# SIMULATIONS OF THE EBR-II TESTS SHRT-17 AND SHRT-45R

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**ABSTRACT**

A four-year International Atomic Energy Agency coordinated research project is currently being performed on two EBR-II Shutdown Heat Removal Tests. The goal of this project is to improve design and simulation capabilities in fast reactor thermal hydraulics, neutronics, plant dynamics, and safety analyses through benchmark analysis of the protected and unprotected loss of flow tests, SHRT-17 and SHRT-45R.

Argonne is both the lead technical organization and a benchmark participant in the modeling and simulation work. In its role as a participant, Argonne has continued to develop a model of EBR-II with the fast reactor safety analysis code SAS4A/SASSYS-1. Recent model analysis has focused on improving agreement with the recorded temperatures and flows. Improvements in flow rate predictions were achieved through adjustments to pump speed models and locked rotor loss coefficients. Examination and reinterpretation of several key temperature measurements resulted in much improved agreement between model results and recorded data for temperatures in the upper plenum and at the Z-Pipe inlet.

Several of the model predictions, such as the IHX temperatures and flow rate through the reflector and blanket subassemblies, still disagree with the measured test data. These discrepancies may be due to uncertainties in the measurements at low-flow conditions or phenomena that cannot be captured by the model and will be the focus of future analysis.

**KEYWORDS**
EBR-II, Sodium, SHRT, LOF, SAS4A/SASSYS-1

## 1. INTRODUCTION

In June 2012, the International Atomic Energy Agency (IAEA) initiated a four-year coordinated research project (CRP), focusing on modeling and simulation of two loss of flow tests performed during the EBR-II Shutdown Heat Removal Test (SHRT) series. [1, 2] SHRT-17 was the most severe protected loss of flow test performed during the SHRT program and demonstrated the effectiveness of natural circulation in cooling the reactor. SHRT-45R was the most severe unprotected loss of flow test and demonstrated the effectiveness of passive feedbacks in EBR-II. Twenty-one organizations representing eleven countries are participating in the benchmark.

The goal of this project is to improve design and simulation capabilities in fast reactor thermal hydraulics, neutronics, plant dynamics, and safety analyses through benchmark analysis of the protected and unprotected loss of flow tests. Phase 1 of the CRP concluded in February 2014. This phase consisted of using the benchmark specifications to develop models and perform blind simulations of both transients.

The recorded test data were distributed to the benchmark participants at the start of Phase 2. Phase 2 activities have focused on modeling refinements and improvements through evaluation of model results against recorded test data as well as sensitivity analyses and comparisons with results from the other organizations.

The Argonne simulations were performed with the fast reactor safety analysis code SAS4A/SASSYS-1. [3] As the other participants did not have access to the recorded test data, Argonne's initial model for Phase 1 was developed using only the information provided in the benchmark specification. Agreement between the initial SAS4A/SASSYS-1 results and the recorded test data was acceptable but with room for improvement.

Argonne's modeling efforts during Phase 2 to improve agreement of the SHRT-17 and SHRT-45R simulations with the recorded temperatures and flows are described below. A number of thermal-hydraulic modeling refinements were investigated and produced some improvements in the SAS4A/SASSYS-1 models for the two transients. Still, agreement is not acceptable in all areas of the simulation. Reasons for the discrepancies are discussed as well as future simulation efforts that may inform and improve the Phase 2 SAS4A/SASSYS-1 models.

## 2. TEST DESCRIPTIONS

The EBR-II plant was a metallic fueled sodium fast reactor designed and operated by Argonne National Laboratory. With a thermal power of 62.5 MW and an electric output of 20 MWe, EBR-II operated from 1964 until 1994. EBR-II operated initially to demonstrate the feasibility of a closed fuel cycle based on Uranium-238 to fuel the breeding process. EBR-II was also closely tied to research into pyrometallurgical reprocessing for irradiated nuclear fuel.

During the last fifteen years of operation, EBR-II was used for experiments designed to demonstrate the feasibility of passive safety in liquid metal reactors (LMR). The Shutdown Heat Removal Test program was carried out in EBR-II between 1984 and 1986. The objectives of the program were to support the U.S. advanced LMR program, provide test data for validation of computer codes, and demonstrate passive reactor shutdown and decay heat removal in response to protected and unprotected transients.

Starting from full power and flow, the SHRT-17 test was initiated by simultaneously tripping both the primary and intermediate-loop coolant pumps and scramming the reactor to simulate a protected loss-of-flow accident. The primary system auxiliary electromagnetic (EM) coolant pump that normally had an emergency battery power supply was turned off. Temperatures in the reactor quickly rose to high, but acceptable levels as the natural circulation characteristics cooled the reactor down safely at decay heat levels. SHRT-17 demonstrated that natural phenomena such as thermal expansion of the sodium coolant and thermal inertia of the primary pool sodium can be effective in protecting the reactor against potentially adverse consequences from protected loss-of-flow and loss-of-heat-sink accidents.

The SHRT-45R test was conducted to demonstrate the effectiveness of EBR-II's inherent feedback mechanisms to terminate the fission process. Also starting from full power and flow, SHRT-45R was initiated by simultaneously tripping both the primary and intermediate-loop coolant pumps to simulate an unprotected loss-of-flow accident. During the test, the plant protection system (PPS) was disabled to prevent a scram. Temperatures in the reactor quickly rose to high, but acceptable levels as the inherent reactivity feedbacks terminated the fission process. SHRT-45R demonstrated that natural phenomena such as thermal expansion of reactor materials can be effective in protecting the reactor against potentially adverse consequences from unprotected loss-of-flow and loss-of-heat-sink accidents.

EBR-II was heavily instrumented to measure flow rates, temperatures, and pressures throughout the primary and intermediate systems. While some instruments failed before the SHRT program began, a large number of measurements are available to compare with benchmark simulation results. Additionally, two instrumented subassemblies were loaded in the core for the SHRT tests to provide in-core temperature measurements for characterizing flow redistribution and temperature profiles during transients. XX09 was a 61-element fueled subassembly loaded in the inner core and XX10 was a 19-element non-fueled subassembly loaded in the reflector region. Most of the thermocouples in XX09 and XX10 were installed at one of three elevations, MTC, TTC, and 14TC, which refer to midplane-of-core, top-of-core, and above-core, respectively. Two flowmeters were also installed at the inlet of each instrumented subassembly.

The benchmark specification provides the information participants need to model the EBR-II core and primary sodium system. The intermediate side of the IHX is treated as a boundary condition with the transient inlet temperature and flow rate specified. For SHRT-17, the measured fission power and pre-transient power history were used to calculate decay heat generation and, therefore, total power production during the test. A separate neutronics benchmark was provided with the data needed to construct a neutronics model of the SHRT-45R core for calculating reactivity feedback coefficients and power distributions.

