SYSTEM-LEVEL VALIDATION OF CATHENA MOD-3.5D FOR EARLY BLOWDOWN PHASE OF LARGE LOCA – RD-14M TESTS B0405-B0413

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ABSTRACT

To investigate the integrated effect of multiple phenomena on CATHENA MOD-3.5d code uncertainty, for the early blowdown phase of large loss of coolant accident (LOCA), one RD-14M test series (B0405-B0413) is used to perform a system-level validation. The peak sheath temperature in the Fuel-Element-Simulator (FES) is selected as the key output parameter used to quantify the code bias and uncertainty in the validation. In the nine tests, the test conditions (break size, pump and power trip time, fluid sub-cooling and pressurizer isolation) are systematically varied and simulated, so that their effects on the magnitude and timing of the peak FES-sheath temperatures are demonstrated.

The base test, B0405 is selected to perform sensitivity and uncertainty analyses. The sensitivity analyses show that the choice of film-boiling heat-transfer correlation has a significant effect on the prediction of the FES-sheath temperatures during the FES quenching period. Uncertainty analysis demonstrates a mean bias of about +20°C, with a range of about ±30°C to the upper and lower bounds. These results compare very well with the estimated code accuracy based on all nine tests of B0405-B0413.

INTRODUCTION

To support the use of CATHENA MOD-3.5d for safety and licensing analyses of ACR[1], previous validations of the CATHENA code are being confirmed for each phenomenon expected to occur during postulated accidents in ACR. The validation activities reported in this paper extend the phenomena-based validation approach to examine the integrated effect of multiple phenomena at a system level.

AECL studies on large LOCA have shown that, for a break at a reactor inlet header (RIH), near-stagnation flow conditions may occur in the channels downstream of the broken header for a brief period early in the depressurization. The break size that results in the longest period of reduced flow (and so the highest fuel sheath temperatures) is referred to as the critical break. The critical RIH LOCA accident scenario is divided into three phases, based on the dominant phenomena during each phase[2]. The present, system-level, validation activities focus on the early blowdown phase (0 to 30 s), before the emergency coolant injection (ECI) acts.

Under the conditions of rapid depressurization and reduced flow, the fuel channels in the core pass downstream of the break void rapidly. This in turn causes a reduction in fuel-to-coolant heat transfer and rapid heat-up of the fuel element sheaths. However, the fuel

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1 ACR™ (Advanced CANDU Reactor™) is a trademark of Atomic Energy of Canada Limited (AECL).

2 The three phases include early blowdown cooling (0 to 30 s), late blowdown cooling/ECI/refill (30 to 200 s) and long term cooling (>200 s)

temperature rise is limited by the reduction in heat generation after reactor trip. As the rate of void generation decreases (along with continued reduction in the inlet-header pressure due to the break and decreasing pump head), reversed flows are established in the broken pass. The fuel is cooled initially by steam, then as liquid drains down into the fuel channels from the end fittings and outlet feeders, quenching occurs. All these features in the early blowdown phase are reflected in the variations of FES-sheath temperature with time.

CATHENA

The acronym CATHENA stands for Canadian Algorithm for THErmalhydraulic Network Analysis that was developed by AECL. CATHENA uses a transient, one-dimensional two-fluid representation of two-phase flow in piping networks. 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 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 code is provided in [1].

DESCRIPTION OF THE EXPERIMENT

RD-14M Facility And Instrumentation

The RD-14M facility, shown schematically in Figure 1, was designed as a near full-elevation scaled representation of the CANDU 6 reactor. It can operate at CANDU 6 primary system pressures (10 MPa) and temperatures (up to 310 °C) to produce similar fluid mass flux, transit time, pressure, and enthalpy distributions in the Heat Transfer System (HTS) as those in a CANDU reactor.

The RD-14M facility possesses most of the key components of the CANDU HTS. The reactor core is simulated by ten, 6 m-long horizontal channels (five channels per pass). Each test section has simulated end-fittings and seven electrical heaters (Figure 2), or FES that have many of the characteristics of the central 7 elements of a 37-element CANDU fuel bundle. An inlet header break orifice (at header HD8) was used in conjunction with the normal 152-mm break valve, MV8 (tests were performed with break orifice sizes of 28, 30 and 32-mm diameter).

The RD-14M loop is extensively instrumented. Over 550 measuring points are scanned and recorded using a dedicated data acquisition system. For the headers, the pressure and fluid temperature in the headers are measured. For each test section inlet and outlet fluid temperatures, pressures, volume flow rates, void fractions (gamma densitometers), and power are measured. Sheath temperatures are measured at several locations along the length of selected FES. FES temperatures are measured at up to 18 locations in each heated section.

