PRE- AND POST-TEST CATHENA SIMULATIONS FOR RD-14M CRITICAL BREAK EXPERIMENTS

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ABSTRACT

Historically, peak fuel element simulator (FES) sheath temperatures in RD-14M Loss-of-Coolant Accident (LOCA) experiments have not exceeded 550°C. However, in licensing analysis scenarios, peak sheath temperatures during the early blowdown phase of a LOCA have been predicted to reach or exceed 1000°C. Experimental data at these conditions can aid in the validation of codes used for licensing analysis purposes.

A series of critical break LOCA experiments was performed in RD-14M to provide experimental FES sheath temperatures up to 1000°C. This paper summarises the CATHENA simulations used to help design the test series. Post test simulations of selected tests are also discussed.

For this test series, RD-14M was modified to use a single channel per pass; all other channels were isolated at the headers. No emergency core cooling was used. Experiments were conducted either with the power supplies ramped to decay levels 2 s after initiating the break or with the power supplies left at initial conditions until the test was terminated by a process protection trip. The FES trip temperature was increased to 1000°C for the final test.

A CATHENA scoping analysis predicted an inlet header break between 15 mm and 20 mm at a loop flow of 3.7 L/s would produce a critical break with this geometry. Experimental results confirmed these predictions. For experiments conducted with an 18 mm inlet header break with no power ramp down, a peak sheath temperature of 968°C was reached. CATHENA accurately predicted the flow split point in the channel. The code overestimated the top, centre FES temperature by 141°C. This is considered to be a conservative estimation of the peak sheath temperatures.

1. INTRODUCTION

Atomic Energy of Canada Limited (AECL), through the CANDU Owner's Group (COG), conducts ongoing research into the safety of CANDU® reactors under both normal and off-normal operating conditions. RD-14M is the most recent in a series of integrated thermalhydraulic test facilities designed and operated for this purpose. Experimental data from the RD-14M facility is used to improve the understanding of the thermalhydraulic processes that occur in CANDU geometries and to validate and improve existing computer models to better simulate reactor behaviour.

During a postulated Loss-of-Coolant Accident (LOCA) scenario in a CANDU, the Primary Heat Transport System (PHTS) rapidly depressurises causing voiding of the coolant in the core. At the same time, core coolant will be discharged through the break at a rate dependent on the break size. This loss of coolant from the break discharge and voiding in the core will reduce the heat transfer to the coolant and the temperature of the fuel will increase. During this voiding process the reactor power may also increase resulting in a further increase in fuel temperatures. It is during this early blowdown phase that peak fuel temperatures are expected to be reached.

The effect of break size on peak sheath temperatures and header-to-header pressure drop in RD-14M LOCA experiments is illustrated in Figures 1 and 2, respectively. In a small break LOCA experiment, the break-induced pressure drop is significantly smaller than the head delivered by the primary pump so that the driving force for primary coolant flow through the heated section is maintained during the blowdown. In a large break LOCA experiment, the break-induced pressure drop is significantly larger than the head delivered by the primary pump. The driving force in a large LOCA becomes the break discharge and coolant flow reverses through the broken pass and is maintained in the reverse direction during the blowdown. In a critical break LOCA experiment, the head delivered by the primary pump upstream of the break, is effectively offset by the pressure drop caused by opening the break. Under these conditions, the inlet and outlet header pressures of the broken pass become nearly equal with flow exiting out of both ends of the heated channel. This condition is referred to as a flow split point in the channel.

Previously, RD-14M critical break experiments have reached peak FES sheath temperatures of 539°C during the early blowdown phase. The critical break experiments discussed here were designed to reach FES sheath temperatures near 1000°C to confirm code predictions used in licensing analysis. A critical break in RD-14M is defined as a break that results in a flow split point developing and lasting for several seconds (2 or 3) in the heated part of the test section during the first five or ten seconds of the transient. The two-fluid thermalhydraulic computer code CATHENA, was used in the pre-test design and the post-test simulation of several of the experiments.

Since these tests were designed to reach temperatures outside the normal operating conditions of RD-14M, the facility was modified to only a single channel per pass (TS8 and TS13). This restricted the possibility of damage to only one test section in the broken pass. Emergency core cooling (ECC) was not used in these experiments since the focus of these tests was the early

CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL) blowdown period, prior to ECC entering the loop. Unlike a reactor scenario, a power pulse was not simulated due to the limitations of the RD-14M power supplies.

2. FACILITY DESCRIPTION

RD-14M is an 11 MW, full-elevation-scaled thermalhydraulic test facility possessing most of the key components of a CANDU PHTS. Figure 3 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, 6 m-long horizontal channels. Each channel has simulated endfittings and seven electrically-heated FES designed to have many of the characteristics of the CANDU fuel bundle. Heated sections are connected to headers via full-length feeders. Above header piping is also CANDU-typical including two full-height, U-tube steam generators or boilers (B01 and B02) and two bottom-suction centrifugal pumps (P1 and P2). Steam generated in the secondary, or shell, side of the steam generators is condensed in a jet condenser (CD1) and returned as feedwater to the boilers. The primary-side pressure is controlled by a pressuriser/surge tank (TK1) using a 100-kW electric heater (HR1). The facility operates at typical CANDU primary system pressures (nominal 10 MPa) and temperatures (up to 310°C) and is designed to produce the same fluid mass flux, transit time, pressure and enthalpy distributions in the primary system as those in a typical CANDU reactor under both forced and natural circulation conditions. A more complete description of the RD-14M facility and its associated instrumentation can be found in Reference [1].

2.1 Modifications For This Test Series

Several modifications were made to the RD-14M facility for this test series. These tests were conducted with a single test section connected in each pass. All other test sections were isolated by the installation of blanks at both the inlet and outlet headers. The broken pass (header 8 to header 5) had only test section 13 (TS13) connected to the headers. Test section 8 (TS8) was the only test section connected in the unbroken pass (header 6 to header 7). Power was individually supplied to each test section. Test sections 8 and 13 were selected for these tests for several reasons. These are "sister" channels which means they are located in different passes but at the same elevation and have the same geometry. Test sections 8 and 13 were also the most accessible for installing supplementary instrumentation for these experiments. These test sections are slightly higher power (nominal 0.946 MW) than some of the other channels (nominal 0.75 MW). The break valve, a 50.8-mm (nominal), remote-control ball valve (MV8), was installed at inlet header 8. The break size was established by placing an appropriately sized orifice immediately upstream of the break valve.

2.2 Instrumentation

The RD-14M loop is extensively instrumented. A total of 266 instruments were scanned and recorded using a dedicated data acquisition system for these experiments. Coolant pressures, temperatures, volumetric flow and void fraction measurements were measured both above and below the headers. Fuel element sheath temperatures were measured around the circumference of the test bundle and along the length of the test section using K-type thermocouples calibrated 0-1050°C (±2°C). In the broken pass (TS13), nine K-type thermocouples were installed on the outside surface of the pressure tube using Thermon (Grade T-63), a high-temperature heat transfer cement. Eight more thermocouples were installed on TS13 inlet and outlet feeders to measure the top and bottom surface temperatures near the inlet and outlet endfittings and near the inlet and outlet headers. In a few locations, Resistance Temperature Detectors (RTDs) were also used to measure temperature. Gamma densitometers and conductivity probes provided indications of void in above- and below-header flows. Loop and channel flow rates were measured with turbine flow meters (TFMs).

