}{d\theta} = KA (C_b - C_w)^n \quad (3.5.1)$$

while the removal rate most likely depends on the amount of turbulent motion near the surface and the adhesive force of the scale. Since these latter two quantities are difficult, if not impossible, to characterize, it may suffice to say that the removal rate is probably larger under highly-agitated conditions than in quiescent conditions.

The observation that a given surface fouls to a greater extent at a higher heat flux may be rationalized as follows. Approximating the solubility of calcium sulfate as linear with temperature, one can write

$$C_b = a - bT_{\text{sat}} \quad (3.5.2a)$$

$$C_w = a - bT_{w,\text{avg}} \quad (3.5.2b)$$

For an inverse soluble salt, b is positive and equation (3.5.1) becomes

$$\frac{dW}{d\theta} = KAb^n (T_{w,\text{avg}} - T_{\text{sat}})^n \quad (3.5.3)$$

The superheat can be written as

$$T_{w,\text{avg}} - T_{\text{sat}} = Q'' / h \quad (3.5.4)$$

so that equation (3.5.3) is

$$\frac{dW}{d\theta} = KA \left[\frac{b}{h} \right]^n Q''^n$$

Assuming K , h and n are independent of heat flux, the deposition rate is seen to increase as the n^{th} power of the heat flux. Taking the deposition rate to be much larger than the removal rate for all heat fluxes, a larger heat flux results in a greater accumulation rate.

The fact that most of the enhanced surfaces experienced less fouling than the plain surface may be explained by again considering the deposition rate equation

$$\frac{dW}{d\theta} = KAb^n (T_{w,\text{avg}} - T_{\text{sat}})^n$$

For a given heat flux, the wall superheat of an enhanced surface is less than that of a plain surface. Assuming that K and n are independent of the surface structure, and taking A to be the nominal surface area (not accounting for the actual surface area of an enhanced surface), one concludes (on the basis of the wall superheat) that an enhanced surface is expected to have a smaller deposit than a plain surface, again neglecting the removal rate. This, of course, does not take into account the effect of the surface structure on fouling.

If one attempts to characterize the actual surface area of an enhanced surface, the resulting deposition rate may be comparable to that of a plain surface, compensating for the decrease in the superheat. This suggests that

the removal rate of the enhanced surface must be greater than that of a plain surface in order for the weight of the deposit on an enhanced surface to be less. In fact, the removal rate for an enhanced surface was speculated to be larger than that for a plain surface due to the greater number of nucleation sites, and hence the more vigorous fluid motion near the boiling surface. In this case, the removal rate for the enhanced surface may be the same order as the deposition rate, resulting in a small net accumulation.

It is important to compare Figures 1.8 and 3.2 to 3.6 with Figure 1.6. Chyu observed fouling over a 32 hour period in Figure 1.8. The fouling curves presented in this study (Figs. 3.2 to 3.6) show that the effects of precipitation fouling generally occur within the first two hours of exposure to a fouling environment. In both instances, substantial effects of fouling were observed to occur in a brief period of time compared to the observations of Gottzmann et al., whose experiment extended over a period of twenty days. It is possible that Gottzmann et al. failed to observe this initial change in the heat transfer performance in Figure 1.6 due to the manner in which the test was conducted. If their test involved industrial equipment, it is likely that the heat transfer surfaces were exposed to the fouling fluid for some time before measurements were made. With this scenario, significant effects of fouling could have gone virtually unnoticed by the experimenters.

PART 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Pool boiling data of structured surfaces in R113/3GS oil mixtures support the following conclusions:

1. A general decrease in heat transfer performance occurs with increasing mass concentration of oil.
2. A substantial degradation in the performance of all surfaces exists at 10% oil.
3. No surface is especially immune or more vulnerable to the presence of oil than another surface.
4. The structured surfaces maintain their original enhancements over the plain surface when both surfaces are exposed to oil. Thus, there is no general trend of the enhancement ratio with increasing oil concentration.
5. The original performance of the enhanced surfaces can be restored after cleaning in de-natured alcohol.

Fouling data of structured surfaces in pool boiling of a saturated aqueous solution of calcium sulfate suggest:

1. The effects of fouling, such as the changes in the wall superheat with time and the deposition weight, are more pronounced at a heat flux of 80 kW/m^2 than at 10 kW/m^2 for all surfaces examined.
2. The effects of precipitation fouling are observed to occur within the first two hours of exposure.

3. High Flux surfaces have lower deposition weights than the other surfaces examined. As a result, the deposition rate is suspected to be strongly dependent on the wall superheat.
4. The numerous nucleation sites of the enhanced surfaces provide more turbulent motion near the boiling surface than for the plain surface. Thus, one would expect the removal rate to be greater for an enhanced surface although no removal of a deposit was observed on any surface during the course of any test.

4.2 Recommendations

Based on the difficulty in determining the wall superheat, the following recommendations are made:

1. More precise temperature sensors, such as thermistors, should replace the thermocouples.
2. A method of instrumentation should be devised to measure the temperature difference directly using differential temperature sensors.
3. A design should be proposed to minimize the effect of cooling the pool due to the reflux of condensate from the condensers.

To thoroughly examine the effect of precipitation fouling, a wider variety of salt solutions should be investigated. Also, the study of other categories of fouling (particulate fouling, for example) should be carried out with the enhanced surfaces.

PART 5

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PART 6

APPENDIX 1: TABULATION OF EXPERIMENTAL DATA

Table 6.1 Reduced Experimental Data

DATE: 25 MAY 89
 FLUID: R113, 17MAY89
 SURFACE: PLAIN, 600
 O.D. (in.): 0.75 ROOM TEMP. (C): 22.2 23.3
 R/r: 1.5 JACKET TEMP. (C): 46.1 58.9
 AREA (m²): 0.0060
 T_{bulk, avg} (C): 47.9

TIME	V (V)	I (A)	T _{w, avg} (C)	T _{w, 1} (C)	T _{w, 2} (C)	T _{w, 3} (C)	T _{w, 4} (C)	T _{w, avg} - T _{b, avg} (C)	Q" (W/m ²)
15:20	0	0.0	48.3	48.0	48.3	48.4	48.6	0.4	0.0E+00
15:26	5	0.2	49.2	48.8	49.1	49.3	49.4	1.3	1.4E+02
15:33	10	0.3	51.1	50.7	51.1	51.2	51.5	3.2	5.1E+02
15:41	15	0.4	53.8	53.4	53.8	53.9	54.2	5.9	1.1E+03
15:48	20	0.6	55.7	55.8	56.3	56.3	54.4	7.8	2.0E+03
15:54	25	0.8	58.6	58.0	58.7	58.6	59.0	10.7	3.1E+03
15:58	30	0.9	60.6	60.0	60.9	60.6	61.0	12.7	4.5E+03
16:04	35	1.0	61.7	60.8	61.9	61.7	62.1	13.7	6.0E+03
16:12	41	1.2	59.0	58.4	59.0	58.8	59.6	11.1	8.1E+03
16:18	50	1.5	60.0	59.5	59.9	59.8	60.7	12.1	1.2E+04
16:23	60	1.8	60.8	60.3	60.8	60.5	61.5	12.8	1.8E+04
16:26	70	2.1	61.5	61.0	61.5	61.1	62.3	13.6	2.4E+04
16:30	81	2.4	61.8	61.4	61.9	61.4	62.6	13.9	3.2E+04
16:34	90	2.6	62.3	61.9	62.4	62.0	63.0	14.4	3.9E+04
16:38	100	2.9	63.1	62.7	63.2	62.8	63.7	15.2	4.8E+04
16:41	109	3.2	63.7	63.3	63.8	63.4	64.3	15.8	5.7E+04
16:45	91	2.7	62.9	62.5	63.0	62.5	63.6	15.0	4.0E+04
16:47	75	2.2	62.2	61.8	62.2	61.9	63.0	14.3	2.7E+04
16:49	60	1.8	61.2	60.7	61.3	61.0	61.9	13.3	1.8E+04
16:52	45	1.3	59.8	59.1	59.8	59.7	60.4	11.9	9.9E+03
16:55	30	0.9	56.4	55.9	56.3	56.4	57.0	8.5	4.3E+03
16:59	20	0.6	54.2	53.6	54.1	54.3	54.8	6.3	1.9E+03
17:03	10	0.3	51.4	50.9	51.3	51.4	51.9	3.5	5.2E+02
17:04	0	0.0	49.4	48.8	49.4	49.5	50.0	1.5	9.5E-04

Table 6.1 (continued)

DATE: 11JUL89
 FLUID: R113, 14JUN89 + 1% 3GS
 SURFACE: PLAIN, 600 ROOM TEMP. (C):
 O.D. (in.): 0.75 JACKET TEMP. (C):
 R/r: 1.5
 AREA (m²): 0.0060
 Tbulk, avg (C): 47.4

START END
 22.2 23.3
 50 43.3

TIME	V (V)	I (A)	Tw, avg (C)	Tw, 1 (C)	Tw, 2 (C)	Tw, 3 (C)	Tw, 4 (C)	Tw, avg- Tb, avg (C)	Q" (W/m ²)
17:57	0	0.0	47.2	47.4	47.1	47.2	47.3	-0.2	0.0E+00
18:03	14	0.4	52.7	52.7	52.5	52.8	52.9	5.3	9.6E+02
18:06	27	0.8	59.6	59.5	59.4	59.8	59.7	12.2	3.6E+03
18:12	35	1.0	63.5	63.5	63.3	63.8	63.6	16.1	5.9E+03
18:16	44	1.3	66.3	66.4	65.8	66.6	66.5	18.9	9.3E+03
18:27	59	1.7	65.2	65.6	64.3	65.3	65.6	17.8	1.7E+04
18:30	71	2.0	66.1	66.0	65.5	66.4	66.6	18.7	2.4E+04
18:33	80	2.3	67.1	66.9	66.4	67.4	67.8	19.7	3.0E+04
18:41	91	2.6	68.5	68.2	67.8	68.8	69.3	21.1	3.9E+04
18:43	100	2.9	69.5	69.2	68.8	69.7	70.3	22.1	4.8E+04
18:47	110	3.1	70.5	70.3	69.8	70.7	71.2	23.1	5.6E+04
18:50	88	2.5	68.1	67.8	67.5	68.3	68.7	20.7	3.6E+04
18:53	69	2.0	65.9	65.9	65.3	66.1	66.5	18.5	2.3E+04
18:56	50	1.4	65.3	65.1	64.9	65.6	65.7	17.9	1.2E+04
19:00	31	0.9	60.2	59.9	59.9	60.5	60.5	12.8	4.6E+03
19:04	11	0.4	51.3	51.2	51.1	51.4	51.4	3.9	6.7E+02

Table 6.1 (continued)

DATE: 29MAY89
 FLUID: R113, 17MAY89 + 5% 3GS
 SURFACE: PLAIN, 600 ROOM TEMP. (C): 22.2 23.3
 O.D. (in.): 0.75 JACKET TEMP. (C): 46.1 58.9
 R/r: 1.5
 AREA (m²): 0.0060
 Tbulk, avg (C): 48.2

TIME	V (V)	I (A)	Tw, avg (C)	Tw, 1 (C)	Tw, 2 (C)	Tw, 3 (C)	Tw, 4 (C)	Tw, avg- Tb, avg (C)	Q" (W/m ²)
15:23	10	0.3	52.6	51.9	52.6	52.8	52.9	4.3	5.2E+02
15:28	20	0.6	58.0	57.2	58.2	58.1	58.4	9.7	2.0E+03
15:35	30	0.9	65.2	64.4	65.4	65.3	65.6	16.9	4.4E+03
15:41	39	1.2	71.5	70.8	71.7	71.5	72.0	23.2	7.4E+03
15:51	48	1.4	71.8	71.1	72.2	71.7	72.4	23.6	1.1E+04
16:16	57	1.7	69.6	69.6	69.7	69.3	69.7	21.3	1.6E+04
16:18	66	1.9	72.1	72.0	72.3	72.0	71.9	23.8	2.1E+04
16:28	76	2.2	74.4	73.9	74.6	74.3	74.6	26.1	2.8E+04
16:33	87	2.5	76.3	76.5	76.6	75.8	76.3	28.0	3.6E+04
16:39	95	2.8	76.9	76.4	77.3	76.6	77.3	28.6	4.4E+04
16:46	110	3.3	79.5	79.1	79.6	79.1	80.3	31.3	5.9E+04
16:53	78	2.3	71.9	71.8	71.9	71.0	72.7	23.6	3.0E+04
16:58	59	1.7	66.5	66.3	66.9	66.1	66.8	18.3	1.7E+04
17:02	41	1.2	62.4	61.9	62.6	62.2	62.8	14.2	8.2E+03
17:06	20	0.6	56.4	56.0	56.6	56.5	56.6	8.2	2.0E+03

Table 6.1 (continued)

DATE: 19 JUL 89
 FLUID: R113,14JUN89 + 10% 3GS
 SURFACE: PLAIN,600 ROOM TEMP.(C): 22.2 23.3
 O.D.(in.): 0.75 JACKET TEMP.(C): 51.1 51.1
 R/r: 1.5
 AREA(m²): 0.0060
 Tbulk,avg(C): 50.8

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
10:54	9	0.3	50.4	50.9	50.3	50.3	50.3	-0.3	3.9E+02
11:01	22	0.6	61.9	62.4	61.8	61.9	61.8	11.1	2.4E+03
11:06	36	1.1	77.3	77.9	77.1	77.4	76.9	26.5	6.2E+03
11:07	36	1.1	74.1	74.6	74.0	74.2	73.7	23.4	6.2E+03
11:12	48	1.4	86.0	86.4	85.7	86.4	85.5	35.2	1.1E+04
11:18	60	1.7	90.7	92.1	90.9	91.2	88.6	39.9	1.7E+04
11:20	60	1.7	92.4	93.8	92.3	93.3	90.2	41.6	1.7E+04
11:25	71	2.0	101.4	102.4	101.2	102.5	99.6	50.6	2.4E+04
11:32	83	2.4	108.6	109.9	108.0	109.6	106.8	57.8	3.2E+04
11:41	93	2.7	112.0	113.9	111.8	113.2	109.2	61.2	4.1E+04
11:49	108	3.1	118.5	121.5	118.1	119.6	114.8	67.7	5.5E+04
11:52	88	2.5	103.2	105.4	103.1	104.2	100.3	52.5	3.7E+04
11:58	66	1.9	87.3	88.5	87.3	87.9	85.4	36.5	2.0E+04
12:02	46	1.3	72.8	73.9	72.6	73.3	71.6	22.1	9.9E+03
12:05	26	0.8	60.6	61.4	60.4	60.6	59.9	9.8	3.4E+03
12:11	16	0.5	55.1	55.7	54.9	55.0	54.9	4.4	1.2E+03