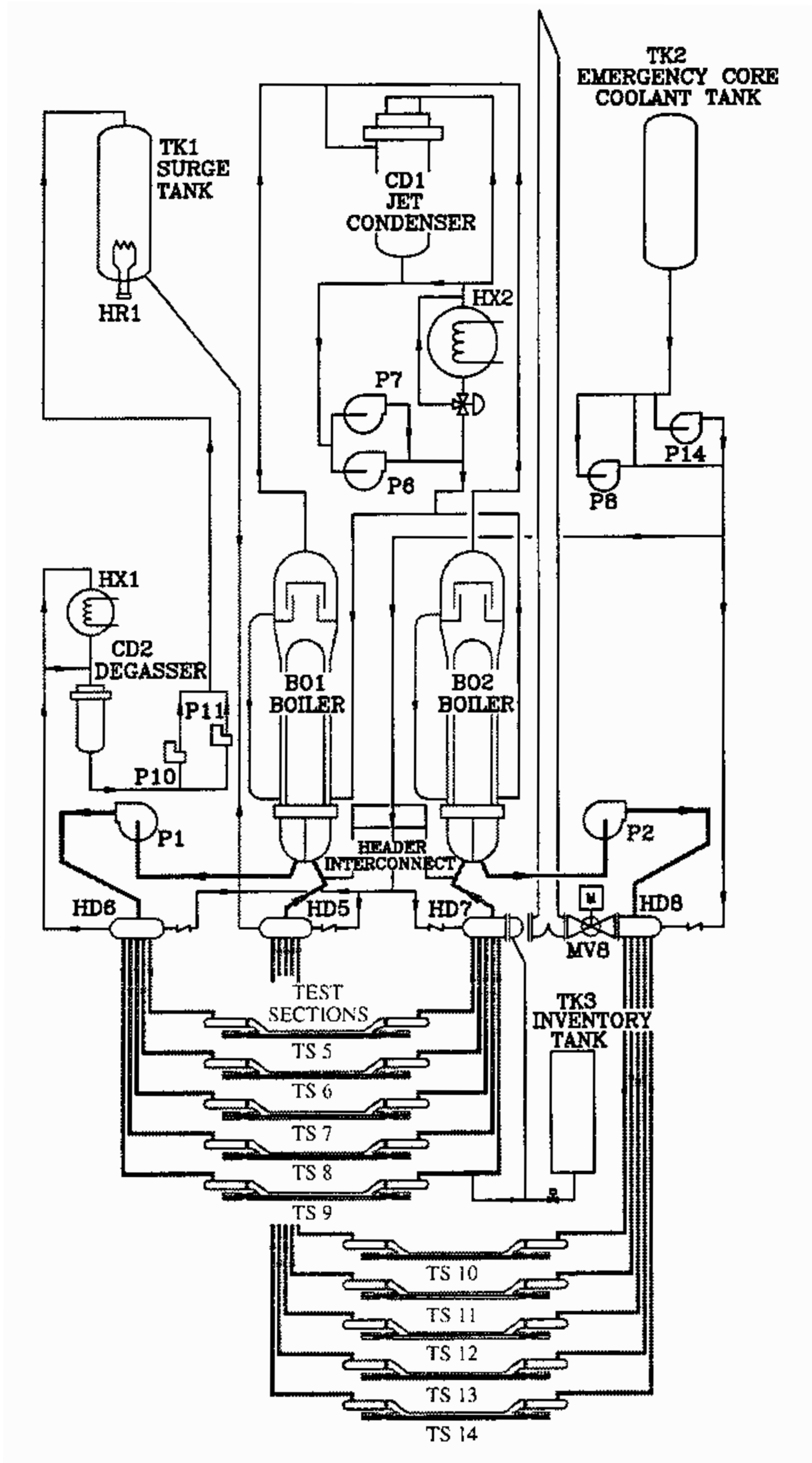

Figure 1 RD-14M Loop Schematic

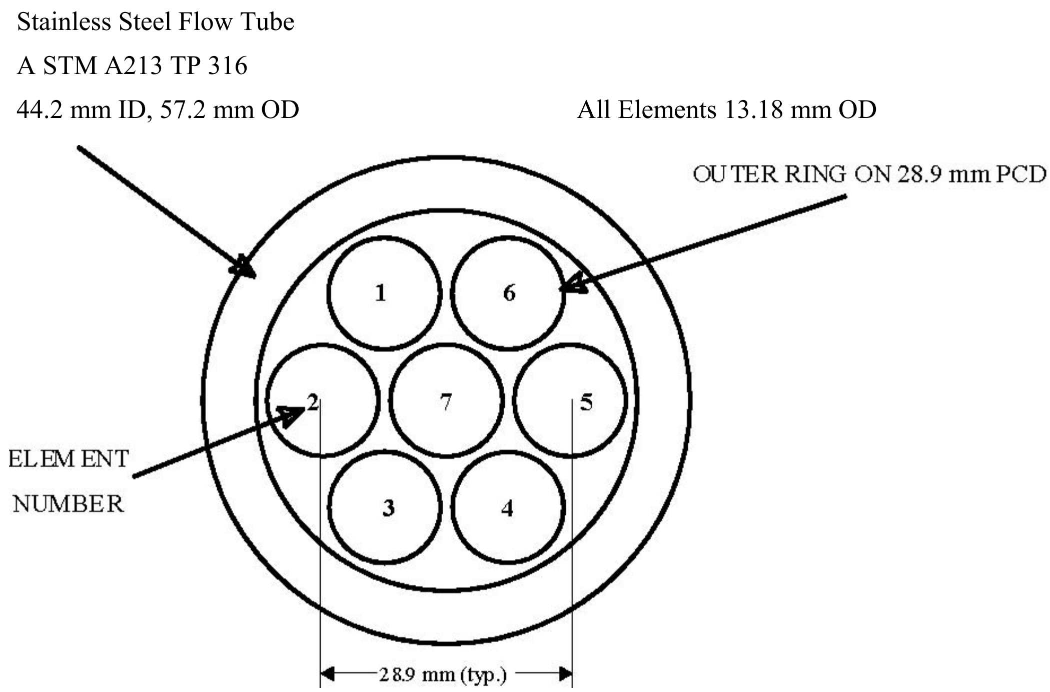

Figure 2 Seven-Element Heater Cross-Section

Test Procedure And Behaviour

The facility was operated for at least 300 s at nominal full-power setting before starting a test, to ensure steady initial conditions. Sixty seconds of steady-state data were recorded prior to the opening of the break valve MV8. Power supplied to the heated sections was then decreased (to represent trip to decay power) and pump rundown was initiated. The timings of the power decrease or pump trip was one of the test parameters studied. The tests were terminated when the FES sheath temperatures in the broken-pass channels all dropped to the saturation temperature.

For B0405-B0413 tests the focus is on the first 40-50 s of the transient. No emergency coolant injection (ECI) was used in these tests.

IDEALIZATION OF THE RD-14M BLOWDOWN FACILITY

The CATHENA idealization used to simulate tests B0405-B0413 is based on the reference idealization (Figure 3) used for all other CATHENA RD-14M validation exercises. Small changes are made to the reference model to represent the specific initial and boundary conditions for these tests. The Henry-Fauske discharge model is applied to the break at inlet header HD8. The default discharge coefficients are used. Wall heat transfer models are included in the idealization to account for heat transfer between the pipe walls, or the FES, and the fluid during the simulation. No attempts were made to change code inputs to minimize any bias in the key output parameter (Tmax).