3. PROCEDURE

The experiments discussed in this paper consisted of:

- B9603: a "bench-marking" experiment conducted using a typical RD-14M LOCA scenario procedure with the power supplies ramped down to decay power levels 2 seconds after opening the break valve and with the FES sheath trip temperatures set at 700°C, and
- B9605: an experiment conducted with the power supplies left at their initial settings and with the FES sheath trip temperatures set at 1000°C.

Table 1 summarises the initial steady-state conditions used for these tests. Once steady-state conditions were achieved, the data acquisition system and the events sequence timer were simultaneously started. The events sequence timer isolated the surge tank, then four seconds later the break valve opened. Two seconds after opening the break, the power supplies were ramped down to decay levels (for the initial "bench-marking" experiment only). For the high temperature tests, the power supplies were left at their original settings for the duration of the test. All tests were terminated when a process protection trip occurred. The FES trip temperature was set to 1000°C for the high temperature tests in order to limit the potential for damage to the heated sections. (The fuel element simulators are designed to operate at heat fluxes of 0.75 MW/m^2 and sheath temperatures up to 1000°C.) Deformation of the heated sections was also a concern since it would be difficult to reproduce or characterise experimental results if the heated section deformed during a test. Table 2 summarises the experimental procedure used for these tests.

TABLE 1

NOMINAL INITIAL EXPERIMENTAL CONDITIONS FOR RD-14M LOCA TESTS

Primary System	Outlet header pressure	-	10 MPa(g)
	Input power	-	750 kW/pass
	Flow*	-	3.7 L/s
Secondary System	Steam drum pressure	-	4.5 MPa(g)
	Feedwater temperature	-	187°C

* Flow rates were determined based on the results of the CATHENA scoping analysis.

TABLE 2

EXPERIMENTAL PROCEDURE FOR RD-14M CRITICAL BREAK EXPERIMENTS

1.	Evacuate, fill and de-gas the primary-side.
2.	Pressurise primary-side to 2 MPa(g) and zero all instruments.
3.	Raise power, pump speed and boiler levels to desired initial conditions.
4.	Scan all instruments as a final check.
5.	Start data acquisition system to collect at a rate of 0.1 second/scan
6.	t = 6 s*, isolate the surge tank.
7.	t = 10 s*, break valve opens.
8.	t = 12 s*, ramp down power supplies if required

* For each experiment, steady-state data was collected for 60 s prior to initiating the break. These times have been referenced to a time 10 s prior to opening the break.

4. CATHENA

4.1 Code Description

CATHENA (Canadian Algorithm for THErmalhydraulic Network Analysis) is a one-dimensional thermalhydraulic code developed by AECL Whiteshell Laboratories (WL), primarily for the analysis of postulated accident conditions in CANDU reactors. The code uses a non-equilibrium, two-fluid thermalhydraulic model to describe the fluid flow. The thermalhydraulic model consists of six partial differential equations for mass, momentum and energy conservation - three for each phase. These conservation equations are coupled by a flow regime-dependent set of constitutive equations defining the transport of mass, momentum and energy between the phases and between each phase and the pipe walls. In addition, the gas phase mass consists of the vapour and zero to four noncondensable gas components (non-condensable gases were not required for these calculations). The numerical solution method used is a staggered-mesh, semi-implicit, finite-difference method that is not transit-time limited.

The wall heat transfer model within CATHENA is referred to as the GENeralized Heat Transfer Package (GENHTP). GENHTP consists of three major modelling components: wall-to-fluid heat transfer, wall-to-wall heat transfer and conduction within solid models. Any number of GENHTP models can be coupled to one or more thermalhydraulic nodes. A set of flow-regime-dependent constitutive relations for heat transfer specify the energy transfer between the fluid and the pipe wall and/or fuel element surfaces. Heat transfer by conduction within the piping and fuel can be modelled in the radial as well as the circumferential directions. Radiative heat transfer and the zirconium-steam reaction can also be included (but were not required for these calculations). Built into this package is the ability to calculate heat transfer from individual groups of pins in a fuel bundle subject to stratified flow. Under these conditions the top pins are exposed to steam while the bottom pins are exposed to liquid.

Component models, which describe the behaviour of pumps, valves, steam separators, surge tanks and discharge through breaks, are available to complete the idealisation of a reactor or thermalhydraulic facility. A more complete description of the CATHENA code is available in Reference [2].

4.2 RD-14M Idealisation

CATHENA treats a pipe network as a series of connected pipe and volume components. Each pipe component has a uniform geometry along its length. The user can further divide each pipe component into a number of nodes. Since CATHENA is a two-fluid code, horizontal and vertical sections are generally modelled separately unless the sections are very short. Sections of piping that are inclined but vary in degree of inclination, were lumped together to simplify the idealisation.

The primary circuit nodalization is shown in Figure 4. The portion of the primary circuit below the headers consists of two identical passes of five heated channels per pass (for simplification, only one pass is shown). The idealisation was modified for these particular tests to reflect the single-channel per pass configuration (HS8 and HS13). The seven FES in each channel were modelled as three pin groups at a lower, a middle and an upper elevation within the channel. This allows heat transfer from the FES to the liquid and vapour during stratified flow conditions to be accurately represented. Heat losses to the environment from all piping, including the feeders, were modelled using imposed heat transfer coefficients and an ambient temperature of 20°C.

The RD-14M headers are divided into four sections to capture the effect of the volumes in the ends of the headers and any effects resulting from the axial distribution of feeder connections. The piping leading from the headers to the relief valves (over pressure protection) represents a significant volume and was included in the idealisation.

The RD-14M steam-generator secondary-side idealisation is shown in Figure 5. Components outside of the steam generator, such as the feedwater system and the jet condenser were not included in the idealisation. The effects of these systems on the steam-generator secondary-side conditions were included using time-dependent boundary conditions. The secondary-side control systems and heat losses from the steam generators were not included.

The primary-circuit loss coefficients were determined from RD-14M commissioning test data. Pressure-drop data from several steady-state single-phase liquid flow tests at various flow rates and temperatures were examined. For simple area changes between pipe components, the pressure drop calculated internally by CATHENA was in agreement with that observed in tests. For more complicated junctions (steam generator plenums and end-fitting simulators) however, the pressure drops measured were applied through junction resistances to achieve more accurate values. Pressure drop measurements were available only for the primary circuit. Standard handbook minor loss values were used for other circuits. A more complete description of the RD-14M idealisation is available in Reference [3].

5. RESULTS

5.1 Pre-test Simulations

For these simulations, the RD-14M idealisation was modified to reflect the single-channel per pass geometry of the experimental facility. The new input deck was used in a scoping analysis aimed at determining the pump speed (expressed as a percentage of full speed) required to obtain steady-state fluid temperatures of (approximately) 300°C in the outlet headers. These conditions would simulate normal operating conditions in RD-14M. Results of this analysis indicated a pump speed of 55% would produce those header temperatures.

The 55% pump speed was then used in subsequent simulations to determine the break orifice size required to produce a critical break in HS13. Simulations were run using 12, 13, 15, 16, 18 and 20 mm break sizes. Results indicated that a critical break behaviour could be obtained with any of the break sizes tested in combination with the 55% pump speed. Since an 18 mm orifice was available, experiment B9603 was conducted with an 18 mm break and a flow split was observed (see Figure 6).

Following the experiment, results were compared with the pre-test simulations from CATHENA (see Figures 7 to 12). The predictions of CATHENA compared reasonably well with the experimental results, with a few exceptions.