Table 6.1 (continued)

DATE: 25 MAY 89
 FLUID: R113, 17MAY89
 SURFACE: LARGE
 ROOM TEMP. (C): 22.8 23.3
 O.D. (in.): 0.7402 JACKET TEMP. (C): 49.44 57.2
 R/r: 1.816
 AREA (m²): 0.0060
 Tbulk, avg (C): 47.8

TIME	V (V)	I (A)	Tw, avg (C)	Tw, 1 (C)	Tw, 2 (C)	Tw, 3 (C)	Tw, 4 (C)	Tw, avg- Tb, avg (C)	Q" (W/m ²)
10:37	5	0.1	47.7	47.6	47.5	47.7	47.9	-0.2	1.2E+02
10:47	10	0.3	51.5	51.4	51.3	51.9	51.8	3.7	5.1E+02
10:54	16	0.5	55.0	54.9	54.8	55.9	55.3	7.2	1.2E+03
11:00	20	0.6	48.0	47.9	47.8	49.6	48.3	0.2	2.1E+03
11:03	31	0.9	48.3	48.1	48.0	52.0	48.6	0.4	4.8E+03
11:06	42	1.3	48.6	48.5	48.3	55.9	49.1	0.8	9.0E+03
11:09	53	1.6	49.1	49.0	48.6	60.3	49.7	1.3	1.4E+04
11:12	69	2.0	50.0	49.8	49.2	68.2	50.9	2.2	2.3E+04
11:15	79	2.4	50.6	50.4	49.6	73.5	51.9	2.8	3.1E+04
11:18	88	2.6	51.4	50.9	50.1	78.4	53.1	3.6	3.8E+04
11:22	95	2.8	51.8	51.2	50.3	82.1	54.0	4.0	4.5E+04
11:26	109	3.3	53.0	52.2	51.0	89.4	55.9	5.2	5.9E+04
11:32	101	3.0	52.3	51.6	50.6	86.0	54.7	4.5	5.1E+04
11:34	89	2.6	51.3	50.9	50.1	78.8	53.0	3.5	3.9E+04
11:38	74	2.2	50.4	50.1	49.6	70.0	51.6	2.6	2.7E+04
11:42	55	1.7	49.4	49.2	48.8	60.2	50.1	1.5	1.5E+04
11:45	41	1.2	48.7	48.5	48.3	54.5	49.2	0.8	8.3E+03
11:48	25	0.8	48.2	48.0	47.9	50.5	48.5	0.3	3.2E+03
11:51	9	0.3	47.8	47.7	47.6	48.3	48.2	0.0	4.1E+02
11:54	1	0.0	47.7	47.6	47.6	47.9	48.0	-0.1	5.5E+00

Table 6.1 (continued)

DATE: 21 JUL 89
 FLUID: R113, 21JUL89
 SURFACE: LARGE
 O.D. (in.): 0.7402
 R/r: 1.715
 AREA (m²): 0.0060
 T_{bulk,avg}: 47.8

ROOM TEMP. (C): 22.8
 JACKET TEMP. (C): 48.9

START 22.2
 END 51.1

TIME	V (V)	I (A)	T _{w,avg} (C)	T _{w,1} (C)	T _{w,2} (C)	T _{w,3} (C)	T _{w,4} (C)	T _{w,avg} T _{b,avg} (C)	Q" (W/m ²)
16:22	0	0.0	48.1	47.9	48.3	48.0	48.1	0.3	9.6E-04
16:25	16	0.5	52.6	52.5	52.8	52.6	52.7	4.8	1.3E+03
16:28	29	0.9	57.8	57.8	57.5	58.0	58.0	10.0	4.2E+03
16:29	29	0.9	48.5	48.4	48.7	48.5	48.5	0.7	4.2E+03
16:31	46	1.4	49.1	49.1	49.1	49.2	49.0	1.3	1.1E+04
16:33	64	1.9	49.9	50.2	49.8	50.1	49.6	2.1	2.0E+04
16:34	80	2.3	50.8	51.4	50.6	51.0	50.3	3.0	3.1E+04
16:36	98	2.9	51.9	53.0	51.6	52.0	51.2	4.1	4.7E+04
16:39	108	3.1	52.5	53.8	52.2	52.4	51.6	4.7	5.6E+04
16:41	87	2.5	51.2	51.9	51.0	51.4	50.6	3.4	3.7E+04
16:43	66	1.9	50.1	50.5	50.0	50.3	49.8	2.3	2.1E+04
16:45	46	1.3	49.2	49.2	49.2	49.3	49.1	1.4	1.0E+04
16:47	28	0.8	48.5	48.4	48.6	48.6	48.6	0.7	3.9E+03
16:49	16	0.5	48.3	48.1	48.4	48.3	48.4	0.5	1.3E+03
16:51	9	0.3	48.2	48.0	48.3	48.1	48.3	0.4	4.1E+02

Table 6.1 (continued)

DATE: 11 JUL 89
 FLUID: R113, 14JUN89 + 1% 3GS
 SURFACE: LARGE ROOM TEMP. (C): 23.3 23.3
 O.D. (in.): 0.7402 JACKET TEMP. (C): 48.9 43.3
 R/r: 1.715
 AREA (m²): 0.0060
 Tbulk, avg (C): 47.4

TIME	V (V)	I (A)	Tw, avg (C)	Tw, 1 (C)	Tw, 2 (C)	Tw, 3 (C)	Tw, 4 (C)	Tw, avg- Tb, avg (C)	Q" (W/m ²)
14:10	0	0.0	47.2	47.4	47.1	47.2	47.3	-0.1	9.6E-04
14:13	12	0.4	48.4	48.6	48.2	48.2	48.5	1.0	8.2E+02
14:19	20	0.6	49.3	49.5	49.0	49.1	49.4	1.9	2.1E+03
14:23	30	0.9	50.6	50.9	50.2	50.3	50.9	3.2	4.4E+03
14:25	40	1.2	51.6	52.0	51.1	51.3	52.0	4.3	7.8E+03
14:28	50	1.5	52.5	53.1	51.8	52.1	53.0	5.1	1.2E+04
14:30	61	1.8	53.3	54.1	52.4	52.8	53.9	5.9	1.8E+04
14:32	70	2.1	53.3	54.1	52.3	52.9	53.9	5.9	2.4E+04
14:35	80	2.4	53.9	55.3	53.0	53.6	53.8	6.6	3.2E+04
14:38	91	2.6	54.4	56.0	53.1	54.1	54.3	7.0	4.0E+04
14:41	101	2.9	54.5	56.4	53.4	54.1	54.2	7.2	4.9E+04
14:45	110	3.2	55.1	57.2	53.7	54.6	54.9	7.7	5.8E+04
14:47	90	2.6	53.1	54.5	52.1	52.9	52.9	5.7	3.9E+04
14:49	69	2.0	51.5	52.3	50.8	51.5	51.4	4.1	2.3E+04
14:53	50	1.5	50.1	50.6	49.7	50.2	50.1	2.8	1.2E+04
14:57	31	0.9	49.0	49.2	48.7	48.9	49.0	1.6	4.8E+03
14:59	12	0.4	48.1	48.2	47.9	48.0	48.2	0.7	6.9E+02

Table 6.1 (continued)

DATE: 09 JUN 89
 FLUID: R113, 30MAY89 + 5% 3GS
 SURFACE: LARGE ROOM TEMP.(C): 21.1 22.2
 O.D.(in.): 0.7402 JACKET TEMP(C): 52.8 46.1
 R/r: 1.715
 AREA(m²): 0.0060
 Tbulk,avg(C): 48.53

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
12:15	0	0.0	48.4	48.2	48.4	48.5	48.6	-0.1	9.6E-04
12:22	6	0.2	50.3	50.1	50.3	50.4	50.5	1.8	2.0E+02
12:29	11	0.3	52.5	52.4	52.5	52.6	52.6	4.0	6.6E+02
12:38	16	0.5	55.9	55.8	55.8	55.9	56.0	7.3	1.3E+03
12:45	21	0.7	57.5	57.4	57.4	57.5	57.5	8.9	2.3E+03
12:46	21	0.7	50.1	50.3	50.0	50.1	50.2	1.6	2.3E+03
12:49	31	0.9	50.7	51.2	50.5	50.4	50.7	2.2	4.6E+03
12:53	40	1.2	51.5	52.4	51.1	51.0	51.4	2.9	8.0E+03
12:57	50	1.5	51.7	53.8	51.6	51.5	52.1	3.2	1.2E+04
13:01	60	1.8	52.4	55.5	52.4	52.0	53.0	3.9	1.8E+04
13:04	70	2.1	53.3	57.4	53.2	52.6	54.0	4.7	2.4E+04
13:10	80	2.4	54.4	59.8	54.3	53.6	55.2	5.8	3.2E+04
13:14	91	2.7	55.5	62.5	55.3	54.5	56.6	6.9	4.0E+04
13:16	101	2.9	56.6	65.2	56.4	55.5	57.9	8.1	4.9E+04
13:19	80	2.4	54.2	59.5	54.1	53.4	55.0	5.6	3.1E+04
13:22	61	1.8	52.6	55.7	52.6	52.1	53.1	4.1	1.8E+04
13:25	41	1.2	51.3	52.6	51.2	51.1	51.5	2.7	8.4E+03
13:29	21	0.6	50.3	50.4	50.2	50.2	50.4	1.7	2.1E+03
13:39	11	0.3	49.6	49.5	49.6	49.7	49.8	1.1	6.0E+02
13:45	0	0.0	47.2	47.0	47.1	47.2	47.3	-1.4	9.6E-04

Table 6.1 (continued)

DATE: 18 JUL 89
 FLUID: R113, 14JUN89 + 10% 3GS
 SURFACE: LARGE ROOM TEMP.(C): 23.3 22.2
 O.D.(in.): 0.7402 JACKET TEMP.(C): 54.4 49.4
 R/r: 1.715
 AREA(m²): 0.0060
 Tbulk,avg(C): 49.0

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
18:09	0	0.0	48.0	48.2	47.8	47.9	48.0	-1.0	9.6E-04
18:14	11	0.3	52.0	52.3	51.8	51.7	52.1	3.0	6.1E+02
18:17	22	0.7	56.1	56.4	55.8	56.0	56.3	7.1	2.5E+03
18:20	33	1.0	53.7	53.9	53.4	54.6	53.0	4.7	5.3E+03
18:23	43	1.3	56.0	56.1	55.5	57.7	54.6	7.0	9.2E+03
18:27	56	1.6	53.9	54.8	54.0	52.5	54.5	4.9	1.5E+04
18:30	72	2.1	56.5	57.3	56.9	54.7	57.2	7.5	2.5E+04
18:32	83	2.4	58.8	59.5	59.5	56.6	59.7	9.8	3.4E+04
18:34	94	2.7	60.0	60.3	60.7	58.1	60.7	10.9	4.3E+04
18:37	104	3.0	60.8	61.2	61.9	58.7	61.4	11.8	5.3E+04
18:40	87	2.5	57.4	57.8	58.0	55.8	58.0	8.4	3.7E+04
18:42	66	1.9	54.4	55.0	54.7	53.2	54.8	5.4	2.1E+04
18:45	47	1.4	52.6	53.3	52.5	51.7	52.8	3.5	1.1E+04
18:47	28	0.8	51.3	52.1	51.1	50.7	51.2	2.2	4.0E+03
18:50	19	0.6	50.7	51.5	50.4	50.2	50.6	1.7	1.8E+03
18:52	10	0.3	50.2	51.0	49.9	49.8	50.0	1.1	4.6E+02

Table 6.1 (continued)

DATE: 22 JUNE 89
 FLUID: R113, 14JUN89
 SURFACE: SMALL ROOM TEMP. (C): 23.8 23.8
 O.D. (in.): 0.75 JACKET TEMP. (C): 46.1 50.5
 R/r: 1.816
 AREA (m²): 0.0060
 T_{bulk,avg}(C): 47.1

TIME	V (V)	I (A)	T _{w,avg} (C)	T _{w,1} (C)	T _{w,2} (C)	T _{w,3} (C)	T _{w,4} (C)	T _{w,avg} - T _{b,avg} (C)	Q'' (W/m ²)
13:52	0	0.0	47.8	47.9	48.0	47.5	47.6	0.6	9.5E-04
14:00	5	0.2	48.3	48.4	48.7	48.0	48.2	1.2	1.2E+02
14:06	12	0.4	51.8	52.0	52.2	51.5	51.7	4.7	8.6E+02
14:10	16	0.6	48.1	48.3	48.5	47.8	47.9	1.0	1.5E+03
14:13	21	0.7	48.2	48.4	48.7	47.9	48.0	1.1	2.6E+03
14:18	30	1.1	48.4	48.6	48.9	47.9	48.0	1.2	5.2E+03
14:23	40	1.4	48.5	48.8	49.1	48.1	48.1	1.4	9.4E+03
14:29	51	1.8	48.7	49.1	49.4	48.2	48.3	1.6	1.5E+04
14:33	60	2.1	49.0	49.4	49.8	48.4	48.4	1.8	2.1E+04
14:42	70	2.5	49.2	49.7	49.9	48.6	48.5	2.0	2.8E+04
14:46	80	2.8	49.6	50.2	50.2	49.1	48.9	2.4	3.7E+04
14:46	90	3.1	50.0	50.6	50.7	49.4	49.1	2.8	4.6E+04
14:50	100	3.5	50.3	51.1	51.0	49.8	49.4	3.2	5.7E+04
14:54	80	2.8	49.5	50.1	50.2	49.0	48.8	2.4	3.6E+04
15:01	60	2.1	49.0	49.4	49.8	48.4	48.4	1.8	2.1E+04
15:05	40	1.4	48.5	48.9	49.3	47.9	48.0	1.4	9.3E+03
15:07	21	0.7	48.2	48.4	48.8	47.7	47.8	1.0	2.5E+03

Table 6.1 (continued)

DATE: 21 JUL 89
 FLUID: R113, 21JUL89
 SURFACE: SMALL ROOM TEMP. (C): 21.7 23.3
 O.D. (in.): 0.75 JACKET TEMP. (C): 52.2 51.1
 R/r: 1.816
 AREA (m²): 0.0060
 Tbulk, avg (C): 47.60

