VALIDATING GOTHIC™ AGAINST RAPID BORON DILUTION TRANSIENTS (ISP-43)

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GOTHIC^{TM} has been used to simulate two test series of International Standard Problem No. 43 (ISP-43). GOTHIC is a versatile and generally applicable software package that solves complex thermal hydraulics problems. It will be demonstrated in this paper that GOTHIC includes the appropriate physics and numerical attributes to accurately model rapid boron dilution transients. The ISP-43 tests were performed in the University of Maryland 2x4 Thermal Hydraulic Loop, which is a reduced height and pressure representation of the TMI 2 reactor system. Test series A tracks the injection of a front of dilute fluid injected into a borated system. The second set, Test series B, is the more practical case of a slug of dilute fluid preceded and followed by borated coolant. In these experiments cold water is used to represent the boron-dilute fluid with thermocouples tracking the spatial and temporal mixing patterns in the downcomer and lower plenum. A GOTHIC model of the facility and boundary conditions was used to simulate both test series, and the results were compared against the experimental data with generally good agreement of both magnitudes and trends. Using GOTHIC over a more traditional CFD analysis package provides distinct advantages in computational cost with about 3 orders of magnitude fewer cells while providing similar accuracy against the experimental data.

I. MOTIVATION AND BACKGROUND

Boron-10, a large cross-section neutron absorber, is used to control the reactivity in pressurized water reactors (PWRs) by varying levels of soluble boric acid (H3BO3) in the reactor coolant. Boron transport and mixing can be important for neutron kinetics and determining if boron precipitation can occur. Particular concerns are boron dilution transients and the potential for recriticality when a un-borated slug of water is transported to the core. The transport and mixing phenomena determine the localized boron concentrations for this event and determine whether recriticality is possible.

International Standard Problem No. 43 (ISP. 43) represents one set of experimental data available for benchmarking computational tools for rapid boron dilution transients. The experiments track the transport of a boron-dilute front and slug into the vessel. Such a scenario could occur due to the actuation of a pump in a previously idle loop. The tests were performed in the University of Maryland 2x4 Thermal Hydraulic Loop, a reduced height, reduced-pressure scale model of the TMI 2 reactor system. Test series A tracks the injection of a front of dilute fluid injected into a borated system. The second set, test series B, is the more realistic case of a slug of dilute fluid preceded and followed by borated coolant. In these experiments cold water is used to simulate the dilute, or un-borated, coolant and hot water is used to simulate the borated primary coolant. A GOTHIC model of the facility and boundary conditions was used to simulate both test series, and the results were compared against the experimental data.

II. TEST DESCRIPTION

The following paragraphs summarize the test facility and the conditions imposed in the two test series. A complete description is provided in Reference 1.

II.A Physical Description of the Test Facility

The facility was an approximately 1/5 scale model of the prototype Babcock and Wilcox (B&W) plant. Figure 1 shows lateral and top view schematics of the facility.

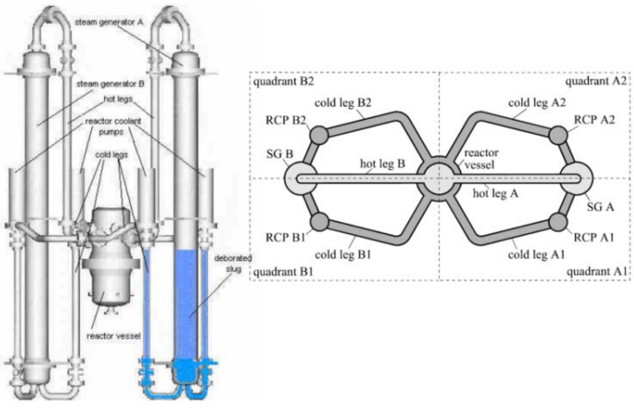

Fig. 1. Lateral and top-view of the UM 2x4 Loop[1]

A cross section of the reactor vessel and instrumentation is shown in Figure 2. The reactor vessel was made of stainless steel and is 1.276 m (50.25 in.) tall with a 0.508 m (20 in.) diameter. The core barrel was made of 304 stainless steel with a 0.419 m (16.5 in.) outer diameter in the upper section and a 0.381 m (15 in.) outer diameter in the lower section. The downcomer gap was thus 31.75 mm (1.25 in.) in the upper region and 50.8 mm (2 in.) in the lower region. These characteristics make the test facility similar to most operating PWRs with the exception of the backwards-facing step in the downcomer and the absence of obstructions in the lower plenum.

The inside surface of the vessel and both surfaces of the core barrel were coated with a thin layer of insulating material to minimize heat transfer from the downcomer region to both the atmosphere and core regions. Heat transfer between the downcomer and these regions could affect the observed mixing pattern. Reference 1 estimates less than 10% of the fluid thermal energy was lost between the entrance and exist of the downcomer.

Two hundred sixty-five thermocouples (TCs) are located in the downcomer and lower plenum at locations shown in Figure 2. In the most highly instrumented levels, TCs are positioned every 15 degrees (24 TCs around the circumference), and in the less instrumented levels, TCs are spaced every 30 degrees.