## 3. SAS4A/SASSYS-1 MODEL

Argonne's benchmark analysis of SHRT-17 and SHRT-45R was performed with the fast reactor safety analysis code SAS4A/SASSYS-1. Although previous EBR-II SAS4A/SASSYS-1 models have been created to analyze the reactor and validate the code, this new model was created using only the information provided in the benchmark specification. It was not based on legacy EBR-II models. The model is described below.

### 3.1. Core

The thermal-hydraulic performance of a reactor core is analyzed in SAS4A/SASSYS-1 with a model consisting of a number of single-pin channels. The channel model provides input to specify a single fuel pin and its associated coolant and structure. A single-pin channel represents the average pin in an assembly, and assemblies with similar reactor physics and thermal-hydraulic characteristics are grouped together.

Six single-pin channel types were created for the driver, partial driver, dummy, reflector, blanket, and control subassembly types. The standard SHRT-17 and SHRT-45R core models use twenty-two channels based on one of these six channel types to represent all 637 core subassemblies. The safety and experimental subassemblies are not modeled with their own channel types but rather are grouped into other channels with similar characteristics. The SHRT-45R core model was created first and later modified for the SHRT-17 core configuration. Figure 1 illustrates the channels in the SHRT-45R model.

For the standard core model, Channel 21 represents XX09 and its six neighboring subassemblies and Channel 22 represents XX10 and its six neighboring subassemblies. Most of the analyses were performed using the standard core model because it runs quickly. But the single-pin channel model cannot capture the radial temperature distributions inside a subassembly. To predict the temperature profiles inside XX09 and XX10, the detailed sub-channel model was used. [4] This model lets users account for the power distribution among pins and cross-flow between the channels within a subassembly. In the standard core model, XX09, XX10, and the twelve neighboring subassemblies are represented by the final two channels so they can be easily replaced when the sub-channel model is used. For simulations using the sub-channel model, 2448 sub-channels replace Channels 21 and 22 to represent these fourteen subassemblies.

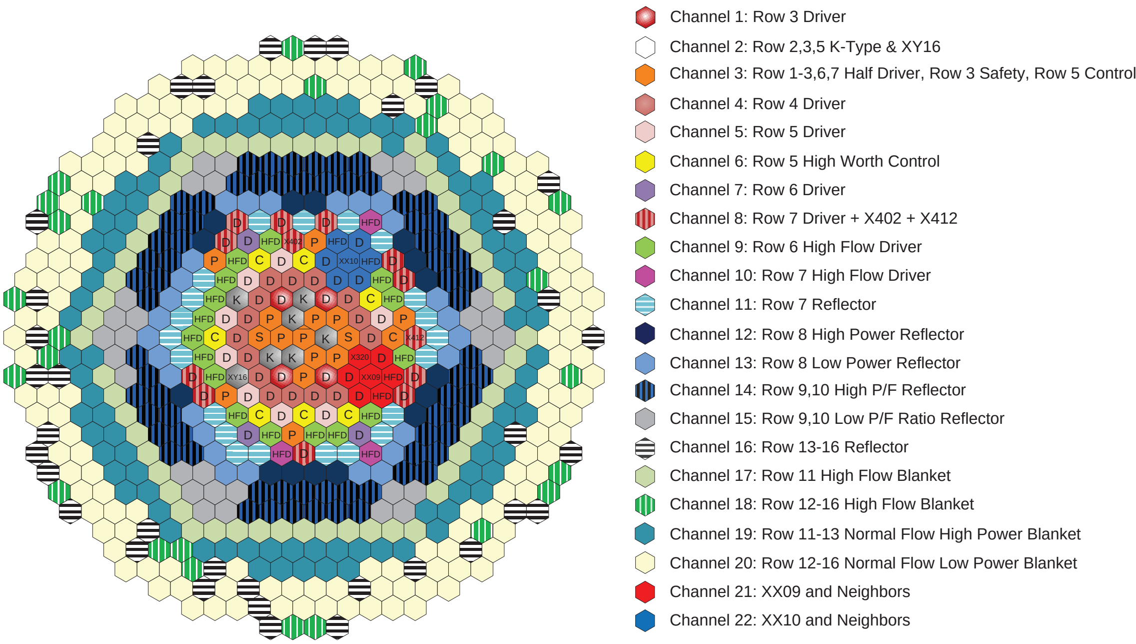


**Figure 1. SHRT-45R SAS4A/SASSYS-1 Channels.**

Reactivity feedback coefficients for the SAS4A/SASSYS-1 model were calculated using Argonne's fast reactor neutronics analysis tools suite. The coefficients for the Doppler, sodium density, and axial fuel and cladding reactivity feedback effects were evaluated using the VARI3D code. [5] The coefficients for the radial core expansion and control rod driveline expansion reactivity feedback effects were calculated with DIF3D. [6]

### 3.2. Coolant System

The PRIMAR-4 module in SAS4A/SASSYS-1 simulates the thermal hydraulics of primary and intermediate systems. Compressible volumes, or CVs, are zero-dimensional volumes that are used to model pipe tees and larger volumes of coolant such as inlet plena, outlet plena, and pools. Compressible volumes are connected by liquid segments, which are composed of one or more elements. Elements are modeled by one-dimensional, incompressible, single-phase flow and can be used to represent pipes, valves, pumps, heat exchangers, steam generators, and more.

Figure 2 illustrates the EBR-II primary system model. The two primary pumps draw sodium from the cold pool and feed the high- and low-pressure flow paths. Sodium flowing through the high-pressure inlet piping (Segments 6 and 9, S6 and S9) discharges into the high-pressure inlet plenum (CV1) before flowing up through the inner core channels (Segment 1, S1). Sodium flowing through the low-pressure inlet piping (Segments 7 and 10, S7 and S10) discharges into the low-pressure inlet plenum (CV2) before flowing up through the outer core channels (Segment 2, S2). The inner core channels represent the first seven rows of subassemblies and the outer core channels represent the remaining subassemblies in rows 8-16. At steady state, flow through the inner core and outer core subassemblies is approximately 390 kg/s and 70 kg/s, respectively.

The inner and outer core channels both discharge into the outlet plenum, which mixes the discharged sodium before it enters the Z-Pipe (Segment 4, S4). The Z-Pipe is a double-walled pipe that contains the auxiliary EM pump. Sodium leaving the Z-Pipe flows through the intermediate heat exchanger before discharging into the cold pool.

