TRAC-B/PC and Relap5/Mod2.5-PC Comparisons to the Oh Critical Heat Flux Experiments

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ABSTRACT

Critical Heat Flux (CHF) is an important aspect of research reactor analysis and simulation. The CHF point determines the transition from nucleate to film boiling. The coolant in most research reactors such as the ATR (Advanced Test Reactor) flows downward in thin gaps between the aluminum-uranium fuel plates. It is important to measure CHF parameters in both down flow and up flow conditions, since a pump trip and transition to natural circulation will result in flow reversal, CHF and up flow. Data from the Oh experiments on CHF conditions for ATR is available for benchmarking thermal hydraulic codes and CHF models. Comparison of the TRAC-B/PC and the Relap5/Mod2.5-PC codes to the Oh data indicate that TRAC-B/PC performs satisfactorily for predicting power to CHF using the Shumway Simplified Boiling Curve and the Hochreiter and Holowach (H/H) CHF correlation. The Relap5/Mod2.5-PC also compares satisfactorily to the Oh data using the Hochreiter and Holowach CHF correlation.

The Hochreiter and Holowach CHF correlation performs well compared to the Oh experiments and will be programmed into the SINDA/Relap methodology for use in performing safety analyses.

1.0 Introduction

The purpose of this report is to discuss the predictive capabilities of the TRAC-B/PC[1] and Relap5/Mod2.5-PC[2] thermal hydraulics computer codes for estimating power to CHF of the Oh[3] experiments. The power to CHF terminology is used to describe the total power used in the experiment when CHF occurs.

TRAC-B and Relap5/Mod2.5 were converted to run on personal computers as part of this effort.

One of the objectives of the analysis performed with TRAC-B/PC and Relap5/Mod2.5-PC is to predict the power requirements needed for a new CHF test facility that is being designed to measure CHF at higher flow rates.[4] The new facility tests are being planned to obtain data for the velocity range of 1-4 feet per second. This data is not presently available in the literature. This new data will be used with the data from Oh[3] and the methodology developed by Hochreiter and Holowach [5,6] to develop a new local CHF correlation. Another objective of the experimental work is to obtain additional knowledge for CHF and related phenomena in research type reactors and the possibility of extending power margins for ATR operations.

This report consists of sections 2.0 and 3.0. Section 2.0 describes selected Oh CHF test comparisons for TRAC-B/PC and the Relap5/Mod2.5-PC codes and models. Section 2.0 also discusses the implementation of the Hochreiter and Holowach CHF correlation in the codes. Section 3.0 summarizes the results and makes recommendations on future modeling and code development to address CHF correlation development and implementation for ATR.

2.0 Oh CHF Experiments

The TRAC-B/PC and Relap5/Mod2.5-PC codes were compared to the Oh tests in order to examine their predictive capability and applicability for the design of the new CHF experimental apparatus. The Oh[3] tests were performed for steady-state subcooled water flow, uniformly heated to boiling in a vertical rectangular channel. A total of 116 runs were performed for a channel gap of 0.00198 meters (m), 0.0508 m in width and 0.6096 m in length. The test section was made of aluminum with a pyrex front plate for flow visualization. The ranges of the variables tested included a system pressure of 10 to 91 kPa, inlet water temperatures of 295 to 343 K and a mass flux rate of 30 to 80 kg/m^2s for up flow and down flow.

The test results indicated that CHF occurs at a 15% lower power level in down flow than in up flow. This is due to a flow instability consisting of counter current flow and its effect of lowering the inlet temperature of the incoming liquid. The basic model for the comparisons is shown in Figure 1.0. It consists of ten vertical cells and eleven junctions. The model shown in Figure 1.0 is for up flow.

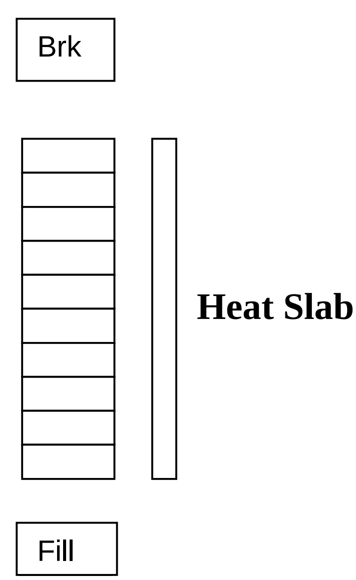


Figure 1.0 Basic Model Geometry

Down flow simulations are performed by switching the fill and break components to the top and bottom of the model. Appendix I contains the calculation worksheet for the model.

The following experiments were chosen for comparison from Appendix A of reference 3. These cases are illustrated in Table 1.

Table 1.0 Oh Cases Modeled

Run #	Pressure (kPa)	Inlet Temperature ^{o}C	Mass Flux kg/m2-s	Pwr at CHF (kW)
59	28.8	63.6	62.4	7.13
35	84.7	27.2	35.6	6.85
92	21.1	24.7	47.5	6.58
84	52.3	26.9	49.2	6.85
8	86.0	61.8	110	9.91

Case numbers less than or equal to 66 are for up flow and case numbers greater than 66 are for down flow. The pressure, temperature and mass flux data in Table 1.0 were used as initial and boundary conditions for the model of Figure 1.0. A fill for a constant velocity, equivalent to the mass flux for each case was used. The pressures and temperatures of Table 1.0 were used for both the fill and break thermodynamic conditions. The flow channel and heat structure were modeled using a pipe component. The aluminum wall heat structure was modeled using the finite difference option with six nodes in the TRAC-B/PC and Relap5/Mod2.5-PC code models. A user input table for the metal properties was used in the models. Boundary conditions used for the heat structures were adiabatic.

A steady state run was executed for each of the models and codes. The transient was initiated from the restart file. The transient was started by a linear ramp of the heat source term over 20-120 seconds for most of the transients. The ramp time was obtained by interpolating the temperature traces for the experiments in Reference 3.

The TRAC-B/PC and Relap5/Mod2.5-PC codes have several correlation options for CHF. However, it was determined that the correlation (model) that worked best at the time this study commenced was the simplified boiling curve (SBC)[1] in TRAC-B/PC, developed by R. Shumway of Reference 1. The Hochreiter/Holowach CHF correlation[5,6] and its methodology were not totally available until recently.

The SBC in TRAC-B/PC assumes departure from nucleate boiling when the wall temperature is greater than the saturation temperature by 25 Kelvin. The different heat transfer regimes are shown in Table II. For TRAC-B/PC, the author[7] recommended determining CHF by a Departure from Nucleate Boiling (DNB), equivalent to a change from mode 7.20 to any of the other modes listed in Table II.