There were two discrepancies between the pressure drop predicted across the heated section of the broken pass and that measured experimentally, shown in Figure 7. Immediately following the break there was a severe dip in the header-to-header and channel differential pressures predicted by CATHENA. This severe dip was not observed experimentally. It is suspected the pressure dip occurred but was damped out by the first order response of the instrument. Somewhat later (Figure 7, 15-20 s), the experimentally measured header and channel pressure drops became substantially more negative than the code predicted. The latter problem seems to occur when steam from the test section is coming back through the header and out the break. The failure to accurately estimate this pressure drop may also explain why CATHENA was slow to predict the FES temperature quench (see Figure 12).

While the inlet and outlet flow rates predicted in the broken pass agreed with experimental values during the initial blowdown, deviations were noted several seconds after the break opened. It should be noted that the experimental flows are measured using bi-directional turbine flow meters calibrated to ± 6 L/s in single-phase liquid conditions. Since voiding occurs in the channel within the first few seconds of opening the break, the TFMs should be used to only indicate flow direction after the first couple of seconds.

5.2 Post-Test Simulations

A comparison of initial experimental conditions with the CATHENA steady-state model, revealed a few significant differences. The pump flows obtained in CATHENA, with the pump model set at 55% of full speed, were higher than the experimental values. In the experiment, the

RD-14M pumps are manually adjusted so that exact settings are not possible. To resolve the difference, the actual percentage of the pump speed was calculated based on the full speed and the measured speed during the experiment. Experimental results showed this value to be 52.3% and the simulations were re-run with this value.

The power curve used in the pre-test simulations (taken from a previous experiment) was also slightly different than that for of the actual experiments. Following experiment B9603 the power curve used in CATHENA simulations was replaced with the measured power rundown. The results of this new simulation were compared with the experimental data as before and showed an improvement over results from the pre-test simulation.

A post-test simulation of B9605 (an 18 mm break with the power left on) was run to further evaluate the model. The CATHENA simulation was run with the power left constant until a trip at 35.3 s after the break opened (the time of the temperature-dependent trip in the experiment). The comparison of the predicted and experimental results shows the code predicted most parameters quite well, with the exception of the top centre FES temperature (see Figure 13). In the experiment, the top centre FES temperature increased when the flow split point developed and quenched when flow likely reversed through the channel (Figure 13, 10-20 s). While CATHENA captured the initial temperature excursion, it did not capture this quench. This results in a conservative prediction by CATHENA.

5.3 Sensitivity Analysis

In an effort to more fully understand the thermalhydraulic behavior during the RD-14M critical break experiments, a sensitivity analysis was performed. While the default code results provide a conservative estimate of FES temperatures, further investigation of differences between CATHENA and the experiments was desired.

The first of these trends was the dip in the ΔP curves. The influence of the condensation rate in inlet header 8 and the discharge flow through the break were investigated. These two aspects were examined independently by adjusting header modelling (condensation) and the discharge model. However, the calculated ΔP curves were insensitive to both the parameters.

A sensitivity analysis of the FES temperature profiles for experiments conducted with no power ramp was also conducted (Figure 13). It was believed that the code was not capturing the quench following the initial temperature excursion because the heat transfer was not large enough to allow the FES to cool below the rewet temperature. To examine the effect of post-CHF heat transfer the sensitivity of the FES temperature to the post-CHF heat transfer correlation was assessed. The code default post-CHF correlation, Groeneveld-Delorme [4], and an alternative, Bromley, was used in the study. The results showed that the Bromley correlation [5] was able to capture the initial temperature excursion and quench and was able to delay the FES heat-up as seen in the experiment (see Figure 14). The code, however, did underestimate the magnitude of the excursion and delayed the FES heat-up following the quench longer than seen in the experiment. It was observed that the Bromley correlation appeared to capture the trend (though not the magnitude) during the first 19 s, and the Groeneveld-Delorme appeared to capture the heat-up rate in the latter part of the simulation. To examine this further, a simulation was run using the two correlations in the respective regions. It was found that this combination most accurately reflected the trends of the experiment (see Figure 14).

6. CONCLUSIONS

CATHENA was successfully used to help determine the experimental conditions (pump speed and break size) required to produce a critical break in a single-channel RD-14M. Post test simulation results agreed well with experimental data. Although not all behaviour was captured exactly, CATHENA provided a conservative estimate of peak sheath temperatures and accurately predicted the flow split point in the channel.

ACKNOWLEDGEMENTS

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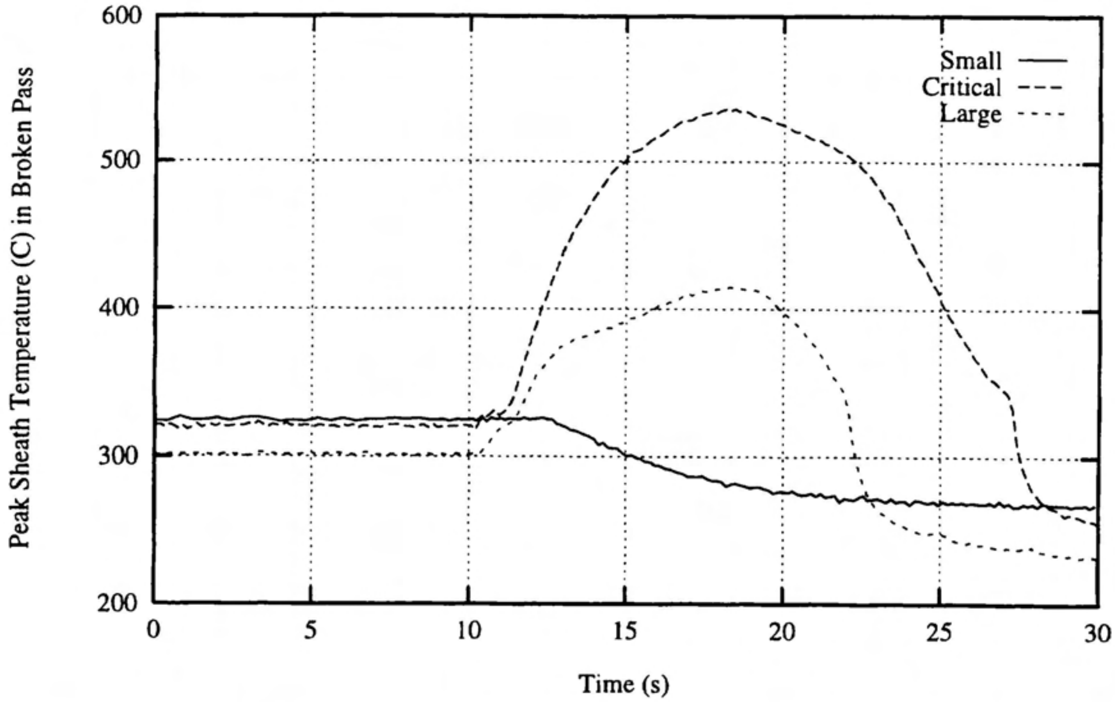