TIME	V (V)	I (A)	Tw, avg (C)	Tw, 1 (C)	Tw, 2 (C)	Tw, 3 (C)	Tw, 4 (C)	Tw, avg- Tb, avg (C)	Q" (W/m ²)
11:26	0	0.0	47.7	47.6	47.9	47.7	47.7	0.1	9.5E-04
11:29	13	0.4	49.9	49.8	50.0	49.8	49.9	2.3	9.3E+02
11:32	26	0.9	49.8	49.7	49.8	49.6	49.9	2.2	3.9E+03
11:34	39	1.4	50.6	50.7	50.3	50.4	50.8	3.0	8.8E+03
11:37	51	1.8	49.8	49.8	49.9	49.9	49.5	2.2	1.5E+04
11:39	60	2.1	50.4	50.3	50.6	50.6	50.0	2.8	2.1E+04
11:42	71	2.5	50.7	50.8	51.0	50.6	50.4	3.1	2.9E+04
11:43	80	2.8	51.0	51.2	51.2	51.1	50.7	3.4	3.7E+04
11:45	89	3.1	51.4	51.7	51.5	51.2	51.0	3.8	4.6E+04
11:47	100	3.5	51.7	52.2	51.6	51.5	51.2	4.1	5.7E+04
11:49	81	2.8	50.6	50.8	50.8	50.5	50.3	3.0	3.7E+04
11:51	60	2.1	49.7	49.8	49.9	49.5	49.5	2.1	2.1E+04
11:53	40	1.4	49.0	49.1	49.1	48.9	49.0	1.4	9.4E+03
11:56	29	1.0	48.8	48.8	48.8	48.7	48.8	1.2	4.9E+03
11:57	19	0.7	48.6	48.5	48.6	48.5	48.6	1.0	2.1E+03
11:59	9	0.3	48.4	48.3	48.6	48.3	48.5	0.8	4.7E+02

Table 6.1 (continued)

DATE: 11 JUL 89
 FLUID: R113,14JUN89 + 1% 3GS
 SURFACE: SMALL ROOM TEMP.(C): 23.3 23.3
 O.D.(in.): 0.75 JACKET TEMP.(C): 50 43.3
 R/r: 1.816
 AREA(m²): 0.0060
 Tbulk,avg(C): 47.5

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
10:40	0	0.0	47.6	48.1	47.4	47.4	47.5	0.1	9.5E-04
10:47	11	0.4	51.4	51.9	51.2	51.3	51.3	3.9	6.6E+02
10:49	18	0.6	48.4	48.9	48.2	48.3	48.2	0.9	1.8E+03
10:51	24	0.9	48.5	49.0	48.3	48.5	48.4	1.0	3.4E+03
10:53	32	1.1	48.7	49.2	48.4	48.6	48.5	1.2	5.9E+03
10:55	41	1.4	48.9	49.4	48.5	48.9	48.7	1.3	9.8E+03
10:57	53	1.8	49.2	49.8	48.7	49.2	49.0	1.7	1.6E+04
10:59	62	2.2	49.5	50.1	49.0	49.6	49.2	2.0	2.2E+04
11:01	69	2.4	49.8	50.4	49.2	49.9	49.6	2.2	2.7E+04
11:03	76	2.7	50.1	50.7	49.5	50.2	49.9	2.6	3.3E+04
11:05	82	2.9	50.4	51.0	49.8	50.6	50.2	2.9	3.9E+04
11:07	89	3.1	50.7	51.3	50.1	50.9	50.5	3.2	4.5E+04
11:09	97	3.3	51.1	51.6	50.5	51.4	51.0	3.6	5.3E+04
11:11	101	3.5	51.4	51.9	50.7	51.6	51.3	3.9	5.8E+04
11:13	88	3.0	50.6	51.2	50.0	50.8	50.5	3.1	4.4E+04
11:15	73	2.5	49.9	50.5	49.4	50.1	49.8	2.4	3.0E+04
11:16	56	1.9	49.3	49.9	48.9	49.4	49.2	1.8	1.8E+04
11:18	40	1.4	48.9	49.4	48.5	48.9	48.7	1.4	9.1E+03
11:19	29	1.0	48.6	49.1	48.4	48.6	48.5	1.1	4.8E+03
11:21	19	0.7	48.4	48.8	48.2	48.4	48.3	0.9	2.1E+03
11:23	11	0.4	48.3	48.6	48.0	48.2	48.2	0.7	7.4E+02

Table 6.1 (continued)

DATE: 02JUN89
 FLUID: R113, 30MAY89 + 5% 3GS
 SURFACE: SMALL ROOM TEMP.(C): 22.2 22.8
 O.D.(in.): 0.75 JACKET TEMP.(C): 55.6 48.8
 R/r: 1.816
 AREA(m²): 0.0060
 Tbulk,avg(C): 48.4

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
11:32	0	0.0	48.5	48.2	48.8	48.6	48.6	0.1	0.0E+00
11:35	5	0.2	49.1	48.7	49.3	49.1	49.3	0.7	1.3E+02
11:40	10	0.4	51.4	51.0	51.6	51.4	51.5	3.0	6.4E+02
11:45	14	0.5	53.3	52.9	53.6	53.3	53.4	4.9	1.2E+03
11:47	21	0.8	49.5	49.1	49.7	49.5	49.5	1.1	2.6E+03
11:54	31	1.1	49.8	49.4	50.0	49.7	49.8	1.4	5.6E+03
11:58	41	1.4	50.1	49.8	50.4	50.1	50.1	1.7	9.6E+03
12:01	50	1.8	50.5	50.2	50.9	50.4	50.4	2.1	1.5E+04
12:03	60	2.1	50.9	50.7	51.4	50.8	50.8	2.5	2.1E+04
12:07	69	2.4	51.5	51.3	51.9	51.3	51.3	3.1	2.8E+04
12:10	80	2.8	52.1	52.0	52.5	52.0	51.9	3.7	3.7E+04
12:13	90	3.2	52.9	52.9	53.3	52.8	52.7	4.5	4.7E+04
12:16	100	3.5	53.9	53.8	54.2	53.8	53.6	5.5	5.8E+04
12:19	105	3.6	54.1	54.1	54.4	54.1	53.9	5.7	6.3E+04
12:22	81	2.8	52.2	52.2	52.7	52.1	52.0	3.8	3.7E+04
12:26	61	2.2	51.0	50.8	51.5	50.9	50.9	2.6	2.2E+04
12:29	40	1.4	50.2	49.9	50.5	50.1	50.2	1.8	9.4E+03
12:32	21	0.7	49.5	49.1	49.7	49.6	49.6	1.1	2.5E+03
12:35	10	0.4	49.2	48.7	49.3	49.3	49.3	0.8	6.3E+02

Table 6.1 (continued)

DATE: 18 JUL 89
 FLUID: R113, 14JUN89 + 10% 3GS
 SURFACE: SMALL ROOM TEMP.(C): 22.2 22.8
 O.D.(in.): 0.75 JACKET TEMP.(C): 51.1 43.3
 R/r: 1.816
 AREA(m²): 0.0060
 Tbulk,avg(C): 49.3

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
14:17	0	0.0	48.3	47.9	47.8	48.6	48.8	-1.0	9.5E-04
14:25	12	0.4	52.8	52.5	52.3	53.0	53.2	3.5	9.2E+02
14:28	21	0.7	56.9	56.6	56.5	57.1	57.3	7.6	2.5E+03
14:29	21	0.7	50.4	50.1	50.1	50.7	50.8	1.2	2.5E+03
14:33	31	1.1	50.9	50.7	50.8	51.1	51.2	1.7	5.5E+03
14:37	40	1.4	51.4	51.2	51.2	51.5	51.6	2.1	9.3E+03
14:40	50	1.8	52.0	51.9	51.8	52.1	52.1	2.7	1.5E+04
14:44	60	2.1	53.0	52.9	52.9	53.0	53.0	3.7	2.1E+04
14:46	69	2.4	54.2	54.2	54.3	54.1	54.2	4.9	2.7E+04
14:50	79	2.7	56.0	56.0	56.2	56.0	56.0	6.8	3.6E+04
14:53	89	3.1	58.1	58.2	58.3	58.0	57.9	8.9	4.5E+04
14:56	100	3.4	61.2	61.3	61.5	61.0	60.9	11.9	5.6E+04
14:58	79	2.7	55.9	56.0	56.0	56.0	55.8	6.7	3.6E+04
15:02	60	2.1	53.0	53.0	52.9	53.0	53.0	3.7	2.1E+04
15:05	40	1.4	51.5	51.3	51.3	51.6	51.7	2.2	9.4E+03
15:09	21	0.7	50.6	50.3	50.4	50.8	50.9	1.4	2.5E+03
15:12	12	0.4	50.1	49.9	49.9	50.3	50.4	0.9	8.6E+02

Table 6.1 (continued)

DATE: 05JUL89
 FLUID: R113, 14JUN89
 SURFACE: VERY OPEN ROOM TEMP.(C): 23.3 23.8
 O.D.(in.): 0.7457 JACKET TEMP.(C): 49.4 50.5
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk,avg(C): 47.8

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
14:16	0	0.0	47.2	47.8	47.1	47.1	46.9	-0.6	9.5E-04
14:20	9	0.3	48.1	48.7	48.0	48.0	47.8	0.4	4.1E+02
14:22	16	0.5	48.4	49.0	48.3	48.4	48.1	0.7	1.3E+03
14:25	24	0.7	48.7	49.3	48.5	48.6	48.3	0.9	2.8E+03
14:27	33	1.0	49.1	49.8	48.9	49.2	48.7	1.4	5.6E+03
14:30	48	1.5	49.8	50.5	49.5	49.9	49.3	2.0	1.2E+04
14:32	59	1.8	50.2	50.9	49.8	50.4	49.6	2.4	1.7E+04
14:35	69	2.1	50.6	51.2	50.3	50.9	50.1	2.9	2.4E+04
14:37	79	2.4	51.1	51.6	50.8	51.5	50.6	3.4	3.1E+04
14:40	89	2.7	51.8	52.2	51.5	52.2	51.2	4.0	4.0E+04
14:42	101	3.0	52.5	52.8	52.2	53.0	51.9	4.7	5.0E+04
14:42	108	3.2	53.0	53.4	52.6	53.5	52.3	5.2	5.8E+04
14:44	94	2.8	51.9	52.4	51.6	52.4	51.3	4.2	4.3E+04
14:46	83	2.5	51.3	51.7	51.0	51.7	50.7	3.5	3.4E+04
14:49	66	2.0	50.4	51.0	50.1	50.7	49.9	2.7	2.2E+04
14:51	49	1.5	49.8	50.5	49.4	49.9	49.3	2.0	1.2E+04
14:54	35	1.1	49.2	49.9	48.9	49.2	48.7	1.4	6.2E+03
14:56	25	0.8	48.8	49.4	48.5	48.7	48.4	1.0	3.2E+03
14:48	16	0.5	48.4	49.0	48.2	48.3	48.0	0.6	1.3E+03
15:01	8	0.2	48.1	48.7	48.0	48.0	47.8	0.4	3.1E+02
15:04	0	0.0	48.0	48.7	47.9	47.9	47.7	0.3	9.5E-04

Table 6.1 (continued)

DATE: 24 JUL 89
 FLUID: R113, 21 JUL 89
 SURFACE: VERY OPEN ROOM TEMP. (C): 23.3 23.3
 O.D. (in.): 0.7457 JACKET TEMP. (C): 52.2 51.1
 R/r: 1.765
 AREA (m²): 0.0060
 T_{bulk, avg} (C): 47.7

TIME	V (V)	I (A)	T _{w, avg} (C)	T _{w, 1} (C)	T _{w, 2} (C)	T _{w, 3} (C)	T _{w, 4} (C)	T _{w, avg} - T _{b, avg} (C)	Q" (W/m ²)
12:40	0	0.0	47.8	47.7	48.0	47.7	47.8	0.1	9.5E-04
12:43	14	0.4	48.1	48.0	48.3	48.0	48.1	0.4	1.0E+03
12:45	31	0.9	48.7	48.6	49.0	48.7	48.5	1.0	4.7E+03
12:47	50	1.5	49.5	49.4	49.9	49.7	49.1	1.8	1.2E+04
12:49	70	2.1	50.3	50.3	50.8	50.7	49.5	2.6	2.4E+04
12:51	89	2.6	51.2	51.3	51.9	51.8	49.9	3.5	3.9E+04
12:54	98	2.9	51.8	51.9	52.5	52.6	50.3	4.1	4.7E+04
12:56	109	3.3	52.6	52.7	53.4	53.5	50.6	4.9	5.9E+04
12:58	87	2.6	51.1	51.1	51.7	51.7	50.0	3.4	3.7E+04
13:00	66	2.0	50.2	50.0	50.6	50.5	49.5	2.4	2.1E+04
13:01	46	1.4	49.3	49.2	49.7	49.5	49.0	1.6	1.1E+04
13:03	28	0.8	48.6	48.5	48.9	48.6	48.5	0.9	3.9E+03
13:05	14	0.4	48.0	47.9	48.3	47.9	48.0	0.3	1.0E+03

Table 6.1 (continued)

DATE: 10 JUL 89
 FLUID: R113, 14JUN89 + 1% 3GS
 SURFACE: VERY OPEN ROOM TEMP.(C): 23.3 23.3
 O.D.(in.): 0.7457 JACKET TEMP.(C): 50 48.3
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk, avg(C): 47.2

TIME	V (V)	I (A)	Tw, avg (C)	Tw, 1 (C)	Tw, 2 (C)	Tw, 3 (C)	Tw, 4 (C)	Tw, avg- Tb, avg (C)	Q" (W/m ²)
12:25	0	0.0	47.0	47.3	46.8	46.9	47.0	-0.2	9.5E-04
12:32	11	0.3	50.5	50.8	50.3	50.3	50.5	3.3	6.3E+02
12:38	21	0.6	56.1	56.5	56.0	55.8	56.2	8.9	2.1E+03
12:42	31	0.9	57.2	57.5	57.0	57.2	57.3	10.0	4.7E+03
12:50	40	1.2	52.4	53.9	53.7	49.6	52.5	5.2	8.0E+03
12:53	50	1.5	50.0	50.3	50.2	49.2	50.4	2.8	1.2E+04
13:00	60	1.8	50.2	50.4	50.4	49.4	50.8	3.0	1.8E+04
13:13	70	2.1	50.2	50.4	50.4	49.4	50.5	3.0	2.4E+04
13:18	80	2.4	50.6	50.8	50.8	49.7	50.9	3.4	3.1E+04
13:20	90	2.7	51.1	51.5	51.5	49.9	51.5	3.9	4.0E+04
13:24	100	3.0	51.3	51.8	51.9	50.0	51.7	4.2	4.9E+04
13:25	109	3.2	51.7	52.3	52.2	50.2	52.1	4.5	5.9E+04
13:27	91	2.7	50.8	51.2	51.2	49.8	51.1	3.6	4.1E+04
13:29	75	2.2	50.3	50.5	50.5	49.5	50.6	3.1	2.8E+04
13:33	56	1.7	49.8	50.0	50.0	49.2	50.1	2.6	1.5E+04
13:36	38	1.2	49.3	49.4	49.3	48.8	49.5	2.1	7.2E+03
13:38	26	0.8	48.9	49.1	48.8	48.7	49.2	1.7	3.4E+03
13:45	15	0.5	48.3	48.4	48.1	48.1	48.4	1.1	1.2E+03
13:48	0	0.0	46.9	47.1	46.7	46.8	46.9	-0.3	9.5E-04

