VALIDATION OF CATHENA FOR CHF AND POST DRYOUT HEAT TRANSFER USING AN RD-14M SMALL-BREAK LOCA TEST

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ABSTRACT

Code validation was performed to assess the ability of CATHENA MOD-3.5d/Rev 1 to simulate the critical heat flux and post dryout heat transfer phenomena. The simulation results calculated by CATHENA MOD-3.5d/Rev 1 are compared with experimental data from the RD-14M small-break LOCA test B9802. With the new post-dryout heat transfer model implemented in the MOD-3.5d code version, the CATHENA-predicted sheath temperatures are in much better agreement with the test measurements than those from the MOD-3.5c/Rev 0 validation.

Key Words: CATHENA, Validation, CHF, Post Dryout Heat Transfer

1 INTRODUCTION

CATHENA is an advanced two-fluid thermalhydraulic code developed by Atomic Energy of Canada (AECL) [1] primarily for the analysis of postulated Loss-Of-Coolant Accident (LOCA) and other upset scenarios in CANDU® reactors. As a tool for reactor safety analysis, the code needs validation to demonstrate confidence that CATHENA reliably and accurately simulates the thermalhydraulic phenomena governing the postulated scenarios. Critical heat flux (CHF) and Post-Dryout (PDO) heat transfer are among these important governing phenomena.

The prediction of the CHF of the fuel bundles is of particular importance because it is one of the main criteria limiting reactor power levels under normal operating conditions. During postulated accidents, such as LOCA, LOR and LOF, a timely reactor shutdown is required to limit the potential challenge to the heat removal capability of the heat transport system. Post-dryout heat transfer is only considered for postulated accident conditions. Accurate prediction of these heat transfer regimes is required to confidently predict fuel and primary system response during the blowdown and refill phases of a LOCA scenario.

This paper summarizes the validation conducted to assess the ability of CATHENA MOD3.5d/Rev 1 to simulate CHF and PDO heat transfer using small-break LOCA tests conducted in the RD-14M facility. In this work, CATHENA simulation results are

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compared with experimental data and previous validation results. Impacts of uncertainties from the experimental measurements and code correlations on the simulation results are also assessed.

2 CATHENA CODE

2.1 General Description

CATHENA uses a transient, one-dimensional two-fluid representation of two-phase flow in piping networks. In the thermalhydraulic model, the liquid and vapour phases may have different pressures, velocities, and temperatures. The thermalhydraulic model consists of six partial differential equations for the conservation of mass, momentum, and energy for each phase. Interface mass, energy, and momentum transfer between the liquid and vapour phases are specified using constitutive relations obtained either from the literature or developed from separate-effect experiments. The code uses a staggered-mesh, one-step, semi-implicit, finite-difference solution method, that is not transit time limited. The extensive wall heat transfer package includes radial and circumferential conduction, solid-solid contact, thermal radiation, pressure-tube deformation, and the zirconium-steam reaction. The heat transfer package is general and allows the connection of multiple wall surfaces to one or more thermalhydraulic nodes. The code also includes component models required to complete loop simulations, such as pumps, valves, tanks, break discharge, separators, and an extensive control system modelling capability. A more complete description of the CATHENA thermalhydraulic code is provided in [1].

2.2 CHF and PDO Heat Transfer Models

The default option for CHF calculations in CATHENA is the Groeneveld-Leung CHF table lookup method [2]. This option actually consist of 8 separate tables, including tables for both light water (H_2O) and heavy water (D_2O) in tubes, 37-element bundles, CANFLEX (43-element) Mk-IV and CANFLEX Mk-V bundles. The input parameters for the table lookup are pressure, mass flux, and equilibrium quality. CATHENA automatically selects the most appropriate table based on the channel geometry defined by the user. The CHF tables were updated for 37-element bundles and new CHF tables were included for CANFLEX bundles in the MOD-3.5d/Rev 1 code version.

In the MOD-3.5d code version, the default correlation for fully developed PDO heat transfer was changed from the Groeneveled-Delorme correlation [3] to the Leung lookup table (based on wall superheat) [4]. The wall-superheat based PDO lookup table provides a value of heat transfer coefficient from known pressure, equilibrium quality, mass flux and wall superheat.

