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FUEL MELTING and RELOCATION in the ADVANCED TEST REACTOR: SIMULANT EXPERIMENTS in a CLOSED GEOMETRY

by

Mark Handrick

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Abstract

FUEL MELTING and RELOCATION in the ADVANCED TEST REACTOR:
SIMULANT EXPERIMENTS in a CLOSED GEOMETRY

Mark Handrick

Under the supervision of Professor Michael L. Corradini

Flow visualization experiments were carried out to qualitatively determine the fuel melting and relocation flow regimes associated with the Advanced Test Reactor (ATR) under accident conditions. These accident scenarios were a loss-of-coolant (LOCA) and a loss-of-flow (LOFA). These simulant experiments were used to characterize the flow regime during melt relocation as either droplet (rivulet) or film (sheet) flow. The approximate time scaling of the accidents was preserved, as were the dimensions of the ATR coolant channel. It was determined that under various ranges of these control parameters, the molten fuel simulant would relocate by means of rivulet flow.

Acknowledgments

I would like to thank my advisor, Professor Michael L. Corradini, for his guidance and thoughtful insight as this project progressed from paper to completion. He always found time in his busy schedule to answer my questions and concerns. I consider myself fortunate to have studied under him, both in the classroom and individually.

Special thanks goes to Jeff Gundersen for sharing the work and headaches associated with this undertaking. Somehow, we made it through this project, leaning on each other many steps of the way.

I am grateful to the people who provided technical support and ideas, most notably Joe Krueger and the staff in the Mechanical Engineering shop.

I will always remember the special times shared with the people of Room 131. I hope the friendships developed there will remain with me in the future.

Finally, I wish to express my deepest thanks and gratitude to the members of my family for their support during the past five years.

Nomenclature

A	Surface area
c	Specific heat capacity
h	Heat transfer coefficient
h_{fg}	Latent heat of vaporization
k	Thermal conductivity
L	Characteristic length
m	Mass
Nu	Nusselt number
P	Power due to resistive dissipation
Q	Power due to decay heat
q''	Heat flux
R	Resistance
Ra	Rayleigh number
t	Time
T	Temperature
V	Voltage
α	Thermal diffusivity
β	Coefficient of volume expansion
ρ	Density
μ	Viscosity
ν	Kinematic viscosity

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Chapter 1: Introduction

1.1 Motivation

The Idaho National Engineering Laboratory's Advanced Test Reactor (ATR) is a unique research reactor designed for the testing of nuclear fuels and other in-vessel components at high thermal neutron fluxes. The ATR is owned by the U.S. Department of Energy and is operated under contract by EG&G Idaho Inc. The ATR employs a plate-type fuel with UAl_x intermetallic powder dispersed in an aluminum cladding. The uranium in the UAl_x fuel core is enriched to 93 wt% ^{235}U. Typical UAl_x powder lots consist of 8 wt% UAl_2, 78 wt% UAl_3, and 14 wt% UAl_4 [1]. The active length of the fuel plates is 4 feet, with 19 fuel plates comprising one fuel assembly (see Figures 1.1 and 1.2). The ATR core consists of 40 fuel assemblies, resulting in a maximum core power of 250 MW_t and power density of 1.0 MW/l. The assemblies are arranged in a serpentine manner, so that the core is shaped like a four leaf clover (see Figure 1.3). The curved arrangement allows the materials under testing to experience a maximum thermal neutron flux of 1 x 10^{15} n/cm^2-s [2].

At these high fluxes available inside of the core, testing specific materials for radiation damage which may have taken too long in a commercial power reactor can be accomplished in a much shorter time in the ATR. However, because of the high neutron flux and power levels required, there is concern about one of the sections of the core melting due to some transient involving a power-flow mismatch. In an attempt to understand the phenomena associated with the melting and subsequent relocation of molten fuel in the ATR core, models of fuel melting/relocation using the computer codes SCDAP/RELAP5 (SR5) have been performed. However since these codes are designed for commercial fuel rod geometry and materials, it is uncertain as to the validity of the results predicted by these codes. To better understand the nature of melting in a narrow flow channel plate-type fuel, simple melt experiments that bound the parameters of the accident sequences being numerically modeled are needed. The initial goal of such experiments is to visualize the dynamics of melting a UAl_X fuel simulant in the presence of a coolant environment, while keeping the key parameters similar to those that exist in the ATR during these accidents.

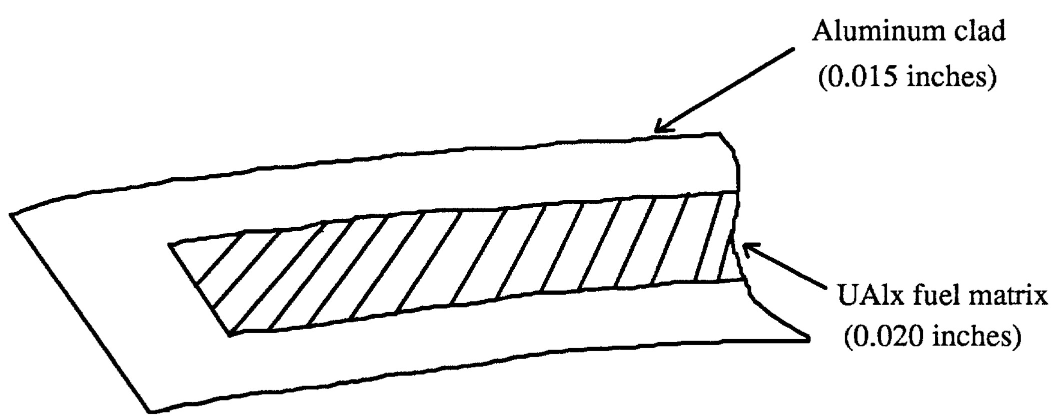

Figure 1-1. Detail of an ATR fuel plate

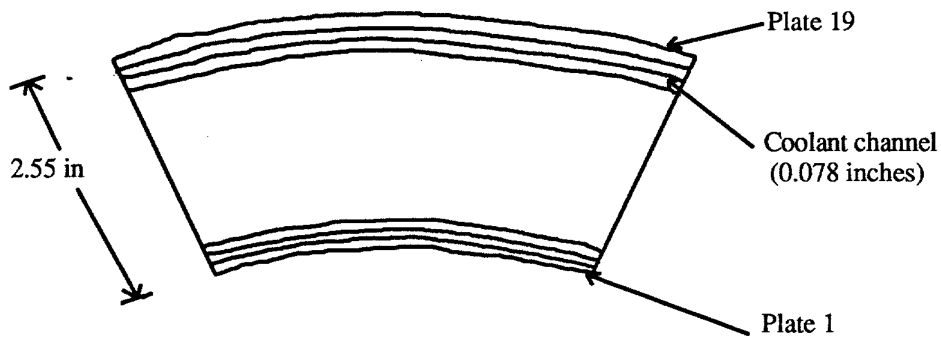

Figure 1-2. ATR fuel assembly (8 of 19 plates shown)

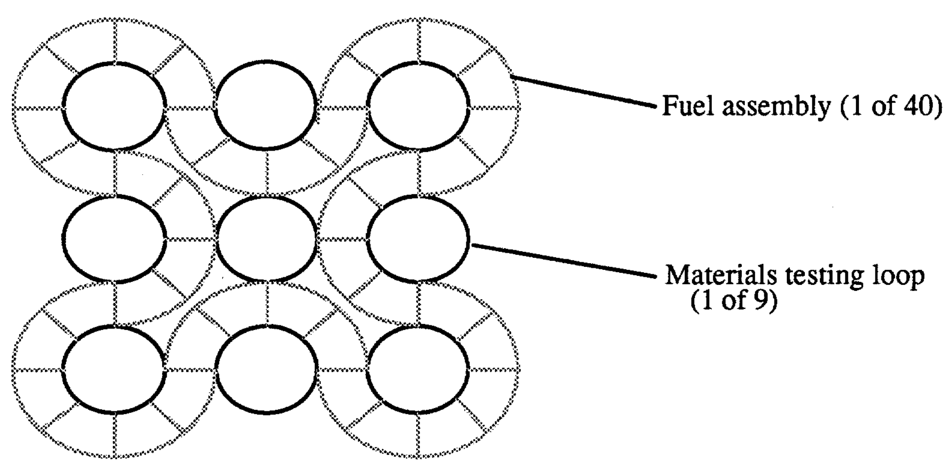

Figure 1-3. Cross section of the ATR core

1.2 Objective and Scope

There are two accident scenarios involving the ATR which have been identified to lead to core melting and relocation. These conditions are those which we are trying to model experimentally. These are a large break loss-of-coolant accident (LOCA), and a loss-of-flow accident (LOFA). These scenarios have been modeled by the codes SR5 as part of Level 2 Probabilistic Risk Assessment (PRA), with results being published in EG&G Internal Technical Reports No. PG-T-92-112 and PG-T-90-022 respectively [3, 4]. One point of uncertainty associated with these computer predictions is the actual mechanism by which the ATR fuel relocates, given the fact that it has reached its melting point. Two possible mechanisms are thought to be likely. One is film, or sheet flow of the molten fuel plates, while the other possibility is droplet, or rivulet flow. The primary goal of these experiments is to determine which of these mechanisms is more likely in the simulations, in addition to determining how well these simulations represent the conditions of the ATR during the two types of accidents.

Since we were not able to duplicate the precise conditions in the ATR core, e.g. using a fuel simulant instead of UAl_x because of temperature constraints, we felt that preserving the correct time scaling of the accidents was of primary importance. Since these experiments are concerned with simulating the phenomena of fuel melting and relocation, the timing of the events which lead to the increase in fuel temperatures are not considered important. Rather what we chose to preserve was the time scale associated with fuel relocation, given that the fuel has reached its melting temperature. For transient events such as these the melt flow regime and associated fluid mechanics would be controlled by its timing. The EG&G reports were used to determine the appropriate time scaling outlined above.

Besides preserving this time scaling, we felt it was necessary to conserve the correct geometric scaling of the ATR fuel plates. It is apparent that the close proximity of the fuel plates may influence the behavior of the molten fuel as it relocates in the core. To simplify our considerations, the simulations employ a parallel plate geometry instead of the complicated structure of the ATR fuel assemblies, with the coolant cross-sectional area being preserved. A brief summary of the SR5 results listed in the EG&G reports are given here.

1.2.1 Loss-of-Coolant Accident (LOCA)

The base case LOCA analysis performed by the staff at EG&G was that of a double-ended offset shear of a 24 inch outlet line with subsequent reactor scram. The primary coolant system thermal-hydraulic response and core damage progression was analyzed using the SR5 computer code. The initial reactor core power was 250 MW with burnup assumed to be 15,000 MWd/MTU, which is equivalent to 60 effective full power days. Other initial conditions of importance are shown in Table 1-1. The decay heat model is based on the 1979 ANS decay heat standard. Upon initiation of the accident, flow into the coolant channels remained positive (downward), although at a continuously reduced level. At approximately 60 seconds into the accident extensive boiling in the core begins. This causes the flow to stagnate and allows the fuel to heat up. This increases the rate of vapor production with void fractions in the range of 0.8 to 1.0, and quickly dries out the coolant channel. Fuel cladding surface temperatures in the southwest (highest powered) lobe rise from approximately 350 K at 60 seconds to the solidus temperature of 913 K at 75 seconds. An additional 10 seconds was needed to add enough energy which corresponds to the latent heat of fusion of the fuel plate. It was assumed that a 20 degree temperature rise accompanied the addition of the latent heat of fusion. Thus molten core relocation occurred at approximately 85 seconds, when the fuel plates reached the temperature of 933 K. The core decay heat power at this time was approximately 8.0 MW. It is this characteristic time, from initial heating to relocation, that was to be preserved during the melt relocation experiments simulating this LOCA accident.

The sequence of events predicted by the SR5 analysis of the 24-in outlet break are shown in Table 1-2 [3].

Table 1-1. Assumed initial conditions for the 24-in outlet LOCA

Parameter	Value
Total core power, MW	250.0
SE lobe power, MW	66.0
SW lobe power, MW	64.1
Center lobe power, MW	55.5
NW lobe power, MW	32.2
NE lobe power, MW	32.2
Peak assembly power, MW	9.1
Coolant inlet temperature, °C	51.7
Coolant inlet flow, kg/s	3007.0
Coolant outlet temperature, °C	71.6

Table 1-2. Sequence of events for the large break LOCA

Event	Time (s)
Transient initiated	0.0
Scram on low inlet pressure	0.01
Break full open	0.1
Core heatup begins	57.2
Initial relocation in southeast quadrant	84.4
Initial relocation in southwest quadrant	85.2
Relocation to lower plenum in SW quadrant	101.2
Relocation to lower plenum in SE quadrant	107.8

1.2.2 Complete Loss of Flow Accident (LOFA)

A series of high pressure core boiloff sequences were also examined by the EG&G staff. The sequence designated LCP15 is initiated by a loss of off-site power, eventually leading to high pressure core uncovery and complete core meltdown. As in the LOCA, SR5 models were used to predict primary system behavior and core damage. It is conservatively assumed that primary coolant flow was not restored and that no makeup flow was provided. Initial conditions are shown in Table 1-3. The reactor was assumed to have been operated at 204 MW for 73.5 days, with a burnup equivalent to 60 effective full power days [4].

Table 1-3. Assumed initial conditions for the high pressure boiloff

Parameter	Value
Total core power, MW	204.0
SE lobe power, MW	55.0
SW lobe power, MW	60.0
Center lobe power, MW	43.0
NW lobe power, MW	23.0
NE lobe power, MW	23.0
Coolant inlet temperature, °C	51.7
Coolant inlet flow, kg/s	2677
Core inlet pressure, MPa	2.53
Coolant outlet temperature, °C	70.0

Upon initiation of the transient, natural convection flow patterns were established within the reactor vessel with coolant flow upward through the core. At 25 hours, saturated nucleate boiling is predicted to occur, thereby increasing the flow rate. The core begins to heat up when the coolant level drops below the reflector tank. The fuel centerline temperatures in the southwest quadrant rise from the saturation temperature of 500 K to the solidus temperature (913 K) in a period of approximately 9 minutes. Relocation occurred 3 minutes later when the fuel temperature reached 933 K. The molten fuel quenched as it relocated downward, causing rapid vapor generation and large flow oscillations. Complete blockage of flow was predicted as a result of core relocation. At this point the calculation was stopped because the SR5 code could not simulate a blocked flow channel. The core decay heat power at time of melting and relocation was approximately 0.7 MW. A summary of events is given in Table 1-4 [4].

Table 1-4. Sequence of events during the boiloff

Event	Time
Loss of all ac-power	0.0 s
Reactor scram	0.9 s
Boiling in core begins	8.5 h
Two phase mixture falls below top of reflector tank	28.6 h
Core begins to heat from saturation temperature	28.76 h
Fuel melting begins in SW quadrant	28.97 h
Fuel relocates in SW quadrant	29.02 h
Calculation stopped	29.18 h

In addition to the high pressure boiloff sequence, an accident initiated with a failure in the ATR pressurizing system was also analyzed. This sequence, named LPP9, results in low pressure core uncovery and subsequent relocation [4]. The details are similar to that of the high pressure boiloff, except that fuel relocation occurs at approximately 10 minutes after fuel heatup.

1.2.3 Goals of the Experiments

To summarize the stated goals of these experiments, we wish to simulate the phenomena of fuel melting and relocation in the ATR. In particular, two distinct accident conditions, a loss-of-coolant (LOCA) and a loss-of-flow (LOFA) are simulated. The primary purpose of these experiments is to determine, at least qualitatively, the physical nature of the melting and relocation. Does the molten fuel material relocate in the form of film or rivulet flow?

The experimental parameters that we have decided to control are the time scales associated with relocation once the fuel simulant is at the melting point, and the dimension of the coolant channel flow area. For the LOCA, the appropriate time scaling is on the order of 20 seconds for the most conservative case involving rapid fuel melting. As an upper limit to this time scale parameter, a time of 2 minutes was chosen. The characteristic time associated with the boiloffs range from 3 to 10 minutes. For both accidents, the dimensions of the coolant channel will range from 2 mm, which corresponds to the actual ATR fuel plate, to an upper value of 6 mm. The 6 mm width was chosen for visual purposes. It is far easier to observe the experiments with this spacing, and yet this choice still retains the ability to simulate the closely spaced ATR fuel plates.

Chapter 2: Description of Experimental Apparatus

2.1 ATR Fuel Simulation

As previously noted, the ATR fuel is comprised of a UAl_x matrix dispersed in elemental aluminum. The Al alloy 6061-O serves as cladding to the fuel. The melting point of the ATR fuel is assumed to be 913 K, the solidus temperature of equilibrium Al + UAl_4 containing 38.3 wt% uranium. This represents the core average uranium content [1]. For simplicity in our experimentation, we chose to model the ATR fuel with a low-melting eutectic called Belmont Alloy 2505. This type of alloy is commonly referred to by its trade name, Wood's metal. Belmont is a registered trademark of Belmont Metals Incorporated. This alloy has a solidus temperature of 70 °C, and a liquidus temperature of 72 °C. The chemical composition of Wood's metal is listed below [5].

Element	Composition (wt%)
Bismuth	50.0
Lead	26.7
Tin	13.3
Cadmium	10.0

A comparison of thermophysical properties between the ATR core materials and the Wood's metal simulant is given in Table 2-1. The values listed for the fuel plate are volume weighted averages of the fuel matrix and the fuel cladding. These volume fractions are 32.4% and

67.6% respectively [6]. The experiments will model the ATR fuel material as a volume weighted fuel plate rather than the UAl_x fuel matrix.

Table 2-1. Comparison of physical properties

Property	**ATR Fuel Matrix**	**ATR Fuel Plate**	**Wood's metal**
Melting Point *°C*	1186 (assumed)	1186 (assumed)	70.0
Density kg/m^3	3680	3017	9383.5
Thermal conductivity *W/m-K*	40.5 @ 900 K	131	18.8
Specific heat *J/kg-K*	813 @ 900 K	1041	167
Thermal diffusivity m^2/s	1.35×10^{-5}	4.17×10^{-5}	1.20×10^{-5}
Latent heat of fusion *kJ/kg*	258	395	32.6

2.2 Choice of Coolant

The ATR is cooled by light water which is pressurized to 355 psig at the reactor inlet, at a temperature of 125 °F. The pressure drop through the core is approximately 100 psi, with an average outlet coolant temperature of 167 °F [2]. For experimental considerations, we chose to use the refrigerant R-113 as the coolant for the experiments. In order to accurately simulate the LOFA, a coolant that boils at a temperature below that of the Wood's metal melting point is required. The saturation temperature of R-113 at one atmosphere is 47.6 °C. Due to the concerns about possibly releasing R-113 to the environment, the experiments are conducted at atmospheric pressure, with the coolant confined to a closed loop. The physical properties of R-113 are listed in Table 2-2 [7].

Table 2-2. Physical properties of refrigerant R-113

Chemical formula	CCl_3F_3
Molecular weight	187.4
Boiling point @ 1 atm	47.6 $°C$
Density of liquid @ 25 °C	1565 kg/m^3
Specific heat of liquid @ 25 °C	913 $J/kg\text{-}K$
Thermal conductivity of liquid @ 25 °C	0.075 $W/m\text{-}K$
Latent heat of vaporization @ 1 atm	147 kJ/kg
Viscosity of liquid @ 25 °C	6.80×10^{-4} $kg/m\text{-}s$

2.3 Equipment Design

The ATR fuel plates are simulated by a thin casting of Wood's metal. To represent the internal heat source due to decay heat generation, electrical resistance heaters were employed. The heaters were placed into channels milled into the back side of an aluminum block. The Wood's metal was cast onto the front face of the aluminum block. A depression 0.125″ deep is milled into the front face to hold the Wood's metal. The edges of the depression are milled at a 45° angle to assist in holding the casting in place during the experiments. The Wood's metal is cast to a thickness of 3 ± 0.2 mm. The dimensions of the aluminum block are 4.25″ x 9.0″ x 0.75″, while those of the Wood's metal casting area are 3.25″ x 8.0″ (see Figure 2-1). The power to the resistance heaters is controlled by a variable ac-power supply. Specifications of the resistance heaters are listed in Appendix A.

The aluminum block is instrumented with K-type thermocouples which are used to record the time-dependent Wood's metal temperatures at several locations on the casting face.

Grooves approximately 1 mm deep were milled into the aluminum face so the thermocouple wires could be placed under the cast Wood's metal without disrupting the surface. The thermocouples are numbered according to the figure below. A thermocouple is placed inside the heating assembly to record the aluminum block temperatures, designated as T9. The coolant bulk temperature was also monitored with a thermocouple.