The Hochreiter/Holowach CHF correlation is based on local thermal hydraulic conditions, which makes it highly amenable to implementation in thermal hydraulic codes. Previous CHF models for test reactors are based on global system parameters developed from the experimental data. The Hochreiter/Holowach CHF correlation is based on local equilibrium quality, defined as

$$x_e = \frac{h - h_f(p)}{h_s(p) - h_f(p)} \quad (1)$$

X_e is the equilibrium quality, h is the mixture enthalpy, h_f and h_s are the liquid and steam saturation enthalpies. The Hochreieter/Holowach CHF correlation[5,6] is given as

$$q''_{chf} = F_p \times C_1 e^{-2.9 x_e} \quad (2)$$

in units of kw/m^2. Fp is the pressure correction term and C_1 is a constant equal to the value 1000 kw/m^2. The pressure correction factor is dimensionless and is given as

$$F_P = \frac{\left(q''_{chf}\right)_P}{\left(q''_{chf}\right)_{Po}} \quad (3)$$

The subscripts P and Po denote local pressure and atmospheric pressure evaluations. More details on this correlation are given in References 5 and 6. The parameters needed for implementation of the correlation are already available in the codes. The (H/H) CHF correlation was implemented in subroutine htcor for TRAC-B/PC and subroutine chfcal for Relap5/Mod2.5-PC.

Table II. TRAC-B/PC Heat Transfer Regimes

Mode #	Description
7.20	Nucleate Boiling (CHEN)
7.26	High Void Interpolation
7.30	Loomis Shumway Transition
7.36	Void Interpolation
7.40	Film Boiling

2.1 Oh Case 59

The up flow cases were evaluated first, since more power is needed to reach CHF in cocurrent up flow. This is because the down flow CHF cases are dominated by countercurrent flow limitations. This case was modeled to assess the predictive capability of TRAC-B/PC and the Relap5/Mod2.5-PC codes for up flow.

2.1.1 TRAC-B/PC Results

Figure 1.0 shows the void fraction obtained in the topmost cell using the Simplified Boiling Curve (SBC), while Figure 2.0 shows the heat transfer modes calculated by TRAC-B/PC for this case, using the SBC option. The code transitions from nucleate boiling (mode 7.2) to high-void interpolation (mode 7.26) at 87 seconds. The code calculation appears to reach dryout (high-void fraction) before departure from nucleate boiling, shown in Figure 1.0. This should be expected for cell 10 since bubbles will be swept upward in the flow. The term dryout has some interpretation, since as shown in Figure 1.0, a void fraction close to 1.0 is not obtained until the time of simulation is greater than 100 seconds. Figure 3.0 illustrates the liquid heat transfer coefficient (HTC) for cell 10 at the wall. Note that the steep rise in the HTC occurs coincident with the heat transfer mode change shown in Figure 2.0 at 87.0 seconds. Examination of the output shows that the heat transfer mode of 7.26 occurs at 87 seconds and is equal to 6.62 kW. The experimental value of the power at CHF from Table II is 7.13 kW, which gives an error of 7.15 % with the calculated value. Figure 4.0 shows the calculated power versus time curve.

The next set of Figures, 5.0, 6.0, 7.0 and 8.0 show the same parameters for the TRAC-B/PC code using the Hochreiter/Holowach CHF correlation. The power at CHF obtained with this CHF correlation was calculated as 6.69 kW. This gives an error of 6.17% with the experimental number (7.13 kW) for power to CHF.

2.1.2 Relap5/Mod2.5-PC Results

The (H/H) CHF correlation was programmed directly into subroutine CHFCAL of Relap5/Mod2.5-PC. Other CHF correlations available in Relap5/Mod2.5-PC yielded results either much less or greater than the Oh experiments power to CHF values. The majority of the time the code would fail before any answer could be obtained.

Figure 9.0 shows the calculated void fraction in cell ten using the correlation. Figure 10 shows the heat structure temperature associated with volume 10 for the transient. The rapid rise in temperature is due to the change in heat transfer modes, shown in Figure 11.

The change from nucleate boiling to saturated film boiling occurs at approximately 192 seconds, as shown in Figure 11. Figure 12 illustrates the total heat input as a function of time. The amount of total heat input at 192 seconds is approximately 5.950 kW. This yields an error of 16.5% with respect to the experimental data.

2.1.3 Summary of TRAC-B and Relap5/Mod2.5-PC Results

In order to obtain good results with either TRAC-B or Relap5/Mod2.5-PC the procedure followed was:

1. Run the steady state options with little or no heat added to the volumes
2. Perform a restart with a linear ramp for added heat or heat flux
3. Use a large time step and run the code to transition film boiling and code failure
4. Repeat the restart with a time step < 0.001 seconds before the transition and run till termination or failure

This procedure generally gives good comparisons. TRAC-B/PC and Relap5/Mod2.5-PC do not have the heat structures and hydrodynamics implicitly coupled. This is most likely why the time step has to be smaller than the Courant Limit for both codes.

Table III. Summary of Predicted Results for Power (kW) to CHF

Case#	TRAC-B/PC	SBC	(H/H)	Relap5/Mod2.5-PC	Experiment
59		6.62	6.69	5.95	7.13
8		13.4	14.6	1.89	9.91
92		5.39	5.26		6.58
35		8.02	6.80	6.7	6.85
84		6.03	6.02		6.85

Sensitivity studies were performed for a 20 cell and 24 heat structure model for Oh down flow case 92. The results were 6.35 kW for the power to CHF. Although the results were improved, the case took almost six times the amount of time to execute. This becomes prohibitive for a 233 MHz PC. Similar results were obtained with Relap5/Mod2.5-PC. Future plans are to install the codes on a 1.5 GHz PC and perform all the cases using a Perl Script.

3.0 Summary and Future Plans

The applicability of the TRAC-B/PC and the Relap5/Mod2.5-PC thermal hydraulics for determining power needed to reach CHF has been ascertained by comparison of the codes to some of the Oh CHF experiments. In general, the results are acceptable, indicating that the predictions of the code for power needed to reach CHF in the next generation CHF test facility would be acceptable. The calculations for the power needed to reach CHF and the results of this investigation will be part of an Engineering Design File (EDF).