In addition, a developing PDO heat transfer model [5], which includes “best-estimate” and “minimum” developing PDO heat transfer calculations, is available in CATHENA MOD-3.5d/Rev 1 for 37-element bundles, CANFLEX Mk IV bundles and tubes. In a tube or bundle with flow and enthalpy non-uniform distributions, the onset of dryout is reached in a non-uniform way on different surfaces. Close to CHF, the dry patch covers only a fraction of a tube or bundle. For a one-dimensional code like CATHENA, the entire surface is assumed to experience fully-developed post-dryout heat transfer conditions after the first occurrence of CHF in the tube or bundle. As a result, the net surface heat flux will be significantly underestimated. The best-estimate PDO heat transfer correlation is used for an "average" heat transfer calculation, based on interpolation of the heat transfer between CHF (i.e., nucleate boiling) and fully-developed film boiling conditions. An important consideration in the application of the best-estimate PDO calculations is that they are based on the average thermalhydraulic conditions for the entire surface of the tube or bundle. The best-estimate PDO heat transfer correlation is used for the developing PDO heat transfer on the whole tube or bundle and the minimum PDO heat transfer correlation is used to compute the maximum sheath temperature on the heat transfer area in film boiling based on the conditions in terms of coolant flow, temperature, void, wall heat flux, CHF and pressure.

3 EXPERIMENTS

From the RD-14M small break tests, test B9802 was selected for CATHENA validation since this test had a lower flow rate and therefore exhibited CHF and post-dryout heat transfer in the high-powered channels.

3.1 Test Facility

RD-14M is an 11 MW, full-elevation-scaled thermalhydraulic test facility possessing most of the key components of a CANDU primary heat transport system [6]. Figure 1 shows a simplified schematic of the RD-14M facility. The facility is arranged in the standard CANDU two-pass, figure-of-eight configuration. The reactor core is simulated by ten (five per pass) 6 m-long horizontal channels (test sections). Each test section has simulated end-fittings and seven electrical heaters (heated sections), or fuel element simulators (FES). Test sections are connected to headers via full-length feeders. The elevation of the above-header piping is also CANDU-typical. The above-header piping includes the piping connected to two full-height, U-tube steam generators, and two bottom-suction centrifugal pumps. Steam generated in the secondary side of the steam generators is condensed in a jet condenser and returned as feedwater to the steam generators. A pressurizer/surge tank controls the primary-side pressure. The test facility is also equipped with Emergency Coolant Injection (ECI) systems.

The FES pins consist of a central core of magnesium oxide surrounded by an electrically heated Inconel 625 tube. The tube is insulated from the 13.18 mm outside diameter stainless steel sheath by a 2 mm thick annulus of boron nitride. Seven FES pins are surrounded by a 44.80 mm inside diameter pressure tube. The FES pins are divided into 12 axial sections, each having a length of 495 mm.

The RD-14M loop is extensively instrumented. Over 550 instruments, measuring various thermalhydraulic parameters, are scanned and recorded using a dedicated data acquisition system during RD-14M experiments. In addition to above-header pressures, temperatures, volumetric flow rates, and void fraction measurements, inlet and outlet feeder temperature, pressure, volumetric flow rate and void fraction (gamma densitometers) are measured for each test section. Sheath temperatures are measured circumferentially along the length of various fuel element simulators.

3.2 Test Procedure

B9802 was a 3-mm inlet-header (HD 8) break blowdown test. It was performed under the CANDU typical pressure and temperature conditions (10 MPa, 300ºC). During the tests the primary pumps continued running and full channel power was maintained until the facility protection trips activated. The ECI system was not used in this test. Test B9802 exhibited CHF and post-dryout heat transfer in the high-powered channels, as indicated by the measured FES temperatures.

Before the test, input power and pump speed were adjusted to bring the test loop to the desired steady state, single-phase starting conditions. Data scanning was started and the primary loop pressurizer was isolated prior to the start of the blowdown. The test was started by opening the blowdown valve at 11.2 seconds after the data scanning. Other test parameters (e.g., pump speeds, channel powers, and secondary side pressure) remained unchanged from their steady-state settings. During the test, the primary loop pressure and flow rate decreased slowly, while the void fraction increased in the loop. By 950 s, the primary flows began to develop a density oscillation in the loop. At 1192 s, the over-voltage protection system tripped Pump 1, while Pump 2 continued to run. This resulted in large oscillations in the primary loop flow rate. As a result, sustained dryout was observed at the outlet ends of the heated sections. The test was terminated when FES temperatures reached their upper temperature limit (600ºC) at 1336 seconds.

4 CATHENA MODEL

This validation exercise is focused on the CHF and post-dryout heat transfer that occurred in the heated sections of the facility. Therefore, this validation exercise used a “slave” channel model to simulate heated section 12, which exhibited CHF and PDO heat transfer. The CATHENA idealization of heated section 12, is based on the RD-14M integrated model [7]. The fluid conditions (i.e., pressure, flow rate, temperature) at the inlet and outlet of test section 12 recorded from the experiment were imposed as boundary conditions on the model. The inlet and outlet void fractions were set to zero as the test data indicated a single-phase liquid flow at the inlet during the test. The value of outlet void fraction is not important since no flow reversals occurred at the outlet of the channel, indicated by the measured outlet flow rate and pressure-drop over the channel.