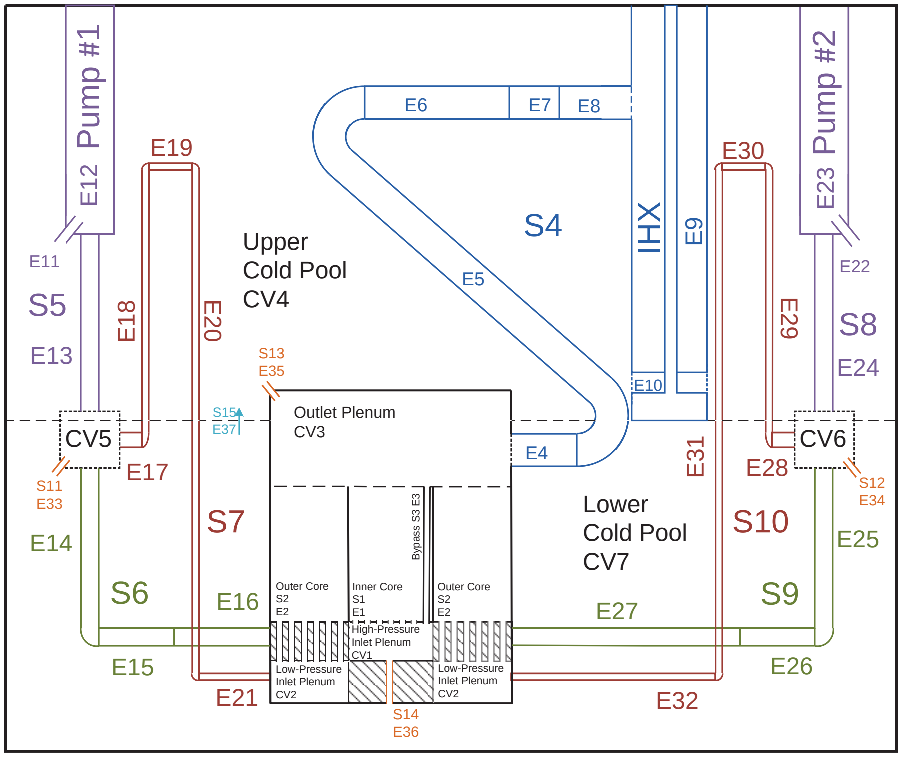


**Figure 2. SAS4A/SASSYS-1 EBR-II Primary Sodium System Model.**

The intermediate loop was not defined in the benchmark. The IHX intermediate side inlet temperatures and mass flow rates are provided as boundary conditions for each transient. This is represented in the SAS4A/SASSYS-1 model with a very simple loop where a surrogate steam generator discharges directly into the IHX. The IHX inlet temperature boundary condition is enforced with the user-specified steam generator outlet temperature model. A simple pump head vs. time model was used to generate the specified intermediate mass flow rate.

## 4. PHASE 1 RESULTS

At the conclusion of Phase 1, the participants were provided with the recorded test data. Simulation results for both tests were compared with the measured data to show where agreement was good and where model updates were required. Phase 1 comparisons with the test data focused on flow and primary system temperature measurements for both tests as well as total power for SHRT-45R. Analysis of the collective results for the CRP participants is discussed in [2].

The Phase 1 SAS4A/SASSYS-1 model predicted both tests reasonably well but there was room for improvement. The total sodium flow rate was well predicted for SHRT-45R but significantly over-predicted for SHRT-17 using the same primary pump model. Uncertainty in the flow rate measurements is higher at lower flows, so the high-pressure flow rate measurement, which was very well predicted for SHRT-45R, is more reliable than the low-pressure flow rate measurement. Furthermore, the long-term SHRT-17 flow rates are two and a half times smaller than the SHRT-45R flow rates, so the SHRT-17 flow measurements have more uncertainty than the SHRT-45R measurements.

Agreement with the core inlet temperature measurements was good because those temperatures did not change much during either test. For the Z-Pipe inlet temperature, the SHRT-45R model agreed significantly better with the measured data than the SHRT-17 results did. For both tests, the IHX primary side inlet temperature predictions did not agree with the measured data.

Total power was predicted reasonably well for SHRT-45R. Agreement was better during the first half of the test. In the second half of the test the power level was very low, around 5%, so small absolute differences led to larger relative differences.

## 5. PHASE 2 ANALYSIS

After the recorded test data were provided to the participants, initial analysis focused on improving the flow rate predictions. During natural circulation conditions, power and flow are tightly coupled. As power increases, the difference in sodium densities between the cold and hot legs increases, which increases the buoyancy head. The pressure drop through the core is much lower during the transient, so a small increase or decrease in the buoyancy head can have a relatively large impact on core flow rates.

The benchmark specifies total power production for SHRT-17 but not for SHRT-45R. Phase 2 SHRT-45R model analysis was performed with total power forced to match the sum of the measured fission power and calculated decay heat. This eliminates the effect that power has on the flow rate predictions. Model adjustments were considered successful if agreement with the measured flow rates improved when total power is enforced. Because reactivity feedbacks are dominated by the inner core, preference was given to model updates that improved the high-pressure flow rate. The SHRT-45R results shown in this section were predicted with total power matching the actual transient. Section 6 presents the results calculated with the point kinetics model that was developed during Phase 1 of the benchmark.

Additional analysis during Phase 2 focused on performing sensitivity analysis on the reactivity feedbacks. However, this analysis was only intended to gain a better understanding of the changes necessary to improve the power prediction. That analysis did not provide a sufficient basis for changing the reactivity feedback coefficients so none of the coefficients were changed during Phase 2.

### 5.1. Pump Model

Figure 3 illustrates the Phase 1 predictions of the Pump #2 inlet piping mass flow rates. Flow measurements are not available for Pump #1. The SHRT-45R flows agreed more with the measured data than the SHRT-17 flows did. Compared with the measured data, the SHRT-45R high-pressure flow is slightly underpredicted. The discrepancy between the measurement data and model predictions is higher for the SHRT-45R low-pressure flow rate, with differences of approximately 40%. However, since the high-pressure flow rate is larger than the low-pressure flow rate, the total flow rate is well predicted. For SHRT-17, the trend was reversed. The low-pressure flow rate agreed well but the high-pressure flow rate was over-predicted by approximately 50%, causing the total flow rate to also be significantly over-predicted.

Further investigation into the primary pump models revealed that both pumps locked during the SHRT-45R simulation but only pump #1 locked during the SHRT-17 simulation. The SAS4A/SASSYS-1 homologous pump model assumes a pump locks when both the pump speed and flow rate through the pump drop below user-specified thresholds. Fifty seconds into the SHRT-17 test, the measured pump #2 speed was sufficiently low that it was assumed the pump locked. However, the measured pump speed remained above the assumed locking threshold, preventing the pump from locking during the simulation.