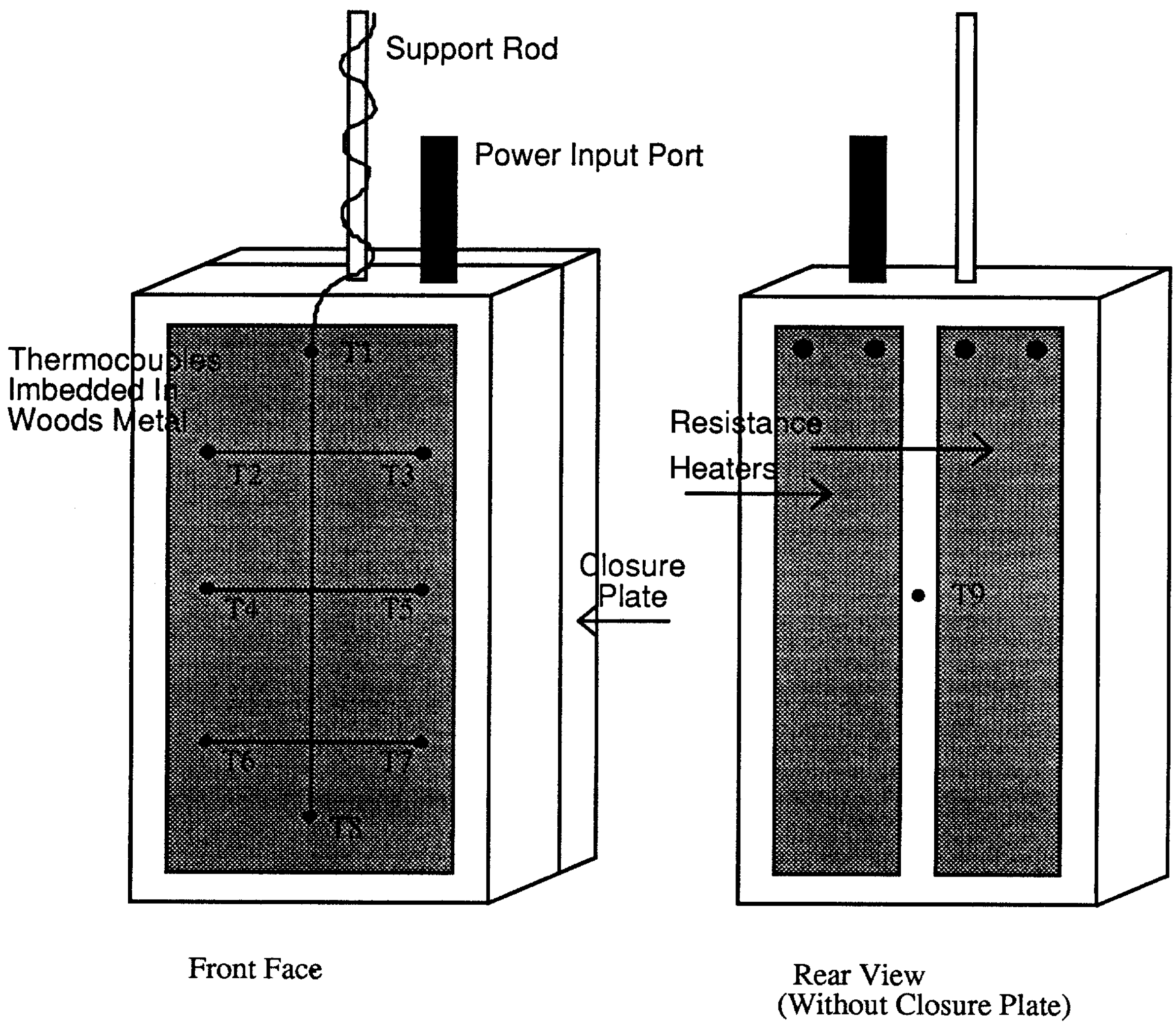

Figure 2-1. Details of heater assembly

The heating assemblies are suspended inside a T-shaped Pyrex chamber containing the coolant. The inner diameter of the chamber is 6.0″, and the vertical section is 18.0″ long. The horizontal section joins at the midpoint of the vertical section. The open end of this section is covered by a plastic plate which is bolted in place. This allows for a viewport so that the experiment can be videotaped.

Coolant enters the chamber through a rubber stopper via a variable speed circulation pump. Vapor produced by the heating assembly is passed first through a condenser and then back to the coolant reservoir. The condenser consists of a wound copper tube immersed in an ice bath. A pressure indicator with a relief valve is located on the top cover plate to monitor conditions in the chamber. The relief valve is primarily a safety measure, opened only if vapor production exceeds the capacity of the condenser. The top cover plate has access ports for the power wires and thermocouples in addition to the pressure indicator. The experimental apparatus is shown schematically in Figure 2-2.

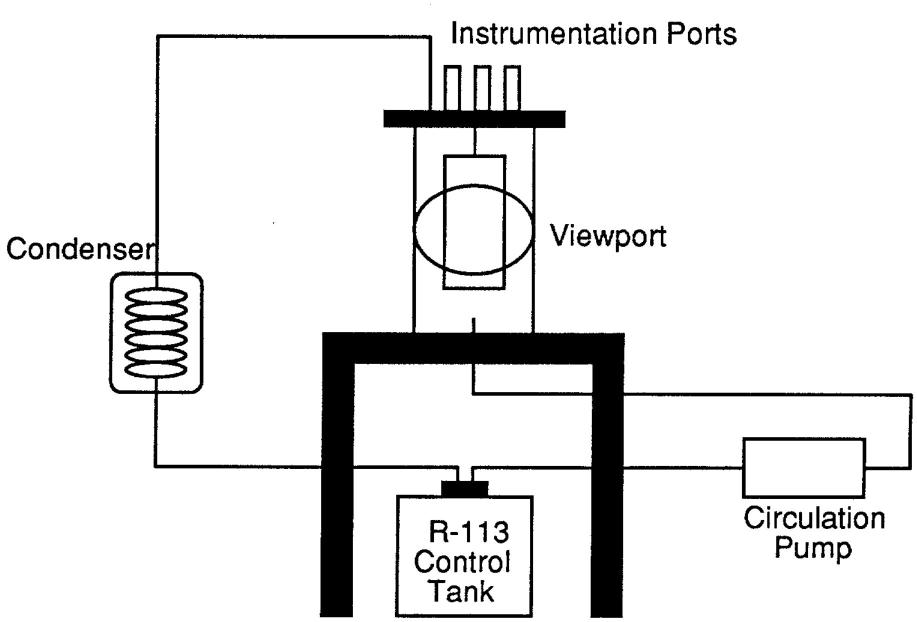

Figure 2-2. Overview of experimental layout

2.4 Data Acquisition

A Keithley 575 Measurement and Control System is used in conjunction with an 80286 IBM compatible computer to record temperatures from the thermocouple network. A Keithley Analog Input Module 7 (AIM 7) card is connected to the 575 system, so that the input voltage signals can be converted to temperatures in °C. A code written in BASIC is used by the Keithley Data Acquisition and Control 500/I software to gather the temperature data. Accuracy of the AIM 7 temperature readings are cited as ± 0.25 °C. The results are written to data files and the computer screen every 5 seconds. This allows for real-time monitoring of the experiments. The code is listed in Appendix B.

A portable video camera is used to record the experimental runs on tape. The resulting videotapes are analyzed to make conclusions regarding the dynamics of fuel plate melting and relocation. As these experiments are primarily visual in nature, the tapes are obviously most critical to understanding the phenomena being modeled.

Chapter 3: Experimental Parameters

3.1 Heat Flux into Wood's metal Casting

One of the most important parameters within control of the experimenter is the heat flux into the Wood's metal supplied by the resistance heaters. The heaters are rated by the manufacturer as having a maximum power output of 500 Watts at the maximum voltage of 120 Volts. Since the rate of heat loss due to resistive dissipation goes as,

$$P = V^2 / R \tag{3-1}$$

the power generated by the heaters as a function of applied voltage can be written as the following.

$$P_{heater} = 500(V_{app} / 120)^2 \tag{3-2}$$

The heated area of the resistance heaters (one side only) is given as 10.22 in^2, or 6.59×10^{-3} m^2 [8]. Therefore, the heat flux at the surface of the heaters can be given in units of W/m^2 as

$$q'' = 5.27 V_{app}^2 \tag{3-3}$$

This assumes that the resistor is 100% efficient in converting electrical energy to heat and all of the heat transfer is out the front surface. Because the heaters are located inside the aluminum assembly, heat must first be transferred through the 0.125 inch aluminum facing before reaching the Wood's metal. During this process, the aluminum assembly temperature will inevitably rise, reducing the value of the heat flux entering the Wood's metal casting until a steady-state is achieved. This effect, along with the non-ideal nature of the heaters, requires that a better estimate be made of the actual heat flux reaching the surface of the Wood's metal casting.

A simplified model of the heat flows both into and out of the Wood's metal casting is shown below in Figure 3-1.

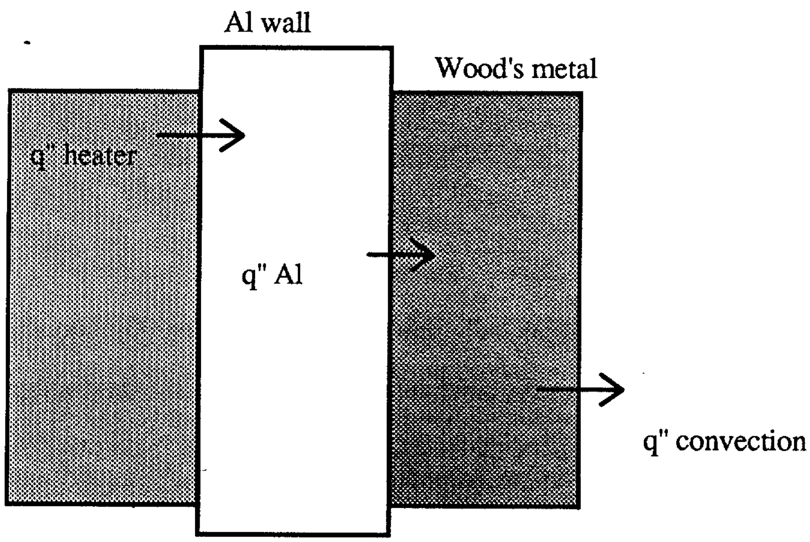

Figure 3-1. Simplified heat flow diagram of assembly

An energy balance on the Wood's metal casting gives the following

$$q''_{AL}\, A\Delta t = mc\Delta T + hA(T_{wm} - T_{\infty})\Delta t \qquad (3\text{-}4)$$

where
A = Wood's metal surface area = 0.01677 m^2
m = mass of Wood's metal = 0.5 kg
c = specific heat of Wood's metal = 167 J/kg-K
ΔT = temperature rise of Wood's metal, $(T_{wm} - T_o)$
h = natural convection heat transfer coefficient
Δt = time from start of heating

Note that the heat flux into the Wood's metal, q''_{Al} , should remain constant during the heating process. Energy transferred into the Wood's metal either increases the casting's internal energy, or it is lost to the surroundings by convection. If the temperature of the

Wood's metal is measured from an initial value, for a given applied voltage setting, then Eq. 3-4 can be solved for the heat flux into the casting.

$$q''_{Al} = \frac{mc(T_{wm}(t) - T_o)}{A\Delta t} + h(T_{wm}(t) - T_\infty) \qquad (3\text{-}5)$$

To test these assumptions, the Wood's metal was heated at voltage settings of 60, 80, 90, and 100 percent of full power. The natural convection heat transfer coefficient of the ambient air was estimated to be 5.0 W/m^2-K (see Appendix C for this calculation).

Temperature readings were recorded as a function of time and stored as data files called `heatflx1.dat`, `heatflx2.dat`, `heatflx3.dat`, and `heatflx4.dat`. These files are found in Appendix D. The temperature profiles are plotted for thermocouple locations T1, T2, T4, T6, and T8. These graphs are shown in Figures 3-2 through 3-3. Using these temperatures, the value of q''_{Al} was computed at distinct time intervals for the various voltage settings. This was done for temperatures T4 and T8 to show the axial variation of heat flux entering the Wood's metal. The results are illustrated in Tables 3-1 through 3-4.

It is seen that the estimated heat flux into the Wood's metal is approximately 6% of the ideal value (Eq. 3-3) for the center of the resistance heaters, at location T4, and about 4% of ideal for the lower end, T8. This difference seems small when compared to the ideal case, but the relative difference between the two estimates is on the order of 1.5. Note once again that the results listed are only an attempt to estimate the real heat flux and should be viewed with caution. For example, the temperature difference implied in the Rayleigh number, needed for the natural convection heat transfer coefficient, is taken to be an average value. At the higher temperatures, this term would become larger, implying greater convective heat transfer, and therefore a larger heat flux value.

Table 3-1. Estimate of heat flux into Wood's metal at 60% power

Measurements at location T4

Δt sec	ΔT °C	q''_{Al} W/m^2
50	15.5	1615
70	21.5	1631
90	28.7	1725
110	34.7	1738
130	39.5	1704
140	42.0	1698
	Average	1685
	Percent of ideal	6.2

Measurements at location T8

Δt sec	ΔT °C	q''_{Al} W/m^2
50	9.6	1004
70	15.6	1188
90	19.2	1158
110	25.2	1267
130	31.2	1351
140	33.6	1363
	Average	1222
	Percent of ideal	4.5

Table 3-2. Estimate of heat flux into Wood's metal at 80% power

Measurements at location T4

Δt sec	ΔT °C	q''_{Al} W/m^2
40	21.6	2785
50	27.6	2875
60	33.5	2936
70	39.6	3003
75	42.0	2987
	Average	2917
	Percent of ideal	6.1

Measurements at location T8

Δt sec	ΔT °C	q''_{Al} W/m^2
40	13.2	1703
50	18.0	1876
60	21.6	1894
70	26.4	2004
75	28.8	2050
	Average	1905
	Percent of ideal	4.0

Table 3-3. Estimate of heat flux into Wood's metal at 90% power

Measurements at location T4

Δt sec	ΔT °C	q''_{Al} W/m^2
40	26.3	3400
45	29.9	3452
50	33.5	3498
55	38.3	3653
60	41.9	3681
65	44.3	3609
	Average	3521
Percent of ideal		5.8

Measurements at location T8

Δt sec	ΔT °C	q''_{Al} W/m^2
40	16.7	2162
45	19.1	2209
50	21.5	2248
55	25.1	2398
60	27.4	2411
65	29.8	2432
	Average	2310
Percent of ideal		3.8

Table 3-4. Estimate of heat flux into Wood's metal at 100% power

Measurements at location T4

Δt sec	ΔT °C	q''_{Al} W/m^2
40	32.3	4180
45	38.3	4430
50	43.1	4508
55	45.5	43.47
	Average	4303
Percent of ideal		5.7

Measurements at location T8

Δt sec	ΔT °C	q''_{Al} W/m^2
40	19.2	2486
45	22.8	2637
50	26.3	2750
55	29.9	2856
	Average	2682
Percent of ideal		3.6

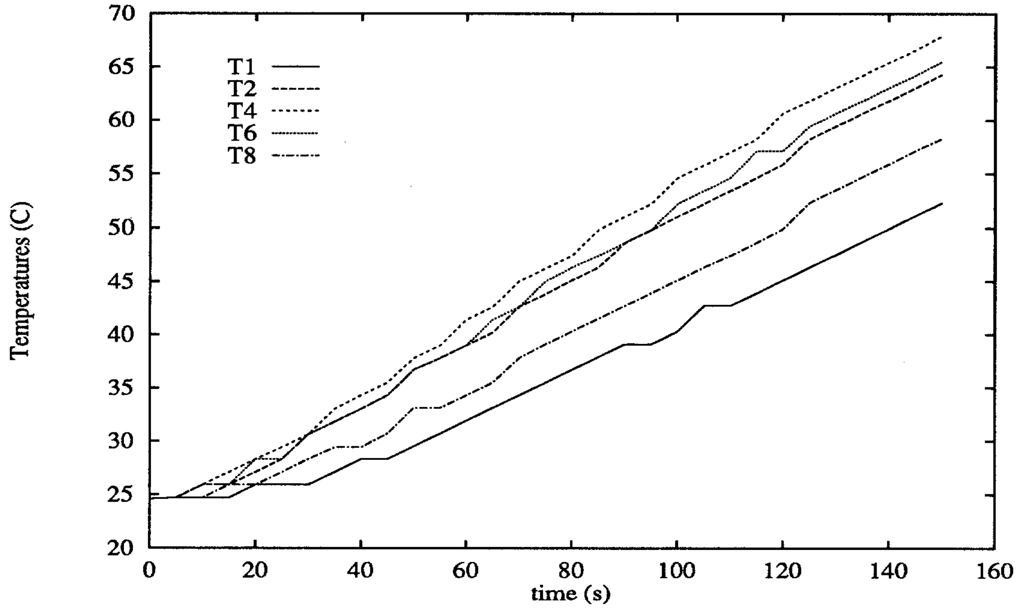

Figure 3-2. Wood's metal temperature profiles at 60% power

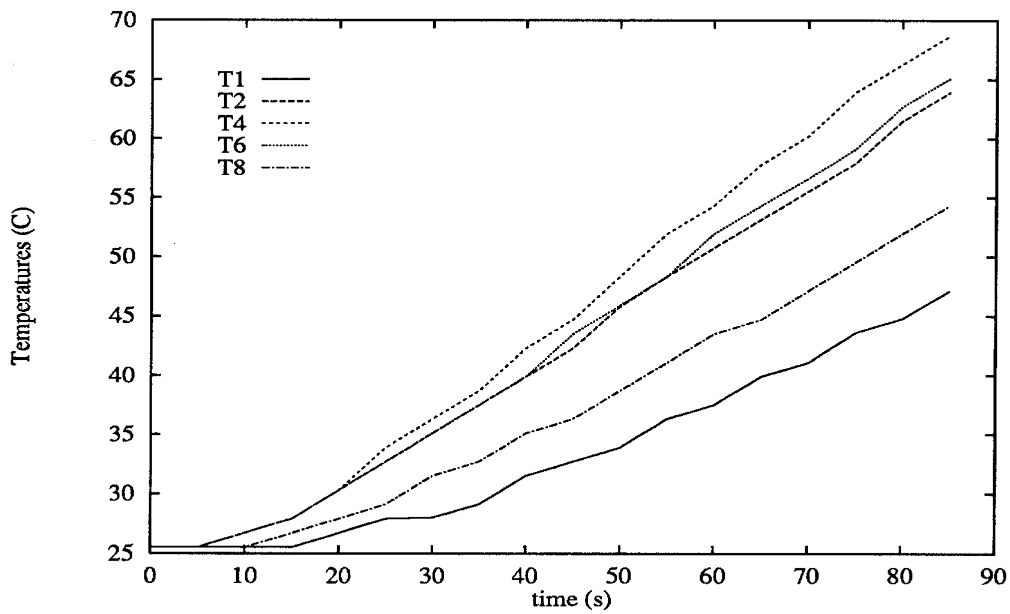

Figure 3-3. Wood's metal temperature profiles at 80% power

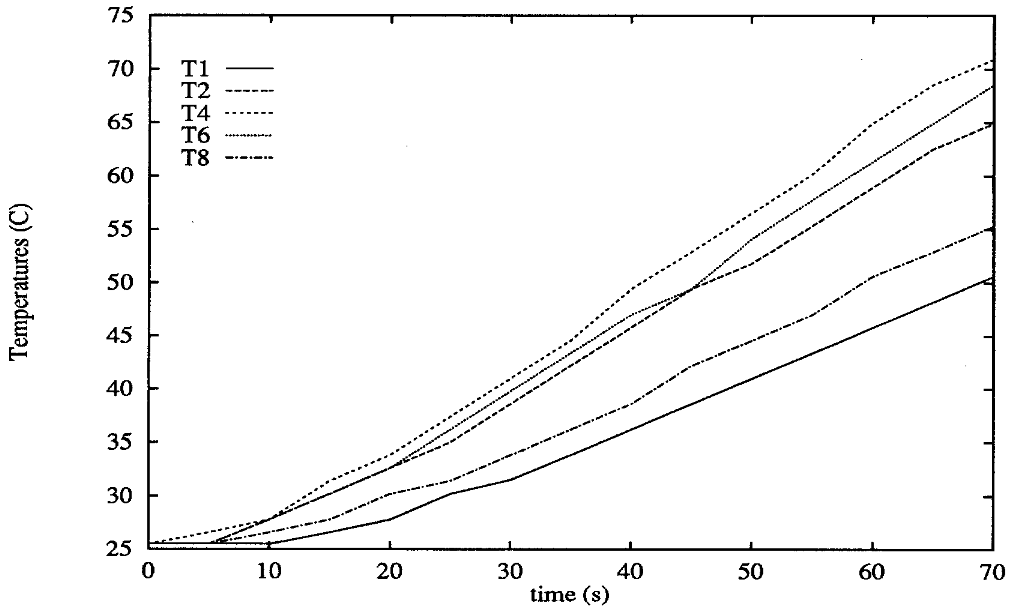

Figure 3-4. Wood's metal temperature profiles at 90% power

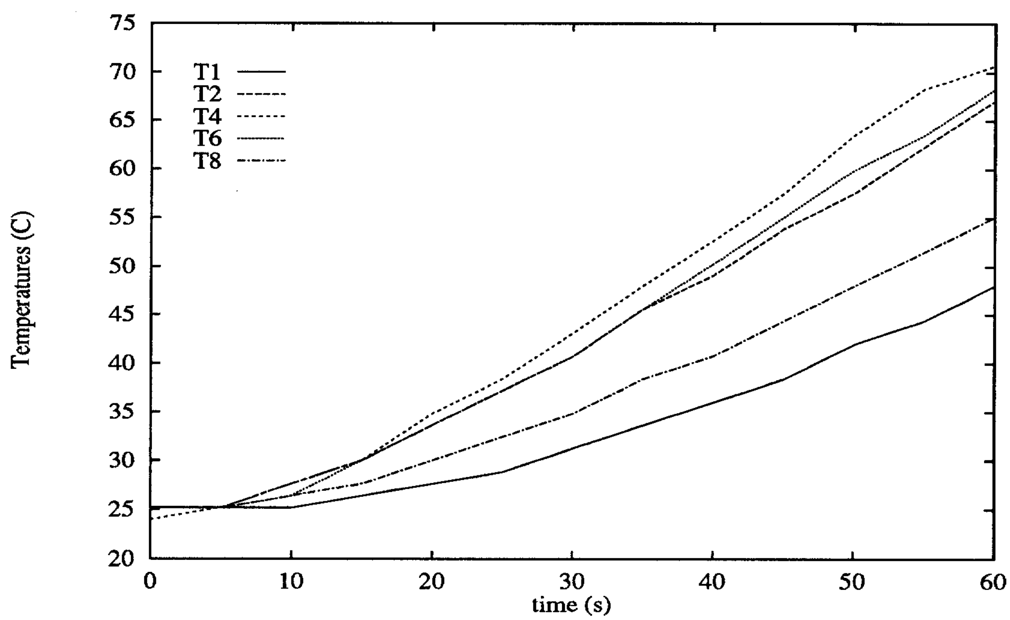

Figure 3-5. Wood's metal temperature profiles at 100% power

3.2 Preservation of Time Scaling

3.2.1 LOCA Analysis

As previously noted, it is desired that the actual time scaling of the accidents be preserved. In the case of the LOCA, the ATR coolant channels are predicted to dryout before fuel melting occurs. If adiabatic boundary conditions are assumed, the temperature increase is governed by

$$Q_{decay} = mc\frac{\Delta T}{\Delta t} \qquad (3\text{-}6)$$

Solving for the time increment

$$\Delta t_{ATR} = mc\frac{\Delta T}{Q_{decay}} \qquad (3\text{-}7)$$

Consider an average ATR fuel plate, number 10 of the 19 per assembly, with a volume of 1.1744 x 10^{-4} m^3 [6]. From the EG&G LOCA computer analysis, the temperature increases to 913 K from approximately 350 K for a ΔT of 560 K. The core decay heat at this time is approximately 8.0 MW, or 3.2% of the 250 MW full power rating. If this percentage is applied the highest powered SE lobe of the core, the decay heat for this average fuel plate at 60 seconds is

$$\frac{(0.032)(66\text{ MW})}{(8\text{ assemblies / lobe})(19\text{ plates / assembly})} = 13.9\text{ kW} \qquad (3\text{-}8)$$

Using the properties listed in Table 2-1, the value of Δt_{ATR} is found to be 14.7 seconds. This is consistent with the SR5 model which indicates a time increment of approximately 20 seconds associated with heating of the southern lobes.