The test section was modelled using a single pipe component with 12 axial nodes, as shown in Figure 2. The inlet and outlet end fittings and the horizontal portions of the inlet and outlet feeders connected to the end fittings were included in this idealization. The RD-14M 7-element FES bundle was represented by three “cylinder groups” to facilitate modelling the heat transfer split between the liquid and vapour phases under stratified flow conditions. The FES bundle was modelled using four radial regions and 12 radial nodes shown in Figure 3. FES internal thermocouples were typically mounted near the inside surface of the FES stainless-steel sheath. Radial node 9 was assumed to be coincident with the internal thermocouple location so the temperature histories at radial node 9 were compared to measured temperatures in this validation. The best-estimate 37-element developing PDO heat transfer model was applied to the FES pin model to improve the bundle PDO heat transfer prediction during the oscillatory phase of the test. In this phase, the FES surfaces experienced dryout and rewet intermittently. CATHENA would overestimate the sheath temperatures significantly if the best-estimate developing PDO heat transfer correlation were not applied.

5 VALIDATION RESULTS

All simulations in this validation exercise were executed on an Intel/Windows XP computer platform, using the CATHENA MOD-3.5d/Rev 1 code version.

5.1 Transient Simulation Results

The key output parameters for this validation were the FES sheath temperatures. Data from the outlet end of heated section 12 was used in the comparisons of predicted and measured FES sheath temperatures. Figure 4 shows the histories of the sheath temperatures on top, middle and bottom pins at the outlet end of the test section. In the figures, the results calculated by CATHENA MOD-3.5d/Rev 1 are compared with the experimental data and the simulation results obtained from MOD-3.5c/Rev 0 validation. Prior to 1000 s, the bundle surfaces were under liquid convective or nucleate boiling heat transfer conditions. To focus on the CHF and PDO heat transfer behaviour in the FES, only sheath temperature histories after 1000 s are shown and discussed.

The test data shows that by 1030 s the inlet flow of test section 12 was fluctuating, resulting in temporary channel flow reversal and stagnation. The sheath temperature spikes were initially in unison with the flow fluctuations. The temperature spikes were assumed to indicate that a localized dry patch on the FES surface, directly opposite the thermocouple location, dried out and exceeded CHF. During the positive flow portions of the flow oscillations, these locations quickly cooled to the base line temperature. Late in the test (around 1200 s), the temperatures rose again and did not cool down. The sheath temperatures were consistently between 400 and 600°C, clearly indicating that these locations were experiencing post-dryout heat transfer.

CATHENA MOD-3.5d/Rev 1 successfully simulated the sheath temperature spikes and fluctuations between 1050 and 1200 s, which indicated that local FES surface was being temporarily dried out and then being rewet. The predicted onsets of CHF were in a good agreement with the measured values. However, CATHENA overestimated the peak temperatures during the period of the temperature excursions. The average over-estimations in the peak temperatures were 105°C, 117°C and 58°C at the outlet ends of the top, middle and bottom pins, respectively. In Figure 4, the predicted sheath temperatures are similar in the top, middle and bottom pins, as they were predicted under the average thermalhydraulic conditions. However, the measured bottom pin temperature was higher than those in the top and middle pins, since the bottom pin sheath temperature was measured at section 11 while the top and middle pin temperatures were recorded at section 12. Section 12 is the last heated section of the FES. The lower temperatures measured at the last section (12) have been attributed to presence of the unheated section of sheath necessary for the electrically heated elements and potential cross-flow in the proximity of the channel to end-fitting connection. During the last period of the transient (after 1200 s), sustained film boiling was predicted at all 3 locations. The CATHENA MOD-3.5d/Rev 1 predicted results generally overestimated the FES sheath temperatures, by 10–190°C. This indicates that the PDO heat transfer coefficients were generally underestimated by CATHENA in this test.

In the prediction using CATHENA MOD-3.5c/Rev 0, the sustained film boiling occurred as early as 1050 s, 150 s earlier than in measured results. Rewet on the sheath surface was not predicted although fluctuations were found in the simulated sheath temperatures. In the test, the FES surface experienced dryout and rewet intermittently due to the flow oscillation between 1050 s and 1200 s. Dry patches were developing but did not form a stable and continuous vapour film on the pin surfaces. The developing PDO heat transfer model, which was implemented in the MOD-3.5d code version, is applicable in this situation. As a result, CATHENA MOD-3.5d/Rev 1 successfully predicted the occurrences of dryout and rewet on the FES surfaces, while MOD-3.5c/Rev 0 did not. During the last period between 1200 and 1300 s, the sheath temperatures simulated by MOD-3.5d/Rev 1 and MOD-3.5c/Rev 0 are very close at all locations.