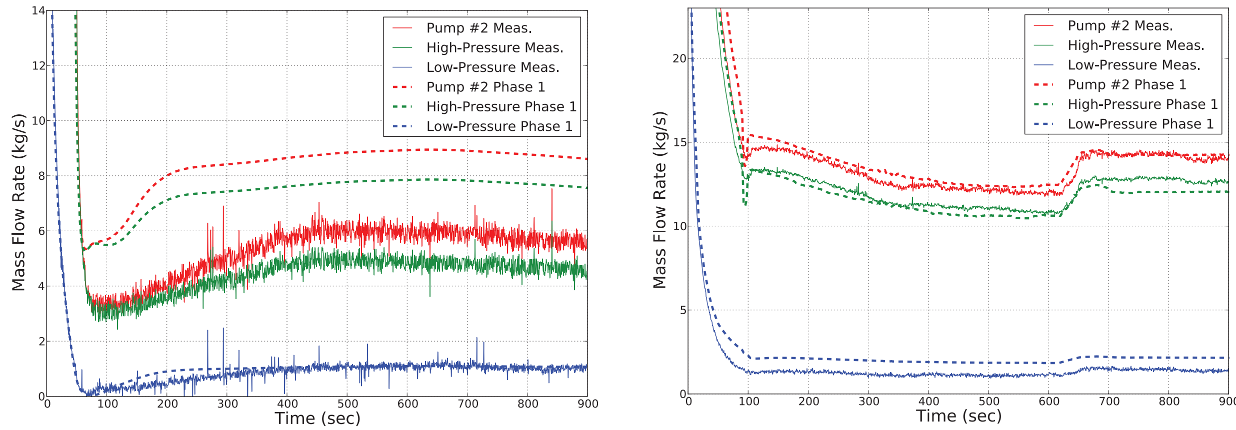


**Figure 3. Phase 1 SHRT-17 (left) and SHRT-45R (right) Pump #2 Flow Rates**

Because the flow rates are significantly higher for SHRT-45R than SHRT-17, it was concluded that the pumps must have locked for SHRT-17 if they locked for SHRT-45R. Calibration for the second pump speed measurement may have been off. Whatever the reason for the high measurement, the SHRT-17 pump #2 speed was decreased below the locked rotor speed threshold to induce locking in the second SHRT-17 pump. With both pumps locking, the SHRT-17 flow was lower but still over-predicted.

The homologous pump model determines the resistance of a locked pump based on a locked rotor loss coefficient. The Phase 1 results assumed a loss coefficient of 1.0. The SHRT-17 flow rate predictions agree very well with the data with a loss coefficient of 3.6. But that higher coefficient causes the SHRT-45R flows to be significantly under-predicted by SAS4A/SASSYS-1. Again noting that flow is much higher for SHRT-45R than for SHRT-17, it was speculated that the SHRT-45R flow rates might have remained above the threshold for locking the pumps. By decreasing the flow rate threshold, the higher locked rotor loss coefficient could be used to improve the SHRT-17 flow rate prediction without affecting the SHRT-45R results.

Figure 4 illustrates the Phase 2 flow rate predictions that were obtained with the higher locked rotor loss coefficient and the assumption that both pumps locked during SHRT-17. These SHRT-45R results were generated with total power matching the actual transient power. Without the small extra resistance through the locked pumps, the SHRT-45R high-pressure flow rate agreement is even better than before. When the point kinetics model is used, the agreement is not as good because the calculated and measured powers do not perfectly agree. Those results are shown in Section 6.

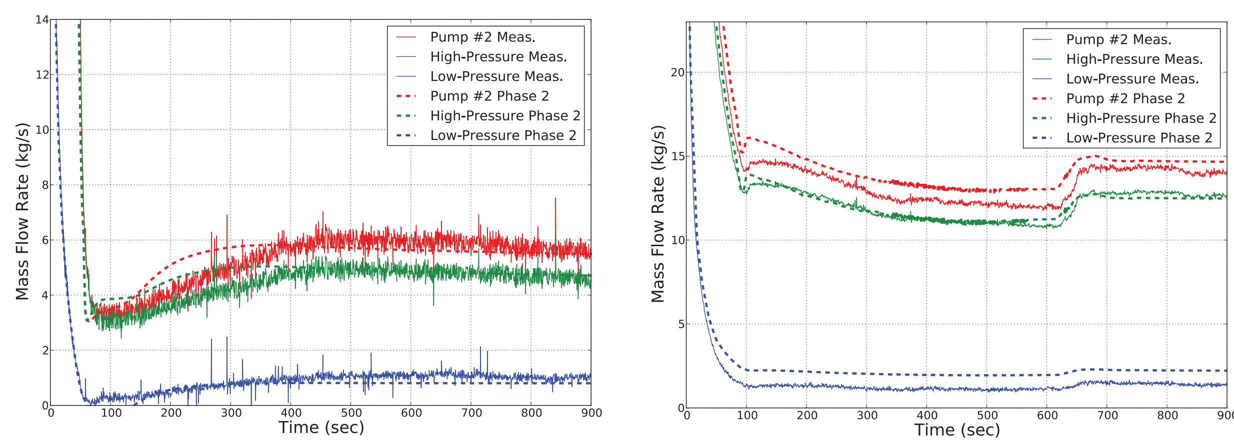


**Figure 4. Phase 2 SHRT-17 (left) and SHRT-45R (right) Pump #2 Flow Rates**

The SHRT-45R low-pressure flow rate still does not agree with the measured data. There are several possible reasons for this discrepancy. Some aspects of the transient, such as thermal stratification in the cold pool, which affects the inlet sodium temperature and density, are not captured by the SAS4A/SASSYS-1 model. The low-pressure inlet sodium may be especially sensitive to density changes because the low-pressure piping travels to much higher and lower portions of the cold pool than the high-pressure piping does. It is also possible that the low-pressure SHRT-45R flow is well predicted, but because the flow rate is so low, the measurement may not be very accurate. However, since the high-pressure flow rate plays a much larger role in the total flow rate and reactivity feedback calculations, the low-pressure flow rate discrepancy is not as concerning.

### 5.2. Upper Plenum Model

Figure 5 illustrates how the Phase 1 SAS4A/SASSYS-1 Z-Pipe inlet temperature predictions compared with the measured data. The SHRT-45R prediction agreed significantly better with the data. Initial analysis focused on improving the SHRT-17 agreement without affecting the SHRT-45R agreement.