As part of this study it was determined that the CHF correlation by Hochreiter and Holowach should be used in the statistical based computational package of SINDA/Relap used for ATR safety analyses. Since this is a local correlation that depends on equilibrium quality, the implementation is relatively user friendly compared to global dependencies such as heated length, flow direction dependencies and subcooling in the present CHF correlation in SINDA/Relap. The (H/H) correlation will be implemented and examined for increased power margin in the safety analyses.

References

1 R. W. Shumway, et al., TRAC-BD1/MOD1: An Advanced Best Estimate Computer Program for Boiling Water Reactor Transient Analysis, Volume 1: Model Description, NUREG/CR-3633, April, 1984.

2 Ransom, V.H., et al., "Relap5/Mod2 Code Users Manual," Egg-TFM-7952, December, 1987.

3 Oh, C.H., Englert, S. B., "ATR Critical Heat Flux Experiments Under Low Pressure and Low Flow Conditions," PG-T-92-004, March, 1992.

4 Mecham, D., et al., LDRD:"Thermal Studies of Potential Increased ATR Power Margins", LDRD Proposal Year 2000.

5 Holowach, M.J., Hochreiter, L.E., Cheung, F-B., Aumiller, D.L., "Critical Heat Flux During Reflood Transients in Small Hydraulic Diameter Geometries," to be published.

6 Holowach, M.J., "The Development of a Reflood Heat Transfer Computational Package for Small Hydraulic Diameter Geometries," Thesis, The Pennsylvania State University, December, 2000.