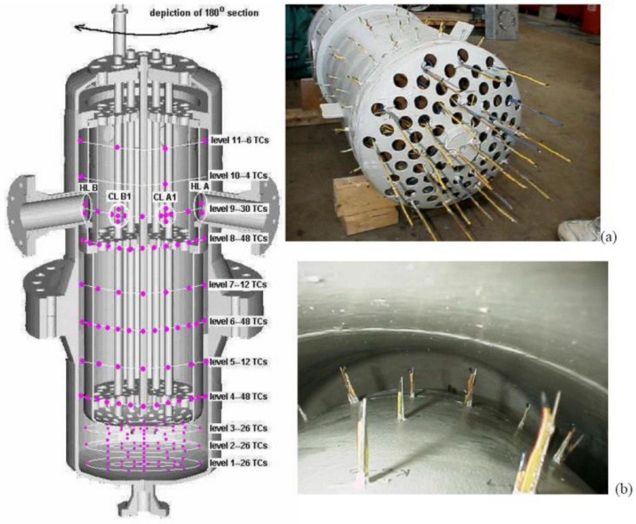

Fig. 2. Thermocouple locations in the downcomer with mountings on the core barrel and final position within the downcomer[1]

II.B Test Parameters

In all test series analyzed herein, 3 of the 4 cold legs were isolated using metal plates inserted in the flanges that attach the cold legs to the reactor vessel. This limited the flow to only CL A1.

The apparatus was configured to inject a cold water front in test series A. The entire system, Figure 3, was filled with cold water. The primary system was heated while a check valve stopped the heated water from entering the external tank. After the system had reached about 75 °C the heaters were turned off and the system was allowed to come to rest for a few minutes. The pump on CL A1 was turned on and continued to run until the injection tank was nearly empty.

Test series B injects a cold water slug using the loop configuration shown in Figure 4. The slug was conditioned separately in the slug injection tank at about 20 °C. The primary system was heated to about 70 °C using the system heaters with flow recirculating through CL A1 and HL A. When the primary system reached the target temperature the recirculation was stopped and the cold water was injected into the lower region of the steam generator. After about 55 L of cold water was injected, the injection tank was isolated from the primary system. The pump on CL A1 was turned on and ran for about 200 seconds, which transported the slug of cold water into the vessel.

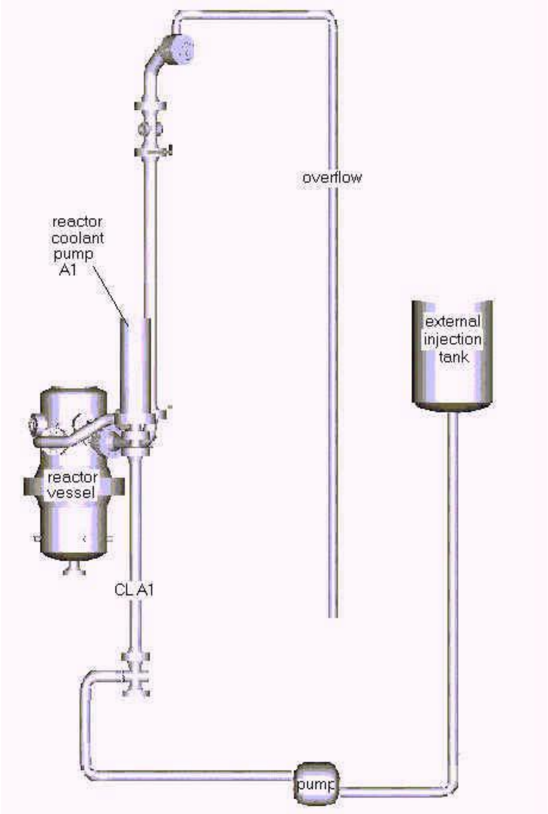

Fig. 3. Test series A loop configuration[1]

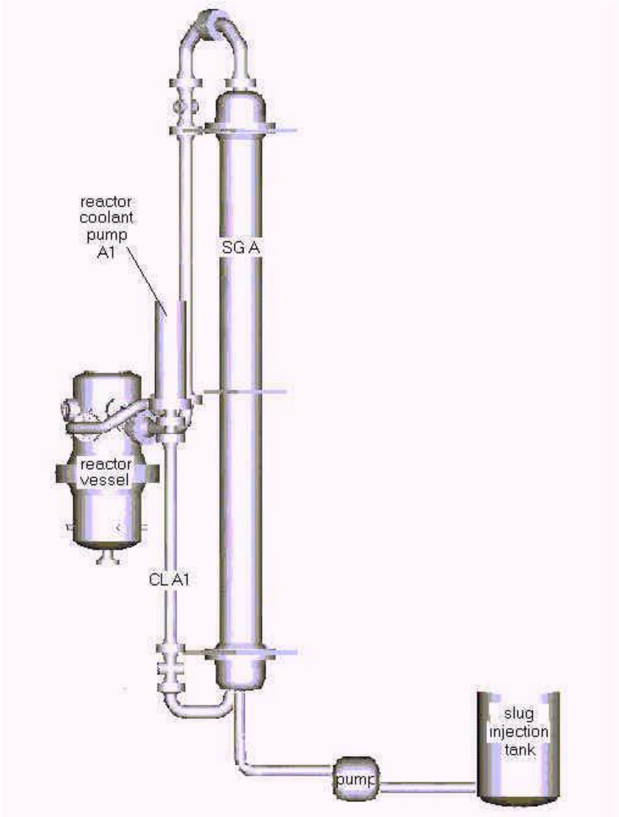

Fig. 4. Test series B loop configuration[1]

III. GOTHIC

GOTHIC is a versatile and generally applicable software package that solves complex thermal hydraulics problems. It solves the conservation equations for mass, momentum and energy for multicomponent, multi-phase flow in lumped parameter and/or multi-dimensional geometries. GOTHIC has several features that make it well suited to tracking boron transport and mixing including: component tracking capability, full treatment of fluid-fluid stress terms in the momentum equations, diffusion (molecular and turbulent), and second-order accurate advection schemes.[2]

III.A. Component Tracking

The component tracking capability included in GOTHIC is very flexible and allows for materials such as aqueous solutions (e.g., boric acid), solid particles (e.g., debris), or dissolved gases to be tracked. Each component is characterized by user defined values for the material density and specific heat. Boron can be treated as a component in the liquid phase with proper input for the material characteristics. GOTHIC models the convective transport as well as molecular and turbulent diffusion for each tracked component. The momentum and energy equations for the continuous liquid field use effective fluid mixture density and heat capacity values that are calculated based on the volume occupied by the component.