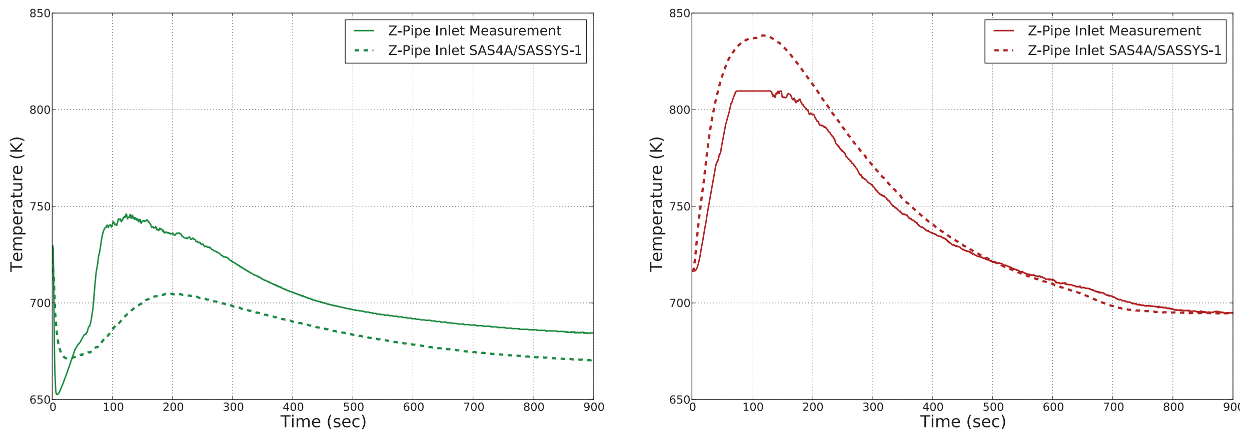


**Figure 5. Phase 1 SHRT-17 (left) and SHRT-45R (right) Z-Pipe Inlet Temperatures**

Sodium that exits the core subassemblies flowed through or around a flow baffle plate before entering the Z-Pipe inlet. There are three flow paths in the outlet plenum:

- Through holes in the flow baffle plate,
- Through gaps below the flow baffle plate, and
- Out a 90 degree opening in the baffle plate and around the side of it.

At the beginning of each test, the inner core outlet temperature predictions were similar to the measurements shown in Figure 5. It was hypothesized that the Z-Pipe was fed primarily by the hotter and faster sodium leaving the inner core during the early portion of the tests. A variety of model updates were attempted to capture the complicated upper plenum flow paths. None of the updates helped, and some introduced significant flow instabilities and large temperature fluctuations.

The reason for the SHRT-17 discrepancy was identified to be an issue with the instrument label. The label for the SHRT-45R Z-Pipe inlet temperature measurement clearly identified that instrument's location. The label for the SHRT-17 measurement suggested that instrument was in a similar location. Discussions with a former EBR-II analyst revealed that the measurement was actually a combination of several measurements, possibly a weighted average of some of the twenty-one subassembly outlet temperature measurements. A specific combination of these measurements could not be found to match the measured data but it was concluded that the measured data for SHRT-17 did not represent the Z-Pipe inlet. The SHRT-45R model also had room for improvement with the Z-Pipe inlet temperature. During the first minute of the test as the pumps are coasting down, the SAS4A/SASSYS-1 temperature rose faster than the measured data. The 0-dimensional compressible volume model cannot capture the delay caused by sodium traveling through the complicated upper plenum flow paths. After about seventy seconds, the measured data leveled off while the SAS4A/SASSYS-1 prediction continued to rise. A closer examination of the data shows that there was a 60 seconds period where the instrument malfunctioned, and this was followed by an adjustment period for approximately the next minute. Therefore, the measured data were neglected between 75 and 200 seconds.

Between 200 and 900 seconds, the SAS4A/SASSYS-1 prediction was close to the measured data but decreased too quickly. Parametric analysis was performed for the heat transfer coefficient between the upper plenum walls and sodium. Because different surfaces have different heat transfer rates, representing heat transfer with a single coefficient is a difficult task in a complicated volume like the upper plenum, especially during a transient with a wide range of flow rates. However some improvement in the SHRT-45R results could be obtained if the heat transfer coefficient is increased from 50 $W/m^2K$ to 700 $W/m^2K$. This new heat transfer coefficient was implemented based solely on the results of the parametric analyses. Future CFD analysis will help provide a better understanding of heat transfer between sodium discharged from the core and the numerous different structures in the upper plenum.

Revised core outlet temperature results for Phase 2 are illustrated in Figure 6. The SHRT-17 measurement is compared with the inner core outlet temperature because the exact instruments used to produce the SHRT-17 measurement are currently unknown.

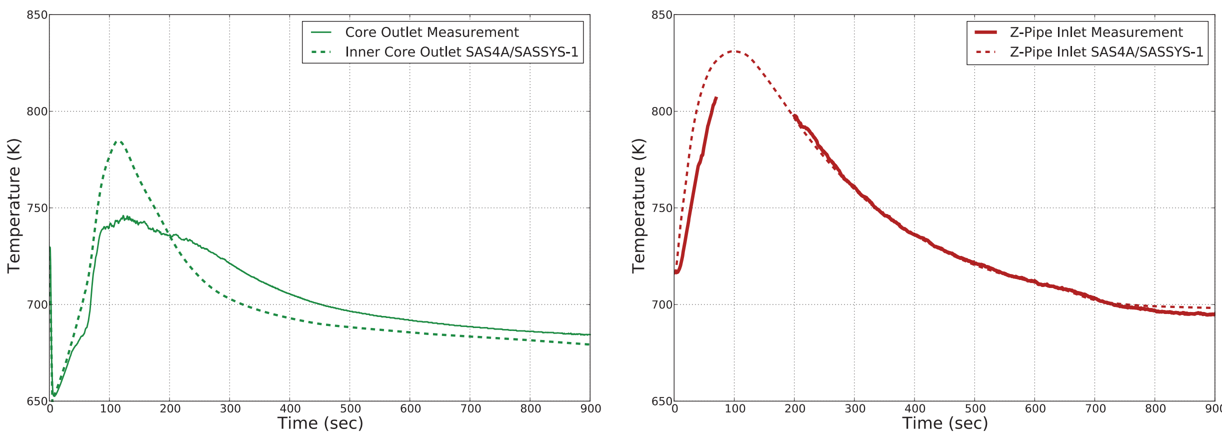


**Figure 6. Phase 2 SHRT-17 Core Outlet (left) and SHRT-45R Z-Pipe Inlet (right) Temperatures**

### 5.3. Z-Pipe Model

While the SAS4A/SASSYS-1 core outlet temperature predictions agree reasonably well with the measured data, one of the harder measurements to predict has been the IHX primary side inlet temperature. Figure 7 illustrates the IHX inlet temperature measurements, along with the measured core outlet temperature for SHRT-17 and the Z-Pipe inlet temperature for SHRT-45R. A thermocouple installed at the end of the Z-Pipe just outside the IHX tubes measured the IHX inlet temperature.