For the experimental LOCA simulation we will attempt to preserve this value of Δt. Equation 3-6 can be rearranged as

$$q''_{Al} = \frac{mc\Delta T}{\Delta t_{wm} A} \qquad (3\text{-}9)$$

From the property values listed for Eq. 3-4, it is possible to calculate the required heat flux into the Wood's metal necessary for a given temperature increase. This temperature difference corresponds to the Wood's metal melting temperature minus the initial temperature during the experiments. Values of the required heat flux are shown below in Table 3-5.

Table 3-5. Heat flux required for specific Wood's metal temperature increases

ΔT (°C)	q" (W/m^2)
5.0	1660
10.0	3320
15.0	4980

The results listed in Table 3-4 indicate that initial Wood's metal temperatures of 10-15 °C below the melting point can be accommodated by the resistance heaters at full power.

3.2.2 LOFA Analysis

For the case of the boiloff, adiabatic boundary conditions do not apply, therefore Eq. 3-6 cannot be used. Including a term that would account for convective heat transfer is difficult as the conditions in the ATR core during this accident range from nucleate boiling to various modes of vapor cooling. Determining a characteristic time scale analytically is not as straightforward. Instead, the approach will be to preserve the time difference associated with fuel relocation, once the fuel has reached its solidus temperature. The SR5 models indicate this to be approximately 3 minutes for the highest powered lobe during the high pressure boiloff, and about 10 minutes for the low pressure sequence [4].

In the experimental model, this time is governed by the rate of coolant boiloff. To accelerate this process, the coolant pump is run in reverse to draw the R-113 out of the test chamber. A dump valve is also employed to assist the pump when short drain times are required. Using the control mechanisms, we can vary the drain time from 2 to 10 minutes, bounding the characteristic time of the ATR fuel relocation predicted by the computer model.

3.3 Coolant Environment

The SR5 model of the LOCA predicts rapid vapor generation and subsequent dryout of the coolant channels. In order to simulate these conditions, we needed to empty the test chamber of coolant as quickly as possible. Since the R-113 must be confined to the condenser-pump loop, the ability to drain the chamber is limited. By using water as the coolant instead of R-113, we were able remove the rubber stopper at the bottom of the chamber, letting the water drain to an open-air container. This produced drain times on the order of 10 seconds, comparable to the dryout times predicted by the computer model. The melting then proceeded in a liquid free environment, similar to the conditions predicted in the ATR for the LOCA accident, where the void fractions approach 1.0 during fuel relocation. The nature of the

LOFA requires that R-113 be used as coolant in order to provide the two phase conditions that exist in the ATR core during the boiloff.

Chapter 4: Description of Melting Experiments

In order to determine the relationship between the experimental parameters discussed previously, and the Wood's metal melt behavior, several different experimental runs were performed for each type of accident. The reasoning behind the choice of the individual parameters is stated below in a general fashion, with more detail being provided in the descriptions of each of the experimental runs.

4.1 LOCA Simulations

The experiments simulating the LOCA will primarily use water as the coolant for the reasons discussed in Chapter 3. However, for the purpose of comparison, an initial test run was done using R-113 as the coolant. This test run was named LOCA 1. To better illustrate the melting process, the gap width between the heated plates was set to 6 mm. The choice of the 6 mm gap represents the maximum value of this experimental parameter. The actual gap width between the ATR fuel plates is on the order of 2 mm. Since it is difficult to observe the melting process while preserving the ATR gap width, we chose to expand this dimension in order to get results we could interpret visually. A drain time of approximately 2 minutes was chosen, representing an upper limit of this characteristic time. At the time of Wood's metal melting and relocation, the resistance heaters were at full power, providing the maximum heat flux capable of the experimental apparatus. All other LOCA experimental runs also maintained this power level at the time of melting.

For the second run, labeled LOCA 2, and all succeeding LOCA runs, water was employed as the coolant. The gap width was maintained at 6 mm, but the drain time was shortened to 10 seconds. This produced much quicker relocation times than were observed in the LOCA 1 run. The lack of R-113, in either liquid or vapor form, is probably the major contributor to this effect.

The third experimental run is labeled LOCA 4. The numbering scheme appears irregular because other melt experiments were being performed concurrently with those of this work. These other experiments examined the affect of an open geometry on the relocation phenomena [10]. The gap width for the LOCA 4 run was narrowed to 2 mm, to observed the melt regime associated with the actual ATR scaling. The coolant drain time was extended to the 2 minutes to establish the conditions of this upper bound.

For the fourth run, labeled LOCA 5, the gap width was kept at 2 mm, the same as in the LOCA 4 run. Since rivulet flow was not readily observed in the LOCA 4 run when the Wood's metal casting was above the water level, the drain time was reduced to approximately 10 seconds to determine if this result is consistent. The rapid draining would expose the entire Wood's metal casting to a liquid-free environment during the relocation process.

The fifth and last loss-of-coolant simulation, LOCA 7, was run with a gap width of 4 mm to determine the affect that this parameter had on the residence time of the slumped Wood's metal in the coolant channel. The drain time was extended to about 1 minute in order to gain further insight as to the dependence of the relocation flow regime on this experimental parameter.

4.1.1 Experimental Run LOCA 1

The heating assembly was initially at 60% power. This was done to raise the Wood's metal temperatures to that of the R-113 saturation point. This corresponds to time zero on the videotape and on the temperature profiles shown in Figure 4-1. During the initial 2 minutes, the Wood's metal temperatures were observed to rise about 2 degrees. During this time, strong nucleate boiling is observed in the coolant channel between the plates. This led to a coolant bulk temperature increase of 4 degrees, from 33 to 37 °C. At 120 seconds the heaters were turned to full power and the pump was actuated at full speed. The secondary drain valve was also opened to assist the pump in emptying the test chamber. This results in a drain rate of about 1.3 mm/s, corresponding to a drain time of approximately 2 minutes. The Wood's metal temperatures are then seen to rise sharply, with melting first occurring near the center region of the casting at approximately 180 seconds. Droplet flow of the liquid Wood's metal then enters the coolant channel.

The boiling of the coolant creates a two-phase mixture which rises about 3 cm above the R-113 liquid level, but is below the point of the observed rivulet flow. As the molten Wood's metal contacts this mixture, it appears to quench and remain suspended in the gap, coalescing to bridge the gap. This occurs at 200 seconds as seen on the videotape. When the two-phase mixture recedes, following the liquid level, the Wood's metal material lodged in the channel appears to remelt and continue its descent. This relocation mechanism is neither rivulet, nor film flow. The partially molten metal simply falls downward, due to gravity. As this is occurring, other sections of the casting are sliding off the aluminum surface, most notably from the top part of the heater assembly. When this happens the temperature readings are seen to increase dramatically, following the aluminum assembly temperature as seen in the temperature profiles below. At 250 seconds the R-113 level is below the heating assembly, and no more two phase mixture is being produced. At this point the lowest sections of the Wood's metal begin to melt. Very strong rivulet flow is observed from the lower region of the assembly at this time, illustrating this type of relocation mechanism. Note the increases in temperatures T7 and T8 at this period in time as the thermocouples become exposed to the aluminum surface. The temperature trace associated with T1, the upper most location, is seen to remain relatively constant at 72 °C. This thermocouple junction is somewhat insulated by the other thermocouple wires that run beneath it, down the length of the aluminum surface. As such, it does not tend to follow the assembly temperature T9, after the Wood's metal relocates. At 300 seconds the power is turned off and the data acquisition is stopped.

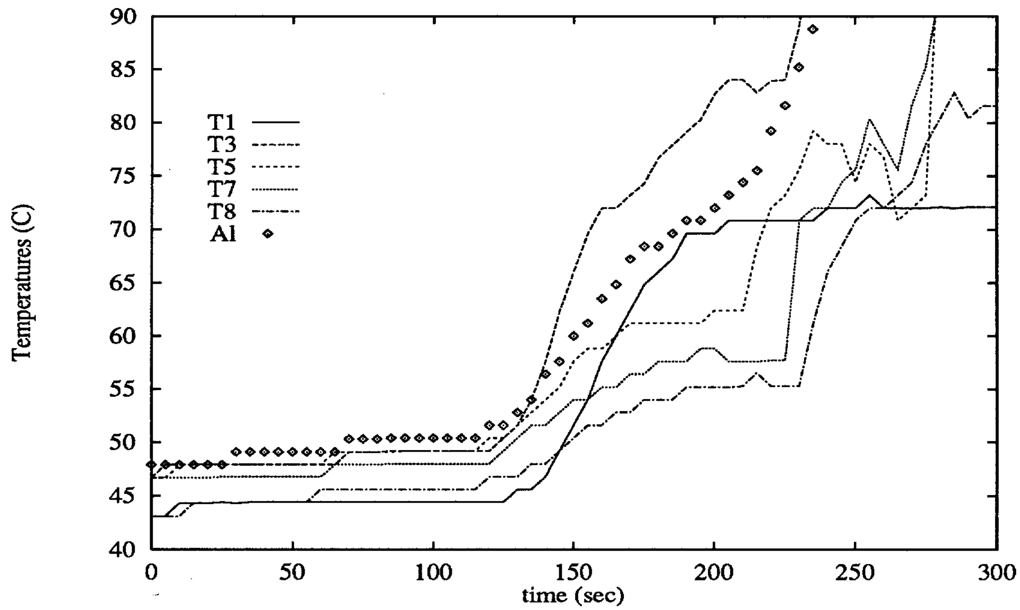

Figure 4-1. Wood's metal temperatures for LOCA 1

4.1.2 Experimental Run LOCA 2

For this test run water was used as the coolant instead of R-113. The gap width between the plates was maintained at 6 mm. Power to the heaters was initially set to 80% until the Wood's metal temperatures reached approximately 65 °C. At this point the data acquisition systems were started. Power was maintained at the initial setting for 90 seconds. Natural convection currents can be seen rising between the plates. During this time the temperatures rise slightly, approaching the 70 °C melting point. The temperatures were allowed to drift to this level because it was desired that the melting proceed as quickly as possible once the coolant channel was voided. At 90 seconds the power was turned to full and the coolant was rapidly drained by pulling out the rubber stopper at the bottom of the test chamber. The chamber was emptied of water in under 10 seconds. This was done to simulate the rapid dryout of the coolant channel expected to occur in the ATR.

Once coolant was removed, the Wood's metal temperatures rose quickly as shown in the temperature profiles of Figure 4-2. Melting is first observed near the center section of the casting at 120 seconds. It appears that the Wood's metal layer adjacent to the aluminum surface melts first, with the molten metal flowing down the outer surface of the casting in rivulet form. The outer layers of the casting seem to remain in a solid form for a short period of time as the heat conduction path from the inner to the outer layers is partially broken. By 140 seconds, large portions of the casting are seen to release from the aluminum surface and slump into the gap between the heater assemblies. These portions appear to be a partially molten mixture of liquid and solid Wood's metal and do not exhibit the same rivulet behavior seen in the initial melting. However, just after these portions slump into the channel, rivulet flow is observed at the same location.

It is very possible that the molten Wood's metal is trapped behind the partially molten outer layer, and once this layer releases from the aluminum surface the trapped liquid can escape in droplet form. As these partially molten portions slump, they become lodged in the gap for only a few seconds before continuing their descent. This is contrasted to the longer residence times observed in the observed in the LOCA 1 experimental run, which were on the order of 30 seconds. One possible explanation for this effect is the absence of R-113 vapor in the test chamber. The residual R-113 vapor present in the LOCA 1 run could have provided sufficient cooling to this slumped mass of Wood's metal, thereby extending the observed residence time. The temperature measurements during this part of the run are seen to be in the range of 75 to 85 °C. This is indicative of the liquid Wood's metal trapped behind the semi-molten outer layers of the casting.

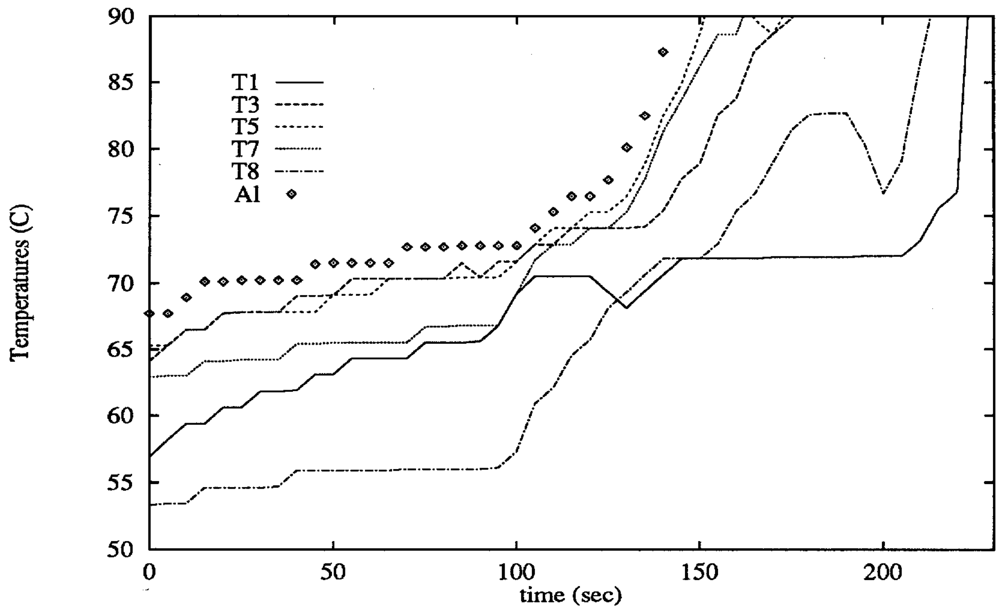

Figure 4-2. Wood's metal temperatures for LOCA 2

4.1.3 Experimental Run LOCA4

This run was performed with the coolant channel gap narrowed to 2 mm, corresponding to the actual dimensions of an ATR fuel assembly. Water was used as the coolant in order to more clearly see the behavior of the melt between the heater assemblies, since bulk boiling of the R-113 obscures the visual path, especially with a 2 mm gap. Initial power to the heaters was set to 80%, allowing the Wood's metal temperatures to reach approximately 70 °C. During this time, air was being pumped into the test chamber to churn the water. This had the effect of maintaining relatively equal temperatures in the axial direction. Without the pumping of air, natural convection currents would cause the water temperature in the upper regions of the test chamber to become larger than in the lower regions. When the Wood's metal temperatures reached 70 °C, the air pumping was stopped. This corresponds to time zero on the videotape and the temperature profiles shown in Figure 4-3.

For the first 90 seconds, the power level was maintained at 80%. Convection currents were again established, and the Wood's metal temperatures begin to rise. At 80 seconds molten metal can be seen dripping slowly from the middle regions of the casting. These droplets solidify into small spheres as they fall through the water. The power to the heaters was increased to 100% at 90 seconds. Also at this time the drain pump was actuated and the secondary dump valve was opened. This corresponds to a drain time of 2 minutes associated with complete heater assembly uncovery. This time scaling was chosen to represent the upper bound of the time required to uncover the ATR core during a LOCA. By 105 seconds, moderate rivulet flow of the molten Wood's metal was observed near the center of the assembly, even though the water level was above this point. At about 140 seconds, the semi-solid Wood's metal sections above the liquid level slumped into the channel. No molten material is observed to drip from these sections once they have slumped into the gap. This material eventually fell through the channel at approximately 205 seconds, resulting in the sharp temperature increases seen in Figure 4-3 at this point in time. Very pronounced rivulet flow is observed at 150 seconds for the lower regions of Wood's metal still covered by water. When this section of the assembly becomes uncovered the rivulet flow ceases and the slumped material remains in the channel, advancing downward slowly. This is indicated by the rather gradual temperature increases of T7 and T8 shown in Figure 4-3, compared to the quite rapid increases depicted for the central locations. It is these center regions which exhibited the strong rivulet flow regimes, leading to faster exposure of the aluminum surface.

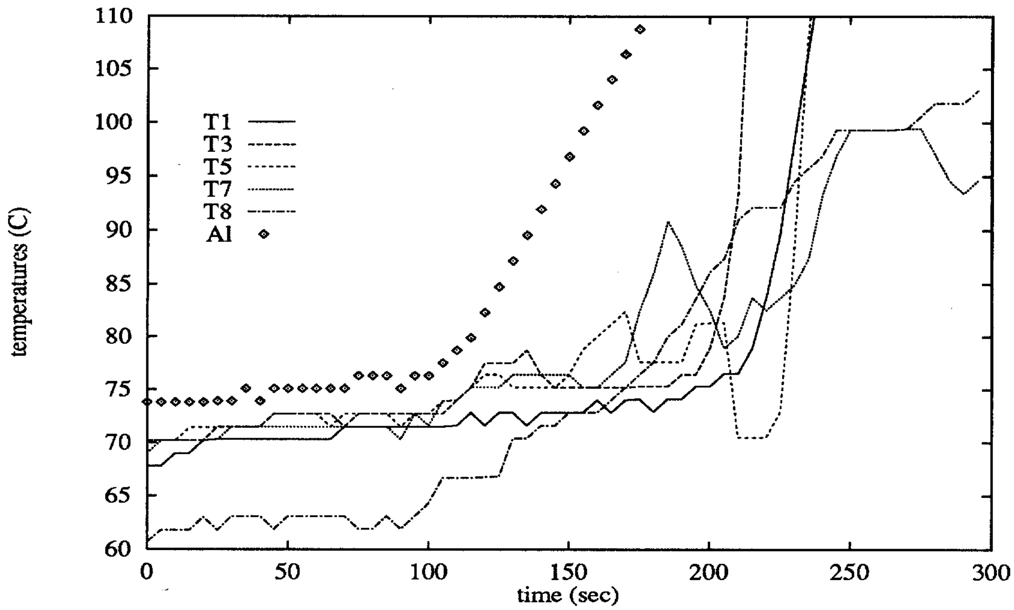

Figure 4-3. Wood's metal temperatures for LOCA 4

4.1.4 Experimental Run LOCA 5

This run is similar to the LOCA 4 experiment in that the gap width was kept at 2 mm and the Wood's metal was slowly heated to just below its melting point. This was done with the heaters at 85% power while pumping air into the test chamber. At time zero, the Wood's metal temperatures were approximately 65 °C and the pumping of air was stopped. As before, natural convection currents were observed in the test chamber and the Wood's metal temperatures drifted slowly towards the melting point. At 2 minutes, full power was applied to the heaters and the coolant was rapidly drained from the test chamber by pulling out the rubber stopper. Immediately after drainage, moderate rivulet flow is observed from the center region of the assembly. However, this does not continue for very long, lasting only 10-15 seconds. At 140 seconds, partially molten Wood's metal slumps into the channel. This particular relocation regime is best described as film, or sheet flow, as it is certainly not rivulet in nature. This type of flow is also observed from the upper regions of the assembly approximately 5 seconds later, corresponding to the sharp increase of the temperature trace T3 shown in Figure 4-4. Most of this material remains lodged in the lower half of the gap, slowly descending towards the bottom of the heater assemblies.