III.B. Fluid-Fluid Stress Terms and Diffusion

GOTHIC provides a 3-dimensional treatment for multiphase flow, including the full treatment of the fluid-fluid stress terms that govern momentum transport due to mixing. GOTHIC considers both viscous shear and turbulent diffusion of momentum, where a two-equation turbulence model is used to calculate the turbulent diffusion coefficients. GOTHIC also includes the effects of molecular, thermal, and turbulent diffusion in the fluid mass and energy equations. Additionally, both molecular and turbulent diffusion contributions are considered in the component (e.g., boron) mass balance equation. All of these terms and contributions are required to accurately capture the localized boron concentration.

III.C. Second-Order Accurate Advection Schemes

GOTHIC includes second-order accurate spatial schemes for the convection terms in the mass, energy and momentum balances. These schemes allow GOTHIC to more accurately model boron transport by reducing the amount of numerical diffusion relative to the first-order upwind schemes that are traditionally applied in thermal-hydraulic codes within the nuclear industry. This is important for capturing and preserving sharp concentration or temperature gradients.

IV. MODEL DESCRIPTION

A GOTHIC model of ISP-43 was constructed using GOTHIC Version 8.1(QA) (Ref. 3), which represents the latest release. Figure 5 shows the control volumes, flow paths, and boundary conditions which represent a complete model of this experiment. The model consists of 2 subdivided control volumes and 6 lumped parameter control volumes. The same GOTHIC model was used for test series A and test series B with initial and boundary conditions being the only modifications.

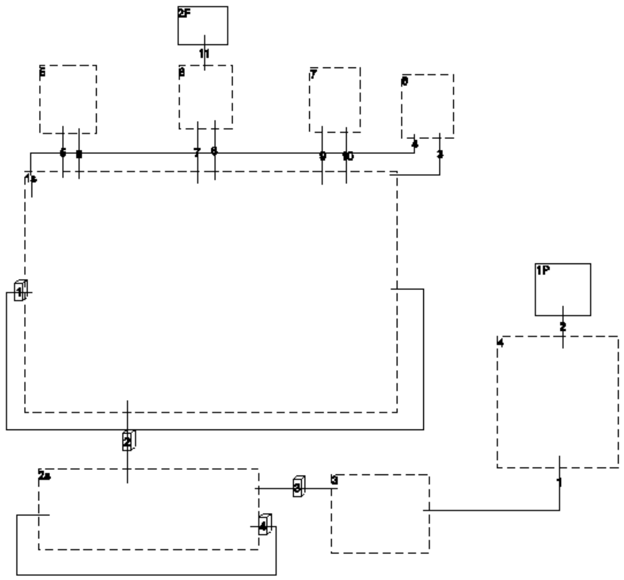

Fig. 5. GOTHIC Model; ISP 43

Volume 1s represents the “unwrapped” downcomer, volume 2s is the “unwrapped” outer region of the lower plenum, volume 3 is the inner region of the lower plenum, volume 4 is the lower part of the core barrel, and volumes 5, 7, and 8 are the portions of the blocked cold legs that connect to the downcomer. Volume 6 represents the inlet cold leg. This volume is made to be much smaller than the other cold legs so that the boundary conditions which are given at the inlet to the downcomer can be used directly for boundary condition 2F, but not so small as to be time step limiting.

The unwrapped downcomer, volume 1s, was subdivided into a 24x2x19 grid which is displayed in Figure 6. Grid lines were divided evenly in the x-direction in 24 intervals to create enough resolution to adequately compare the azimuthal temperature distribution to the experimental results. The y-coordinate represents the radial direction in the downcomer and was divided into two intervals to model the gap change from the upper to lower downcomer. The 19 z-direction cells were set up to match the measurement levels from the experiment and to maintain fairly consistent cell size throughout the volume. The hot legs were modeled as cylindrical blockages at the appropriate coordinates as shown in Figure 6.

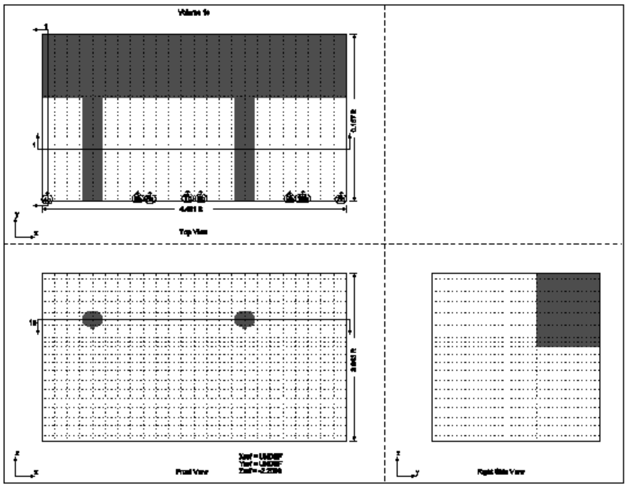

Fig 6. Unwrapped Downcomer Subdivided Volume

Flow paths and 3-D connectors are used to connect the volumes and to wrap flow around the downcomer and outer region of the lower plenum. Area changes from the cold legs to downcomer, downcomer to lower plenum, and lower plenum to core barrel are modeled as sudden expansions or contractions with appropriate loss coefficients.