The Z-Pipe was a double-walled structure designed to insulate the hot sodium leaving the core from the cold pool. It was expected that the IHX inlet temperature would be similar to the Z-Pipe inlet temperature, with similar temperature increases and decreases. But the measured data do not reflect that. In SHRT-17 very different IHX inlet and core outlet temperatures were measured. The IHX inlet temperature also drops nearly 20 degrees below the relatively unchanged core inlet temperature. For SHRT-45R the IHX and Z-Pipe inlet temperature measurements were very different during the first half of the test but they showed almost the same trend during the second half of the test.

Initial analysis focused on the steady state Z-Pipe temperature drop, which for SHRT-17 is 9.4 K. This represents a loss of almost 5 MW to the cold pool. Based on the IHX temperature measurements, the primary side rejects 53 MW but the intermediate side receives 60 MW. Losses through the primary vessel walls were small so the intermediate side value is considered more reliable. Additional intermediate temperature measurements upstream and downstream from the IHX also suggest a similar heat rejection rate of 60 MW. The Z-Pipe temperature drop for all full power and full flow SHRT tests was consistently 8 or 9 degrees. The consistency in the IHX inlet temperature measurement suggests that it was not a measure of the average inlet temperature.

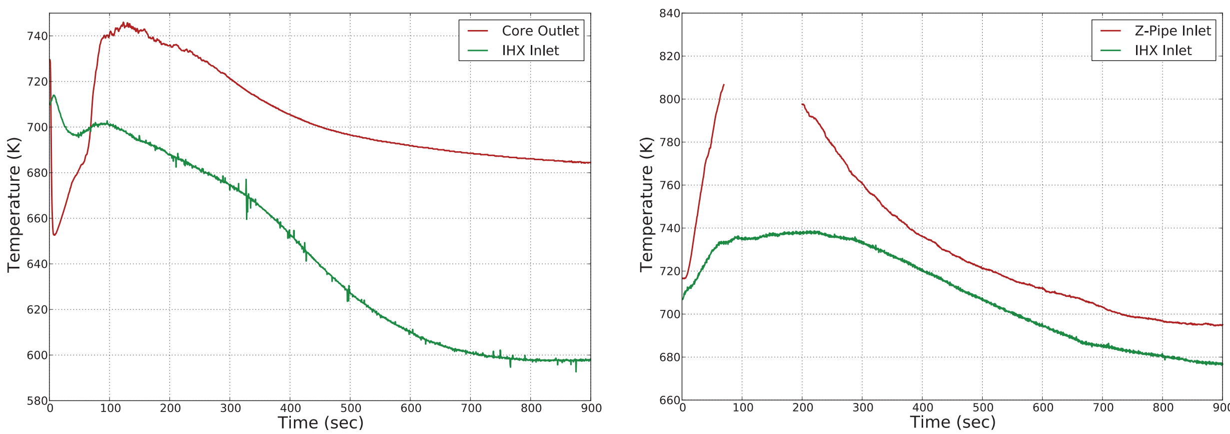


**Figure 7. Measured SHRT-17 (left) and SHRT-45R (right) Hot Leg Temperatures**

To further confirm that the Z-Pipe temperature drop was not as large as the measurements suggest, the overall heat transfer coefficient necessary to reject 5 MW to the cold pool was analyzed. Based on the geometry of the Z-Pipe, a coefficient of 3800 $W/m^2K$ is required. However, the thermal resistance of one stainless steel pipe wall alone limits the heat transfer coefficient to approximately 2900 $W/m^2K$. The second pipe wall and stagnant sodium between the pipe walls would further insulate the sodium in the Z-Pipe. It was therefore concluded that the measurement did not reflect the average temperature of sodium entering the IHX.

After the steady state analysis, the transient IHX inlet temperature measurement was analyzed. The SAS4A/SASSYS-1 model for both tests predicts that the IHX and Z-Pipe inlet temperatures had similar transient shapes. A series of parametrics were performed with the Z-Pipe model to obtain an IHX inlet temperature with a similar shape as the measurement. These parametrics focused on variables that affect the amount of heat rejected to the cold pool, such as heat transfer coefficients and the pipe wall heat capacity and mass. The IHX inlet temperature predicted could not be noticeably improved. Because the Z-Pipe was nearly a foot in diameter and the thermocouple was installed inside the IHX, spatial effects likely affected what temperature was actually recorded. Section 7 describes future analysis that will be performed to better understand the temperature distributions in the IHX inlet and whether the SAS4A/SASSYS-1 Z-Pipe outlet temperature prediction is accurate.

## 6. PHASE 2 RESULTS

### 6.1. SHRT-17 Results

The largest improvement in the Argonne SHRT-17 results from Phase 1 to Phase 2 was in the total flow rate. Adjustments to the pump locked rotor loss coefficient and locking thresholds, which were described in Section 5.1, led to a more accurate high-pressure flow rate prediction. The Phase 1 low-pressure flow rate prediction showed better agreement with the measured data, but accuracy in the high-pressure flow rate is more important to the transient results.

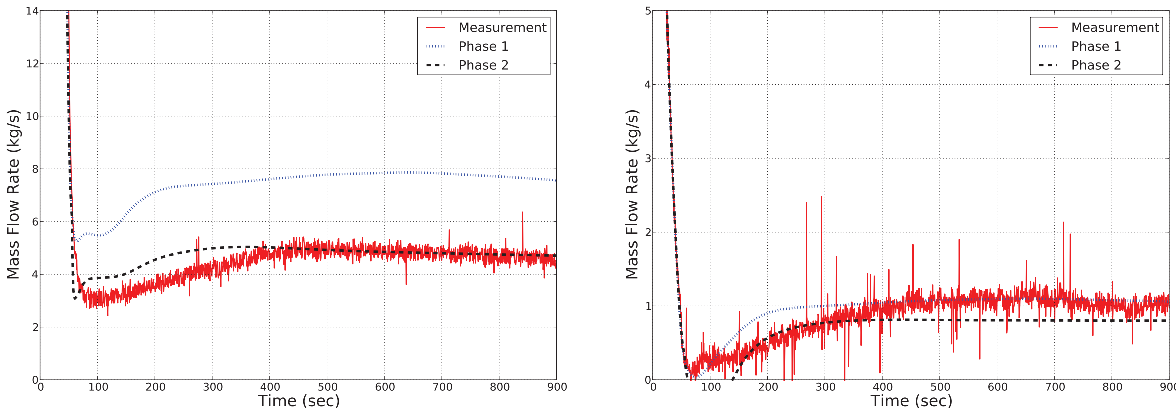


**Figure 8. High-Pressure (Left) and Low-Pressure (Right) SHRT-17 Flow Rates**

Because the primary vessel is so large, the cold pool temperature does not change much during SHRT-17. This leads to rather flat high-and low-pressure inlet plena temperature profiles. The low-pressure inlet plenum temperature decreases several degrees during the test, likely due to heating and cooling in the upper and lower parts of the stratified cold pool. SAS4A/SASSYS-1 predicts relatively flat inlet temperatures because of large thermal inertia. The model does not capture the heat transfer between sodium in the inlet pipes and the stratified cold pool.