Measured surge tank and boiler pressures, heated section powers, boiler feedwater flows and temperatures, and primary pump speeds were used to establish the initial steady state. With the exception of surge tank pressure, these measured values were also used as time-varying boundary conditions during the transient simulations.

RESULTS

Trends of Peak FES Sheath Temperatures in Tests B0405-B0413

The peak FES-sheath temperature in each heated section during the transient (T_{max}) is selected as the key output parameter, since it can reflect the combined effect from different thermal-hydraulic processes. The T_{max} values during the early blowdown phase of the transient occur in channels HS10 to HS14, which are connected downstream of the broken header HD8. The effect on the timing and magnitude of T_{max} is examined by systematically perturbing the conditions of the 9 tests (B0405-B0413), i.e. break size, pump and power trip time, fluid sub-cooling and pressurizer isolation (Table 1).

The base case B0405 is first examined. In all the five channels downstream of header HD8 (only the highest-power channels HS12 and HS13 are shown in Figure 4 and Figure 5), both the measured and predicted FES sheath temperatures rapidly increase immediately after the break occurs at HD8. The FES sheath temperatures reach a maximum value between 450°C and 520°C, between 5 and 8 s after the break occurs. The timing of the temperature increase and peak value are well captured by CATHENA. Note that in Figure 4 and 5, the three lines shown represent the measured temperature (with error bars) at the location of measured Tmax, the predicted temperature at the location of measured Tmax and the predicted temperature at the location of predicted Tmax. This is also applied to the plots in other figures.