FIGURE 1: RD-14M Temperature Transients for Small, Large and Critical Breaks

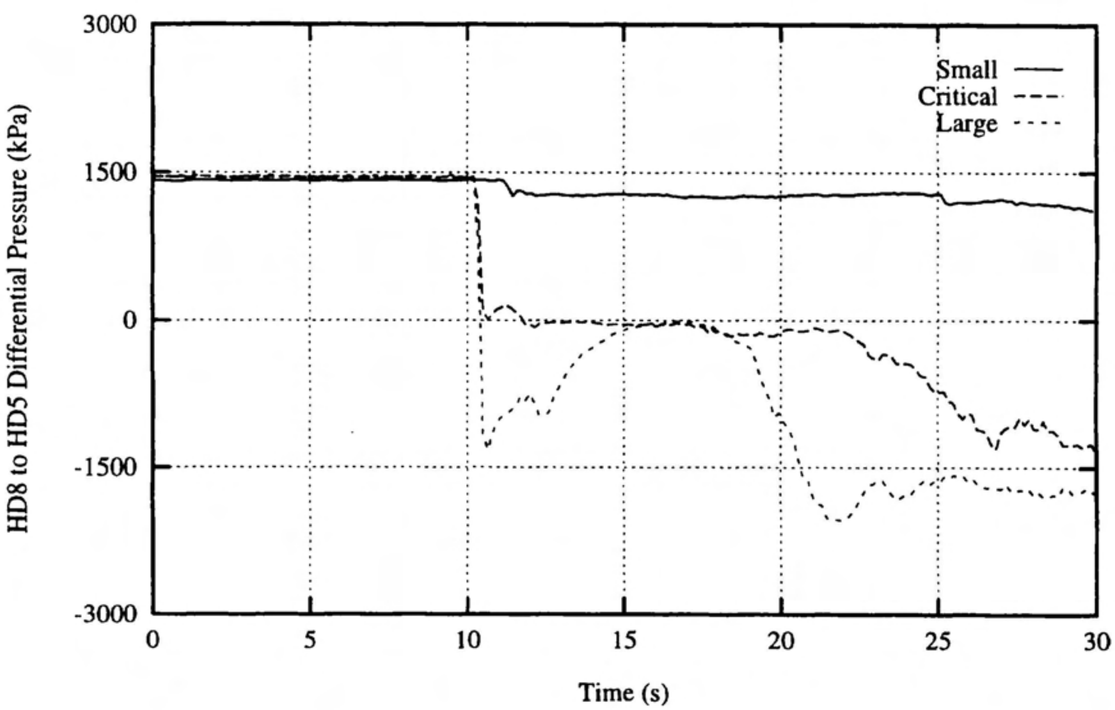

FIGURE 2: RD-14M Pressure Transients for Small, Large and Critical Breaks

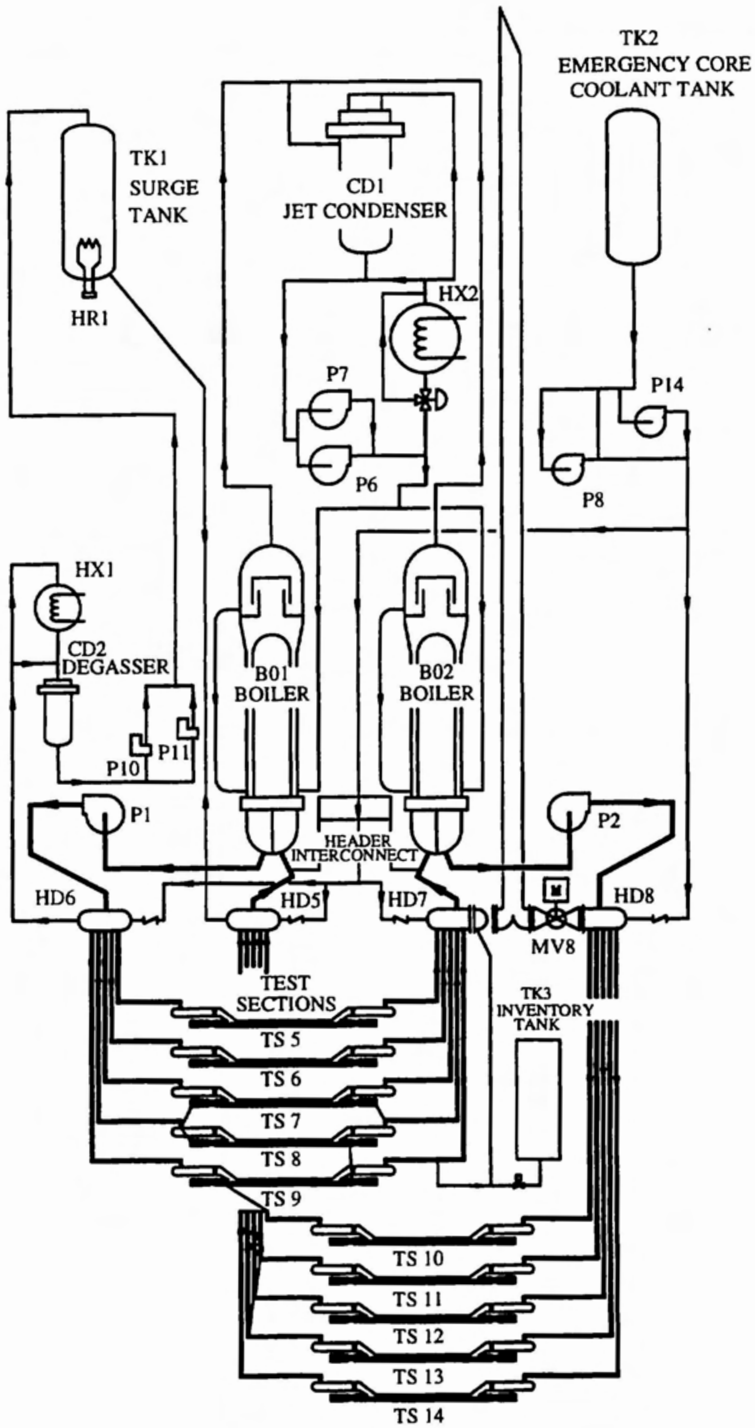

FIGURE 3: Schematic of RD-14M Facility