The left side of Figure 6 in Section 5.2 illustrates the SHRT-17 core outlet temperature predictions. By correctly identifying the measured data in that figure as a core outlet temperature measurement, not a Z-Pipe inlet temperature, a large discrepancy with the SAS4A/SASSYS-1 prediction was eliminated. Upper plenum and Z-Pipe model modification did not greatly influence the IHX inlet temperature prediction, shown in Figure 9, but further analysis is required to better understand the IHX inlet temperature measurement and the accuracy of the SAS4A/SASSYS-1 Z-Pipe outlet temperature prediction.

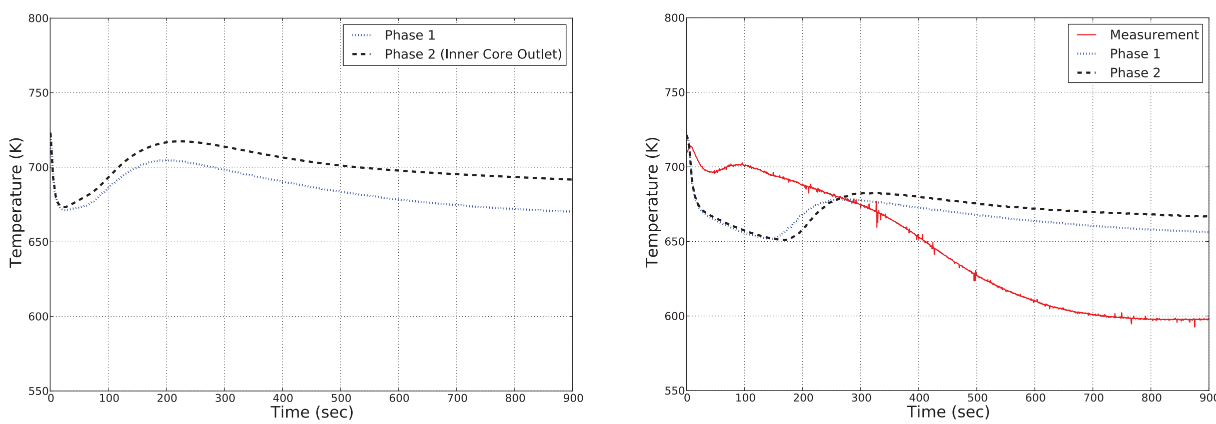


**Figure 9. Z-Pipe Inlet (Left) and IHX Inlet (Right) Temperatures for SHRT-17**

## 6.2. SHRT-45R Results

The SHRT-45R results presented below were calculated using the point kinetics parameters and reactivity feedback coefficients calculated with the Argonne fast reactor neutronics analysis tools suite. Figure 10 compares the predicted total power level with the transient power level, which is the sum of the measured fission power and calculated decay heat. Because the reactivity feedback coefficients were not updated for the Phase 2 model, the Phase 1 and Phase 2 results are very close to each other. The Phase 2 power prediction is slightly higher at the end of the test due to the higher predicted core flow rate.

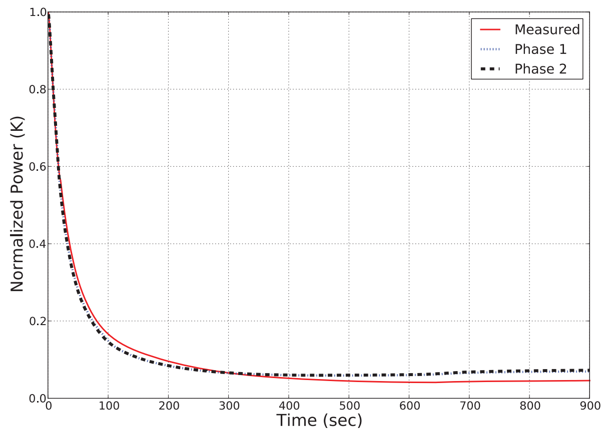


**Figure 10. Total Power for SHRT-45R**

While the absolute differences between the SAS4A/SASSYS-1 and measured power levels are small, the relative differences cannot be neglected. SAS4A/SASSYS-1 underpredicts total power by approximately 20% during the first 200 seconds. At the end of the test, SAS4A/SASSYS-1 overpredicts total power by approximately 60%.

Separate analysis was performed to understand how sensitive the power prediction is to the reactivity feedback coefficients. Part of this analysis used the measured core inlet temperature and flow rate as boundary conditions. Eliminating the core inlet discrepancies reduced the difference at the end of the test from 60% to 33%. Another effect that may be responsible for a large portion of the difference is the radial core expansion model. Currently, the simple radial core expansion is used. A simple subassembly bowing model was tested, improving the power level agreement early in the test. A more detailed bowing model may be required to further improve the power prediction.

Figure 11 illustrates the Phase 1 and Phase 2 flow rate predictions. The slightly higher Phase 2 flow rates are caused by the lower pump locking threshold, which reduces the flow resistance through the pumps. The high-pressure flow rate agreement is not as good as when power is set to the measured data. Those results were illustrated in Figure 4. Underpredicting the power in the beginning of the test leads to lower sodium densities in the hot leg, which causes a smaller driving head and underpredicted flow rates. Similarly, when power is overpredicted at the end of the test, sodium densities are higher and the high-pressure flow rate is overpredicted.

The measured and predicted low-pressure flow rates still disagree. Because the low-pressure flow rate measurement is so low, it is difficult to know if the problem is the SAS4A/SASSYS-1 prediction or an inaccurate measurement. Either way, this is less of a concern because the low-pressure flow rate represents a small fraction of the total flow rate and the high-pressure flow rate is much more important for the reactivity feedback calculations.