7 Shumway, R., *Private Communication*, March, 2001.

Figures

Figure 1.0

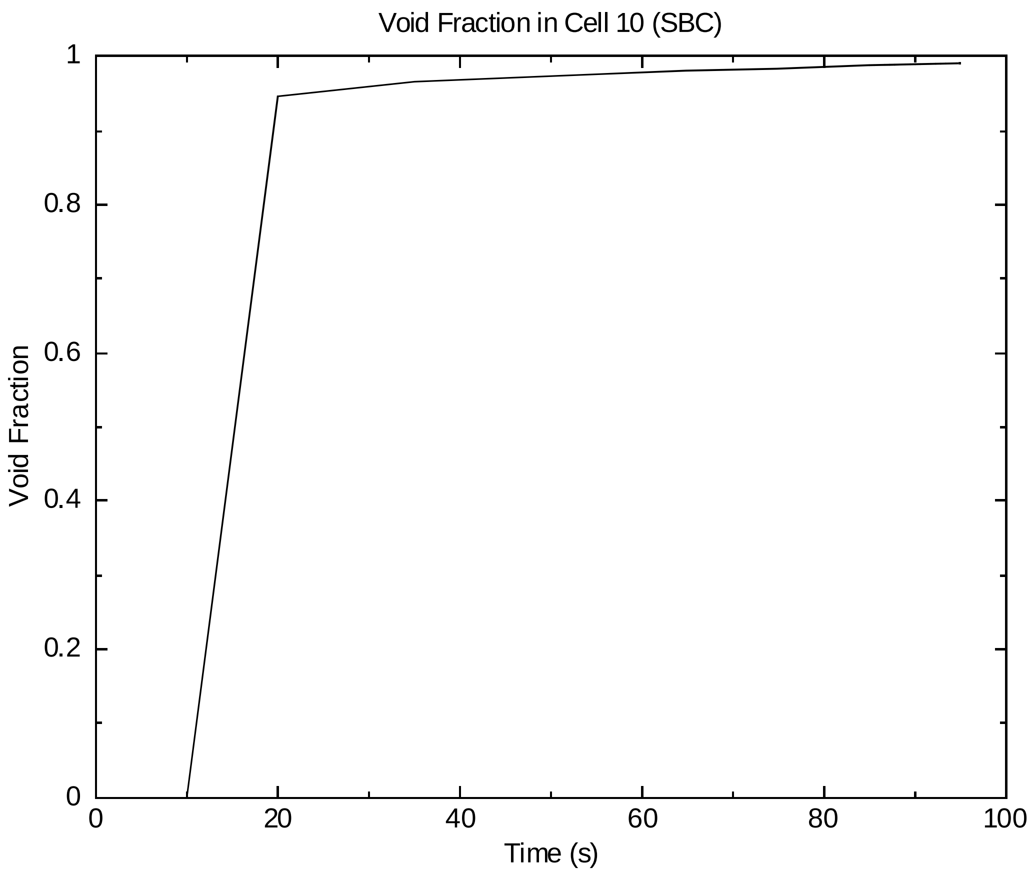


Figure 2.0

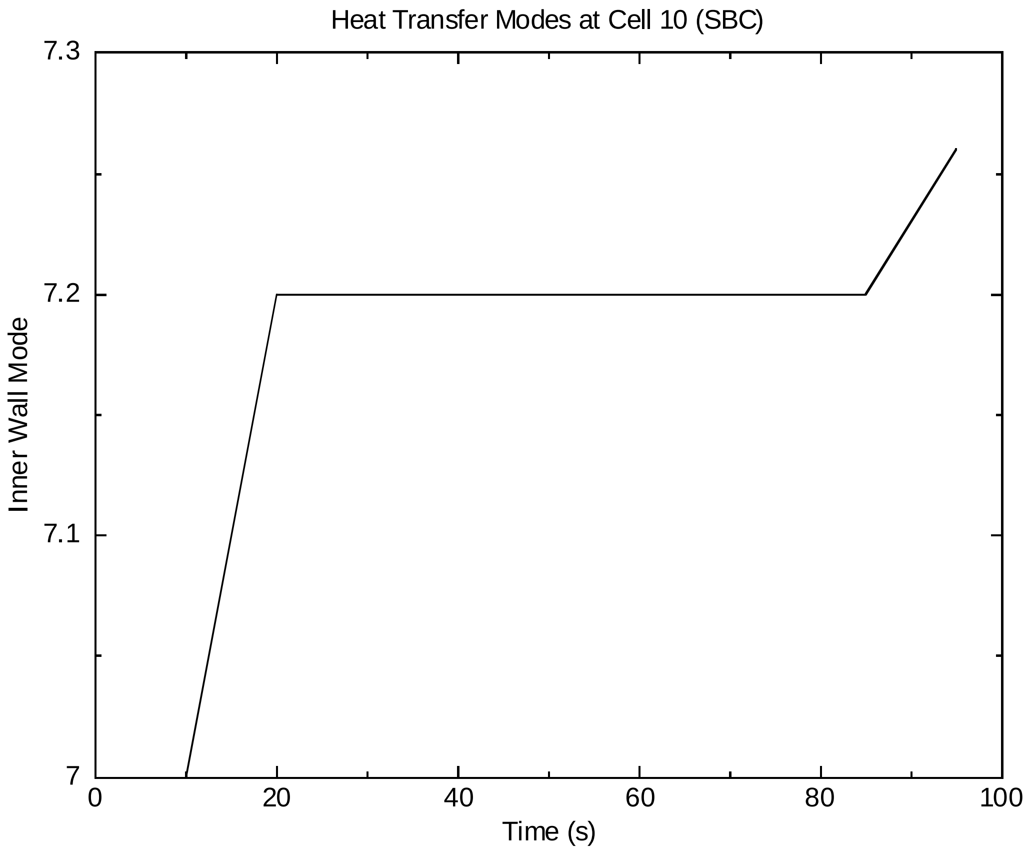

Heat Transfer Modes at Cell 10 (SBC)
Inner Wall Mode
7.3
7.2
7.1
7
0
20
40
60
80
100
Time (s)