The initial conditions are set to match the measured conditions at a nearly uniform temperature of 75°C (167°F) for test series A and 70°C (158°F) for test series B. For the inlet boundary condition at CL A1, the temperature and flow rate are matched to the experimental data shown in Figures 7 and 8 for test series A and B respectively. The outlet boundary condition is set to atmospheric pressure.

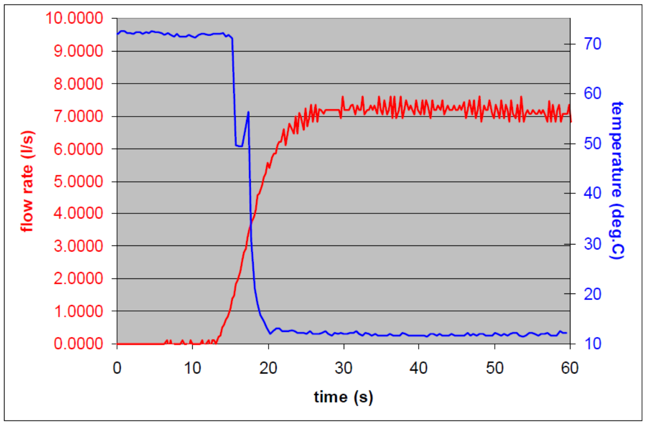

Fig. 7. Test series A inlet boundary conditions[1]

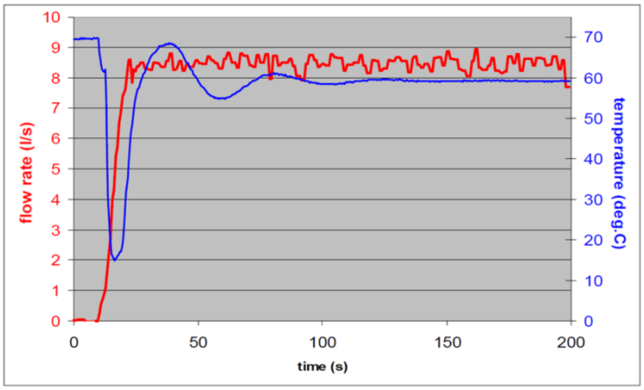

Fig. 8. Test series B inlet boundary conditions[1]

Consistent with the minimal thermal losses stated in Reference 1, heat transfer to and from the walls was neglected in the GOTHIC simulations.

V. RESULTS

Generally, good agreement between GOTHIC predictions and experimental data is obtained for both test series A and test series B. 3-D color contour plots were used to help visualize the flow and verify that flow patterns were developing as expected. The experimental flow pattern in Figure 9 and the result of the GOTHIC simulation in Figure 10 verify that GOTHIC is capturing the relevant phenomenon to replicate the flow profile from the experiment.

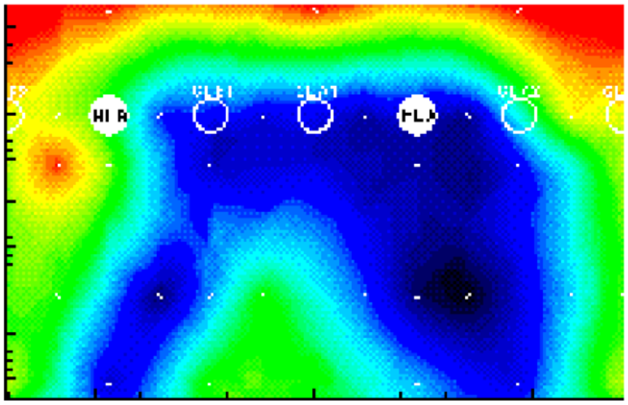

Fig. 9. Experimental temperature contour plot of "unwrapped" downcomer for test B at 48 liters injected[1]

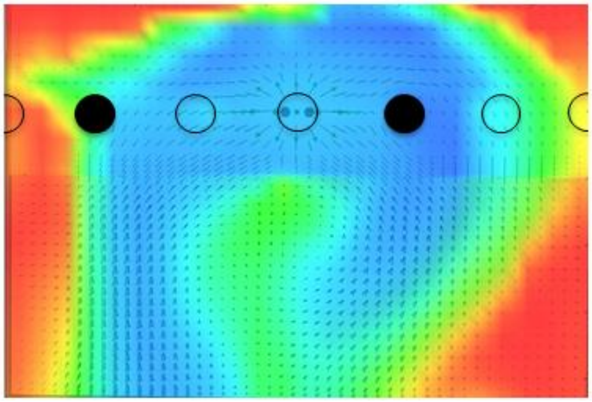

Fig. 10. GOTHIC temperature contours and velocity vectors for test B at 48 liters injected

For more objective comparison of the flow mixing characteristics, the average, standard deviation, maximum, and minimum temperatures at the exit of the downcomer (level 4) and at the elevation just below the inlet (level 8) from the experiments and simulations were compared. Azimuthal distributions for these levels at select times were also evaluated. Based on the color contour plots there does appear to be some notable discrepancy between the experimental data and GOTHIC results in the area directly above CL A1. However, there was much less experimental data collected in this region so the discussion will focus on the other areas.