5.2 Uncertainty Analysis

An integrated uncertainty analysis was conducted to assess the combined impact on the key output parameter (FES sheath temperature) of all significant sources of uncertainty, including experiment conditions and empirical models in the code. Following the uncertainty analysis methodology pioneered by Glaeser *et al.* [8], a minimum number of 93 simulations with randomly-perturbed code inputs are required to achieve 95%/95% tolerance limits[1]. The code inputs with their uncertainties and biases are summarized in Table 1.

The time-dependent maximum and minimum values of FES temperature from the 93 simulations (the 95%/95% tolerance limits), as well as the best-estimate (BE) simulation, are shown in Figure 5. At the outlet end of the top pin, the earliest onset of CHF was predicted at around 1050s, the same time as the first onset of CHF in the experiment. The BE and minimum temperature curves captured the measured onset of continuous PDO heat transfer at 1200 s. The minimum temperatures were higher than the experimental data during the periods when FES temperature excursions occurred, which indicated the PDO heat transfer coefficients were underestimated. The mean and median of the 93 simulations (not shown in Figure 5) closely follow the BE prediction.

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[1] The upper and lower 95%/95% tolerance limits span 95% of the probability content of the distribution of code response, at a confidence level of 95%.

The code bias (ε) is defined as the difference between the best-estimate CATHENA predicted key output parameter and the corresponding measured value. Figure 6 shows the time-dependent code bias with the upper and lower uncertainty limits, which are calculated from the 95%/95% prediction tolerance limits and the 95% confidence measurement uncertainty, namely:

$$\varepsilon^{+} = \varepsilon + \Delta\varepsilon^{+} = \varepsilon + \sqrt{(x_{\max} - x_{BE})^2 + (1.96\sigma_{\exp})^2} \quad \text{and}$$

$$\varepsilon^{-} = \varepsilon - \Delta\varepsilon^{-} = \varepsilon - \sqrt{(x_{BE} - x_{\min})^2 + (1.96\sigma_{\exp})^2} \;;$$

where x_{BE}, $x_{\max}$ and $x_{\min}$ are the best-estimate, maximum and minimum predicted results shown in Figure 5, $\sigma_{\exp}$ is the measurement uncertainty. The measurement uncertainty in sheath temperature is 1ºC in RD-14M tests.

The significant code bias appears when the surface is in dryout and heat transfer is in the developing PDO regime. This code bias is attributed to the underestimation of heat transfer coefficient in this regime. The maximum code bias is 183°C at 1240 s. Although the developing PDO heat transfer model in CATHENA MOD-3.5d results in a significant improvement in sheath temperature predictions, the model underestimates heat transfer coefficients at very low flow rates. Further improvements to the heat transfer model in the post-dryout regime are indicated. Once the heat transfer on the sheath surface enters the stable film-boiling heat transfer regime, the code bias begins to decrease.

Table 2 shows correlation coefficients between uncertain code inputs and the key output parameter at 12 different times. In this table, only the code inputs with significant correlation coefficients (absolute value > 0.2) are listed. Different code inputs had a significant correlation to the key output parameter at different times in the transient. Generally, the CHF and developed PDO correlations are most significant influential factors on the prediction of the CHF and PDO phenomena. The liquid convective and nucleate boiling heat transfer rate has a significant effect on the onset of CHF as well. The pressure boundary condition has an impact on the sheath temperatures mainly in the nucleate boiling regime.

6 CONCLUSIONS

This work was performed to assess the ability of CATHENA to predict the CHF and post-dryout heat transfer phenomena using data from RD-14M test B9802.

The simulation results using the slave channel model captured the timings of the onset of CHF, as well as the repeating temperature spikes observed during the oscillatory phase of the test. However, the simulated FES temperatures generally overestimate the measurements in the film-boiling regime (temperature excursions), indicating that the PDO heat transfer coefficients were underestimated.

Compared to the MOD-3.5c/Rev 0 code version, CATHENA MOD-3.5d/Rev 1 improved the predictions in the onset of sustained dryout, the temperature spikes and fluctuations. The improvement can be attributed to the implementation of the developing PDO heat transfer model in the MOD-3.5d code version.