Figure 3.0

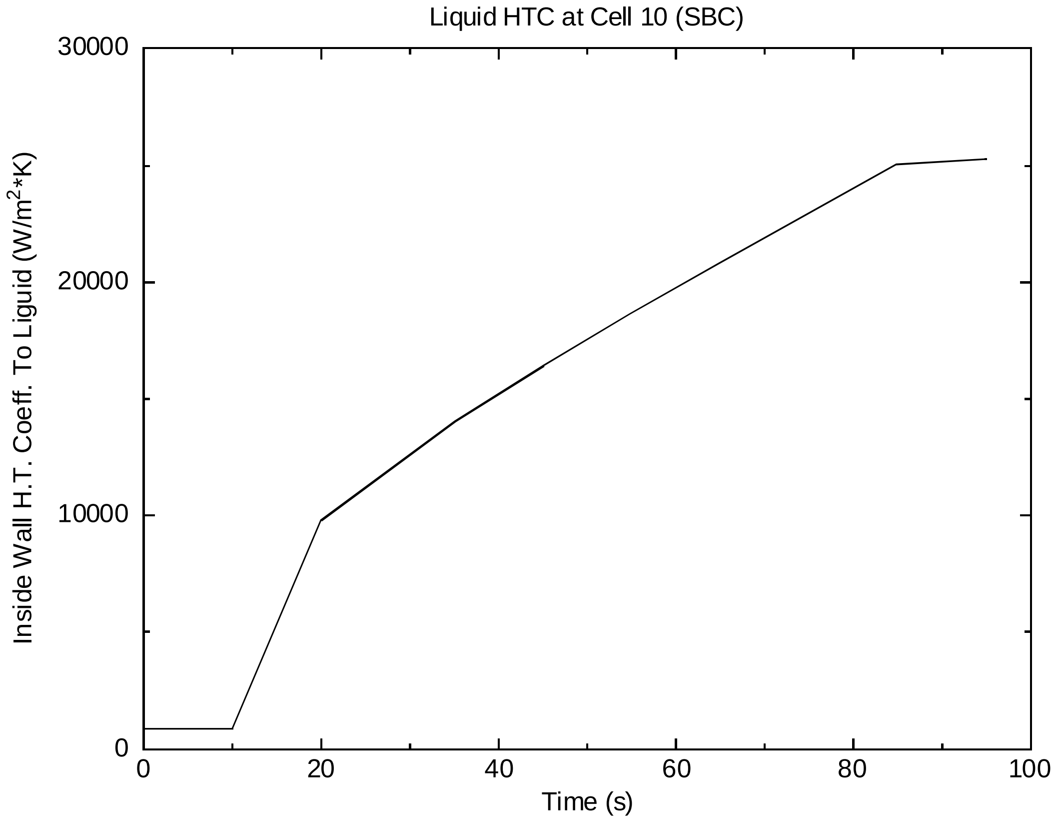


Figure 4.0

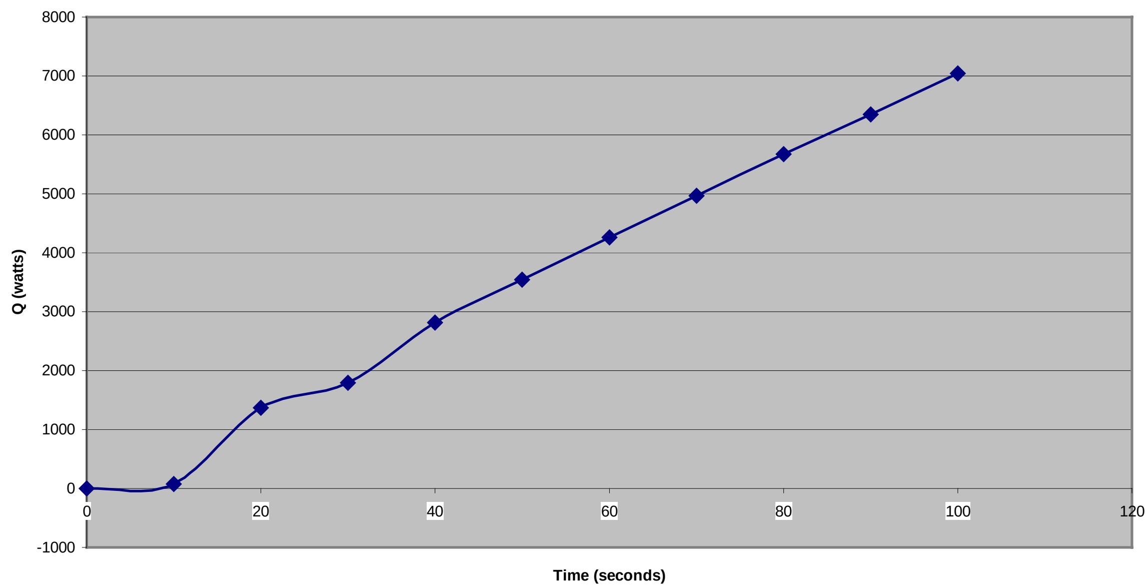


Figure 5.0

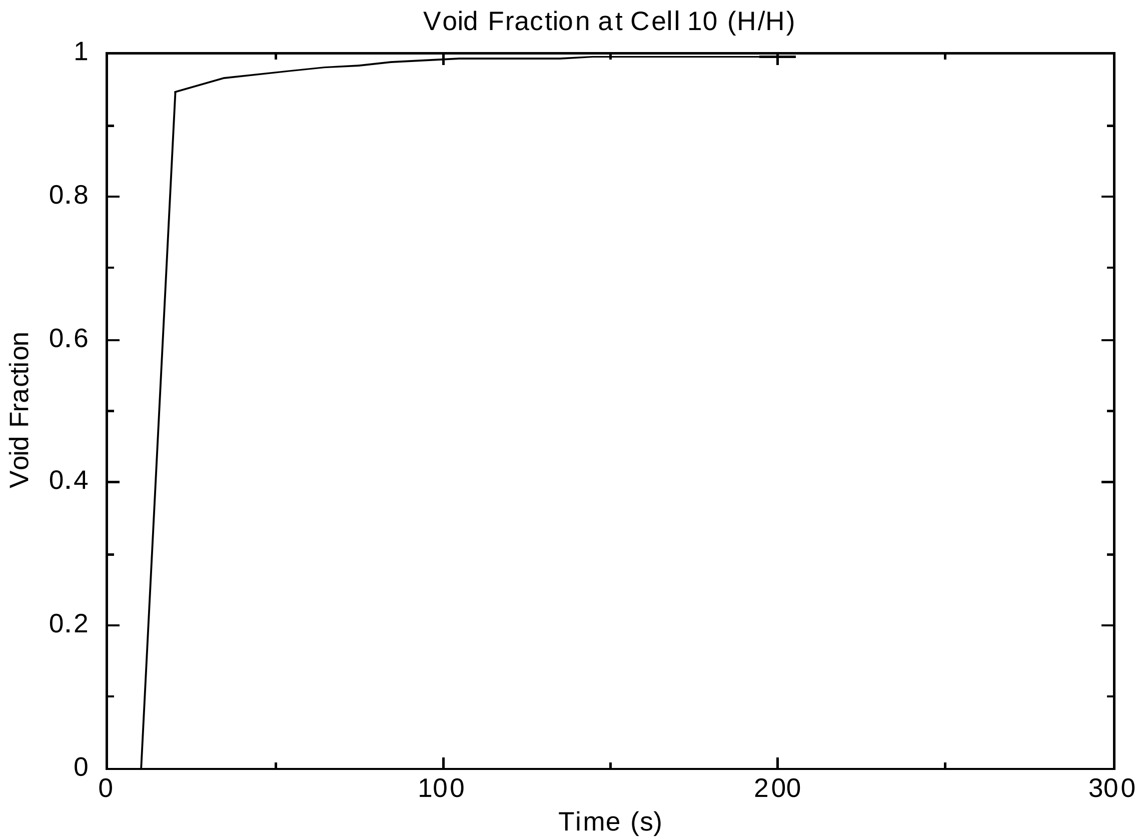

Void Fraction at Cell 10 (H/H)
Void Fraction
1
0.8
0.6
0.4
0.2
0
0
100
200
300
Time (s)

Figure 6.0

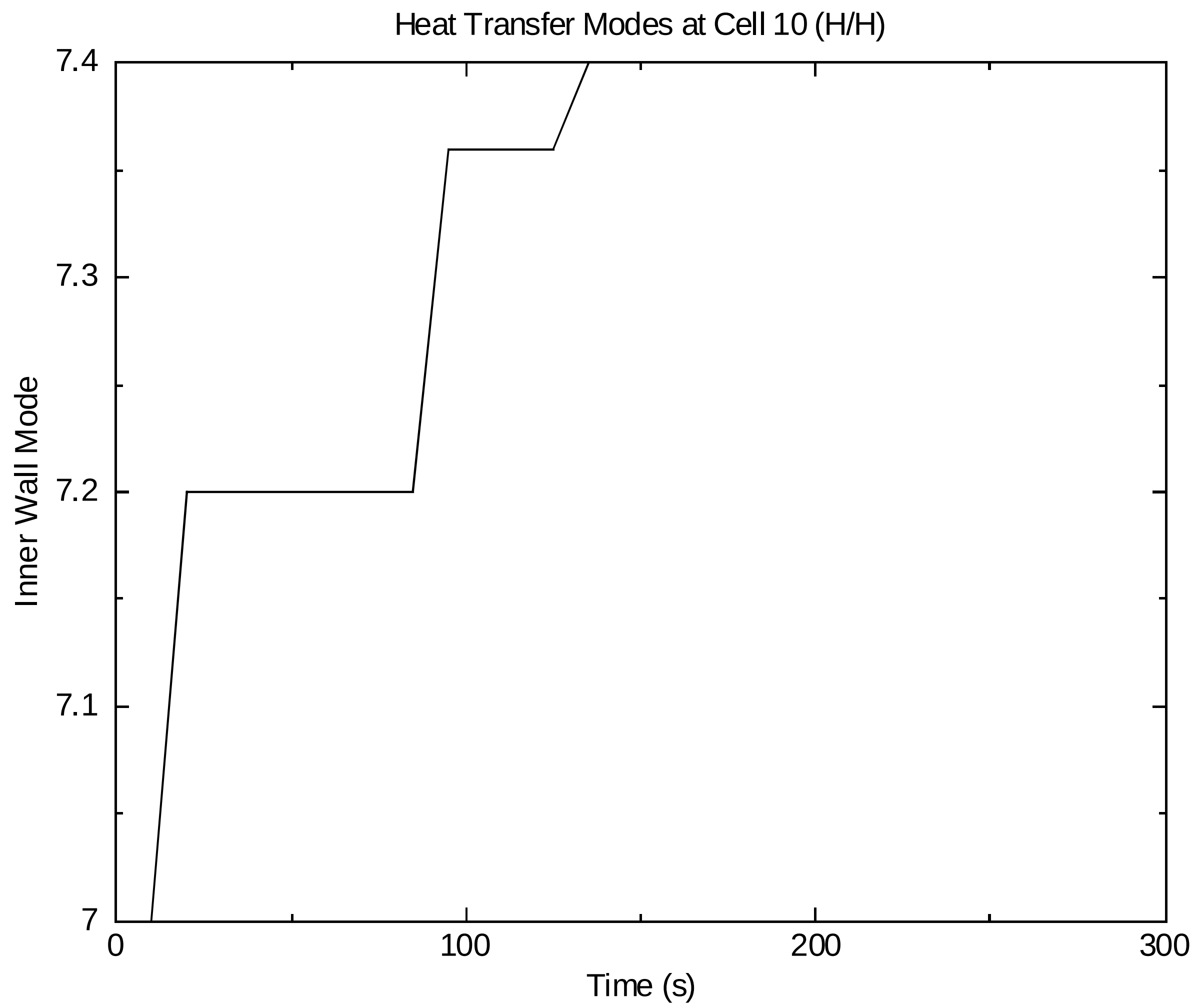

Heat Transfer Modes at Cell 10 (H/H)
7.4
7.3
7.2
7.1
7
Inner Wall Mode
0
100
200
300
Time (s)