Table 6.1 (continued)

DATE: 17 JUL 89
 FLUID: R113, 14JUN89 + 5% 3GS
 SURFACE: VERY OPEN ROOM TEMP. (C): START END
 22.2 23.3
 O.D. (in.): 0.7457 JACKET TEMP. (C): 50 43.3
 R/r: 1.765
 AREA (m²): 0.0060
 T_{bulk}, avg (C): 48.30

TIME	V (V)	I (A)	T _w , avg (C)	T _w , 1 (C)	T _w , 2 (C)	T _w , 3 (C)	T _w , 4 (C)	T _w , avg- T _b , avg (C)	Q" (W/m ²)
11:25	0	0.0	48.3	48.9	48.2	48.1	48.1	0.0	9.5E-04
11:29	12	0.4	49.7	50.3	49.7	49.6	49.4	1.4	7.8E+02
11:31	23	0.7	50.7	51.3	50.8	50.6	50.3	2.4	2.6E+03
11:33	32	1.0	51.2	51.8	51.4	51.1	50.7	2.9	5.2E+03
11:36	43	1.3	51.7	52.1	52.0	51.5	51.1	3.4	9.2E+03
11:39	58	1.7	52.2	52.7	52.8	52.0	51.4	3.9	1.6E+04
11:41	70	2.1	52.6	53.0	53.3	52.5	51.6	4.3	2.4E+04
11:46	83	2.5	53.0	53.5	53.7	52.9	51.7	4.7	3.4E+04
11:49	92	2.7	53.4	54.0	54.3	53.5	51.8	5.1	4.2E+04
11:52	102	3.0	53.9	54.4	54.9	54.1	52.2	5.6	5.1E+04
11:54	110	3.2	54.5	55.1	55.6	54.7	52.5	6.2	5.9E+04
11:56	87	2.6	53.1	53.6	54.0	53.2	51.7	4.8	3.7E+04
11:59	70	2.1	52.4	52.8	53.0	52.3	51.4	4.1	2.4E+04
12:01	50	1.5	51.7	52.2	52.1	51.4	51.1	3.4	1.3E+04
12:04	32	1.0	51.0	51.6	51.1	50.8	50.5	2.7	5.1E+03
12:06	20	0.6	50.3	50.9	50.2	50.1	50.0	2.0	2.1E+03
12:07	9	0.3	49.2	49.9	49.1	49.0	49.0	0.9	4.3E+02

Table 6.1 (continued)

DATE: 19 JUL 89
 FLUID: R113, 14JUN89 + 10% 3GS
 SURFACE: VERY OPEN ROOM TEMP.(C): 23.3 23.3
 O.D.(in.): 0.7457 JACKET TEMP.(C): 50 51.1
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk,avg(C): 48.90

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
14:57	11	0.3	50.3	50.4	50.3	50.3	50.2	1.4	6.5E+02
15:00	22	0.7	51.8	52.0	51.6	52.0	51.8	2.9	2.3E+03
15:02	32	1.0	53.2	53.4	52.7	53.5	53.1	4.3	5.0E+03
15:05	41	1.2	53.5	53.7	53.1	53.9	53.5	4.6	8.2E+03
15:06	50	1.5	53.9	54.1	53.4	54.4	53.9	5.0	1.2E+04
15:08	60	1.8	54.6	54.7	53.9	55.1	54.6	5.7	1.8E+04
15:11	70	2.1	54.9	54.9	54.2	55.5	54.9	6.0	2.4E+04
15:14	79	2.4	55.2	55.3	54.2	55.9	55.2	6.3	3.1E+04
15:15	90	2.7	55.8	55.9	54.8	56.6	55.8	6.9	3.9E+04
15:17	101	3.0	56.4	56.6	54.8	57.5	56.8	7.5	5.0E+04
15:20	106	3.1	56.7	56.8	54.9	58.0	57.1	7.8	5.5E+04
15:22	80	2.4	54.8	55.0	53.2	55.9	55.2	5.9	3.1E+04
15:26	60	1.8	53.9	54.0	53.2	54.4	53.9	5.0	1.8E+04
15:29	41	1.2	53.2	53.4	52.8	53.6	53.2	4.3	8.2E+03
15:32	20	0.7	51.7	51.9	51.4	51.8	51.7	2.8	2.3E+03

Table 6.1 (continued)

DATE: 06JUL89
 FLUID: R113,14JUN89
 SURFACE: VERY CLOSED ROOM TEMP.(C): 23.3
 O.D.(in.): 0.7457 JACKET TEMP.(C): 49.4
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk,avg(C): 47.3

TIME	V	I	T _{w,avg}	T _{w,1}	T _{w,2}	T _{w,3}	T _{w,avg} - T _{b,avg} q"	
	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(W/m ²)
18:02	0	0.0	47.2	47.5	46.9	47.1	-0.1	9.5E-04
18:04	9	0.3	47.7	48.1	47.5	47.7	0.4	4.1E+02
18:06	21	0.6	48.1	48.5	47.8	48.1	0.8	2.2E+03
18:08	32	0.9	48.6	49.0	48.2	48.5	1.3	4.9E+03
18:10	41	1.2	49.0	49.5	48.6	48.9	1.7	8.4E+03
18:12	51	1.5	49.5	50.1	49.0	49.4	2.2	1.3E+04
18:14	61	1.8	50.2	50.9	49.6	50.0	2.9	1.8E+04
18:16	72	2.1	51.0	51.8	50.3	50.8	3.7	2.6E+04
18:18	81	2.4	51.7	52.8	50.9	51.5	4.4	3.2E+04
18:19	91	2.7	52.6	53.8	51.7	52.4	5.3	4.0E+04
18:21	101	3.0	53.6	55.0	52.5	53.4	6.3	5.0E+04
18:21	112	3.3	54.8	56.4	53.5	54.5	7.5	6.1E+04
18:22	98	2.9	53.2	54.4	52.2	53.0	5.9	4.6E+04
18:24	83	2.5	51.9	52.9	51.1	51.7	4.6	3.4E+04
18:26	67	2.0	50.6	51.4	50.0	50.5	3.3	2.2E+04
18:28	47	1.4	49.4	49.9	48.9	49.3	2.1	1.1E+04
18:30	35	1.0	48.7	49.1	48.4	48.6	1.4	5.9E+03
18:32	24	0.7	48.2	48.6	47.9	48.1	0.9	2.7E+03
18:33	13	0.4	47.9	48.2	47.6	47.8	0.6	8.8E+02
18:35	0	0.0	47.5	47.9	47.3	47.4	0.2	9.5E-04

Table 6.1 (continued)

DATE: 24 JUL 89
 FLUID: R113,21JUL89
 SURFACE: VERY CLOSED ROOM TEMP.(C): START 23.3 END 23.3
 O.D.(in.): 0.7457 JACKET TEMP.(C): 54.4 53.3
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk,avg(C): 47.7

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
15:35	0	0.0	48.1	47.9	48.3	48.0	0.4	9.5E-04
15:38	21	0.6	48.5	48.7	48.4	48.4	0.8	2.3E+03
15:41	41	1.2	49.7	49.9	49.6	49.6	2.0	8.2E+03
15:43	60	1.8	51.2	51.5	51.0	51.1	3.5	1.8E+04
15:46	79	2.3	52.8	53.3	52.4	52.7	5.0	3.1E+04
15:47	100	2.9	54.6	55.1	54.1	54.5	6.9	4.9E+04
15:49	107	3.1	55.1	55.8	54.6	55.0	7.4	5.5E+04
15:49	100	2.9	54.4	55.0	54.0	54.3	6.7	4.8E+04
15:52	80	2.3	52.7	53.2	52.3	52.6	5.0	3.1E+04
15:54	59	1.7	51.1	51.5	50.9	51.0	3.4	1.7E+04
15:55	40	1.2	49.7	49.9	49.5	49.6	2.0	7.8E+03
15:57	21	0.6	48.5	48.7	48.4	48.3	0.8	2.3E+03

Table 6.1 (continued)

DATE: 10 JUL 89
 FLUID: R113, 14JUN89 + 1% 3GS
 SURFACE: VERY CLOSED ROOM TEMP.(C):
 O.D.(in.): 0.7457 JACKET TEMP.(C):
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk,avg(C): 47.3

START END
 23.3 23.3
 50 43.3

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
16:30	0	0.0	47.3	47.7	47.2	47.2	47.3	0.0	9.5E-04
16:34	10	0.3	47.7	48.1	47.6	47.6	47.7	0.4	4.9E+02
16:37	21	0.6	48.3	48.7	48.1	48.2	48.3	1.0	2.1E+03
16:40	31	0.9	48.9	49.4	48.7	48.8	48.9	1.6	4.6E+03
16:42	40	1.2	49.6	50.1	49.2	49.4	49.6	2.3	7.8E+03
16:47	50	1.5	50.4	51.0	49.9	50.1	50.4	3.0	1.2E+04
16:50	61	1.8	51.1	51.9	50.6	50.8	51.2	3.8	1.8E+04
16:53	70	2.1	51.8	52.7	51.1	51.5	51.9	4.5	2.4E+04
16:58	80	2.3	52.7	53.9	51.9	52.3	52.8	5.4	3.1E+04
17:01	90	2.6	53.7	55.0	52.8	53.3	53.7	6.4	4.0E+04
17:05	101	2.9	54.9	56.5	53.8	54.5	54.8	7.6	4.9E+04
17:07	109	3.2	55.8	57.6	54.6	55.4	55.7	8.5	5.8E+04
17:09	91	2.7	53.8	55.1	52.8	53.4	53.7	6.5	4.0E+04
17:12	70	2.1	51.8	52.7	51.1	51.6	51.9	4.5	2.4E+04
17:14	50	1.5	50.2	50.7	49.8	50.0	50.3	2.9	1.2E+04
17:17	31	0.9	48.9	49.3	48.7	48.8	49.0	1.6	4.6E+03
17:19	11	0.3	47.7	48.0	47.6	47.6	47.8	0.4	5.7E+02
17:22	0	0.0	46.8	46.9	46.6	46.7	46.8	-0.6	9.5E-04

Table 6.1 (continued)

DATE: 17 JUL 89
 FLUID: R113, 14JUN89 + 5% 3GS
 SURFACE: VERY CLOSED ROOM TEMP.(C): START END
 O.D.(in.): 0.7457 JACKET TEMP.(C): 22.2 23.3
 R/r: 1.765 50 43.3
 AREA(m²): 0.0060
 Tbulk,avg(C): 48.5

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
16:50	0	0.0	48.7	49.1	48.6	48.5	48.7	0.2	9.5E-04
16:53	12	0.4	49.3	49.7	49.2	49.1	49.3	0.8	7.1E+02
16:56	22	0.6	50.1	50.5	50.0	49.9	50.1	1.6	2.3E+03
16:58	31	0.9	50.8	51.2	50.6	50.6	50.9	2.3	4.7E+03
17:01	40	1.2	51.5	51.9	51.2	51.3	51.6	3.0	7.9E+03
17:03	50	1.5	52.3	52.7	51.9	52.1	52.5	3.8	1.2E+04
17:10	61	1.8	53.3	53.7	52.8	53.2	53.7	4.8	1.8E+04
17:12	71	2.1	54.4	54.7	53.7	54.2	54.9	5.9	2.4E+04
17:15	81	2.4	55.6	55.9	54.8	55.5	56.4	7.1	3.2E+04
17:18	91	2.6	56.8	57.0	55.9	56.5	57.8	8.3	4.0E+04
17:20	100	2.9	58.0	58.2	57.0	57.7	59.2	9.5	4.8E+04
17:22	106	3.1	58.7	58.9	57.6	58.3	60.0	10.2	5.5E+04
17:25	91	2.6	56.7	56.8	55.8	56.5	57.6	8.2	4.0E+04
17:26	70	2.0	54.3	54.5	53.6	54.1	54.8	5.8	2.4E+04
17:28	51	1.5	52.4	52.7	51.9	52.2	52.6	3.8	1.3E+04
17:30	32	0.9	50.9	51.2	50.6	50.8	50.9	2.4	4.9E+03
17:31	11	0.3	49.2	49.6	49.1	49.1	49.1	0.7	5.7E+02

Table 6.1 (continued)

DATE: 20 JUL 89
 FLUID: R113, 14JUN89 + 10% 3GS
 SURFACE: VERY CLOSED ROOM TEMP.(C):
 O.D.(in.): 0.7457 JACKET TEMP.(C):
 R/r: 1.765
 AREA(m²): 0.0060
 Tbulk,avg(C): 49.2

TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tb,avg (C)	Q" (W/m ²)
15:52	0	0.0	48.6	49.2	48.4	48.4	48.4	-0.6	9.5E-04
16:02	12	0.3	53.4	54.0	53.2	53.2	53.3	4.2	6.7E+02
16:04	22	0.7	54.7	55.2	54.6	54.2	54.8	5.5	2.5E+03
16:07	32	0.9	54.7	55.2	54.6	54.4	54.6	5.5	4.9E+03
16:09	40	1.2	56.4	56.9	56.3	56.0	56.3	7.2	7.7E+03
16:12	50	1.5	58.0	58.5	57.9	57.7	57.8	8.8	1.2E+04
16:13	59	1.7	59.8	60.3	59.8	59.7	59.4	10.6	1.7E+04
16:15	70	2.0	58.1	58.2	58.3	58.0	58.1	8.9	2.3E+04
16:17	80	2.3	59.8	59.8	60.1	59.7	59.8	10.6	3.1E+04
16:18	90	2.6	61.7	61.5	61.9	61.7	61.7	12.5	3.9E+04
16:20	100	2.9	63.8	63.5	63.9	63.9	63.8	14.6	4.8E+04
16:22	104	3.0	64.4	63.9	64.7	64.5	64.5	15.2	5.2E+04
16:24	80	2.3	59.6	59.5	59.8	59.6	59.6	10.4	3.1E+04
16:25	61	1.8	56.9	57.1	57.0	56.8	56.9	7.7	1.8E+04
16:26	41	1.2	54.5	54.8	54.4	54.2	54.5	5.3	8.2E+03
16:28	22	0.7	51.7	52.3	51.5	51.5	51.6	2.5	2.4E+03