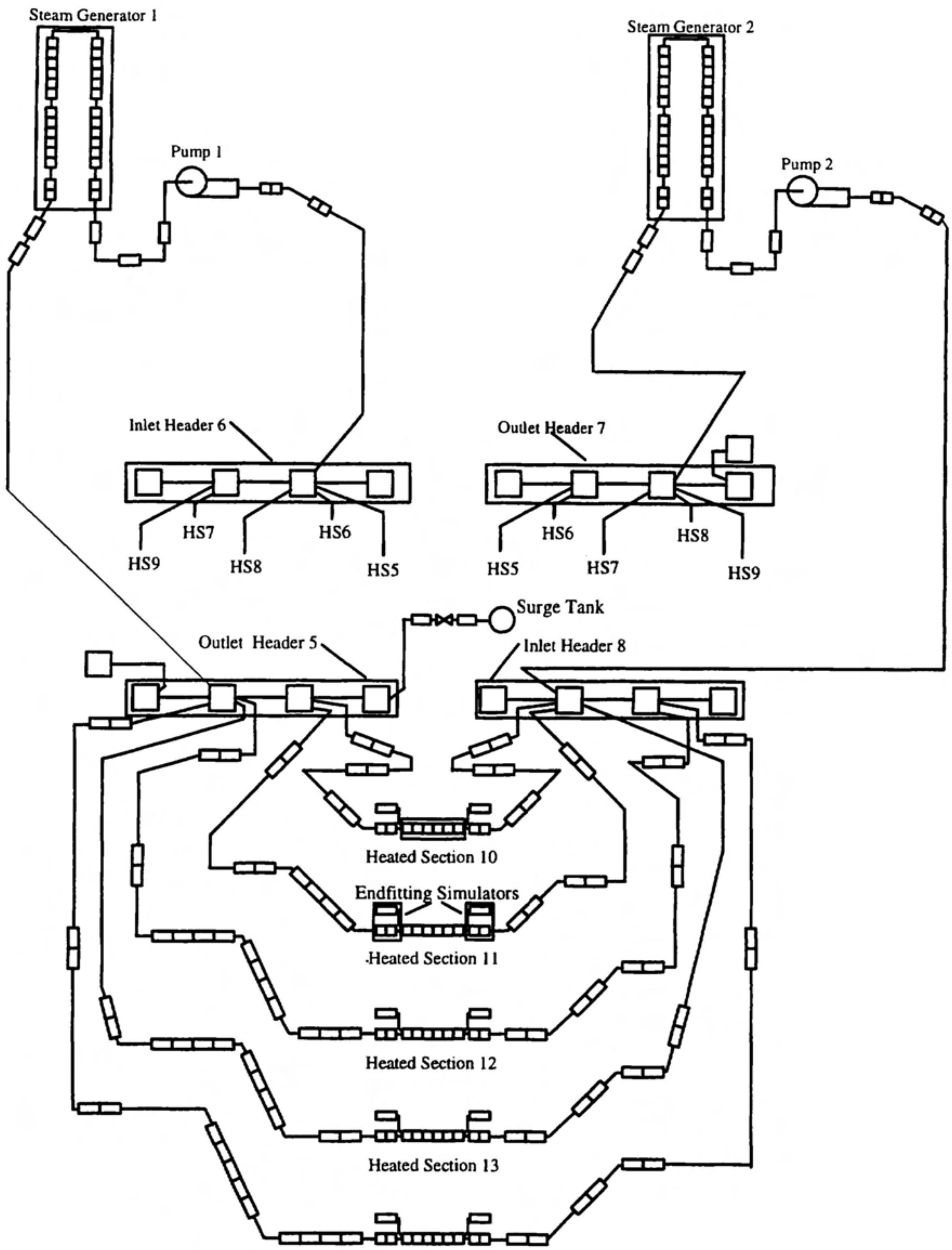

FIGURE 4: CATHENA Idealisation of RD-14M Primary Side

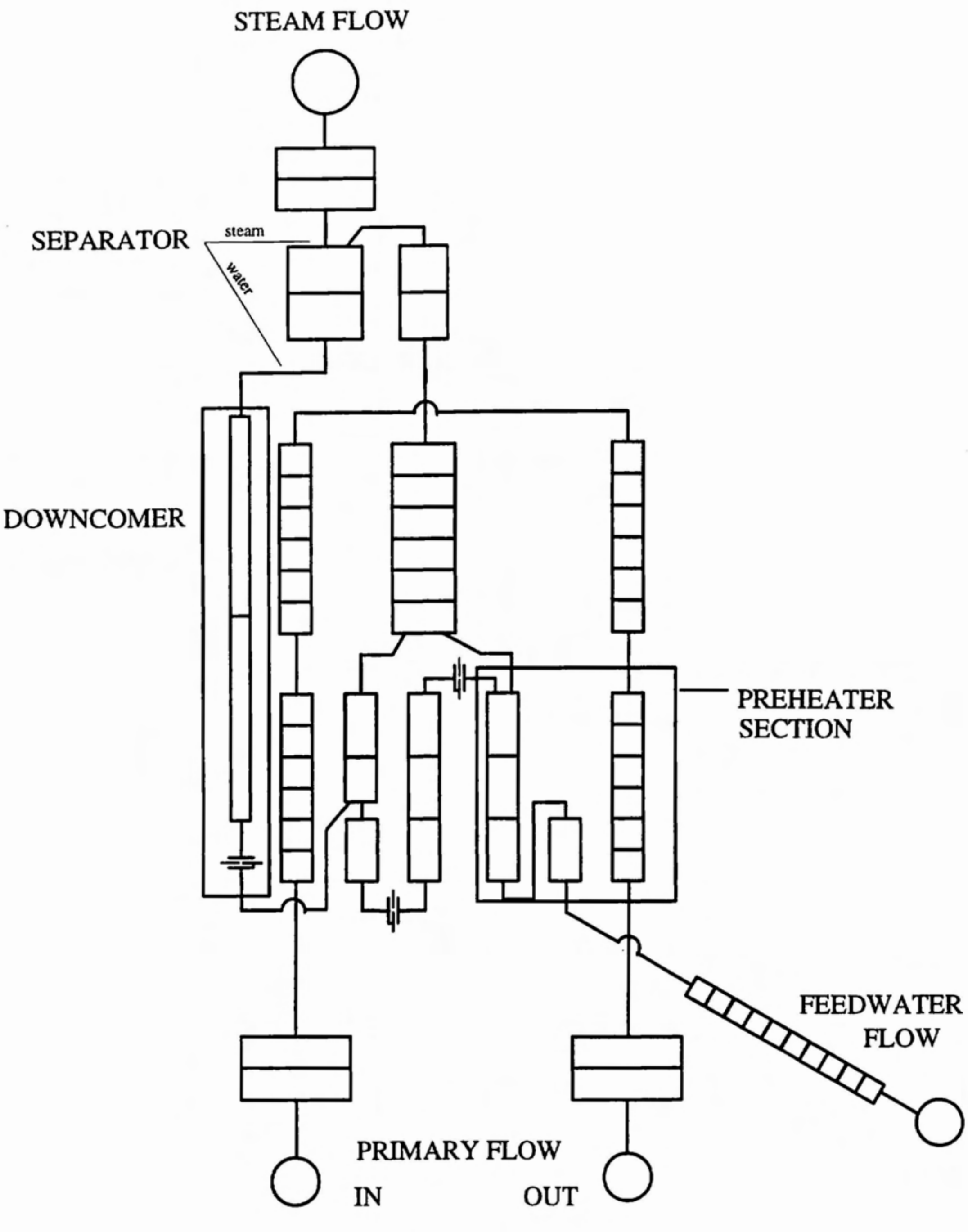

FIGURE 5: CATHENA Idealisation of RD-14M Secondary Side

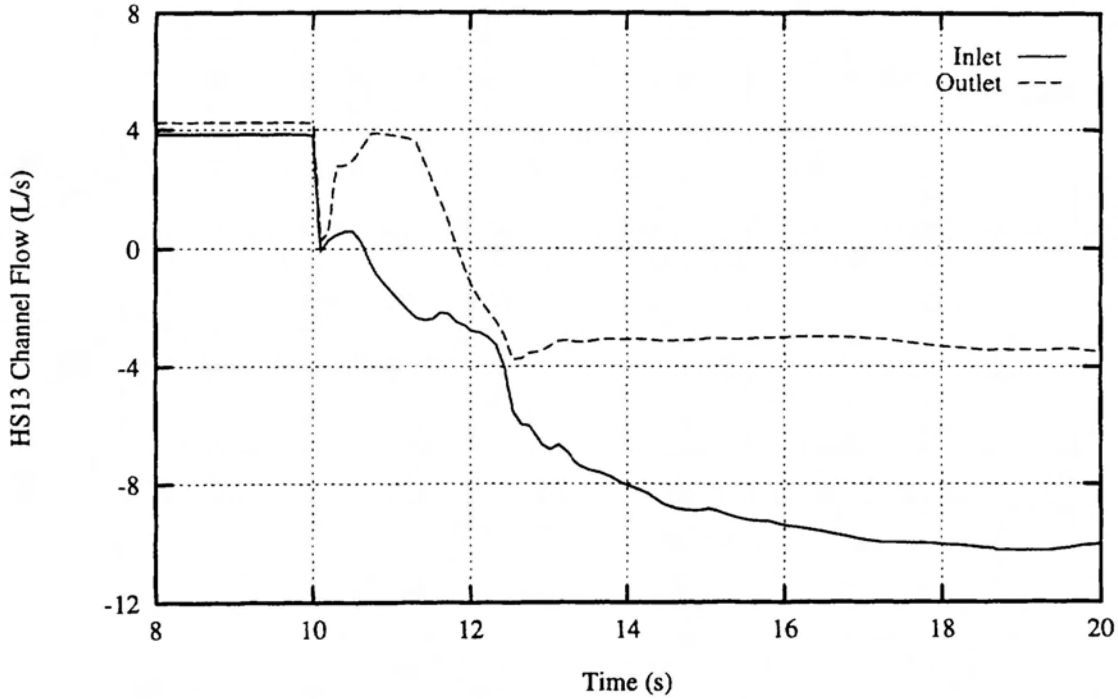