The integrated uncertainty analysis showed that the uncertainty in the CHF and developed PDO correlations were most significant contributors to the overall uncertainty in the calculated FES temperature in the developing PDO and film boiling heat transfer regimes. The uncertainty in the liquid convective and nucleate boiling heat transfer correlation also contributes to the uncertainty in CHF. The most significant code bias appears when the surface is in dryout and heat transfer is in the film-boiling regime. This code bias was attributed to the underestimation of the developing and developed PDO heat transfer rates. Therefore, further improvements to the post-dryout heat transfer model at low flow rates are suggested.

7 REFERENCES

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Table 1: Code Inputs and Uncertainties for Test B9802

Inputs	Description	Distri-bution	Unit	Standard Deviation	Bias
Boundary Conditions	Outlet Pressure	Normal	kPa	37.5	0.0
	Inlet Temperature	Normal	°C	1.0	0.0
	Inlet Flow Rate	Normal	L/s	0.02	0.0
	Channel Power	Normal	%	0.75	0.0
CATHENA Correlations	Onset of Nucleate Boiling Temperature	Normal	°C	1.0	0.0
	CHF Lookup Table	Normal	%	7.82	+0.69
	Liquid Convective and Nucleate Boiling Heat Transfer	Normal	%	12.9	0.0
	Transition Boiling Heat Transfer	Normal	%	8.1	0.0
	Developed PDO Heat Transfer	Normal	%	10.63	+0.03
	37-element Bundle Developing PDO Heat Transfer	Normal	%	5.3	-0.02
	Two-Phase Flow Friction Factor Multiplier	Normal	%	4.34	-0.16
	Interphase Heat Transfer Coefficients	Normal	%	20	0.0

Table 2: Correlation Coefficients between Code Inputs and Key Output Parameter

Time	1025	1050	1075	1100	1125	1150	1175	1200	1225	1250	1275	1300
Outlet Pressure	0.482	0.464	-0.005	-0.034	0.048	0.018	-0.027	-0.127	-0.092	-0.073	-0.095	-0.100
Liq. Conv.& Nucl. Boil.	-0.766	-0.788	0.261	0.311	0.098	0.084	0.054	0.192	-0.026	0.088	0.030	0.088
CHF	0.062	0.063	-0.264	-0.453	-0.334	-0.352	-0.378	-0.415	0.131	0.062	-0.045	-0.013
Developed PDO	0.073	0.068	-0.717	-0.693	-0.371	-0.378	-0.387	-0.588	-0.970	-0.981	-0.950	-0.958