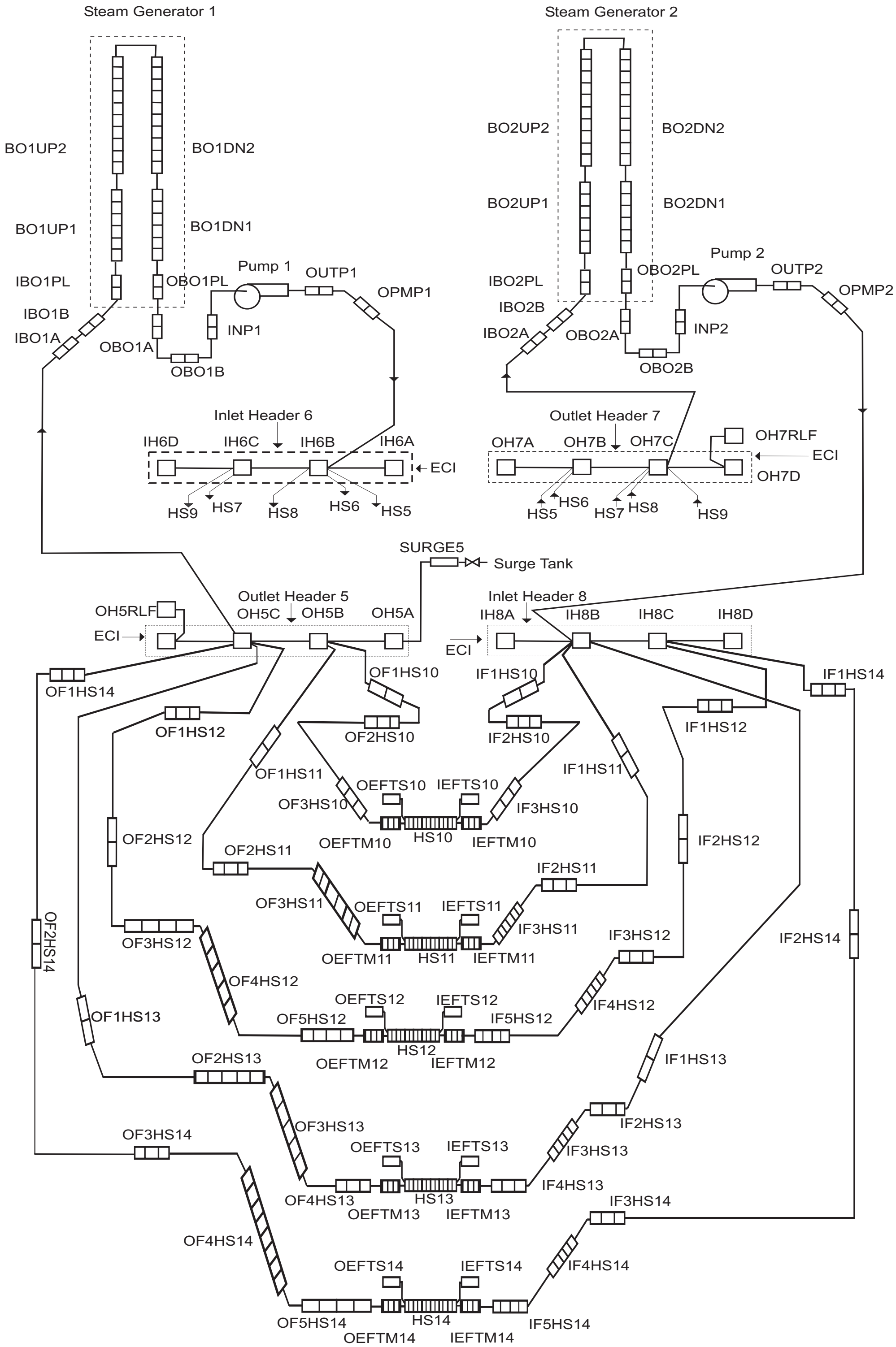

Figure 3 Idealization of RD-14M Facility

Table 1: RD-14M Early Blowdown Experimental Matrix

<table>
<tr><th>Test Number</th><th>Break Size* (mm)</th><th>Start of Pump Transient+</th><th>Initial Secondary-Side Pressure</th><th>Start of Channel Power Decay†</th><th>Pressurizer Status‡</th><th>Comment</th></tr>
<tr><td>B0405</td><td rowspan="3">30.0</td><td>2 sec.</td><td rowspan="6">4.5 MPa(g)</td><td rowspan="5">2 sec.</td><td rowspan="8">Online</td><td>Base test</td></tr>
<tr><td>B0406</td><td>0 sec.</td><td rowspan="2">Effect of primary-pump ramp</td></tr>
<tr><td>B0407</td><td>4 sec.</td></tr>
<tr><td>B0413</td><td>32.0</td><td rowspan="6">2 sec.</td><td rowspan="2">Effect of break size</td></tr>
<tr><td>B0412</td><td>28.0</td></tr>
<tr><td>B0411</td><td rowspan="4">30.0</td><td>4 sec.</td><td>Effect of channel power</td></tr>
<tr><td>B0408</td><td>4.9 MPa(g)</td><td rowspan="3">2 sec.</td><td rowspan="2">Effect of initial inlet-header subcooling</td></tr>
<tr><td>B0409</td><td>4.1 MPa(g)</td></tr>
<tr><td>B0410</td><td>4.5 MPa(g)</td><td>Offline</td><td>Effect of pressurizer status</td></tr>
</table>

* Diameter of inlet header break.

\+ Programmed exponential pump ramp simulating loss of class IV power. Start of pump transient is relative to the opening of the break valve (MV8).

† Programmed decrease in channel powers to decay level. Start of power decrease is relative to the opening of the break valve (MV8).

‡ Online refers to the pressurizer connected through the entire test duration. Offline refers to the pressurizer isolated from the system ~10 seconds prior to opening the break valve.

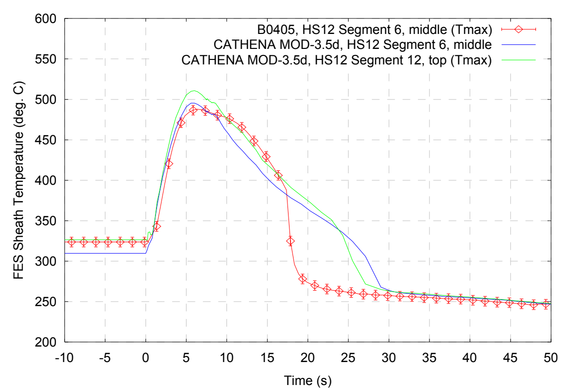

Figure 4: FES-Sheath Temperatures in HS12, Test B0405

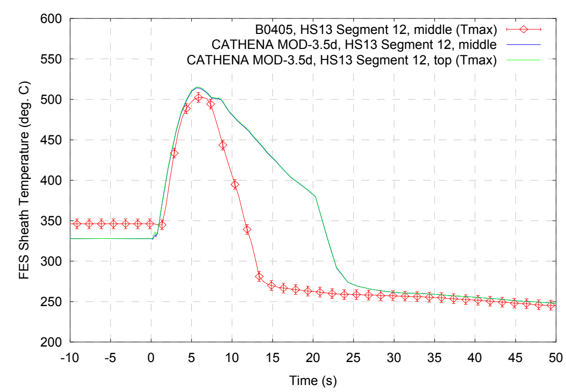

Figure 5 FES-Sheath Temper-atures in HS13, Test B0405

The changes to test conditions for tests B0406 to B0413 are all relative to the base test B0405. The effects of test conditions on the magnitude and timing of T_{max} are summarized in Table 2 and may be stated as the follows:

- In eight of the nine tests the T_{max} values predicted by CATHENA are higher than those measured. The exception is one heated section in B0411 (with the power trip delayed 2 s). The difference between predicted and measured T_{max} ranges between +50°C to -5°C, as summarized in Table 3.
- Comparing tests B0405, B0406 and B0407, T_{max}, and the time at which it occurs varies with the time of the start of the pump rundown. Initiating the pump ramp earlier or later (-2 or +2 s) resulted in earlier and lower T_{max}, or later and higher T_{max}, in both experiment and CATHENA prediction. When the pump begins to run down earlier, flow reversal in the downstream channels is allowed to occur earlier, resulting in earlier quench of the FES. The earlier quench also corresponds to a lower peak FES temperature. Such trends are caught correctly by CATHENA.
- Comparing tests B0405, B0408 and B0409, T_{max} tends to vary with the boiler pressure. Increasing or decreasing the boiler pressure (+0.4 MPa or –0.4 MPa) increases or decreases the heated section inlet temperature. This resulted in higher or lower predicted T_{max} whereas measured T_{max} is higher in both B0408 and B0409, but little change in timing (<0.2 s) of T_{max} in both experiment and CATHENA prediction.
- Comparing tests B0405 and B0410, isolating the surge tank resulted in higher and later T_{max} in the experiment. Isolating the surge tank allows the outlet header pressure to decrease more quickly, delaying the flow reversal in heated sections HS10 to HS14. This trend is captured by CATHENA.
- Comparing tests B0405 and B0411, delaying the power trip (2 s) increased the energy deposited in the heated sections, and resulted in much higher and later T_{max} in both the experiment and CATHENA prediction.
- Comparing tests B0405, B0412 and B0413, decreasing the break diameter (-2 mm) had no significant effect on either the value or timing of T_{max} in the experiment; however, CATHENA predicted higher T_{max}, occurring later. Increasing the break diameter (+2 mm) resulted in lower and earlier T_{max} in both experiment and CATHENA prediction. These variations in T_{max} with break size are expected, as the 30-mm break is the critical inlet header break for RD-14M.