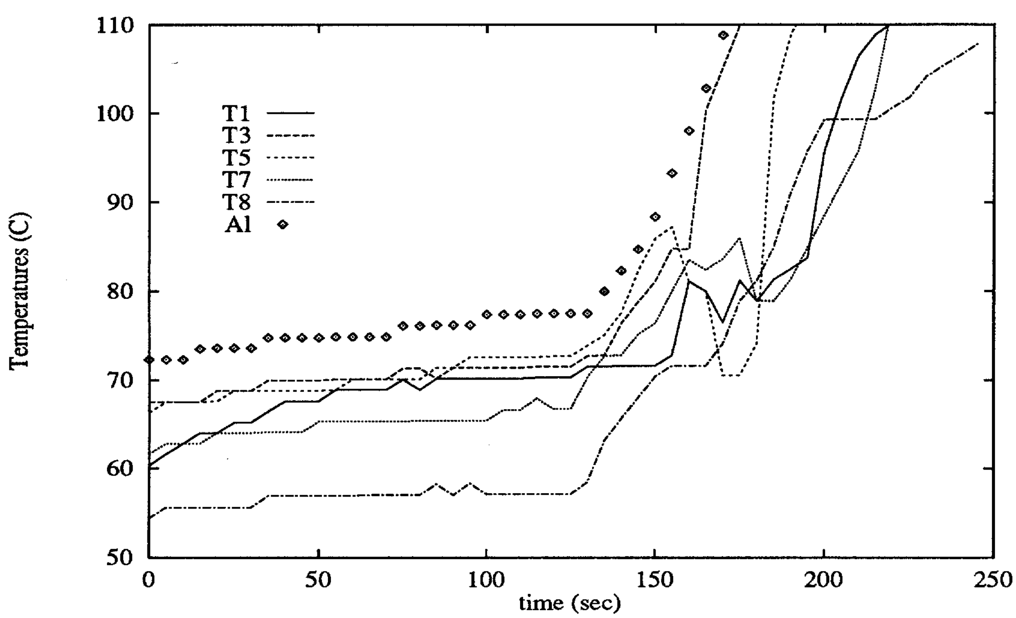

Figure 4-4. Wood's metal temperatures for LOCA 5

From this run it is apparent that heavy rivulet flow is observed primarily when water is present to cover the Wood's metal casting. This is consistent with more effective heat transfer to the liquid coolant, thereby slowing down the temperature increase of the fuel simulant. Rivulet flow is a consequence of this reduced heating. With no liquid available for convective heat transfer, the entire thickness of the Wood's metal casting becomes, at least partially, molten. This leads to the film flow observed during this run.

4.1.5 Experimental Run LOCA 7

This run is similar to the LOCA 4 run in that the drain time was extended beyond the lower limit of 10 seconds to approximately 1 minute. The gap width was expanded to 4 mm from the 2 mm gap width used in LOCA 4. The Wood's metal was initially heated at 50% power, raising the temperatures to approximately 40 °C. This represents time zero on the videotape and on Figure 4-5. At 30 seconds the power level was increased to 100% so that the thermal inertia of the heater assembly would be overcome when the coolant draining began.

At approximately 100 seconds the drain pump was actuated at full speed and the secondary dump valve was opened. Modest rivulet flow was observed from the upper section of the casting surface at approximately 140 seconds. This type of flow regime did not persist long, only about 10 seconds after the coolant level had receded from this region of the Wood's metal casting. The Wood's metal in the center region released from the aluminum surface at approximately 190 seconds and was lodged in the channel. Film flow of the metal was not as apparent as was observed in the LOCA 5 run. This material then began to slide down the gap about 15 seconds later. This residence time is slightly longer than that which was observed in the LOCA 2 run, which was only a few seconds. This suggests that the narrowing of the channel does contribute to observed flow regime. The smaller gap widths may act to impede the progression of the Wood's metal front as it advances down the assembly.

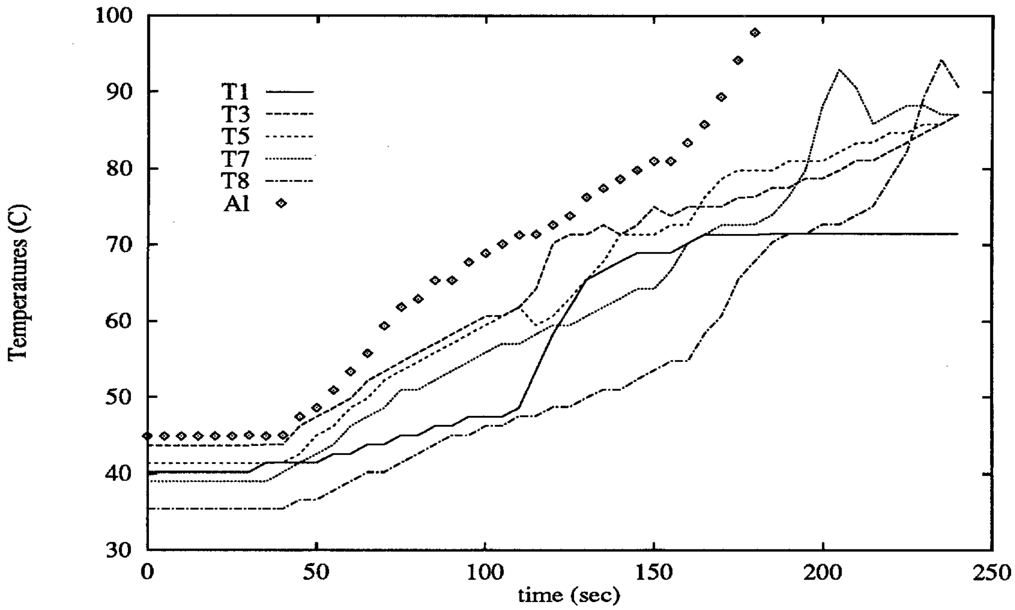

Figure 4-5. Wood's metal temperatures for LOCA 7

4.2 LOFA Simulations

The first of the LOFA simulations tries to preserve as many of the actual ATR scalings as possible. The channel width is set at 2 mm, and a complete assembly uncovery time of approximately 10 minutes is employed. The power to the resistance heaters at the time of relocation is maintained at 80%. This represents the lower value of decay heat experienced in the ATR fuel plates at the predicted time of melting and relocation.

For the second simulation, the gap width is increased to 6 mm and the drain time shortened to about 4 minutes. This is done to determine if these parameters will affect the behavior of the melt as it relocates during the experiment. Some bridging of the coolant channel by the Wood's metal was observed in the first run. This run examines the bridging phenomena subject to this different conditions.

The third LOFA run was also designed to analyze this bridging behavior and help determine the dependence of the relocating Wood's metal on the experimental parameters. The coolant channel width is set to an intermediate value of 4 mm, and the drain time of 7 minutes also represents an intermediate value.

In order to determine if film flow could be produced in the simulations, the power level for the last LOFA run is increased to 100%. The gap width is narrowed to 2 mm, and a 6 minute drain time is used. These parameters were chosen to promote film flow and to retard the bridging behavior observed in the previous experimental runs.

4.2.1 Experimental Run LOFA 1

The first of the loss-of-flow simulations is an attempt at preserving as many of the actual ATR characteristics as possible. The gap width is set to 2 mm in order to represent the dimensions of the ATR coolant channel. The power level to the heaters is initially set to 60%, since the decay heat is much reduced for this type of accident. The computer models described in Chapter 1 predict fuel melting at a time of approximately 29 hours from the point of reactor scram, instead of the 80 seconds given for the loss-of-coolant accident.

At time zero of the videotape and the temperature profiles shown in Figure 4-6, the Wood's metal temperatures are above the saturation point of the R-113 and strong nucleate boiling is observed between the heated plates. The drain pump is started at 60 seconds to speed up the process of uncovering the Wood's metal. The pump controller was set to a value of 4.5, on a scale of 10, which corresponds to a receding R-113 liquid level of approximately 0.2 mm/s. This will uncover the entire heating assembly in about 10 minutes, which is the upper value chosen for this particular experimental parameter. By 150 seconds into the run, the liquid level is about 2.5 inches below the top of the heater assembly and a bubbling region of two-phase coolant is observed to extend above this liquid level all the way to the top of the assembly. This bubbling region provides adequate cooling of the Wood's metal as seen on Figure 4-6. The temperatures of the upper locations do not exceed those of the lower.

By 500 seconds into the experiment, the liquid level is approximately 2.5 inches from the bottom of the heater assembly and the top of the two-phase bubbling region extends upward about 5 inches, nearly covering the entire casting surface. The Wood's metal temperatures of the middle and lower locations are approximately 55 °C at this time. In order to escalate the melting process, the power to the heaters was increased to 80% at 515 seconds. The exposed upper sections of the casting near thermocouples T1 and T3 now begin to heat more rapidly as shown in the temperature profiles. Melting is first observed at about 600 seconds at these locations. The initial relocation mechanism is rivulet in nature. The flow runs down the casting surface until it reaches the top of the two-phase mixture where it appears to quench. As more material relocates, the edge of the Wood's metal front becomes larger and quickly bridges the narrow 2 mm gap. The axial length of the bridged material grows as the Wood's metal front advances with the receding two-phase level.

Melting occurs near the middle section of the assembly at about 660 seconds. As before, this material appears to become lodged in the gap. By approximately 680 seconds, the liquid level reaches the bottom of the assembly, halting further vapor production. This allows the material lodged in the gap to heat up and start sliding down the gap in large chunks, since the R-113 vapor cooling mechanism has ended. Also observable at this time is some rivulet flow emanating from the lower-most sections of the casting. Because there is no coolant in the gap to quench this molten metal, it is free to drip downward.

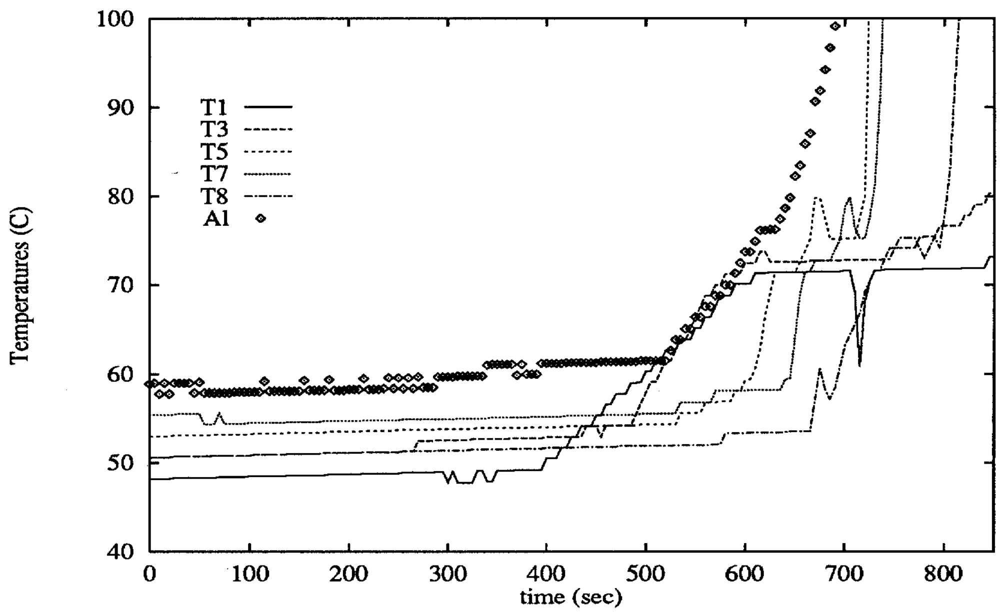

Figure 4-6. Wood's metal temperatures for LOFA 1

The temperatures T5 and T7 are observed to spike at 730 seconds as the Wood's metal slides down the channel, since the thermocouple junctions are very close to the aluminum surface. When the casting falls downward, the thermocouples tend to register the actual temperature of the heater assembly and the temperature traces mimic that of the aluminum block, T9. At 850 seconds the power to the heaters is shut off.

4.2.2 Experimental Run LOFA 3

For this experiment the gap width is set to 6 mm in order to determine if the bridging effect is dependent upon the gap size. The power to the heaters is initially shut off for 30 seconds to establish a baseline reading. At 30 seconds the heaters were turned up to full power. This was done to see if the increase in heat flux would affect the type of relocation flow regime. Nucleate boiling is observed in the channel at approximately 90 seconds, when the Wood's metal temperatures reach the saturation point of the R-113. At 200 seconds the drain pump is started at a speed of 6.0 and the secondary dump valve is opened. This results in a downward velocity of the R-113 coolant of approximately 0.7 mm/s, which corresponds to a drain time of about 4 minutes for exposing the entire heater assembly. This represents the minimum value chosen for this experimental parameter. The Wood's metal temperatures are in the range of 60 °C at this point. The boiling is vigorous, producing a two-phase mixture that extends approximately 3 cm above the R-113 liquid level. For this reason the initial R-113 level was chosen such that about 2.5 inches of the upper Wood's metal surface was left exposed. Since the two-phase mixture provides adequate cooling, the initial R-113 level was reduced to save time.

As the liquid level drops due to the draining, melting of the Wood's metal is first observed on the left-hand plate at approximately 240 seconds, just above the two-phase region of coolant. This initial melting appears to be the same as was observed in the LOFA 1 run. The rivulet flow is quenched by the coolant, resulting in another slowly advancing Wood's metal front. Approximately 30 seconds later the right-hand plate starts to melt, again with rivulet flow as the relocation mechanism. Because of the increased gap size, the bridging effect seen previously in not as evident in this experimental run. During this time, only the upper temperature readings are seen to be at or near the melting temperature (see Figure 4-7).

By 350 seconds the liquid level is about 2.5 inches from the bottom of the assembly, with the two-phase level extending to the center. Most of the channel is blocked with material that has been quenched by the bubbling coolant or R-113 vapor. The mass of material does not appear to advance down the channel as long as vapor production continues. The center and lower temperatures still read below the melting point. By 380 seconds the temperature in the center region, T5, is above 70 °C and molten Wood's metal can be seen dripping from the mass of material still remaining in the channel. Large portions of this mass are then observed to slide down between the plates at about 420 seconds. This corresponds to the time when the coolant has reached the bottom of the heater assembly and no further R-113 boiling occurs. As the Wood's metal mass slides away from the aluminum surface, the thermocouples start to record the assembly temperature. This is illustrated in Figure 4-7. By the end of the run, only a small fraction of the channel near the bottom still contained any Wood's metal.

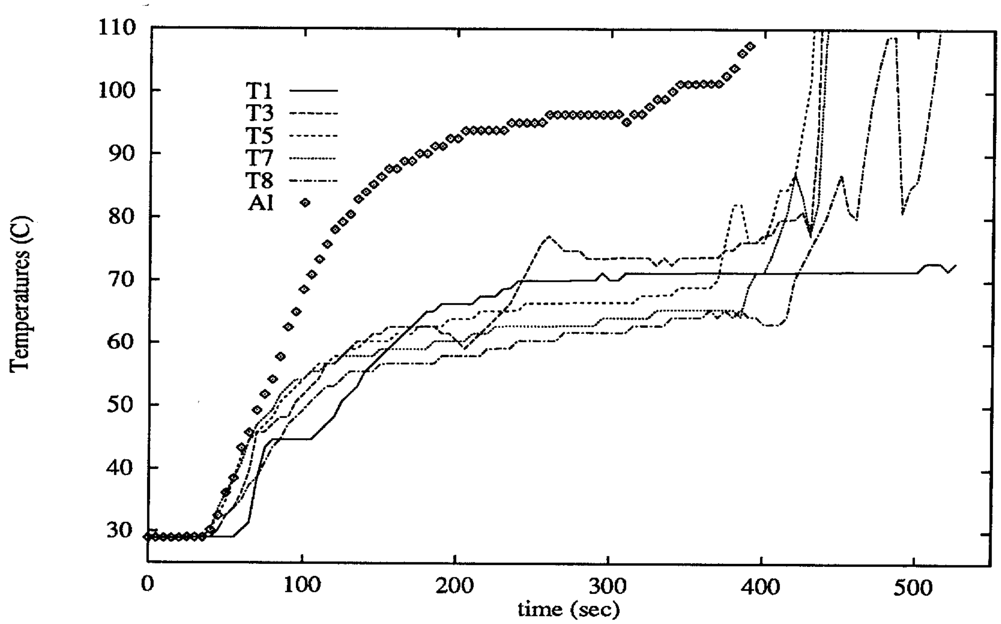

Figure 4-7. Wood's metal temperature for LOFA 3

4.2.3 Experimental Run LOFA 5

This simulation was done with a 4 mm gap width to obtain results for an intermediate choice of this experimental parameter. The bridging behavior observed in the 2 mm run was not as prevalent in the run with the 6 mm gap width. The power to the heaters was set at 30% initially, until the bulk temperature of the R-113 coolant was approximately 10 °C below the saturation point. The initial coolant level is about 1 inch above the halfway point in order to save time. At time zero the power was increased to 80%. By 150 seconds the bubbling mixture caused by strong nucleate boiling reached nearly to the top of the aluminum assembly. At three minutes the run the drain pump was started at a speed of 5. This produced an uncovery time on the order of 7 minutes, comparable to that of the run LOFA 1.

At approximately 400 seconds the liquid level is at the lower third of the assembly, with the bubbling mixture covering the middle third. Melting is observed just above the two-phase region, as was the case for the previous experimental runs. The molten metal again drips down in rivulet form until it contacts the coolant, where it is quenched. Bridging of the channel is again observed as the relocation progresses. This partially molten front noticeably follows the receding level of the bubbling coolant. Not all of the casting above this moving front has melted however, and some of the Wood's metal is still attached to the aluminum surface, especially near the top of the assembly. By about 560 seconds the liquid level had reached the bottom of the heater assembly. Approximately 15 seconds later, large sections of the casting slump into the gap from the upper regions of the block. This relocation mechanism is more film flow than rivulet. This is probably due to the ceased production of R-113 vapor which would otherwise provide some degree of cooling to these sections. The material that was lodged in the center region of the gap then starts to slowly advance down the channel. This behavior continues until the power is turned off at 700 seconds. It appears that the longer draining time used for this run had little effect on the relocation flow regime. Initial rivulet flow followed by a slow advance of the molten front is observed for all the LOFA runs, regardless of drain time. The only qualitative effect observed is the relative speed of the advancing Wood's metal front.

The temperature data for this run was accidentally erased just after the test was completed. Those darn computers...

4.2.4 Experimental Run LOFA 7

In order to determine if film flow could be produced during the loss-of-flow simulations, the power level for the final run was increased to 100% at the time of relocation. The gap width for this run was set to 2 mm to match the conditions of the ATR. The initial coolant level was about halfway up the channel, again for the purpose of saving time during the experiment. The assembly was heated at a power level of 40% until the coolant was just about to its saturation point. This corresponds to time zero on the temperature profiles shown in Figure 4-8 and on the videotape. This power level was maintained for 30 seconds to establish baseline conditions. At the 30 second mark the power was increased to 100% and the drain pump was started at a speed of 5. This would yield an uncovery time of approximately 6 minutes. Since the drain time parameter does not seem to have a dominant effect on the relocation flow regime, an intermediate value was chosen for this run.

By 60 seconds, the two-phase coolant mixture extends to the upper parts of the assembly and the corresponding temperatures are observed to decrease as shown in Figure 4-8. This trend continues until about 100 seconds, when the upper temperatures start to rise because of the descending R-113 liquid level. The temperatures of the central and lower locations continue to gradually increase during this time. By 310 seconds into the run, the upper temperatures have reached the melting point and a partially molten front is observed moving down the coolant channel, similar to all of the preceding LOFA simulations. It is difficult to determine what the initial melt regime actually was due to the narrow gap, but rivulet flow is suspected.

The center regions of the casting start melting at approximately 340 seconds and contribute to the slowly moving Wood's metal mass. Bridging is still observed in the gap, but the residence time is reduced from that of the LOFA 1 run. This is probably due to the higher heat flux at the aluminum surface, and also the choice of a somewhat shorter drain time. The coolant reaches the bottom of the assembly at about 360 seconds. At this time rivulet flow can be seen coming from the lower sections of the casting as vapor production has ceased. Shortly after this is observed, rivulet flow emanates from the upper part of the heater assembly. This flow is relatively strong in nature, but still cannot be described as film flow. It is difficult to imagine experimental conditions that produce film flow, and yet retain an accurate resemblance to the conditions of the ATR during this type of accident. This relocation exposes the thermocouples at this location, with the corresponding jump in temperature illustrated in Figure 4-8. Most of this mass remains lodged in the upper sections of the gap for the duration of the run. The Wood's metal lodged in the lower half of the channel does slowly slide down the gap as this experimental run comes to an end. Power to the heaters was stopped at 415 seconds.