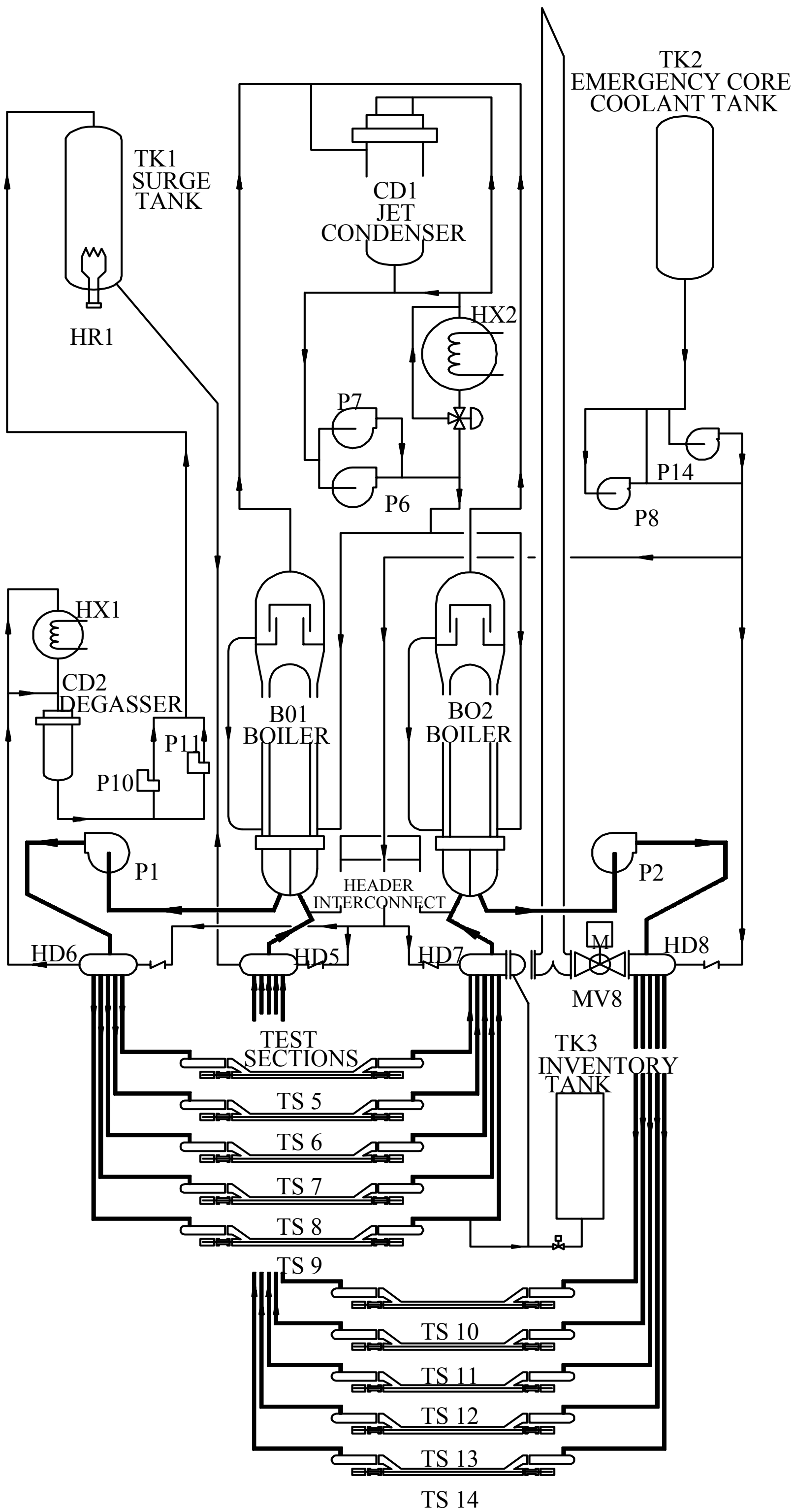

Figure 1: RD-14M Loop Schematic

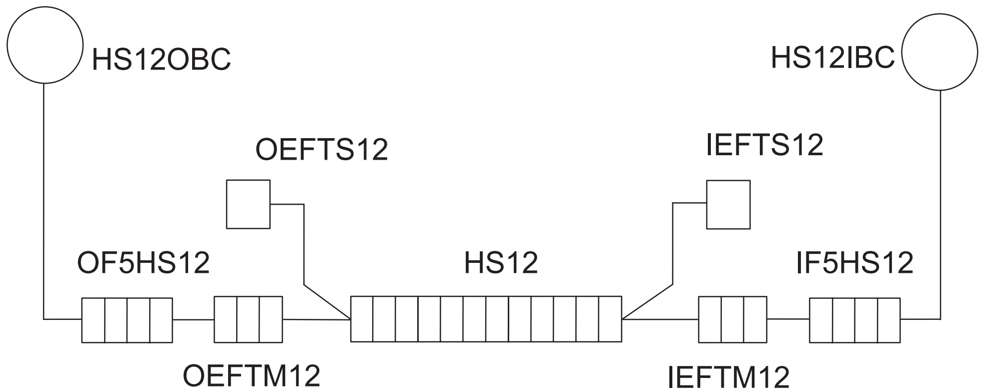

Figure 2: CATHENA Idealization of Test Section 12

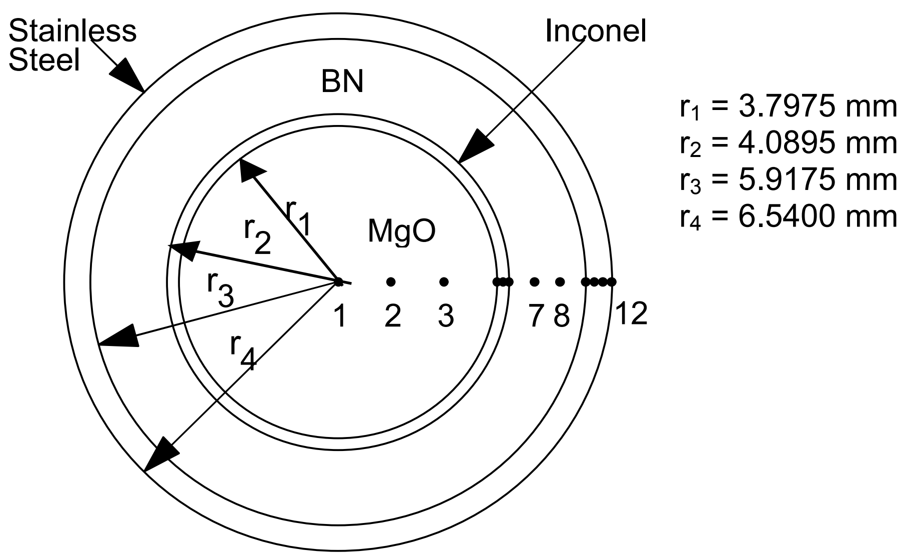