FIGURE 6: Break Size Scoping - 18 mm Break with 55% Pump Speed

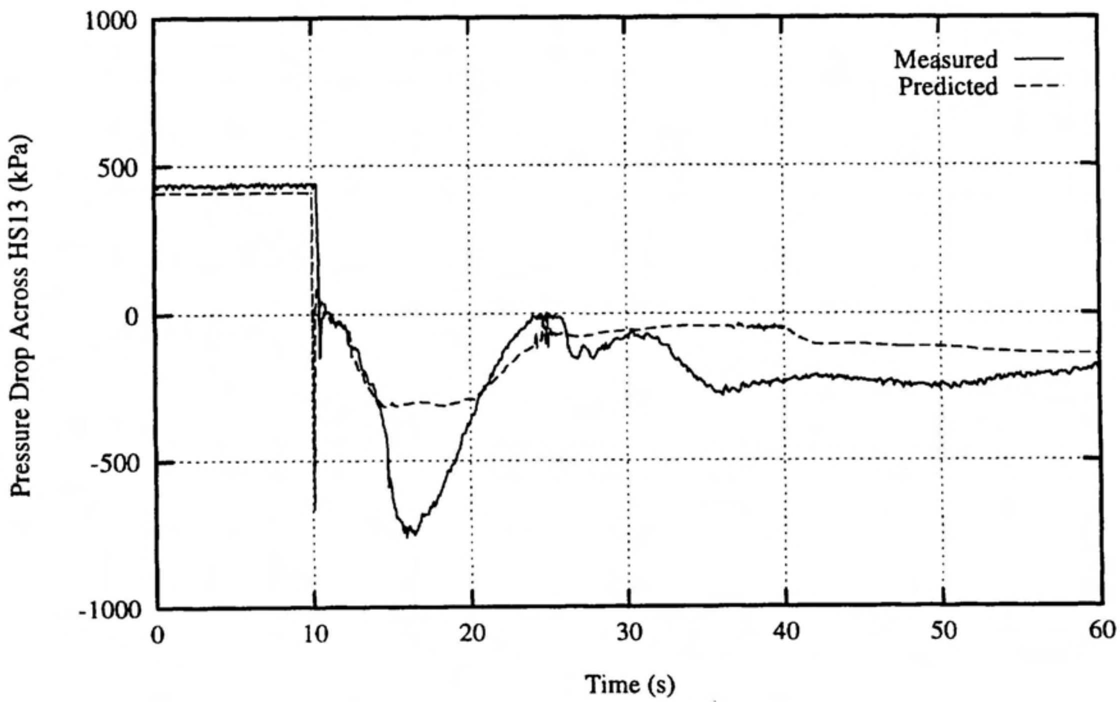

FIGURE 7: B9603 Pre-Test Simulation

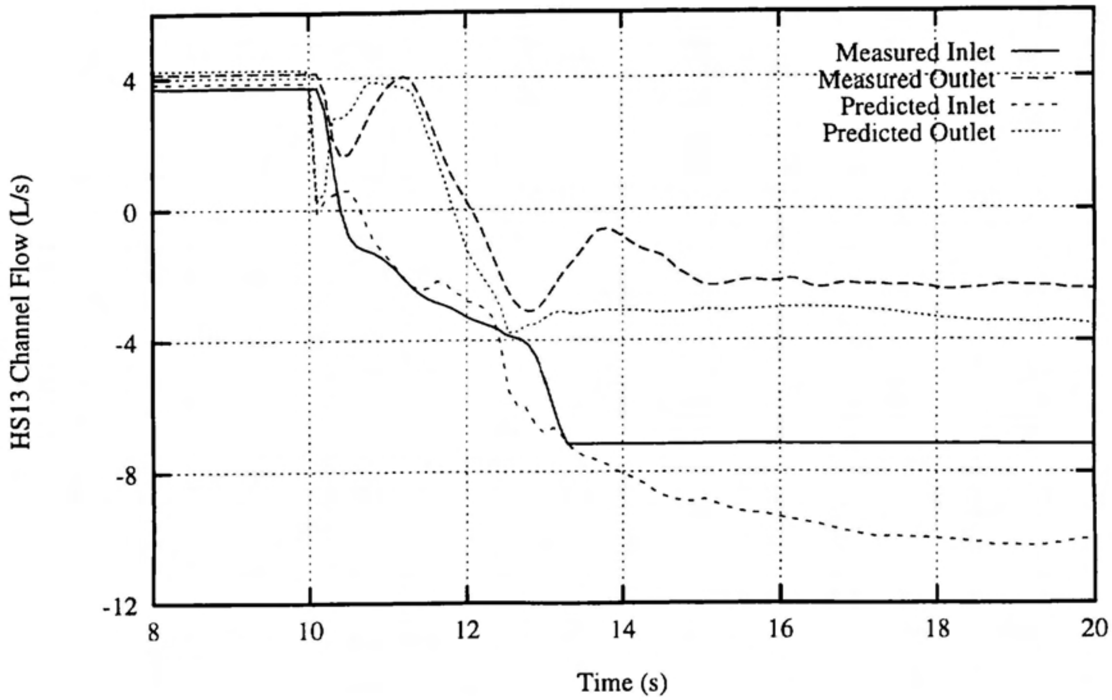

FIGURE 8: B9603 Pre-Test Simulation

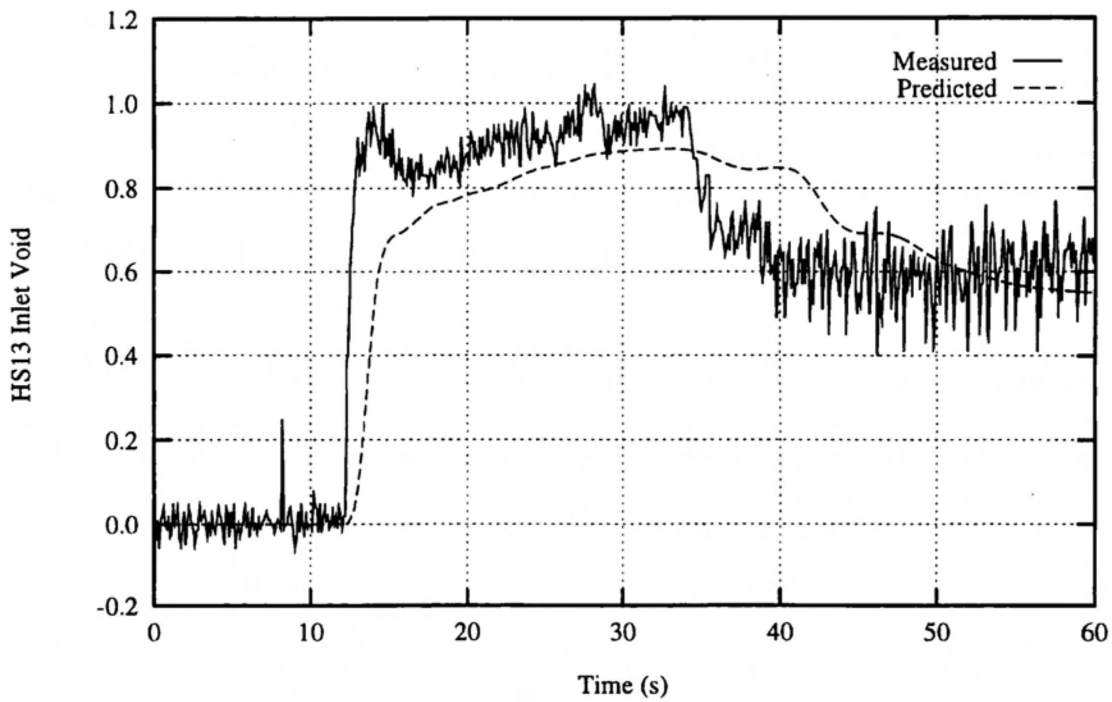

FIGURE 9: B9603 Pre-Test Simulation