Table 2: Maximum Pin-Sheath Temperatures, Test B0405-B0413

		Tmax (°C)		Location*		Time (s)	
Test	Condition	Experi-ment	CATHENA	Experiment Axial Segment	CATHENA Axial Segment	Experi-ment	CATHENA
B0405	Base case	502.3	519.4	12	12	5.8	5.9
B0406	Pump ramp 2 s earlier	501.1	513.1	7	12*	5.2	5.8
B0407	Pump ramp 2 s later	524.8	537.7	12	12	6.9	6.8
B0408	Boiler pressure +0.4 MPa	509.8	527.8	12	12	6.0	5.9
B0409	Boiler pressure -0.4 MPa	507.3	512.3	12	10	5.9	6.1
B0410	TK1 Pressure Offline	522.9	545.8	12	12	7.6	9.6
B0411	Power decay 2 s later	563.5	558.9	12	12	6.8	8.6
B0412	Break size -2 mm	501.1	536.2	12	12	5.6	6.6
B0413	Break size +2 mm	479.8	504.3	8	12*	4.5	5.2

* Measured T_{max} occcurs in HS13 in all tests. Predicted T_{max} occurs in HS13 in tests B0405, B0407, B0408, B0409, B0410 and B0411, and in HS12 in tests B0406 and B0413

Table 3: Bias[3] Summary for Maximum Pin-Sheath Temperature in HS10 to HS14, for Tests B0405 to B0413

Bias (°C)	HS10	HS11	HS12	HS13	HS14
B0405	16.6	30.6	26.6	17.1	43.4
B0406	15.5	27.5	15.2	10.7	37.6
B0407	17.0	19.2	25.4	12.9	34.1
B0408	17.8	31.5	33.4	18.0	44.0
B0409	15.1	23.0	14.4	5.0	38.9
B0410	25.3	50.5	28.0	22.9	45.1
B0411	4.5	12.2	4.4	-4.6	26.0
B0412	34.7	40.3	35.3	35.1	49.9
B0413	22.0	40.4	31.4	23.5	46.1

[3] The bias is defined as the predicted minus measured peak sheath temperature in each heated section.

Effect of Film Boiling Heat Transfer Correlation

To test the effect of the choice of film boiling heat transfer correlation on the prediction for peak pin-sheath temperatures, the optional Bromley correlation was selected instead of the default (Leung lookup table). Figures 6 and 7 show the resulting predicted FES sheath temperatures in HS12 and HS13, respectively. Compared with the results obtained using the default film boiling correlation (Figures 4 to 5), the following observations are made:

1. the timing of the predicted peak FES sheath temperature is about the same;
2. the value of T_{max} is reduced by about 25°C;
3. after the peak, the FES sheath temperatures decrease more quickly than the measured temperatures; using the default film boiling correlation results in temperatures decreasing slower than the measured values.

As shown above, the predictions of pin-sheath temperatures are very sensitive to the selection of film boiling heat transfer correlation after the FES temperature peak, when the FES surfaces are rewetting. For the RD-14M 7-element bundle under the conditions of test B0405, the Bromley correlation appears to significantly over-estimate the heat transfer during this quenching process, while the default Leung lookup table appears to under-estimate the heat transfer during quenching.

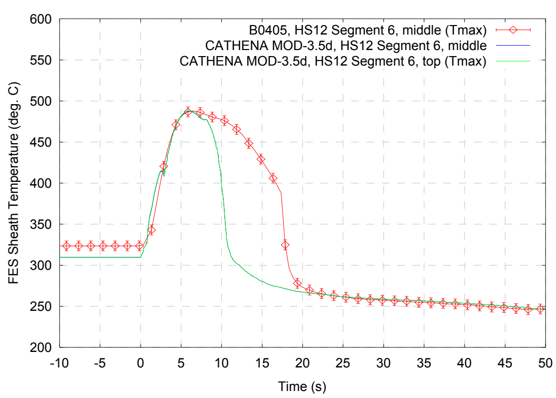

Figure 6 FES-Sheath Tempera-tures in HS12, Test B0405, using Bromley's Film Boiling (PDO) Heat Transfer Correlation