Figure 3: CATHENA Idealization of FES Pin

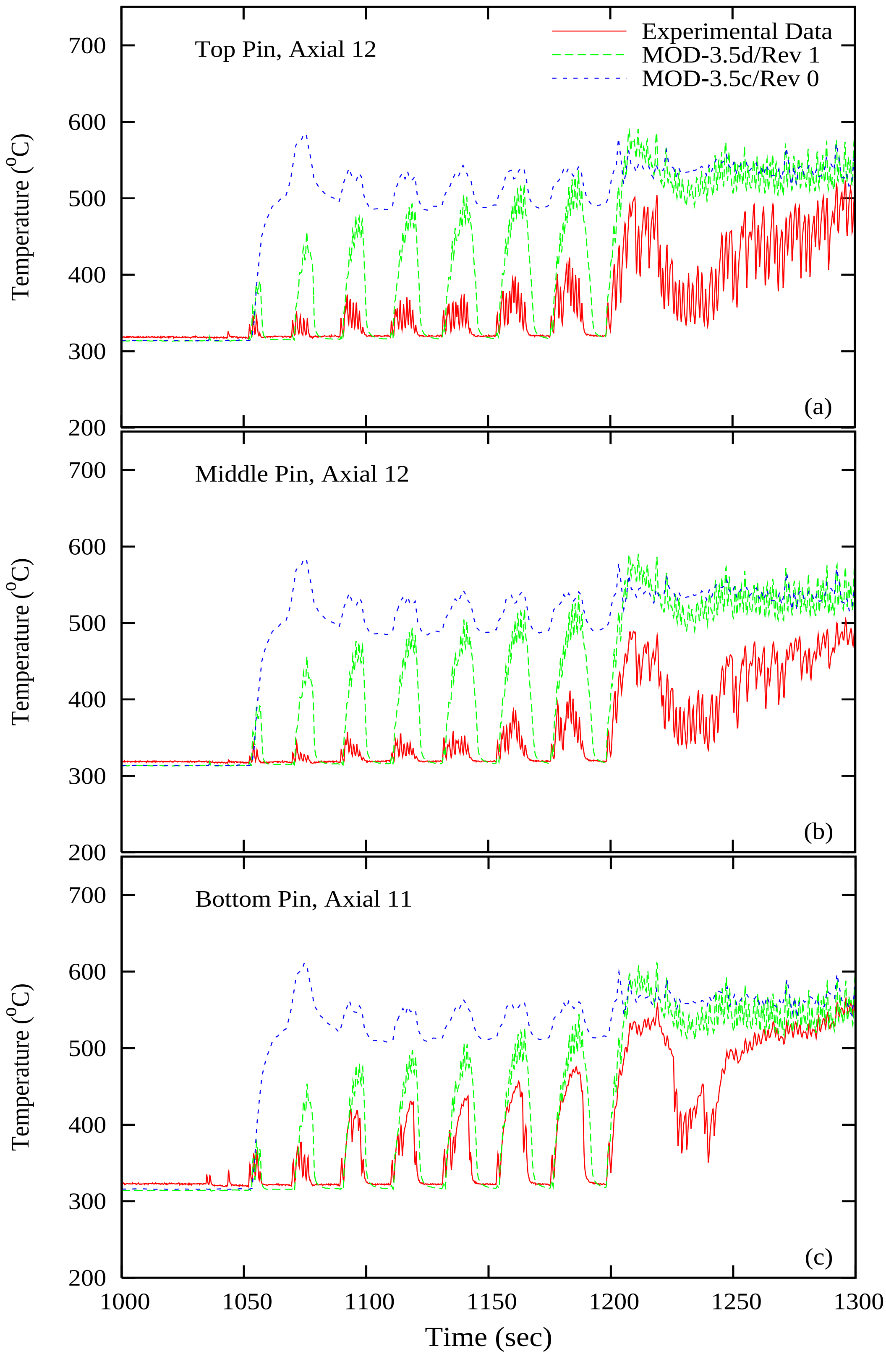

Figure 4: Measured and Predicted FES Temperatures in the (a) Top Pins (b) Middle Pins and (c) Bottom Pins Near the Outlet End of Heated Section 12