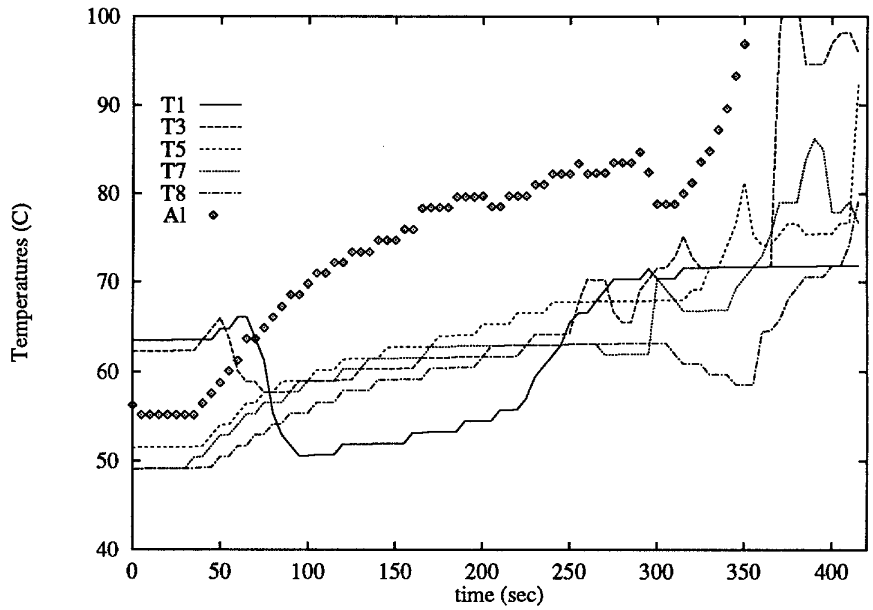

Figure 4-8. Wood's metal temperatures for LOFA 7

Chapter 5: Conclusions and Recommendations

5.1 Limitations of the Experimental Simulation

The experiments described in this work are simulations of the ATR response phenomena expected to occur for two distinct accident scenarios. The main emphasis of the experiments was to provide a visual interpretation of fuel plate melting during these events at the appropriate time scales. In the interest of practicality, many of the physical characteristics of the actual accident scenarios were not strictly adhered to, such as temperature of the fuel and coolant, and the pressure in the ATR vessel. We were somewhat limited in the types of coolant regimes that we could create in the test chamber. Nucleate boiling of the R-113 refrigerant produced a bubbling mixture of liquid and vapor between the heater assemblies that extended a great deal above the R-113 liquid level. This effect was more pronounced at the higher power levels, especially when a narrow gap width was employed. It is not clear that these exact conditions exist in the ATR under the accident scenarios, although it would be qualitatively similar.

In the case of the LOCA, the very high heat flux at the fuel plate surface is predicted to cause rapid dryout of the coolant channel, resulting in void fractions in excess of 0.8 for extended periods of time. I do not believe that the bubbling mixture of R-113 duplicates this situation accurately. Although a two-phase mixture is produced, it appears that the void fraction associated with it is much less than that predicted for the ATR. As an alternative, water was used as the coolant for most of the LOCA simulations. By rapidly emptying the test chamber of water when the Wood's metal temperatures were just below the melting point, we could more realistically simulate the rapid dryout of the ATR coolant channel. However, this may be a bit too drastic, as this technique results in an effective void fraction of 1.0 in the test chamber. Nevertheless, I do believe that these two approaches bound the conditions of interest for the LOCA simulations, and the observed melting flow regime and its evolution remain unchanged over this wide void variation.

The exclusive use of R-113 as the coolant for the LOFA simulations is justifiable since the time scales are one order of magnitude longer. The water coolant in the ATR is at its saturation temperature during the time of fuel melting, and experiences bulk boiling. Also, there is no sudden flashing of coolant associated with rapid pressure drops, as occurs during the LOCA accident. These conditions are met with the choice of R-113.

To minimize the effect on the melting Wood's metal, the thermocouple wires were placed in shallow grooves milled into aluminum surface. The thermocouple junctions were therefore very close to the interface between the heating surface and the Wood's metal. I am confident that the temperature readings are not influenced by the temperature of the aluminum block, as long as the Wood's metal is in the solid phase. All of the temperature profiles show a difference between the casting temperatures and that of the assembly, T9. When the Wood's metal does start to melt, the temperatures are observed to rise. It is possible that some of the Wood's metal in liquid phase is trapped by the outer layers, which could still be partially solid. It is not until the Wood's metal actually falls from the aluminum surface that the temperature traces shoot upward, following the assembly temperature. Thus the temperature profiles are useful for determining when particular sections of the casting release from the heating surface. Interpretations of the temperature profiles are generally irrelevant after this event has occurred.

5.2 Physical Insights Gained

One of the most interesting features observed during the experiments was the quenching behavior of the molten Wood's metal as it contacted the R-113 coolant. This effect was more noticeable in the LOFA simulations, where the molten front could be seen following the receding level of the bubbling mixture. This may in fact be representative of the conditions that exist in the ATR core during the loss-of-flow accidents. Because of the relatively long time from reactor scram to the onset of core melt, the heat flux due to decay heat generation is not as large as in the case of the loss-of-coolant accident. This slowly advancing Wood's metal melt front is observed regardless of the choice for the channel gap width. It is possible that the bubbling action of the R-113 may act to hold up the molten material as it descends down the channel. This would be difficult to prove experimentally however. In the case of the 2 mm gap however, this mass is observed to move more slowly than in the experiments with larger gap widths. This appears to be the result of the partially molten Wood's metal material "bridging" the gap between the plates. This behavior is not as readily observed when the gap width exceeds 2 mm.

When the LOCA simulations are carried out in water, it is observed that the molten Wood's metal does not quench when it contacts the coolant. The rivulet flow continues down the outer face of the casting. This may be more representative of the molten fuel plates in the ATR during this type of accident. Since the internal heat generation due to decay heat is much larger for this accident scenario, the energy carried with the molten fuel plates could be enough to overcome the quenching behavior. In the experiments, when the material becomes separated from the aluminum surface it remains stuck in the channel if it is not completely molten. This is usually the case for the outer layers of the Wood's metal, which separate from the assembly when the inner layers melt and drip down in rivulet form. It is possible that these partially molten sections of Wood's metal may represent the aluminum cladding of the ATR fuel plates. The experiments were designed to model the fuel plates as a homogeneous material and the cladding was not specifically taken into account. It is conceivable that some of the ATR cladding may not melt entirely with the fuel matrix.

The effect of the gap thickness had consequences primarily for the LOFA simulations. With a narrow gap, the two phase mixture was observed to extend far up the channel, well above the liquid level of the R-113. This height was seen to decrease when the gap width was increased. Since the Wood's metal generally did not melt when exposed to this coolant environment, the choice of drain pump speed was not truly independent of the gap width. The choice of a narrow gap width coupled with a quicker drain time was roughly equivalent to a larger gap width with a longer drain time. Once the coolant level was below the bottom of the assembly and no further two phase mixture was being produced, the material lodged in the narrow gap seemed to take longer to slide down the channel. This is not an unexpected result.

For the LOCA simulations, the choice of gap width was not as much of a determining factor in the melt progression. The molten material lodged in the gap was observed to eventually slide down the channel regardless of gap width. The primary benefit of choosing the larger widths was visual. It was much easier to see into the 6 mm gap and determine the actual behavior of the molten Wood's metal. From our observations, it is clear that rivulet flow of the melt is the predominant mechanism for initial fuel relocation. When this type of flow is not observed, it is most probably due to one or more of the experimental limitations or peculiarities outlined previously.

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Appendix A: Equipment Specifications

A.1 Resistance heaters

The heaters used in the experiments were purchased from the Watlow Electric Company. They are listed in the 1990-91 Watlow catalog as MI strip heaters with code number MS1J8AS1. The heaters employ a nickel chrome element wire imbedded in a mineral insulation of high thermal conductivity and dielectric strength. Heat flows from the element wire to the stainless steel outer sheath. The measured resistance of the individual heaters is approximately 28 ohms. The overall dimensions of the heaters are 1.5″ x 8.0″ x 0.156″ with a heated area of one side listed as 1.5″ x 6.8125″ for a total of 10.22 in^2. The heaters are rated at a maximum power output of 500 Watts at the maximum applied voltage of 120 V. Power to the heaters is controlled by a variable transformer with an input AC voltage of 120 V. The output is controlled by a dial which indicates the percent of input voltage. This percentage is the power level referred to in the descriptions of the experimental runs.

A.2 Coolant pump

The pump used to control the coolant level in the test chamber is a Masterflex® model number 7018, manufactured by the Cole-Parmer Instrument Company. The system consists of a 0.1 hp permanent magnet DC motor and a variable speed controller. The revolving pump head contains three rollers which displace the coolant via plastic tubing as shown below.

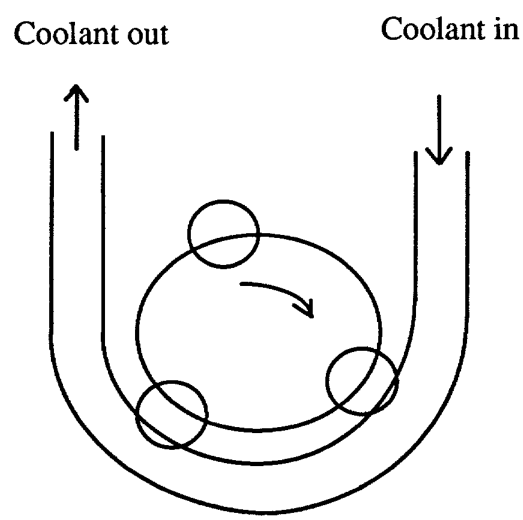

Figure A-1. Schematic of coolant pump head

A.3 Temperature measurement system

Keithley MetraByte's Model 575 Data Acquisition Instrument is a high-speed, high-resolution data acquisition system for analog or digital input and output. The 575 can provide 16-bit measurements at a rate of 50000 samples per second. Expansion slots are provided for specialized measurement requirements. To measure temperatures, an analog input module, or AIM 7 Thermocouple Input Module is employed with the 575 system. The AIM 7 provides 16 channel selection through on-card multiplexing and a fixed gain of 100 volts/volt. On-card cold junction circuitry provides an accurate temperature reference for measurements. All thermocouple inputs are applied to screw terminals located on an isothermal block to minimize errors caused by temperature differences between input connectors and the reference junction sensor. The cold junction reference sensor itself is mounted in the isothermal block to measure accurately the temperature of the block. The accuracy of the temperature measurements is given as ± 0.25 °C.

The AIM 7 is supported by Keithley's KDAC 500/I software package for data acquisition and control. The software runs under Microsoft GW BASIC. A BASIC code written by the user employs various KDAC 500 commands to control the data acquisition process executed by the 575 and AIM 7 hardware.

Appendix B: Data acquisition code

```
10      '
20      '       This program will read temperatures as determined by the AIM 7 module using
30      '       KDAC 500 commands
40      '
50      CLS
60      CALL KDINIT
70      KEY (1) ON
80      ON KEY (1) GOSUB 400
90      OPEN "LOCA1.DAT" FOR OUTPUT AS #1
100     '
110     '       Create BASIC arrays for writing data to the screen and data files
120     '
130     TIME!=0!
140     T1!(0)=0!
150     T2!(0)=0!
160     T3!(0)=0!
170     T4!(0)=0!
180     T5!(0)=0!
190     T6!(0)=0!
200     T7!(0)=0!
210     T8!(0)=0!
220     T9!(0)=0!
230     T10!(0)=0!
240     '
250     '       Instruct the AIM 7 module to take the temperature measurements
260     '
270     CALL FGREAD'("TMP1"."NONE",T1!(),"C.THCU.K","NT")
280     CALL FGREAD'("TMP2"."NONE",T2!(),"C.THCU.K","NT")
290     CALL FGREAD'("TMP3"."NONE",T3!(),"C.THCU.K","NT")
300     CALL FGREAD'("TMP4"."NONE",T4!(),"C.THCU.K","NT")
310     CALL FGREAD'("TMP5"."NONE",T5!(),"C.THCU.K","NT")
320     CALL FGREAD'("TMP6"."NONE",T6!(),"C.THCU.K","NT")
330     CALL FGREAD'("TMP7"."NONE",T7!(),"C.THCU.K","NT")
340     CALL FGREAD'("TMP8"."NONE",T8!(),"C.THCU.K","NT")
350     CALL FGREAD'("TMP9"."NONE",T9!(),"C.THCU.K","NT")
360     CALL FGREAD'("TMP10"."NONE",T10!(),"C.THCU.K","NT")
370     '
380     '       Print the time-dependent temperatures to the screen and the data file
390     '
400     PRINT USING "###.# "; TIME, T1!(0), T2!(0), T3!(0), T4!(0), T5!(0), T6!(0), T7!(0), T8!(0),
        T9!(0), T10!(0)
410     '
420     PRINT #1,USING"###.# "; TIME, T1!(0), T2!(0), T3!(0), T4!(0), T5!(0), T6!(0), T7!(0), T8!(0),
        T9!(0), T10!(0)
430     '
```

```
440    '        Increment the time counter by five seconds
450    TIME=TIME + 5!
460    '
470    '        Pause the program before looping back to take the next readings
480    '
490    CALL KPAUSE'(3,"SEC")
500    '
510    '        Read the temperatures at the next time step
520    '
530    GOTO 140
540    '
550    '        Close the data file and exit the program when the experiment is completed
560    '
570    CLOSE #1
580    END
```

Appendix C: Determination of Natural Convection Heat Transfer Coefficient

Experiments with thin, heated vertical plates of characteristic length L suspended in air have been correlated, with the result given as [9]

$$Nu = 0.59 Ra^{1/4} \qquad 10^4 < Ra < 10^9 \tag{C-1}$$

The Rayleigh number is

$$Ra = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{C-2}$$

For air at 300 K

$$\begin{array}{ll} \beta = 0.0033 & K^{-1} \\ \nu = 15.9 \text{ x } 10^{-6} & m^2/s \\ \alpha = 22.5 \text{ x } 10^{-6} & m^2/s \\ k = 0.026 & W/m\text{-}K \end{array}$$

For an average Wood's metal temperature of 325 K and a characteristic length of the heater assembly of 20 cm, Eq. C-2 gives the Rayleigh number as $1.83 \text{ x } 10^7$. The Nusselt number then obtained from Eq. C-1 is 38.6

The natural convection heat transfer coefficient as obtained from the Nusselt number is

$$h = \frac{Nu\, k}{L} \tag{C-3}$$

Using the stated value for the characteristic length, the heat transfer coefficient is calculated to be 5.0 W/m-K.

Appendix D: Wood's metal temperature data files

Temperature data from `heatflx1.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6
5.0	24.7	24.7	24.7	24.7	24.7	24.7	24.7	24.7	24.7	24.7
10.0	24.7	25.9	25.9	25.9	25.9	25.9	25.9	24.7	25.9	24.7
15.0	24.7	25.9	27.1	27.1	25.9	25.9	25.9	25.9	25.9	24.7
20.0	25.9	27.1	28.3	28.3	28.3	28.3	28.3	25.9	28.3	24.7
25.0	25.9	28.3	29.4	29.4	29.4	28.3	29.4	27.1	29.4	24.7
30.0	25.9	30.6	30.6	30.6	30.6	30.6	30.6	28.3	30.6	24.7
35.0	27.1	31.8	31.8	33.0	33.0	31.8	31.9	29.4	31.8	24.7
40.0	28.3	33.0	33.0	34.3	34.3	33.0	33.1	29.4	34.2	24.7
45.0	28.3	34.3	35.5	35.5	36.7	34.3	35.5	30.7	36.7	24.7
50.0	29.5	36.7	36.7	37.8	37.8	36.7	36.7	33.1	37.8	24.7
55.0	30.7	37.8	37.8	39.0	40.2	37.8	37.8	33.1	40.2	24.7
60.0	31.9	39.0	40.2	41.4	41.4	39.0	40.2	34.3	41.4	24.7
65.0	33.1	40.2	41.4	42.6	43.8	41.4	41.4	35.5	42.6	24.7
70.0	34.3	42.6	42.6	45.0	45.0	42.6	42.6	37.8	45.0	24.7
75.0	35.5	43.8	43.8	46.2	47.4	45.0	45.0	39.1	46.2	24.7
80.0	36.7	45.1	45.0	47.4	48.6	46.3	46.3	40.3	48.6	24.8
85.0	37.9	46.3	47.4	49.8	49.8	47.4	47.4	41.5	49.8	24.8
90.0	39.1	48.6	48.6	51.0	52.2	48.6	49.8	42.7	51.0	24.8
95.0	39.1	49.8	49.8	52.2	53.4	49.8	51.0	43.9	53.4	24.8
100.0	40.3	51.0	51.0	54.6	54.6	52.2	52.2	45.1	54.6	24.8
105.0	42.7	52.2	52.2	55.8	57.0	53.4	53.4	46.3	55.8	24.8
110.0	42.7	53.4	53.4	57.0	58.2	54.6	55.8	47.4	57.0	24.8
115.0	43.9	54.6	55.9	58.2	59.4	57.1	57.0	48.6	59.4	24.8
120.0	45.1	55.9	57.1	60.6	60.6	57.1	58.2	49.9	60.6	24.8
125.0	46.3	58.2	58.2	61.8	61.8	59.4	59.4	52.3	61.8	24.8
130.0	47.5	59.4	59.4	63.0	64.2	60.6	60.6	53.5	63.0	24.8
135.0	48.7	60.6	60.6	64.2	65.4	61.8	63.0	54.7	64.2	24.8
140.0	49.9	61.8	61.8	65.4	66.6	63.0	63.0	55.9	65.4	24.8
145.0	51.1	63.0	63.0	66.6	67.8	64.2	64.2	57.1	66.6	24.8
150.0	52.3	64.3	64.3	67.9	69.1	65.5	66.7	58.3	69.1	24.8

Temperature data from `heatflx2.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	24.3
5.0	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	24.3
10.0	25.5	26.7	26.7	26.7	26.7	26.7	26.7	25.5	26.7	24.3
15.0	25.5	27.9	29.1	27.9	27.9	27.9	29.1	26.7	27.9	24.3
20.0	26.7	30.3	30.3	30.3	31.5	30.3	30.3	27.9	30.3	24.3
25.0	27.9	32.7	33.9	33.9	33.9	32.7	32.7	29.1	33.9	24.3
30.0	28.0	35.1	36.3	36.3	36.3	35.1	36.3	31.5	36.3	24.3
35.0	29.1	37.5	38.7	38.7	39.9	37.5	38.7	32.7	39.9	24.4
40.0	31.5	39.9	41.1	42.3	42.3	39.9	41.1	35.1	42.3	24.4
45.0	32.7	42.3	43.5	44.7	45.8	43.5	44.7	36.3	45.8	24.4
50.0	33.9	45.8	45.9	48.3	49.4	45.9	47.0	38.7	48.3	24.4
55.0	36.3	48.3	49.5	51.9	53.1	48.3	49.5	41.1	51.9	24.4
60.0	37.5	50.7	51.9	54.3	55.5	51.9	53.1	43.5	55.5	24.4
65.0	39.9	53.1	54.3	57.8	59.0	54.3	55.5	44.7	57.8	24.4
70.0	41.1	55.5	56.6	60.2	61.4	56.6	57.8	47.1	61.4	24.4
75.0	43.6	57.9	59.1	63.9	63.9	59.1	60.3	49.5	63.9	24.4
80.0	44.8	61.5	61.5	66.3	67.5	62.7	63.9	51.9	66.3	24.5
85.0	47.1	63.9	63.9	68.7	69.8	65.1	66.3	54.3	69.8	24.5

Temperature data from `heatflx3.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	24.3
5.0	25.5	25.5	26.6	26.6	26.6	25.5	26.6	25.5	25.5	25.5
10.0	25.5	27.8	27.8	27.8	27.8	27.8	27.8	26.6	27.8	25.5
15.0	26.6	30.2	30.2	31.4	30.2	30.2	30.2	27.8	30.2	24.3
20.0	27.8	32.6	33.8	33.8	33.8	32.6	33.8	30.2	33.8	24.3
25.0	30.2	35.0	37.4	37.4	37.4	36.2	37.4	31.4	37.4	25.5
30.0	31.5	38.6	39.8	41.0	41.0	39.8	39.8	33.8	41.0	25.5
35.0	33.8	42.2	43.4	44.6	44.6	43.4	43.4	36.2	45.8	25.5
40.0	36.2	45.8	47.0	49.4	48.2	47.0	47.0	38.6	49.4	25.5
45.0	38.6	49.4	50.6	52.9	52.9	49.4	50.6	42.2	54.1	25.5
50.0	41.0	51.8	54.1	56.5	56.5	54.1	55.3	44.6	57.7	25.5
55.0	43.4	55.3	56.5	60.1	60.1	57.7	58.9	47.0	61.3	25.5
60.0	45.8	58.9	60.1	64.9	64.9	61.3	61.3	50.6	66.1	25.5
65.0	48.2	62.5	63.7	68.5	68.5	64.9	64.9	52.9	69.7	24.3
70.0	50.6	64.9	66.1	70.9	70.9	68.5	69.7	55.3	73.3	24.3

Temperature data from `heatflx4.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	25.2	25.2	25.2	24.0	25.2	25.2	25.2	25.2	25.2	25.2
5.0	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2	25.2
10.0	25.2	27.6	27.6	27.6	27.6	26.4	27.6	26.4	27.6	25.2
15.0	26.4	30.0	31.2	30.0	30.0	30.0	31.2	27.6	30.0	25.2
20.0	27.6	33.6	34.8	34.8	34.8	33.6	34.8	30.0	34.8	25.2
25.0	28.8	37.2	38.4	38.4	38.4	37.2	38.4	32.4	38.4	25.2
30.0	31.2	40.7	43.1	43.1	44.3	40.7	43.2	34.8	43.1	25.3
35.0	33.6	45.6	46.8	48.0	49.1	45.6	46.8	38.4	49.1	25.3
40.0	36.0	49.1	51.5	52.7	53.9	50.3	51.5	40.8	53.9	25.3
45.0	38.4	53.9	55.1	57.5	59.9	55.1	56.3	44.4	59.9	25.3
50.0	42.0	57.5	59.9	63.5	64.7	59.9	61.1	48.0	64.7	25.3
55.0	44.4	62.3	63.5	68.3	69.5	63.5	65.9	51.5	69.5	25.3
60.0	48.0	67.1	67.1	70.7	70.7	68.3	70.7	55.1	74.3	24.1