Table 6.1 (continued)

DATE:	28 JUN 89								
FLUID:	DISTILLED WATER								
SURFACE:	PLAIN, 600		ROOM TEMP. (C):			START	END		
O.D. (in.):	0.75		JACKET TEMP. (C):			22.2	23.3		
R/r:	1.5					120	125		
AREA (m ²):	0.0060								
PRESSURE (psi):	14.8								
Tsat (C):	100.2		Tb, avg (C):			99.1			
TIME	V	I	Tw, avg	Tw, 1	Tw, 2	Tw, 3	Tw, 4	Tw, avg - Tsat	Q"
	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(C)	(W/m ²)
9:07	10	0.3	99.7	99.5	99.6	99.8	99.9	-0.5	4.9E+02
9:13	21	0.6	101.1	100.9	101.0	101.3	101.3	0.9	2.1E+03
9:16	31	0.9	102.1	101.9	101.9	102.3	102.2	1.9	4.4E+03
9:21	41	1.2	102.2	102.1	101.9	102.5	102.3	2.0	8.0E+03
9:26	51	1.5	102.8	102.7	102.5	103.2	102.9	2.6	1.2E+04
9:34	63	1.8	103.3	103.3	102.7	103.9	103.5	3.1	1.9E+04
9:42	73	2.1	104.1	103.9	103.4	104.7	104.5	3.9	2.5E+04
9:52	85	2.4	104.6	104.6	103.8	105.3	104.9	4.4	3.4E+04
9:57	99	2.9	105.4	105.6	104.5	106.2	105.6	5.2	4.7E+04
10:02	115	3.3	106.3		105.2	107.1	106.6	6.1	6.3E+04
10:05	100	2.9	105.5		104.5	106.2	105.8	5.3	4.7E+04
10:10	89	2.6	105.2		104.3	105.9	105.5	5.0	3.8E+04
10:15	78	2.2	104.7		103.8	105.3	105.1	4.5	2.9E+04
10:20	58	1.7	104.0		103.3	104.4	104.4	3.8	1.6E+04
10:28	46	1.3	103.0		102.5	103.4	103.2	2.8	9.9E+03
10:35	34	1.0	102.3		101.8	102.6	102.4	2.0	5.6E+03
10:38	24	0.7	101.4		101.1	101.5	101.5	1.2	2.9E+03
10:42	13	0.4	100.0		99.9	100.0	100.0	-0.2	7.8E+02

Table 6.1 (continued)

DATE: 16AUG89
 FLUID: CaSO₄
 SURFACE: PLAIN, 600 ROOM TEMP. (C): 23.3 23.3
 O.D. (in.): 0.75 JACKET TEMP. (C): 110 120
 R/r: 1.5 pH: 6.1 6.73
 AREA (m²): 0.0060 CONDUCTIVITY
 PRESSURE (psi): 14.8 (micromhos/cm): 19000 20000
 Tsat (C): 100.2 Tb, avg (C): 100.0

TIME (hr.)	V (V)	I (A)	T _{w,avg} (C)	T _{w,1} (C)	T _{w,2} (C)	T _{w,3} (C)	T _{w,4} (C)	T _{w,avg} - T _{sat} (C)	Q" (W/m ²)
0.00	0	0	100.0	100.3	99.6	100.0	100.0	-0.3	0.0E+00
0.03	46	1.336	104.4	104.4	104.7	103.6	104.8	4.2	1.0E+04
0.07	46	1.336	104.6	104.6	104.8	103.8	105.1	4.3	1.0E+04
0.18	46	1.336	104.8	104.7	105.1	104.0	105.3	4.5	1.0E+04
0.35	46	1.336	105.0	105.1	105.1	104.2	105.5	4.7	1.0E+04
0.60	46	1.336	105.4	105.5	105.5	104.6	105.9	5.1	1.0E+04
0.85	46	1.336	105.8	105.8	106.0	105.1	106.3	5.6	1.0E+04
1.35	46	1.336	105.6	105.6	105.7	104.8	106.1	5.3	1.0E+04
2.85	46.4	1.343	105.8	106.0	105.9	105.0	106.3	5.5	1.0E+04
4.68	46.4	1.343	105.7	105.8	105.8	105.0	106.1	5.4	1.0E+04
6.85	46.4	1.343	105.6	105.7	105.8	105.0	106.1	5.4	1.0E+04
7.85	46.4	1.343	105.7	105.1	105.9	105.4	106.5	5.5	1.0E+04
9.13	45.6	1.323	105.5	104.9	105.8	105.2	106.3	5.3	9.9E+03
21.85	45.8	1.327	105.7	105.6	105.8	105.3	106.1	5.5	1.0E+04
22.85	45.8	1.327	106.2	106.2	106.3	105.8	106.6	6.0	1.0E+04
23.90	45.8	1.327	105.6	105.8	105.6	105.1	106.0	5.4	1.0E+04

Table 6.1 (continued)

DATE: 23AUG89
 FLUID: CaSO₄
 SURFACE: PLAIN, 600 ROOM TEMP. (C): 23.3 23.3
 O.D. (in.): 0.75 JACKET TEMP. (C): 110 120
 R/r: 1.5 pH: 5.24 5.85
 AREA (m²): 0.0060 CONDUCTIVITY
 PRESSURE (psi): 14.8 (micromhos/cm): 21000 18000
 Tsat (C): 100.2 Tb, avg (C): 99.7

TIME (hr.)	V (V)	I (A)	T _{w,avg} (C)	T _{w,1} (C)	T _{w,2} (C)	T _{w,3} (C)	T _{w,4} (C)	T _{w,avg} - T _{sat} (C)	Q" (W/m ²)
0.00	0	0.0	100.0	99.6	99.8	100.2	100.3	-0.2	0.0E+00
0.08	131	3.7	110.5	106.8	110.1	107.8	110.9	10.3	8.0E+04
0.17	131	3.7	111.0	107.7	110.7	108.2	111.4	10.8	8.0E+04
0.25	131	3.7	111.3	107.8	110.9	108.4	111.6	11.1	8.0E+04
0.38	131	3.7	111.8	108.3	111.6	108.5	111.9	11.6	8.0E+04
0.63	131	3.7	112.1	108.7	112.0	108.9	112.2	11.9	8.0E+04
0.88	131	3.7	112.0	108.9	112.0	109.0	112.0	11.8	8.0E+04
1.38	132	3.8	111.6	108.9	111.7	108.7	111.5	11.4	8.1E+04
1.88	132	3.8	111.4	108.5	111.5	108.1	111.2	11.2	8.1E+04
2.88	132	3.8	111.4	108.5	111.5	107.8	111.2	11.2	8.1E+04
3.88	132	3.8	111.3	108.0	111.5	107.5	111.2	11.2	8.1E+04
4.88	132	3.8	111.7	108.2	111.8	107.7	111.5	11.5	8.1E+04
6.13	132	3.8	112.0	108.5	112.1	107.8	111.9	11.8	8.1E+04
7.13	131	3.7	112.2	108.3	112.3	107.9	112.1	12.0	8.0E+04
19.88	131	3.7	113.0	108.8	113.3	108.3	112.7	12.8	8.0E+04
20.88	131	3.7	113.0	109.2	113.3	108.5	112.7	12.8	8.0E+04

Table 6.1 (continued)

DATE: 27 JUL 89
 FLUID: DISTILLED WATER
 SURFACE: LARGE ROOM TEMP.(C): 21.7 23.3
 O.D.(in.): 0.7402 JACKET TEMP.(C): 130 58.9
 R/r: 1.715
 AREA(m²): 0.0060
 PRESSURE(psi): 14.8
 Tsat(C): 100.1 Tb,avg(C): 99.1

TIME	V (V)	I (A)	T _{w,avg} (C)	T _{w,1} (C)	T _{w,2} (C)	T _{w,3} (C)	T _{w,4} (C)	T _{w,avg} - T _{sat} (C)	Q" (W/m ²)
16:10	30	0.9	100.7	100.5	101.1	100.5	100.7	0.6	4.4E+03
16:12	45	1.3	101.5	101.4	101.9	101.4	101.4	1.4	9.9E+03
16:18	57	1.7	102.1	101.9	102.6	102.1	101.8	2.0	1.6E+04
16:23	67	2.0	102.6	102.2	103.1	102.8	102.1	2.4	2.2E+04
16:25	78	2.3	103.1	102.7	103.6	103.5	102.5	3.0	2.9E+04
16:28	89	2.6	103.5	102.9	104.1	104.2	102.8	3.4	3.8E+04
16:31	99	2.9	104.0	103.3	104.4	105.0	103.1	3.8	4.7E+04
16:34	80	2.3	103.0	102.5	103.5	103.5	102.4	2.8	3.1E+04
16:37	64	1.9	102.2	102.0	102.7	102.4	101.8	2.1	2.0E+04
16:40	49	1.4	101.7	101.5	102.1	101.7	101.4	1.5	1.2E+04
16:43	35	1.0	101.2	101.1	101.6	101.1	101.1	1.1	6.0E+03
16:46	24	0.7	100.9	100.8	101.3	100.7	100.8	0.8	2.9E+03

Table 6.1 (continued)

DATE: 29AUG89			START	END
FLUID: CaSO ₄		ROOM TEMP.(C):	22.2	23.3
SURFACE: LARGE		JACKET TEMP.(C):	130	135
O.D.(in.):	0.7402	pH:	6.1	6.72
AREA(m ²):	0.0060	CONDUCTIVITY		
PRESSURE(psi):	14.7	(micromhos/cm):	18000	18000
Tsat(C):	100.1	Tb,avg(C):	99.3	

TIME (hr.)	V (V)	I (A)	T _{w,avg} (C)	T _{w,1} (C)	T _{w,2} (C)	T _{w,3} (C)	T _{w,4} (C)	T _{w,avg} - T _{sat} (C)	Q" (W/m ²)
0.00	0	0.0	99.4	100.5	99.7	99.5	99.0	-0.7	0E+00
0.05	46	1.4	100.6	103.8	101.0	100.8	99.8	0.5	1.0E+04
0.22	46	1.4	100.6	104.1	101.1	101.1	99.7	0.5	1.0E+04
0.47	46	1.4	100.8	104.2	101.3	101.1	99.9	0.7	1.0E+04
0.97	45	1.3	100.8	104.1	101.3	101.2	99.9	0.7	9.9E+03
1.97	46	1.4	101.0	104.0	101.4	101.4	100.0	0.9	1.0E+04
2.97	46	1.4	101.1	104.1	101.4	101.5	100.4	1.0	1.0E+04
3.97	46	1.4	100.9	104.3	101.3	101.2	100.3	0.8	1.0E+04
5.22	46	1.4	100.9	104.4	101.2	101.3	100.3	0.8	1.0E+04
18.22	46	1.4	100.7	104.1	101.1	101.0	100.1	0.6	1.0E+04
19.22	46	1.4	100.8	104.1	101.1	101.0	100.3	0.7	1.0E+04
21.22	46	1.4	100.7	104.2	101.1	101.0	100.1	0.6	1.1E+04

Table 6.1 (continued)

DATE: 24AUG89
 FLUID: CaSO₄
 SURFACE: LARGE
 O.D.(in.): 0.7402
 R/r: 1.715
 AREA(m²): 0.0060
 PRESSURE(psi): 14.9
 Tsat(C): 100.3

ROOM TEMP.(C): 22.2
 JACKET TEMP.(C): 130
 pH: 6
 CONDUCTIVITY (micromhos/cm): 20000
 Tb,avg(C): 99.4

START 22.2
 END 23.3
 126
 6.56

TIME (hr.)	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tsat (C)	Q" (W/m ²)
0.00	0	0.0	100.2	99.7	100.0	100.5	100.6	-0.1	0.0E+00
0.05	129	3.7	104.7	102.5	107.4	104.0	105.0	4.4	8.0E+04
0.08	129	3.7	104.8	102.5	107.6	104.0	105.3	4.5	8.0E+04
0.17	129	3.7	105.2	102.9	107.9	104.5	105.6	4.9	8.0E+04
0.25	129	3.7	105.4	103.1	108.1	104.6	105.6	5.0	8.0E+04
0.42	130	3.7	105.6	103.3	108.3	104.9	106.0	5.3	8.0E+04
0.67	130	3.7	105.9	103.5	108.7	105.2	106.3	5.6	8.0E+04
0.92	130	3.7	106.2	103.8	108.9	105.5	106.7	5.9	8.0E+04
2.00	130	3.7	106.9	104.2	109.6	106.2	107.4	6.5	8.0E+04
2.92	129	3.7	107.0	104.5	109.7	106.2	107.5	6.6	8.0E+04
7.10	129	3.7	106.9	104.7	109.3	106.1	107.4	6.5	8.0E+04
18.92	128	3.7	107.0	104.9	109.6	106.3	107.2	6.7	7.9E+04
20.02	128	3.7	106.7	104.8	109.1	105.9	107.0	6.4	7.9E+04
21.08	129	3.7	106.8	104.7	109.3	106.1	107.2	6.5	8.0E+04

Table 6.1 (continued)