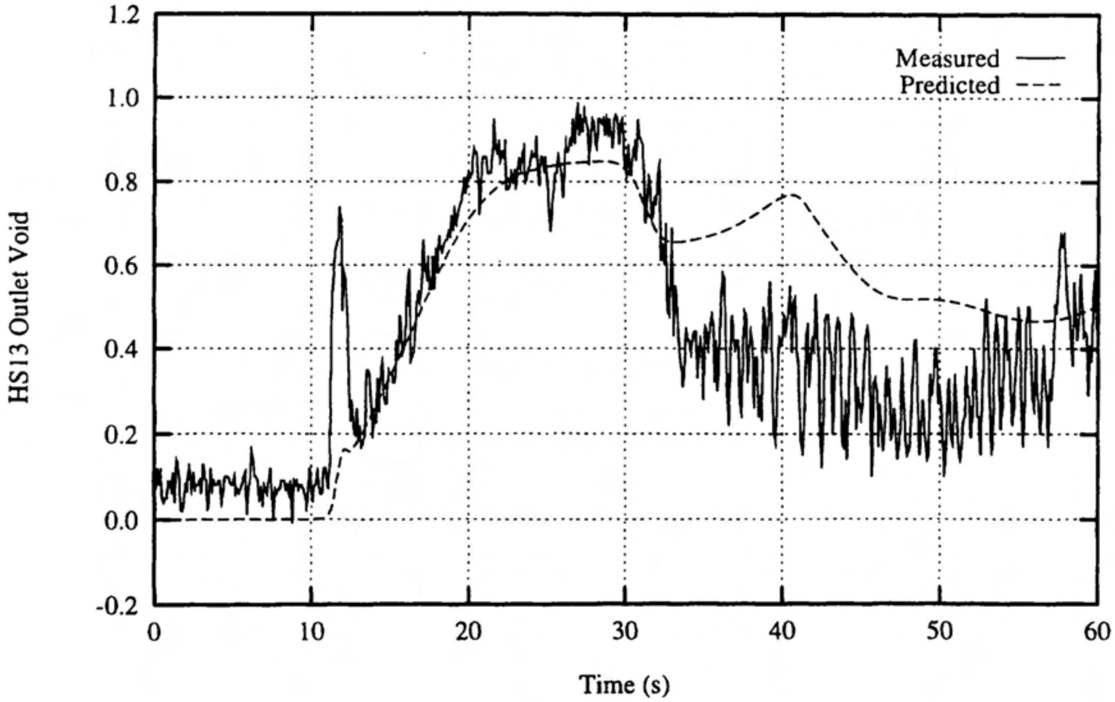

FIGURE 10: B9603 Pre-Test Simulation

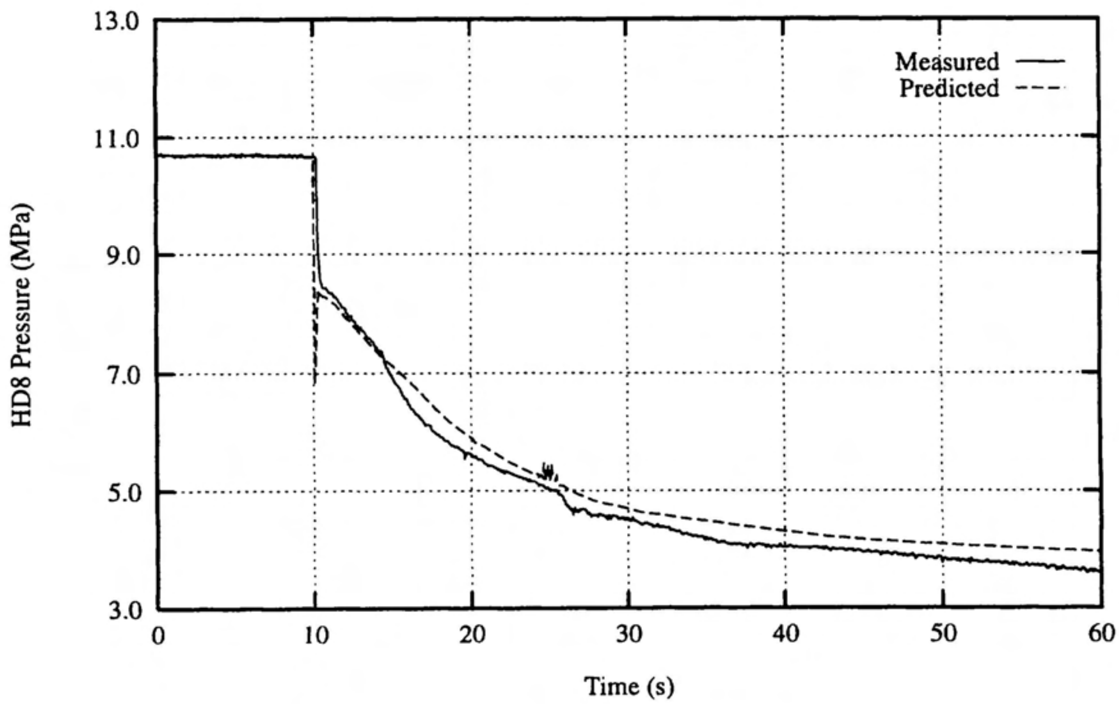

FIGURE 11: B9603 Pre-Test Simulation

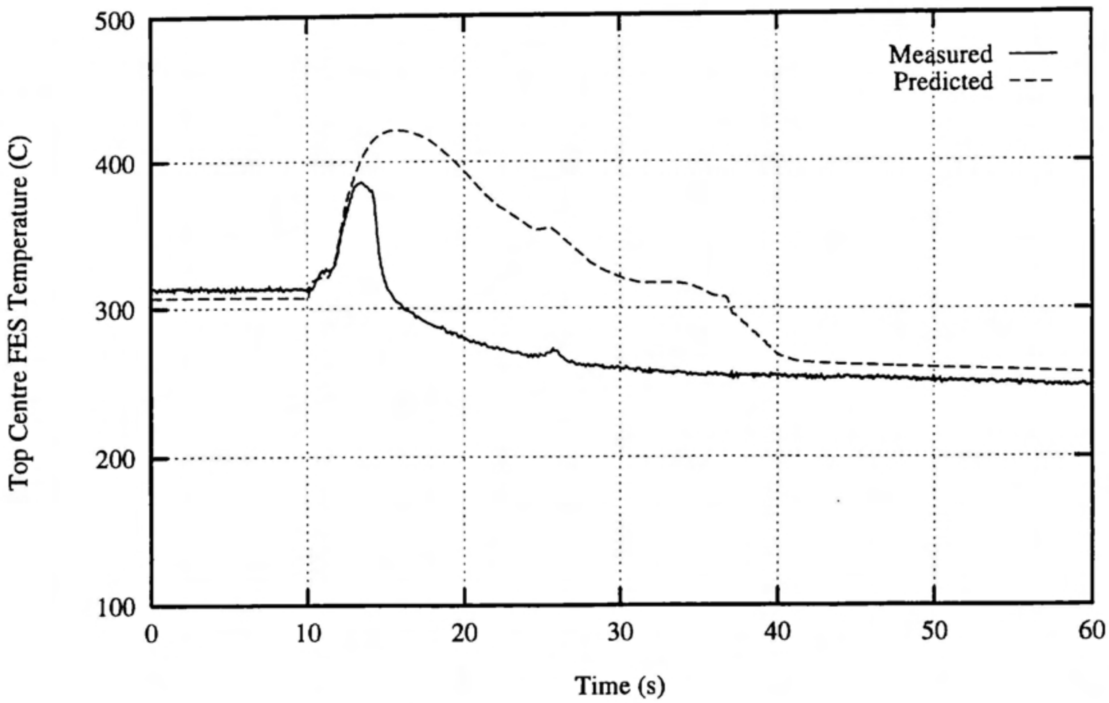

FIGURE 12: B9603 Pre-Test Simulation