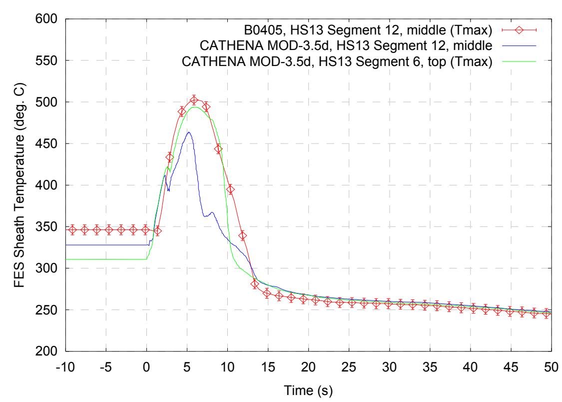

Figure 7 FES-Sheath Temperatures in HS13, Test B0405, using Bromley's Film Boiling (PDO) Heat Transfer Correlation

Uncertainty Analysis

An integrated uncertainty analysis was performed to estimate the overall uncertainty in the predicted peak FES-sheath temperature, following the method of order statistics originally used at Gesellschaft fuer Anlagen-und Reaktorsicherheit (GRS) method [2]. Applying Wilks' formula, a minimum sample size of 93 is required to obtain the 95%/95% tolerance limits. Each of the 93 samples is a code simulation in which the identified code inputs are randomly and simultaneously perturbed within a subjective probability distribution function for their uncertainty. Test B0405 is used for all these uncertainty analyses. Table 4 lists the perturbed code inputs.

Table 4: Code Inputs Perturbed in Uncertainty Analysis

Code Inputs or Outputs	Description and Symbol	Distribution and Standard Deviation or Range
Key Output Parameter [8]	FES Sheath Temperature, T_{max}	Unknown, σ = 3 °C
Code Inputs for CATHENA Boundary & Initial Conditions [8]	Feedwater Temperature	Normal, σ = 2 °C
	Feedwater Flow	Normal, σ = 1.25%
	Secondary Pressure	Normal, σ = 0.025 MPa
	Heated Section Power	Normal, σ = 1.0%
	Main Pump Speed	Normal, σ = 1.0%
	Initial Pressure (in Surge Tank)	Normal, σ = 0.05 MPa
Code Inputs for CATHENA Correlations	Break Discharge Correlation	Uniform, Range = +15% to –16.8%
	Two-Phase Friction Multiplier,	Normal, σ = 23%
	Colebrook-White Friction Factor	Normal, σ = 15%
	Interphase Area (bubbly)	Normal, σ = 40%
	Interphase Area (droplet)	Normal, σ = 10%
	Interphase Area (slug)	Normal, σ = 20%
	Interphase HTC[!] (bubbly)	Normal, σ = 20%
	Interphase HTC (slug/churn)	Normal, σ = 20%
	Interphase HTC (droplet)	Normal, σ = 20%
	Interphase HTC (vapour)	Normal, σ = 20%
	Interphase HTC (subcooled steam)	Normal, σ = 20%
	Interphase HTC (superheated liquid)	Normal, σ = 20%
	Interphase HTC (stratified)	Normal, σ = 20%
	Interphase HTC (annular)	Normal, σ = 20%
	Interphase HTC (piston)	Normal, σ = 20%
	ONB	Uniform, Range = 0 to 2 °C
	CHF (Groeneveld-Leung table)	Normal, σ = 7.82%
	Convection + Nucleate Boiling HT (modified CHEN)	Normal, σ = 13%
	Transition Boiling (Bjornard-Griffith)	Normal, σ = 8%
	Film Boiling (PDO table Tsup)	Normal, σ = 10.63%
	OSV (Saha-Zuber)	Normal, σ = 10%

! Heat Transfer Coefficient (HTC)

Figure 8 shows the best-estimate simulation, and the 95%/95% upper and lower bounds of T_{max} from the 93 simulations in which the inputs listed in Table 4 were perturbed. Figure 9 shows the uncertainty in code bias, including the uncertainty in the measured FES temperature. Note that at the time T_{max} occurs (5.9 s), Figure 9 shows that the code bias is 17°C, and the maximum and minimum bounds are 49°C and -22°C respectively. Later in the experiment (between 10 s and 30 s), during the quench/rewet phase, the bias is much larger.