DATE:	27 JUL 89								
FLUID:	DISTILLED WATER								
SURFACE:	SMALL	ROOM TEMP.(C):						START	END
O.D.(in.):	0.75	JACKET TEMP.(C):						22.2	23.3
R/r:	1.816								
AREA(m ²):	0.0060								
PRESSURE(psi):	14.8								
Tsat(C):	100.3	Tb,avg(C):						99.3	
TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tsat (C)	Q" (W/m ²)
13:35	29	1.0	101.5	101.9	101.8	100.9	101.2	1.2	4.9E+03
13:39	45	1.6	102.1	102.6	102.4	101.5	101.7	1.8	1.2E+04
13:42	58	2.0	102.6	103.3	102.8	102.1	102.2	2.3	2.0E+04
13:46	69	2.4	103.1	103.9	103.2	102.7	102.6	2.8	2.7E+04
13:50	79	2.8	103.6	104.4	103.6	103.3	103.2	3.4	3.6E+04
13:54	90	3.1	104.1	104.9	103.9	103.9	103.8	3.9	4.7E+04
13:58	100	3.5	104.4	105.4	104.1	104.1	104.2	4.2	5.7E+04
14:01	84	2.9	103.5	104.4	103.4	103.1	103.1	3.3	4.0E+04
14:04	66	2.3	102.6	103.3	102.8	102.1	102.2	2.4	2.5E+04
14:07	48	1.7	101.9	102.4	102.2	101.5	101.5	1.7	1.3E+04
14:12	37	1.3	101.5	101.9	101.8	101.1	101.3	1.3	7.9E+03
14:15	27	1.0	101.2	101.6	101.5	100.8	101.1	1.0	4.2E+03
14:17	19	0.7	100.9	101.2	101.2	100.5	100.9	0.7	2.2E+03

Table 6.1 (continued)

DATE:	28AUG89								
FLUID:	CaSO ₄								
SURFACE:	SMALL								
O.D.(in.):	0.75		ROOM TEMP.(C):						START END
R/r:	1.816		JACKET TEMP.(C):						23.3 23.3
AREA(m ²):	0.0060		pH:						130 130
PRESSURE(psi):	14.9		CONDUCTIVITY						5.3 6.48
Tsat(C):	100.4		Tb,avg(C):						19000 18000
									100.2
									Tw,avg-
TIME	V	I	Tw,avg	Tw,1	Tw,2	Tw,3	Tw,4	Tsat	Q"
(hrs.)	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(C)	(W/m ²)
0.00	0	0.0	100.0	100.1	100.1	100.1	99.5	-0.4	0.0E+00
0.03	42	1.5	100.9	101.2	100.9	101.0	100.4	0.5	1.0E+04
0.10	42	1.5	101.1	101.4	101.3	101.1	100.7	0.7	1.0E+04
0.25	42	1.5	101.2	101.7	101.4	101.2	100.5	0.8	1.0E+04
0.50	43	1.4	101.2	101.7	101.3	101.2	100.5	0.8	1.0E+04
1.00	43	1.4	101.1	101.7	101.2	100.9	100.3	0.6	1.0E+04
2.08	43	1.4	101.0	101.9	101.2	100.8	100.1	0.6	1.0E+04
3.00	43	1.5	101.0	102.0	101.2	100.8	100.0	0.6	1.0E+04
4.17	43	1.5	101.0	102.1	101.1	100.8	100.0	0.6	1.0E+04
5.25	43	1.5	101.1	102.4	101.2	100.8	100.0	0.7	1.0E+04
7.08	43	1.5	101.1	102.4	101.1	100.6	100.1	0.7	1.1E+04
19.75	42	1.5	101.1	102.1	101.0	100.8	100.5	0.7	1.0E+04
21.00	42	1.4	100.9	102.1	100.7	100.7	100.2	0.5	9.9E+03

Table 6.1 (continued)

DATE:	02AUG89						START	END		
FLUID:	CaSO4									
SURFACE:	SMALL		ROOM TEMP.(C):		23.3		23.3			
O.D.(in.):	0.75		JACKET TEMP.(C):		130		127			
R/r:	1.816		pH:		6.93		6.02			
AREA(m^2):	0.0060		CONDUCTIVITY							
PRESSURE(psi):	14.8		(micromhos/cm):		22000		20000			
Tsat(C):	100.2		Tb,avg(C):		99.6					
								Tw,avg-		
TIME	V	I	Tw,avg	Tw,1	Tw,2	Tw,3	Tw,4	Tsat	Q"	
(hrs.)	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(C)	(W/m^2)	
0.00	0	0.0	99.2	99.3	98.7	99.2	99.5	-1.1	0.0E+00	
0.02	119	4.1	104.1	103.6	103.6	104.0	105.3	3.9	8.0E+04	
0.03	119	4.1	104.5	104.1	104.1	104.3	105.6	4.3	8.0E+04	
0.05	119	4.1	104.3	104.0	104.0	104.0	105.3	4.1	8.0E+04	
0.07	119	4.1	104.4	104.1	104.0	104.2	105.3	4.2	8.0E+04	
0.13	119	4.1	104.5	104.2	104.1	104.2	105.5	4.3	8.0E+04	
0.22	119	4.1	104.4	104.2	104.2	104.1	105.2	4.2	8.0E+04	
0.33	119	4.1	104.4	104.2	104.2	104.1	105.3	4.2	8.0E+04	
0.43	119	4.1	104.4	104.2	104.1	104.2	105.3	4.2	8.0E+04	
0.55	119	4.1	104.4	104.1	104.1	104.0	105.3	4.2	8.0E+04	
0.70	119	4.1	104.5	104.2	104.2	104.2	105.3	4.2	8.0E+04	
0.80	119	4.1	104.4	104.1	104.1	104.1	105.2	4.1	8.0E+04	
1.18	119	4.1	104.5	104.2	104.2	104.2	105.3	4.2	8.0E+04	
1.42	119	4.1	104.5	104.2	104.2	104.2	105.3	4.3	8.0E+04	
1.63	119	4.1	104.5	104.2	104.3	104.2	105.4	4.3	8.0E+04	
2.57	121	4.1	104.5	104.6	104.2	104.1	105.2	4.3	8.2E+04	
2.92	121	4.1	104.7	104.8	104.4	104.2	105.3	4.5	8.2E+04	
3.92	121	4.1	104.7	104.9	104.4	104.2	105.3	4.5	8.2E+04	
5.17	121	4.1	104.7	105.0	104.4	104.2	105.2	4.5	8.2E+04	
6.18	121	4.1	104.6	105.1	104.2	104.0	105.1	4.4	8.2E+04	
7.18	119	4.0	104.5	105.0	104.1	103.9	105.0	4.3	7.8E+04	
8.18	121	4.1	104.8	104.8	104.5	104.4	105.6	4.6	8.2E+04	
9.00	121	4.1	104.8	104.7	104.5	104.4	105.6	4.6	8.2E+04	
21.35	122	4.2	104.2	104.8	103.9	103.5	104.9	4.0	8.4E+04	
22.17	121	4.1	104.1	104.5	103.8	103.4	104.9	3.9	8.2E+04	

Table 6.1 (continued)

DATE:	26 JUL 89				START	END			
FLUID:	DISTILLED WATER				21.7	23.3			
SURFACE:	VERY OPEN	ROOM TEMP.(C):			132	58.9			
O.D.(in.):	0.7457	JACKET TEMP.(C):							
R/r:	1.765								
AREA(m^2):	0.0060								
PRESSURE (psi):	14.9								
Tsat(C):	100.4	Tb,avg(C):	99.6						
TIME	V	I	Tw,avg	Tw,1	Tw,2	Tw,3	Tw,4	Tw,avg-Tsat	Q"
	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(C)	(W/m^2)
13:34	18	0.5	100.1	100.3	99.9	99.9	100.2	-0.3	1.6E+03
14:22	31	0.9	100.1	100.3	99.8	99.8	100.1	-0.3	4.8E+03
14:29	49	1.5	100.2	100.5	99.9	100.0	100.2	-0.2	1.2E+04
14:35	69	2.1	100.5	100.9	99.8	100.1	100.4	0.1	2.4E+04
14:38	89	2.6	100.8	101.5	99.8	100.3	100.6	0.4	3.8E+04
14:42	101	3.0	100.9	101.7	99.6	100.4	100.7	0.5	4.9E+04
15:18	111	3.3	101.2	102.2	99.9	100.6	100.9	0.8	6.0E+04
15:23	91	2.7	100.7	101.5	99.9	100.1	100.4	0.3	4.0E+04
15:26	71	2.1	100.3	100.9	99.9	99.8	100.1	-0.1	2.5E+04
15:29	51	1.5	100.0	100.5	100.0	99.6	99.8	-0.4	1.3E+04
15:34	31	0.9	99.9	100.3	100.1	99.6	99.8	-0.5	4.8E+03
15:36	12	0.4	99.9	100.2	100.1	99.6	99.7	-0.5	6.9E+02

Table 6.1 (continued)

DATE: 14AUG89
 FLUID: CaSO₄
 SURFACE: VERY OPEN ROOM TEMP.(C): 23.3 23.3
 O.D.(in.): 0.7457 JACKET TEMP.(C): 130 128
 R/r: 1.765 pH: 6.34 7.37
 AREA(m²): 0.0060 CONDUCTIVITY
 PRESSURE(psi): 14.8 (micromhos/cm): 20000 19000
 Tsat(C): 100.3 Tb,avg(C): 99.8

TIME (hrs.)	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tsat (C)	Q" (W/m ²)
0.00	0	0.0	99.6	99.5	99.3	99.1	100.3	-0.7	0.0E+00
0.02	45	1.3	99.9	99.7	99.6	99.6	100.8	-0.4	9.9E+03
0.05	45	1.3	99.9	99.7	99.6	99.6	100.7	-0.4	9.9E+03
0.12	45	1.3	100.0	99.7	99.8	99.6	100.9	-0.3	9.9E+03
0.28	46	1.3	100.0	99.7	99.7	99.6	101.0	-0.3	1.0E+04
0.53	46	1.3	99.9	99.9	99.7	99.4	100.8	-0.3	1.0E+04
0.78	46	1.3	99.8	99.7	99.6	99.3	100.5	-0.5	1.0E+04
1.28	47	1.4	99.9	99.7	99.9	99.5	100.6	-0.3	1.1E+04
2.28	47	1.4	100.1	100.0	100.0	99.8	100.7	-0.1	1.1E+04
3.28	47	1.4	100.0	100.1	99.9	99.7	100.4	-0.2	1.1E+04
4.28	47	1.4	100.0	100.4	99.7	99.5	100.3	-0.3	1.1E+04
5.28	47	1.4	99.9	100.4	99.7	99.2	100.2	-0.4	1.1E+04
6.28	47	1.4	99.7	100.3	99.4	99.1	100.0	-0.5	1.1E+04
7.28	46	1.3	99.8	100.5	99.6	99.2	100.1	-0.4	1.0E+04
20.28	46	1.3	99.7	100.4	99.4	98.9	100.1	-0.6	1.0E+04
21.28	47	1.3	99.8	100.4	99.4	99.0	100.3	-0.5	1.0E+04

Table 6.1 (continued)

DATE:	07AUG89									
FLUID:	CaSO4						START		END	
SURFACE:	VERY OPEN		ROOM TEMP.(C):		23.3		23.3			
O.D.(in.):	0.7457		JACKET TEMP.(C):		130		134			
R/r:	1.765		pH:		6.63		6.7			
AREA(m^2):	0.0060		CONDUCTIVITY							
PRESSURE(psi):	14.7		(micromhos/cm):		22000		24000			
Tsat(C):	100.1		Tb,avg(C):		99.3					
								Tw,avg-		
TIME	V	I	Tw,avg	Tw,1	Tw,2	Tw,3	Tw,4	Tsat	Q"	
(hrs.)	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(C)	(W/m^2)	
0.00	0	0.0	98.4	98.0	98.2	98.7	98.8	-1.6	0.0E+00	
0.02	128	3.8	101.4	99.0	101.0	101.8	102.9	1.3	8.0E+04	
0.03	128	3.8	101.7	99.1	101.3	102.0	103.1	1.6	8.0E+04	
0.05	128	3.8	101.7	99.1	101.4	102.1	103.3	1.6	8.0E+04	
0.15	128	3.8	101.8	99.2	101.5	102.2	103.5	1.8	8.0E+04	
0.23	128	3.8	101.9	99.3	101.5	102.2	103.5	1.8	8.0E+04	
0.32	128	3.8	102.1	99.4	101.7	102.5	103.7	2.0	8.0E+04	
0.40	128	3.8	102.0	99.4	101.6	102.4	103.6	1.9	8.0E+04	
0.48	128	3.7	102.1	99.4	101.7	102.5	103.8	2.0	7.9E+04	
0.65	128	3.7	102.1	99.6	101.8	102.4	103.6	2.1	7.9E+04	
0.82	128	3.7	102.0	99.5	101.6	102.4	103.5	1.9	7.9E+04	
1.10	128	3.7	102.2	99.5	101.8	102.5	103.9	2.1	7.9E+04	
1.60	127	3.7	102.2	99.9	101.8	102.6	103.9	2.1	7.8E+04	
2.10	127	3.7	102.4	100.1	102.1	102.8	104.1	2.3	7.8E+04	
2.60	128	3.7	102.7	100.1	102.3	103.0	104.3	2.6	7.9E+04	
3.60	128	3.7	102.7	100.3	102.5	103.0	104.4	2.7	7.9E+04	
4.60	128	3.7	103.0	100.4	102.8	103.3	104.8	2.9	7.9E+04	
5.60	128	3.6	103.2	100.6	103.0	103.3	104.8	3.1	7.7E+04	
18.85	126	3.7	104.7	101.3	104.3	105.1	106.2	4.6	7.6E+04	
19.85	127	3.7	104.8	101.3	104.3	105.3	106.4	4.7	7.7E+04	

Table 6.1 (continued)

DATE:	26 JUL 89								
FLUID:	DISTILLED WATER								
SURFACE:	VERY CLOSED ROOM TEMP.(C):						START	END	
O.D.(in.):	0.7457 JACKET TEMP.(C):						22.2	23.3	
R/r:	1.765						132.2	128	
AREA(m ²):	0.0060								
PRESSURE(psi):	14.839								
Tsat(C):	100.3 Tb,avg(C):						99.2		
TIME	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tsat (C)	Q" (W/m ²)
18:47	22	0.7	100.1	100.4	100.4	99.5	99.3	-0.2	2.4E+03
18:50	43	1.3	100.4	100.6	100.7	99.8	99.3	0.1	9.0E+03
18:53	61	1.8	100.7	100.8	101.1	100.1	99.2	0.4	1.8E+04
18:56	82	2.4	101.0	101.1	101.5	100.4	99.0	0.7	3.2E+04
18:59	102	3.0	101.5	101.5	102.0	101.0	98.8	1.2	5.0E+04
19:02	112	3.2	101.8	101.8	102.4	101.3	98.7	1.5	6.0E+04
19:05	90	2.6	101.4	101.5	101.8	100.8	98.9	1.1	3.8E+04
19:08	70	2.0	101.0	101.2	101.4	100.5	99.1	0.7	2.4E+04
19:10	49	1.4	100.7	100.9	101.1	100.1	99.3	0.4	1.2E+04
19:13	30	0.9	100.3	100.6	100.8	99.7	99.3	0.0	4.3E+03
19:15	16	0.5	100.2	100.4	100.6	99.4	99.3	-0.1	1.2E+03