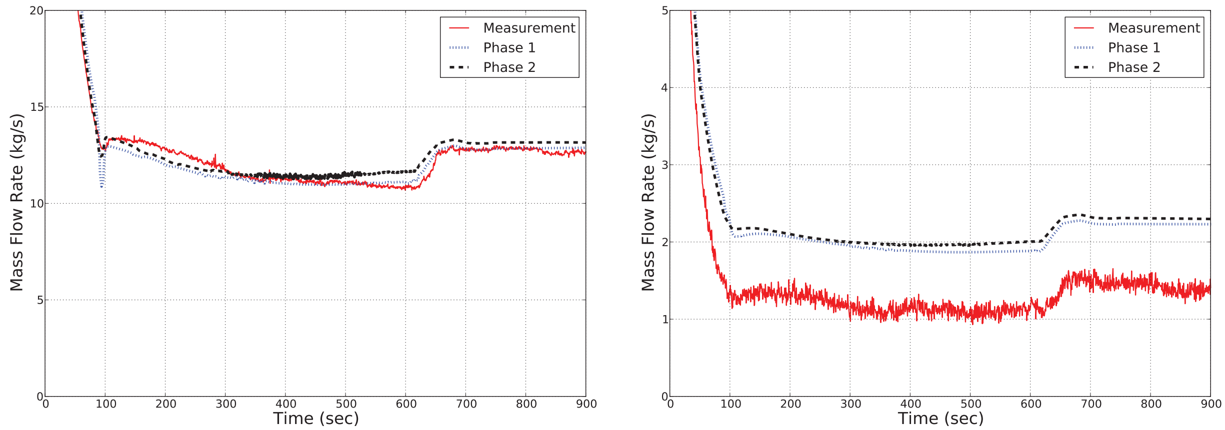


**Figure 11. High-Pressure (Left) and Low-Pressure (Right) SHRT-45R Flow Rates**

Like the SHRT-17 results, the SHRT-45R inlet temperatures do not change much during the test. The high-pressure inlet temperature increases by 5 K while the low-pressure inlet temperature decreases by 4 K. The SAS4A/SASSYS-1 model does not capture these changes because the cold pool stratification is not accounted for and therefore the cold pool does not heat or cool the sodium in the inlet piping.

Finally, Figure 12 illustrates the Z-Pipe and IHX inlet temperature predictions and measurements. Higher Phase 2 flow rates lead to lower core outlet temperatures and therefore lower temperatures in the Z-Pipe. The Z-Pipe inlet temperature rises faster than the measured data because the upper plenum is modeled as a zero-dimensional volume. There is no delay as hotter sodium enters the volume, flows through or around the baffle plate, and enters the Z-Pipe. The Z-Pipe inlet temperature is overpredicted in the second half of the test because the power is overpredicted.

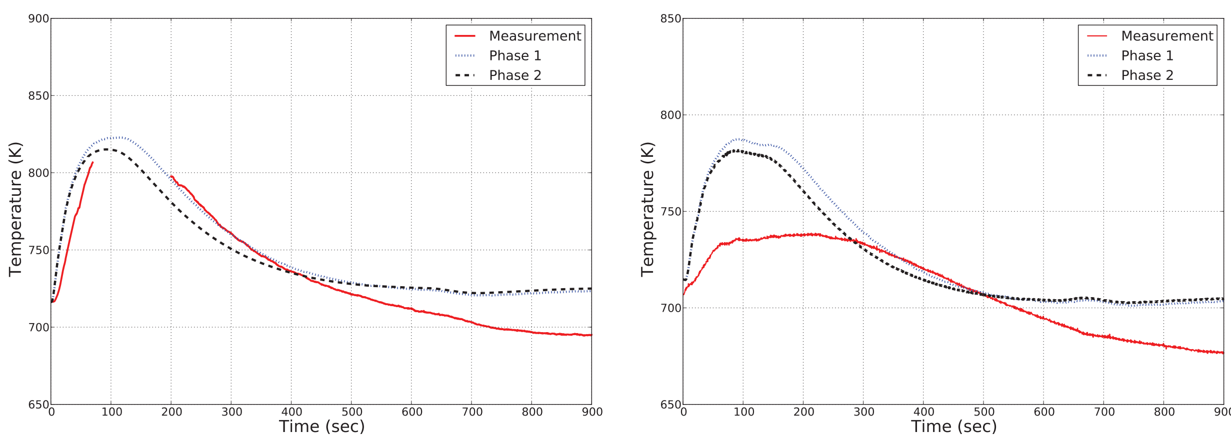


**Figure 12. Z-Pipe Inlet (Left) and IHX Inlet (Right) Temperatures for SHRT-45R**

There is a discrepancy between the SHRT-45R IHX inlet temperature measurement and model prediction. Because the IHX inlet temperature was installed inside the IHX along the outer surface of a tube, not at the inlet where higher flow mixing is expected, it is speculated that the IHX inlet thermocouple did not measure the average temperature of sodium leaving the Z-Pipe. The SAS4A/SASSYS-1 model can provide only the average Z-Pipe outlet temperature so disagreement between the measurement and the model is expected.

## 7. CONCLUSIONS

Overall the SHRT-17 and SHRT-45R tests are well predicted by SAS4A/SASSYS-1. Total power agrees well for SHRT-45R, but larger relative differences in the second half of the test require attention. The high-pressure flow rates are very well predicted for both tests but the low-pressure flow rates are not. Core inlet and outlet temperatures are well predicted but IHX temperatures are not. Future analysis will focus on improving the SHRT-45R power prediction and better understanding the flow phenomena in the IHX inlet.

SHRT-45R reactivity feedback sensitivity studies that were performed separately from the analysis presented above assumed that the measured flow rates were correct. But flow measurement uncertainty is much higher at low flows. Two loss of heat sink (LOHS) tests, BOP-301 and BOP-302, will be evaluated with the SAS4A/SASSYS-1 model. The model predictions can then be evaluated for full primary flow tests and smaller flow measurement uncertainty. Repeating the reactivity feedback analysis for the LOHS tests may provide a better understanding of the power prediction.

Computational fluid dynamics (CFD) analysis of the Z-Pipe and IHX inlet may be performed to better understand the IHX inlet temperature measurement. Heat losses to the cold pool cannot be evaluated properly or modeled correctly without better understanding temperature variations in that region. By using higher fidelity models, the accuracy of the IHX inlet temperature measurement can be determined. If a CFD model can predict similar temperatures, then the CFD model could also be used to evaluate the SAS4A/SASSYS-1 prediction of the average Z-Pipe outlet temperature. Analysis of the LOHS tests may illustrate if the IHX inlet temperature predicted by SAS4A/SASSYS-1 is more accurate at higher flow rates when the IHX inlet temperature likely follows a similar trend as the average Z-Pipe outlet temperature.

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