The reported data in Reference 1 represented averages of several runs with significant variation in the experimental results due to small changes in the initial and boundary conditions. These changes potentially spanned the transition between momentum and buoyancy driven flow mixing, as evidenced by the two distinct mixing patterns reported in Reference 1. For this reason, only one trial from each test series was used as the nominal test case with the boundary conditions shown in Figures 7 and 8. GOTHIC was setup to use the initial and boundary conditions from these two test cases and the results of the simulations are compared to the corresponding experimental data for each nominal test case.

V.A. Test Series A

The circumferential average temperature just above the downcomer outlet (level 4) is shown in Figure 11. The maximum, minimum, and standard deviation at that elevation are shown in Figures 12, 13, and 14. The GOTHIC results were post-processed in a similar manner as the experimental data. Figures 12 and 14 show that there are some areas in the GOTHIC model at level 4 that don't see much mixing and remain quite hot for some time until eventually mixing around 50 seconds. Meanwhile, Figure 13 shows that there is at least one location that was not well mixed at the start of the experiment or has an error in the measurement because the minimum is about 3°C (6°F) below the mostly uniform starting temperature.

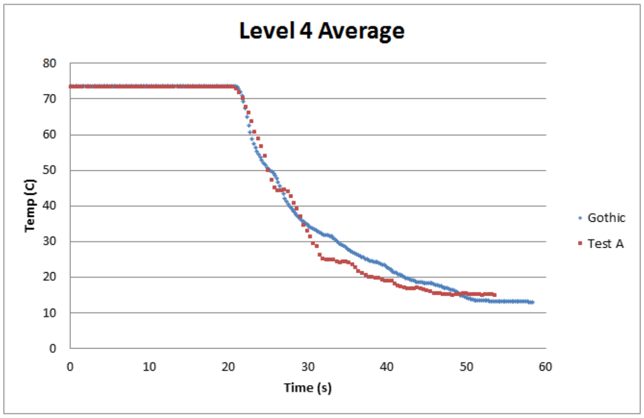

Fig. 11. Average temperature at level 4 for test series A

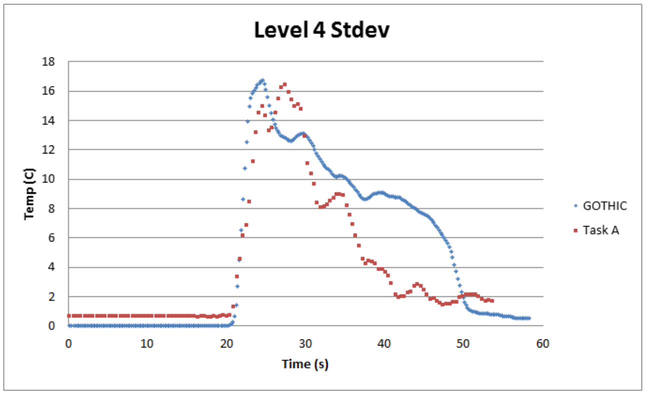

Fig. 12. Standard deviation of temperature at level 4 for test series A

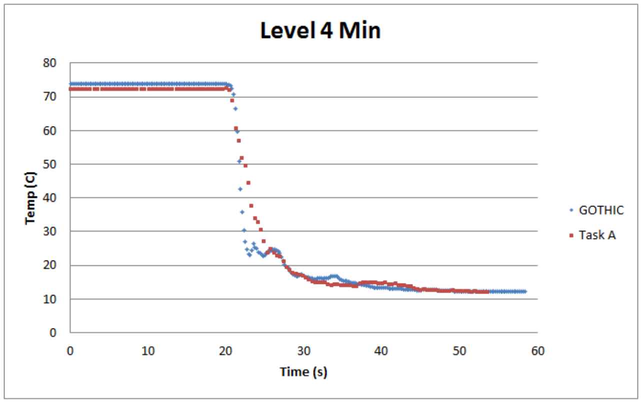

Fig. 13. Minimum temperature at level 4 for test series A

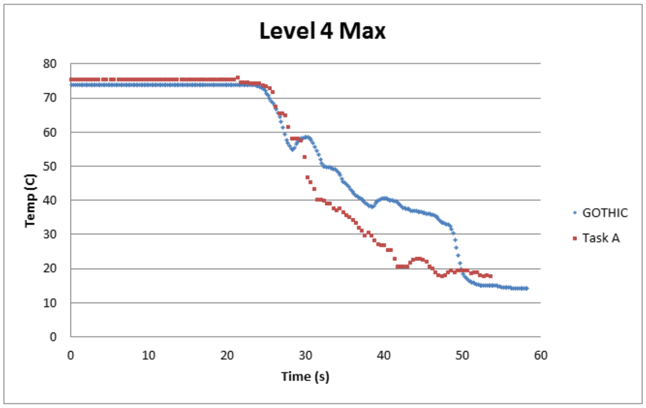

Fig. 14. Maximum temperature level 4 for test series A

Results from the experiment and GOTHIC model for the level just below the inlet, level 8, are shown in Figures 15-18. The model shows good agreement at this level with the one discrepancy that some channels become significantly colder very quickly in the GOTHIC model, leading to a higher standard deviation in the temperature distribution. The localized difference in initial vessel temperature that was seen at level 4 is even more pronounced at level 8 with an initial difference of about 4°C (7 °F).