Figure 7.0

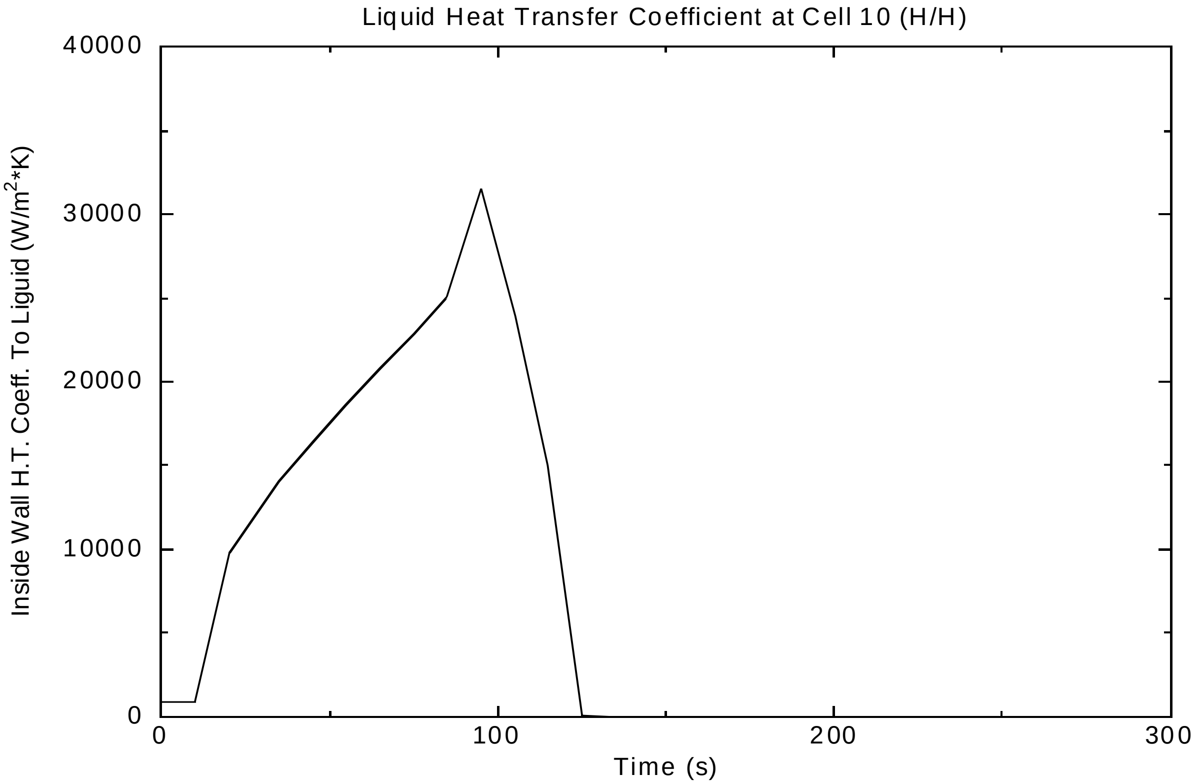


Figure 8.0

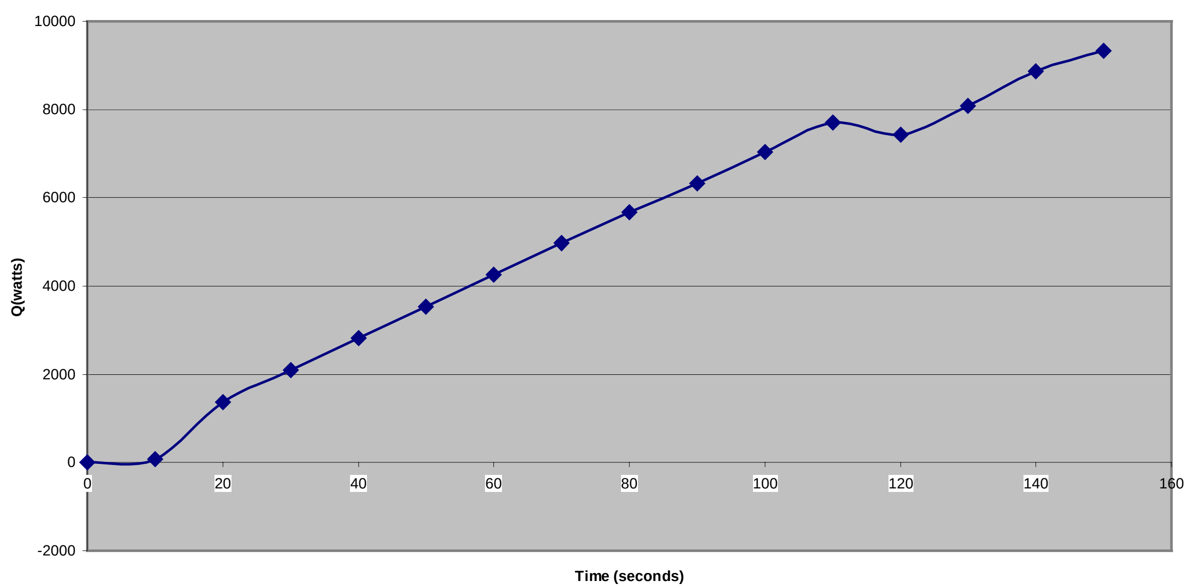