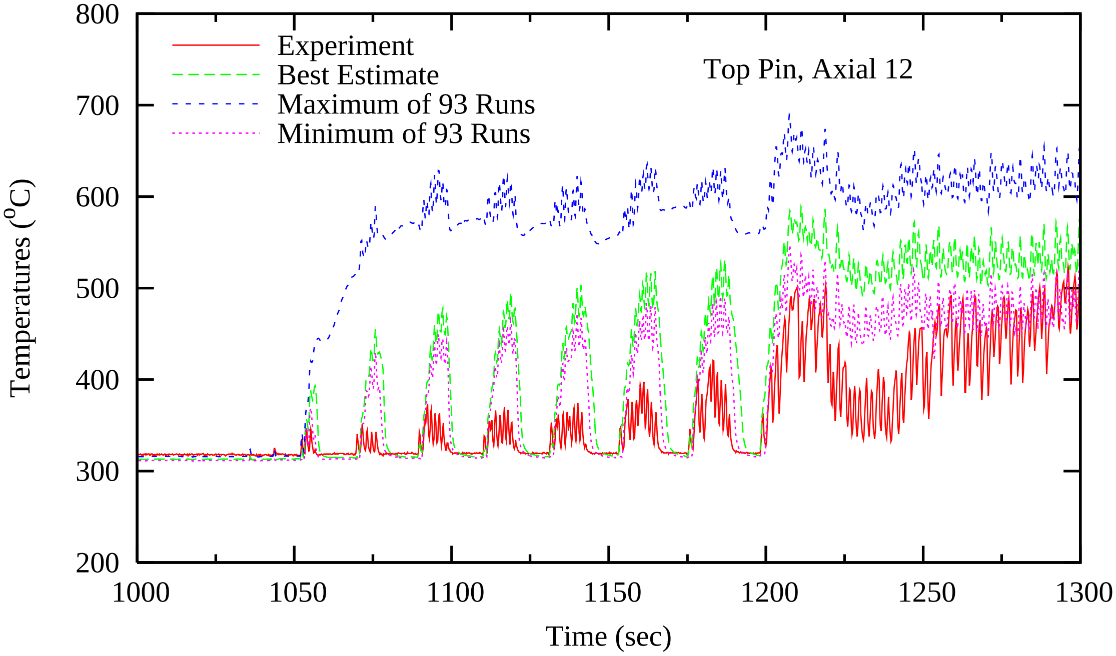

Figure 5: BE simulated and statistics FES Temperatures from 93 Simulations

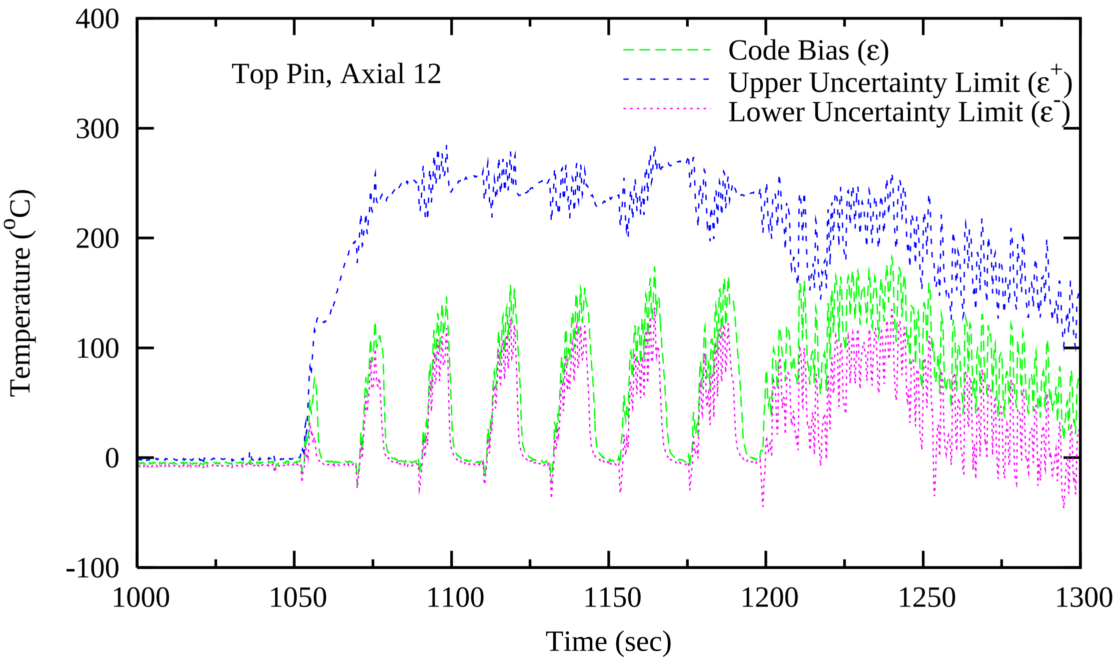

Figure 6: Code Bias in Predicted FES Temperatures