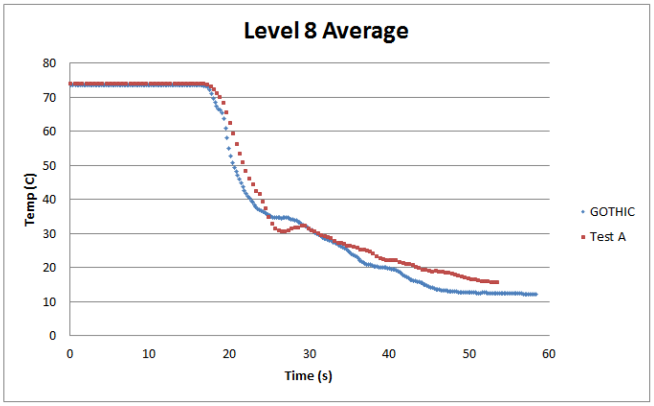

Fig. 15. Average temperature at level 8 for test series A

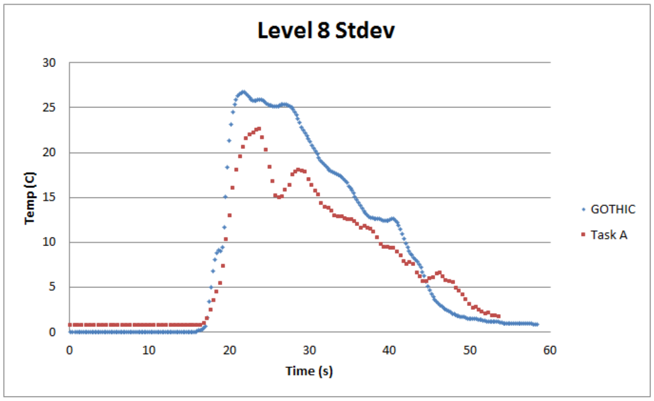

Fig. 16. Standard deviation of temperature at level 8 for test series A

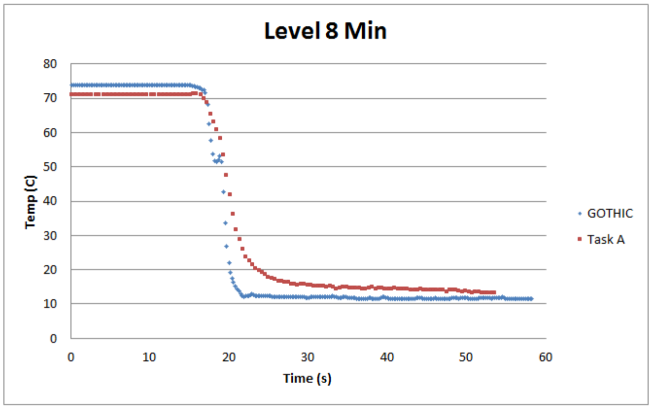

Fig. 17. Minimum temperature at level 8 for test series A

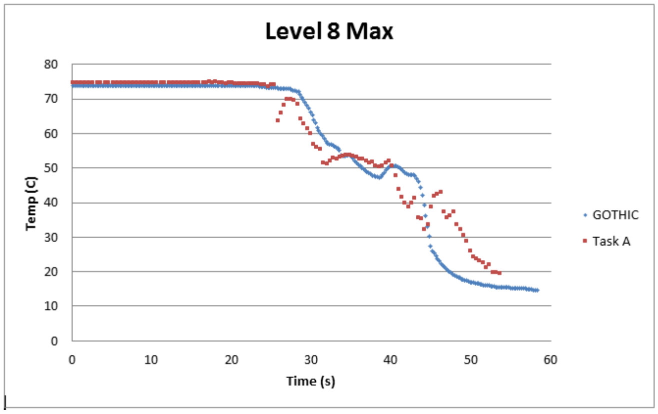

Fig. 18. Maximum temperature at level 8 for test series A

Azimuthal distributions of levels 4 and 8 are also included in the comparisons. Figures 19-22 show good general agreement from the GOTHIC model and the experiment.