Figure 9

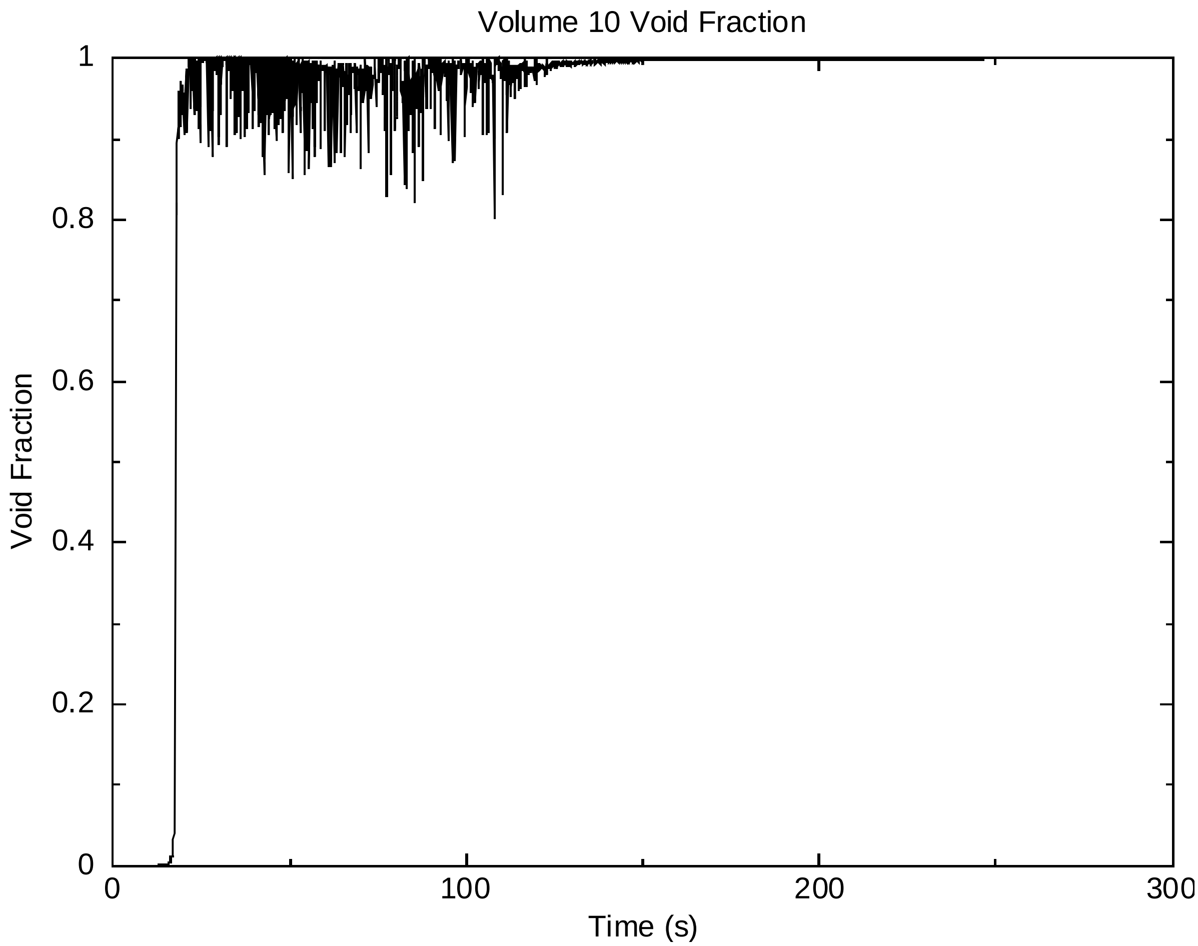
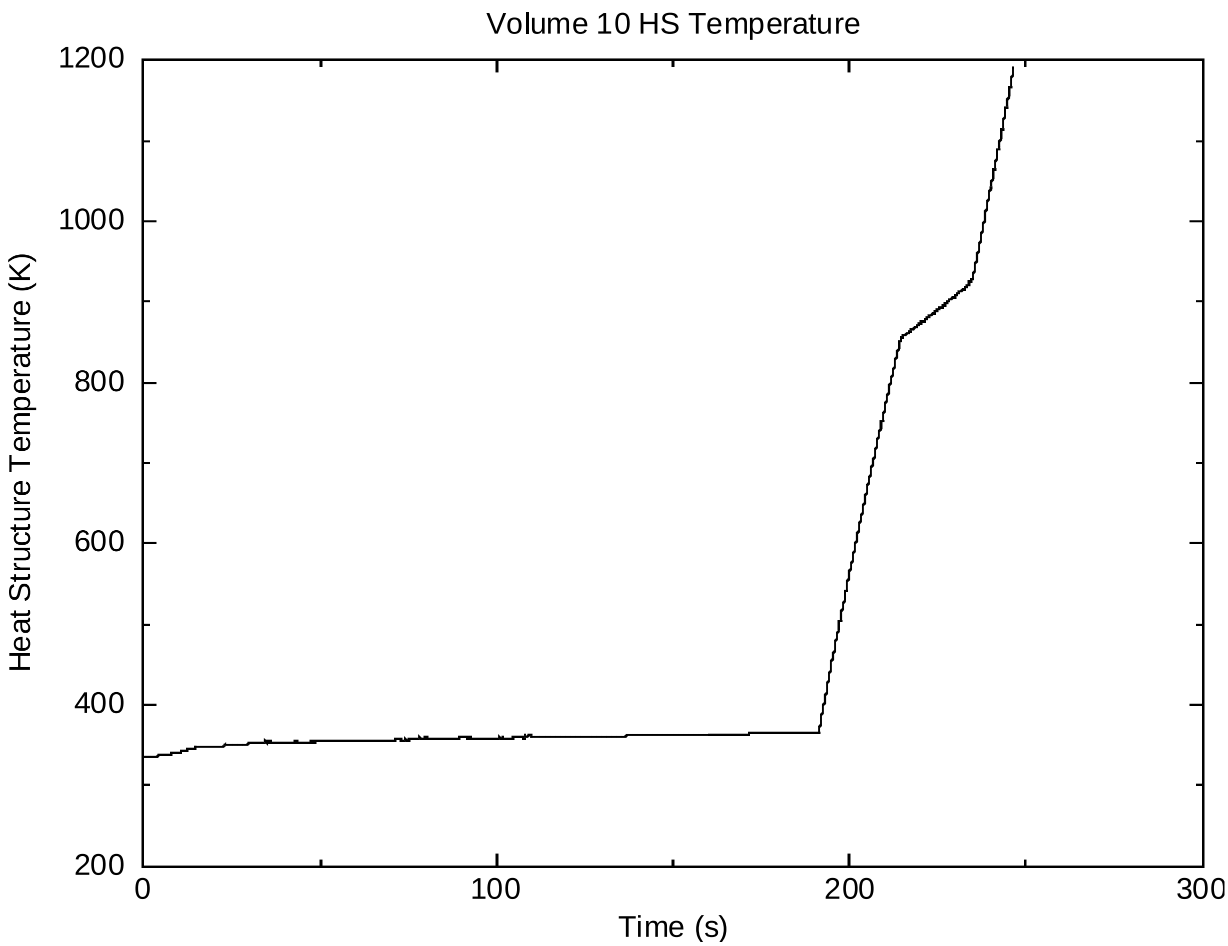