Table 6.1 (continued)

DATE:	21AUG89				START		END		
FLUID:	CaSO4								
SURFACE:	VERY CLOSED ROOM TEMP.(C):				23.3	23.3			
O.D.(in.):	0.7457 JACKET TEMP.(C):				130	128			
R/r:	1.765 pH:				5.3	5.82			
AREA(m^2):	0.0060 CONDUCTIVITY								
PRESSURE(psi):	14.8 (micromhos/cm):				20000	20000			
Tsat(C):	100.2 Tb,avg(C):				99.9				
					Tw,avg-				
TIME	V	I	Tw,avg	Tw,1	Tw,2	Tw,3	Tw,4	Tsat	Q"
(hrs.)	(V)	(A)	(C)	(C)	(C)	(C)	(C)	(C)	(W/m^2)
0.00	0	0	99.3	99.8	98.7	99.2	99.5	-0.9	0.0E+00
0.03	44.5	1.37	99.5	100.1	99.3	99.2	99.5	-0.6	1.0E+04
0.10	44.5	1.37	99.9	100.5	99.5	99.7	100.1	-0.3	1.0E+04
0.18	44.5	1.37	100.0	100.7	99.5	99.8	99.9	-0.2	1.0E+04
0.43	44.5	1.37	99.9	100.8	99.6	99.5	99.9	-0.2	1.0E+04
0.93	44.5	1.37	100.2	101.2	99.9	99.7	100.0	0.0	1.0E+04
1.47	44.5	1.37	100.2	101.0	99.9	99.8	100.1	0.0	1.0E+04
2.43	44.5	1.37	100.4	101.2	100.1	100.0	100.2	0.2	1.0E+04
3.43	45.3	1.355	100.3	101.1	100.0	99.9	100.2	0.1	1.0E+04
16.43	45.2	1.347	100.4	101.2	100.0	99.9	100.3	0.2	1.0E+04
17.43	45.2	1.347	100.5	100.7	100.2	100.3	100.7	0.3	1.0E+04
18.43	45.2	1.347	100.6	100.6	100.4	100.4	100.9	0.4	1.0E+04
19.43	45.2	1.347	100.6	100.7	100.4	100.5	100.9	0.4	1.0E+04
21.43	44.4	1.321	100.5	101.0	100.3	100.2	100.5	0.3	9.7E+03

Table 6.1 (continued)

DATE: 03AUG89
 FLUID: CaSO₄
 SURFACE: VERY CLOSED ROOM TEMP.(C): 23.3 23.3
 O.D.(in.): 0.7457 JACKET TEMP.(C): 130 129
 R/r: 1.765 pH: 6.75 7.25
 AREA(m²): 0.0060 CONDUCTIVITY
 PRESSURE(psi): 14.7 (micromhos/cm): 24000 23000
 Tsat(C): 100.1 Tb,avg(C): 99.3

TIME (hrs.)	V (V)	I (A)	Tw,avg (C)	Tw,1 (C)	Tw,2 (C)	Tw,3 (C)	Tw,4 (C)	Tw,avg- Tsat (C)	Q" (W/m ²)
0.00	0	0.0	99.8	100.3	99.4	99.7	99.9	-0.3	0.0E+00
0.02	125	3.6	100.8	ERR	100.3	102.2	101.3	0.7	7.5E+04
0.03	125	3.6	102.2	ERR	101.8	103.8	102.6	2.1	7.5E+04
0.05	125	3.6	102.6	ERR	102.4	104.2	102.9	2.5	7.5E+04
0.07	125	3.6	102.8	ERR	102.5	104.4	103.0	2.7	7.5E+04
0.08	125	3.6	102.9	ERR	102.6	104.6	103.2	2.8	7.5E+04
0.12	125	3.6	103.1	ERR	102.8	104.8	103.4	3.0	7.5E+04
0.15	125	3.6	103.1	102.8	102.9	105.3	103.5	3.0	7.5E+04
0.18	125	3.6	103.1	102.8	103.1	105.4	103.5	3.0	7.5E+04
0.22	125	3.6	103.3	103.1	103.3	105.4	103.6	3.2	7.5E+04
0.30	125	3.6	103.2	102.4	103.4	105.7	103.7	3.1	7.5E+04
0.38	125	3.6	103.2	102.5	103.4	105.8	103.7	3.1	7.5E+04
0.47	125	3.6	103.4	102.8	103.4	105.6	103.9	3.3	7.5E+04
0.63	125	3.6	103.2	102.4	103.4	105.7	103.8	3.1	7.5E+04
1.48	125	3.6	103.0	102.4	103.2	105.5	103.6	3.0	7.4E+04
2.53	125	3.6	103.2	103.1	103.2	105.2	103.5	3.1	7.4E+04
3.55	126	3.6	103.1	103.4	103.0	104.7	103.0	3.1	7.6E+04
4.55	124	3.6	103.3	103.5	103.2	105.0	103.2	3.2	7.3E+04
5.58	123	3.5	103.3	103.9	103.0	104.7	103.1	3.2	7.2E+04
18.63	123	3.6	103.5	103.7	103.4	105.2	103.4	3.4	7.2E+04
19.72	124	3.6	103.3	103.7	103.1	105.0	103.1	3.2	7.3E+04
20.72	124	3.6	103.3	103.2	103.2	105.2	103.5	3.2	7.3E+04
22.72	125	3.5	103.4	103.0	103.4	105.4	103.7	3.3	7.3E+04

Table 6.1 (continued)

SURFACE	HEAT	AMOUNT	(DELTA T) _{fouled} -
	FLUX	CaSO ₄	(DELTA T) _{clean}
	(kW/m ²)	(mg)	(°C)
LARGE	10	47	0.7
LARGE	80	82	1.0
SMALL	10	55	-0.7
SMALL	80	81	-1.1
VERY OPEN	10	60	-0.6
VERY OPEN	80	329	3.1
VERY CLOSED	10	135	0.0
VERY CLOSED	80	262	1.2
PLAIN	10	245	2.6
PLAIN	80	289	6.0

PART 7

APPENDIX 2: SPREADSHEET FOR DATA REDUCTION

Raw data was entered into a Lotus spreadsheet where it was reduced using the formulae presented in sections 2.3 and 3.3. The format of the reduced data is identical to the tables presented in Appendix 1. Figure 7.1 is a sample spreadsheet with a list of formulae.

Headings appearing in the spreadsheet have the following equivalent nomenclature:

$$\text{Ch 2.A2} = T_{\text{wall},1}$$

$$\text{Ch 8.A2} = T_{\text{wall},2}$$

$$\text{Ch 9.A2} = T_{\text{wall},3}$$

$$\text{Ch 10.A2} = T_{\text{wall},4}$$

$$\text{Ch 7.A2} = \text{TOP } T_{\text{pool}}$$

$$V_{\text{shunt}} = 10 I_{\text{heater}} (R_{\text{shunt}} = 0.01 \Omega)$$

The conversion of thermocouple voltages to temperatures was accomplished with the National Bureau of Standards' type-T curvefit [38]:

$$T = a_0 + a_1x + a_2x^2 + \dots + a_7x^7 \text{ } ^\circ\text{C}$$

where

$$a_0 = 0.100860910$$

$$a_1 = 25727.94369$$

$$a_2 = -767345.8295$$

$$a_3 = 78025595.81$$

$$a_4 = -9247486589$$

$$a_5 = 6.97688 \times 10^{11}$$

A1:

READY

	A	B	C	D	E	F	G	H
1				Ptube(atm	H (in.)			START
2	DATE:	25 MAY 89		0.102116	4	ROOM TEMP (C)		22.2
3	FLUID:	R113,17 M Tsat (C)		47.79		JACKET TEMP (C)		46.1
4	SURFACE:	PLAIN,600		0.75 inch o.d.		Patm (in. Hg)		754.8
5	HEATER:	120.7		0.006080 m^2		Ppool (in. H2O)		
6								
7	TIME	Vheater	Vshunt	Ch 2.A2	Ch 8.A2	Ch 9.A2	Ch 10.A2	Ch 7.A2
8		(V)	(mv)	(mv)	(mv)	(mv)	(mv)	(mv)
9								
10	15:20	0.00024	0.24	1.956	1.971	1.975	1.985	1.968
11	15:26	5.34	1.64	1.991	2.007	2.012	2.02	1.971
12	15:33	10.16	3.07	2.075	2.093	2.097	2.107	1.967
13	15:41	14.86	4.45	2.189	2.208	2.21	2.223	1.978
14	15:48	20.38	6.07	2.293	2.318	2.314	2.236	1.973
15	15:54	25.32	7.54	2.39	2.421	2.418	2.435	1.973
16	15:58	30.45	9.06	2.478	2.517	2.505	2.524	1.957
17	16:04	34.91	10.39	2.514	2.564	2.554	2.572	1.956
18	16:12	40.6	12.07	2.41	2.437	2.429	2.464	1.952
19	16:18	49.95	14.82	2.46	2.478	2.471	2.51	1.946
20	16:23	60.02	17.75	2.496	2.517	2.504	2.55	1.941
	03-Oct-89 12:34 PM					CALC	NUM	

S1: 7

READY

	L	M	N	O	P	Q	R	S
1	0	1	2	3	4	5	6	7
2	0.100860	25727.94	-767345.	78025595	-9.2E+09	7.0E+11	-2.7E+13	3.9E+14
3								
4								
5								
6								
7	Vheater	Iheater	AVERAGE				TOP	
8	(V)	(A)	Twall	Twall,1	Twall,2	Twall,3	Twall,4	Tpool
9			(C)	(C)	(C)	(C)	(C)	(C)
10	0.00024	0.024	48.3	48.0	48.3	48.4	48.6	48.2
11	5.34	0.164	49.2	48.8	49.1	49.3	49.4	48.3
12	10.16	0.307	51.1	50.7	51.1	51.2	51.5	48.2
13	14.86	0.445	53.8	53.4	53.8	53.9	54.2	48.5
14	20.38	0.607	55.7	55.8	56.3	56.3	54.4	48.4
15	25.32	0.754	58.6	58.0	58.7	58.6	59.0	48.4
16	30.45	0.906	60.6	60.0	60.9	60.6	61.0	48.0
17	34.91	1.039	61.7	60.8	61.9	61.7	62.1	48.0
18	40.6	1.207	59.0	58.4	59.0	58.8	59.6	47.9
19	49.95	1.482	60.0	59.5	59.9	59.8	60.7	47.7
20	60.02	1.775	60.8	60.3	60.8	60.5	61.5	47.6
	03-Oct-89 12:35 PM					CALC	NUM	

L10: +B10

M10: +C10/10

N10: (F1) @AVG(O10..R10)

O10: (F1) +\$LS2+\$MS2*D10/1000+\$NS2*(D10/1000)^2+\$OS2*(D10/1000)^3+\$PS2*(D10/

P10: (F1) +\$LS2+\$MS2*E10/1000+\$NS2*(E10/1000)^2+\$OS2*(E10/1000)^3+\$PS2*(E10/

Q10: (F1) +\$LS2+\$MS2*F10/1000+\$NS2*(F10/1000)^2+\$OS2*(F10/1000)^3+\$PS2*(F10/

R10: (F1) +\$LS2+\$MS2*G10/1000+\$NS2*(G10/1000)^2+\$OS2*(G10/1000)^3+\$PS2*(G10/

S10: (F1) +\$LS2+\$MS2*H10/1000+\$NS2*(H10/1000)^2+\$OS2*(H10/1000)^3+\$PS2*(H10/

Figure 7.1 Sample Spreadsheet

$$a_6 = -2.66192 \times 10^{13}$$

$$a_7 = 3.94078 \times 10^{14}$$

and x is the thermocouple emf in volts.

The saturation temperature of pure water was determined from the pressure at the tube axis using a curvefit of the ASME Steam Tables [46]:

$$T_{\text{sat}} = 139.276781 + 6.4757873 X - 0.1036991 X^2$$

where $X = 0.49115 p_{\text{atm}} + 0.036127 H$

(in psi) and H is the level of the liquid (in inches).

PART 8

APPENDIX 3: THERMOPHYSICAL PROPERTIES

Saturated Refrigerant 113 (trichlorotrifluoroethane, a halogenated hydrocarbon) has a saturation temperature of 47.56 °C and a liquid density of 1507.3 kg/m³ at a standard atmospheric pressure of 101.325 kPa.[31]

Suniso brand 3GS refrigeration oil (naphthenic) has a viscosity of 33.1 centistokes (155 SSU) at 100 °C and a density of about 890 kg/m³ at 48 °C [32].

Various properties of refrigerant/oil mixtures are presented by Baustian, et al. [10].

The thermal conductivity of commercial copper is taken to be 386 $\frac{W}{m \text{ } ^\circ C}$ at 48 °C [36].

Saturated pure water has a saturation temperature of 100.00 °C and a liquid density of 957.9 kg/m³ at a standard atmospheric pressure of 101.33 kPa [36].

Disodium EDTA has a molecular weight of 336.21 and a formula weight (hydrate) of 372.24. Calcium sulfate (CaSO₄) has a molecular weight of 136.17. [33]

PART 9

APPENDIX 4: PRECISION ANALYSIS

The precision of an indirect measurement which depends on N variables, $X^{(i)}$ ($i = 1, \dots, N$), related by

$$S = S[X^{(1)}, X^{(2)}, \dots, X^{(N)}]$$

is given by

$$\omega_S^2 = \sum_{i=1}^N \left[\frac{\partial S}{\partial X^{(i)}} \right]^2 \omega_i^2 \quad (9.1)$$

assuming statistically independent measurements.

The heat flux is determined from

$$Q'' = \frac{V \cdot I}{A}$$

By virtue of equation (9.1), the precision of the measurement is

$$\omega_{Q''}^2 = \left[\frac{\partial Q''}{\partial V} \right]^2 \omega_V^2 + \left[\frac{\partial Q''}{\partial I} \right]^2 \omega_I^2 + \left[\frac{\partial Q''}{\partial A} \right]^2 \omega_A^2$$

The precision of the voltmeter yields [39]:

$$\omega_V = \pm 1.15 \text{ volts}$$

$$\omega_I = \pm 0.115 \text{ amps}$$

Jung [37] estimates

$$\omega_A = \pm 1.22 \times 10^{-5} \text{ m}^2$$

For $V = 80$ volts, $I = 2.4$ amps, and $Q'' = 30 \text{ kW/m}^2$, one obtains

$$\omega_{Q''} = \pm 1581 \text{ W/m}^2.$$

The temperature difference between the surface and bulk is given by

$$\Delta T = T_{w,avg} - T_{b,avg}$$

where $T_{w,avg} = \sum_{i=1}^4 T_{w,i}$ and $T_{b,avg} = \sum_{j=1}^{20} T_{b,j}$, $T_{w,i}$ is determined by

$$T_{w,i} = T_{i,r} - \frac{Q''R}{k} \ln \left[\frac{R}{r} \right]$$

while $T_{i,r}$ and $T_{b,j}$ are calculated from the National Bureau of Standards' type T thermocouple curvefit (see Appendix 2).