Temperature data from `LOCA1.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	43.1	46.7	46.7	46.7	46.7	46.7	46.7	43.1	47.9	33.6
5.0	43.1	46.7	47.9	46.7	46.7	46.7	46.7	43.1	47.9	33.6
10.0	44.3	46.7	47.9	46.7	47.9	46.7	46.7	43.1	47.9	33.6
15.0	44.3	46.7	47.9	46.7	47.9	46.7	46.7	44.3	47.9	33.6
20.0	44.3	46.7	47.9	46.7	47.9	46.7	46.7	44.3	47.9	34.8
25.0	44.4	46.8	47.9	46.8	47.9	47.9	46.8	44.4	47.9	34.8
30.0	44.3	47.9	47.9	46.7	47.9	47.9	46.8	44.3	49.1	34.8
35.0	44.4	47.9	47.9	46.8	47.9	47.9	46.8	44.4	49.1	34.8
40.0	44.4	47.9	47.9	47.9	47.9	47.9	46.8	44.4	49.1	34.8
45.0	44.4	47.9	47.9	47.9	47.9	47.9	46.8	44.4	49.1	34.8
50.0	44.4	47.9	47.9	47.9	47.9	47.9	46.8	44.4	49.1	34.8
55.0	44.4	47.9	47.9	47.9	47.9	47.9	46.8	44.4	49.1	34.8
60.0	44.4	47.9	47.9	47.9	47.9	47.9	46.8	45.6	49.1	36.0
65.0	44.4	47.9	47.9	47.9	49.1	47.9	47.9	45.6	49.1	36.0
70.0	44.4	47.9	49.1	47.9	49.1	47.9	47.9	45.6	50.3	36.0
75.0	44.4	47.9	49.1	47.9	49.1	47.9	47.9	45.6	50.3	36.0
80.0	44.4	47.9	49.1	47.9	49.1	49.1	47.9	45.6	50.3	36.0
85.0	44.4	47.9	49.2	49.2	49.1	49.2	48.0	45.6	50.4	36.1
90.0	44.4	48.0	49.2	48.0	49.2	49.2	48.0	45.6	50.4	36.1
95.0	44.4	48.0	49.2	49.2	49.2	49.2	48.0	45.6	50.4	36.1
100.0	44.4	48.0	49.2	49.2	49.2	49.2	48.0	45.6	50.4	37.3
105.0	44.4	49.2	49.2	49.2	49.2	49.2	48.0	45.6	50.4	37.3
110.0	44.4	49.2	49.2	49.2	49.2	49.2	48.0	45.6	50.4	37.3
115.0	44.4	49.2	49.2	49.2	49.2	49.2	48.0	45.6	50.4	37.3
120.0	44.4	49.2	49.2	49.2	50.4	49.2	48.0	46.8	51.6	37.3
125.0	44.4	49.2	50.4	50.4	50.4	50.4	49.2	46.8	51.6	38.4
130.0	45.6	50.4	51.6	51.6	51.6	51.6	50.4	46.8	52.8	38.4
135.0	45.6	52.8	54.0	51.6	52.8	52.8	51.6	48.0	54.0	38.4
140.0	46.8	57.6	57.6	52.8	54.0	52.8	51.6	48.0	56.4	38.4
145.0	49.2	61.1	62.3	54.0	55.2	54.0	52.8	49.2	57.6	39.6
150.0	51.6	64.7	66.0	55.2	57.6	55.2	54.0	50.4	60.0	39.7
155.0	54.0	68.4	69.6	56.4	58.8	55.2	54.0	51.6	61.2	40.9
160.0	57.6	70.8	72.0	57.6	58.8	56.4	55.2	51.6	63.5	39.7
165.0	60.0	72.0	72.0	58.8	60.0	57.6	55.2	52.8	64.8	39.7
170.0	62.4	72.0	73.2	60.0	61.2	57.6	56.4	52.8	67.2	39.7
175.0	64.8	72.0	74.3	60.0	61.2	58.8	56.4	54.0	68.4	39.7
180.0	66.0	72.0	76.7	60.0	61.2	58.8	57.6	54.0	68.4	40.9
185.0	67.2	74.3	77.9	60.0	61.2	58.8	57.6	54.0	69.6	42.1
190.0	69.6	81.5	79.1	60.0	61.2	60.0	57.6	55.2	70.8	43.3
195.0	69.6	82.7	80.3	60.0	61.2	60.0	58.8	55.2	70.8	43.3
200.0	69.6	82.8	82.7	61.2	62.4	60.0	58.8	55.2	72.0	43.3
205.0	70.8	79.2	84.0	61.2	62.4	60.0	57.6	55.2	73.2	44.5
210.0	70.8	79.2	84.0	62.4	62.4	60.0	57.6	55.3	74.4	44.5
215.0	70.8	78.0	82.8	69.6	68.4	60.0	57.6	56.5	75.5	44.5
220.0	70.8	78.0	83.9	70.8	72.0	60.0	57.7	55.3	79.2	44.5
225.0	70.8	78.0	84.0	72.0	73.2	61.2	57.7	55.3	81.6	44.5
230.0	70.8	80.4	88.8	74.4	75.6	72.0	70.8	55.3	85.2	44.5
235.0	70.8	79.2	97.2	81.6	79.2	72.0	72.0	61.2	88.8	43.3

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
240.0	72.0	80.4	100.8	81.6	78.0	73.2	72.0	66.0	93.6	42.1
245.0	72.0	81.6	103.2	81.6	78.0	74.4	74.4	68.4	98.4	40.9
250.0	72.0	85.2	108.0	84.0	74.4	76.8	75.6	70.8	104.4	35.0
255.0	73.2	87.6	111.6	84.0	78.0	85.2	80.4	72.0	109.2	36.2
260.0	72.0	91.2	115.2	82.8	76.8	82.8	78.0	72.0	114.0	35.0
265.0	72.0	93.6	117.6	81.6	70.8	79.2	75.6	73.2	118.8	36.2
270.0	72.0	90.0	121.2	80.4	72.0	81.6	81.6	74.4	123.6	37.4
275.0	72.0	85.2	126.0	78.0	73.2	82.8	85.2	78.0	128.5	38.5
280.0	72.1	84.0	129.7	78.0	98.4	84.0	92.4	80.4	132.1	38.6
285.0	72.0	81.6	132.0	80.4	106.8	96.0	99.6	82.8	136.8	38.5
290.0	72.1	81.6	135.7	85.2	110.4	100.8	102.0	80.4	140.4	38.5
295.0	72.1	81.6	138.1	87.6	115.2	104.4	106.8	81.6	144.1	38.6
300.0	72.1	82.8	140.5	90.0	118.8	106.8	109.2	81.6	147.7	38.6

Temperature data from `LOCA2.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	56.9	61.7	64.1	62.9	65.3	59.3	62.9	53.3	67.7	42.6
5.0	58.2	63.0	65.3	64.1	65.3	60.6	63.0	53.4	67.7	42.6
10.0	59.4	64.1	66.5	64.1	66.5	60.6	63.0	53.4	68.9	42.6
15.0	59.4	64.1	66.5	65.3	66.5	60.6	64.1	54.6	70.1	42.6
20.0	60.6	65.3	67.7	65.3	67.7	60.6	64.1	54.6	70.1	42.6
25.0	60.6	65.4	67.8	65.4	67.8	61.8	64.2	54.6	70.2	42.7
30.0	61.8	65.4	67.8	65.4	67.8	61.8	64.2	54.6	70.2	42.7
35.0	61.8	65.4	67.8	66.6	67.8	61.9	64.2	54.7	70.2	42.7
40.0	61.9	65.4	69.0	66.6	67.8	63.1	65.4	55.9	70.2	41.5
45.0	63.1	66.6	69.0	66.6	67.8	63.1	65.4	55.9	71.4	41.5
50.0	63.1	66.7	69.1	67.9	69.1	63.1	65.5	55.9	71.5	41.6
55.0	64.3	66.7	70.3	67.9	69.1	63.1	65.5	55.9	71.5	41.6
60.0	64.3	66.7	70.3	67.9	69.1	63.1	65.5	55.9	71.5	42.8
65.0	64.3	66.7	70.3	67.9	70.3	63.1	65.5	55.9	71.5	42.8
70.0	64.3	67.9	70.3	67.9	70.3	63.1	65.5	56.0	72.7	42.8
75.0	65.5	67.9	70.3	67.9	70.3	64.3	66.7	56.0	72.7	42.8
80.0	65.5	67.9	70.3	69.1	70.3	64.3	66.7	56.0	72.7	42.8
85.0	65.5	69.1	71.5	69.2	70.4	64.4	66.8	56.0	72.8	42.8
90.0	65.6	69.2	70.4	69.2	70.4	64.4	66.8	56.0	72.8	42.9
95.0	66.8	68.0	71.6	69.2	70.4	64.4	66.8	56.1	72.8	42.9
100.0	69.2	70.4	71.6	70.4	71.6	68.0	69.2	57.3	72.8	50.1
105.0	70.5	71.7	72.9	71.6	72.9	70.5	71.7	60.9	74.1	29.9
110.0	70.5	71.7	72.9	71.7	74.1	71.7	72.9	62.1	75.3	31.1
115.0	70.5	71.7	74.1	71.7	74.1	71.7	72.9	64.5	76.5	31.1
120.0	70.5	71.7	74.1	72.9	75.3	71.7	74.1	65.7	76.5	29.9
125.0	69.3	71.7	74.1	72.9	75.3	71.7	74.1	68.1	77.7	29.9
130.0	68.1	72.9	74.1	74.1	76.5	72.9	75.3	69.3	80.1	29.9
135.0	69.4	74.2	74.2	77.8	78.9	74.2	77.8	70.6	82.5	28.8
140.0	70.6	75.4	75.4	81.3	82.5	77.8	81.3	71.8	87.3	28.8
145.0	71.8	76.6	77.8	80.1	84.9	80.1	83.7	71.8	93.3	30.0
150.0	71.8	77.8	78.9	81.3	88.6	77.8	86.2	71.8	98.2	30.0
155.0	71.8	79.0	82.6	83.8	93.4	81.4	88.6	73.0	104.2	31.2
160.0	71.8	79.0	83.8	83.8	93.4	88.6	88.6	75.4	110.2	32.4
165.0	71.8	77.8	87.4	83.8	89.8	91.0	92.2	76.7	115.0	32.4
170.0	71.9	76.7	88.6	86.2	88.6	91.0	98.2	79.0	119.8	33.6
175.0	71.9	75.5	89.8	88.6	91.0	92.2	100.6	81.4	124.7	33.6
180.0	71.9	75.5	91.0	91.0	92.2	95.8	103.0	82.6	129.5	34.8
185.0	71.9	75.5	91.1	93.5	93.5	99.5	104.3	82.7	131.9	34.9
190.0	71.9	76.7	99.5	94.7	95.9	103.1	106.7	82.7	136.7	36.1
195.0	72.0	76.7	113.9	98.3	100.7	106.7	109.1	80.3	140.4	36.1
200.0	72.0	77.9	126.0	100.7	123.5	110.3	112.7	76.7	142.8	36.1
205.0	72.0	79.1	129.6	103.1	126.0	115.1	115.1	79.1	146.4	36.1
210.0	73.2	82.7	133.2	106.7	128.4	118.7	122.3	86.3	148.8	36.1
215.0	75.6	104.4	132.0	99.6	128.4	123.5	129.6	92.4	152.5	36.2
220.0	76.8	118.8	136.8	103.2	133.2	126.0	133.2	96.0	154.9	37.4
225.0	98.4	127.2	132.0	108.0	134.4	128.4	136.8	99.6	158.5	37.4
230.0	108.0	129.6	132.0	118.8	139.3	130.9	136.9	102.0	159.8	37.4

Temperature data from `LOCA4.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	67.8	69.0	70.2	69.0	70.2	66.6	69.0	60.7	73.8	41.5
5.0	67.8	70.2	70.2	69.0	70.2	66.6	70.2	61.8	73.8	41.5
10.0	69.0	70.2	70.2	69.0	70.2	66.6	70.2	61.8	73.8	41.5
15.0	69.0	70.2	70.2	70.2	71.4	67.8	70.2	61.8	73.8	41.5
20.0	70.2	70.2	70.2	70.2	71.4	67.9	70.2	63.0	73.8	41.6
25.0	70.3	70.3	71.5	70.3	71.4	67.8	70.3	61.8	73.9	41.5
30.0	70.3	70.3	71.5	70.3	71.5	67.9	71.5	63.1	73.9	41.6
35.0	70.3	70.3	71.5	70.3	71.5	67.9	71.5	63.1	75.1	41.6
40.0	70.3	70.3	71.5	70.3	71.5	67.9	71.5	63.1	73.9	41.6
45.0	70.3	71.5	72.7	70.3	72.7	67.9	71.5	61.9	75.1	41.6
50.0	70.3	71.5	72.7	70.3	72.7	67.9	71.5	63.1	75.1	41.6
55.0	70.3	71.5	72.7	70.3	72.7	67.9	71.5	63.1	75.1	41.6
60.0	70.3	71.5	72.7	70.3	72.7	67.9	71.5	63.1	75.1	41.6
65.0	70.3	71.5	72.7	71.5	71.5	69.1	71.5	63.1	75.1	42.8
70.0	71.5	71.5	71.5	71.5	72.7	69.1	71.5	63.1	75.1	42.8
75.0	71.5	71.5	72.7	70.3	72.7	67.9	71.5	61.9	76.3	41.6
80.0	71.5	71.5	72.7	70.3	72.7	67.9	71.5	61.9	76.3	41.6
85.0	71.5	72.7	72.7	70.3	72.7	67.9	71.5	63.1	76.3	41.6
90.0	71.5	72.7	72.7	71.5	71.5	67.9	70.3	61.9	75.1	42.8
95.0	71.5	72.7	72.7	71.5	72.7	69.1	72.7	63.1	76.3	42.8
100.0	71.5	71.5	72.7	72.7	72.7	70.3	71.6	64.3	76.3	42.8
105.0	71.5	72.8	72.7	72.7	73.9	71.5	73.9	66.7	77.5	42.8
110.0	71.6	72.8	74.0	72.8	74.0	71.6	74.0	66.7	78.7	42.9
115.0	72.8	71.6	75.2	72.8	75.2	72.8	75.2	66.7	79.9	44.1
120.0	71.6	72.8	77.5	74.0	76.4	71.6	75.2	66.8	82.3	44.1
125.0	72.8	72.8	77.5	72.8	76.4	72.8	75.2	66.8	84.7	44.1
130.0	72.8	72.8	77.5	74.0	75.2	74.0	76.4	70.4	87.1	44.1
135.0	71.6	74.0	78.7	74.0	75.2	74.0	76.4	70.4	89.5	45.3
140.0	72.8	75.2	76.4	75.2	75.2	74.0	76.4	71.6	91.9	45.3
145.0	72.8	75.2	75.2	75.2	75.2	75.2	76.4	71.6	94.3	46.5
150.0	72.8	76.4	75.2	76.4	76.4	76.4	76.4	72.8	96.8	48.9
155.0	72.8	76.4	75.2	76.4	78.8	74.0	75.2	72.8	99.2	50.1
160.0	74.0	77.6	75.2	77.6	80.0	74.0	75.2	72.8	101.6	52.5
165.0	72.8	78.8	75.2	78.8	81.2	76.4	76.4	74.0	104.0	54.9
170.0	74.0	78.8	75.2	80.0	82.4	76.4	77.6	75.2	106.4	54.9
175.0	74.1	80.0	75.3	81.2	77.6	77.6	82.4	76.4	108.8	43.0
180.0	72.9	82.4	75.3	82.4	77.6	81.2	86.0	77.6	112.4	38.2
185.0	74.1	83.6	75.3	83.6	77.6	84.8	90.8	80.0	114.8	37.0
190.0	74.1	84.8	76.4	83.6	77.6	86.0	88.4	81.2	118.4	37.0
195.0	75.3	86.0	76.4	86.0	81.2	88.5	84.8	83.6	119.6	37.0
200.0	75.3	88.5	78.9	88.5	81.3	89.6	82.5	86.1	123.3	37.1
205.0	76.5	89.7	83.7	89.7	81.3	89.7	78.9	87.3	125.7	38.3
210.0	76.5	105.3	93.3	76.5	70.5	86.1	80.1	90.9	128.1	38.3
215.0	78.9	124.5	118.5	92.1	70.5	89.7	83.7	92.1	130.5	39.4
220.0	83.7	130.5	126.9	96.9	70.5	92.1	82.5	92.1	132.9	39.4
225.0	89.7	134.1	130.5	101.7	72.9	95.7	83.7	92.1	136.5	39.4
230.0	98.1	137.7	133.0	124.5	88.5	94.5	84.9	94.5	138.9	40.6
235.0	106.5	140.1	135.3	128.2	107.7	96.9	87.3	95.7	142.6	41.8

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
240.0	114.9	143.8	139.0	136.6	120.9	99.3	93.3	96.9	145.0	43.1
245.0	119.7	146.2	141.4	143.8	129.4	100.5	96.9	99.3	147.4	41.9
250.0	124.5	149.8	143.8	147.4	135.4	101.7	99.3	99.3	151.0	43.1
255.0	128.2	152.2	147.4	149.8	140.2	116.1	99.3	99.3	153.4	44.3
260.0	133.0	154.6	151.0	153.4	145.0	119.7	99.3	99.3	157.1	45.5
265.0	137.8	157.1	154.6	155.9	148.6	122.1	99.3	99.3	159.5	47.9
270.0	141.4	159.5	157.1	159.5	152.3	123.4	99.4	99.4	161.9	49.1
275.0	145.1	163.1	160.7	161.9	155.9	125.8	99.4	100.6	165.5	47.9
280.0	148.7	165.5	163.1	165.5	159.5	128.2	97.0	101.8	168.0	50.3
285.0	151.1	168.0	166.8	168.0	163.1	129.4	94.6	101.8	171.6	51.5
290.0	154.7	170.4	169.2	172.8	165.5	133.0	93.4	101.8	171.6	52.7
295.0	158.3	172.8	171.6	175.2	168.0	135.4	94.6	103.0	172.8	51.5

Temperature data from LOCA5.dat

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	60.3	62.8	67.5	66.3	66.3	64.0	61.6	54.4	72.3	38.8
5.0	61.6	64.0	67.5	66.3	67.5	64.0	62.8	55.6	72.3	38.9
10.0	62.8	64.0	67.5	67.5	67.5	65.2	62.8	55.6	72.3	38.9
15.0	64.0	66.3	67.5	67.5	67.5	65.2	62.8	55.6	73.5	40.1
20.0	64.0	65.2	68.8	67.6	67.6	65.2	64.0	55.6	73.6	40.1
25.0	65.2	66.4	68.8	67.6	68.8	66.4	64.0	55.6	73.6	40.1
30.0	65.2	66.4	68.8	68.8	68.8	66.4	64.0	55.6	73.6	40.1
35.0	66.4	66.4	70.0	68.8	68.8	66.4	64.1	56.9	74.8	40.2
40.0	67.6	67.6	70.0	68.8	68.8	66.4	64.1	56.9	74.8	40.2
45.0	67.6	67.6	70.0	68.8	68.8	66.4	64.1	56.9	74.8	40.2
50.0	67.6	67.6	70.0	68.8	68.8	66.5	65.3	56.9	74.8	40.2
55.0	68.9	68.9	70.1	70.1	68.9	66.5	65.3	56.9	74.9	40.2
60.0	68.9	67.7	70.1	68.9	70.1	66.5	65.3	56.9	74.9	40.2
65.0	68.9	68.9	70.1	70.1	70.1	66.5	65.3	57.0	74.9	40.3
70.0	68.9	68.9	70.1	70.1	70.1	66.5	65.3	57.0	74.9	40.3
75.0	70.1	68.9	71.3	70.1	70.1	67.7	65.3	57.0	76.1	40.3
80.0	68.9	69.0	71.3	70.1	70.1	67.7	65.4	57.0	76.1	40.3
85.0	70.2	69.0	70.2	70.2	71.4	66.6	65.4	58.2	76.2	40.3
90.0	70.2	69.0	71.4	70.2	71.4	67.8	65.4	57.0	76.2	40.3
95.0	70.2	70.2	71.4	70.2	72.6	67.8	65.4	58.3	76.2	40.3
100.0	70.2	70.2	71.4	70.2	72.6	67.8	65.4	57.1	77.4	40.4
105.0	70.2	70.2	71.4	70.2	72.6	66.6	66.6	57.1	77.4	40.4
110.0	70.2	70.2	71.4	70.2	72.6	67.8	66.6	57.1	77.4	40.4
115.0	70.3	70.3	71.5	71.5	72.6	67.9	67.9	57.1	77.5	40.4
120.0	70.3	70.3	71.5	71.5	72.7	66.7	66.7	57.1	77.5	40.4
125.0	70.3	71.5	71.5	71.5	72.7	66.7	66.7	57.1	77.5	40.4
130.0	71.5	71.5	72.7	71.5	73.9	70.3	70.3	58.4	77.5	52.3
135.0	71.5	72.7	72.8	71.5	75.1	71.5	72.7	63.1	80.0	39.3
140.0	71.6	75.2	76.4	74.0	77.6	71.6	72.8	65.6	82.3	39.3
145.0	71.6	77.6	78.8	77.6	82.3	72.8	75.2	68.0	84.7	39.3
150.0	71.6	78.8	81.1	80.0	85.9	76.4	76.4	70.4	88.3	39.3
155.0	72.8	78.8	84.8	82.4	87.2	80.0	80.0	71.6	93.2	38.2
160.0	81.1	87.1	84.7	88.3	81.1	84.7	83.5	71.6	98.0	38.1
165.0	80.0	96.8	100.4	83.6	80.0	86.0	82.4	71.6	102.8	38.2
170.0	76.5	105.2	105.2	92.0	70.5	86.0	83.6	74.1	108.8	38.2
175.0	81.2	110.0	110.0	105.2	70.5	89.6	86.0	78.9	113.6	38.2
180.0	78.9	113.6	113.6	108.8	74.1	95.6	78.9	81.2	118.4	38.2
185.0	81.3	117.3	117.3	112.5	101.7	98.1	78.9	84.9	123.3	38.3
190.0	82.5	122.1	120.9	116.1	108.9	96.9	81.3	90.9	128.1	39.5
195.0	83.7	125.7	124.5	120.9	112.5	96.9	84.9	95.7	131.7	38.3
200.0	95.7	129.3	128.2	120.9	116.1	99.3	88.5	99.3	135.3	39.5
205.0	101.7	133.0	130.6	123.3	118.5	104.1	92.1	99.3	140.2	39.5
210.0	106.5	135.4	134.2	129.4	120.9	106.5	95.7	99.3	143.8	39.5
215.0	108.9	139.0	137.8	140.2	123.3	108.9	102.9	99.3	146.3	39.5
220.0	110.2	142.7	140.2	146.3	125.8	112.6	112.6	100.6	151.1	40.7
225.0	113.8	146.3	143.9	151.1	129.4	116.2	117.4	101.8	153.5	40.7
230.0	116.2	148.7	146.3	154.7	133.0	118.6	121.0	104.2	157.1	40.7
235.0	119.8	151.1	149.9	157.2	135.5	121.0	125.9	105.4	159.6	41.9