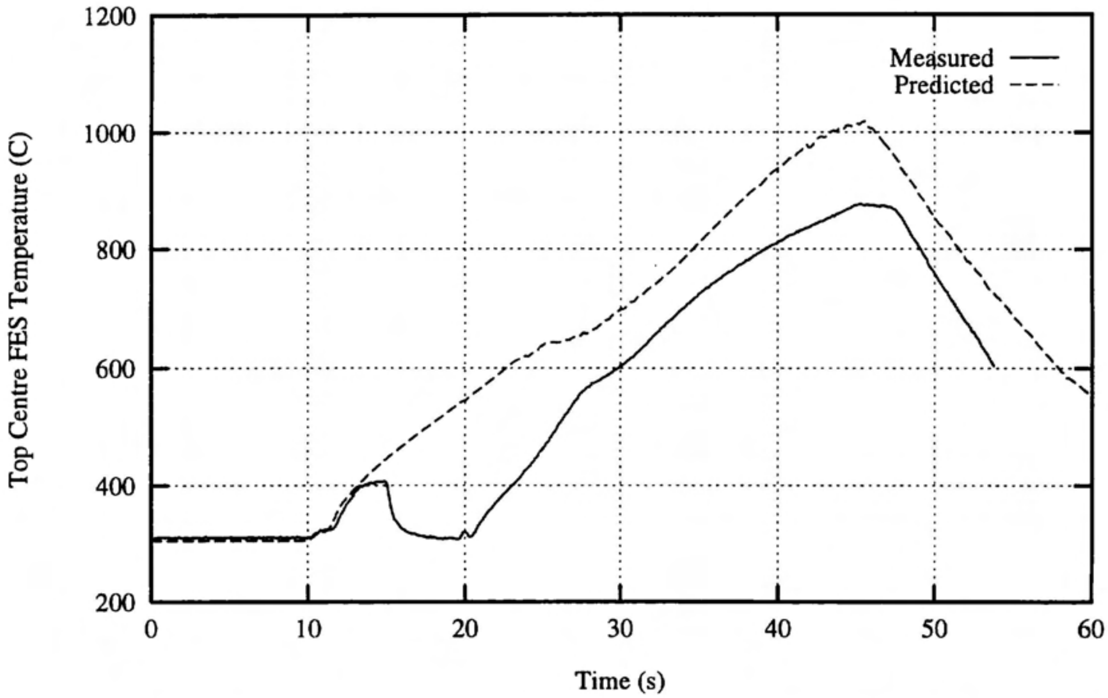

FIGURE 13: B9605 Post Test Simulation with Default Film Boiling Correlation

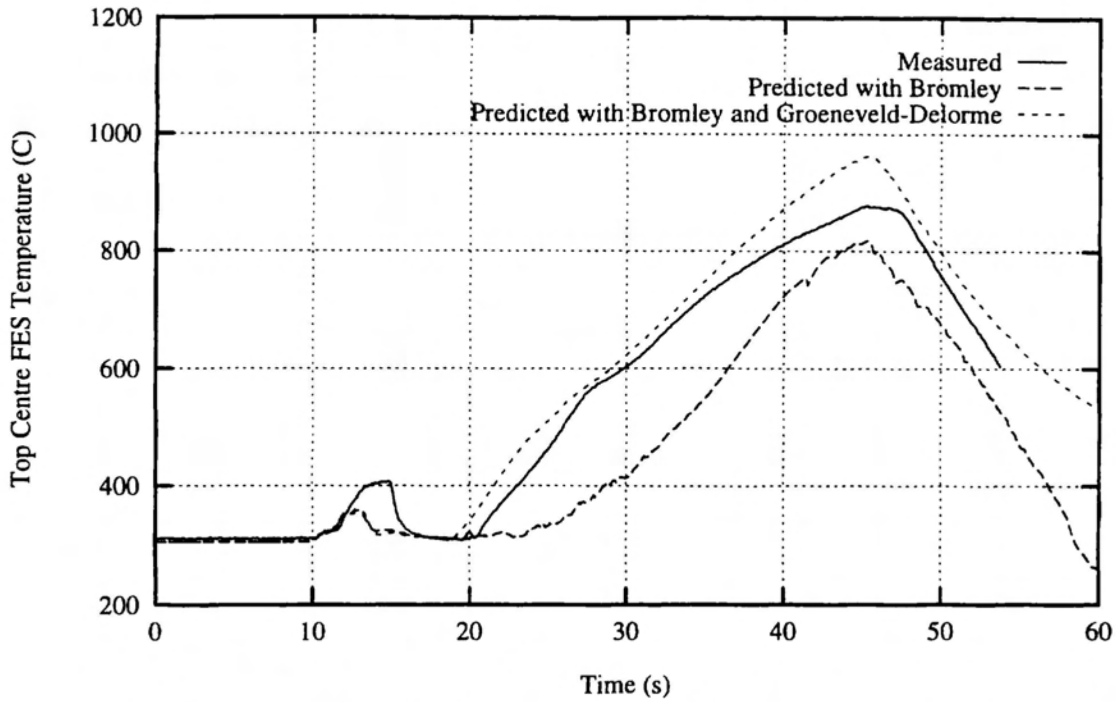

FIGURE 14: B9605 Post-Test Simulation with Bromley Correlation and with Combined Bromley and Default Correlations