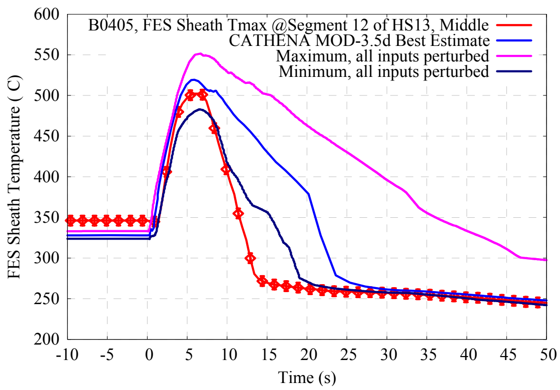

Figure 8: FES Sheath Temperature Uncertainty Predicted in HS13

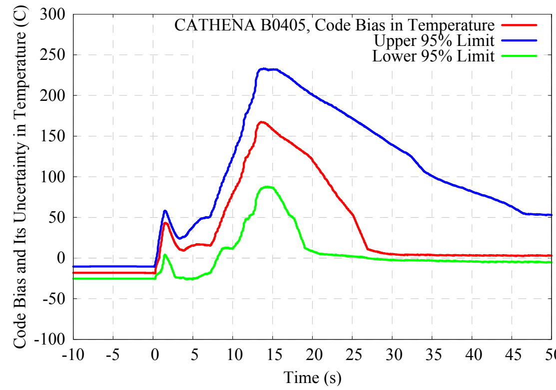

Figure 9: Code Bias in the Predicted Peak FES Sheath Temperature in HS13

The influence of code inputs on the key output can be demonstrated from the correlation coefficients between code inputs and maximum pin-sheath temperature at different times. Uncertainty in the break discharge correlation, and in the power supplied to HS12 and HS13 are the code inputs that have the most significant effect on the predicted T_{max}.

Estimate of Code Accuracy Based on All Nine Tests

In the nine tests (B0405-B0413), the code bias defined by the difference between maximum predicted and measured FES temperature is summarized in Table 3. The mean of the 45 bias values given in Table 3 is 26°C, and the values range between –5°C and +50°C. These results compare very well with the GRS-method uncertainty analysis results presented above, which indicates a mean bias in T_{max} of about 20°C, with a range about ±30°C to the 95%/95% upper and lower bounds.

CONCLUSIONS

Nine RD-14M experiments, B0405 to B0413, were simulated using CATHENA MOD-3.5d to validate the code for system-level or integrated effect of phenomena occurring during the early blowdown phase of large LOCA scenarios.

In test B0405 (used as base test), for the five heated sections (HS10 to HS14) directly connected to the broken inlet header, the timing when FES sheath temperature rapidly increased is predicted to occur right after the break at the inlet header HD8. The predicted peak FES temperature occurs at 5.9 s after the start of the transient. The predicted timing of the peak FES sheath temperatures (T_{max}) is in agreement with the experiment (within 0.1 s). The value predicted for T_{max} is higher than the measured value by 17°C.

The other 8 tests provide one-parameter-at-a-time variation comparisons with B0405. Starting the pump rundown earlier or later (-2 or +2 s) resulted in earlier and lower, or later and higher T_{max} in both the experiments and CATHENA predictions. Increasing or decreasing the boiler secondary-side pressure (+0.4 or -0.4 MPa) led to higher or lower T_{max}, but little change in timing of T_{max} in both the experiments and CATHENA simulations. Isolating the surge tank (or pressurizer) prior to the break opening resulted in higher and later T_{max} in both the experiment, and the CATHENA prediction. Delaying the power trip (2 s) led to higher and later T_{max} in both the experiment and CATHENA simulation. Decreasing the break diameter by 2 mm resulted in no significant change to the value and timing of T_{max} in the experiment, however CATHENA predicted a higher and later T_{max}. Increasing the break diameter by 2 mm resulted in a lower, earlier T_{max} in both the experiment, and CATHENA prediction.

The sensitivity of T_{max} to the PDO heat transfer correlations, Leung lookup table (CATHENA default) or Bromley, was explored. The choice of PDO correlation had no significant effect on T_{max} but had a significant effect on the predicted sheath temperatures during quenching and rewet. During quenching process the film heat transfer is under predicted by the default correlation, and over-predicted by the Bromley correlation.

The uncertainty analyses using the GRS method demonstrate a mean bias of about +20°C, with a range of about ±30°C to the 95%/95% upper and lower bounds. These results compare very well with the estimated code accuracy based on all nine tests of B0405-B0413.

ACKNOWLEDGMENTS

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[2] H. Glaeser and E. Hofer, “Mathematical Techniques for Uncertainty and Sensitivity Analysis”, ASME/JSME Fluid Engineering and Laser Anemometry Conference and Exhibition, Hilton Head, South Carolina, 1995.