Since the derivatives in equation (9.1) are unity in this case, we have

$$\omega_{\Delta T}^2 = \omega_{T_{w,avg}}^2 + \omega_{T_{b,avg}}^2 \quad (9.2)$$

But

$$\omega_{T_{w,avg}}^2 = \sum_{i=1}^4 \frac{\partial T_{w,avg}}{\partial T_i} \omega_{T_{w,i}}^2$$

and

$$\omega_{T_{w,i}} = \left[\left[\frac{\partial T_{w,i}}{\partial T_{i,r}} \right]^2 \omega_{T_{i,r}}^2 + \left[\frac{\partial T_{w,i}}{\partial Q''} \right]^2 \omega_{Q''}^2 \right]^{1/2} + \frac{\partial T_{w,i}}{\partial r} e_r$$

neglecting the uncertainty in the tube radius (R) and the tube thermal conductivity. The uncertainty $\omega_{T_{i,r}}^2$ is from

$$\omega_{T_{i,r}}^2 = \left[\frac{\partial T_{i,r}}{\partial (\text{emf})} \right]^2 \omega_{\text{emf}}^2 + \omega_{\text{TC wire}}^2$$

Taking $\omega_{\text{emf}} = \pm 0.01 \text{ mV}$ [39], $\omega_{\text{TC wire}} = \pm 0.50 \text{ }^\circ\text{C}$ [40], and $\text{emf} = 0.002 \text{ mV}$ (corresponding to $50 \text{ }^\circ\text{C}$), one obtains

$$\omega_{T_{i,r}} = \pm 0.552 \text{ }^\circ\text{C}$$

The systematic error in the position (r) of the thermocouple bead, e_r , is estimated to be no more than one half the diameter of the sleeve which encloses it. So,

$$e_r = \pm \left[\frac{3/32}{2} \right] \text{ inch} = \pm 1.191 \times 10^{-3} \text{ m.}$$

Taking $Q'' = 30 \text{ kW/m}^2$, $k = 386 \frac{\text{W}}{\text{m } ^\circ\text{C}}$, and $R/r = 1.5$, one finds

$$\omega_{T_{w,i}} = \pm 0.693 \text{ }^\circ\text{C}$$

Finally,

$$\omega_{T_{w,\text{avg}}} = \pm 0.346 \text{ }^\circ\text{C.}$$

Also,

$$\omega_{T_{b,avg}}^2 = \sum_{j=1}^{20} \frac{\partial T_{b,avg}}{\partial T_j} \omega_{T_{b,j}}^2$$

The uncertainty $\omega_{T_{b,j}}$ is equal to $\omega_{T_{i,R}}$ so that one finds

$$\omega_{T_{b,avg}} = \pm 0.123 \text{ } ^\circ\text{C}.$$

Substituting the results into equation (9.2), the overall uncertainty in the temperature difference is

$$\omega_{\Delta T} = \pm 0.367 \text{ } ^\circ\text{C}$$

The mass concentration of oil present in the pool is given by

$$P_{oil} = \frac{\rho_{oil} V_{oil}}{\rho_{oil} V_{oil} + \rho_{R113} V_{R113}} \times 100$$

Neglecting the uncertainty in the densities, equation (9.1) yields

$$\omega_{p_{oil}}^2 = \left[\frac{\partial(\% \text{ oil})}{\partial V_{oil}} \right]^2 \omega_{V_{oil}}^2 + \left[\frac{\partial(\% \text{ oil})}{\partial V_{R113}} \right]^2 \omega_{V_{R113}}^2$$

The uncertainty in measuring the volume of oil is taken to be one half of the gradation on the measuring cylinder, so $\omega_{V_{oil}} = \pm 5 \text{ ml}$. The volume of R113 present in the tank is measured by the deviation in the liquid level (ΔH) from a point where the volume was measured to be 6.88 ℓ , i.e.

$$V_{R113} = 6.88 \ell \pm l \times w \times \Delta H$$

where l and w are the dimensions of the tank. The uncertainty in measuring 6.88ℓ is estimated to be $\pm 10 \text{ ml}$ (one half the least count of the graduated cylinder) and the uncertainty in measuring ΔH is $\pm 1.796 \times 10^{-3} \text{ m}$ (using one half the least count of the ruler). Employing equation (9.1), one obtains $\omega_{V_{R113}} = \pm 78 \text{ ml}$. With an oil density of $0.89 \text{ kg}/\ell$, a R113 density of $1.5073 \text{ kg}/\ell$, a volume of 6.88ℓ of R113 and a volume of 500 ml of oil, one obtains

$$\omega_{P_{oil}} = \pm 0.062 \%$$

The enhancement ratio (E.R.) is computed as

$$\text{E.R.} = \frac{\Delta T_{\text{plain}}}{\Delta T_{\text{enhanced}}}$$

Using equation (9.1), one has

$$\begin{aligned} \omega_{\text{E.R.}}^2 &= \left[\frac{\partial(\text{E.R.})}{\partial(\Delta T_{\text{plain}})} \right]^2 \omega_{\Delta T_{\text{plain}}}^2 \\ &+ \left[\frac{\partial(\text{E.R.})}{\partial(\Delta T_{\text{enhanced}})} \right]^2 \omega_{\Delta T_{\text{enhanced}}}^2 \end{aligned}$$

where $\omega_{\Delta T_{\text{plain}}} = \omega_{\Delta T_{\text{enhanced}}} = \omega_{\Delta T} = \pm 0.367^\circ \text{C}$. For a typical

value of $\Delta T_{\text{enhanced}} = 2^{\circ}\text{C}$ and an enhancement ratio of 5, one obtains

$$\omega_{\text{E.R.}} = \pm 0.936$$

The ratio of heat transfer coefficients is given by

$$\frac{\Delta T_{\text{without oil}}}{\Delta T_{\text{with oil}}}$$

Equation (9.1) gives $\omega_{\Delta T/\Delta T} = \pm 0.10^{\circ}\text{C}$ for $\omega_{\Delta T} = \pm 0.367^{\circ}\text{C}$, a ratio of 0.74 for the boiling coefficients, and $\Delta T_{\text{with oil}} = 4.6^{\circ}\text{C}$.

The uncertainty in the calculated saturation temperature is found from

$$\omega_{T_{\text{sat}}} = \left[\frac{\partial T_{\text{sat}}}{\partial X} \right] \omega_X$$

Taking $\omega_X = \pm 0.01822967$ (from $\omega_{p_{\text{atm}}} = \pm 0.005$ inch and $\omega_H = \pm 0.5$ inch), one obtains $\omega_{T_{\text{sat}}} = \pm 0.062^{\circ}\text{C}$. This results in an uncertainty of $\pm 0.352^{\circ}\text{C}$ in the wall superheat (from equation 9.2).

The difference in temperature differences for the fouling experiment is

$$\Delta(\Delta T) = \Delta T_{\text{end}} - \Delta T_{\text{start}}$$

Equation (9.1) gives

$$\omega_{\Delta(\Delta T)}^2 = \omega_{\Delta T_{\text{end}}}^2 + \omega_{\Delta T_{\text{start}}}^2$$

where $\omega_{\Delta T_{\text{end}}}$ and $\omega_{\Delta T_{\text{start}}}^2$ are simply $\omega_{\Delta T} = \pm 0.367^\circ\text{C}$. As a result,

$$\omega_{\Delta(\Delta T)} = \pm 0.519^\circ\text{C}.$$

The number of grams of CaSO_4 (m_{CaSO_4}) is determined by

$$m_{\text{CaSO}_4} = \left[\frac{\text{Amount titrate added } (\ell)}{\text{}} \right] \cdot (M \text{ EDTA}) \cdot \left[\frac{1}{50 \text{ ml sample}} \right] \\ \times \left[\frac{\text{Total sample volume (ml)}}{\text{}} \right] \cdot \left[\frac{136170 \text{ mg CaSO}_4}{1 \text{ mole CaSO}_4} \right]$$

Neglecting the uncertainty in the molecular weights, equation (9.1) gives

$$\omega_{m_{\text{CaSO}_4}}^2 = \left[\frac{\partial(\text{mg CaSO}_4)}{\partial \left[\frac{\text{Amount titrate added}}{\text{}} \right]} \right]^2 \omega_{\text{Amount titrate added}}^2 \\ + \left[\frac{\partial(\text{mg CaSO}_4)}{\partial (M \text{ EDTA})} \right]^2 \omega_{M \text{ EDTA}}^2 \\ + \left[\frac{\partial(\text{mg CaSO}_4)}{\partial (50 \text{ ml sample})} \right]^2 \omega_{50 \text{ ml sample}}^2 \\ + \left[\frac{\partial(\text{mg CaSO}_4)}{\partial \left[\frac{\text{Total sample volume}}{\text{}} \right]} \right]^2 \omega_{\text{Total sample volume}}^2$$

The molarity of EDTA (M EDTA) is given by

$$M \text{ EDTA} = \frac{g \text{ EDTA}}{\ell \text{ H}_2\text{O}} \cdot \frac{1 \text{ mole EDTA}}{372.24 \text{ g}}$$

Using equation (9.1),

$$\omega_{M \text{ EDTA}}^2 = \left[\frac{\partial(M \text{ EDTA})}{\partial(g \text{ EDTA})} \right]^2 \omega_g^2 \text{ EDTA} + \left[\frac{\partial(M \text{ EDTA})}{\partial(\ell \text{ H}_2\text{O})} \right]^2 \omega_{\ell \text{ H}_2\text{O}}^2$$

Taking $\omega_g \text{ EDTA} = \pm 0.005$, $\omega_{\ell \text{ H}_2\text{O}} = \pm 5 \text{ ml}$ (from one half of the least counts of the measuring devices), $0.8 \ell \text{ H}_2\text{O}$, and 4.0 g EDTA , one finds

$$\omega_{M \text{ EDTA}} = \pm 8.56 \times 10^{-5}$$

Again taking one half of the least counts, the following uncertainties are determined:

$$\omega_{\text{Amount titrate added}} = \pm 0.05 \text{ ml}$$

$$\omega_{50 \text{ ml sample}} = \pm 0.5 \text{ ml}$$

$$\omega_{\text{Total sample volume}} = 10 \text{ ml}$$

With 5 ml of titrate added, a 0.01343 M solution of EDTA, and a total volume sample of 1ℓ , it is found that

$$\omega_{m\text{CaSO}_4} = \pm 2.84 \text{ mg}$$

PART 10

APPENDIX 5: PREPARATION OF SATURATED CALCIUM SULFATE SOLUTION

The following procedure recommended by Palen [21] was used to obtain a saturated, aqueous solution of calcium sulfate.

1. Dissolve 25.7 g of reagent grade calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) in 10 ℓ of distilled water.
2. Boil off approximately 1/4 of the total volume.
3. Allow solution to stand and cool overnight.

Since precipitate was always present at room temperature, the solution was also saturated when again heated to the boiling point [21].

PART 11

APPENDIX 6: TITRATION

The amount of calcium dissolved in a sample of water was determined by EDTA titration [42]. The reagent solution was obtained by dissolving 4.0 g of disodium EDTA in 800 ml of distilled water and adding 0.86 g of sodium hydroxide. The indicator was prepared by mixing 0.20 g of Murexide and 100 g of sodium chloride and grinding into a powder with a mortar and pestle. The following procedure was used:

1. Place 50 ml of the water to be analyzed in an Erlenmeyer flask.
2. Add 2 ml of 1N sodium hydroxide solution and 0.2 g of the indicator to the flask. The sample will become pink if calcium is present.
3. Using a buret, slowly titrate with the reagent solution until the pink color becomes purple.
4. Add another drop of the reagent until no further color change is apparent.

The analysis is based on the equation:

where Y represents the EDTA radical.[34] At the endpoint of the titration, the number of moles of EDTA added to the sample is exactly equal to the number of moles of Ca^{+2} in the sample. The molarity of the reagent is:

$$\left[\frac{4\text{g EDTA}}{0.8\ell} \right] \cdot \left[\frac{1\text{ mole EDTA}}{372.24\text{g EDTA}} \right] = 0.0134 \frac{\text{mole}}{\ell}$$

The number of moles of EDTA added is:

$$\left[\frac{\text{Amount titrate added } (\ell)}{\ell} \right] \cdot \left[0.0134 \frac{\text{mole EDTA}}{\ell} \right]$$

This quantity is also the number of moles of Ca^{+2} in the 50 ml sample.

The total number of moles of Ca^{+2} in the entire sample is given by:

$$\left[\frac{\text{moles } \text{Ca}^{+2}}{50\text{ ml}} \right] \cdot \left[\frac{\text{Total sample volume (ml)}}{\text{ml}} \right]$$

By virtue of the reaction

the number of moles of Ca^{+2} is equal to the number of moles of CaSO_4 .

It is assumed that only calcium sulfate anhydrite is present when calculating the number of grams of calcium sulfate present. Thus, the total amount of CaSO_4 in grams is given by:

$$\left[\frac{\text{Total number of moles of } \text{CaSO}_4}{\text{moles of } \text{CaSO}_4} \right] \cdot \left[\frac{136.17\text{g } \text{CaSO}_4}{1\text{ mole } \text{CaSO}_4} \right]$$

PART 12

APPENDIX 7: PHOTOGRAPHY

Time-lapse photography was accomplished with a tripod-mounted 35mm Canon F-1 camera with a 50mm lens and a motor drive. The camera was located about two feet in front of the test section. A 750 Watt lamp placed at a 45° angle to the test section approximately one foot away illuminated the test section. Kodak Tri-X Pan film was used with a shutter speed of $\frac{1}{2000}$ second, an aperture of 2.8, and an iso setting of 800. In some instances a hood was employed and the room lights were switched off to reduce glare on the lens. The film was developed and prints were obtained (with Ilford 100 MG III paper) using standard methods. [35]