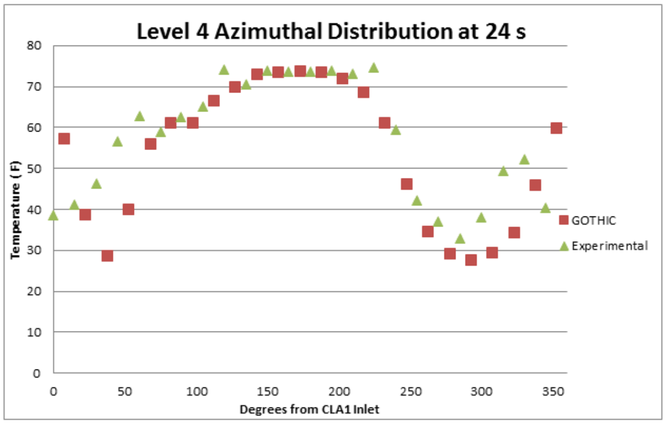

Fig. 19. Azimuthal distribution at level 4 at 24 seconds for Test A

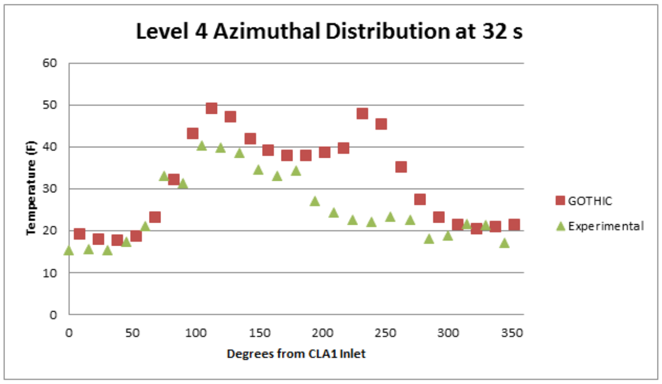

Fig. 20. Azimuthal distribution at level 4 at 32 seconds for Test A

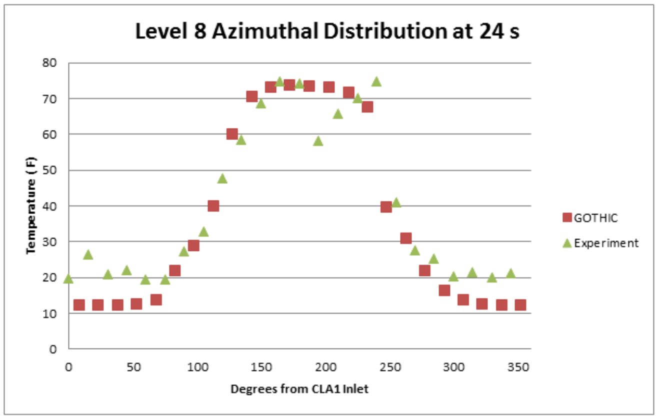

Fig. 21. Azimuthal distribution at level 8 at 24 seconds for Test A

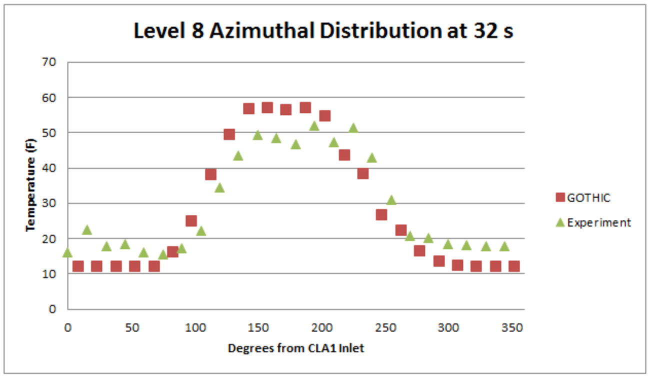

Fig. 22. Azimuthal distribution at level 8 at 24 seconds for Test A

V.B. Test Series B

Test series B will use the same principle figures of merit as test series A. Figures 23-26 show the level 4 average, maximum, minimum, and standard deviation for test series B. There is excellent agreement between GOTHIC and the experimental results in both magnitude and trends. Comparisons for level 8 are shown in Figures 27-30 where excellent agreement is also observed.