Temperature data from `LOCA7.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	40.2	41.3	43.7	42.5	41.3	39.0	39.0	35.4	44.9	29.4
5.0	40.2	41.3	43.7	42.5	41.3	39.0	39.0	35.4	44.9	29.4
10.0	40.2	42.5	43.7	42.5	41.3	39.0	39.0	35.4	44.9	29.4
15.0	40.2	42.5	43.7	42.5	41.3	39.0	39.0	35.4	44.9	29.4
20.0	40.2	42.5	43.7	42.5	41.3	39.0	39.0	35.4	44.9	30.6
25.0	40.2	42.5	43.7	42.5	41.3	39.0	39.0	35.4	44.9	29.4
30.0	40.2	42.5	43.7	42.5	41.3	39.0	39.0	35.4	45.0	30.6
35.0	41.4	42.5	43.8	42.6	41.3	40.2	39.0	35.4	44.9	30.6
40.0	41.4	42.6	43.8	42.6	41.4	40.2	40.2	35.4	45.0	30.7
45.0	41.4	43.8	46.2	43.8	42.6	41.4	41.4	36.6	47.4	30.7
50.0	41.4	43.8	47.4	46.2	45.0	42.6	42.6	36.6	48.6	30.7
55.0	42.6	45.0	48.6	47.4	46.2	45.0	43.8	37.8	50.9	30.7
60.0	42.6	46.2	49.8	49.8	48.6	46.2	46.2	39.0	53.3	30.7
65.0	43.8	47.4	52.1	52.1	49.8	47.4	47.4	40.2	55.7	30.7
70.0	43.8	48.6	53.3	53.3	52.2	49.8	48.6	40.2	59.3	30.7
75.0	45.0	49.8	54.6	55.8	53.4	51.0	51.0	41.4	61.8	30.7
80.0	45.0	51.0	55.8	57.0	54.6	52.2	51.0	42.6	62.9	30.7
85.0	46.2	51.0	57.0	58.2	55.8	53.4	52.2	43.8	65.3	30.7
90.0	46.2	52.2	58.2	59.4	57.0	54.6	53.4	45.0	65.3	30.7
95.0	47.4	53.4	59.4	60.6	58.2	54.6	54.6	45.0	67.7	30.7
100.0	47.4	54.6	60.6	61.8	59.4	55.8	55.8	46.2	68.9	30.7
105.0	47.4	54.6	60.6	62.9	60.6	57.0	57.0	46.2	70.1	30.7
110.0	48.6	57.0	61.8	64.1	61.8	58.2	57.0	47.5	71.3	30.7
115.0	53.4	59.4	64.2	64.2	59.4	59.4	58.2	47.5	71.4	31.9
120.0	58.2	66.6	70.2	64.2	60.6	59.4	59.4	48.7	72.6	33.1
125.0	61.8	71.4	71.4	64.2	63.0	60.6	59.4	48.7	73.8	33.1
130.0	65.4	71.4	71.4	66.6	65.4	61.8	60.6	49.9	76.2	34.3
135.0	66.6	71.4	72.6	69.0	67.8	61.8	61.8	51.0	77.4	40.3
140.0	67.8	72.6	71.4	71.4	71.4	63.0	63.0	51.0	78.6	51.0
145.0	69.0	72.6	72.6	71.4	71.4	65.4	64.2	52.3	79.8	43.9
150.0	69.0	72.6	75.0	73.8	71.4	66.6	64.2	53.5	81.0	38.0
155.0	69.0	72.6	73.8	76.2	72.6	67.8	66.6	54.7	81.0	36.8
160.0	70.2	72.6	75.0	78.6	72.6	70.2	70.2	54.7	83.4	35.6
165.0	71.4	72.6	75.0	81.0	76.2	71.4	71.4	58.3	85.8	35.6
170.0	71.4	72.6	75.0	79.8	78.6	71.4	72.6	60.7	89.4	34.4
175.0	71.4	72.6	76.2	81.0	79.8	72.6	72.6	65.5	94.2	34.4
180.0	71.4	73.9	76.3	83.4	79.8	73.9	72.7	67.9	97.8	34.4
185.0	71.5	73.9	77.5	84.6	79.8	77.5	73.9	70.3	102.6	34.4
190.0	71.5	75.1	77.5	85.8	81.0	83.4	76.3	71.5	107.4	35.6
195.0	71.5	75.1	78.7	84.6	81.0	90.6	79.8	71.5	111.0	35.6
200.0	71.5	76.3	78.7	83.4	81.0	95.4	88.2	72.7	114.6	35.6
205.0	71.5	76.3	79.8	85.8	82.2	99.0	93.0	72.7	119.4	35.6
210.0	71.5	77.5	81.1	88.3	83.4	99.0	90.6	73.9	123.1	35.7
215.0	71.5	79.9	81.1	111.1	83.5	93.1	85.9	75.1	126.7	34.5
220.0	71.5	81.1	82.3	115.9	84.7	91.9	87.1	78.7	130.3	35.7
225.0	71.5	83.5	83.5	121.9	84.7	93.1	88.3	82.3	133.9	35.7
230.0	71.5	84.7	84.7	130.3	85.9	99.1	88.3	89.5	136.3	34.5
235.0	71.5	88.3	85.9	133.9	85.9	97.9	87.1	94.3	139.9	35.7

Temperature data from `LOFA1.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	48.2	50.6	50.6	51.8	53.0	54.2	55.4	50.6	58.9	47.0
5 .0	48.2	50.6	50.6	53.0	53.0	54.2	55.4	50.6	59.0	47.0
10.0	48.2	50.6	50.6	51.8	53.0	54.2	55.4	50.6	57.8	47.1
15.0	48.2	50.6	50.6	51.8	53.0	54.2	55.4	50.6	59.0	47.1
20.0	48.2	50.6	50.6	51.8	53.0	54.2	55.4	50.6	57.8	47.1
25.0	48.3	50.7	50.7	51.8	53.1	54.3	55.4	50.7	59.0	47.1
30.0	48.3	50.7	50.7	51.9	53.1	54.3	55.5	50.7	59.0	47.1
35.0	48.3	50.7	50.7	51.9	53.1	54.3	55.5	50.7	59.0	47.1
40.0	48.3	50.7	50.7	51.9	53.1	54.3	55.5	50.7	59.0	47.1
45.0	48.3	50.7	50.7	51.9	53.1	54.3	55.5	50.7	57.9	47.1
50.0	48.3	50.7	50.7	51.9	53.1	54.3	55.5	50.7	59.1	47.1
55.0	48.3	50.7	50.7	51.9	53.1	54.3	54.3	50.7	57.9	47.1
60.0	48.3	50.7	50.8	51.9	53.1	54.3	54.3	50.7	57.9	47.1
65.0	48.3	50.8	50.8	52.0	53.2	54.4	54.4	50.8	57.9	47.2
70.0	48.4	50.8	50.8	52.0	53.2	54.4	55.6	50.8	57.9	47.2
75.0	48.4	50.8	50.8	52.0	53.2	54.4	54.4	50.8	57.9	47.2
80.0	48.4	50.8	50.8	52.0	53.2	54.4	54.4	50.8	57.9	47.2
85.0	48.4	50.8	50.8	52.0	53.2	54.4	54.4	50.8	58.0	47.2
90.0	48.4	50.8	50.8	52.0	53.2	54.4	54.4	50.8	58.0	47.2
95.0	48.4	50.8	50.8	52.0	53.2	54.4	54.4	50.8	58.0	47.2
100.0	48.5	50.8	50.8	52.0	53.2	54.5	54.5	50.8	58.0	47.2
105.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	58.0	47.3
110.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	58.0	47.3
115.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	59.2	47.3
120.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	58.1	47.3
125.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	58.1	47.3
130.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	58.1	47.3
135.0	48.5	50.9	50.9	52.1	53.3	54.5	54.5	50.9	58.1	47.3
140.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	58.1	47.4
145.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	58.1	47.4
150.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	58.1	47.4
155.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	59.3	47.4
160.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	58.2	47.4
165.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	58.2	47.4
170.0	48.6	51.0	51.0	52.2	53.4	54.6	54.6	51.0	58.2	47.4
175.0	48.6	51.0	51.1	52.3	53.4	54.7	54.7	51.1	58.2	47.4
180.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	59.4	47.5
185.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	58.2	47.5
190.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	58.2	47.5
195.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	58.2	47.5
200.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	58.3	47.5
205.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	58.3	47.5
210.0	48.7	51.1	51.1	52.3	53.5	54.7	54.7	51.1	58.3	47.5
215.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	59.5	47.6
220.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	58.3	47.6
225.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	58.3	47.6

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
230.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	58.3	47.6
235.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	58.4	47.6
240.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	59.6	47.6
245.0	48.8	51.2	51.2	52.4	53.6	54.8	54.8	51.2	58.4	47.6
250.0	48.8	51.2	51.2	52.5	53.7	54.8	54.8	51.2	59.6	47.7
255.0	48.9	51.3	51.3	52.5	53.7	54.9	54.9	51.3	58.4	47.7
260.0	48.9	51.3	51.3	52.5	53.7	54.9	54.9	51.3	59.6	47.7
265.0	48.9	51.3	51.3	52.5	53.7	53.7	54.9	51.3	58.4	47.7
270.0	48.9	52.5	52.5	52.5	53.7	54.9	54.9	51.3	59.7	47.7
275.0	48.9	51.3	52.5	52.5	53.7	54.9	54.9	51.3	58.5	47.7
280.0	48.9	52.5	52.5	52.5	53.7	54.9	54.9	51.3	58.5	47.7
285.0	48.9	52.5	52.5	52.5	53.7	54.9	54.9	51.3	58.5	47.7
290.0	49.0	52.6	52.6	52.6	53.8	54.9	54.9	51.4	59.7	47.8
295.0	49.0	52.6	52.6	52.6	53.8	54.9	54.9	51.4	59.7	47.8
300.0	47.8	52.6	52.6	52.6	53.8	54.9	54.9	51.4	59.7	47.8
305.0	49.0	52.6	52.6	52.6	53.8	53.8	54.9	51.4	59.7	47.8
310.0	47.8	52.6	52.6	52.6	53.8	55.0	55.0	51.4	59.8	47.8
315.0	47.8	52.6	52.6	52.6	53.8	55.0	55.0	51.4	59.8	47.8
320.0	47.8	52.6	52.6	52.6	53.8	55.0	55.0	51.4	59.8	47.8
325.0	47.8	52.6	52.7	52.6	53.8	55.0	55.0	51.5	59.8	47.8
330.0	49.1	52.7	52.7	52.7	53.9	55.0	55.0	51.5	59.8	47.9
335.0	49.1	52.7	52.7	52.7	53.9	53.9	55.0	51.5	59.8	47.9
340.0	47.9	52.7	52.7	52.7	53.9	55.0	55.0	51.5	61.0	47.9
345.0	47.9	52.7	52.7	52.7	53.9	55.1	55.1	51.5	61.1	47.9
350.0	49.1	52.7	52.7	52.7	53.9	55.1	55.1	51.5	61.1	47.9
355.0	49.1	52.7	52.7	52.7	53.9	55.1	55.1	51.5	61.1	47.9
360.0	49.1	52.7	52.7	53.9	53.9	55.1	55.1	51.5	61.1	47.9
365.0	49.1	52.8	52.8	52.8	53.9	55.1	55.1	51.6	61.1	48.0
370.0	49.2	52.8	52.8	52.8	53.9	55.1	55.1	51.6	59.9	48.0
375.0	49.2	52.8	52.8	52.8	53.9	55.1	55.1	51.6	61.1	48.0
380.0	49.2	52.8	52.8	52.8	53.9	55.2	55.1	51.6	60.0	48.0
385.0	49.2	52.8	52.8	52.8	54.0	55.2	55.2	51.6	60.0	48.0
390.0	49.2	52.8	52.8	52.8	54.0	55.2	55.2	51.6	60.0	48.0
395.0	49.2	54.0	52.8	52.8	54.0	55.2	55.2	51.6	61.2	48.0
400.0	50.5	52.9	52.9	52.8	54.0	55.2	55.2	51.7	61.2	48.1
405.0	50.5	54.0	52.9	52.9	54.0	55.2	55.2	51.7	61.2	48.1
410.0	50.5	54.0	52.9	52.9	54.0	55.2	55.2	51.7	61.2	48.1
415.0	51.7	54.0	52.9	52.9	54.0	55.2	55.2	51.7	61.2	48.1
420.0	51.7	54.1	52.9	52.9	54.1	55.3	55.3	51.7	61.3	48.1
425.0	52.9	54.1	52.9	54.1	54.1	55.3	55.3	51.7	61.3	48.1
430.0	52.9	54.1	52.9	54.1	54.1	55.3	55.3	51.7	61.3	48.1
435.0	54.1	54.1	52.9	54.1	54.1	54.1	55.3	51.8	61.3	48.1
440.0	54.1	54.1	54.1	54.1	54.1	55.3	55.3	51.8	61.3	48.2
445.0	54.1	54.1	54.1	54.1	54.1	55.3	55.3	51.8	61.3	48.2
450.0	55.3	54.1	54.1	54.1	54.1	54.1	55.3	51.8	61.3	48.2
455.0	55.3	52.9	52.9	54.1	54.1	54.1	55.3	51.8	61.4	48.2
460.0	56.6	53.0	54.2	54.2	54.2	55.4	55.4	51.8	61.4	48.2
465.0	56.6	54.2	54.2	54.2	54.2	54.2	55.4	51.8	61.4	48.2
470.0	57.8	54.2	54.2	54.2	54.2	54.2	55.4	51.8	61.4	48.2
475.0	57.8	56.6	54.2	54.2	54.2	54.2	55.4	51.9	61.4	48.3

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
485.0	59.0	59.0	54.2	54.2	54.2	54.2	55.4	51.9	61.4	48.3
490.0	59.0	60.2	55.4	54.3	54.2	54.2	55.4	51.9	61.4	48.3
495.0	59.1	61.5	56.7	54.3	54.3	54.2	55.5	51.9	61.5	48.3
500.0	60.3	61.5	57.9	54.3	54.3	54.3	55.5	51.9	61.5	48.3
505.0	60.3	62.7	59.1	54.3	54.3	54.3	55.5	51.9	61.5	48.3
510.0	61.5	62.7	59.1	54.3	54.3	54.3	55.5	51.9	61.5	48.3
515.0	61.5	63.9	60.3	54.3	54.3	54.3	55.5	51.9	61.5	48.4
520.0	62.7	63.9	61.5	54.3	54.3	54.3	55.5	51.9	61.5	48.4
525.0	62.7	65.1	61.5	54.3	54.3	55.5	55.5	51.9	62.7	48.4
530.0	62.8	66.3	62.7	54.4	54.3	55.6	55.6	52.0	63.9	48.4
535.0	63.9	67.5	63.9	55.6	55.6	55.6	56.8	52.0	63.9	48.4
540.0	63.9	67.5	63.9	55.6	55.6	55.6	56.8	52.0	65.1	48.4
545.0	63.9	68.7	65.1	55.6	55.6	55.6	56.8	52.0	65.1	48.4
550.0	65.2	70.0	66.4	55.6	55.6	56.8	56.8	52.0	66.4	48.5
555.0	65.2	70.0	67.6	55.6	55.6	56.8	56.8	52.0	66.4	48.5
560.0	66.4	70.0	68.8	56.8	56.8	56.8	56.8	52.0	67.6	48.5
565.0	66.4	71.2	68.8	56.8	56.8	56.8	56.8	52.0	67.6	48.5
570.0	67.6	71.2	70.0	56.9	56.8	56.9	58.1	52.1	68.8	48.5
575.0	68.8	71.2	70.0	56.9	56.9	56.9	58.1	52.1	68.8	48.5
580.0	68.8	71.2	71.2	56.9	56.9	56.9	58.1	53.3	70.0	48.5
585.0	68.8	71.2	71.2	58.1	56.9	56.9	58.1	53.3	70.0	48.5
590.0	70.1	71.3	71.3	58.1	58.1	58.1	58.1	53.3	71.3	48.6
595.0	70.1	71.3	71.3	58.1	58.1	56.9	58.1	53.3	72.5	48.6
600.0	70.1	72.5	72.5	58.1	59.3	56.9	58.1	53.3	73.7	48.6
605.0	70.1	72.5	72.5	60.6	59.4	57.0	58.2	53.4	73.7	48.6
610.0	71.3	74.9	72.5	64.1	60.6	58.2	58.2	53.4	74.9	48.6
615.0	71.3	76.1	73.7	66.5	62.9	58.2	58.2	53.4	76.1	48.6
620.0	71.3	76.1	73.7	68.9	66.5	58.2	58.2	53.4	76.1	48.6
625.0	71.4	77.4	72.6	70.2	69.0	58.2	58.2	53.4	76.2	48.7
630.0	71.4	78.6	72.6	71.4	71.4	58.2	58.2	53.4	76.2	48.7
635.0	71.4	79.7	72.6	71.4	71.4	58.2	58.2	53.4	77.4	48.7
640.0	71.4	80.9	72.6	71.4	71.4	58.2	59.4	53.4	78.6	48.7
645.0	71.4	82.2	72.6	71.4	71.4	58.3	59.5	53.5	79.8	48.7
650.0	71.4	83.4	72.6	71.4	71.4	59.5	64.2	53.5	82.2	48.7
655.0	71.4	87.0	72.6	72.6	72.6	60.7	69.0	53.5	83.4	48.7
660.0	71.4	89.4	72.6	77.4	73.8	61.8	71.4	53.5	85.8	48.7
665.0	71.5	91.8	72.7	78.7	75.1	64.3	71.5	53.5	87.0	48.8
670.0	71.5	96.6	72.7	78.7	79.8	65.5	72.7	57.1	90.6	48.8
675.0	71.5	97.8	72.7	78.7	79.8	70.3	72.7	60.7	91.8	48.8
680.0	71.5	99.0	72.7	77.5	77.5	71.5	72.7	58.3	94.2	48.8
685.0	71.5	100.3	72.7	77.5	75.1	72.7	72.7	57.2	96.7	47.6
690.0	71.5	102.7	72.7	77.5	75.1	72.7	73.9	58.4	99.1	47.6
695.0	71.5	102.7	72.7	77.5	75.1	73.9	75.1	60.8	101.5	47.6
700.0	71.6	103.9	72.8	77.6	75.2	75.2	78.7	63.2	103.9	47.6
705.0	71.6	103.9	72.8	77.6	75.2	78.7	79.9	64.4	106.3	47.7
710.0	69.2	103.9	72.8	77.6	75.2	77.6	76.4	65.6	108.7	47.7
715.0	60.8	107.5	72.8	78.7	77.6	75.2	75.2	66.8	112.3	47.7
720.0	68.0	109.9	72.8	78.7	79.9	75.2	75.2	69.2	113.6	47.7
725.0	70.4	112.4	72.8	88.4	106.4	75.2	77.6	70.4	116.0	47.7
730.0	71.6	113.6	72.8	90.8	110.0	77.6	81.2	71.6	117.2	47.7

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
740.0	71.7	116.0	72.9	95.6	113.6	92.0	106.4	72.9	122.0	46.5
745.0	71.7	117.2	74.1	96.8	113.6	96.8	108.8	72.9	123.2	46.6
750.0	71.7	118.4	74.1	99.2	114.8	99.2	111.2	74.1	124.4	46.6
755.0	71.7	119.6	74.1	101.6	112.4	99.2	113.6	75.3	126.9	46.6
760.0	71.7	120.9	74.1	104.1	112.5	98.1	116.1	75.3	129.3	45.4
765.0	71.7	122.1	74.1	106.5	114.9	99.3	117.3	75.3	130.5	45.4
770.0	71.7	123.3	74.1	108.9	116.1	105.3	119.7	75.3	131.7	46.6
775.0	71.7	124.5	75.3	110.1	118.5	106.5	122.1	74.1	132.9	45.4
780.0	71.8	125.8	75.4	111.3	119.7	110.1	123.3	73.0	135.4	45.5
785.0	71.8	127.0	75.4	111.3	122.1	107.7	125.8	74.2	136.6	45.5
790.0	71.8	129.4	75.4	112.5	122.1	108.9	128.2	75.4	137.8	45.5
795.0	71.8	129.4	76.5	113.7	122.1	108.9	130.6	74.2	139.0	46.7
800.0	71.8	131.8	76.6	115.0	125.8	113.8	131.8	77.8	141.4	46.7
805.0	71.8	131.8	76.6	116.2	128.2	115.0	134.2	82.6	142.6	46.7
810.0	71.8	134.2	76.6	118.6	128.2	116.2	135.4	92.2	143.9	46.7
815.0	71.8	135.4	76.6	119.8	130.6	117.4	136.6	100.6	146.3	45.5
820.0	71.9	135.5	77.8	121.0	131.9	117.4	137.9	105.4	147.5	45.6
825.0	71.9	136.7	77.8	122.2	133.1	118.6	139.1	107.8	148.7	45.6
830.0	71.9	139.1	79.0	124.6	135.5	119.8	139.1	110.2	149.9	45.6
835.0	71.9	140.3	79.0	125.8	136.7	117.4	140.3	112.6	151.1	45.6
840.0	71.9	142.7	79.1	127.1	136.7	115.1	141.5	115.1	152.4	45.6
845.0	73.1	142.7	80.3	128.3	136.7	116.3	140.3	116.3	153.6	45.6
850.0	73.1	144.0	80.3	130.7	136.7	117.5	139.1	117.5	156.0	45.6
855.0	73.1	145.2	80.3	131.9	136.7	125.9	138.0	106.7	157.2	45.6