Volume 10 Void Fraction
Void Fraction
Time (s)
0
0.2
0.4
0.6
0.8
1
0
100
200
300

Figure 10


Volume 10 HS Temperature
Heat Structure Temperature (K)
Time (s)
1200
1000
800
600
400
200
0
100
200
300

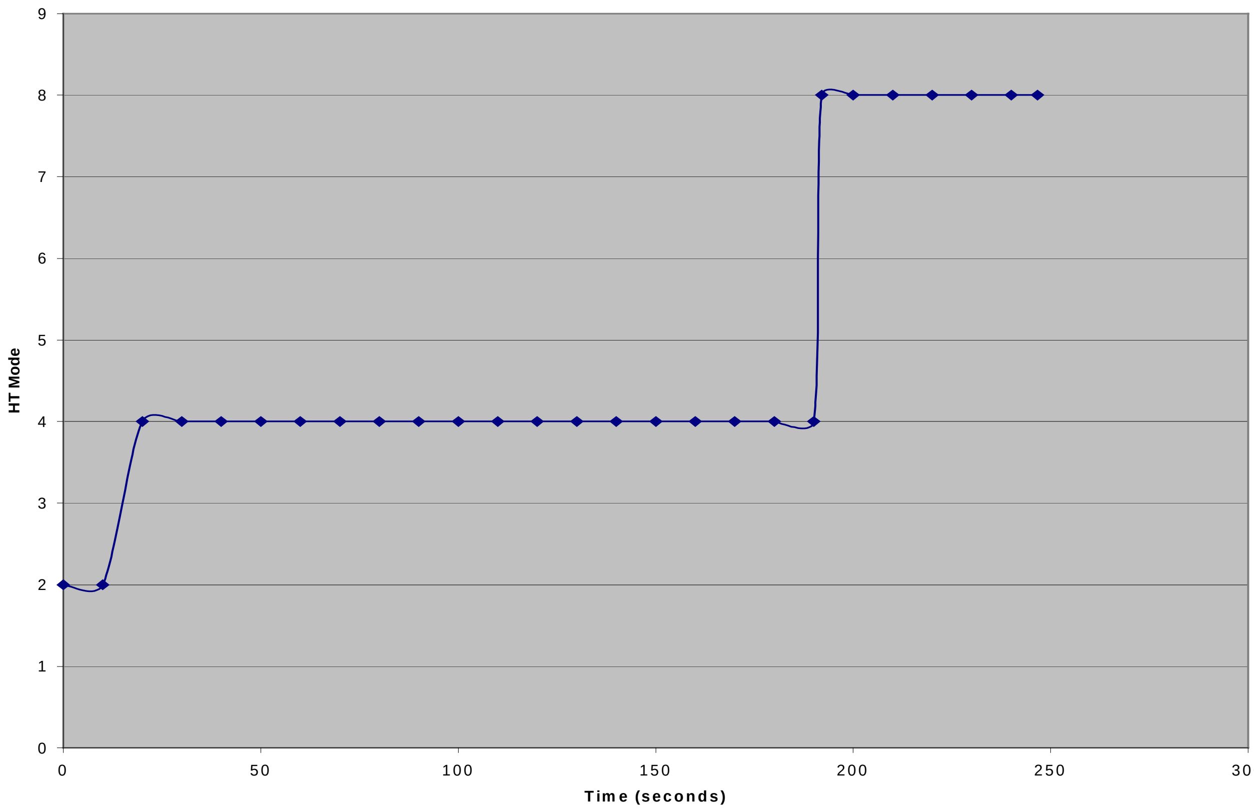


Figure 11

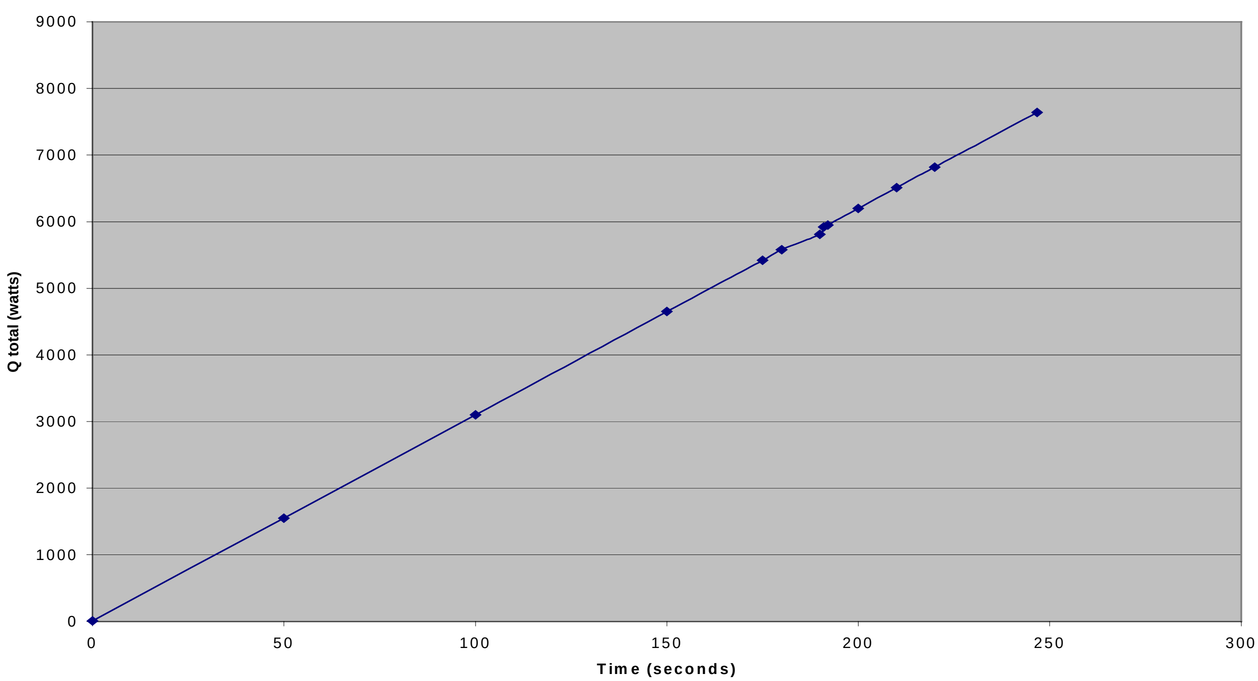


Figure 12