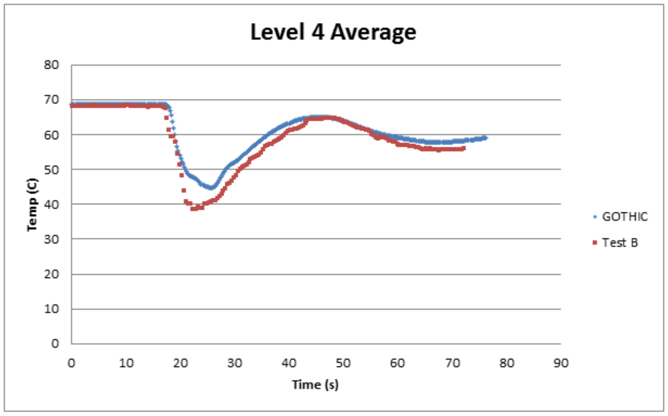

Fig. 23. Average temperature at level 4 for test series B

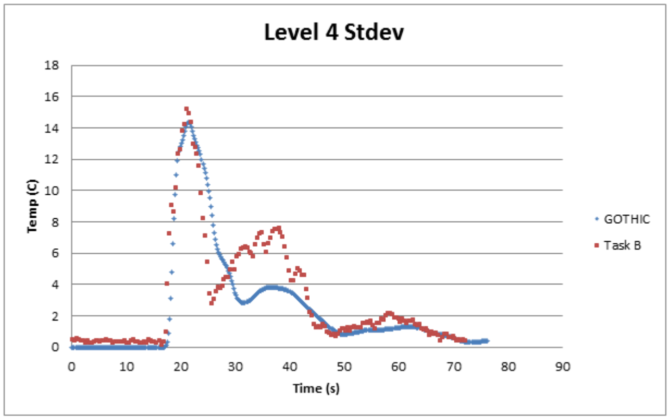

Fig. 24. Standard deviation of temperature at level 4 for Test B

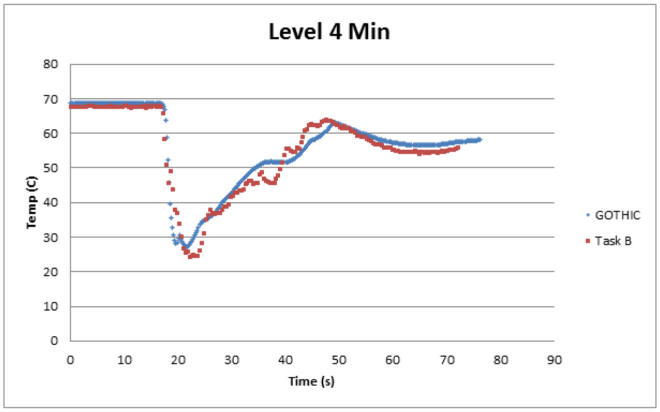

Fig. 25. Minimum temperature at level 4 for Test B

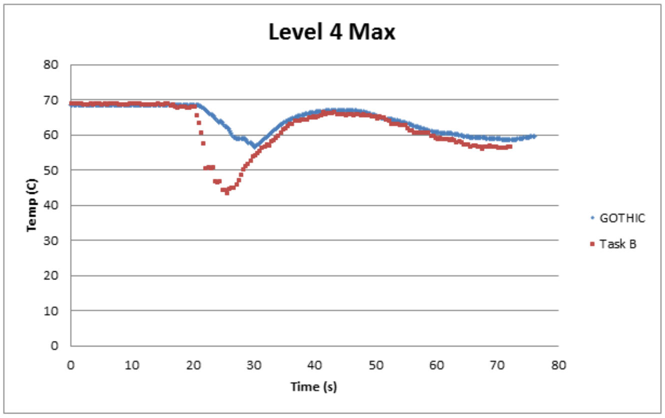

Figure 26. Maximum temperature at level 4 for Test B

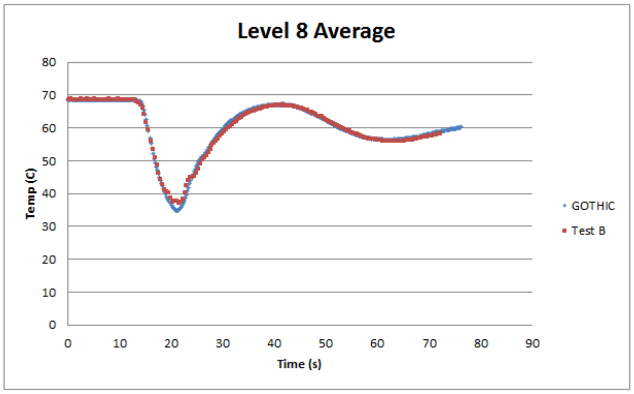

Figure 27. Average temperature at level 8 for Test B

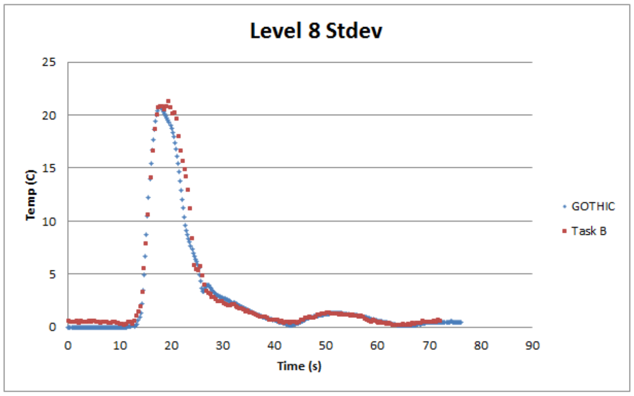

Figure 28. Standard deviation of temperature at level 8 for Test B

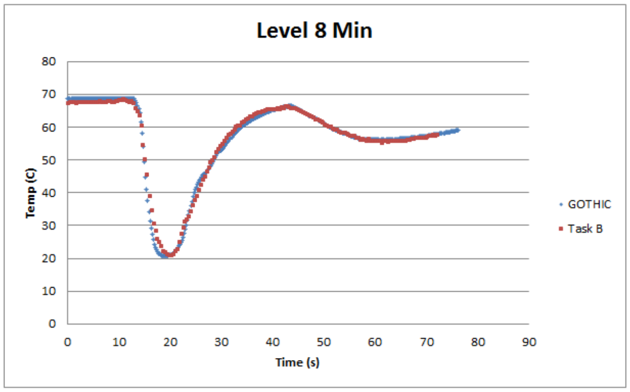

Figure 29. Minimum temperature at level 8 for Test B

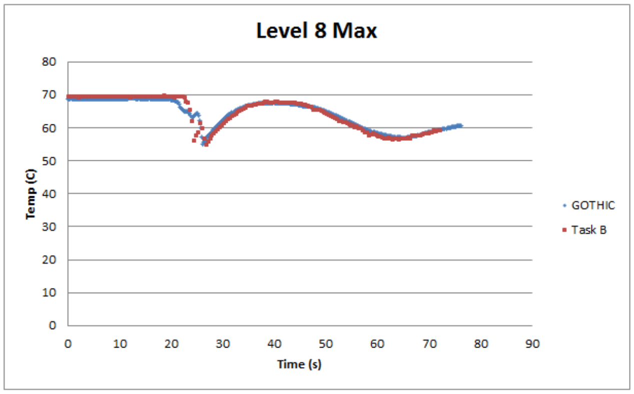

Figure 30. Maximum temperature at level 8 for Test B

VI. CONCLUSION

The results of this benchmark have shown that GOTHIC provides a computationally efficient solution for boron mixing without sacrificing accuracy. The GOTHIC simulations use about 3 orders of magnitude fewer computational cells compared to the CFD tools used in Reference 1 and proved to be at least as accurate if not more accurate than the results documented in that same reference. The capability to analyze boron mixing further extends the range of applications that can be evaluated in GOTHIC.

ACKNOWLEDGMENTS

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REFERENCES

1. NEA/CSNI/R(2000)22, ISP-43: Rapid Boron Dilution Transient Experiment, Comparison Report, March 2001.
2. J. W. Lane and T. L. George, “Development of a Multiple Liquid Component Capability in GOTHIC to Better Support Boric Acid, Radiological, and GSI-191 Analyses”, NURETH-16, Chicago, IL, August 2015.
3. GOTHIC Thermal Hydraulic Analysis Package, Version 8.1(QA). EPRI, Palo Alto, CA: 2014.