Temperature data from `LOFA3.dat`

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	28.9	28.9	28.9	27.7	28.9	28.9	28.9	28.9	28.9	28.9
5.0	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9
10.0	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9
15.0	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9
20.0	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9
25.0	29.0	29.0	29.0	28.9	28.9	29.0	29.0	29.0	29.0	28.9
30.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0
35.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0
40.0	29.0	29.0	29.0	29.0	30.2	30.2	30.2	29.0	30.2	29.0
45.0	29.0	29.0	30.2	31.3	32.5	32.5	33.7	30.2	32.5	29.0
50.0	29.0	30.2	32.5	33.7	34.9	33.7	36.1	32.5	36.1	29.0
55.0	29.0	31.3	33.7	36.1	38.5	36.1	38.5	33.7	38.5	29.0
60.0	30.2	32.6	36.2	38.5	42.1	39.7	40.9	35.0	43.3	30.2
65.0	31.4	35.0	39.7	40.9	44.5	42.1	44.5	37.4	45.7	30.2
70.0	38.5	44.5	45.7	43.3	45.7	44.5	46.9	38.6	49.2	30.2
75.0	43.3	45.7	45.8	44.5	46.9	46.9	48.1	41.0	51.7	31.4
80.0	44.6	45.8	47.0	45.8	48.1	47.0	49.3	43.4	54.1	31.4
85.0	44.6	45.8	48.1	45.8	50.5	48.1	51.7	44.6	57.7	31.4
90.0	44.6	45.8	48.1	45.8	51.7	49.3	52.9	47.0	62.5	29.1
95.0	44.6	45.8	50.5	44.6	52.9	49.3	54.1	48.1	64.9	30.2
100.0	44.6	45.8	51.7	45.8	54.1	50.5	54.1	49.3	68.5	30.2
105.0	44.6	47.0	53.0	45.8	55.4	50.6	55.4	50.6	70.9	30.3
110.0	45.8	48.2	54.2	45.8	56.6	51.8	55.4	51.8	73.3	31.5
115.0	47.0	49.4	56.6	45.8	56.6	53.0	56.6	53.0	75.7	31.5
120.0	48.2	50.6	56.6	45.8	57.8	53.0	56.6	53.0	78.1	32.7
125.0	50.6	51.8	57.8	47.0	57.8	54.2	57.8	54.2	79.3	31.5
130.0	51.8	53.0	59.0	47.1	59.0	54.2	57.8	55.4	80.5	32.7
135.0	53.0	54.2	60.2	47.1	59.0	54.2	57.8	55.4	82.9	32.7
140.0	55.4	55.4	60.2	48.2	60.2	54.2	57.8	55.4	84.1	32.7
145.0	56.6	56.6	61.4	48.2	60.2	54.2	57.8	55.4	85.3	33.9
150.0	57.8	57.9	61.4	48.2	60.2	55.4	59.0	56.6	86.5	33.9
155.0	59.0	57.9	62.6	48.3	60.2	55.4	59.0	56.7	87.8	34.0
160.0	60.2	57.9	62.6	48.3	61.4	55.5	59.0	56.7	87.8	35.2
165.0	61.4	59.0	62.6	49.5	61.4	55.5	59.0	56.7	89.0	35.2
170.0	62.6	59.0	62.6	49.5	61.4	55.5	59.0	56.7	89.0	36.4
175.0	63.8	57.9	62.6	49.5	62.6	55.5	59.0	56.7	90.2	36.4
180.0	65.0	57.9	62.7	49.5	62.7	56.7	59.0	56.7	90.2	37.6
185.0	65.1	56.7	62.7	49.5	62.7	56.7	60.3	56.7	91.4	38.8
190.0	66.3	56.7	61.5	50.7	62.7	56.7	60.3	57.9	91.4	37.6
195.0	66.3	57.9	61.5	50.7	63.9	56.7	60.3	57.9	92.6	37.6
200.0	66.3	57.9	60.3	50.7	63.9	56.7	60.3	57.9	92.6	38.8
205.0	66.3	59.1	59.1	50.7	63.9	56.8	60.3	57.9	93.8	38.8
210.0	66.3	61.5	60.3	50.8	63.9	57.9	61.5	57.9	93.9	37.6
215.0	67.5	66.3	61.5	50.8	65.1	57.9	61.5	57.9	93.9	38.8
220.0	67.5	72.3	62.7	50.8	65.1	57.9	61.5	59.1	93.9	40.0
225.0	67.5	75.9	63.9	52.0	65.1	59.1	62.7	59.1	93.9	38.8
230.0	68.7	78.3	65.1	52.0	65.1	59.1	62.7	59.2	93.9	40.0
235.0	68.8	72.3	66.4	52.0	65.2	59.2	62.8	59.2	95.1	41.3

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
240.0	70.0	71.2	68.8	52.0	65.2	59.2	62.8	60.4	95.1	41.3
245.0	70.0	71.2	71.2	52.0	66.4	59.2	62.8	60.4	95.1	41.3
250.0	70.0	71.2	73.5	52.0	66.4	59.2	62.8	60.4	95.1	42.5
255.0	70.0	71.2	75.9	52.0	66.4	59.2	62.8	60.4	95.2	43.7
260.0	70.0	71.2	77.2	53.3	66.4	60.4	62.8	60.4	96.4	43.7
265.0	70.0	71.2	76.0	53.3	66.4	60.4	62.8	60.4	96.4	43.7
270.0	70.0	71.3	74.8	53.3	66.4	60.4	62.9	61.7	96.4	45.0
275.0	70.1	71.3	74.8	53.3	66.5	60.5	62.9	61.7	96.4	45.0
280.0	70.1	71.3	74.8	53.3	66.5	60.5	62.9	61.7	96.4	45.0
285.0	70.1	71.3	73.6	53.3	66.5	60.5	62.9	61.7	96.4	46.1
290.0	70.1	72.4	73.6	53.3	66.5	60.5	62.9	61.7	96.4	46.1
295.0	71.3	72.4	73.6	53.3	66.5	60.5	64.1	61.7	96.4	46.1
300.0	70.1	72.4	73.6	53.3	66.5	60.5	64.1	61.7	96.4	47.3
305.0	70.1	72.5	73.7	53.4	66.5	60.5	64.1	61.7	96.5	47.4
310.0	71.3	72.5	73.7	53.4	66.5	60.5	64.1	61.7	95.3	47.4
315.0	71.3	72.5	73.7	53.4	66.5	61.7	64.1	62.9	96.5	47.4
320.0	71.3	72.5	73.7	53.4	67.7	61.7	64.1	62.9	96.5	47.4
325.0	71.3	72.5	73.7	54.6	67.7	61.7	64.1	62.9	97.7	48.6
330.0	71.3	72.5	72.5	54.6	67.7	61.7	65.3	62.9	98.9	48.6
335.0	71.3	73.7	73.7	54.6	67.8	61.8	65.4	62.9	98.9	48.6
340.0	71.3	73.7	72.5	55.8	67.8	61.8	65.4	64.2	100.1	48.6
345.0	71.3	73.7	73.7	55.8	69.0	61.8	65.4	64.2	101.3	48.6
350.0	71.3	73.7	73.7	57.0	69.0	61.8	65.4	64.2	101.3	48.6
355.0	71.3	73.7	73.7	73.7	69.0	61.8	65.4	64.2	101.3	49.8
360.0	71.4	73.8	73.8	74.9	69.0	61.8	65.4	64.2	101.4	49.8
365.0	71.4	73.8	73.8	76.2	69.0	61.8	65.4	65.4	101.4	49.9
370.0	71.4	73.8	73.8	78.6	70.2	61.8	65.4	64.2	101.4	49.9
375.0	71.4	73.8	75.0	81.0	76.2	61.8	65.4	65.4	102.6	49.9
380.0	71.4	75.0	75.0	77.4	82.2	61.8	65.4	64.2	103.8	49.9
385.0	71.4	75.0	76.2	76.2	82.2	61.9	64.3	65.5	106.2	49.9
390.0	71.4	72.6	76.2	75.0	76.2	69.1	69.1	64.3	107.4	49.9
395.0	71.4	72.6	76.2	75.0	76.2	70.2	71.4	64.3	112.2	49.9
400.0	71.4	72.6	77.4	75.0	76.2	70.2	71.4	63.1	115.8	49.9
405.0	71.4	75.1	77.5	75.0	79.8	72.6	73.9	63.1	119.4	49.9
410.0	71.4	76.2	79.8	75.0	84.6	76.2	77.4	63.1	124.2	49.9
415.0	71.4	76.2	79.8	75.0	84.6	81.0	81.0	64.3	129.0	48.7
420.0	71.4	75.1	79.9	76.3	87.1	77.5	87.1	70.3	133.9	48.8
425.0	71.5	76.3	81.1	77.5	94.3	76.3	83.5	72.7	138.7	48.8
430.0	71.5	75.1	77.5	79.9	101.5	76.3	77.5	75.1	142.3	47.6
435.0	71.5	73.9	94.3	85.9	125.5	75.1	82.3	77.5	145.9	47.6
440.0	71.5	73.9	138.8	115.9	135.1	94.3	107.5	79.9	150.8	47.6
445.0	71.5	75.1	140.0	125.5	138.8	106.3	118.3	83.5	153.2	46.4
450.0	71.5	76.3	144.8	132.7	142.4	113.5	124.3	87.1	156.8	46.4
455.0	71.6	77.5	147.2	137.6	146.0	118.3	129.1	81.1	160.5	46.4
460.0	71.6	77.6	140.0	140.0	149.7	122.0	132.8	80.0	162.9	47.7
465.0	71.6	87.2	135.2	142.4	152.1	129.2	137.6	89.6	166.5	48.9
470.0	71.6	98.0	134.0	146.0	155.7	132.8	141.2	98.0	170.1	51.3
475.0	71.6	100.4	134.0	148.5	158.1	131.6	144.8	104.0	172.6	52.5
480.0	71.6	101.6	135.2	149.7	160.5	130.4	134.0	108.8	176.2	53.7

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
485.0	71.6	104.0	137.6	144.8	164.1	140.0	149.7	108.8	178.6	53.7
490.0	71.6	104.0	140.1	148.5	167.8	144.9	154.5	81.2	181.1	53.7
495.0	71.6	105.2	141.3	153.3	170.2	98.0	154.5	84.8	183.5	54.9
500.0	71.6	106.4	142.5	158.1	166.6	112.4	160.6	86.0	185.9	54.9
505.0	72.8	107.7	144.9	159.3	169.0	138.9	164.2	93.2	188.3	56.1
510.0	72.9	107.7	147.3	160.6	167.8	142.5	167.8	101.6	190.8	56.1
515.0	72.9	107.7	148.5	164.2	173.9	148.5	167.8	111.3	193.2	57.3
520.0	71.7	107.7	151.0	165.4	179.9	148.5	167.8	113.7	195.6	57.3
525.0	72.9	107.7	149.8	169.0	183.5	146.1	169.0	122.1	198.0	57.3

Temperature data from LOFA7.dat

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
0.0	63.5	63.5	62.3	51.5	51.5	50.3	49.1	49.1	56.3	45.6
5.0	63.5	63.5	62.3	51.6	51.6	50.4	49.1	49.1	55.2	44.4
10.0	63.5	63.5	62.3	51.6	51.6	50.4	49.2	49.2	55.2	45.6
15.0	63.5	63.5	62.3	51.6	51.6	50.4	49.2	49.2	55.2	44.4
20.0	63.5	63.5	62.3	51.6	51.6	50.4	49.2	49.2	55.2	45.6
25.0	63.6	63.6	62.4	51.6	51.6	50.4	49.2	49.2	55.2	45.7
30.0	63.6	63.6	62.4	51.6	51.6	50.4	49.2	49.2	55.2	45.7
35.0	63.6	63.6	62.4	51.6	51.6	50.4	50.4	49.2	55.2	45.7
40.0	63.6	63.6	63.6	52.9	51.7	51.7	50.5	49.3	56.5	45.7
45.0	63.6	66.0	64.8	54.1	52.9	52.9	51.7	49.3	57.6	45.7
50.0	64.8	66.0	66.0	55.3	54.1	54.1	52.9	50.5	58.8	45.7
55.0	64.8	62.5	63.7	56.5	54.1	55.3	52.9	50.5	60.1	45.7
60.0	66.1	58.9	60.1	56.5	55.3	56.5	54.1	51.7	61.3	45.8
65.0	66.1	57.7	58.9	57.7	56.5	57.7	55.3	51.7	63.7	45.8
70.0	63.7	57.7	58.9	58.9	56.5	57.7	55.3	53.0	63.7	45.8
75.0	61.3	57.7	57.7	58.9	57.7	58.9	56.6	53.0	64.9	45.8
80.0	55.4	57.7	57.7	58.9	57.7	58.9	56.6	54.2	66.1	45.8
85.0	53.0	58.9	57.7	60.1	58.9	60.1	56.6	54.2	67.3	45.8
90.0	51.8	59.0	57.8	60.2	59.0	60.2	57.8	55.4	68.6	45.8
95.0	50.6	59.0	59.0	60.2	59.0	61.4	57.8	55.4	68.6	45.8
100.0	50.6	59.0	59.0	61.4	59.0	61.4	59.0	55.4	69.8	45.8
105.0	50.7	59.0	59.0	61.4	60.2	62.6	59.0	56.6	71.0	47.1
110.0	50.7	60.2	59.0	62.6	60.2	62.6	59.0	56.6	71.0	47.1
115.0	50.7	60.2	59.0	62.6	60.2	62.6	59.0	56.6	72.2	47.1
120.0	51.9	60.2	59.1	62.7	61.4	63.9	60.3	57.9	72.2	47.1
125.0	51.9	60.3	59.1	63.9	61.5	63.9	60.3	57.9	73.4	47.1
130.0	51.9	60.3	60.3	63.9	61.5	63.9	60.3	57.9	73.4	47.1
135.0	51.9	61.5	60.3	63.9	61.5	65.1	61.5	57.9	73.4	48.3
140.0	52.0	61.5	60.3	63.9	61.5	65.1	61.5	59.1	74.7	48.4
145.0	52.0	61.5	60.3	63.9	62.7	65.1	61.5	59.1	74.7	48.4
150.0	52.0	61.5	60.3	65.2	62.8	65.1	61.5	59.1	74.7	48.4
155.0	52.0	62.8	60.4	65.2	62.8	65.2	61.6	59.2	75.9	48.4
160.0	53.2	62.8	60.4	65.2	62.8	65.2	61.6	59.2	75.9	48.4
165.0	53.2	62.8	61.6	65.2	62.8	65.2	61.6	59.2	78.3	49.6
170.0	53.3	62.8	61.6	65.2	62.8	66.4	62.8	60.4	78.4	49.6
175.0	53.3	62.8	61.6	65.2	64.0	66.4	62.8	60.4	78.4	49.7
180.0	53.3	64.1	61.6	66.4	64.0	66.4	62.8	60.4	78.4	49.7
185.0	53.3	64.1	61.7	65.3	64.1	66.5	62.9	60.5	79.6	49.7
190.0	54.5	64.1	61.7	66.5	64.1	66.5	62.9	60.5	79.6	49.7
195.0	54.5	64.1	61.7	66.5	64.1	66.5	62.9	60.5	79.6	49.7
200.0	54.5	64.1	61.7	66.5	65.3	66.5	62.9	61.7	79.7	49.8
205.0	54.5	64.1	62.9	66.5	65.3	66.5	62.9	61.7	78.5	51.0
210.0	55.7	64.1	62.9	65.3	65.3	66.5	62.9	61.7	78.5	51.0
215.0	55.7	65.3	63.0	65.3	65.3	66.6	63.0	61.7	79.7	51.0
220.0	55.8	65.4	63.0	66.6	66.6	66.6	63.0	61.8	79.7	51.0
225.0	57.0	66.6	63.0	66.6	66.6	66.6	63.0	63.0	79.7	51.0
230.0	59.4	66.6	64.2	66.6	66.6	66.6	63.0	63.0	81.0	51.0
235.0	60.6	66.6	64.2	66.6	66.6	66.6	63.0	63.0	81.0	52.3

time	T1	T2	T3	T4	T5	T6	T7	T8	T9	Coolant
240.0	61.8	67.8	64.2	66.6	67.8	66.6	63.0	63.0	82.2	52.3
245.0	63.0	69.0	64.2	66.6	67.8	65.4	63.0	63.0	82.2	51.1
250.0	65.5	69.0	64.3	66.6	67.8	66.6	63.1	63.1	82.2	52.3
255.0	66.6	69.0	67.8	66.6	67.8	66.6	63.1	63.1	83.4	52.3
260.0	66.6	69.0	70.3	67.8	67.8	66.6	63.1	63.1	82.2	52.3
265.0	67.9	67.8	70.2	67.9	67.9	65.5	63.1	63.1	82.3	52.4
270.0	69.1	67.9	70.3	67.9	67.9	65.5	61.9	63.1	82.3	52.4
275.0	70.3	67.9	66.7	69.1	67.9	65.5	61.9	63.1	83.5	52.4
280.0	70.3	69.1	65.5	69.1	67.9	66.7	62.0	63.2	83.5	52.4
285.0	70.3	69.1	65.5	69.1	67.9	67.9	62.0	63.2	83.5	52.4
290.0	70.3	69.1	69.1	70.3	67.9	67.9	62.0	63.2	84.7	52.4
295.0	71.5	71.5	70.3	69.1	67.9	67.9	62.0	63.2	82.4	52.4
300.0	70.4	71.6	71.6	69.2	68.0	68.0	70.4	63.2	78.8	52.4
305.0	70.4	72.8	71.6	69.2	68.0	68.0	69.2	63.2	78.8	52.4
310.0	70.4	74.0	72.8	69.2	68.0	68.0	68.0	62.0	78.8	52.4
315.0	71.6	74.0	75.2	69.2	68.0	66.8	66.8	60.9	80.0	52.5
320.0	71.6	74.0	72.8	70.4	69.2	66.8	66.8	60.9	81.2	52.5
325.0	71.6	72.8	71.6	70.4	69.2	65.6	66.8	60.9	83.6	51.3
330.0	71.6	74.1	71.7	71.7	71.6	65.7	66.9	59.7	84.8	51.4
335.0	71.7	72.9	71.7	71.7	71.7	65.7	66.9	59.7	87.2	51.4
340.0	71.7	74.1	71.7	75.3	74.1	66.9	66.9	59.7	89.6	51.4
345.0	71.7	74.1	71.7	82.5	76.5	68.1	69.3	58.6	93.3	50.2
350.0	71.7	74.1	71.7	86.1	81.3	68.1	70.5	58.6	96.9	50.2
355.0	71.7	74.1	71.7	76.5	75.3	69.3	71.7	58.6	101.7	50.2
360.0	71.7	74.2	71.7	76.5	74.2	70.5	73.0	64.5	106.5	49.0
365.0	71.8	75.4	71.8	77.8	74.2	70.6	75.4	64.6	111.3	49.1
370.0	71.8	76.6	98.1	87.3	75.4	71.8	79.0	65.8	117.3	49.1
375.0	71.8	96.9	106.5	73.0	76.6	74.2	79.0	68.2	121.0	49.1
380.0	71.8	107.8	101.8	71.8	76.6	73.0	79.0	69.4	125.8	49.1
385.0	71.8	112.6	94.6	73.0	75.4	74.2	83.8	70.6	131.8	49.1
390.0	71.8	117.4	94.6	73.0	75.4	80.2	86.2	70.6	136.6	49.1
395.0	71.9	125.9	94.6	73.1	75.5	76.7	85.0	70.6	141.5	47.9
400.0	71.9	131.9	97.0	74.3	75.5	76.7	77.9	71.9	145.1	48.0
405.0	71.9	134.3	98.2	76.7	76.7	80.3	77.9	71.9	149.9	48.0
410.0	71.9	136.7	98.2	85.0	76.7	79.1	79.1	74.3	152.3	48.0
415.0	71.9	141.6	95.9	93.5	92.3	98.3	76.7	79.1	156.0	48.0

FUEL MELTING and RELOCATION in the ADVANCED TEST REACTOR: SIMULANT EXPERIMENTS in a CLOSED GEOMETRY

Mark Handrick

Under the supervision of Professor Michael L. Corradini

Approved:

8-19-93 Michael Corradini

Date

Prof. Michael L. Corradini
Nuclear Engineering and Engineering Physics